“SEEING LIKE A ROVER”:
IMAGES IN INTERACTION ON THE MARS EXPLORATION ROVER MISSION

A Dissertation
Presented to the Faculty of the Graduate School
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Doctor of Philosophy

by
Janet Amelia Vertesi
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This dissertation analyzes the use of images on the Mars Exploration Rover mission to both conduct scientific investigations of Mars and plan robotic operations on its surface. Drawing upon three years of fieldwork with the Mars Rover team including ethnography, participant observation, and interviews, the dissertation contributes to the literature in Science & Technology Studies by advancing the analytical framework of *drawing as*: a practical corollary to Wittgenstein and Hanson’s concepts of *seeing as* that allows the analyst to explore the work of producing scientific images that *draw* natural objects as analytical objects to enable future representations and interactions. Further, images of Mars betray the social organization of the mission team and its commitment to consensus operations. Observing how images of Mars are *drawn as* trustworthy documents, *drawn as* a hypothesis or as a record of collective agreement, *drawn as* a map for the Rover and *drawn as* a public space, the dissertation demonstrates how interactions with and around Mars Rover images support this political orientation, making the Rover’s body a body politic.
Janet Vertesi’s interest in representation in scientific practice is evidenced in several published projects in Science and Technology Studies. Her work on the seventeenth-century controversy over lunar mapping conventions has been published in *Studies in History and Philosophy of Science* and in *Endeavour* magazine, while her contemporary study of the London Underground Map and users’ representations of urban space was published in *Social Studies of Science*, earned the Hacker-Mullins prize from the American Sociological Association’s Science, Knowledge and Technology section, and was highlighted in *National Geographic* magazine. In addition, Vertesi’s engagement with the Human-Computer Interaction community, including an internship at Intel’s User-Centered Design group and participation at CHI and CSCW, has resulted in publications with Jofish Kaye et al. on personal archiving practices, with Kirsten Boehner, Phoebe Sengers and Paul Dourish on cultural probes in design practice, and with Carl DiSalvo on imaging the city.

Vertesi was born in Vancouver, Canada; she holds an M.Phil. in the History and Philosophy of Science from the University of Cambridge, and a B.A. in Religion, Literature and the Arts and Science Studies from the University of British Columbia. At Cornell, Vertesi served as President and as Events Chair of the Graduate and Professional Student Assembly and Graduate Chair of the University Assembly, where she established the tradition of the Grad Ball, negotiated a graduate student seat on the Board of Trustees and spearheaded the campus-wide Graduate Community Initiative. She is one of the inaugural Action Canada Fellows and a Young Woman of Distinction Nominee. An avid traveller and committed to internationalism, she has lived in six countries and studied eight languages. In her spare time, she enjoys singing, playing classical piano, and jamming with jazz bands on her bright blue electric concert harp.
For Anna, Nick and Peg.
ACKNOWLEDGEMENTS

Throughout my Ph.D., I have been fortunate to work with some of the finest scholars in my field: scholars whose work consistently challenges my thinking about science and technology and pushes my ideas to the next level. First and foremost, I owe enormous thanks to my committee chair, Michael Lynch. Mike’s deep intellectual engagement with my work always helped me to articulate my ideas more clearly and explore them more deeply. At the same time, his belief in my work throughout my graduate career has sustained me through the highs and lows of academic research. I thank him and his wife Nancy Richards for being an important part of my family in Ithaca, and for letting me “do too much.”

Reading *The Golem* as a sophomore I realized that I wanted to pursue a career in Science Studies, and I am therefore honored by the opportunity to work with Trevor Pinch; as his advisee and teaching assistant I have always valued his keen and knowledgeable perspective on the sociology of technology and scientific knowledge. Phoebe Sengers quite literally changed the way I think about technology; by opening up avenues to collaboration with the human-computer interaction community she also changed the way I think about my potential contribution as a scholar. I also benefitted tremendously from the guidance of Peter Dear, whose sharp and insightful comments on my work are highly valued. My undergraduate advisor Stephen Straker followed my studies with enthusiasm until his death in 2004; I can imagine the sparkle in his eyes if he only knew what I ended up writing about ...

While my early training is in the history of science, I chose Science & Technology Studies at Cornell because I believe that the history, philosophy and sociology of science share critical questions which can only be answered with a dialogical, comparative approach. When I first moved from a historical site to a
contemporary one, then, I was excited to get out of the archive and see “how science is really done.” I told myself that while I couldn’t be in the room when Cassini and Huygens heatedly discussed their observations of Saturn in the Paris Observatory, I could be in the room when famous Mars Rover scientists traded theories over their images and instruments. What I discovered in the Rover team was an active and engaged community of scientists who pushed the boundaries of my methodological toolkit in researching and writing up this dissertation. It is one thing to cite interviews conducted in laboratories or office desks, to transcribe meeting recordings, or search through a myriad emails and publications -- all of which form much of the primary material in this dissertation. But the term “Personal Conversation” fails to capture the subtleties of dinner invitations and conference happy hours let alone discussing the mission with team members while joining their department’s 10-mile bike ride; trying to conduct an interview while keeping up with a MER scientist on his daily run around a large urban park in the sweltering heat; learning about Martian geology on the dance floor with a scientist conducting his weekly salsa class; or providing the ceremony music for an instrument operator’s wedding. For this analyst, learning to “see like a Rover” was an immersive experience.

I was privileged in my fieldwork for this dissertation to meet so many of the scientists, students and personnel involved in the Rover mission, and to be welcomed to the MER team as one of their family. With the occasional exception of high-profile members of the community, the names of my study participants herein have been changed for the purposes of confidentiality; however, I want to take this opportunity to express my deepest thanks to the mission members who contributed to this project. I owe an enormous debt to Steve Squyres and to Jim Bell, without whose welcome, interest, assistance and patience I could not have produced this dissertation. In addition to Steve and Jim, several MER team members endured ongoing conversations
beyond meetings and interviews: especial thanks to James Ashley, Diane Bollen, Emily Dean, Paul Geissler, Jeff Johnson, Jeff Moore, Steve Ruff, Michael Sims, Rob Sullivan and Dale Theiling. I thank Ray Arvidson (Washington University St Louis), Phil Christensen (Arizona State University), Bill Farrand (SSI), Ken Herkenhoff and Jeff Johnson (USGS), Jeff Moore (NASA Ames Research Center), Ron Li (Ohio State University), Alistair Kusak (Honeybee Robotics), Mark Powell and Cindy Alarcon-Rivera (JPL) for welcoming me to their respective institutions as a visitor and enabling me to tour their labs, observe how they conducted their science, and interview so many of their students, staff, and faculty colleagues. I am grateful for interviews, observations, lab tours and other conversations with Oded Aharonson, Ray Arvidson, Don Banfield, Charlie Barnhart, Shianne Beers, Ross Beyer, Natalie Cabrol, Wei Chen, Bill Clancey, Barbara Cohen, Larry Crumpler, David Desmarais, Kaiching Di, Doug Ellison, Trevor Graff, Ron Greeley, Amitabh Ghosh, John Grant, John Grotzinger, Ed Guinness, Shaojun He, Ken Herkenhoff, Scott Hubbard, Ju Won Hwangbo, Byron Jones, Jonathan Joseph, Kjartan Kinch, Thomas Kneissel, Amy Knudson, Laszlo Keszthelyi, Geoff Landis, Ron Li, Kim Lichtenberg, Scott Maxwell, Justin Maki, Tim McCoy, Patrick McGuire, Mary Mulvanerton, Elaina McCartney, Tim McConnaughy, Chase Million, Gerhard Neukum, Jeff Norris, Cindy Ota, Oleg Parisen, Gale Paulsen, Sylvan Piqueux, Jon Proton, Mariek Schmitt, J.R. Skok, Pamela Smith, Larry Soderblom, Nicole Spanovich, Bob Sucharski, Ashitey Trebi-Ollennu, Roxana Wales, Lorenz Wendt, Don Wilhelms, Sandra Wiseman, Bo Wu, Lin Yan and Aileen Yingst. I also thank Cindy Alarcon-Rivera and Mary Mulvanerton for their invaluable assistance with managing access restrictions.

In terms of financial support, a Doctoral Dissertation Improvement Grant from the National Science Foundation (Award No. 0645945) permitted me to visit so many of these scientists in their home institutions, at conferences and scientific meetings. I
am thankful also to the Social Sciences and Humanities Research Council of Canada for a Doctoral Research Fellowship (Award No. 752-2003-0451), to the Action Canada Foundation, and to Cornell University for financial support through their Sage Fellowship program. As a Doctoral Fellow at the Conell Society for the Humanities I enjoyed the space and collegial atmosphere in which to turn hundreds of pages of field notes, meeting transcripts and photographs into a dissertation, and I thank Brett de Bary, Tsitsi Jaji and Rachel Prentice for their encouragement during that time. A grant from the History of Science Society in conjunction with the NASA History Office allowed me to spend a semester at NASA Ames Research Center exploring the history of this mission: I thank Bill Clancey, Charlotte Linde, and Michael Sims for their engagement with my project and for facilitating my visit to the Intelligent Systems division. Chapters of this dissertation have been presented at three Social Studies of Science Society annual meetings, at alt.CHI, and at the American Sociological Association. I am also grateful to speaking invitations and the opportunity to hone my ideas among colleagues at the University of Fribourg, the Max Planck Institute for the History of Science, the Massachusetts Institute of Technology, Pennsylvania State University, and the Athena Science Team Meeting in Washington, DC.

But a committee, a fieldsite and funding do not a dissertation make. I could not have completed this work without a group of friends and family whose caring support, insight and sense of adventure sustained me throughout this journey. Jofish Kaye has helped me think through many of the ideas in this dissertation and in other papers, and I am grateful for his intellectual and personal companionship as much as for his dinner parties and interventionist massages. I am also extremely grateful for the tight friendship and rigorous conversation of my S&TS cohort, Shay David, Lisa Onaga and Alan Dafoe; my fellow S&TS students Katie Proctor, Nicole Nelson, Anna Geltzer
and Manjari Mahajan; and close friends Deladem Kusi-Appouh, Dave Proctor, and Emily Dean. Thank you for being my Ithaca family.

In addition to this tight-knit group, members of the S&TS department at Cornell sat through so many of my department and conference talks, offering their advice and criticisms to help me refine my ideas; I thank them as well as Stacey Sullivan, Debbie Van Gelder and Judy Yonkin for their crucial administrative support. Also at Cornell, the Culturally Embedded Computing Group provided an exciting space for exploring ideas, building close friendships and a critical mass of ‘cool kids’ at CHI. My talented bandmates in CU Jazz provided a creative outlet and source of balance, especially Matt Robbins, Josh Abraham and the much-missed Evan Wade. My years of service on the Graduate and Professional Student Assembly were lightened by the companionship of Michael Walsh, Michelle Leinfelder, and Amy Richter, and the support of the Cornell Office of Assemblies, Dean of Students and the Graduate School with whom I worked so closely. At home in Vancouver I could always count on sushi with Carina Perel-Panar and Pip Stanaway as well as many trips and holiday celebrations with the “family camping” crew; I also thank Trevor Pugh for saving the day.

My family has been a constant source of strength throughout this process. I cannot thank my parents Les and Catherine Vertesi enough for their endless love and encouragement and my brothers and sister-in law, Campbell, Dave and Bryn, for their unfailing friendship and superb music that continues to sustain me.

Over the course of my most intensive year of fieldwork on the Rover mission -- between September 2006 and September 2007 -- I lost all three of my remaining grandparents. This dissertation is dedicated to their memory.
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>APXS</td>
<td>Alpha Particle X-ray Spectrometer, an Athena science instrument on the Rovers.</td>
</tr>
<tr>
<td>ATC</td>
<td>Approximate True Color, an algorithm for producing images that approximate the color sensitivity of the human eye.</td>
</tr>
<tr>
<td>Athena</td>
<td>The project name for the suite of interrelated instruments that the Rovers carry as their “science payload”.</td>
</tr>
<tr>
<td>EOS</td>
<td>End of Sol: a weekly meeting at which scientists discuss their ongoing scientific work and Long Term Planning issues.</td>
</tr>
<tr>
<td>ESA</td>
<td>The European Space Agency.</td>
</tr>
<tr>
<td>Hazcam</td>
<td>Hazard Avoidance Cameras, two pairs of cameras with fish-eye optics mounted on the front and rear of the Rovers under the deck looking over the wheels.</td>
</tr>
<tr>
<td>HiRISE</td>
<td>High Resolution Imaging Science Experiment, color camera on board the Mars Reconnaissance Orbiter.</td>
</tr>
<tr>
<td>ITAR</td>
<td>International Traffic in Arms Regulations: the legal restrictions on foreign nationals involved in American space missions.</td>
</tr>
<tr>
<td>JPL</td>
<td>The Jet Propulsion Laboratory in Pasadena, CA. A part of California Technical Institute (CalTech), JPL is a NASA contractor for most robotic missions, such as the Rovers. JPL engineers tested, built, and now operate both Rovers on Mars.</td>
</tr>
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LTP  Long Term Planning: the activity of producing “strategic” plans for the Rovers, i.e. longer duration goals for driving or science. LTP discussions occur during End of Sol meetings. The “LTP Lead” is the scientist in charge of managing these discussions and keeping the big picture in mind during the immediacy of “tactical”, or day-to-day, operations. This position rotates every few weeks among a group of mission scientists.

MAESTRO or SAP  The Rovers’ science activity planning software. Allows the team to keep track of planned scientific observations alongside engineering operations over the course of the day on Mars.

MER  Mars Exploration Rover: standard abbreviation for the mission team, personnel and robots.


MI  Microscopic imager, an Athena science instrument on the Rovers.

MiniTES  Miniature Thermal Emission Spectrometer, an Athena science instrument on the Rovers. Modeled on TES and Themis, the Thermal Emission Spectrometers in orbit around Mars on *Odyssey* and *Mars Global Surveyor*.

MOC  Mars Orbital Camera, built by Malin Space Science Systems, on board the *Mars Global Surveyor* orbiter, although an earlier version was lost with the *Mars Observer* spacecraft.
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>MOLA</td>
<td>Mars Orbiter Laser Altimeter, an instrument that uses a laser sensor to determine topography of Martian terrain. The colorful MOLA map of Mars is considered the standard projection for Mars: one MER scientist called it “the control for the planet.”</td>
</tr>
<tr>
<td>Mössbauer</td>
<td>Mössbauer spectrometer, an Athena science instrument on the Rovers.</td>
</tr>
<tr>
<td>MRO</td>
<td>Mars Reconnaissance Orbiter, a NASA vehicle in orbit around Mars from November 2006.</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration, the sponsoring agency for the MER project.</td>
</tr>
<tr>
<td>Navcam</td>
<td>Navigation Cameras, stereo black and white engineering cameras mounted on Rovers, slightly inset from the Pancams.</td>
</tr>
<tr>
<td>OMEGA</td>
<td>Orbital spectrometer, built by a French team, aboard the European Space Agency’s Mars Express orbiter.</td>
</tr>
<tr>
<td>Pancam</td>
<td>Panoramic Cameras, the ‘science cameras’ on the Athena Science payload, providing stereo color imaging.</td>
</tr>
<tr>
<td>PDL</td>
<td>Payload Downlink Lead, person in charge of monitoring instrument health and recent communication activities from the spacecraft. This position rotates among a group of scientists.</td>
</tr>
<tr>
<td>PUL</td>
<td>Payload Uplink Lead, person in charge of compiling commands for the Rovers’ upcoming operations on daily basis. In the case of the Pancams, RAT and MI, the position is occupied by one of a few specially-trained PULs; PULs for other instruments rotate among engineers, scientists and graduate students on the team.</td>
</tr>
</tbody>
</table>
RAT  Rock Abrasion Tool, a grinding tool that can brush or grind away outer ‘rinds’ of rocks, part of the Athena Science suite on board the Rovers.

RP  Rover Planner, the specialist engineers at JPL responsible for driving the Rovers.

Sol  A Martian Solar day, 24 hours, 39 minutes and 35 seconds long. Also used to abbreviate the day of the mission: i.e. Sol 1500 is the Rover’s 1500th day on Mars. Each Rover landing counts as Sol 1 for that Rover.

SOWG  Science and Operations Working Group. Refers to the daily tactical meeting of scientists and engineers in which a plan is agreed upon for the next day’s operations.

Team Meeting  Biannual meetings among the science team when they meet face to face to discuss their ongoing scientific results and Long Term Planning strategies.

TES  Thermal Emission Spectrometer, in orbit on Mars Global Surveyer (lost in November 2006). TES is the orbital version of the Rovers’ MiniTES.

THEMIS  Thermal Emission Imaging System, infrared spectrometer in orbit on the Mars Odyssey orbiter. Made by the same group of scientists who made TES and MiniTES. THEMIS infrared data is used as the baseline for most geological maps of Mars.

VIZ  Software Visualization suite developed at NASA Ames Research Center, specializing in 3-dimensional modeling.
INTRODUCTION: SEEING MARS AND DRAWING MARS

“The image never changes, but you can manipulate the image, and everyone sees something different.” (Kwame, Rover Planner)

Figure 1 NASA’s Mars Exploration Rover. Courtesy NASA/JPL/Cornell.

It is April 2006 on Earth, and NASA’s two Mars Exploration Rovers, called *Spirit* and *Opportunity* (Figure 1), have been on Mars for more than a full Martian year -- that is, over two Earth years. *Opportunity*’s landing site on Meridiani Planum is located very close to the Martian equator, but *Spirit*’s location on the other side of the
planet at Gusev Crater is a few degrees to the South.¹ At Gusev, winter is coming, and as the hours of sunlight in each Martian day dwindle, Spirit's solar panels generate a declining flow of power. Millions of miles away on Earth, the specialist engineers at NASA's Jet Propulsion Laboratory who drive the Rovers -- called Rover Planners -- examine hundreds of images of Spirit's location in order to identify a “Winter Haven” for the robot. They are looking for a slight rise in the nearby terrain where the slope will naturally tilt the Rover’s solar panels towards the winter sun as it treks across the Martian sky. The clock is ticking: the engineering team knows that if Spirit cannot make it to its Winter Haven in time, it will not survive the winter.

The team locates a place for the Rover to spend the winter -- which they name McCool Hill, after an astronaut lost on board the Space Shuttle Columbia -- and commands the vehicle to begin the drive to that location. But on its way there, Spirit’s wheels dig deep into a sandy patch of reddish brown soil and grind to a halt. The Rover is trapped. As if the pressure of the coming winter weren’t enough, Spirit’s right front wheel had recently stopped responding to commands. Almost 700 days past its 90-day warrantee the wheel has jammed into an awkward angle, never to turn again, and the robot must now be driven backwards – and gingerly at that. The engineering team struggles to free their crippled Rover, driving back and forth over the Martian terrain. As they do so, they order the robot to take pictures of the sand beneath its wheels so that they can analyze the soil and figure out a way for the Rover to get out. As the days pass, it becomes clear that Spirit will never make it to McCool Hill in time. When the vehicle is finally extracted from the sand trap, its robotic mast swivels to take a picture (Figure 2) of its roughed up tracks etched in the Martian soil with its stereo, color Panoramic Cameras, called the Pancams, before driving to a small ridge a few meters away and parking for the season.

¹ An overview of the Mars Exploration Rover Mission is in Squyres et al. (2004). Traverse maps for both Rovers are located in Appendix A.
As Spirit becomes a “lander” for a few months, and as Opportunity is busy on the other side of the planet driving several kilometers towards Victoria Crater, this provides a chance for the members of the Mars Exploration Rover team to shift their focus to other related projects. At the Jet Propulsion Laboratory the Rover Planners convene in their local “test bed”, a site at JPL designed to simulate Mars, to practice with their Earth-bound Rover how best to drive Spirit with only five working wheels. At Cornell University the Payload Element Lead for the Rovers’ Panoramic Cameras puts the finishing touches on his book of Martian images, Postcards from Mars (Bell, 2006), the Principal Investigator balances his popular freshman course with visits to NASA Headquarters in Washington, and both punctuate this work with frequent speaking engagements around the United States and Europe. Participating Scientists at their private and public universities, or at research centers like the Smithsonian, NASA Ames, or the US Geological Survey head out to field sites with a similarity to Mars -- the Spanish Rio Tinto, or the Atacama Desert, or Antarctica -- to conduct
research in these “Mars Analog” environments. Scientists placed in the “Long Term Planning” group call each other to discuss orbital images of the area and agree on how best to get Opportunity to Victoria Crater, or which direction Spirit should drive when power levels rise again. Emails flurry among the mission listserves circulating drafts of papers, posters and abstracts for comments and contributions before they are set off to journals like Science or Nature and conferences like the yearly Lunar and Planetary Science Conference or the American Geophysical Union. And several times a week, this far-flung group of scientists and engineers dials into meetings on a teleconference line to check in with their Rovers and with each other, to request specific observations from Spirit and Opportunity, and to plan each Rover’s operations over the next few days.

Susan Lee, one of the collaborating scientists tenured at a private university in the United States, decided to put her time to use by learning how to work with the Pancam instrument. A physicist by training who builds spectrometers and studies the chemistry of soils, Susan was attracted to the opportunity to complement her work with Rover instruments like the MiniTES thermal emissions or APXS alpha particle and x-ray spectrometers with the Pancam’s imaging capabilities. As she put it, “You shouldn’t limit yourself to one [Rover] instrument, it’s the most foolish thing you can do.” During Spirit’s winter season Susan traveled to Cornell to spend time with the Pancam operators there, to train for the role of Pancam Downlink Lead which requires reporting daily on the status of the remote instrument, and to learn how to use the Pancam image processing tools. During her training she practiced her newfound skills on recently-acquired images, including the pictures of the patch of roughed up soil,

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2 Consistent with Cornell Institutional Research Board requirements, the names of team members have been changed throughout this dissertation to protect their identity. The few exceptions are when the individual’s position on the team is central to the story at hand and therefore impossible to anonymize.

3 Interview, Susan, June 18, 2007.
now called “Tyrone.” Shortly thereafter, Susan suggested at the daily teleconferenced planning meetings that the team reconsider Tyrone as one of the top priorities for investigation once the winter was over and solar power was up. The rest of the scientists and engineers, on the other hand, had little interest in returning to what they saw as a dangerous sand-trap, and were instead discussing moving west to explore another side of the plateau-like region they had named Home Plate.

In October 2006, Susan made a presentation at one of the weekly teleconferenced science team meetings, called the “End of Sol.” This was not a particularly momentous occasion: all members of the science team, whether professors or graduate students, staff scientists at universities or civil servants at NASA centers, are regularly encouraged to share their in-progress results with the rest of the team at these meetings before the findings are published. As the name implies, End of Sol meetings used to be held daily at the end of the Martian day, but due to funding and time constraints implemented after the first 90 days of the mission, they are now held once a week. Susan was the last on the agenda for the day, after a discussion of results from the Rover’s spectrometers. Her thirty-two Powerpoint slides used the team’s two Pancam images of Tyrone to produce a number of visual transformations: True Color, black and white, annotated, false color, and even spectral graphs (Figure 3). According to Susan, while the Rover was struggling to free itself from Tyrone it had revealed

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4 Rover naming conventions arose in the thick of the Primary Mission and are based on the precedent set by Pathfinder as well as on a set of written recommendations by NASA Ames Human Factors Engineers (Wales, Bass, and Shalin, 2004). While it is beyond the scope of this dissertation to discuss the naming of places on Mars as a political matter, it is worth noting that different sites that the Rover visits on Mars are assigned a thematic group of names based on elements of the team’s experience related to the site. A team member is responsible for collecting names related to that theme: these are circulated and then names are selected among the list as new ‘targets’ -- rocks, driving locations, points of interest, features on the landscape -- are identified. Schemes have included names of towns in China or Denmark to honour national holidays; words related to American holidays like Thanksgiving; the names of the All American Women’s Baseball League or the American Negro League team players in honour of International Women’s Day or African American Heritage Month; names related to Magellan’s or Cook’s voyage of discovery; or even things you put in bowls in honour of the concave shape of a feature. The scheme in operation at the time of Tyrone’s naming was due to St. Patrick’s Day: Tyrone is a county in Ireland. (Documentarian Report, Sol 784, March 18, 2006)
some light-toned soil that was compositionally different than the rest of the reddish brown soil in the area. Further, her visual transformations made the point that there were actually two different kinds of white soil, that they were some kind of salt, that one was possibly deeper than the other; and that the soil turfed up from the deeper layer was changing over time to share spectral characteristics with the soil from the upper layer. The presentation took over one hour, and at the end one of her colleagues laughingly called it, “the visual equivalent of drinking from a firehose” -- but the team ultimately acknowledged that they could see the two toned soil that she pointed to and that it was intriguing, and discussed taking further images of Tyrone from their winter haven position.5

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5 End of Sol meeting, October 11, 2006.
A few months later, in February 2007, the Rover mission’s participating scientists came together for a face-to-face meeting at Caltech in Pasadena, California: a site close to JPL so that the engineers and NASA personnel involved in the mission could attend, but located at a university where members of the science team would not require security clearance to participate. The agenda was packed with presentations of ongoing work by science team members, their graduate students and assistants, and questions flew from the audience at every presentation. Susan’s talk was moved to the last day of the meeting to make time for a discussion about Opportunity’s upcoming exploration of Victoria Crater, but when she finally took the floor, her audience was excited by her results. In her presentation, Susan took three ways of showing the two-toned soil and applied them to eight different pictures of Rover tracks from across the region; she then mapped the location of these tracks to make a claim about the light-toned soil’s stratigraphic location and possible provenance as a water-borne salt deposit. Suddenly the team not only saw the two-toned light soil: they saw it everywhere.

Following Susan’s presentation there was sufficient excitement that the Principal Investigator extended the agenda for an hour-long discussion about the light soil. Scientists around the room excitedly and rapidly traded hypotheses as to what the soil was, where it came from, and what observations would be required to resolve those questions. Is it a salty deposit laid down by water? Is it layers of volcanic deposits from a recently active volcano? When exposed to the atmosphere does it change chemically and turn red to look like the top layer of Martian soil? Suddenly, this was no longer Susan’s observation: this was the Light Soil Campaign, and was considered one of the higher science priorities of the mission. After the meeting, NASA issued a press release including a color picture of Tyrone and announcing the discovery. Despite the danger of getting stuck again in the sands of Tyrone and the
press to move westward to Home Plate, the science team requested that as soon as Spirit had enough power to move that the Rover Planners drive the Rover eastward, back to Tyrone, for more imaging. The series of events that unfolded eventually revealed evidence that the Home Plate area had once been a Yellowstone-like hotspring, and a year later earned a publication in *Science* magazine (Squyres et al., 2008) as one of the most significant discoveries of the mission.

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This brief introductory story offers a snapshot of many of the issues this dissertation will discuss and to which I will return in subsequent chapters. But it also offers a window into life on the Mars Exploration Rover mission for its robots and for the human team members on Earth. As my readers will notice, the two robots on Mars are controlled by a team of people at a distance of millions of miles, and these team members are located hundreds of miles apart from each other too, in different institutions and different time zones. This team is divided into a group of scientists and engineers, each with different responsibilities towards the Rover and with different backgrounds and skills. Some are professors, others are professionals. Graduate students, professors, postdoctoral or staff scientists work virtually alongside civil servants, robotics or software engineers, and hardware developers in private companies. The mission is demanding in terms of their time and their resources, bringing them together multiple times a week for teleconferences and several times a year for face-to-face presentations. Based on these different heritages and different tasks-at-hand, each has a different way of working with the digital images that the Rover returns from Mars. However, without images -- of Tyrone or of any other part of Mars -- it would be impossible for these scientists and engineers to claim to discover anything at all on the Red Planet.
Work with images is central to the science and the operation of the Mars Exploration Rover (MER) mission. Most of the MER team’s scientists are trained geologists, geochemists, or atmospheric scientists, professions with a strong emphasis on field and lab work alongside statistical analysis of large datasets. But given their considerable distance from their field site, the MER team must rely on imagery and software tools to craft knowledge about Mars. Digital image processing to a large extent comprises the essence of ‘doing science’ on another planet; image interpretation, processing and annotations make it possible for a group of scientists located on Earth to discover, explore, or experiment at a distance of millions of miles from their field site. As one scientist explained to me, gesturing to the colored images he was in the middle of processing on his screen, “This is my fieldwork these days, and I sort of get used to the fact that this is the data you have to work with. I would almost feel frustrated being in the field and not having Pancam!” Another concurred, telling me, “We [planetary scientists] have all become what they call ‘pixel-pushers’, instead of field geologists.”

Telling the story about how Susan came to see a new feature of an alien terrain, the analyst could turn to the psychology of perception, evaluate the image’s verisimilitude, or examine the aesthetic qualities that guide Susan’s visualizations. But there is a powerful way to address this story that focuses on the work that Susan does with these images such that her colleagues come to see the two toned white soil -- and see it everywhere. And even before Susan can show these images to her colleagues, taking pictures on a distant planet with robots takes considerable work; it then takes digital and analog work to turn the stream of bits and pixel numbers into an image, and more work to calibrate and tame that image into a trustworthy object of analysis. It

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6 Interview, Ben, June 11, 2007.

7 Interview, Julie, June 12, 2007.
takes further computational work to reveal and conceal different aspects of the image in order to present features for scientific investigation. And all this work is inextricably bound up in the context of the Rover team’s operation of their vehicle on a daily basis, the contingency of site selection and movement between locations on Mars, and the processing of bits returned from cameras, spectrometers, and other instruments on board the Rovers. It is also bound up with the interpersonal, social and political work that the team must achieve daily in and through the operation of two shared robots. Describing and analyzing this work in detail is the subject of the present study.

In this dissertation I ask: how does practical image craft construct meaningful, workable relationships with an alien planet? To answer this question I examine work with digital images as it is embedded in the practices of managing the Rover and managing its human team. As I hope to show, seeing, drawing, and interacting with Mars are iterative activities, inspiring and contingent upon each other in the unrolling narrative of robotic exploration. In their myriad interpretations and projections, and even in their planning and assembly, the Rover team employs images as a resource both to conduct their science and to manage their community.

In my analysis of the use of images in these various interactions on the Mars Exploration Rover mission, I offer three contributions to the study of representation in scientific practice in the field of Science and Technology Studies (STS). Of primary significance is the development of the analytical framework of drawing as. Envisioned as a practical corollary to Wittgenstein’s (1953) seeing as, in which vision is informed by interpretation, drawing as interweaves the related issues of theory-laden observation, disciplinary practices, subject, object and audience in producing an image that relevant actors consider “scientific.” As I aim to show, producing a scientific image is a question of isolating a salient aspect of an object for representation: drawing an object of study as an analytical object. Approaching image work in this
way brings the analyst’s attention to the purposeful practices of visual construal, the work of crafting images such that one can see a particular or even novel aspect of the imaged object through such techniques as image planning, processing, or annotation.

*Drawing as* is an analytical frame, although it is associated with practices that the scientists I study call “teasing out detail” or “making things pop out” of an image. But while it is not an actor’s category, instead of asking what is drawn, asking how and what it is *drawn as* may prove a useful turn of phrase for the analysis of images in the history, philosophy and sociology of science. It requires the analyst to inquire into the work involved in crafting an image that can be taken up in practice as a transparent representation of the object in question. This bypasses questions of reference -- how the image is tied to an object in the external world or whether the depiction reveals the object’s essential nature -- to reveal how image-making in science inscribes a scientific community’s values, organization of work, or epistemology onto the object at hand.

This practical image craft does not take place in a vacuum. A combination of the human, robotic, and computational elements of the MER team dictate how images are *drawn as* in the first place, making the conditions of Rover image production deeply sociotechnical. The Mars Exploration Rovers may be searching for traces of past water on Mars, but to do so they are directed by a team of scientists and engineers for whom an underlying goal for mission success is the continued satisfaction and proper involvement of team members. Images thus not only enable MER scientists to move between representation, vision and interaction with Mars: they also arise from and feed back into a micro-political process of achieving consensus among team members. While discussing how and what images are *drawn as*, I place these images into the context of this unstated but critical mission goal: achieving consensus. Throughout the dissertation, I hope to show how this image work operates within and reinforces the social structure of the team, bringing them together behind the Rover’s
eyes as a unified body engaged in a singular project of remote exploration, and enabling agreement among members of the team. Thus the second contribution of this dissertation to STS is a study of the role of practical image craft within such a sociotechnical system, sustaining and supporting the overall political structure of consensus management.

A final contribution to STS is in the study of techniques of managing trustworthiness in image production under the digital photographic regime. This combines two foci of recent STS literature. First, the issue of trust as essential to a scientific community’s management of truth claims has been well-explored in the history and sociology of science, and has also received much attention in the studies of image-making in science (see especially Shapin, 1994; Daston & Galison, 1992 and 2007; Tucker, 1997). Like other image-making technologies such as photography and drawing, digital images are subject to the critique that because they are manipulated, they might too easily reveal their author’s theory of the world instead of the world as-it-is. MER scientists’ management of such critiques is complicated by the fact that doing science with digital images requires computational manipulation. Second, since the original laboratory studies were conducted in the 1970’s (Knorr-Cetina, 1981; Latour & Woolgar, 1986; Lynch 1985a; Traweek, 1988), practices have changed to encompass new technologies of representation effected in the virtual spaces of keyboards and hard-drives, which may demand that we revisit concepts developed in the early ethnographies in order to open up new questions for analysis and re-evaluate our analytical toolkit. After all, digital labs and artifacts make the identification of “where the action is” (Goffman, 1967) difficult to identify in the lived space of a laboratory until one takes into account the “topical contexture” (Lynch, 1991a) of the digital sites where work is performed; and what qualifies as an “inscription” (Latour, 1990) when digital images are variously composed and recomposed in the ephemeral
space of the computer screen? With these two streams of past work in mind, I show how Rover scientists’ practices of crafting trustworthy, scientific representations of Mars requires a multimodal approach in which the moral and epistemic elements of both expert drawing and passive photography are mutually invoked, in which different kinds of labour must be assigned to the human and to the machine, in which laboratory and field work are called upon to “constrain” digital work to support or challenge hypotheses, and in which the individual scientist is disciplined alongside their images.

**Prior Work And Contribution**

Scientific images are an established topic for research in Science & Technology Studies. Even the first laboratory studies drew attention to the use of pictures in the lab; Bruno Latour’s concepts of inscriptions and immutable mobiles (1990) remain classic STS formulations for the production and dissemination of images. Following their observation that the laboratory functions to turn rats into paper (Latour & Woolgar, 1986), Latour and Woolgar described the inscription of natural objects onto paper and their ensuing circulation as essential to scientific practice. Michael Lynch’s analysis of the art of distinguishing data from artifact in the laboratory setting (1985a) fueled his discussion of pictorial and graphic images as an externalized retina (1990), and Karin Knorr-Cetina and Klaus Amman’s careful conversation analysis in a biology laboratory uncovered some of the talk-in-interaction that stabilizes images and their representational relationships to phenomena (Amann & Knorr Cetina, 1990; Knorr Cetina & Amann, 1990).

These early works spawned great attention to imaging from STS scholars, especially in studies of the biomedical sciences. For example, recent work by Joseph Dumit (2004) and Anne Beaulieu (2001, 2002) has examined PET brain imaging scans, while Hirschauer (1991) and Prentice (2005, 2007) have explored the relationship between visualization and practice in surgery, paying attention to the
construction of meaning through visual interpretation and embodied practices. In a similar vein, Lisa Cartwright (1995) discusses images and models of the female body in medicine that portray differing ideals about sexual difference; Kelly Joyce’s (2008) study of Magnetic Resonance Imaging explores the historical privileging of sight as diagnostic tool and its implications for changing practices in medicine; and Catelijne Coopmans (2006) discusses the complications of data mobility with respect to digital mammogram interpretation, sharing and management. Attention to imaging in fields such as nanotechnology has focused on its science fiction visions of the possibilities that the field might eventually offer (Milburn, 2002). Astronomical images have received somewhat less attention in studies of contemporary science, with the exception of Michael Lynch and Sam Edgerton’s study of the Harvard Smithsonian Observatory (1988, 1996) and Beth Kessler’s recent study of the Hubble Space Telescope (2006). Such studies are essential departure points for this dissertation in terms of how they examine images as the site of practical work that constructs a local meaning for the imaged object, and will be drawn upon throughout whether their examples are of DNA gels or rats, patients’ bodies or distant galaxies.

The history of science, too, has produced several contributions to the visual studies of science that inform this dissertation. Martin Rudwick’s analysis of the visual language of geology (1976) first posited the relationship between a scientific discipline's developing attention to particular objects of study, and scientists’ methods of representing these objects: drawing as takes place at the intersection of these two axes. Lorraine Daston and Peter Galison (1992, 2007) have examined the tension inherent in ‘objective’ representation in their study of scientific atlases, a relationship that I will explore in terms of how images are locally drawn as trustworthy documents. Turning in the final chapter to images produced for wider audiences, Shapin and Schaffer’s concept of virtual witnessing (1985) and Mario Biagioli’s
(1993, 2007) discussion of emblems and patronage prove important for exploring how Mars is drawn as a public space.

Finally, previous studies of representing Mars have also addressed the question of the relationship between overarching commitments to what Mars is like and how it can be known, and how it is drawn. In her doctoral dissertation and in a publication in ISIS, Maria Lane (2005) demonstrates how terrestrial cartographic methods were applied to Mars by competing mappers such as Nathaniel Green, Percival Lowell and Giovanni Schiaparelli. Peter Galison (1998) uses the examples of Lowell’s drawings and subsequent photographs of Mars to demonstrate the importance accorded to the mechanical eye of the camera, and the tension Lowell faced in managing his photographs’ ambiguity as documentary proof of the existence of canals. In such cases we see the importance of existing theories and practices of observing and representing Mars, and how these are balanced alongside methods that can be considered rigorous and scientific by the actors in question.

I complement this literature on imaging in science by showing that the construction of scientific images is a question of drawing a natural object as an analytical object, such that theories, assumptions about and interactions with the object are inscribed into the very image of the object itself, and are taken as its own natural qualities. At stake here is an understanding of how scientific images represent. Because of the ready incorporation of naturalism into scientific drawing and because of the rhetoric of truth value, it can be easy to assume that scientific images can exactly show “the things themselves as they appear” (Hooke, 1665; see also Kemp, 1990). In such a scheme, a “good” scientific image depicts the object with less bias than others, or may require a Borgesian approach to absurdist cartography, wherein a drive to represent terrain ever more ‘perfectly’ requires a complete recreation of the
area. Rather, this dissertation shifts analytical attention to how an object is made visible in representation and to whom it is made visible: what drawn characteristics give it meaning and reference, which are its “principles of inclusion and exclusion” (Fyfe and Law, 1988, p.1), and how the image reflects or projects the values of the community that inscribes it. Precisely which aspects of an imaged object are revealed and which are hidden, why, how, and under what circumstances, is crucial to understanding the role of images in scientific practice. Alongside interest in how images drawn by the MER team represent Mars, therefore, we must remain attuned to how Rover images of Mars represent the team.

The Rover team provides an ideal case study for exploring these interrelated questions of representing and intervening, theory and practice in image craft for several reasons. Images are daily requested, parsed, processed and presented as the working objects of the mission. The team relies on the images returned from the Rovers to present a local context for the Rover’s daily activities. Further, because the team works communally yet is distributed across the United States and parts of Europe, image analysis is a social process, requiring verbalization of local observations across teleconference lines so that others can “see the same thing,” recognize the same detail as salient, and work together to further characterize that detail through the dedicated use of the Rovers’ suite of instruments. That is, scientists must articulate through images, words or some combination thereof, what they are seeing in order to share this viewpoint across the team. Seeing, as an activity, thus moves from being something that happens at the back of the retinal wall or within the brain, to something that is traceable, observable and reportable as collective, verbalized and practical activity. The practical activities of drawing, in this case the

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8 Borges (1946). Such a story calls attention to the ways in which representation is always necessarily selective: indeed, a one-to-one scale “map” would defeat the purpose of mapping entirely, just as an exact replication of an object in its representational form is a pipe dream, no matter how strictly the conventions of naturalism are followed.
digital manipulation of pixels on a screen, comprise what Coulter and Parsons (1991, p.252) would call “the praxiology of perception”: an “appreciation of the modes of perceptual orientation as forms of practical, social actions, capacities and achievements” (italics in original). Knowledge about Mars is practically achieved through MER team members’ daily work with and around images: whether in conversation with each other, in synergy with the remote robots, or through in-house digital imaging software.

Practical action is central to this dissertation in several respects. On the one hand, it betrays an ethnomethodological concern for the kinds of practical activities or statements that account for or otherwise construct meaning in social interaction (Garfinkel, 1967). My attention to the details of how the Rover team manages and manipulates images of Mars is thus rooted in the conviction that such directed activities with images construct both knowledge of Mars and social order among team members themselves. It is also centered in the conviction that these activities can be meaningfully traced through social or material interactions. But on the other hand, paying attention to activity with images inspires renewed attention to the question of the relationship between representing and intervening, famously explored by philosopher of science Ian Hacking (1983). While Hacking believes how an object is represented relies upon how it is interacted with, in this dissertation I demonstrate a counter-claim: that practices of representing are essential to intervening. Interaction is crucial here, as image work on MER not only produces Mars’ visibility, but also presents its possibilities for interaction. How Mars is drawn presents implications for where the Rover drives next.

Rover images in all stages of their production, inception, distribution, and manipulation document this process of visual sense-making. Issues such as professional identity and embodiment are also essential to the process. For example,
prior work on “theory-laden observation” in the philosophy of science posits the importance of theory and/or interpretation to observation in science (Hanson, 1958; Radder 2006), while the concept of “professional vision” (Goodwin, 1994) has brought anthropological attention to the disciplining and disciplinary skills of identifying relevant details in a visual field. Recent studies in STS have also explored the ways in which bodies are conscripted into making sense of phenomena or their representations (Alač, 2008; Myers, 2008; Prentice, 2007). These themes reverberate within cybernetics and artificial intelligence, where research on “active vision” (Findlay & Gilchrist, 2003) in cognitive psychology continues to inspire system-builders to move away from the idea of a passive recipient of visual stimuli that might scan an image for content, to an active and embodied seer whose moving and being in the world actively constructs and makes sense of what is to be seen (see also Letwin et al., 1959; Ballard, 1989). Further, MER images serve as calls to other team members to adopt a scientist’s particular, local vision, suggesting to others how to ‘see the same thing’ and act upon it, recalling Hutchins’ concept of distributed cognition (Hutchins, 1995). This is a visual epistemology rooted in iterative, situated and collective techniques of representation, observation and interaction.

Throughout the dissertation my emphasis is on continuity rather than revolution: I intentionally refer to digital image craft as “drawing” to recall this orientation. This does not mean that I am blind to the unique affordances or challenges that digital media present, but rather that I wish to focus attention on the ways in which digital image making is continuous with other, analog practices in scientific representation, situating digital work within a historical account of image making in scientific practice. This is consistent with STS work that explores how analog practices and the politics of production and representation are encoded into software and hardware as engineers and surgeons, musicians and designers move from analog
to digital tools (Gillespie, 2007; Henderson, 1999; Prentice, 2008). And while the digital has opened up questions about trustworthiness in representation it is important to remember that similar questions plagued early debates about photography (Tucker, 1997) and other optical or witnessing technologies such as fingerprints, microscopes or telescopes (Cole, 2001; Dennis, 1989; Vertesi, 2007). Rather than ask whether or how these questions are unique to digital media, attention to how such questions are managed within the context of the Mars Rover Mission animates the present discussion.

**How Digital Images Work And How To Work With Digital Images**

The analysis in this dissertation relies upon a basic understanding of Rover imagery, digital images and digital image processing that, for the sake of introduction, I outline briefly in this section. Just as Dumit (2004) and Beaulieu (2002) describe communities of researchers who declare that knowing the process of PET scanning determines the right kind of value placed on the image data, my interest in how scientists characterize their instrument’s workings is not so much a technical description as a description of a particular “knowing how” of the instrument’s workings that permits the right kind of “knowing that” about its resulting images.

Each Mars Exploration Rover is equipped with nine cameras: two color panoramic cameras (Pancams) and two black and white navigation cameras (Navcams) atop the Rovers’ masts, two cameras perched over the front and two over the rear wheels of the Rovers under their decks (Hazcams), and one Microscopic Imager (MI) attached to the Rovers’ extendible arm (called the Instrument Deployment Device, or IDD). The navcams and hazcams are considered the Rovers’ engineering cameras, as their images are used to make decisions about where and how the Rovers can drive, while the Pancams and MI are considered part of the Rovers’ scientific suite of instruments and are often programmed to take images related to
specific experiments. I discuss images from each of these instruments in this dissertation, alongside two other kinds of images of note: those produced in association with the MiniTES spectrometer, and images taken from orbital cameras on board the Mars Global Surveyor and Mars Reconnaissance orbiter. The basic description of camera function, pixels, and processing holds for these cameras as well.

To understand how the Pancam in particular can be considered “scientific” it is helpful to review how planetary geologists characterize their cameras and the images these instruments produce. Central to this story is the pixel, or “picture element”: a quantification of the amount of light that hits an electrical photographic detector, called the Charge-Coupled Device (CCD). Instead of a photographic plate that changes color with exposure to light, the scientists on the Rover mission speak of electrical detectors that precisely count the number of photons that hit them. The standard explanatory analogy is that of the “water bucket”: in this account, detectors sit passively like buckets, counting the number of water drops, or photons, fall into them; these are then tallied up and become numerical values associated with each pixel in an image (Figure 4). This pixel can either be displayed as a number, or as a value of a shade of grey in a spectrum from black (zero photons) to white (many). A widely used textbook in introductory image processing presents the waterbucket analogy as a unified story for the activity of astronomical image processors around the CCD array, and a vocabulary about pixels and photons that is elementary to the field:

The simplest and very understandable analogy for the operation of a CCD … in which buckets represent pixels on the CCD array, and a rainstorm provides the incoming photons (rain drops). Imagine a field covered with buckets aligned neatly in rows and columns throughout the entirety of the area … After the rainstorm (CCD integration), each bucket is transferred in turn and metered to determine the amount of water collected. A written record (final CCD
The image that results from this photographic activity is composed of these pixels, numerical records of photon interactions with the CCD plate. Importantly, then, the digital image is both pictorial and numerical. Digital image processors therefore take the pixel seriously as a direct measurement of both photon quantity and photon quality: quality because the light is collected through filters that admit only a particular slice of the spectrum of visible light, and quantity because the number of photons that hits the CCD array results in the numerical pixel value. Scientists may view pixel data in both a numerical and a pictorial way. Indeed, it is always possible to view the raw pixel values listed as a stream of numbers in a text document, although because Pancam images contain 1024 rows and 1024 columns of pixels, the sheer volume of numbers can quickly become overwhelming. Therefore many prefer to plot pixel values on a graph or to apply a mathematical function to them, as will be described.

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9 This story of CCD operation has been in circulation for a considerable amount of time: Michael Lynch recalls it as the standard explanation in use in the Harvard Smithsonian Observatory that he studied with Sam Edgerton, and the image of the waterbucket was also reproduced in Sky and Telescope magazine in the 1980’s.

10 The present discussion is based not only on extensive conversations and observations with MER participants, but also on participation in Dr. Jim Bell’s Planetary Image Processing class at Cornell, Astronomy 310, in the fall of 2005. I am grateful to Dr Jim Bell for allowing me to attend his class as part of my fieldwork on the mission.
further in this dissertation. One might go so far as to say, along with one graduate student I interviewed, that crafting digital images of Mars in color is “really just a visualization tool: all you get from the CCD is a bunch of numbers.” ¹¹

A lot of revolutionary rhetoric surrounds the CCD. Employed in Earth-based surveillance and mapping and first flown to another planet on the Galileo mission to Jupiter, the “new camera system” replaced the vidicom tubes of previous missions like Voyager or Viking and was expected to “provid[e] a much greater spectral response than the television-type cameras.” ¹² And a widely-used introductory textbook on the subject states that the instrument, “will take [its] place in astronomical history along with other important discoveries such as the telescope, photographic plates, prisms, and spectroscopy” (Howell, 2006, p.4). The source of this revolutionary discourse is the idea that, as direct measurements of numbers and qualities of photons, pixels both compose an image by which to identify remote objects, and contain quantitative information about the object’s ability to reflect light, critical to making claims about the its composition and weathering.

Importantly, images on the MER mission are not singular views. In front of the two Panoramic Camera lenses, thirteen carefully chosen color filters rotate on a wheel (Bell, 2003; Figure 5), which enable different filtered images of Mars to be taken from the same camera angle. The resulting frames produce images the same object, but taken through different optical filters that specify a particular subset of wavelengths of light. Combining these filtered images through red, green and blue channels in an image processor produces varying color images of the Martian landscape. Indeed, MER scientists and others speak of the combination of these filtered images as comprising an image “cube” (or “qub”) that can be worked with in different ways: the

¹¹ Thomas, Interview, September 12, 2006.

cube can be “sliced” through at a single pixel point to generate a mineralogical graph, or different images in the cube can be combined in groups of three through red, green and blue channels to create different images described below. Also, the right and left eye images can be combined to create an 3-D view called an anaglyph, viewed through red-blue glasses. This process and the pipeline for imaging in general is illustrated in Figure 6.

Figure 5 The Panoramic Camera, exploded view. Note filter wheel bottom middle of image. Courtesy NASA/JPL/Cornell.

When team members request an image from a Rover, they do so by specifying particular filters. This process is discussed further in Chapter Four. Raw image data that returns from Mars is then constructed and reconstructed into multiple visions of the Martian terrain. For example, combining one set of filters through red, green and blue channels in an image processing program results in what the Rover team calls a “True Color” image to produce “an estimate of the actual colors that you would see if
Figure 6 Diagram of image pipeline on MER. Images courtesy NASA/JPL/Cornell and by permission.
you were there on Mars.” One might also produce a “false color” image by combining a different set of filters through the red, green and blue channels that bear no relationship to the human eye’s sensitivity. To produce these pictures, scientists work with a suite of tools in their image processing software of choice, ranging from hand programming in a language like IDL, to the Pancam software suite, to the USGS’s software ISIS, to commercially-available tools like ARC-GIS or even Adobe Photoshop. While slightly different in terms of their focus, all of these programs allow a scientist to select several frames they wish to combine, dictate which color channels to assign to which frames, and to tweak the resulting color image. At every click of the button, the selected frames can combine to create new visions of Mars.

A note here on the distinction between True Color and false color is essential. True Color is a technical, trademarked term and an actor’s category; instead of assigning a positivist truth value to one kind of image manipulation, it refers to a particular combination of filters that approximates the range and type of light sensitivity exemplified by the human eye. Images generated in some form of True Color have a variety of names, distinguishing different algorithms that encode decisions about what that sensitivity is. On the Rover mission, True Color images released to the public are combined according to an algorithm developed at Cornell called “Approximate True Color” (ATC), so named to emphasize the very constructed code manufactured by a human decision made on Earth instead of from direct experience of Mars. On other missions this algorithm may be differently construed and differently named, as in for example the “Natural Color” images released by the Mars Reconnaissance Orbiter’s HiRISE camera.

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13 I discuss the broader political orientation of “True Color” processing in Chapter Eight.

14 A discussion of disciplinary software preferences follows in Chapter Seven.
As it is used in planetary science, the term “false color” applies to any combination of colors that is not restricted to the human eye’s sensitivity. As will be discussed in detail below, scientists often combine these color filters to reveal aspects of the Martian terrain that their eyes cannot see, such as the infrared, or mineralogical composition. This is critical on Mars, where to the human eye most aspects of the terrain simply appear a dull, reddish-brown. Although spectrometers and altimeters use color gradients to demonstrate height, depth, or temperature, color is not usually applied to a dataset to light up known compositional elements in a scene. Rather, the displayed colors are the result of a ratio between the images inserted into each of the red, green and blue channels on the image processor, and the differences between the image frames are the result of capturing different wavelengths of light. Thus the distribution of colors in a false color image demarcates, highlights or otherwise identifies invisible features of the imaged terrain.

False color is thus said to arise naturally from the mathematical relationship between these image frames, enabling the viewer to see patches of compositional difference when the same rock reflects light in different wavelengths differently. It is therefore not the case that false color is any less truthful or faithful to the represented object than True Color representations, but rather that it stands as a counterfactual to True Color, revealing different aspects of the object. After all, false color makes the otherwise invisible, visible. As one graduate student I interviewed said, pointing at a false color image that revealed Martian thermal data, “That is something you cannot see, so it looks like something you can see.”15

Additionally, slicing through the image cube to create a graph is seen as a diagnostic tool for identifying the imaged object’s mineralogical composition. Because the object will absorb and reflect different quantities of light wavelengths depending

15 Martin, Interview, June 8, 2007.
on the combination of elements and minerals that comprise it, observing that object’s “spectral signature” -- the graph of pixel intensity at a point through each filter -- can inform a scientist that water or iron are present in the rock’s composition. Deciphering what the resulting graph means is often referred to as an “art” that requires deep skill and a “feeling for the spectra”, discussed further in Chapter Seven. Scientists who specialize in reading these spectra refer to “Spectral Libraries”: collections of mineralogical spectra with which they compare and contrast their sample, looking for characteristic swoops and dips with which to identify the object’s composition. Several computer programs also exist that attempt to interpret, or “deconvolve”, complex spectra that result from a mixture of mineralogical components.

On the Rover mission, certain conventions have arisen that are considered particularly good ways of seeing locally relevant details. For example, when Opportunity landed on Meridiani Planum, the Rover was surrounded by spherical hematite concretions that the team now calls blueberries. The mineral hematite is often formed in aqueous environments, and appears to the human eye as dusty grey stone. But because it is slightly less red than most of Mars, combining the images produced by the fifth and seventh filters on the right-eye Pancam (abbreviated R5-R7) which capture infrared frequencies, makes the hematite light up bright blue in the resulting combined picture. The team calls this combination “the blueberry finder”\(^{16}\) and describe it as making the blueberries “pop out” (Figure 7). When looking for traces of hematite on Mars, they combine those filters on Earth to produce an increasingly standardized false color view of Mars.

\(^{16}\) “There’s more of an upturn between R5 and R7 … that’s our blueberry finder.” Opportunity SOWG meeting, September 9, 2006.
Because the filters are carefully selected to permit only a particular range of wavelengths of light to strike the CCD plate, each filtered image of a single object (such as Tyrone, or blueberries) will return different pixel values, and the variation among these values across filters is understood to be due to the object’s mineral composition, as this affects its ability to reflect light in different wavelengths. Combining these frames in an image processor is a process of revealing the quantitative relationship between pixels in different filters -- represented pictorially as different colors -- that corresponds to particular mineralogical characteristics. That is, as the ratio between the pixels changes between the red and green channels, this change is “expressed” with the use color on the spectrum from red through yellow to green. Scientists are attuned to the different colors that result from combining three or more filtered Pancam images in which there is a difference between the pixel values, as the intensity and variety of color can indicate that a rock that looks like it is made

Figure 7 Combining the L257 filters makes the hematite spherules in the rock Berry Bowl appear blue. *Opportunity* Sol 43. Courtesy NASA/JPL/Cornell.
out of a single mineral may instead be composed of two or more kinds of materials. The question of what guides scientists’ choices as they select Pancam frames and assign them to color channels to produce True Color or false color images will be discussed in detail throughout the remainder of the dissertation.

Methods

The questions that inform my study of the Mars Exploration Rover mission are rooted in and illustrated by examples from both historical and sociological studies of science and technology. As images are employed in so many ways across the Rover mission, I draw upon this historical, philosophical and sociological literature to produce a synthetic account of image-craft in the context of knowledge production and practical interaction with objects. However, I am fortunate to have access to a team of contemporary scientists to observe how they manage these issues of concern in scientific representation. Thus my methods for the present study arise from the ethnography of scientific practice, using observation, interviews, participant observation and ethnomethodology\(^\text{17}\) to explore how these images are constructed and presented in the everyday context of spacecraft science and operations.

Unlike work on the Mars Rover Mission by Zara Mirmalek (2008) or Bill Clancey (2006; forthcoming), my study of the team took place over three years of the “extended” phase of mission operations, beginning at about sol 600 and continuing until sol 1500 and beyond. By this time scientists were no longer collocated at JPL but had returned to their home institutions to engage in “remote operations”, relying on networked technologies such as tele- and video-conferencing and shared software, with routines based on local, Earth time zones. In the course of my study I therefore

\(^{17}\) While originally developed as a sociological approach to the situated production of social order (Garfinkel, 1967; Goffman, 1967, 1986; Sacks, 1974, 1992), ethnomethodology has been adopted in the sociological studies of science through work by Lynch (1993) and others, and the sociology of technology by Suchman (1987), with reverberations in human-computer interaction design studies (see, for example, Button & Dourish, 1996; Crabtree, 2004; Dourish, 2004).
visited ten different institutions affiliated with the mission, ranging from NASA centers to universities to private companies, to observe how science was done at these local centers and to interview scientists and graduate students in their home institutions. Based at Cornell for the majority of my fieldwork, I was privileged to observe mission planning meetings as they occurred over tele- and video-conference, to attend weekly teleconferenced End of Sol meetings and several face-to-face science Team Meetings. Historical material was accessed mainly through actors’ reports and publications. Except for the names of prominent figures or when identity is crucial to understanding a particular decision or representation, the names of team members discussed herein have been changed for the sake of confidentiality, although a complete list of participating interviewees and institutional visits is in the acknowledgements section prefacing this dissertation.

Given such intensive interactions with the team, this dissertation is based upon four different kinds of source materials. The first is attendance at the regular meetings that constitute the majority of team interactions from 2006-2008: these include the daily (three to five days a week) Science and Operations Working Group meetings (SOWG) at which Rover operations are discussed, End of Sol meetings (EOS) once a week at which scientific results and future Rover plans are discussed, and Team Meetings, the twice-yearly face-to-face team conference at which science team members discuss their results with each other in person. At each of these meetings I attended and took careful notes of team members’ activities, interactions with each other and with visual material, including verbatim transcriptions and outlines of meeting proceedings and discussions. I employed audio and video recordings and photography during these meetings to more accurately record these verbal and visual interactions and for the sake of accurate transcription. I later reviewed and coded these meeting notes for general themes, types of interactions, and the outline of typical
conversations. These meetings are noted in this dissertation’s text with the type of meeting and Earth date or Martian Sol number at which the interaction was recorded. In this dissertation I also reproduce images that the team has not necessarily published, but which were produced for the purposes of display and discussion at these meetings and were essential for planning Rover interactions. I have attempted to indicate at which meetings these images were shown and have obtained permission from appropriate team members to reproduce these images here.

Second, in the summer of 2007 I visited ten institutional sites associated with the Rover mission, where I observed mission scientists in the process of their daily work, and interviewed many Rover participants. These interviews and ethnographic observations were transcribed in whole or in part and analyzed for thematic and procedural content -- that is, both what people said about what they did with images, and what they did to the images under analysis. Alongside textual records of these site visits I took hundreds of photographs and short video clips, focusing on scientific apparati and procedures, and sequences of image manipulation that followed scientists as they worked with several iterations of an image. These images and video stills were printed in color, reviewed and coded according to thematic and procedural content. Micro-exchanges captured on video or audio recordings were analyzed with particular attention to talk, gesture, and digital image work through which scientists came to make sense of an image, account for its significance, or narrate what the image revealed or showed to its viewers. To manage confidentiality, quotes and observations obtained from these one-on-one observational interviews are noted throughout the dissertation with dates and pseudonyms.

Third, I participated in the mission as a calibrator for the duration of my fieldwork. The chapter on calibration in particular draws extensively from interviews and training sessions as I trained to join the Pancam Calibration Crew in the spring of
2006. The dissertation benefited overall from this experience of working with digital images, as well as from auditing the Pancam Payload Element Lead’s senior undergraduate course on digital image processing in the fall of 2005. This experience gave me first-hand, practical knowledge of how digital images work and how they are worked with in the course of the mission, and deeply informs the discussion of digital image processing practices in this dissertation.

Fourth, I use published and manuscript documents in this dissertation drawn from three main sources. The first are scientific publications produced by the Rover team members. These documents prove particularly interesting as the outcome or frontstage products of conversations that I have been privileged to witness backstage, in the SOWG, EOS and Team Meeting environments and therefore do not constitute primary sources for analysis. But because of extensive backstage interaction, it was not possible to document completely all of my interactions with Rover team members, despite my best efforts. Thus my many ongoing conversations with team members were impossible to document fully. I have therefore referred to their public publications (i.e. Squyres’ Roving Mars, 2005 and Bell’s Postcards from Mars, 2006) only at times when issues they discussed with me directly are described succinctly therein. It is important to note, however, that these publications are in the main quite removed from my primary sources -- that is, the daily interactions I was privileged to observe. I therefore use them sparingly as “stand-ins” for conversations I wish I had been able to record in more detail.

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18. The distinction between “frontstage” and “backstage” science is discussed by Hilgartner (2000), although the theatrical analogy is well known from sociological literature on self-presentation (Goffman, 1959). Hilgartner’s study of the Recommended Dietary Allowances issued by the US’s national health advisory board details the production and display of expert advice in a public arena as opposed to the “backstage” interactions that construct such expertise. “Frontstage” presentations and impression management of the Rover mission will be discussed somewhat in Chapter Eight, but as I was privileged to observe backstage interactions among the Rover team, this aspect of the team will remain primary in my analysis.
Finally, I was privileged to spend the fall of 2008 as a visitor at NASA Ames Research Center, where I conducted historical studies of archival documents: especially the collections of Elliott Levinthal and Al Sieff, participants on past unmanned exploration missions from Viking to Pathfinder. This archival work gave me a deeper understanding of the history of the Mars Exploration Rover mission and robotic space exploration more generally, discussed in detail in Chapter One. These three kinds of documents -- scientific publications, public publications, and archival resources -- furnished the key literary sources cited in this dissertation according to bibliographic convention.

Access Restrictions

While this study was broad in scope in terms of the number of people I spoke to, the diversity of my fieldsites, and the intensity of my interaction with the team, there are some important limits to my experience of the mission. Foreign nationals are not permitted to access technical details about spacecraft design or operations under United States law as set forth in the International Traffic in Armaments Regulations (ITAR). As a Canadian citizen I was therefore limited to discussing and witnessing only the science of the mission, avoiding any discussion of technical details of the Rovers and their operations and all situations when such details would be discussed or displayed. As an ethnographer I take these regulations extremely seriously: after all, their disobedience could cause my participants harm. As a result, I did not have access to emails distributed on the Rover listserves or to document sharing sites related to uplink activities, was not permitted to view the programming of Rover operations through their software tools, and did not attend any meetings in which technical details or sequencing was discussed (and left the room if any meeting conversation turned

19 Code of Federal Regulations, Section 22.1.M. 121-130. The same legal restrictions cover all systems related to national security and defense such as military weapons, nuclear technologies, ciphering and encryption. The relationship between space science and US national security initiatives is discussed in DeVorkin (1992) and Sheehan (2007).
nor did I witness any of the code or technical side of its production and uplink to the Rover. Backstage chatter that usually occurs over teleconference lines after the open meetings was also off-limits due to implied virtual co-presence in the engineers’ workroom. The only activities and meetings I witnessed were not subject to technical restrictions (i.e. science meetings and downlink-related activities). Any discussion in this dissertation that touches upon the technical side of the Rovers is anecdotally derived and technically non-specific, or published and therefore public-domain.

Despite these restrictions, the degree of access I was permitted generated enough material for an extremely fruitful study, and I am deeply grateful to mission co-ordinators -- especially Principal Investigator Steve Squyres, Project Manager John Callas, and Pancam Payload Element Lead Jim Bell -- under whose generous permission I was able to study this mission to the extent legally possible. Further, I do not believe that my study was compromised by this restriction in that I might misrepresent the team in terms of their practices or outlook. Quite the contrary: this necessary and sometimes very much embodied attention to the politics of the mission actually augmented my experience in the field and forced my attention to the issues that the team finds critical in the practice of planetary exploration today.

In the context of this dissertation, therefore, when I refer to “operations” this does not include any technical details of Rover operations that NASA would consider a security violation. I use the terms “science” and “operations” to mirror the team’s own distinction between decisions, image data, and people involved in ‘doing science’ with images, and the decisions, image data and people related to the movement or management of the spacecraft. After all, as I will discuss, “science” and “operations” are some of the strongest actor’s categories on the mission, revealing distinctions made and enforced by the team for the purposes of distributing
responsibilities for the spacecraft in the management of Rover resources, maintaining professional identities on a multi-disciplinary and multi-institutional team, managing consensus and interdisciplinary communication, and for managing team members in order to maintain compliance with federal regulations (as the mission does have an essential international component). This may appear problematic to STS scholars, who are accustomed to discussing the social, scientific and the technical as intrinsically interrelated and indistinguishable. However, this distinction remains in my dissertation as an artifact of my access to the fieldsite. My attention to these terms’ deployment in the field therefore does not imply illegal access to restricted technical details on the one hand, nor ignorance of core S&TS concepts on the other; but is herein discussed in terms of the sociological effects of this actors’ distinction in context. I will discuss the Rover mission’s political context further in Chapters One and Eight, but for the purposes of this introduction it is important to note that a) due to security restrictions I did not have access to all information or all parts of the Rover team, b) my participants were clearly informed of my status as a foreign national and their responsibilities to uphold ITAR before I conducted any interviews or observations of their scientific work, and c) no ITAR restrictions were knowingly violated in the production of this dissertation.

**Plan Of The Work**

All ethnographic projects face the problem of artificially organizing activities and themes for the purposes of argument or exposition that are in practice intermeshed and entangled. I have chosen to begin in Chapter One with a review of the relevant historical and social aspects of the Mars Exploration Rover mission: specifically contributions of previous missions, and the importance of the organization and management of the team. Shorthanded as “the Social Life of Spacecraft” (recalling Appadurai, 1988), this chapter will also introduce the mission’s organization, its
participants and consensus-based model of decision-making, to show how managing the Rover is bound up in the activity of managing the team. This background is essential to understanding how work with images, or *drawing as*, can be used as a resource to manage the mission more generally.

In **Chapter Two** I move to the scientists’ desks and screens to see “where the action is” (Goffman, 1967; Lynch, 1991a): how scientists “do science” with Rover image data. Following two scientists in particular as they work with image processing tools to tease out an aspect of the imaged object for further access or intervention, I develop the analytical framework of *drawing as* in close detail. I show how different kinds of visual transformations effected with digital tools bring different aspects of image data into the foreground such as slope, atmospheric opacity, soil composition, Rover trafficability or rock morphology. Thus the MER scientists use digital tools to *draw Mars as* consisting of different kinds of materials or surfaces, such that one Rover Planner I interviewed explained, “The image never changes, but you can manipulate the image, and everyone sees something different.”

Looking at how images are *drawn as*, in **Chapter Three** I examine how and why requested images must be calibrated before team members can begin to work with them as scientific artifacts. This chapter contributes to the existing STS literature on calibration through a participant-observation study of the Pancam’s Calibration team, exploring how images from the Pancams must be retroactively altered to approximate standardized conditions on Mars. Going behind the scenes to the essential human and machine operations that guarantee trustworthy images, the chapter continues the interrelated themes of *drawing as*, the organization of labour, and trust in digital image processing.

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Chapter Four moves into the daily planning meetings – the Science Operations Working Group (SOWG) meetings – to demonstrate how observations are drawn as documents of consensus structure. Because all activities on Mars must be carefully budgeted in terms of megabits, time and power constraints, attention to these accounting practices and their negotiation among team members demonstrates how Martian imaging is a practical activity that must be carefully managed, accounted for, and negotiated. Governing this negotiation are tightly delineated patterns of interaction among team members, such as the closing response pair, “Are you happy?”-“I’m happy.” I explore the ritual character of these interactions (Goffman, 1967) and related expressions of solidarity (Durkheim, 1933[1893]) to show how images of Mars are the products of a particular locally produced and enacted social structure with associated norms and resources.

Chapter Five elaborates another role for images in this consensus environment by showing how images are annotated to capture or suggest moments of collective agreement in mission planning. Annotated images are often crafted and circulated during planning meetings and serve to situate the team on Mars, argue for one or another observation or drive, or record consensus around a particular plan. I show how images can be drawn as a map or plan of activity within this consensus environment to reinforce the social organization of the team and ensure continued cohesion -- and therefore, in actors’ terms, mission success.

In addition to these drawing as activities, how an object is visually construed has implications for how it is interacted with. In Chapter Six, I examine this move from representation to interaction by exploring the visual transformations and embodied practices that enable Rover operations on Mars. Such activities, known as “seeing like a Rover” by the team, add a phenomenological perspective to the theory of drawing as, demonstrating how visualization is as much an embodied practice as it
is a question of “theory” or representational techniques. It also forges a tight link between the themes of drawing as and the organization of human-robotic teams. Moving away from an individual scientist or technician interacting with an image at their screen, we see how the kind of seeing as initiated by this drawing as activity not only requires team members to adopt a “Rover’s eye view” but also to function as a collective, together inhabiting the Rover’s body politic in order to perform mission operations in a consensus environment.

In Chapter Seven I return to the theme of trust by exploring what MER team members consider to be constraints upon drawing as. Manipulating digital images in planetary geology reveals scientific information, but these very manipulations can leave the resulting images open to suspicion. As the interpretative work is made visible in the production of manipulated images, scientists account for their movement between degrees of externality in their observational reports (Pinch, 1985) by employing a language of constraints to describe what they consider to be trustworthy data manipulations. This account often relies on an appeal both to the mathematical functions of the computer and the pixel, and to analogous experiences on Earth to support their scientific hypotheses and suggestions for how and what Mars should be drawn as. Such interpretative constraints are often invoked in concert, but in the case of the discovery of silica at Home Plate, they may constrain not only scientists’ interpretations but also the scientists themselves.

Finally, while the MER team is the subject of my study, the Rovers are tied to the American public through the support of NASA and congressional funding. In Chapter Eight, I explore those images for public release that are drawn as human visions of Mars -- “What it would look like if you were standing on Mars” -- in the context of securing continuing public patronage for the mission. This is contrasted with ‘scientific’ activities of image making, especially as they are made for (and by) an
amateur public audience. I present the aesthetic characteristics of the “Martian Picturesque,” including the use of Approximate True Color, frontier imagery, and the situated position of the virtual witness who is asked to view Mars through the Rover’s eyes. As these images open the body politic of the Rover to a wider audience, inviting them to experience Mars together, they also aim to ensure the Rovers’ political survival on the alien wilderness of the Red Planet.
CHAPTER 1: THE SOCIAL LIFE OF SPACECRAFT
THE MER MISSION AS A SOCIOTECHNICAL SYSTEM

Sitting in his office chair at the US Geological Survey in Flagstaff, Arizona, Michael Jensen looks thoughtfully at the large image of a promontory at Victoria Crater on one of the large cinematic display screens on his desk. The image is actually a collage of many different photographs taken by the Mars Rover Opportunity’s Panoramic Cameras (Pancams), draped a three dimensional model generated from the same images. Michael is a veteran of many robotic space missions, stretching back to the Mariner missions of the 1960’s, and as he stares at his screen he articulates for me, his interviewer, what he believes sets the Rover mission apart from his other experiences on robotic spacecraft teams:

I have a belief that every mission is kind of like a living organism, it has a personality and it has a style, and that personality and style is sort of gained at the beginning of the mission and it never changes, even though the people migrate through the change, you change out the people and you still have the same mission personality… I would say that the, it's the people involved … they're intensely focused and they're supremely talented… and also it's extremely cordial, very strong teamwork. I've seen other missions that were less so by a long margin…¹

Sociologists might want to distinguish between Michael’s designation of both structural effects and individuals as the source of a mission’s “personality” or “style,” but for Michael these aspects are inseparable: they relate both to the roles and

¹ Interview, Michael, June 12, 2007.
individuals in those roles that enable strong working relationships among members of the team. He continues:

[Y]ou can develop a mission in which the science teams aren't at odds with each other, you can develop a mission in which different [NASA] centers are involved and it's like, the Viking mission Langley [a NASA Research Center] was responsible for the lander and JPL for the orbiters, there wasn't a lot of love lost. … [On MER] I think it was a very close, strong engineering-science collaboration from the beginning and it stayed that way. It's kind of a we-can-do-anything kind of attitude.2

This emphasis on “cordiality,” “closeness,” “strength” and even “love” between scientists, scientists and engineers, and NASA centers, is echoed across the team as a shared narrative about the uniqueness of their mission and the rationale for the guidelines that structure team members’ mutual interactions. As I will argue, these attributes are built into the modus operandi of the MER mission team in the political arrangement of its management structure and decision-making strategies such that operating the Rovers is a question of enacting these values. For Michael, at least, this approach gives MER an identity as “one of the more elegant missions.”

The question of the “style,” “personality” and even the politics of a technological artifact and the social system in which it is embedded is of long-standing interest in Science and Technology Studies. Langdon Winner’s foundational piece, “Do Artifacts Have Politics?” makes the claim that “technical things have political qualities” and “can embody specific forms of power and authority” (Winner, 1986, p. 19). Although this article remains hotly debated,3 much literature in STS since the

2 Interview, Michael, June 12, 2007.

3 See, i.e. Joerges (1999), Woolgar & Cooper (1999), Latour (2004). The Social Studies of Science Society Annual Meeting in 2005 also included a heated roundtable discussion on “Reconsidering Do Artifacts Have Politics?”
mid-1980’s has addressed the issue of the political and social values of technological objects -- or, as Joerges (1999) puts it, the relationship between “material form and social content.” The Social Construction of Technology school proposed a relationship between designers’ values and the ultimate form of a successful technology, showing how everyday objects like bicycles, automobiles, or light bulbs prescribe and circumscribe particular uses and users, and not others (see especially Pinch & Bijker, 1987; Kline & Pinch, 1996; Bijker, 1995). Recent studies by Oudshoorn and Pinch (2003) or Akrich (1992) draw attention to the role of the user, not just the designer, in appropriating or rejecting new or transferred technologies designed in different social contexts. And work by Thomas Hughes and others developed the term “sociotechnical system” to articulate how such factors as the organization of labour or management hierarchy can also be enmeshed in the physicality of a built technical system like a power grid, giving the system a particular “style” (Hughes, 1999).

In this chapter, I pick up on these related themes in STS to explore the social and historical characteristics that inform the design and operation of the Mars Exploration Rovers: both the robots and their human team. In the first section, I show how previous mission operations have impacted the Rovers’ construction, the community of scientists who operate them, and the mission’s timing in the early 21st century. In the second section, I show how both the human and robotic components of the Rover mission are organized to support and project a politics of consensus.

In my interactions with the MER team, members constantly impress upon me the importance of consensus for their mission; and in my observations of their work with the Rovers, with Rover imagery and with each other, the narrative of consensus-building and related stories such as inclusion, listening to fellow team-mates, and bridge-building between groups such as scientists and engineers is constantly invoked.

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This does not mean that communication never breaks down, that team members never clash over differences of opinion or experience difficulty in coming to consensus. Rather, it means that when the team engages in operating their Rovers, making decisions about where they should go and what they should do, or in scientific discussions about the results of their image processing work, they have another goal in mind alongside the task-at-hand: achieving unity of opinion and purpose and maintaining the commitment of contributors, often short-handed as “being happy.” The work of the mission is deeply attuned to the work of attaining this state.

This initial description may produce concern among STS scholars about the status of my analysis. After all, early literature in STS has established controversy as an effective way of studying the politics of science. Scholars have shown that studying communities in crisis over differently-interpreted objects like lunar samples (Mitroff, 1974), expert versus lay authority over diseases like AIDS (Epstein, 1995), expensive projects like neutrino detection (Pinch, 1985), or public failures like the Challenger disaster (Vaughan, 1996), exposes the political mechanisms at play in science, including social positioning, crafting insider/outsider status, manipulation of media, the role of publication and reputation building. But what should an STS analyst do when studying a micro-community whose activities are geared towards the consistent achievement of consensus and unity? And for the sociologist to take consensus work seriously, does this necessarily imply discarding skepticism and “buying in” to a story of naïve happiness shared by team members?

But just because the team operates by consensus does not mean that there are no politics on board the Mars Exploration Rover mission. Instead, one must come to see consensus-building as the politics -- a complex and difficult human task that requires just as much backstage discussion, argument, subtlety, respect of interests, attention to communication and concession as any other form of political organization.
or expression. It is also the product of a particular social system, an organization of team members and their interactions, that is reproduced and enacted through the activity of Rover management. Instead of hunting for the moments when consensus breaks down and politics rears its ugly head, therefore, I choose instead to treat the building and management of consensus as the social work that is enmeshed with the technical work of operating the spacecraft. As I will show in subsequent chapters, images are one of the central products and currencies of this activity. For the sake of this chapter, however, I provide an overview of the MER mission in which the remainder of the analysis is situated. I therefore turn analytical attention to how the robots’ design and deployment reinforces the team’s values in Rover operation. This is crucial for understanding the context in which images of Mars are generated and put to use, as the practices of making and interpreting Rover images arise from and are enmeshed within the political values of the team. Although the MER team spends much of their time discussing the Rovers, caring for them, planning for them, and managing them at an extreme distance, a particular social dynamic presides over these activities such that, as this dissertation hopes to show, the management of the team and the management of the Rovers are the same activity. As Liz, a camera operator on the MER team poignantly expressed to me, “After those Rovers leave Earth, the team is all we’ve got.”

Such a formulation of the team’s management and work structure recalls a statement central to Science & Technology Studies: that “solutions to the problem of knowledge are solutions to the problem of social order” (Shapin & Shaffer, 1985, p. 332). Indeed, the social order that governs activities on the MER mission is inscribed into the practical activities of knowledge-making discussed in this chapter. As such the story of consensus and the patterns of interaction it entails must be seen not as

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5 Liz, personal conversation, February 6, 2008.
Mertonian “norms” (Merton, 1973[1942]) generalizeable to scientific practice as a whole. Nor does “consensus” here apply to the entire community of Mars scientists, but rather to a single relevant social group, the primary users (and in some cases, the designers) of the Rovers. More useful for the present dissertation may be Michael Mulkay’s recasting of the “normative structure of science” as a local “ideology” (Mulkay, 1976) that serves such purposes as social control, policing group membership, and distribution of rewards alongside being a “repertoire” (Mulkay, 1976, p.645) that scientists may draw upon as a resource, or the “vehicle through which … tension is expressed” (Gouldner, in Mulkay, 1976, p.644). According to Mulkay, recasting such a vocabulary as the normative structure of science can serve particular interests and justify scientific activities to outside observers. Such an approach is reflected in Shapin and Schaffer’s description of “the experimental life” (1985), the Wittgensteinian “form of life” (1953) that governs, regulates, and discriminates scientific behaviour and analysis. Similarly, I suggest, the very local discourse of consensus on the MER team makes available certain repertoires, such as vocabularies and roles, which can be drawn upon as resources by members of the team. The effects of this discourse can be seen in the overall structure of the mission team, local interactions among members, and even the robots themselves, which together form a unified sociotechnical system with a tightly disciplined and self-policing mode of operation. Casting the MER team’s discourse of consensus as a local form of life can help the analyst to trace the interrelationships between structural categories, the discipline inherent in participant interactions and the operation of the vehicles, as well as how this group justifies its activities to outsiders.

This chapter will address these issues by describing the MER mission as a sociotechnical system with a heritage reaching back to the early days of space exploration. I begin with a review of previous missions such as *Viking* and the Mars
missions of the 1990’s to reveal the historical dynamics that shaped the Rover team, their directives and their vehicle’s ultimate form. I will then move to describe the MER team in more detail, their composition and consensus model of operation, and articulate how these attributes are reflected in the robots’ technical construction and the data they return, in turn shaping the team’s interactions with their robots.

**Where Do Rovers Come From? A Selective History Of The MER Project**

Although launched in 2003, the MER mission has roots in the Apollo era of spaceflight, and was shaped by NASA’s history and changing mission mandates. Even at NASA’s inception in 1958, visions of space exploration put forward by physicist Werner Von Braun, science fiction author Arthur C. Clarke or space illustrator Chesley Bonestill featured elaborate plans for Martian exploration involving space stations, a human presence on the Red Planet, and robots.\(^6\) It is unfortunately beyond the scope of this dissertation to delve deeply into the history of Mars exploration in the 20\(^{th}\) century or even NASA’s institutional history; these stories have been told in other places.\(^7\) But I engage here in a cursory overview of some of MER’s predecessors in the 1960’s, 1970’s and 1990’s to present some of the institutional pressures and relationships that shaped the mission from its inception. These include the rise of a community of geologists engaged in planetary exploration through remote sensing imagery, the search for water on Mars as metonymic for the search for life and as achieved through the practices of geology, and the restructuring of a failed Mars program in the 1990’s.

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\(^6\) Science fiction continues to be an important part of contemporary Mars scientists’ imaginaries. At least one member of the MER team is an accomplished science fiction writer: see Landis (2001).

\(^7\) On NASA’s institutional history and challenges see, for example, Feldman (2004), Launius (2000), McCurdy (1993), Vaughan (1996), Westwick (2007); on Mars exploration more specifically see, for example, Chaikin (2008), Ezell & Ezell (1984), Morton (2002), Squyres (2005).
Studies of the space race place much emphasis on the race to the Moon, but a race to Mars ran in parallel. As early as 1960 -- only three years after Sputnik -- the Russians sent the first of their Mars series of spacecraft to the Red Planet, although neither of the two probes were successful in landing or achieving orbit. The Americans followed closely behind with their Mariner series of space probes: a collection of increasingly complex spacecraft funded under the same mission scheme, all designed to fly past planets in the Solar System and return basic images and spectral readings to Earth. In 1964 Mariner 4 flew past Mars, the handful of pictures it returned revealing a surface pitted and pockmarked with craters like the Moon -- a far cry from the expected canals posited by Percival Lowell due to telescopic observations at the turn of the 20th century (Lowell, 1895). Publications based on the few, low resolution orbital images began to make the case that perhaps there had once been water on Mars, as the impact craters on the surface appeared to have been modified or filled in with processes since their initial formation. But attempts to return to Mars under the Mariner scheme to corroborate these claims were besieged with technical difficulties; while Mariner 6 and 7 flew past safely, in 1971 the upper stage of the Mariner 8 spacecraft failed shortly before achieving Earth orbit, and Mariner 9 was inserted into Mars orbit just at the planet was being enveloped in a planetary dust storm that obscured all but two features on the planet’s surface: Olympus Mons, the largest volcano yet observed in the solar system, and the Martian polar ice caps. The loss of the contemporary Russian Mars-3 and Mars-4 probes was also attributed to the effects

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of the dust storm on spacecraft systems, and concerns circulated among *Viking* team members that the Russian landers had been swallowed by Martian quicksand.\(^9\)

Alongside Mariner, NASA had put aside the resources to support two orbiter-lander pairs to tour the solar system, originally slated for 1973, launched in 1975 and eventually arriving at Mars in 1976.\(^10\) Initially entitled *Voyager* in their inception in the 1960’s,\(^11\) the mission was renamed *Viking* by 1969 and focus was placed squarely on Mars. The spacecraft sported a suite of complex instruments aimed at answering the question of whether or not life existed at present or in the past on Mars. But this was a difficult question to answer successfully: reminiscing about his experience on *Viking*, a current MER team member explained “It was not too long after people thought there were canals on Mars; we didn’t know what to expect.”\(^12\)

Weighing over 3,000 pounds each, the landers were equipped with a robotic arm for gathering and analyzing a sample of soil, to search for the presence of carbon and other molecules, with stereo color cameras that could also run a motion detector (in case “macrobiotic”

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\(^9\) See Siddiqi (2000) on the Soviet/US space race. The Russians and the Americans signed an agreement in 1971 to share results from the Mars missions, but it is fair to suggest that the countries were still in competition. Still some information passed between the two camps. Sagan in particular was concerned to locate landing sites for the *Vikings* that would avoid the quicksand that doomed the Russian missions (Ezell & Ezell, 1977).

\(^10\) The landers were initially scheduled to touch down in 1974, but the mission was besieged by difficulties that pushed back this expected arrival date. Soaring costs combined with a miscalculation in the 1973 budget prompted President Nixon to set back the mission two years. Preliminary results from a Russian probe that managed to send back precious little data before failing revealed that the atmosphere was composed of at least 15% argon, instead of 3% as previously believed, causing many of the instrument teams to go back to the drawing board. Shooting instead for a July 4 1976 landing date, which would mark the 200\(^{th}\) anniversary of American independence, after painstaking analysis of and negotiation over *Mariner 9* images to identify the best places to set down the landers, the images returned by the *Viking* orbiter just before the lander’s insertion revealed that what the team had assumed was a flat lava bed was in fact a jagged river basin, originally obscured by dust but presenting too many hazards to land the ships safely. Or, as one *Viking* team member recalled it to me in personal conversation, the response to the images was, “Oh my god, we have no idea what this stuff is!” The site was subsequently changed and the landing date adjusted to July 20,1976, the anniversary of the first manned lunar landing. A detailed history of the *Viking* mission is Ezell & Ezell (1984); a copy of the manuscript focusing on the selection of the landing site is in Ezell & Ezell (1977).


\(^12\) Interview, James, June 21, 2007.
forms moved in front of the camera), and with a variety of other atmospheric and soil experiment apparatus.  

Detecting “life,” for the Viking instruments, meant detecting the presence of hydrocarbons or methane, or observing microbial or larger living beings on the surface of Mars. Like the Earth-bound neutrino-detection experiments relying upon traces of argon, the Viking experiments were not only costly but presented a difficult measurement of success. After all, if life or signs of life as we know it were not detected, would that indicate a mission failure? With such “high risk” experiments on board, the cameras were positioned as the one aspect of the mission that could guarantee success for the mission, whatever results the other instruments generated. The orbital camera team’s leader was particularly expressive of this fact when cost-cutting measures on the mission threatened to “de-scope” (remove) his instrument:

One of Viking's characteristics is its high-risk, high-gain mode of focusing on a search for life. Negative results on all the biologic experiments is not unlikely; the seismometer may never see a quake. To run a billion dollar mission and obtain largely negative results would be embarrassing politically for the project as well as for NASA as an agency. Whether negative results reflect the lack of life, or the wrong kinds of experiments or the wrong landing locations might be difficult to see … Thus the high-resolution imaging system may be considered as the “meat and potatoes” low-risk but guaranteed significant-gain experiment in the mission.  

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13 Full details of the Viking payload are outlined in Volume 16 of *Icarus: International Journal of Solar System Studies*, published by the Division for Planetary Sciences of the American Astronomical Society. In a similar vein, the Athena science team published a description of the instruments on board the Mars Rovers in issue 305 of *Science* magazine (see Squyres et al. 2004), and special issues have appeared since then devoted to discoveries on the mission.

This statement was prescient: the results of the lander-based tests were at best inconclusive and at worst, negative. In his *Cosmos* television series *Viking* imaging team member Carl Sagan (1989) called the results “tantalizing, annoying, provocative, stimulating and deeply ambiguous.” But the images were presented as a mission result, such that returning pictures from the field became in itself a goal for subsequent missions. The Viking imaging team developed sophisticated computerized tools for the combination of stereo imaging to produce 3-dimensional displays that could depict the topography of the terrain. Such technologies fed into the development of Rover robotic vision requirements as well as into the kinds of computerized stereoscopic displays used on the MER mission and others today. Pictures from the lander were also circulated among scientists and the general public; the deputy lead of the camera team invested considerable time and resources into developing expensive and cumbersome devices for 3-D film display at conferences and public outreach events. And certainly no less significant were the circling orbiters, whose Martian mapping campaign relayed images of the planet back to Earth. The program of Martian science that began in earnest around these images had several effects on the development of the Mars Exploration Program within NASA and explains some of the characteristics of the Mars Rover mission.

Geology already played a central role in planetary exploration due to its close association with the *Apollo* missions of the 1960’s. As a retired planetary geologist who worked with the *Apollo* program recalls, when it was decided that experimental pilots, not scientists, should be astronauts, US Geological Survey and space-aficionado Eugene Shoemaker successfully negotiated with NASA to allow him and his colleagues to train the *Apollo* astronauts in geology. If they were going to the

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16 See Mindell (2008) for more on the characteristics and personalities of this debate.
moon, Shoemaker argued, taking pictures and even collecting samples there, the astronauts would need to know what they were looking at in order to judge best which samples to bring back to Earth to awaiting scientists. The rise of aerial reconnaissance techniques developed during World War II and refined during the Cold War had also fed into the enlargement of geological expertise; geologists played an important role with natural resource companies, not only for their ability to determine where and when to mine or drill on the ground, but also because from the 1950’s onwards they needed to be just as expert in looking at aerial photographs of a region as they would be on the ground, in the field, analyzing samples. While there were no Martian samples to analyze after Viking, the close relationship between the USGS and NASA established by Shoemaker cemented a role for a “planetary geologists”, who could look at Viking or Mariner images of Mars and make pronouncements about the geological history of the planet. After all, geologists practiced in interpreting aerial photographs of the Earth had the requisite skill set to determine whether or not features visible on Mars could have been caused by the presence of water. Later missions such as Voyager and Galileo further reinforced this role as images of the volcanic moon Io, the ice moon Europa, or the methane-lake-ridden Titan inspired controversies among planetary geologists attempting to interpret these features of

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17 See Wilhelms (1993). I am grateful to Don Wilhelms for conversation with him about this topic.

18 Established techniques included photogrammetry, a method of measurement derived from triangulation techniques using stereo photographs. According to internal memos circulated among board members, by 1978 the field of Photogrammetry was facing the decision whether to split off into two groups or to admit a new and growing field of Remote Sensing, largely associated with images derived from spacecraft and aeroplanes. Such was the climate that Viking imaging team member Elliott Levinthal encountered when asked to present his 3-D movie of footage from the orbital and lander cameras to the American Society of Photogrammetry in 1979 and the parallel International Society in 1980. The film may have appealed to both sides of the debate by combining both remote sensing techniques of using robots and orbiters with the traditional photogrammetric techniques of stereoscopic image analysis. The field eventually saw the incorporation of photographic interpretative techniques with aerial photography and other sensing instruments such as spectrometers and orbital imagery. PP02.02, Elliott C. Levinthal Viking Lander Imaging Science Team Papers, 1970-1980, NASA Ames History Office, NASA Ames Research Center. Moffett Field, California, 13:21.
geologic interest from orbital images. Thus, while some may have training in optical astronomy and some in atmospheric science, the vast majority of the scientists on the MER mission are geologists, not astronomers. Indeed, agencies such as the US Geological Survey continue to maintain a close relationship to NASA and mission planning, and several key members of the MER team -- including Michael Jensen -- are located at USGS centers today.

Also as a result of Viking image analysis the story of water on Mars moved from a story about current standing water, to a story about past standing water on Mars. When the Viking science team selected their landing site, they looked for a place that they hoped would be wet or at least moist; when they landed, however, they found Mars a cold, dry place. In the story about life on Mars, however, water continues to figure predominantly in narratives of Mars’ history and development, although not as liquid water present on the surface today. So while NASA’s stated mission goals for the Mars Exploration Program include the slogan “Follow the Water,” the MER mission satisfied this directive by arguing that the Rovers would not seek out standing water or moisture, as Viking aimed to do, but would rather use the skills and tools of geologists to find evidence of where water once was, such as chemically or morphologically altered rocks. Thus the scientists on the Rover team use their robots to look for features on the surface that might have been formed through some relationship with water: whether chemically altered, deposited in water, or betraying morphological features of water in their formation. As the Principal Investigator frequently puts it,

Our Rovers should be thought of as robotic field geologists. Their job is to go to two places on the Martian surface where we believe that there may once have been water, and to assess whether or not at some point in the past, these are places that would have been habitable, would have been suitable for life.
It’s about reading the record in the rocks. So what we have done is equipped our vehicles with a set of tools for reading the geologic record.¹⁹

For the above reasons, then, equipping Mars Rovers with robotic versions of the field geologist’s toolkit such as a microscope and a hammer, and with the nickname of “Robotic Geologists,” makes sense both to NASA and to the planetary scientists who advise its Mars Exploration Program.

Ultimately, however, the *Viking* missions made clear the importance of investing in landed vehicles with some mobility. Perhaps the *Viking* results were inconclusive, but how representative was this or that patch of soil under the lander? Perhaps only a few meters away the story could be different. The *Viking* results combined with the lunar sampling missions of the early 1970s, as discussed by Ian Mitroff (1974) in his study of the *Apollo* lunar samples, suggested that only Martian rocks in hand would allow scientists to truly understand the planet’s history. The initial proposals for *Voyager* and *Viking* included plans for wheeled rovers, and several internal NASA publications betray plans to design driving robots to be deployed as *Viking 3* and *4*; a 1978 National Academy of Sciences report also recommended “that intensive study of Mars by spacecraft be achieved within the period 1977-1987.”²⁰ A NASA study group was convened on Machine Intelligence and Robotics to exchange ideas about the development of roving Martian vehicles (Figure 8). But despite plans in place as early as 1974 for driving robots that could collect, analyze and even send samples back to Earth and an ongoing research program into robotics requirements (Darnell & Wessel, 1974), the missions were cut from NASA’s funding agenda. NASA would not return to Mars until the 1990s.

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Several factors contributed to the decline of the early Mars Rovers proposals. *Viking* ended up grossly over budget, coming in at around $1.8 billion 1976-dollars, such that plans for a Viking-class Rover in 1979 or 1981 were cut in favour of funding for other initiatives as SkyLab, the International Space Station and the Space Shuttle program (Ezell & Ezell, 1977). This coincided with the decline of federal spending on the space program more generally in the post-Vietnam War era. One-time spacecraft were becoming too expensive to fly, and as Presidential directives focused on the shared costs of collaborative missions and development of the renewable means of going into space like the new Space Shuttle, Mars exploration faded into the background.

While NASA distinguishes in its basic organizational structure between manned and unmanned missions, it is unlikely that competition between the two sides was responsible for the pause in Mars exploration during the 1980’s. After all, the spectacular success of the *Voyager* Grand Tour missions in the 1970s and 1980s involved many famous planetary scientists and enabled young students to cut their teeth on a robotic exploration mission. MER Principal Investigator Steve Squyres was one such student, working with Eugene Shoemaker on *Voyager* images of Ganymede and studying at Cornell under Carl Sagan.\textsuperscript{21} Several other MER scientists were involved in a subsequent mission, *Galileo*, where their knowledge of terrestrial geology was tested over controversial images of the Jovian satellites.\textsuperscript{22} And the unmanned side of NASA missions were also deeply affected by the shock and furor over the *Challenger* explosion\textsuperscript{23}: the *Galileo* probe was supposed to launch in 1986 from the Shuttle cargo bay but was delayed until 1989 in the fallout from *Challenger*.\textsuperscript{24} Finally, *Viking* had been an immensely costly mission: it was, after all, a “Flagship” mission, a category of NASA funding only reserved for the largest, most publicly visible, and most expensive of NASA projects.\textsuperscript{25} While it pioneered some important technologies, the next project that the science community pushed for was a

\textsuperscript{21} Squyres, personal conversation, February 2007.

\textsuperscript{22} The controversy on *Galileo* raged over the interpretation of the few images of Europa that returned from the mission due to the failure of the high-gain antenna (see fn 23 below). The question of whether Europa’s icy crust was thin or thick divided scientists and their graduate students on the imaging team, many of whom work together today on the MER mission, and remains a driver for a future NASA mission to the Jovian moon. See Billings and Katterhorn (2005), Schenk et al. (2004).

\textsuperscript{23} For a detailed examination of the *Challenger* disaster, the inquiry into its reasons for failure, and the NASA and media frenzy that followed, see Vaughan (1996).

\textsuperscript{24} *Galileo* was to be launched from the cargo bay of the Space Shuttle, demonstrating a use for the shuttle and the end of relying on costly rockets. The political climate affected the spacecraft; its being taken on and off the launch pad as a result may have been the cause of its main communications antenna failure. Another generation of MER scientists hails from this era, having studied as graduate students under science team members on the Galileo mission. On *Galileo* see Harland (2000).

\textsuperscript{25} MER is not a Flagship mission; it was funded under a different scheme through the Mars Exploration Program for reasons discussed below and in the MER PI’s book, *Roving Mars* (2005). This allows the team some flexibility in terms of organizational structure, funding and planning.
robot that could both move and return a sample of rocks from Mars: a mission so costly that NASA, with its budget determined by US Congress every fiscal year, could not commit to its feasibility. Every few years the projected launch window for this robot, called the Mars Sample Return (MSR) mission, was pushed back another two to five years, a practice that has been ongoing since the 1960’s and which continues to affect mission budgets and schedules. Still, throughout this time an engineering community actively worked on the problem of robotic rovers, pulling together a range of research streams on such topics as robotic motion and vision, command software development, landing capabilities, and artificial intelligence.

Despite the lack of missions, however, in the period following Viking there was continued interest in Mars science and exploration, mainly expressed through the development of Mars Analog studies. This kind of fieldwork again rests on the assumption of a close relationship between the studies of Earth and the studies of Mars. Just as Shoemaker believed that training Apollo astronauts in places like Meteor Crater on Earth would better equip them to locate good rock samples on the Moon, experience on Earth is likewise used to judge and make hypotheses about the Martian habitat and history. Thus the young field of planetary science experienced publications not simply based on Viking data, but on data amassed from fieldwork on Earth that was assumed to be similar to Mars. This work continues today on MER and is frequently invoked as a “constraint” on photo-interpretation, as will be discussed in Chapter Seven. But the scientists who conducted this work throughout the 1980’s continually pressed for a return to Mars to better corroborate their terrestrial findings. For example, a group often referred to as “the Mars Underground” started with young

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26 Mars Sample Return is still on the table, slated for 2022 at time of dissertation defense. The mission has been revived and discarded again, mostly for funding reasons, many times over the last 50 years: the earliest I have seen mention of it is in 1962, in the design sketches for what became Viking. Although it has never been flown, MSR plays a significant role in the history of Mars Exploration largely though what it makes not possible, i.e. slashing funding for current missions based on the expected long-term investment of a projected MSR.
graduate students in the 1970’s who were interested in the ongoing *Viking* mission. Convened at first as an informal, one-semester, one-credit graduate reading course called “Life On Mars” at the University of Colorado, this association of Mars aficionados instigated ground-breaking programs of Mars research on Earth in places like the Atacama desert or Antarctica, pushing all the while through conferences, policy papers, and in the foundation of The Mars Society for a return to the Red Planet.27

Although separated from the *Vikings* from almost 30 years, the two Mars Exploration Rovers that were eventually sent into space in 2003 inherited much from their predecessors. They inherited stereo, color imaging capacities as a way to engage scientists and the public, as well as to fuel robotic vision. They inherited a community of geologists who identify themselves as Planetary Geologists, who developed remote sensing techniques such as image analysis and complementary analog studies of Earth to conduct scientific studies of planets at significant distances. From this community they inherited a scientific charge and a toolkit geared to that purpose: to look for signs of past water on Mars using geological methods and tools. But they also inherited a funding agency reeling from costly efforts to explore the planets, and from the very public failure of the Space Shuttle. These issues and others would come to a head in the 1990’s, and their resolution would play directly into the Rovers’ development.

*The 1990’s*

At the close of the Cold War, two Russian probes were sent to the Martian moon Phobos in 1988, and one managed to move into planetary orbit. Shortly thereafter, Ames Research Center proposed that NASA return to the surface of Mars in

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1991 with a mission they called MESUR -- Mars Environmental Survey. The plan was to fund a network of small, landed rovers and stations around the planet that would eventually have sample return capacity. NASA’s funding of MESUR signaled renewed interest in a Martian exploration program that would be effected by unmanned spacecraft, but the period that followed would see a generation of failed Martian probes that would crash or otherwise be lost on the surface. Further, NASA in the 1990’s was still recovering from the Challenger disaster in 1986, and their new Director, Dan Goldin, was trumpeting the motto “Faster, Better, Cheaper” as the solution to the agency’s woes. Just as the success of Viking was foundational for MER in establishing a community of Mars scientists who practiced planetary geology and became involved with robotic space exploration and image interpretation, MER also reflects the pressure generated by NASA in the 1990’s, with the agency’s public embarrassments and budgetary constraints.

NASA re-entered the Mars race with the launch of its Mars Observer orbiter in 1992, but contact was lost with Mars Observer shortly before it entered orbit. The Russians launched a mission in 1996 (originally scheduled for 1994) but the system failed to reach orbit, instead crashing and sinking in the Pacific Ocean near the Easter Islands. Technology from these two failed missions was salvaged -- not from the wrecks, but by using “flight spares.” Copies of the instruments flown on the spacecraft, meant to remain on Earth in case the instrument in space needed troubleshooting, were in many cases dredged up and tacked onto new spacecraft to produce the subsequent NASA Mars Global Surveyor in 1996 and the European Space Agency’s Mars Express satellite respectively, the latter relaunching in 2003.

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29 This would happen again in 2007 with the Phoenix lander, a revived Scout-class mission based on the failed Mars Polar Lander probe of 1999.
Three events mark 1996-1997 as an important year in MER’s pre-history. The prototype for the MESUR mission, *Pathfinder*, was launched in 1996 and arrived on Mars in 1997. Envisioned as primarily an engineering exercise because it would test such capacities as landing and operating a robot on another planet, *Pathfinder* returned the first images from the Martian surface acquired in twenty years. Many MER scientists and engineers were involved in *Pathfinder*, and certain parts of MER such as its APXS instrument and unique wheel chassis are inherited from this early prototype. The lander and its attached Rover, *Sojourner Truth*, outlasted their warrantee by surviving for eighty-nine days on Mars (Mishkin, 2003; Shirley, 1998).

NASA Ames Research Center had fronted the MESUR proposal as they hoped to draw upon their expertise from the *Pioneer* missions they had commandeered to take leadership in this proposed series of Mars missions. But when NASA Headquarters accepted the proposal, they gave the contract to the Jet Propulsion Laboratory (JPL). This move changed the scope of the mission; first envisioned as the prototype for a series of probes, *Pathfinder* became an engineering end unto itself. Its lightweight status bolstered the “Faster Better Cheaper” model, and thus also the credibility of the engineers and managers at JPL. Thus the ground was laid for JPL to serve as the contracting centre to build and operate the MER Rovers, a bid which was no doubt helped by the laboratory’s stance on the failure of the subsequent Mars mission, *Surveyor*: as due to the attempt to operate it externally, from UCLA, and to build it in association with a private contractor, Lockheed Martin. Despite the truncation of MESUR to the single flight of *Pathfinder*, the dream to put more roving vehicles on Mars was not lost. Steve Squyres’ proposal for a Rover mission would receive support a few years later under the purview of a Mars Exploration Program administrator who had served on the MESUR committee with Squyres, then the proposed mission’s lead scientist.
Heightening the excitement around *Pathfinder* was the announcement in the summer of 1996 by David McKay, Chief Scientist for Astrobiology at Johnson Space Center in Houston, that a Martian meteorite discovered in Antarctica (ALH84001) betrayed qualities of life forms in the rock’s structure and texture. While bitterly contested among the scientific community, the discovery announcement prompted remarks by President Clinton guaranteeing support for NASA’s Mars Exploration program. The exact outlines of this controversy are beyond the scope of this dissertation, but for the purposes of the present story it is worth noting that the swell of public interest around the meteorite prompted renewed excitement about and funding for Mars exploration and undoubtedly tipped the scales in favor of a Mars Rover. A new Mars Exploration Program with its own funding line was developed that would eventually accept Squyres’ proposal for the Rover mission.

MER was not Squyres’ first proposal for a Mars Rover mission. Listed as the lead scientist for MESUR, in 1992 he had proposed an imaging system for the *Pathfinder*, which had been unsuccessful. Following this rejection he joined forces with a former competitor to put in for the 1999 launch. This was again rejected in favour of *Mars Surveyor*, a mission suite consisting of an orbiter and a lander that, launched separately, would conduct climate and geological observations at the Martian pole. Following that rejection, however, another competitor joined forces with his team, who would prove to be the MER Rover’s Deputy PI. Squyres and his new team, under the mission name Athena, put in for the new NASA Discovery grants, a system that allowed PIs to design a mission holistically, with several instruments aimed together at solving specific scientific questions. Perhaps due to the founding of the

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30 *Science*, Aug 16, 1996. The asteroid is now located in the special collections of the Smithsonian Institute for Natural History; I thank MER team scientist Tim McCoy for the opportunity to see and microscopically examine ALH84001.

new Mars Exploration Program following the discovery of ALH84001, the proposal for the Discovery Program was rejected. This mission was finally proposed to the Mars Exploration Program and accepted the next year for launch in 2001, along with another orbiter, later named *Mars Odyssey*. Thus the Athena suite of instruments, when it was finally selected in 1997 for launch in 2001 (although not launched until 2003), was the result of several years’ work and several teams’ proposals, combined under a single framework with the aim to explore the geological properties of the Martian surface.

As the data from *Mars Global Surveyor* flooded in, between the high-resolution images from its Mars Orbiter Camera (MOC), the infrared data gathered from the Thermal Emissions Spectrometer (TES), and the topographic data derived from the Mars Orbiter Laser Altimeter (MOLA), the growing community of Mars scientists had a fresh supply of data to explore. Indeed, *MGS* played a considerable role on the MER mission as it provided the orbital topographical, spectroscopic and image data used for evaluating landing sites and drive directions until the satellite’s loss in late 2006. From the moment the Rovers arrived on Mars in 2004 until the orbiter’s failure in 2006, *MGS* along with *Mars Odyssey* both provided satellite relay links for both Rovers to communicate with their command centers on Earth. The MGS’s TES instrument and Odyssey’s Themis instrument were also the basis for the

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32 Upon *Mars Global Surveyor*’s arrival at the planet, a failure with its solar panels caused it to be unable to brake properly to enter orbit. The teams who were reviewing and selecting proposed missions for the upcoming launch opportunities were meeting during the week when the engineering team scrambled to save the spacecraft. A scientist I interviewed who sat on one of those committees recalls that the selection team was asked to take into account the possibility of a crippled *MGS* orbiter in their decisions. This scientist indicated that the potential failure or undesirable orbit of *MGS* in the first week led the team to select a suite of instruments that could best integrate with *MGS* results in case the orbiter was unable to map the whole planet, including a spectrometer that matched *MGS*’s TES in terms of its spectral range for observation. The later *Mars Express* orbiter, launched by the European Space Agency, bore a French spectrometer sensitive to a different range of features, leading to the discovery of spectral signatures that suggested the past presence of water on the planet. This scientist shrugged when recounting the story: had they selected differently, had *MGS* not been in danger at the time, “we would have discovered all the stuff that the Europeans discovered when we got there.”
Mini-TES, developed by the same scientist for the MER Rover, providing ‘ground truth’ for orbital readings.

The two Mars Surveyor mission spacecraft launched in 1999 consisted, Viking-style, of an orbiter (Mars Climate Orbiter) and a lander (Mars Polar Lander). But both spacecraft failed, earning MPL the nickname of “Mars Polar Crasher” from its team. It was later discovered that the orbiter’s failure was due to one part of the spacecraft operating in metric and another in English units. A MER administrator involved with the program at the time called the loss of the spacecraft, “a terrible shock and embarrassment to the agency,”33 and the debate over the cause of the miscommunication leading to the crash quickly revealed the fractured nature of NASA inter-institutional and inter-vendor politics and relations among competing stakeholders. The English-unit component was built by a private contractor, Lockheed Martin, and the mission was to be operated from an academic institution, UCLA. JPL claimed that the loss could have been avoided if they had been the sole contracting and operating agency. But scientists also blamed NASA’s “Faster, Better, Cheaper” model for pressuring them to cut corners on the design of the mission. In private correspondence a MER team member explained to me that “faster better cheaper is great for NASA and exploration but very bad for who is building the missions” [sic].34 Another MER team member who was on Mars Polar Lander recalled for me the signs that his colleagues sported in protest, including “Faster, Better, Cheaper: Pick Two”

33 Interview, May 23, 2007.
34 Rover scientist, instant message conversation, October 19, 2008.
and an administrator I interviewed admitted the official slogan was “widely misinterpreted as, it’s okay to be sloppy.”

This was the environment in which then-NASA Ames administrator Scott Hubbard, later known as the “Mars Czar,” was called upon to reorganize and rescue the Mars Exploration Program. The first item on the table was to cut the 2001 lander mission, which had rapidly outgrown the funding and schedule allocated for it. The orbiter, *Odyssey*, would still fly, but the mission that currently bore the Athena payload (which Squyres called the Athena Precursor Experiment as he was disappointed with its redesign; see Squyres, 2005) would be cancelled. Following the public disasters of 1999 so hot on the heels of the ALH840001 meteorite frenzy, NASA administrators faced the challenge of what to fly in the next launch window. Flying nothing and simply focusing on restructuring was an option, but was rejected, as Hubbard recalled, because “it's unacceptable to do nothing, that's the chicken way out. This is supposed to be a bold agency.”

A JPL engineer suggested launching the Athena payload on a Rover that could fit inside the Pathfinder landing system; the idea was successfully pitched to Headquarters. Soon thereafter Steve Squyres received a call from Headquarters asking him if he could build his MER Rover, if he could build it in time to launch in 2003 -- and if he could build two Rovers, just in case one didn’t survive.

Further emphasizing the difficult odds, while the flurry of activities to build, test, and deploy the new MER mission was in full swing, yet another spacecraft approached Mars: Europe’s *Mars Express* orbiter, reborn from its originally-Russian 1996

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35 Rover scientist, personal conversation, October 2008; Interview, May 23, 2007. In the controversy that followed over how the mission was lost, a staff member recalls that NASA took the mission off their website, as though it didn’t exist. This did little to assuage the distress of mission team members at the time or since. Indeed, stories continue about how the PI for this mission and for the ESA's lost *Beagle 2* still request images from the new high resolution cameras around Mars to see if they can locate their lost spacecraft.

36 Interview, Scott Hubbard, May 23, 2007.

incarnation but now with an attached lander, Beagle 2, named for Charles Darwin’s ship. Mars Express successfully slipped into orbit, but the Beagle 2 crashed on the surface, joining its robotic predecessors in what is commonly referred to as “the spacecraft graveyard” of Mars.

Just as the 1960’s and 1970’s established the conditions for a successful Mars mission and the conditions for Mars science, the highs and lows of the 1990’s established an environment in which the success or failure of the MER mission essentially equaled the success or failure of NASA’s Mars Exploration Program more generally. President Clinton had issued a call for Mars exploration that had galvanized the country and, for once, provided the necessary funds to send a Rover to Mars, a mission that had been planned but put off since the 1970’s. But NASA expected a “faster, better, cheaper” robot with a two-for-the-price-of-one guarantee and an extremely short period between the Rovers’ selection and their launch (1.5 years). It also expected a mission that would redeem the loss of the Mars Observer, Mars Climate Orbiter and Mars Polar Lander missions, as well as the Russian-ESA Mars ‘96 and Beagle 2. The loss of these projects, further, had fractured a community in which NASA centers fought for contracts with each other and with private sector developers, and in which mistrust reigned between scientists based in academic institutions and NASA facilities. It is not far-fetched to suggest that by the time the two Mars Exploration Rovers were being built for launch in 2003, the weight of an entire scientific community that had built up since Viking was riding on their -- and their team’s -- shoulders.

This brief overview of the history of NASA’s robotic space exploration program reminds us that the Mars Exploration Rover mission did not spring fully formed out of the head of its Principal Investigator (despite the name of the suite of instruments the Rovers carry: Athena). Rather, it was the product of a particular social
group -- the American community of Mars scientists -- identifying relevant problems and the means by which they could be resolved (Pinch & Bijker, 1987). From Viking the MER Rovers inherited a tight-knit community of planetary geologists whose search for life on Mars shifted from a search for liquid water and existing microbes to an examination of the geological history of the planet. This work demanded a “robotic geologist” -- instead of, say, a biologist or an astronomer -- to carry out tasks in the field that could correlate with research on Earth. The Rovers were built and equipped with instruments to fulfill those tasks. Further, this community had outlined a central role for imaging in the co-ordination of remote sensing and public outreach efforts, a role that would be repeated on the MER mission. The high price tag on Viking postponed a return to Mars, in that plans for a mobile Martian lander were delayed for almost two decades for funding reasons. The tumult of the 1990’s, on the other hand, generated another set of relevant problems for this group to solve. Following the high-profile loss of several Mars missions the Rovers faced overwhelming institutional pressure to land and complete their “nominal” 90-day mission successfully, affecting the construction of hardware to the extent that not one but two Rovers were flown to mitigate the keenly-felt risks of loss. The social group was reorganized in response to this pressure, such that the Rovers flew under a new funding system, the Mars Program, under the “follow the water” banner (Hubbard et al., 2001), and with JPL at the controls. These historical elements shaped Spirit and Opportunity from the ground up, from their reason for deployment to their suite of instruments, from their human team members to their institutional affiliations, from their “birthdates” to their identities as “twins”.

But the Rovers’ design and implementation were not only shaped by historical circumstance: they also betray the elements of a sociotechnical system in which the organization of the human elements reflects the organization of technical elements,
and vice-versa. The daily activities of operating the Rover craft a tight relationship between the organization of work around the Rovers and their technical operation. In the remainder of this chapter I outline these principles of social organization, as they are bound up in the operation of the spacecraft and the data the spacecraft generates. I do this by drawing our attention to the MER team itself, its members and its organization.

**What Are Rovers Made Of? The MER Team As Sociotechnical System**

Michael Jensen’s description of a mission’s “style” and “personality” that opened this chapter -- with its emphasis on the organizational elements of a social system alongside the individual components or experiences -- resonates with work in Science and Technology Studies that relates the organization of human elements in a sociotechnical system with the operation of its technical components. For example, in his study of a large power grid, Thomas Hughes claims,

… the management structure of an electric light and power utility, as suggested by its organizational chart, depends on the character of the functioning hardware, or artifacts, in the system. In turn, management in a technological system often chooses technical components that support the structure, or organizational form, of management. (Hughes, 1999, p.203)

This relationship between humans and machines -- the “style” of the sociotechnical system, as Hughes calls it -- can be configured in different ways, often according to different values. For example, scholars in the history of manned missions such as Slava Gerovitch (2007), Roger Launius (2005), and David Mindell (2008) have shown how the relationship between human and mechanical components on the spacecraft reflected the contrasting political ideologies of the Soviet or American citizen. The dashing pilot figure of the astronaut places emphasis on American individual, while the automated Soviet spacecraft contain passive passengers
reflecting the “cog in the wheel” approach to collective identity. In contrast to these approaches, as Michael and others frequently describe the MER team, a strong theme of teamwork, collaboration, and communication emerged as the key to the mission’s infrastructure. In this section I explore these and other values that structure the Rovers as a sociotechnical system and how they are made concrete in the operations and management of the spacecraft. Unlike models centered around individual or state heroism, the organization of the robotic and human components of the Rover mission crafts an identity for the humans and robots of the mission to act as a single, unified team.

**Instruments And Investigators**

At the time of construction, the MER team involved approximately 5,000 engineers, scientists, and managers. During the first 90 days on Mars, called the Primary Mission, many of these scientists and engineers were co-located at the Jet Propulsion Laboratory. There they lived on Mars Time, the 24.7 hour per day clock, with the same schedule as their Rovers. But NASA funding was not guaranteed far past the Rovers’ 90-sol warrantee, and soon the scientists returned to their home institutions. The MER team that I observed for this fieldwork therefore consisted of approximately 150 core members, including the engineers at JPL and the Participating Scientists distributed at institutions across the United States. At time of this dissertation’s defense, the Rovers approached the 5-year anniversary of their landing on Mars with over 1700 Martian days of operation apiece.

In my interviews with Mars Exploration Rover team members, they consistently characterize their mission as uniquely successful and harmonious among NASA-funded unmanned missions. Resonating with Michael’s above-quoted comments, they state that previous missions were characterized by rigid hierarchies and fragmentation -- both among members of competing science teams tied to
different instruments, and between scientists and engineers -- leading to antagonistic relationships between members of the spacecrafts’ science and operations teams. In contrast, they claim, their mission sports a flattened hierarchy and espouses a consensus model of operations. Key to their story of mission success is the social organization of the team around different aspects of the Rover’s hardware. In order to explore this organization it is important to say something about just what that hardware is and how humans have traditionally interacted with it.

Although NASA plays a central role in long term mission planning and management, a mission like MER is not the sole product of a single agency. When an opportunity for a launch becomes available, NASA releases an Announcement of Opportunity (AO) to scientists at large calling for proposed missions that fit their planned guidelines. This could be a call for a lander or an orbiter, something geared towards astrobiology or towards climate sensing, something to characterize the moon, Mars, the outer planets or perhaps even comets. Once the proposals are received and reviewed by the appropriate panel, NASA then provides the financial, managerial, and engineering support to underwrite the selected project. The Mars Exploration Rover mission was just such a mission, proposed by a group of scientists headed by Steve Squyres located externally to NASA at universities across the United States and Europe, and selected by a NASA panel to receive money for associated scientists to build and operate instruments and conduct data analysis, and to receive the resources of the Jet Propulsion Laboratory to implement their experiments by providing NASA-contracted engineers to build, launch, and operate the Rovers. The instruments were therefore chosen by Squyres to fulfill particular scientific goals; in selecting his package of instrument, NASA also selected his team of scientists associated with those

38 In contrast, the European Space Agency releases AO’s that call for fully-funded contributions from its member countries, with the ESA itself providing coordination but very little of the operating costs.
instruments (Co-Investigators), and opened a call to further participation from relevant members of the science community (Participating Scientists).

Consistent with the funding scheme, the spacecraft can be divided into two components. One is the physical ‘base’ of the Rover itself: the circuits and wheels, the navigation and hazard avoidance cameras essential for robotic driving, and communications functions, all supplied by NASA. The human beings responsible for this side of the Rover are typically engineers, mostly based at JPL, in a group often referred to as the “Dream Team” or the “A-Team” for their high level of achievement, expertise and history of success. This human and technical component of the Rover is referred to as the “Operations” side of the mission.

In addition to the “flight hardware,” the Rovers also carry a scientific “payload”: the instruments that conduct observations aimed at answering particular scientific questions or characterizing one or another aspect of Mars. The payload for the MER Rovers is called Athena and consists of instruments such as the Panoramic Cameras (Pancam), the Miniature Thermal Emissions Spectrometer (MiniTES), the Microscopic Imager (MI), the Alpha Particle X-Ray Spectrometer (APXS), the Mössbauer Spectrometer, and the Rock Abrasion Tool (RAT) (Figure 9). Associated with these instruments is the Athena Science Team, those scientists who contributed the instruments and who are responsible for their data collection and analysis. These instruments and scientists are referred to as the “Science” side of the mission.

The division between Science and Operations is a consistent feature of spacecraft design in robotic space exploration. Establishing and maintaining these categories and their associated social relations does important work for such teams: it
can elucidate where particular lines of funding should be directed, or articulate which aspects of the mission are state secrets versus information that can be shared with international partners (more on this below). But it can also lead to fragmentation among mission personnel. In addition, scientists and engineers are further subdivided as science teams coalesce around particular instruments. The package of instruments that may be selected to place on an unmanned spacecraft is usually associated with several teams of scientists, each organized around an individual instrument.\textsuperscript{39} Thus \textit{Viking}, \textit{Galileo}, \textit{Voyager}, \textit{Cassini}, and others all involved “instrument teams”, each with an associated Principal Investigator and group of scientists.

\textsuperscript{39} The exception is NASA’s new Scout class of missions, aimed at funding smaller missions with single PIs headed out of a single or small group of institutions.
Relationships between scientists in independent instrument teams can become easily strained. After all, if the spacecraft only has so much time and so many bytes with which to operate, requests by one group of scientists to perform observations with their instrument have to be negotiated with other instrument teams who may be disadvantaged by the observation. Further, while NASA negotiates with each group of scientists to release their data to their publicly accessible Planetary Data System after an initial proprietary period of 6-18 months, there is no requirement that teams share their data or their data analysis systems with each other unless they so choose. Fractured relationships among science teams can also lead to fractured relationships with the engineering team whose job it is to craft the code to operate the vehicle, especially when the engineers turn down a heavily-negotiated scientific observation for reasons of vehicle safety.

Many of the MER science team members I interviewed recalled their dissatisfaction with the experience of “doing science” on those missions. According to these informants, the rigid hierarchies of seniority, the strict division between scientists and engineers, and the argumentative negotiations for spacecraft resources led to miscommunication and breakdown among spacecraft teams, with implications for the practice of science. A MER team member who was a graduate student on Mariner 9 described that project as having an “old school, British system of ‘don’t speak unless spoken to’”\textsuperscript{40}: it was unheard of for graduate students to speak up at meetings. Another recalled waiting breathlessly outside the room for his graduate advisor to present his own results to the other Principal Investigators on the Voyager mission and to argue on behalf of his observation. The young scientist was nervous that the PI would claim credit for his discovery, or that the observation would never win out over competing PIs’ interests. Yet another MER scientist described a

\textsuperscript{40} Interview, MER science team member, June 7, 2007.
spacecraft team with thirteen instruments and thirteen different PIs as being so antagonistic that “it’s a wonder the spacecraft didn’t fly apart into thirteen pieces!” Such a statement reveals the deep sociotechnical nature of these missions, whereby the relationship between members of the human team is equated with the physical functionality of the spacecraft. This same scientist was reportedly so disgusted at what he saw as the negative interference of politics with the science of space exploration that he vowed never to get involved with a mission again.

This scientist recalled for me that he changed his mind when approached by a Principal Investigator who promised a different approach. The Athena Payload on the Mars Exploration Rovers sports a single Principal Investigator with the support of a Deputy PI, who usually trade responsibility for oversight over Spirit or Opportunity’s planning cycles over long-term periods. Instruments are managed by “Payload Element Leads,” who are responsible for building and providing the software and human resources to operate their instruments. Separate from the payload elements are a group of Participating Scientists, whose interests in Mars range across instruments. These scientists are organized into Science Theme Groups, like Atmospheres, Geochemistry, Mineralogy, or Geomorphology, which meet regularly to discuss research questions and list observations to request from the Payload in general. Graduate students, postdoctoral students and other staff scientists or administrative assistants associated with Payload Element Leads or Participating Scientists are encouraged to get involved in many aspects of the mission, including light operations roles, and may all offer informed suggestions at the table to weigh in on driving decisions or when scientific results are reported. While most team members prefer one or another instrument well-tailored to the kinds of science they are interested in conducting, any scientist can request an observation or use data from any instrument.
While roles with weighty responsibilities are prescribed on MER, especially related to the details of spacecraft operation, this does not entail a rigid hierarchy that structures the decision-making process: while roles and their responsibilities are carefully defined and adhered to, all members of the team are exhorted to speak up, propose observations or challenge interpretations whenever possible. Above all, however, the majority of decisions about where the Rover should go and what the Rover should do are made by consensus. At the end of every SOWG meeting where the scientists and engineers come together to craft a plan for the next day on Mars, every member of the team on the line must agree, typically by saying the words, “I’m happy,” before they can proceed with coding and implementing the plan. As several MER team members explained to me, “I’m happy” usually operates as a shorthand for a variety of statements, such as “I’m satisfied” or “I have all the information I need to plan this observation,” or “I feel like I have been listened to.” Regardless, the phrase restates the approach to working relationships that the team believes is essential to their success.

An internal MER document called “The Rules of the Road” is revealing for how it articulates the structure of the MER team to “ensure [its] orderly conduct” (p. 6). Written by the PI and periodically updated, this document is circulated to all mission participants when they join the team so that they are clear about their engagement with the Rovers and with each other.41 A section entitled “Definitions” proclaims that “there is no distinction between the original Athena Co-Investigator’s and the Participating Scientists” (p.6), meaning that the scientists who were responsible for building the instruments, such as the Pancam or MI, are not higher up

41 In my research I have encountered many “Rules of the Road” documents outlining collaborating scientists’ responsibilities to each other and to their data in terms of sharing and publication rights. The MER document informing this study is Squyres, S. “Mars Exploration Rover (MER) Project Athena 'Rules of the Road' Document,” Draft Revision F, November 13, 2005. The document appears to have been initially compiled in June, 2002.
on a decision tree than those who joined the mission after its selection as interested scientists. It also identifies a role for “Collaborators” which can include “typically people such as graduate students or postdoctoral research associates who work at the home institutions of team members” (p.6) and who are usually funded by the grant that accompanies the Rovers’ operation. Data rights and publication policies, discussed below, maintain this approach as they are shared across the mission team.

In contrast, a similar document specifying the relationship between members of the Galileo Imaging Science Team, the group of scientists responsible for the camera systems on board Galileo, sports hierarchical diagrams and a long list of roles on the mission, including “team members, the team leader, guest investigators, and associated IDS’s [interdisciplinary scientists]” and six permanent working groups during the camera’s development (p.5). Each of these roles bears different “responsibilities and authority” and paths for communication, consultation and spokespersonship, for example the fact that “Working group leaders will not, except under special circumstances, be authorized as spokesmen for the team.” (p.7) Where the Galileo document is interested in delineating boundaries that circumscribe team members’ interactions, the MER document seems more interested in boundary work for how it can afford for boundary crossings between members of their team. Social order, for MER team members, is maintained through a flattened hierarchy and

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43 The division of labor and categorization of scientists and their intellectual property inherent in these discussions recalls work on boundary management in the sciences; classic sources on this intellectual work and movement of objects within it include Gieryn (1999); Star & Griesemer (1999); Galison (1999). It is also important to note another category of scientists not mentioned here: non-members of the team. These are described as “the science community,” a group external to MER but to whom the MER mission is indebted in its operation. According to the Rules of the Road document, science community members can be co-authors or even primary authors on MER publication, subject to the PI’s approval. The MER team often invokes their responsibility to providing observations for their peers when discussing what the Rover should do, but in practice it is difficult for external scientists to participate in Rover science because of the situated nature of the mission. I will discuss MER relationships with external scientists further in Chapter Eight.
policies that encourage broadened engagement in both science planning decision-making and publication.

This overarching emphasis on unity is interesting for how it enlists a team that could otherwise have many reasons to work independently. The proposal for Athena was first devised when two former competitors for a Mars Rover Announcement of Opportunity decided to join forces to create a single proposal under a single Principal Investigator (the other accepted Deputy status due to managerial involvement in several other ongoing missions). The two also brought scientists on board who had built instruments for other Mars missions as collaborators instead of as competitors. Because planetary science is still a young field, many of the MER Participating Scientists have already worked together as graduate students or on previous missions, where they sometimes presented competing results.44 Similarly, while funding and the technological infrastructure to support the MER mission is provided by NASA, the space agency is not the only patron of the mission: the engineers who built and operate the Rovers are located at the NASA JPL center in Pasadena, California, the Athena Science Team scientists are located at institutions such as universities, government agencies or private companies across the United States and in some European countries, each with their own associated pressures and responsibilities. Even within NASA, old inter-institutional rivalries, such as that between JPL and Ames, reveals a “confederation of cultures” (McCurdy, 1993, p.22) instead of a homogeneous agency. This combined with the pressure of producing flight hardware in record-breaking time could easily have led to a team that would crack under pressure.

44 This was especially true for the ‘generation’ of Participating Scientists who were graduate students during Galileo’s mission, as much of the battle between the two sides of the Europa controversy were reportedly waged through graduate student presentations at conferences.
Instead, five years into their 90-day mission, MER team members continue to tell a story about lively and collaborative scientific engagement. Even the choice of landing sites for the Rovers plays into the continuation of this local narrative.\textsuperscript{45} Geologists are often divided into two camps: minerologists, who characterize rocks by their mineralogical components and chemical properties, and geomorphologists, who characterize them by visible physical characteristics. The Mars Exploration Rovers possess a suite of instruments that incorporates both of these epistemic cultures (Knorr-Cetina, 1999) -- different kinds of cameras for morphology, and different spectrometers for mineralogy. And team members regularly declare themselves as one or another type of scientist related to one or another type of image analysis: as a mineralogist put a plot of chemical abundances on the screen during an End of Sol he proclaimed, “I’m a geochemist so I have to put up one of these graphs,” while a geomorphologist I spoke to stated, “I’m a geomorphologist so I’ll always take the higher resolution image.”

Selecting a site for the MER Rovers to go to could easily exclude one or another of these ways of knowing from the equation. Indeed, a perusal of the proposed landing sites and preliminary scientific investigations of them drew on geomorphological evidence like topography from the Laser Altimeter and images from the Mars Orbiter Camera, and spectroscopic evidence like THEMIS and TES datasets. But having two Rovers meant that the team could select two sites. One, Gusev Crater, was selected due to its geomorphological characteristics: from orbit, it looked like a crater with a river running into it, forming a possible lake. The other, Meridiani, was selected because of the hematite signature that the TES spectrometer detected from

\textsuperscript{45} I am grateful to MER team members for their recollections of the landing site selection process; also to Project Scientist John Grotzinger for permission to attend the Mars Science Laboratory landing site workshop in September, 2008 to get a feel for the process and pressures of selecting a site. Many of the documents related to the MER landing site selection are available at: http://marsoweb.nas.nasa.gov/landingsites/index.html# (Accessed November 17, 2008).
orbit. As a mineral primarily formed due to interaction with water, hematite was a smoking gun for a mission looking for evidence of past water on Mars. Thus both types of scientists were satisfied with the landing site selection, and both continue to interact with the Rovers and their results.\footnote{Sending two Rovers could easily have divided the team into two camps: the geomorphologists with Spirit in Gusev and the minerologists with Opportunity on Meridiani. Instead, however, scientists moved from one Rover to the other when it was discovered that the initial landing site at Gusev was covered in volcanic rocks, and Meridiani was mineralogically homogeneous but with rich potential for geomorphological investigation. This may have allowed for some early shake-up of the team and an opportunity for scientists to work together across these two platforms.}

In three years of observing the team I can report that the story of consensus, sharing, and collaboration constitutes a powerful narrative for common practices on the mission. I have witnessed undergraduate students questioning senior scientists, and engineers and scientists alike asking detailed questions of their colleagues’ intentions to determine how or if things could be done differently. I was also present the day that members of the team cheered as the scientist who built the APXS spectrometer requested his first Pancam image, three years into the mission. And I have witnessed meeting after meeting ending with the ritual chorus of “I’m happy” resounding across the teleconference lines. Together with the principles outlined in the “Rules of the Road,” the rules, roles and resources available to collaborators in this system, and even the chosen landing sites, these elements comprise the practical activities that support and reinforce the the MER team’s “form of life” (Shapin & Schaffer, 1985).

The Politics Of Inclusion

Consensus and bridge-building between different groups are part of a larger story about the importance of maintaining such working relationships, and a story about the functioning of the Rover itself. Alongside the consensus-building strategies of building unity among team members, the Principal Investigator encourages his team to think of the Rover as a single instrument, possessing many different capabilities that
they may use together or separately at any time: “like a Swiss Army Knife,” he once explained to me. Similarly, they are encouraged to think of themselves as a single, unified team. This unification is also associated with the “happiness” of team members. Indeed, in the course of many conversations the Principal Investigator often equated the happiness of his team with the conduct of good science, and poor science with fragmentation and infighting. For example, when I worried that pushing back Spirit’s deadline for approaching Home Plate would be bad for team morale, Squyres insisted instead that it was more valuable that “they’re [the scientists] driving around, having a great time… doing good science.” Thus team members draw an association between the breakdown of boundaries between instruments, scientists and engineers, senior and junior team members, with happiness and with the conduct of strong scientific analysis.

Given this approach, then, why retain the inherited distinction between Science and Operations? As will be discussed in Chapter Four, distinguishing between the science and the operations of the mission usefully demarcates particular tasks and the outline of the day on Mars, identifying which constraints on the mission timeline are from the Rover (i.e. solar power) and which are requests from scientists (i.e. this or that observation). Drawing these boundaries also draws attention to how such boundaries may be broken down or breached. MER team members most often invoke the distinction between scientists and engineers when they aim to break down the boundaries between them. However, the boundary allows useful demarcations of what “belongs” to NASA and JPL, and what “belongs” to the scientists. For scientists associated with different institutions, this affords some protection for the conduct of their scientific investigations from the institutionalization of NASA, Also, sharing technical data relating to spacecraft operations with foreign partners is a violation of national security (discussed further below) but sharing scientific data resulting from
the instruments of scientific research is allowed; distinguishing Science from Operations enables MER team members to legally continue to engage non-American scientists with their mission. Thus, although it may seem contradictory at first, the Rover team puts the distinction to work in the context of their team’s normative structure.

These interests do not constitute a naïve story, but rather an approach that is tied to the operation of the spacecraft in so many ways that the social structure of the team is enacted and reproduced every time team members interact with the Rover and its data. This is accomplished in many ways. On the one hand, certain roles on the mission build tight relationships among different team members and their robots, leading to strengthened communication and sharing of goals. For example, a variety of light engineering jobs that scientists can sign up and train for appear on the surface to be structured around an “operations” task, but also have the advantage of encouraging ongoing communication between scientists and engineers. An example are the Downlink and Uplink Leads: Downlink Leads monitor and report in daily meetings on an instrument’s health, while Uplink Leads take the recommended operations for the day and provide the code for their instrument to fulfill those tasks. This requires them to stay on the teleconference line for the rest of the day with the Rover Planners, the engineers at JPL who command the Rovers, as well as the other PUL’s. Because PULs in particular must “stay on the line” with engineers throughout the day to monitor an instrument’s command sequences, participation as a PDL or PUL contributes to building relationships between scientists and engineers and heightens the scientists’ sense of the Rover as a physical device requiring their care and supervision instead of an instrument operated for them by “invisible technicians” (Shapin 1989). Such local activities bridge the purported divide between scientists and engineers. Instead of scientists issuing all the commands and engineers
being responsible for executing them, scientists instead learn to engage on an engineering level, gaining familiarity with the operation side of the spacecraft, as well as forging social ties with the engineers on the other end of the line which may be called upon in the heat of observation planning and development. Thus the social, technical, and political are intermeshed in the practice of operating the spacecraft.

Another method of enlisting the technical operation of the spacecraft to further the local political structure is through the management of data release and publication rights. Typically, in the multiple-PI model, each instrument team holds responsibility for and priority publication rights over their own data. NASA requires them to calibrate this data and produce it in a standard file format so that it can be delivered to the Planetary Data System. In return, PIs can “skim the cream off the top,” as one MER scientist put it to me; that is, take sufficient time with their data before its release to their colleagues and competitors to comb it for publishable material. This data-guarding policy could be taken to extremes either by groups who fell behind in their processing and never delivered to the PDS on time, or by PIs who chose an almost DRM-approach to their data.47 A PDS manager I interviewed complained about this practice, exclaiming “[the contractor] made up his own [data format] for his own data products … you had to have his software to produce the images he was funded to release!”48 The result was an instrument that looked inexpensive when first proposed to NASA but whose data could only be processed by a narrow group unless a higher fee was paid. Further, these PIs were not required to discriminate between releasing to the PDS and releasing to other PIs serving on the same mission. Thus it was up to the individual instrument PIs to decide whether or not and according to what schedule.

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47 On Digital Rights Management and embedding intellectual property rights into digital files and media players, see Gillespie (2007).

48 Interview, Jane, June 11, 2007.
they wanted to share data with other scientists whose observations came from the same spacecraft.

MER team members espouse the belief that this proprietary approach to data management compromises their open community of scientists. Thus the MER Principal Investigator and the Pancam Payload Element Lead declared that they would post all Rover images immediately to the internet, “without restrictions or embargoes, as quickly as possible…” (Bell, 2006, p.66). In conversation, this Payload Element Lead described to me how the engineers at JPL were so used to PIs who demanded the absolute security and privacy of their data, that they “practically fell on the floor when Steve [Squyres] and I walked into the room and asked then, ‘okay, how do we get our data out there and as widely available as possible as soon as possible?’”\(^{49}\) One member of the managerial side of MER recalls that the conversation about ownership of MER data was directly in response to a PI who “tended to only put things out when he was ready to.” This placed “a lot of tension between the project office, headquarters and [the PI] to put this stuff out there.”\(^{50}\) Calibrated data is still only released to the PDS on a latent time schedule, but on the shortened timescale of once every three months. But it is released to fellow Rover team members as soon as it is downlinked; a stipulation clearly stated in “The Rules of the Road” and daily followed by the team.

Thus, just as all MER team members can request observations from any instrument, all MER team members have access to all Rover data, regardless of the instrument. This data-sharing occurs on the fly during the day-to-day operation of the spacecraft, but it also occurs during data processing and analysis, fostering collaborations between scientists leading to team publications. One scientist spoke of the importance of this “science network” for generating better explanations:

\(^{49}\) Interview, Pancam Payload Element Lead, September 2007.

\(^{50}\) Interview, MER administrator, May 2007.
You’re starting with one instrument, you use all the data, all the instruments, you use topography, you use local geology, then you use something from the orbiter, then you use something with lab experiment, that’s kind of the science network.51

This leads to creative combinations of team members working on particular problems. For example, when Opportunity was stuck in a dune, a scientist with more experience with imagery teamed up with another scientist with an interest in spectroscopy and an engineer at JPL who could build physical models from Rover wheel data to inquire into the character of Martian soil and therefore extract the Rover. In another case, two scientists found themselves working on the same Pancam dataset with the same toolset: instead of seeing themselves in competition and guarding their work, they started emailing and talking by telephone more frequently, sharing their visualizations and presenting their preliminary results at End of Sol science meetings to each other. Both mentioned to me in separate interviews that they welcomed the opportunity to have a close colleague comment on and collaborate with their work so that the team as a whole could better understand the rock’s characteristics.

This collaborative framework is also reflected in publication policies and practices. According to “The Rules of the Road,” major report publications, such as special issues of Science, sport the names of all team members; other publications on special topics are regularly circulated in advance among the Athena email list and authors on the team are required to be open to participation in those publications by team members who choose to make contributions. Similarly, published papers are also circulated and kept on a site for team members to read, share, and cite each other’s work. Many of the scientists I spoke to used this opportunity to gain input on their

51 Interview, June 18, 2007.
work, and in the days leading up to conference deadlines papers are posted to the team’s site and email list welcoming comments from other team members. The result are publications that bear the names and the weight of a team speaking with a unified voice. This norm of cooperation and collaboration is strongly enforced among team members, such that a few team members present at the beginning of the mission who did not agree with this approach to data sharing have since limited their participation on the mission. And a young scientist spoke candidly to me of the undertone of competition inherent in collaboration: as he put it, “Your colleagues, they’re your competition, they have control over your future, for example your grants.” Sharing one’s data with these colleagues leaves one vulnerable to research competition, but on the other hand not playing by the rules alongside one’s collaborators could prove disadvantageous in peer grant evaluations in the future. Such examples should serve to remind the reader that collaboration and consensus-building are not devoid of politics on this mission, but are rather constitutive of it.

This political orientation towards data is also built into the instruments on board the mission and the data products they return. Just as the PI who wished to have optimal control over his data encoded it in such a way that only his team could read it, MER instruments address the opposite challenge of how to make as much data available as possible, using a format that is easily combinable with other instruments. Combinability is key: as will be discussed in a later chapter, much of the science of the mission consists of “co-registering” data sets so as to see, for example, the thermal differences along a geological contact by combining MiniTES and Pancam data. As Susan mentioned, quoted in the introduction, “You shouldn’t limit yourself to one instrument, it’s the most foolish thing you can do.” This requirement featured heavily in the design of the Rover, such that both Rover hardware and software is designed

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52 Interview, MER scientist, June 2007.
from the ground up to permit liberal data sharing between instruments and between scientists. In this way the values of openness and communal sharing of data are built into the technical apparatus of the spacecraft.

Inclusions And Exclusions

It is worth noting that alongside principles of inclusion come principles of exclusion. The community’s open, sharing approach and flattened hierarchy, expressed through such issues as boundary-breaking roles and publication methods, do allow for close working relationships and easier consensus-building that heightens the team’s sense of productivity and engagement. But this value of communalism can also be daunting for outsiders and create friction. For example, the fact that many of the MER members worked together on previous missions or were graduate students together means that they can draw upon long-standing relationships with their colleagues when solving problems or proposing theories. This is especially valuable in the extended mission phase, when team members are located far from each other and communication cues such as body language are lost. But such a tight community can also be daunting for outsiders, as one MER member who was not trained in the United States admitted in our interview,

… that part actually bothers me … It’s harder for me, sometimes you have a hard time to communicate with people, because you don’t know them and you don’t know their teacher and you don’t know where they come from… this kind of tradition is very good, but it’s harder for outsiders.

Similarly, someone who was not a member of the MER team commented privately on the “us and them” mentality in operation as a result of the team’s cohesiveness and unified stance on issues. The MER team’s scientific interpretations carry considerable weight: on the one hand because they are the voice of a large and reputable team of scientists, whose collaborative approach to publishing means that
they have an ever-increasing record of papers under their belt, and on the other hand because the tight connection they believe exists between cohesiveness and good science can lead them to be passionately protective of their team when arguing for their results. When external pressure to include confronts internal team pressure to exclude, it can prompt some members of the team to become defensive about their group’s science and to resist external interpretations.53

The value of communalism especially creates tension as it directly conflicts with governmental policies regarding the sharing of information about spacecraft. NASA’s oversight of the mission promotes a vision of the Rovers as an American asset, in tension with the MER scientists’ ties to and impassioned belief in an international scientific community.54 The clearest manifestation of this on the mission is the strict enforcement of ITAR, the International Trafficking in Armaments Regulations. First adopted by the United States government shortly after World War II to preserve technical national defense secrets, ITAR also restricts foreign nationals’ involvement with spacecraft and satellite technology. Following a failed collaboration between private American company Hughes Aerospace and a Chinese satellite company in 1999 which resulted in fines of several million dollars, it became clear to the aerospace industry, private and public alike, that the cost of ITAR violation was extremely high. The situation has only tightened since the events of September 11, 2001 and the subsequent Patriot Act.

The Rovers are subject to ITAR restrictions, although they carry key instruments obtained under technical license agreements by German, Danish and French collaborators on the Athena Science Team. In spite of their essential technical and scientific roles on the mission, non-American members of the team are denied

53 It is also very difficult to do science with MER data if one is not on the mission, as will be discussed further in Chapter Eight.

54 On international (US-Japan) collaboration on satellite technology, see Plafcan (2007).
access to key systems, documents, and even on occasion their own technical plans for troubleshooting the instrument under American law. For example, during the primary mission, the French and German operators of the Mössbauer spectrometer were cordoned off into a walled office away from the Rover Planners, from whence they were allowed to remotely but only partially access the machines that would let them command their instrument. Without a printer, they tried to borrow an old commercial printer that sat abandoned in another room, and were promptly chastised for using a piece of equipment that was not cleared from export-control. When their own instrument malfunctioned, the German team that built the Mössbauer was required to stand outside the room while JPL engineers debated how to fix it; similarly, the Indian student who wrote the software to support the MiniTES instrument was restricted from debugging his own code once it had been delivered to NASA.

Like the technologies of bureaucracy during the South African Apartheid regime described by Bowker and Star (1999), ITAR requires a complex bureaucracy of paperwork and legal personnel to turn categories into rigid boundaries complete with dangerous transgressions (Figure 10). Also like the technologies of apartheid, the enactment and enforcement of ITAR regulations on the ground produce what the authors have called “torque”: defined as “when a formal classification system is mismatched with an individual’s biographical trajectory, memberships or location.” (Bowker & Star, 1999, p.223) This is not uncommon given that the Rover mission involves scientists at NASA centers but also private companies, public scientific agencies, public and private universities, each with different goals, mandates, and infrastructure for managing security regulations. Local expressions of torque were readily visible in the ten affiliated sites during my fieldwork. At each location ITAR was respected and enforced, enacted with mechanisms from bright red
badges and security escorts, to restricted rooms or machines. Despite extensive training, team members commonly report difficulty in consistent interpretation of the regulations, which are frequently described as contradictory, unclear, and conflicting with their institutions’ goals and mandates. Specifically, they often explain, the regulations have not been updated to reflect technological developments essential to

55 On my tour of Rover-related sites I always informed my participants of my citizenship, and together we avoided ITAR-sensitive material or conversations. I also remained compliant with my home institution’s regulations surrounding ITAR-compliance in addition to obeying local rules at my host institutions. I am deeply grateful to my study participants, their local legal assistants and visitor compliance personnel for assisting me in this regard.
current spacecraft systems designs and operations. For example, if a string of computer code is said to be ITAR-sensitive, does that restrict the line of code, or the software package, or the computer it is running on, or the building that the computer is in, or the entire institution in which the computer running the code is located? More complex still, yet a core activity in remote operations, does a line of code running in a software package on a machine located in a room at a particular institution restrict remote team members from being on a telephone or video-conference line with a team member located in that room? While the regulations present challenges in consistent interpretation, this does not mean that institutions adopt relaxed postures towards them: instead, because actors can use discrepancies that arise in local interpretation as a resource to fuel inter-institutional competition, individual actors and institutions are disciplined into conformity and reveal a level of perpetual anxiety about unknowingly breaking the rules. Discovering that another location does not follow locally-adopted procedures can open the door to accusations of incompliance, often to further local institutional aims; as one scientist insisted, a partner institution “loves ITAR because they use it as a weapon to keep things proprietary.”

As Bowker and Star document how the bureaucratic sorting-out of white from non-white both presents “politically and socially charged agendas … as purely technical” (1999, p.196) and inscribes notions of value and mobility onto South African apartheid-era bodies, foreign nationals on the Rover mission internalize ITAR’s policies on the grounds of the very category of the “purely technical.” They write ITAR onto their bodies as they are instructed to shield their eyes, plug their ears or simply leave the room, regardless of how pliantly or docile they behave or how

56 “Remote Operations” refers not to the status of the spacecraft, but to the status of mission participants as located at different institutions in extended mission phases. Believed to be more economical than bringing a large team together at a single facility, remote operations requires its own bricolage of cyberinfrastructure.

57 MER scientist, personal conversation, October 28, 2008.
central to mission operations their work is. This does not go unnoticed by their colleagues. Reflecting on this state of affairs, a team member spoke out angrily at a meeting,

I’m embarrassed by this. Fully a third of our payload comes from Europe … and we still cannot involve these teams from overseas who enabled this mission … . The foreign nationals on this team are too used to being treated like second-class citizens, and too polite to complain about it as much as they should.58

In spite of general dissatisfaction with the regulation echoed across the scientific community,59 MER scientists must comply with ITAR or face the shut-down of their mission. As a result, ITAR is most visible to the analyst in the work practices that structure the MER mission. For example, because the operational side of the mission is ITAR-controlled, maintaining a distinction between scientists and engineers, and ‘the science’ and ‘the operations’ side of the mission, is critical for the mission’s continued legal compliance as a whole. Locally, institutions must enable the critical work of the mission while remaining ITAR-compliant. This results in complex organizational labour arrangements that present unique local expressions of “torque.”

For example, one lab has hired an undergraduate US citizen whose only job it is to gain access to the NASA servers and download key data as soon as it has been downlinked to Earth such that the international students in the lab can process this

58 MER scientist, Team Meeting July 6 2007.

59 Criticisms of ITAR abound, both within and outside the United States. Several countries, notably France and Australia, have publicly rejected American collaboration on scientific projects due to their disapproval of ITAR and the bureaucracy it requires. Scientists also claim that the regulation ultimately does more harm than good in terms of safe-guarding American weapons technology. Restricted from forming partnerships with American companies who might provide a small piece of a weapons’ puzzle but retain the technical details at home, members of the planetary science community from foreign countries I interviewed admitted that their countries invested in local Research and Development to promote their own home-grown technologies. This, many of them noted, had actually proved advantageous to their nations’ own mission planning, as they could start a system redesign from scratch using new technologies and tools, instead of being entrenched in the older engineering designs and practices that informed the American systems.
data, considered essential to timely mission operations and decision-making. Team meetings are held at neutral facilities like CalTech or the Smithsonian Institutions to encourage the broadest possible involvement of science team members and their students, although international colleagues are often asked to leave the room if something sensitive, such as new releases of mission software, is presented. Such expressions of torque are especially uncomfortable for team members as they come into direct conflict with the communalist ethos that guides the team’s interactions.

When institutional pressure to exclude confronts internal team pressure to include, this can cause strain on team members, especially as the categories are likely to shift. One such case of “acute torque” (Bowker & Star, 1999, p.219) and the resulting suffering it prompted occurred when Pat, a scientist who worked on the mission for several years had their privileges revoked due to changes in institutional status. Several team members worked hard to resolve this conflict, but it was several months before Pat could resume participation on the mission. The torque occurred because while Pat’s status in the bureaucratic category of team membership had shifted, Pat’s membership in the social category had not. This created the discomfiting sense of conflicting requirements and movements from each category of membership: specifically, balancing rigorous exclusion from mission activity on the one hand with the MER team’s expected practice of sharing data and results on the other. Conflicted, Pat nonetheless sent a copy of a draft paper out to the MER mailing list out of a sense of loyalty to the team and a belief that it was not MER teammates that were the problem but national policy.

Pat’s discomfort reveals the acute torque associated with the politics of inclusion when embedded in a network engaged in competing practices of exclusion. And Pat’s experience is not unique; many foreign nationals shared with me their perceived limitations of the inclusion-based language of MER team members based on
their experiences of running up against NASA institutional exclusions. A tug-of-war over who is allowed to dictate the categories of inclusion -- the MER team, local institutions, or national regulations -- can compromise the dynamics the team believes are important to their success and to the successful operation of their Rovers.

Conclusion

Artifacts like the Mars Exploration Rovers possess both a rich history and politics. The *Mariner* and *Viking* missions were essential for constructing a group of planetary geologists, who identified the problem of finding life on Mars as a geological problem that required a robotic geologist to solve it. This group honed the methods of image interpretation and analysis that would be critical to Rover operations and science. The events of the 1990’s also created national pressure to achieve a Mars landing and crafted the timing, number of Rovers and participants of the mission that was eventually flown. In addition to this history, the Rovers themselves are part of a sociotechnical system, a collection of human and mechanical components arranged along the lines of a flattened hierarchy and consensus model of operations. This is expressed not only in documentation and conversation about the mission, but also through practices of operating the Rover and doing science with its data. Values of inclusion, sharing and collaboration affect the robots’ technical construction and the data they return, and in turn shape the team’s ongoing interactions with them. While this inclusionary politics can cause difficulty for external members, overall it constructs a team who subscribes to a deep belief in the contribution of individual members across mission roles, whether graduate student, Principal Investigator or engineer; in the dissolution of boundaries through attention to communication practices; and in keeping each other “happy” and affirming this “happiness” daily. This arrangement and the consensus-building it supports, they argue, results in “the best possible science.”
In this way, the Rovers do “have politics,” although perhaps unlike those Winner suggested. Criticisms of Winner’s position often undermine the ability for a bridge or another technological artifact to have political agency in and of themselves, for example. The Rover story, told only in small part here, suggests another way in which artifacts enable human agency and possess politics. It is in the Rovers’ sociotechnical system, the way in which the organization of people and the organization of machines both reflect and project a particular normative structure of scientific practice and human interaction, that the Rovers have politics. That is, constructed roles, activities, and artifacts enable such a local ideology and associated politics to be achieved through working with the Rover, such that the work of managing the Rover is bound up in the work of managing the team.

Work with images thus allows MER team members to achieve many different goals as they “follow the water.” Just as mission goals of consensus and unity are produced and enforced through the operation of the Rovers, images arise from this context and play a critical role in this endeavor. It is not my purpose here to extol the virtues or to expose the dark underside of the political model that the MER team espouses. Rather, as I explore the many uses of images on the team in this dissertation, I aim to show how work with images is part of the work of team and Rover management; how this work and the images it produces are important resources within the mission that circulate and are employed according to the MER form of life, through which both community norms and tensions can be expressed (Mulkay, 1976). I will return to these ideas in later chapters; in the following chapter, however, I will examine just what work scientists do with digital images and how these transformations reveal aspects of the Martian terrain.
CHAPTER 2: DRAWING AS
CERCEDILLA, TYRONE, AND REPRESENTATION IN SCIENTIFIC PRACTICE

The constant chatter of the Rover teleconference line is silent, replaced by gentle classical music broadcast by a satellite radio station. I sit with MER scientist Ben Quinn at his desk at the US Geological Survey offices in Flagstaff, Arizona in front of two large Dell screens. An Athena Science Team member, Ben has worked at the USGS for several years as a planetary scientist. He is currently peering at the display on his screens of an image of Cercedilla, a rock imaged by Opportunity at the edge of Victoria Crater (Figure 11).

Figure 11 Cercedilla, single filter Pancam view.

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1 In addition to Earth-based mapping, the US Geological Survey is extensively involved in mapping other planets in the solar system: several of the participating scientists on the Rover team have published geological maps of Mars in association with the USGS, and the organization maintains records of lunar maps, maps of Venus and Mercury, and image data from all orbital missions to Mars.

2 Cercedilla was chosen because in false color it is the same color as two other massive pieces of rock just beneath the lip of the crater, but different than the rest of the rocks on Meridiani Planum. The team originally wanted to go to the larger rocks, but settled for Cercedilla because it was the only one accessible to the Rover.
To Ben, Cercedilla looks suspiciously like a piece of rock thrown outwards from the deep innards of Victoria Crater during the impact event that formed the crater; if this were the case, it would prove advantageous to a scientist who wants to know more about the geological characteristics of the deeper (and therefore older) stratigraphic layers that the crater’s formation exposed. Cercedilla also appears in Pancam images to be covered with and surrounded by blueberries, the ubiquitous hematite concretions, but are these embedded in the rock or are they sitting on top of it, windblown into place from across the Meridiani plain? If the rock is a piece of ejecta from within Victoria, then both possibilities present different possible geological histories for Victoria’s deep interior. To learn more about Cercedilla, the Rover team has commanded Opportunity to take pictures of the rock using all of the Pancams’ thirteen filters, to use its Rock Abrasion Tool to grind away the weathering on the surface, and then to take more pictures of the rock post-grind. The team also commands the Rover to use its APXS and Mössbauer spectrometers on the rock both on the weathered surface and in the “rat-hole”, the circular area ground by the RAT. Results from these observations have been “downlinked” to Earth, and the APXS and Mössbauer scientists reported that there was no discernable difference in the rock’s elemental chemistry compared to the other rocks the Rover has already examined on Meridiani Planum. But a cursory look at false color Pancam and orbital imagery shows that Cercedilla is a different color than its neighboring rocks, suggesting that its composition is somehow different after all.

Ben has decided to use Pancam images to explore what he calls these “frustrating” questions, and to “characterize” -- that is, analytically describe -- the rock Cercedilla. In particular, he is interested in seeing which parts of the image reflect light differently, as he believes that this corresponds to different mineralogical composition. He therefore asks the computer to show him aspects of Mars that the
human eye cannot see but the Rover’s ‘eyes’ can: the near infra-red region spectrum of light. He loads the Pancam image processing software, selects several different filtered frames of Cercedilla pictures from among the Pancam thirteen filter set, and combines them until the image on his screen brightens with false color (Figure 12). As Ben explains, putting an image into false color allows the scientist brings out new features in the image that are otherwise hidden in black and white or true color. When seen in false color, “A lot of these … rocks suddenly ‘pop out’ that weren’t there before.”

Figure 12 Cercedilla, False Color view.

One of the affordances of digital images is their malleability and combinability, and digital image processing techniques that reveal and present different properties of distant photographed objects. This is the computational work that one of my interviewees, discussing its centrality to planetary science, called “pixel-pushing.” In this chapter, I examine pixel-pushing as the work of “doing science” with digital images to develop the main theoretical line of reasoning in this dissertation: the concept of drawing as, an analytical framework for analyzing the production and use
of images in scientific practice. I begin by showing how the same image offers different possibilities for visual construal, recalling the Wittgensteinian notion of seeing as. Following Ben as he works with digital images I develop the idea of drawing as, a practical corollary to seeing as that brings attention to the purposefulness of image crafting that pixel-pushing entails. I then return to the story of Susan’s work with images of Tyrone to further elaborate aspects of drawing as, showing how pixel-pushing work with visual materials not only reveals but also conscripts viewers to a particular vision of the object at hand.

“Making It Pop Out:” Image Work And The Dawn Of Aspect

As described in the introduction, the raw images produced by the Mars Exploration Rovers afford multiple views. Each camera pointing can return up to thirteen differently-filtered black and white photographs of the same object, a measurement of the object’s ability to reflect light in that limited range of wavelengths. As photons hit the CCD plate, they are counted into pixel values. These values can be displayed along a gradient from white (lots of photons) to black (none). When three images of the same object are combined in an image processor, that gradient changes to shades of red, green and blue, producing a colorful image that may or may not align with what can be seen with the human eye. Because the more extreme colors are produced by wider disparities in pixel values between the filtered images in the red, green and blue channels, these colors are considered diagnostic of some kind of minerological composition. After all, while the minerals common to Mars commonly appear red to the human eye, they reflect and absorb light differently in other wavelengths.
On the MER mission, standardized views have emerged involving the combination of particular sets of filters or processing choices, like the blueberries discussed in the introduction. These filter sets are considered particularly useful for seeing particular kinds of features, and are often combined and recombined in the course of mission operations depending on which features individual scientists are most interested in examining. For example, a soil scientist interested in the composition of the terrain of Cape Verde, a promontory on Victoria Crater, assembled the left Pancam second, fifth and seventh filters (abbreviated L257) into false-color; this combination was judged helpful for revealing a wide range of textural and compositional differences (Figure 13a). The resulting picture was well-received by soil scientists and doubled as a good image for planning a drive into the crater as it highlighted different types of soil that may be hazardous or safe for Rover wheels. But

Figure 13 Pancam frames of the same observation of Cape Verde assembled in a) L257 false color (above) and b) Approximate True Color with adjusted contrast (below). Opportunity Sol 952. Courtesy NASA/JPL/Cornell.
another geologist pointed to the same transformed image, saying: “we think we’re getting all this [great data] but look what do we get? [points to shadowed region] Artifact Soup.” This scientist was most interested in characterizing the crater’s stratigraphy: for him, “lighting and geometry” were more important than compositional difference as they would allow him to measure the exact shapes, sizes and depths of the crevices on the cliff face. He therefore combined the filtered frames that showed the least variation in pixel values and adjusted the lighting saturation to better reveal these distinctions (Figure 13b).

In these two renderings of the same image we see a switch between the artifact and the object of scientific analysis: composition and texture at the expense of lighting, or stratigraphy at the expense of composition. It also demonstrates how the selection and combination of multiple raw data products varies based on the image processor’s intent: i.e. what they want to show. But the flexibility to see it both ways is crucial to the science and operations of the mission: the geologist would not be satisfied with the soil scientist’s picture, and a Rover driver could not hope to identify slippery soil in the geologist’s image. Both representations were derived from exactly the same data set, the same set of pixels, but as a result of the choices of the image processor a different set of features is revealed or subdued each time. The result of this plethora of possibilities is that one is often confronted with an image of an object on Mars repeated through different filters or processing algorithms. With so many possible viewings, and recalling that True Color and false color refer to specifics of filter combinations and not to any claim to object essentiality, it is clear that there is no one best way of picturing Mars. Rather, such images represent different ways of seeing and knowing the Martian surface.
In fact, it is often necessary to see different things in the same image. For example, as discussed in the next chapter, when calibrating images that return from the Panoramic Cameras a human operator must go through a complicated number of steps to locate and eliminate light pollution, scattering and dust. The resulting equation is applied across the board to an entire suite of images to systematically subtract a value from all pixels so that the images are corrected for dust and atmospheric opacity on any given day. But one person’s artifact is another’s data: many of the atmospheric scientists rely on these dust values to understand the atmosphere and Martian weather patterns, and soil scientists try to understand the optical quality of the dust itself. They therefore use the output from the calibration procedure to get the dust information, and would rather see the dust than the image it obscures.\(^3\) The multiple views that result are therefore not an attempt to hone in on a better representation of Mars in some absolute sense, but are rather the result of multiple construals of a visual field for different purposes.

The ability to see the same visual data in different ways recalls the famous gestalt images which were central to mid twentieth century epistemologies of observation.\(^4\) In his *Philosophical Investigations* (1953), Ludwig Wittgenstein explores the conditions under which it makes sense to say “I see it as x” as opposed to “I see x.” He notes that usually, people do not say “I see it as” about their visual experiences -- they just see -- but the ability to say, “I see it as…” arises in situations where there is some ambiguity as to which features are salient: which elements form the background and which the foreground. The most famous example is, of course, the duck-rabbit image, in which the gestalt switch from seeing it as a rabbit to seeing it as

\(^3\) See, for instance, Kinch et al. (2007).

\(^4\) The use of the term ‘gestalt’ may be confusing to some readers due to its heritage in psychology and the cognitive sciences. However it is also extensively used in the analysis of artistic techniques (Gombrich, 1960), in the philosophy of scientific observation (Hanson, 1958), in the sociology of scientific imaging (Lynch, 1991b) and, interestingly, as a case study for image processors (Rosenfeld & Kak, 1982).
a duck is an example of “the expression of a new perception and at the same time of the perception’s being unchanged.” (Wittgenstein, 1953, p.167) Wittgenstein calls this “dawning of aspect,” a change in the organization of visual experience wherein the foreground and the background, or the artifact and the object, shift. Although the object does not change, this change of aspect produces a different observation, “quite as if the object had altered before my eyes” (p.195). The duck-rabbit example implies a kind of ambiguity in which there are only two possible ways of seeing, but Wittgenstein also uses the example of the “aspects” of a triangle to show that multiple seeing as experiences are possible:

This triangle

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can be seen as a triangular hole, as a solid, as a geometrical drawing, as standing on its base, as hanging from its apex; as a mountain, as a wedge, as an arrow or pointer, as an overturned object which is meant to stand on the shorter side of the right angle, as a half parallelogram, and as various other things.

“You can think now of this now of this as you look at it, can regard it now as this now as this, and then you will see it now this way, now this. (Wittgenstein, 1953, p.171. Quotes and triangle in original.)

Wittgenstein’s discussion of seeing as is essential to philosopher of science Norwood Russell Hanson, in his discussion of theory-laden observation. In his Patterns of Discovery (1958), Hanson makes the claim that scientific seeing is not a question of freeing observations from bias, but rather a question of acquiring a theoretical and practical orientation that enables the scientist to see as: thus the physicist sees the glass object as a cathode ray tube, and Kepler sees a sunrise as the sun standing still in the sky while the Earth moves around it. In acquiring this aspect, scientists can thenceforth distinguish foreground from background and signal from
noise, giving the visual field coherence, recognizeability and meaning. Observational reports in science thus involve interpretation at their most basic level, as “theories and interpretations are ‘there’ in the seeing from the outset” (p.10).

The skill of seeing as that Hanson identifies as essential to scientific practice is also evidenced in the above images of Mars. Like the triangle pictured above we might see Cape Verde as a stratified cliff face or see it as composed of different soils; with respect to digital images, too, we can see the image as a picture or see the image as numbers. But unlike the triangle example, these seeing as experiences are not “found” but crafted experiences, the result of directed image processing activities that compose the image into something meaningful, distinguishing foreground from background or object from artifact. Through the work of pixel pushing, an interpretation or skilled vision is crafted into the image from the outset, such that the resulting picture incorporates elements of what it ought to be seen as.

As an example of this kind of crafting activity, let us return to Ben’s desk in Flagstaff. Still engaged with Cercedilla, Ben heightens the contrast between the different filters in his image by creating a decorrelation stretch. “Stretching” here is a technical term that refers to increasing the level of contrast between pixels, roughly analogous to using the “contrast” tool on Photoshop. In a decorrelation stretch, the scientist increases the contrast in at least one of the combined filtered images by a certain factor, but does not necessarily apply the same factor of stretch across the board to the other images in the combination. This changes the “correlation” between the pixels across the image frames, and results in an even more extreme, garish false-color image which often elicits comparisons to the work of the modern artist Andy Warhol.⁵ Again, these different colors are related to different kinds of objects, whose different mineralogy is displayed in the color image.

⁵ See Lynch and Edgerton (1996) on further connections between astronomical image making and modern art.
As Ben looks at his decorrelation stretch image of Cercedilla (Figure 14), he exclaims, “If you look at it like this [stretched], wow! That’s really a different color. Suddenly there’s differences in what I thought were really the same [thing].” This moment recalls Wittgenstein’s characterization of the instant when the duck-rabbit resolves into just a rabbit, the “dawning of aspect” (1953, p.166), when a change of aspect produces a different observation, “quite as if the object had altered before my eyes” (p.167). In this case, the image does indeed alter before Ben’s eyes, enabling him to better see one or another aspect of the object at hand.

The scientists I spoke to in my research repeatedly explained to me that the point of false color and decorrelation stretched images was “to see new things,” to make a hidden feature “pop out,” to discriminate between different units that otherwise appeared the same in one filtered image but which might, upon combination with other filtered images, prove to have different spectral characteristics, pointing to a difference in composition. For example, a scientist I interviewed who was looking
for sulphate content on Mars explained, “if you get a particular [filter] combination the sulphates just jump out at you. It’s like they turn green or blue or something.” But this does not imply a change in the underlying dataset, only a change in orientation or aspect. Another scientist explained to me, “The data is the same, the difference is in what you see.” A Rover Planner on the team echoed this statement: “The image never changes, but you can manipulate the image, and everyone sees something different.”

Ben insists that this ability to see something different with each click of the mouse is the key to his digital work with Pancam images:

If you were walking around with your rock on Mars without Pancam you might not even know that these were different! … The ability to discriminate between these units is the real power of Pancam …

But the *seeing as* experiences that the Pancam permits are due to particular practices with visual materials: purposeful image construal so as to see, discriminate and characterize, and enforce a change in aspect that allows new elements in the image to be appreciated as foreground instead of background. The observer in this case is not passive, but rather actively composes the image into something meaningful.

This is especially evident as Ben moves from simply discriminating between colored materials to characterizing them in order to say something about their classification or origin. As he explains, “… the reason why I’m doing all this is to see if any spatial pattern jumps out that’s really obvious. … Some folks may say that you know it’s all the same unit, but that assumes that you know that, and why not avoid that assumption?” Thus Ben moves to the numerical side of the Pancam image, *drawing* the Pancam image *as* a photometric dataset to quantify the qualitative claims he makes about the different colors he sees. As different minerals reflect different

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6 Compare to “I *see* that it has not changed; and yet I *see* it differently” (Wittgenstein, 1953, p. 165),
amounts of light in different wavelengths, the resulting graph can be diagnostic, presenting features that are particular to special minerals or combinations of minerals present in the scene.

Using the false colors as a guide to suggest which areas of the image might correspond to parts of the rock that are composed of different substances, Ben then uses a software tool that, based on selecting a few pixels of interest, can generate a graph of average pixel values across that selected set of filtered images. He selects an area on the rock in the middle of the hole left by the Rock Abrasion Tool as it ground into the rock: the software colors his selection red on the picture, and a graph pops up showing thirteen red points connected by a red line (Figure 15). “Interesting,” he says. With his cursor he sweeps over the tail end of the graph. “See the upturn? That’s kind of blueberry-like. And it’s from this center spot.” He moves his gaze and his cursor from the graph to the image, pointing to the red swatch of color. “So I’m gonna choose a different color and look at --” he selects a region on the edge of the RAT hole in green “-- that.” Thirteen green points show up on the graph alongside the red, but do not follow the characteristic blueberry curve. He gestures again with his mouse, first sliding over the green lines, then the red lines to point out the differences between
them. “So there’s the difference in spectra between the RAT hole [on Cercedilla] and a spot outside of where the Mössbauer got its data. And so, why are the spectra so different?”

Further transformations reveal other aspects of Cercedilla. To determine where the blueberry signature shows up and whether or not it is responsible for Cercedilla’s unusual spectral characteristics, Ben uses tools that combine the mathematical and the pictorial elements of the pixel. He creates a “slope map,” selecting two filters and requesting that the computer show him the slope generated by the difference between the pixel values at the same point in the two filtered images: this slope is expressed as a color on a gray scale from black to white. He requests a ratio image between the bluest and reddest filters (Figure 16a), producing an image where the ratio between the two filters is expressed as a shade of gray, but as he says, “it still doesn’t tell me why [there’s a difference in spectra].” He asks for a band depth image (Figure 16b), computing the difference between the range of pixels returned by one filter compared

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7 After two hours of digital work, Ben still feels he has only taken the first step towards addressing the “frustrating” question of why Cercedilla presents different colors in Pancam data than other rocks in the region, in spite of looking the same to the APXS and Mossbauer. He concludes that he looks forward to comparing his results to those of his colleague at another institution before the next team meeting, and hopes that that correspondence of results will generate some sense of why. At subsequent operations meetings he requests further observations of other pieces of ejecta in the region to see if he can correlate his findings with other similar rocks.
to another. Each of these requests are mathematical calculations involving the numerical side of the pixel, but are returned as pictures, with different Cercedilla-shaped collections of dark and light pixels. While these images do not necessarily align with what is seen or what can be seen, we might say of them what psychologist of art Ernst Gombrich’s claims about visual languages: that they are “not a faithful record of a visual experience but the faithful construction of a relational model” (Gombrich, 1960, p.90). Appearing to the untrained eye like a version of a photographic negative in their relationship to the raw image data, they reveal different aspects of the images, different aspects of the relationships between image frames, different aspects of Cercedilla.

Just as an ambiguous gestalt figure may resolve into the picture of a duck or of a rabbit, the image of Cercedilla resolves at each click into a false color image, a decorrelation stretch, or a graph of its blueberry components. But unlike the gestalt figures, which remain stable as the perception of them changes, with each new composition Cercedilla is presented differently. Clicking through these various constructions Ben attempts to disambiguate the visual experience of Cercedilla by isolating only a single aspect of it at a time, blinding or curtailing alternative aspects. To demonstrate this activity’s relationship to the different seeing as experiences it produces, I call this work of image-making: drawing as.

I use the term “drawing” here intentionally, for two reasons. The first is that I wish to suggest that this technique is not unique to digital image processing or to twenty-first century space exploration, but that it presents broader applications and implications across the history, philosophy and sociology of scientific practice. An excellent example from early modern astronomical image processing is that of Galileo’s images of the moon in Siderius Nuncius (1610) as drawn through a telescope.
Historians of science would call it historiographically unsound to guess at Galileo’s perceptual experience, and this is where simply using seeing as without its practical corollary of drawing as can be problematic; but his visual production -- his images -- presents an interesting point of comparison. In Galileo’s images, there can be no ambiguity about what the patches of shadow on the moon’s surface are. A simple and widely-recognized shading technique (chiaroscuro) is employed to represent craters and pockmarks, to draw the moon as a topographical body. But due to the longstanding Ptolemaic assumption that superlunary physics were fundamentally different than terrestrial physics, identifying the features of a heavenly body as craters and other Earthly imperfections reveals profound Copernican commitments. That is, in depicting a planet with imperfections and topography, Galileos’ lunar drawings in *Siderius Nuncius* have become a canonical case in the history of images in science. Samuel Edgerton (1984) has famously shown how Galileo’s training as an artist at the *Accademia del Desegno* was instrumental in enabling him to not only see, but also to depict and measure craters and pockmarks on the lunar surface, and Winkler and Van Helden (1992) speak of Galileo as a founder of visual astronomy, inspiring subsequent generations of astronomers to include illustrations alongside cosmological diagrams in their texts.

Interestingly, this ‘shape from shading’ technique has resonances in contemporary photointerpretation practices in planetary geology. A branch of photogrammetry called *photoclinometry* uses measurements of shadows projected by features on other planets to provide an estimate of the feature’s topography.
Galileo drew the moon as a Copernican object. The images in *Siderius Nunicus* thus present an excellent example of how visual and theoretical insight is produced in and through a technique of *drawing as*. The drawing is not just a projection of what Galileo saw. In an important sense -- and like Ben’s or Susan’s digital image work -- it is *where* the discovery emerges. Instead of talking about the great idea that occurs to Galileo’s *prepared mind*, it is possible to speak of a novel inscription produced by his *prepared hand*.

The second point about “drawing” follows from this sense of the *prepared hand*. The verb brings our attention to the craft and the intentional work of purposeful image construal. Each of Ben’s mouse clicks is essential to a kind of image-making aimed at revealing or otherwise showing an aspect of an object at hand. “Seeing is *work*,” say Amann and Knorr-Cetina (1990, p.90), and producing images that make the seeing possible, that sets up a narrative that makes sense of objects, and that “fixates” visual evidence comprises much of this work on the MER mission. Producing such images is not a question of finding an ambiguous image in the world and interpreting it; it is instead a question of skilled eyes and hands working in concert. It recalls what Coulter and Parsons call the “praxiology of perception,” “modes of perceptual orientation as forms of practical, social actions, capacities and achievements” (1991, p.252). Thus the skills of visual interpretation arise from and are enmeshed in skills of image manipulation, in this case a kind of drawing work with digital tools.

*Drawing as* also recalls anthropologist Charles Goodwin’s (1994) accounts of “Professional Vision”: honed viewing practices and/or tacit abilities to discriminate and make distinctions with visual material. Goodwin turns to examples of the courtroom and the archaeology plot to observe how an overabundance of data is honed into salient details and from there made representable to other members of the field.
The kind of classifying, sorting out, and discriminating work that Goodwin describes is also practiced by Ben as he pixel-pushes the image of Cercedilla. Related work by Lynch and Edgerton (1996) on planetary image processing or Law and Lynch (1990) on bird-watching similarly focuses the analyst’s attention on the virtuosity required to both produce specialized images and practice skilled readings or deployments of said images in the field. Martin Rudwick’s discussion of visual languages in the history of geology (1976) is also an instructive touchstone here: for Rudwick, a discipline’s visual language both gives the scientist a way of expressing analytical objects to their peers and, as the application of the visual language in practice reveals objects of analytical importance, it provides an essential tool for the conduct of science.

In Ben’s work with Cercedilla we see similar themes, but here the classifying, sorting out and discriminating work of observing arises from and is recorded in the work of image making. With each transformation of Cercedilla Ben purposefully includes particular features which he considers salient, such as blueberries, and excludes or silences other features, relegating them to the background. The intention of such an activity is to highlight or even to restrict the subsequent visual experience to that aspect, to enforce a situation of seeing as. Thus “just seeing” the band depth, the slope map, the photometry, or the blueberries is the result of highly skilled, disciplinary drawing practices that enforce an aspect to organize visual experience and characterize the object at hand. One might as well draw a duck-rabbit as a duck to purposefully encourage a viewer to see the image as a duck, and preclude any possibility of seeing a rabbit, enforcing an aspect-blindness which curtails the ability to see the same image as something different. The viewer only sees the one aspect of the illustration along with the features that the artist or scientist has determined are

10 Although here we should note that even drawing an ambiguous figure is a difficult achievement: as the discussion of gestalt switches suggests, it is hard to simultaneously hold two ways of seeing a single figure as a different object. One must instead go back and forth between two or more aspects of appreciating the object’s features.
salient -- what is drawn in, not what is drawn out. As one MER scientist explained, “you have to throw out something in order to make it [the data] understandable.”

Talk of “throwing out” data reveals the deeply disciplinary nature of image craft. I do not use the term “discipline” lightly here. After all, revealing a particular aspect, making something “pop out” while excluding or silencing other perspectives recalls the familiar Foucauldian theme (Foucault, 1977) and its incorporation into the study of representation in science (Lynch, 1985b). Even the language used to discuss this kind of work often betrays a kind of violence as pixels are “pushed” or “stretched” into conformity; another scientist talked about the necessity to “pull information out of digital data”; and Ben as explained to me in our interview, “you need to pound the data to this level to be able to see the secondary differences between things…” But we might say that pixel pushing, or more broadly drawing as, is a disciplinary activity in other ways. To make something “pop out,” the pixels in the image must be constrained and made to reveal only one side of their meaning. But drawing as is also disciplinary in the sense that different disciplines have different ways of drawing their objects of analysis, due to the different features that interest them. Both Ben Quinn and Susan Lee submit their pixels to transformations of interest to a photometrist or spatial analyst, but different transformations interest other kinds of scientists who resort to different software and datasets to reveal their information of interest, as further examples in this dissertation will discuss. Finally, just as Daston and Galison (2007) have shown that particular configurations of scientific images require particular kinds of scientists with particular identities, we might also say that the scientists themselves are disciplined through this way of seeing and interacting with their data. I will return to this theme in later chapters.
On the Rover mission I have witnessed many examples of images drawn to exhibit a specific aspect, but these are often brought into conversation with each other. That is, unlike the duck-rabbit disambiguation, the views are not considered incommensurable but rather complementary. In each of the Mars image cases the producer, the intended audience and/or context of use can be slightly different, and the single aspect that the image presents may preclude other ways of knowing – the slope map doesn’t tell you the band depth, and the graph doesn’t tell you where the blueberries are located, and none of those images tell you what Mars looks like to the human eye. To counter this effect, attempting to produce multiple concurrent views of the same data product is considered essential for teasing out what is knowable in the imaged object. A comparison here might be the kind of gestalt work in which multiple figures are found within a complex background.\textsuperscript{11} Recall that Ben did not stop at one transformation, but rather produced iteration after iteration of the Cercedilla frames, seeing something different each time. Taken together, these multiple partial perspectives are believed to construct a more holistic sense of the object at hand.\textsuperscript{12} As another team member explained, “when you see it in all these different ways, then you get to know it.” Limiting aspect through \textit{drawing as} activities both restricts scientific interpretations and produces them.

\textsuperscript{11} On such “Where’s Waldo?” work see Garfinkel et al. (1981), Lynch et al. (1983).

\textsuperscript{12} Feminist science studies has seen a substantial discussion on the value of partial perspectives, famously by Haraway (1991) and Traweek (1992). The view from the Rover mission compares to philosopher of science Helen Longino’s claim that “the greater the number of different points of view included in a given community, the more likely it is that its scientific practice will be objective” (1990, p.80).
**Drawing And Seeing: The Case Of Tyrone**

Ben jokingly refers to his work as “just simple data mining” or “goofing around to find stuff,” but there is an implication in this kind of work for further visions of and interactions with the Martian terrain. Specifically, there is an iterative relationship between these representational practices and subsequent, collective or shared seeing experiences. This relationship between representing and intervening has been explored before in Science Studies; for example, by philosopher of science Ian Hacking (1983), who argues for the primacy of interventions to representations, or by sociologist of medicine Stefan Hirschauer (1991), who discusses the transformation of the patient’s body into the represented anatomical body through surgical practice. In both of these cases the work of making aspects of an object visible and making representations are tightly linked. Certainly there is also an implication here for Rover activities on Mars, as disambiguating an image could reveal a rock target that the Rover may eventually visit or deploy its instruments upon, like Cercedilla. But here I want to point to another iterative relationship between representation and vision in practice. This is especially evident in the example that opened this dissertation: Susan Lee and the two-toned soil at Tyrone.

Like Ben’s playful approach to image analysis, Susan also explains her discovery as due to being “naïve.” Despite her deep experience with mineralogy, spectroscopy, and instrument-building, Susan had never served on a mission before and describes herself as relatively new to geology. She asserts that the “naïve” approach is important for generating initial sets of questions as it is part of the “common sense” practice of geology:

> In geology you use your common sense … This rock looks darker, this rock looks lighter, then why is it lighter?\(^\text{13}\)

\[^\text{13}\text{ Interview, Susan, June 18 2007.}\]
But visual analysis requires more than just naïveté to answer the question, and convince her peers to “see something obvious.” Describing an investigation at the outset of Spirit’s mission, she recalls:

We see some really dark rock, we see some light toned rock. Maybe people who already work on Mars … [know that] the light toned and the dark toned rocks don't show much difference … But I'm very excited … I'm very, very naïve … At the beginning it's hard … to get people to accept that [the rocks are] different … [but after using the instruments] we did find that light toned rock was different than the dark toned rock … So my naïveness at the beginning is not so foolish … .

Getting her colleagues to see that there was a difference between the rocks required going beyond judging rocks to be light or dark in Approximate True Color images: it also required fluency with the other instruments on board the Rover. Following this initial incident, Susan chose to learn more about how to use the Pancam, attracted to its dual advantage of presenting both spectral (phase) information and spatial information about where those phases are located:

Pancam is the only [instrument on this Rover] which can see the coexistence of different phases and spatial correlation of these phases…. Tyrone is a very good example to show that you get the two phases, which has difference in Pancam spectra. Then you can see the correlation of the two phases. That’s how I come to see that the yellow one is deeper and the white one is higher… Then you can develop a story.

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14 Interview, Susan, June 18 2007.
15 Interview, Susan, June 18 2007.
“Coming to see” the yellow and white soils and “develop a story” about their spatial location on the surface of Mars was the process of specific, skilled (not naïve) work with images of Tyrone. As Susan recalls it, she was working with Tyrone as a test object on which to learn Pancam image processing techniques during her stay at Cornell. While practicing her techniques of making false color composites, she noticed that what looked like a just a patch of white soil seemed to display as two slightly different colors in the false color imagery. Intrigued by how something that looked the same could be made of two different types of material, Susan, like Ben, turned to the numerical side of the image in order to characterize what she saw in the false color image. This would help her to isolate the spectral properties of the two different kinds of soils and possibly make a determination about their composition. As she declared, “I’m not looking at pretty image, I use histogram… if my purpose [is] to see if [it is] two different type [of] material.”

Instead of asking the computer to generate a graph for a particular region of the image, like Ben, Susan instead asked the computer to display all the pixel values at once on a graph (Figure 18a). That is, she drew the pictorial data as a histogram, a graph in which individual pixel values are plotted together. Construed in this way, the image data showed two distinct clusters of pixel values. Susan interpreted these two branches of the histogram as two different types of material, whose properties of light absorption were so different that they produced radically different pixel values.

But while her histogram showed that two different kinds of material were present in the image data, it did not show where that material was located. She therefore used another Pancam tool to “separate them [the two materials] spatially.” Coloring in one branch of the histogram in green, all the pixels plotted on that branch lit up in green on the picture version of the file (Figure 18b). She could then see where

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16 Interview, Susan, June 18 2007.
Figure 18 From top: a) Tyrone filtered image on left, histogram on right, b) coloring in a branch of the histogram in green lights up the location of those pixel values in the image, c) coloring in the other branch yellow to locate the second type of material.
that material was scattered. She proceeded to color the other branch of the histogram in yellow, lighting up a different patch of white soil (Figure 18c). Thus two different kinds of soil with different spectral characteristics were confirmed. And because of where those different patches of soil lit up in the image in green and yellow -- what Susan calls “spatial correlation” -- she could show that the yellow material was buried deeper in the wheel track than the green. She thus made an assertion in her End of Sol presentation in October 2006 about the stratigraphic layering of the soil deposits, suggesting that Spirit’s recently-broken wheel had turfed up a deeper layer of soil that was previously invisible to the team:

[In] the decorrelation stretch, you can see that the yellow material originally [marked] in the histogram is now kind of an orange yellow, and the green is now kind of a green yellow… And if we go down to the next slide, which is the material exposed at the back of the Rover … here is the orange colour .. in the decorrelation stretch, which is exposed by the first forward drive, and also by the third arc drive, which exposed much deeper material on the back of the Rover.\(^\text{17}\)

So far, this story is not unlike Ben’s. As Susan draws Tyrone as a histogram, then as composed of two kinds of soil, her processing techniques reveal an aspect to organize visual experience, and bringing several of these aspects together in concert she makes a claim about a particular region of Mars. But each of these transformations also allows her to make an interpretative claim not just about evidence for two-toned materials, but about what the two-toned material is evidence of in terms of Mars’ history. Thus Susan follows up on these visual analytical techniques with a story about why these two types of soil are so different. Presenting her work to her colleagues, she shows the images taken while the engineers struggled to extract the Rover:

\(^{17}\) End of Sol meeting, October 11, 2006.
The next slide shows in [Sol] 792 when we did the first forward drive and we really used the front right wheel to dig very deeply into the soil and get some more white material exposed. Then the next slide shows [how] the second forward driving exposed some white material but not as much as the first drive … We did some forward and back driving in Sol 794 and the [image] shows again the front exposed material covered by the previous Pancam. And we see we exposed more white material in the Rover tracks again. 18

Susan’s comparison of these images along with her verbal descriptions shows the appearance of more, different and deeper light soils with every maneuver. “With one wheel rolling … only brings up a little bit of material,” she says, “but when we drag the Rover wheel, then we will bring more stuff up. At this area we make lots of tracks, and the right front wheel makes the trench, a much deeper track.” Ultimately, comparing false color and decorrelation stretch images of Tyrone with images of another lowland area where white soil appeared under the Rover’s wheels, Arad, she suggests the hypothesis that there might be “a water story in Gusev”:

We see Tyrone actually is enclosed or located at the lowest portion of this area … which has the lowest elevation. And it suggests that maybe this material was brought here by some sort of a fluid … it can be the wind, can be the water, can be something else. 19

Pixel-pushing allows Susan to discriminate between different kinds of soils in the image of Tyrone; it also allows her to construct a story about what these soils are (salts) and why they are there (“a water story”). But it is also interesting to note that Susan’s drawing Tyrone as composed of two kinds of salts prompted future

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18 End of Sol meeting, October 11, 2006.
observations, representations and even interactions with Tyrone and other patches of light soil across the region.

While Spirit sat only a few meters away from Tyrone over the Martian winter, Susan requested a “Christmas Wish List” for periodic images of Tyrone to confirm her analysis. Because the Rover was immobile and there were few other competing observations, the team agreed and programmed the images she requested. Applying the same techniques to the subsequent images, Susan noted that the histogram changed; that the yellow branch started to conflate with the green one (Figure 19).

![Figure 19](image.png)

This suggested to her that the yellow material was changing in some way to become more like the green, perhaps due to its recent and unexpected exposure to the Martian surface. Such observations were also crafted visual experiences, as the subsequent Rover images were taken with the Pancam filters that enabled her to perform the same transformations as she had done initially. Thus subsequent images of Tyrone were...
drawn as two-toned salt deposits from the ground up as the filters are requested from the Rover to craft a conventionalized display of visual information and produce this seeing as experience. And this initial drawing as practice prompted further observations along the same lines, with further iterations of the same view. As Susan later applied the same technique to images of Rover tracks from across the region, an increasingly standardized view of the light toned soil emerged and was applied across Gusev crater. Applying the same visual conventions to each area, Susan then made the visual argument that the light-toned soil across the region was the same kind of thing, a feature of the Martian terrain, and an object to be contended with.

In this part of the story of Tyrone we might note how, as they become conventional, drawing techniques enable a community of users to draw natural objects as analytical objects on a regular basis. This reflects and projects theories, practices or a whole form of life onto the represented object. Consistent with Martin Rudwick’s work on emerging graphic conventions within the geological community in the nineteenth century, we might adopt Gombrich’s term “visual language” to draw attention to these new conventions of illustration, and how they “required new modes of perception by those who looked at them” (Rudwick, 1976, p.155). The visual language may be best understood as a disciplinary community’s established way to draw as: a suite of honed pictorial conventions that present certain relationships and salient features of an object to its viewer -- but not others. Many of these visual conventions are already tightly honed on the Rover mission: one geochemist is always explicit about how, because he is a geochemist, he has to include a particular kind of graph in his presentations, and at another point he laughed that “No APXS talk is complete without a graph of sulfur versus chlorine.” This may explain Susan’s narrowing down on several representational conventions, some home grown and some borrowed, to display the different spectral properties of Tyrone -- and how the more
successful of these conventions were applied beyond Tyrone and across Gusev Crater to retroactively reinterpret past visited sites. It may also explain why the image processor’s choice of tools is more often dictated by disciplinary heritage than it is by institutional affiliation. A scientist trained in astronomy and optics prefers the programming language IDL, while another scientist trained in terrestrial geographical information systems uses ARC-GIS in his lab, and yet another prefers to use the Cornell-built Pancam tools to work with Pancam images -- despite being the lead developer of his home institution’s popular image processing software.

Susan’s story also neatly illustrates how techniques of drawing as present an aspect to an audience, resulting in transmitting a seeing as experience to subsequent viewers. While Susan is adamant that the distinction and changes in the soil revealed by the use of yellow and green colors is based in fact -- “the change was real,” she says -- this use of color is important for “showing” this distinction both to herself and to others. Her initial interest in the light and dark rocks on the mission made clear the work associated with conscripting other scientists to her point of view. With respect to Tyrone, as she puts it:

You decide the color you want to show, the color you want to use, but the data is there, it’s not the color… Because the existing data [images] contains this kind of information, you decide how you want to show [the data].

Green and yellow became convenient ways of reconfiguring the pictorial representation of the image such that this feature of the soil lit up. They also depict “information” which is “contain[ed]” in the image, not glossed onto it in interpretative annotations. This is important to team members, who distinguish between annotations as interpretations (discussed in Chapter Five) versus image processing work that presents distinctions in the data that demand or otherwise acquire interpretations. But

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20 Interview, Susan, June 18, 2007.
while the image “contains this kind of information” (the spectral properties of the soil) it is at Susan’s discretion to “decide how to show” the data. That is, *drawing as* allowed her to both see a distinction in the soil and to *show her colleagues what to see* in the soil. Reconfiguring the soil in this way means that every time scientists look at the image of Tyrone, they see the two-toned white soil. In this way, *drawing as* not only reveals new aspects of a visual dataset but also *shows subsequent viewers what to see*. Once the distinction has been made in one aspect, it cannot be unseen.

This is not limited to Susan’s transformations of Tyrone, or to Pancam imagery alone. Across the mission, team members articulate the Wittgenstenian dawning of aspect when presented with a digital image that has been drawn so as to present particular properties. Expressions such as, “now I see!” can be heard in SOWG meetings, End of Sol and Science Team Meetings, as well as at scientists’ desks as they go through different image processing routines or present these interpreted image products to their colleagues. As one scientist examined an image produced in his lab, he expressed, “It’s efficient to have something like that [image] to communicate what you’re showing, what your interpretation [is].” Even in operating the MiniTES thermal spectrometer, a team member explained that he had to “show other spectra to teach [the team] what to see,” or that he took the approach of “I’m only gonna show you the part I want you to pay attention to.” This is not hiding data that might be essential to interpretation, but rather limiting data to only that part which is relevant: an attempt to *draw as*, to delimit aspect in order to produce and reproduce a seeing as experience across the team. As a graduate student on the team stated, “you have to throw out something to make it [the data] understandable.” And this use of purposeful image construal to direct a viewer’s attention in turn presents implications for the kinds of science and operations that are eventually planned as a result of this visual
interpretation. After all, as a MiniTES PUL explained to me, “the science questions come out of the imagery.”

But as mentioned in the telling of this story at the outset of this dissertation, an additional, important implication of drawing as also arose from Susan’s work with Tyrone. After all, following her presentation in October of 2006, Susan applied the same visual transformations that helped her and her colleagues to see the distinction in the soil at Tyrone, to the broader region around the Spirit Rover. She started her presentation at the followup meeting in February with the image of Tyrone, saying, “You’re all familiar with this beautiful Pancam image,” and then displayed the histogram and decorrelation stretch of Tyrone:

I always use these three pairs [i.e. the filter combination, L572, R237] … this is the filter for the left eye, so you will see the yellowish soil [in the histogram] will show as the orange reddish [in the stretch], and here on the right [eye] I use this pair of filters so that the yellowish soil [in the histogram] will show as purplish [in the stretch].

Immediately following this slide, Susan applied the same transformation to images taken at Arad, at Paso Robles, and at Wishing Well (Figure 20):

A similar situation happened in the Arad area, where we see the spectral difference, and also color difference. This yellowish area shows this kind of spectra, and you have the slope at this kind of peak … And when we do the decorrelation stretch we see the yellowish soil shows in the orangeish in this area… also the purpleish in the right eye is in the decorrelation stretch… And at Paso Robles, we also see this area is the yellowish and the whitish [soil, in

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True Color] … At Wishing Well we also exposed some kind of lateral material … we see there are also color differences … 22

She followed up this observation with applying the same stretch to the Pancam images of Tyrone taken at different times in the mission to show that the histogram was changing slope, indicating a change in the properties of the white material due. As she said, “We need to be sure this change is real, so I checked several factors.” Reviewing and dismissing the effects of a “diffuse sky” that could affect how “the spectra behave” due to no significant change in atmospheric opacity, and optical effects of the camera, Susan claimed, did not affect “the basic phenomena of this observation.” Instead, she suggested a change due to atmospheric exposure and the subsequent dehydration of the salt properties of the soil. She corroborated this hypothesis with an experiment in her laboratory on Earth, showing that ferric sulphates decreased in acidity and could have affected the detected slope. Finally, she mapped the locations of the light toned soil to emphasize the importance of geographical distribution, as its persistent availability in lower regions suggested that the salts could have been deposited there by pooling water. “I’m going to show a beautiful Pancam picture and pretend I’m a geologist,” she laughed as she neared the end of her presentation.

The response to the presentation was an excited exchange of ideas and hypotheses among the Athena Science Team. One scientist stated that “these observations make a compelling case” for a liquid water transport system in the deposit of the soils, while another -- his former student -- questioned whether wind, instead of water, would result in the same distribution. Another still raised the question of whether or not volcanic processes could be responsible for laying down the salty

22 Team Meeting, February 14, 2007.
Figure 20 Susan’s Tyrone decorrelation stretch applied to Paso Robles and Wishing Well. Three slides from End of Sol Presentation, October 11 2006.
deposits due to their high sulphur content, while another put up a slide showing an image of an environment “from Iceland,” which she suggested “might be more consistent with what we’re seeing” at Gusev. Several scientists took up the discussion of how old the salty deposits were, ranging from millions to billions of years old. The discussion was then extended past the projected end of the meeting to accommodate further conversation as scientists exchanged “what if” scenarios and raised challenges to each others’ explanations. All present treated the existence of the two-toned soil and its distribution as a given fact: the question up for discussion was not whether or not “the basic phenomena of this observation” existed or how to see it, but why it was there and how it got there. Discussion thus centered around different hypotheses about its origin and depositional mechanisms and generated proposed observations with the Rover’s suite of instruments to determine which of these hypotheses might be ruled out and which might be feasible or worth pursuing. When the discussion was summarized at a subsequent LTP presentation it was dubbed “The Light Soil Campaign” and encompassed a variety of observations aimed at better characterizing the two-toned soil at Tyrone and elsewhere. These observations formed the basis of Rover operations for the following two weeks, and follow-up investigations on light-toned nodules that were also requested as part of the Light Soil Campaign formed the crux of Spirit’s remaining investigations on the Western edge of Home Plate until forced to retreat to a third Winter Haven. Susan’s drawing as practices – drawing Tyrone as composed of two distinct kinds of salty soils distributed at different vertical layers, and then drawing Arad, Paso Robles and Wishing Well as Tyrone – encouraged the rest of the team to see Tyrone as composed of those materials as she suggested, and to see other examples as cases of the same phenomenon. Arising from this work of drawing and seeing were a suite of Rover interactions with the phenomenon in
question too – and, eventually, a published paper bearing Susan’s name along with those of her Athena Science Team colleagues.

I emphasize that the story of the white soil at Tyrone is not the only case study in which we might trace this relationship between drawing and seeing, and the importance of image construal to subsequent visions of, representations of, and interactions with natural objects. The Tyrone case stands in for a wide range of similar activities that occur with frequency on the Rover mission as scientists use digital image processing techniques -- “pixel-pushing” -- to reveal and then show properties of the Martian surface, with subsequent effects on future representations. For example, a particular kind of decorrelation stretch was used by a scientist to show distinctions between rock layers at Endurance Crater, and was subsequently produced when Opportunity arrived at Victoria Crater years later to reveal similar distinctions and make claims about the history of the region and the similarities and differences between the two craters. The “blueberry-finder” is similarly invoked and deployed with great frequency. In later chapters I will show how Rover Planners draw Mars as trafficable or untrafficable terrain to produce drive plans for each Rover, and how image calibrators produce standardized views of Mars that delimit certain aspects of the planet so that scientists can see Mars as unencumbered by optical distortions created by dust in the atmosphere. Such activities are not underhanded or unscientific: they are the very activities that comprise “doing science” with digital images.

Nor is this relationship between drawing and seeing unique to digital image processing: it also applies to scientific image making in other historical contexts. Galileo’s image of the moon in 1610, too, clearly showed others a new way of seeing the moon as a topographical object, and drawing it that way ever after. Following a tour to the New World where he had mapped the territory of Virginia, Queen Elizabeth I’s geometer Thomas Harriot turned his telescope to the moon in 1609 and,
presumably, drew what he saw: a crescent, some shading, and a dark patch near the center (Figure 21a). But in 1610, following the release of Galileo’s images, Harriot produced a radically different set of drawings of the moon, this time clearly emulating the Galilean view: a pockmarked moon, divided perpendicularly into light and shade, with a giant crater in the center (Figure 21b). The story here is not that knowledge of the technique of chiaroscoro shading helped Galileo to uncover the moon’s “true” nature, as art historian Sam Edgerton has claimed, but rather (like the green and yellow pixels at Tyrone) that it was a tool that enabled Galileo’s knowledge of the moon to be effectively communicated and reproduced. Galileo’s drawing therefore not only “founded visual astronomy”, as Winkler and Van Helden (1992) suggest, but it also influenced future viewings, depictions and theoretical understandings of the moon, blinding viewers to other aspects such that the European scientific community might “just see” and draw the moon according to Galileo’s vision.

Figure 21 Harriot draws the moon a) in 1609 (left) and b) in 1610 (right). Reproduced in Edgerton (1984).

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23 Edgerton also uses this case study of the comparison between Galileo and Harriot as an example of “the beholder’s share”, a term he borrows from art historian Ernst Gombrich. That is, Galileo’s artistic training gave Galileo “the right theoretical framework for solving the riddle of the moon’s ‘strange spottednesse’” (Edgerton, 1984, p.227), which then enabled Harriot to see the moon correctly.
Three hundred years later we witness a similar arrangement with the use of early astronomical photography, when the American astronomer Percival Lowell was invited to submit his photographs of the planet Mars, taken through his famous telescope at his Observatory in Flagstaff, to the Dresden Photographic Exhibit (Figure 22). Lowell and his colleagues Vesto Slipher and Carl Lampland were particularly eager to use this opportunity to drive home their conviction of canals on Mars, which they had been observing for some time both at Flagstaff and at a new telescope in Chile. However, it was clear to these astronomers that just presenting row upon row of tiny photographs was not enough: the public had to be shown how to see them. As Slipher wrote with some concern to Lowell and Lampland:

What do you think should be placed along with the Mars Photographs in the way of drawings? To those who are not familiar with the difficulties in the way of success in such work (and they are 99.99%) the photographs might not come up to expectation if shown along-side drawings... Now on the other hand, there must be something with the photographs to point out what to expect and look for in the photographs.24

Figure 22 Photographs of Mars by Percival Lowell, c. 1909. Lowell Archives, Flagstaff Arizona.

24 V.M. Slipher to C.O. Lampland, Jan. 30 1909, Lowell Archives. For more on Lowell’s opinions about the habitability of Mars, see Lowell, 1895; on his images, see Galison (1998); Lane (2005).
The question here is again an interrelated issue of salience, of expectation, and of visual expertise. On the one hand, the photograph offered an unparalleled appeal to the public to “see for themselves” the unambiguous presentation of Mars as crisscrossed with canals. On the other hand, the scientists were aware that the photograph was potentially ambiguous. Shades of light and dark played over the planet’s surface, mechanically and passively inscribed, perhaps, but demonstrating precious little. To disambiguate the photograph and teach the viewer what to see, Slipher’s solution was to draw Mars as a canal-crossed planet. One solution was to annotate the images -- a technique that will be discussed in following chapters -- by placing drawings next to the photographs. This would direct the observer’s attention to the features that Slipher, Lampland and Lowell had determined to be canals, parsing the photograph so that others could see them too. There is also evidence that Lowell experimented with the technique of photographic composites, combining photographs of Mars with photographs of his drawings of Mars in order to aid the observer to see what he could see. Thus this team of astronomers also used the tools of purposeful visual construal, drawing with, drawing upon and drawing alongside the photographs so as to see and present to their audience the details that they thought were relevant and convincing of their theory of water on Mars.

Presumably, Lowell’s acolytes Slipher and Lampland didn’t see Mars as covered in canals: they “just saw” and “just drew” the planet. Similarly, Harriot didn’t see the moon as a topographical object, but ‘just saw’ and ‘just drew’ the moon. This does not mean that they did so in the absence of interpretation, however. Drawing as

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25 Lowell Observatory Archives. Lowell’s canals were not discredited until the late 1960’s, when NASA’s Mariner spacecraft flew past the planet. Between Mariner and Viking, Lowell’s albedo map, showing patches of dark and light across the surface but without the crisscrossing canals, was still in use. The map of Mars has changed significantly since then, using global coverage from the Viking orbiters, supplemented by images from the Mars Orbiter Camera (MOC), altimetric data from the Mars Orbiter Laser Altimeter (MOLA), spectral and thermal data from TES and THEMIS instruments also aboard Mars orbiters. These datasets were later used to choose Spirit and Opportunity’s landing sites on Mars.
is most effective when the resulting image can efface this interpretation and generate experiences in which the viewer claims they are “just seeing”, not *seeing as*. As Law and Lynch’s study of ornithological field guides suggests, the question is not necessarily one of drawing a bird correctly, but one of establishing a game of recognition and proper use of the drawings in a field context (Law & Lynch, 1990).

We may even employ speech or gesturing through which we make sense of the object: Amann and Knorr-Cetina call this “optical induction,” or “visual operations carried out through talk” (1990, p.100). But these visual operations or interpretative situations are not referentially open, or at least not intentionally left open. The illustration is not innocent. Instead, “analyzability is built into the record from the beginning,” (Amann and Knorr-Cetina, 1990, p.107) not only in the design of the experiment, but also in the construction of the image. That is, the scientific image gains analyzability if it can present the relevant or important features that are analyzable: it is thus recognizable because it has been *drawn as* something recognizable, a presentation of a particular kind of thing.

The Mars Exploration Rover scientists who witnessed Susan’s presentation at the Team Meeting in February of 2007 acquired her aspect, and this particular vision of the surface generated excitement about specific possibilities for further interaction and exploration. By *drawing* Tyrone as composed of two-toned salts, Susan showed her colleagues that further observations were necessary to narrow down their hypotheses about what caused the salty deposits. Not only did this *drawing as* activity focus their attention on particular features at Tyrone and elsewhere across Gusev Crater, it as also became the basis for two weeks’ worth of further Rover maneuvers at Tyrone, a subsequent Light Soil Campaign -- and suite of related observations and discoveries that ultimately delayed *Spirit’s* return to Home Plate by an entire Earth year and uncovered further discoveries in the process. Thus unlike Hacking’s famous
point that how an object is interacted with informs how it is represented, the reverse is also true: practical interaction with an object (like Tyrone) is predicated upon how that object is visually construed: how and what it is *drawn as*.

**Conclusion**

In his *Art and Illusion: The Psychology of Pictorial Representation*, Ernst Gombrich recalls learning to draw chubby babies, like the cherubs in Renaissance paintings. While he had never noticed such especially chubby babies before, after learning to draw them, “Suddenly I saw such babies everywhere.” As Susan’s way of drawing and seeing Mars began to take hold a similar effect took place: suddenly the entire team began to see such soil everywhere, and the two-toned soil moved from an individual vision of peripheral interest and idiosyncratic representation, to one of the central questions of the mission and a key way of representing two-toned Martian soil at Gusev crater. This vision of Mars did not come from ‘simply seeing’ the terrain. It was the result of ‘pixel pushing’, specific practices of image processing that *drew* the soil *such that* the team could see what Susan saw. And, as this visual framework was applied across Gusev crater, the scientists no longer *saw* the white soil as two-toned: they ‘just saw’ the two-toned soil, and saw it everywhere. Lest this seem like a simple example of perceptual suggestibility, recall how this interpretation is *drawn into*, inscribed in, the very images that present the phenomenon, *such that* the phenomenon can be seen. Thus the practical craft of digital image processing constructs meaningful, workable knowledge of an alien planet and inscribes this knowledge into an image – with consequences for continued exploration and discovery.
As we have seen, the purpose of drawing as is to present a particular aspect of an object -- to highlight selected features, making them “pop out” -- or to visually demonstrate an object’s distinction from or relationship to other objects. Pixel-pushing is just such a drawing as activity, wherein work with visible materials is a matter of making a field visible, knowable, and interact-able. If seeing as is the successful visual apprehension of a particular aspect of an object, then drawing as is the depiction of an aspect of that object, parsing objects by inscribing and enhancing visible boundaries, thus enabling conceptualization of forms and kinds. Further, drawing as is one of the praxes by which a seeing as experience is produced. Drawing in order to see is therefore not only the goal of disciplining activity, but also the means by which an object may be tamed. And if drawing as can make the subsequent seeing as experience into simply seeing, we arrive at the special power of the scientific image: that drawn properties of an object become phenomenological or even ontological. Drawing as thus makes epistemology look like ontology.

With this in mind, we might begin to address the central question of this dissertation: that is, how does practical image craft construct meaningful, workable relationships with an alien planet? Meaningful and workable are not found categories -- they are built into an object by drawing it as something. Visualization in scientific practice is not a question of creating an ever more true or singular image of an object. Rather, practical work with images shuts down other ways of seeing in order to focus on one aspect, one set of salient relationships. It is a practical activity of drawing a natural object as an analytical object, inscribing a value of what that object is and what makes it interesting directly into its representation, such that subsequent viewers and image-makers will see, draw and interact with that same object the same way. And

26 Here one is reminded of Bruno Latour’s phrase, “drawing things together” (1988): relationships between objects may be just as important salient features to highlight visually as object properties. Hanson cites Wittgenstein on this point, noting that the dawning of aspect can reveal “an internal relation between it and other objects.” (Hanson, 1958, 22).
here we especially see the value of the praxiological perspective that inspires *drawing as*’ analytical frame. After all, operating the Rovers is not a question of a single scientist conceptualizing an image, but is a directed activity that requires collectively seeing and interpreting images and agreeing upon what those images mean and what they should do next. In subsequent chapters I continue this focus on what MER scientists do with images, how the images are transformed and publicly interpreted -- how and what they are *drawn as*. I turn next to examining how the raw image data that returns from Mars must be *drawn as* trustworthy even before it can be subject to Ben’s, Susan’s, or other scientists’ pixel-pushing activities.
CHAPTER 3: TAMING THE PANCAM

INSTRUMENTAL CALIBRATION AND DIGITAL OBJECTIVITY

Introducing the concept of calibration in his book, *Roving Mars*, Mars Exploration Rover Principal Investigator Steve Squyres makes a strong statement:

Calibration is essential for any instrument you send into space. You’re going into an unknown environment, measuring things that no one has ever encountered before. So how do you know you can trust what your instrument’s telling you? … without [calibration] we’d never be able to figure out what our readings on Mars meant. (Squyres, 2005, p.168)

This emphasis on calibration is echoed across the mission, with each instrument team on board the Rovers maintaining their own calibration tools and routines.¹ In this chapter, I will analyze the work of calibrating the Rovers’ “eyes,” the Panoramic Cameras. A pixel-pushing routine involving a closely-followed script and a team of student technicians, calibrating the Pancams requires *drawing* Mars *as* a tamed subject, disciplining the images that return from the surface so that they can be *seen as* trustworthy documents. In effect, the daily work of calibration is an actors’ solution to the problem of producing images -- and hypotheses and conclusions about them -- that can be considered scientific. The organization and implementation of this work reveals what characteristics MER team members ascribe to the human and machine, and the management of trust around these resources.

¹ The Athena Science Payload’s instruments are each operated by a different group of scientists based at different institutions: the Pancams are operated from Cornell but other instruments, such as the Microscopic Imager and the MiniTES (Thermal-Emission Spectrometer) are managed from other institutions and require their own calibration targets or specialized scripts. It is beyond the scope of this chapter to compare instrumental procedures across the Rover mission, but each broadly requires the same mixture of ground truth, automation and human intervention in attending to remote instruments.
While Pancam calibration effectively takes place away from the collective virtual workspace of the MER team in a laboratory not connected to the main teleconference lines, the work of calibration is still highly visible within the mission. Specific Pancam sequences essential to calibration are written into the Rover’s uplink instructions in daily Operations meetings, a large computer lab in next door to the Mars Rover operation outpost at Cornell University is devoted to the Calibration Crew, and MER scientists wait anxiously for calibrated images to appear on the server before they begin their pixel-pushing analyses. Indeed, so essential is calibration to the Rover project that in the first ninety days of the mission, calibrators were on shift around the clock to adjust images as soon as they were downlinked from the Rovers, and the first image received from Spirit after landing was of the calibration target (Figure 25). Certainly, the Pancam’s centrality to the mission cannot be overstated; as already discussed, in day-to-day operations its images inform tactical decision-making, and planetary geologists are trained to analyze rock formations from visual inspection of morphology, shadow-casting, and photo-interpretation, confirmed but not always facilitated by spectroscopic analysis. But instead of providing a direct window onto Mars through the Rover’s camera-eyes, the resulting images are deemed untrustworthy for scientific digital analysis unless they have been subject to calibration. What does this process entail, what tensions does it reveal in scientists’ work with digital images, and what is Mars drawn as as a result of this digital image processing? This chapter will explore the place of visual instrumental calibration in the Mars Rover mission, detailing how images from Mars must be drawn and disciplined before and such that they can be subject to scientific analysis or public release.2

2 My examples in this chapter are informed by my experience as a participant observer on Cornell’s Pancam Calibration Crew (CCC) in the local laboratory attached to the MER mission where major aspects of mission planning and activity take place. I am grateful to Professor Jim Bell for the opportunity to volunteer on the CCC.
Calibration has already received some attention from sociologists of science and technology, most notably from within the Empirical Program of Relativism. Harry Collins, for example, points to precisely the philosophical problem that Squyres outlines above: how to detect something -- in Collins’ case, a gravity wave (2004) --- that has never before been detected? In his *Changing Order* (1985) he argues that calibration, a “test of a test,” can only complete the vicious circle of the experimenter’s regress; i.e. fine-tuning an instrument to produce good results requires a preconceived notion of what those results are, what they ought to look like, and how they can be detected. Trevor Pinch (1985) has further explored this aspect of calibration with respect to solar neutrino detection, concluding that successful calibration experiments draw on social and technical resources in a restricted evidentiary context to limit any challenges of undue ‘similarity assumptions’ between the calibration and the main experiment. Meanwhile, critics of the Sociology of Scientific Knowledge have attempted to demonstrate how it is possible to appeal to criteria external to the calibration setup, thus breaking free of Collins’ experimenter’s regress and the confines of theory-laden experiment (Franklin, 1997). Historians of science have also become interested in the kinds of work calibration entails, in cases ranging from astronomy to x-ray science to mental chronometry. Such analyses reveal the role of calibration in experiment, in the laboratory, and in disciplinary organization.

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3 The literature on testing is vast (see, for example, Pinch, 1993), but the calibration procedures outlined here do not involve ongoing equipment “testing” in a traditional sense, and many of the issues -- making similarity judgments between a test site and the site of deployment, for example -- did not apply to this specific case study, although such issues do play a role in instrument manufacture, pre-flight calibration, and photo-interpretation.

4 Benschop and Draaisma (2000) have catalogued Wundt, Cattell and Berger’s attempts to bring precision to both “minds and machines” in the work of mental chronometry, Simon Schaffer (1988) has detailed how astronomers attempted to eliminate the ‘personal equation’ in observational reports, and Arne Hessenbruch (2000) has explored the organization of labour and economy around the standardization of X-Ray work.
It is one thing for a scientist to toggle switches and make local adjustments to accommodate daily changes in the laboratory, but what do you do when your instrument is located on a field site twenty light-minutes away, where the environment is, literally, alien? The answer is a routinized set of practices which retroactively alter the instrument’s results (the image data) to two constants -- one derived from pre-flight instrument behaviour and one determined from local Martian conditions of use -- in order to trust that the images from the Rovers show “what Mars is really like.” While routine, these practices are not all entirely mechanized: rather, they are the responsibility of a trained team of human operators, the Cornell Calibration Crew (CCC). Calibration therefore relies on an artful negotiation of human and machine interactions with image data in order to produce an objective image with which scientists may proceed to “do science.”

The Rover mission provides perhaps a more revealing case study in terms of how instrumental calibration directly affects and even fundamentally alters observational results than traditional cases in Science and Technology Studies, where calibration occurs before instruments produce observational data. On the one hand, there are comparative examples of the pre- and post-calibrated images, instead of a single stream of data, and comparison of these data streams is an essential part of the Calibrator’s production pipeline. But on the other hand, the distance between the Rover and its terrestrial teammates and the organization of work around the production and circulation of images isolates the calibration activity as distinct from the technical operation of the instrument. Calibrators are not Pancam Uplink or Downlink Leads and are not involved in the instrument’s day-to-day management. This isolation of practices draws attention to the very particular work associated with calibration as a component of instrument operation as a whole.
Finally, employing both computational and human practices to tame a digital observational instrument in the field presents a challenge to the traditional notions of inscription and objectivity within Science Studies. But as these practices produce a standardized vision of Mars they also reveal the values that MER scientists believe lend their images status as evidentiary documents. In this chapter I will expose some of the work of drawing images as trustworthy statements by providing an ethnographic account of this ongoing, active discipline exerted over instrumental results and operators, accomplished through an artful combination of human judgment and mechanical manipulation.

“We Want A Human Eye”

The Cornell Calibration Crew is made up of about a dozen students, mostly undergraduates with an interest (not necessarily a major) in astronomy or geology. The Pancam Payload Element Lead, the scientist who designed the cameras, leads the Crew, although in practice the group is managed by a science staff member and supervised by a number of graduate and postgraduate students. Calibration takes place in a central space on the fourth floor of the Space Sciences building at Cornell University near to the MER remote operations videoconference room, in a room with no windows, restricted keycard access (but which is shared with graduate students and is often left open), and computer monitors positioned around the periphery. A central table displays recent science team publications and a model of a Rover, while technical diagrams and large, colorful Martian panoramas decorate the walls. The calibrator gets four screens: two for calibrating images from Spirit at the Spirit workstation, and two for Opportunity at the Opportunity workstation. These processes take place simultaneously and while the side-by-side stations are distinct, Linux-operating computers, at each Rover’s “station” the two screens are contiguous such

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5 The Pancams have also been extensively calibrated before flight, but analyzing this process is unfortunately beyond the scope of this chapter.
that images may spread across both displays (Figure 23). At any given moment in the calibration process, the calibrator will be attuned to at least two out of the four screens, with a number of applications open at the same time: these include a standardized calibration log in a text editor, a self-updating module indicating how many images await calibration, a terminal window in which prompts may be entered, and another window in which scripts can be executed in IDL (an image-processing platform preferred by astronomers), as well as whatever in-house applications might be open for viewing and interacting with images (Figure 24).

Figure 23 The calibration station. Each Rover is assigned one computer with two screens. Calibration procedures for both Rovers usually run simultaneously.

Upon joining the team, members receive fifteen pages of instructions, outlining step-by step which programs to run, which passwords to input, and what to look for. These instructions codify and control the ways in which CCC members interact with the system, and may even be seen as a highly explicit and written version of a technological ‘script’ that guides users’ interactions with a particular system (Akrich, 1992); in this case designed by expert users for CCC users to circumscribe their interactions with the calibrating computers and images. The instructions are evolving
and new versions come out every few weeks with additions or subtractions: students are exhorted to “Always refer to the procedures! They may change from day to day.” The instructions do not necessarily tell students what the programs are doing or what the acronyms in use mean, and this may result in some confusion in internal terminology and a black-boxed sense of the software scripts as they are executed. However, new members are assigned to five or six training sessions with a more senior student on the team, where they might be lucky to pick up definitions of terms and an idea of what the programs are doing to the image files.

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6 Pancam Calibration Procedures, version 1.29. The document is evolving and therefore maintains remnants of earlier versions, sometimes including instructions that were more important in the early days of the program (i.e. what to do with high priority image data for JPL while new images are coming in) which are now ignored, or even missing steps (i.e. “6.02 (Step removed)”).

7 I was trained by a student who has been with the program since its inception: while the Rovers were en route to Mars, he calibrated images sent back from the ‘test pit’ at JPL to practice the procedures, and worked ‘on call’ to calibrate images as they came down during the first few manic weeks of the MER mission. Since then, calibration no longer occurs on an image-by-image basis, but rather according to students’ schedules, and may involve up to 400 images from each Rover at a time.
Training is necessary because the Calibration Pipeline, as the CCC calls the routine, does not simply involve following the 10-step programmatic procedures as outlined in detail on the instruction sheet, or executing programs and waiting for them to run through to completion before starting the next program. It also, crucially, involves the ability to make judgments about images at each stage of the process, to determine which are acceptable and which are not, whether or not calibration has gone according to procedure or if something looks unusual: when, as my instructor warned me, “sometimes, strange stuff happens.”8 Therefore, instructors not only demonstrate technical procedures, but also talk about the images they see and try to articulate what makes an image acceptable or not, or how they know that the procedures have gone correctly, so that their trainees can “get an idea of what you’re used to seeing.”9 This human monitoring, my instructor informed me, was not only essential to give undergraduates a job on the team, but also because “we want a human eye to look over”10 the images: computers could not be trusted with the complex judgments of image quality. I will return to this theme of judgment in Chapter Seven, but for our purposes here it is worth noting that visual knowledge of Mars is one of the most important kinds of tacit knowledges (Polanyi, 1966; Collins, 1985) transmitted in training phase, as this accumulated expertise enables human calibrators to do their job well.

After logging into the system, calibrators initiate their routine with a process of visual inspection, running a program that shows the thumbnails of all the images that have come down from the Rovers in the last downlink sorted by Martian day (called a “sol”). Calibrators are encouraged to “Look through the images to get a sense of what

8 February 2, 2006. “Strange stuff” rarely happens.

9 February 2, 2006. Instructional situations can provide an excellent opportunity for the articulation of tacit knowledge, as demonstrated in recent studies by Kaiser (2005a, 2005b) and Prentice (2005).

10 February 2, 2006.
has been downlinked” and note any “obvious anomalies” -- image saturation, single pixel images, compression errors or data dropouts -- in their Operator Notes textfile report. The calibrator must go through the datasets and mark each image either usable or unusable by clicking on the thumbnail and marking in a dialog box any dropouts or problems, changing the picture border to red for an unusable image or green for a usable one. Through this process, the images themselves become familiar and the local Martian landscape is tamed. Scrolling through the images builds up a visual vocabulary for the neophyte and confirms the expected for the experienced, such that the problematic or perhaps the geologically interesting features in the images can be more readily located. As my instructor casually commented while scrolling through “good” images, “Typically you have an idea of what Mars looks like.”

This appeal to “an idea of what Mars looks like” elides a number of practices that contribute to such a view. I am informed that earlier in the mission, calibrators relied on their knowledge of the camera to know whether or not Mars was being represented fairly. However, many of these early calibrators were heavily involved in the camera’s construction, programming, and pre-flight calibration (not discussed in this chapter). Three and a half years into the mission, new calibrators now rely on knowing what Mars looks like to get a sense of how the camera is working. This idea of “what Mars looks like” is important for being able to identify errors, artifacts or novel phenomena, but identifying just what an unexpected value means is a

11 Pancam Calibration Procedures for Extended Mission, Version 1.29. Step 5.04. Single pixel images are used to aim the camera at a particular target to set up a shot, and thus are not due to problems with the camera but rather to explicit instructions sent to the Rover. However, there was some disagreement between my instructor and the team leader as to whether or not this made an image usable or unusable. Data dropouts occur when, due to interference, the datastream in an image is interrupted, resulting in a big black square in the image. Interestingly, these are not seen as sources of information about, for example, a problem on board the spacecraft or identifying asteroids, space junk, or cosmic rays, but rather as an obstruction in the data, a problem that must be solved by asking the Rover to send the image again. Finally, sometimes “pixels get mixed up” (March 5, 2006), as a result of compression errors. The calibrator’s notes in their report, therefore, identify to the team which images to re-request on the next transmission.

12 Personal Correspondence, August 8, 2007.
task left for the scientists: if students find something in their data that they sense is suspicious, they are encouraged to contact senior members of the team or make a note in the log for the mission scientists and programmers to review. Additionally, getting a sense of what the dataset looks like enables calibrators to determine at the end of the routine if the data has gone through the software mill correctly.

**Erring On The Side Of Caution**

Following this preliminary inspection, calibrators move on to the core of the procedure: the “caltargets”. Short for “calibration targets”, these refer to digital photographs taken of a little sundial placed at the rear of each Rover (Figure 25). The sundial is specially crafted for the purpose of image calibration: essentially, the Rover was built to be calibrated from a distance. Sometimes more than once a day, the Pancam is instructed to take a suite of pictures of this calibration target, one with each of the up to thirteen filters required for the day’s observations, in order to determine local conditions on Mars.

![Figure 25 The caltarget before being affixed to the back of the Rovers. Courtesy NASA/JPL/Cornell](image)

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13 The sundial, one of astronomy’s most ancient tools, is decorated with a schematic diagram of the Earth’s relative position to Mars, the planet’s name in several different languages, and images selected from a competition of children’s drawings. It thus serves a function as publicity for the Rovers on Earth as well as a device that might instruct future visitors to Mars about terrestrial civilization. However, the solar system diagram regularly frustrates calibrators, who curse at the location of ‘Earth’ and ‘Mars’ as they make the identification of caltarget regions particularly difficult.
The Pancam Payload Element Lead explained the purpose of the caltarget as confronting the problem of not knowing what Mars looks like. As he put it, “On Mars we cheat, we say we know what this piece is we brought with us … to have a bit of ground truth.” As it ventures into the unknown, the Rover takes its own unit of measurement with it. The dial is carefully crafted with red, green, blue and yellow corners, and three different scales of grey filling the inner circles. Each of these colors and shapes was specifically selected with full knowledge of their size and wavelength before launch. Since the team knows what the sundial ought to look like under familiar conditions, this can represent an absolute value. By comparing the collected images with their expected values and observing the quality of the gnomon’s shadow, the calibrator can determine the target’s relative value: that is, an indication of just how much the local conditions are affecting the collection of photons in the other images the Pancam returns. Or, as a neophyte calibrator explained it to me, “Because we know exactly like to the wavelength, what these colors are, so we can match them.” Another explained the purpose as one of perfecting the colors in the eventual image composites: “It’s to help when they make the mosaics to know what the colors are.”

However, the calibrator does not actually determine the values of local conditions: this is left to a computer, which can run through lengthily algorithms to transform image after image in a standardized way. What the calibrator must do, however, is to help the computer to recognize the zones on the caltarget such that it

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14 Astronomy 310, Lecture 13, November 22, 2005. So central is the notion of ‘ground truth’ to remote sensing that Rover data is sometimes employed to help calibrate orbital data from the Mars Express or Mars Reconnaissance Orbiter instruments.

15 The caltarget’s familiarity is highly reassuring, as it provides an example of a known background feature against which novel experiences can be checked. If they know what a caltarget image ought to look like, and the returned images can be made to match this expectation, the team trusts the camera by extension to take pictures of unfamiliar objects just as faithfully.

16 March 2, 2006.

17 March 2, 2006.
can calculate how much each filtered image must be adjusted to subtract external factors from the scene. From the calibrator’s perspective, this is a practice of aiding machine vision, of using humans to accomplish what computers are not particularly good at: judgment. The calibrator thus uses a software tool to manually draw on each image, using colors to identify each region so that the computer can compare local to ideal values and establish the unique metrics for each iteration of the routine.

Figure 26 Colouring in a caltarget for computer recognition. Note how colours identify regions of the target, a reminder of what the target looks like in true color pasted on the bottom of the left screen, and the check-up graph on the right screen.

The process of hand-marking the caltarget images is painstaking and time-consuming (Figure 26): so much so that my instructor, one of the central students in the CCC, wrote a software plug-in for the calibration tool that enables calibrators to click a single button and have the computer “Automatically Select Regions of Interest.” However, he admits that the program isn’t perfect. A key factor in the routine is to be sure that border pixels are avoided. If the light blue smudge that identifies the outer ring of the sundial comes too close to the next ring, the shadow from the gnomon, or even the ‘Earth’ painted in orbit around the gnomon, this could adversely
affect the resulting routine. CCC members are therefore highly cautious about their regional identification. They will run the automatic program, but then spend a considerable amount of time carefully inspecting each filtered version of the same image, shaving slices off the automatically-colored sections pixel by pixel so as to give adjacent regions a generously wide berth. This aspect of the calibration pipeline is often pointed to as one of the reasons why machines can’t just run the whole procedure by themselves: human intervention and judgment are needed to *overcorrect* the images, so that the team can “be on the safe side”. Humans may be subject to a “personal equation” of error, but CCC members are trained to err consistently on the side of caution: one instructor I witnessed told her trainee, “It’s always better to get too little [of the region] than too much.”

18

Such an emphasis on human judgment versus mechanical automation recalls Peter Galison’s identification of “judgment” as replacing the nineteenth century value of “mechanical” objectivity (Galison, 1998). I will return to this theme at the close of the chapter, but in the meanwhile it is interesting to note that these judgments do not establish an ideal type, nor do they affect the content or form of the image or stand in contrast to mechanical operations. Rather, the story users tell here is one of a symbiotic relationship between humans and machines. Computers are just not very good at making these kinds of similarity and difference judgments: but humans are, or can be trained to be. Using humans to “get too little” shields the computer from making mistakes due to precision equations that might jeopardize the resulting calibration process; conversely, enlisting circumscribed human error on the side of caution protects the calibration routine from any damaging results of human intervention, allowing trust in the eventual results. Erring in this particular way, therefore, is part of the human calibrator’s contribution to the routine.

18 March 2, 2006.
Once all the regions have been identified to the calibrator’s satisfaction, a series of graphs are automatically generated for visual inspection. Each of the colors placed on the regions of the caltargets appears as crosses on a plot alongside a white diagonal line (visible on the right screen in Figure 24). Calibrators are called upon again to judge, this time how closely the different colored plots align with the diagonal line, which varies in location for each filtered image. Interestingly, none of the calibrators I spoke to could identify what the graph was or what it meant, even though all could tell when they had done something correctly or incorrectly. Inspecting one of her graphs, a trainee noticed that the light blue dot was a bit farther from the line than she’d liked. She went back to the image, shaved more edges off her light blue section identifying the outer ring of the caltarget, and returned to regenerate the graph to see if it had had any effect at all: it was unclear. And when one of my plots turned up with every point on the line, my instructor for the day insisted it was “perfect,” and wondered aloud how I did it.\textsuperscript{19} Here again, the instruction sheet provided little indication of how the plot was generated or what the graph represented. But the invisibility of the code and indeed much of the calibration process to the calibrators created a metonymic effect, whereby the proximity of colored dots to a diagonal white line had a direct, albeit seemingly random, bearing on the success of the calibration practice in general. Even those who presented a story of a correlation between the colors on the caltarget and the colors on the plot could not predict how altering the space occupied by a region on the caltarget would change the graph for the “better” or “worse”. Still, a basic visual inspection, which did not require understanding what the underlying processes were, was enough of a “check” on the system to encourage trust in the eventual results.

\textsuperscript{19} This is not because I am a particularly talented calibrator: neither she nor I could explain how the plots were calculated.
The opacity of underlying processes persisted throughout most of the CCC members’ interactions with the MER software. While team members achieve fluency in achieving their tasks, the computerized aspects of the calibration pipeline were seen as a magical process, set in place by the team leaders and involving an array of bewildering code streaming across the screen. Team members respond to this “magic” in different ways. One experienced calibrator is content to stay ignorant about anything but the big picture about what the software is doing. When I asked her about a program, she answered vaguely, shrugged and offered, “I think this is part of not knowing how [the code] works.” A new addition to the team, however, had already purchased a book on how to program in IDL. “I don’t know what’s going on behind the scenes,” she said, “I wanna know what they do with the software.” This interest was fuelled by curiosity, but only one current team member, who has been with the team since the beginning and who takes pride in his computer skills, has taken to actually tinkering with the process. However, he does not “hack” the software scripts themselves: instead he has written a few supplemental programs, such as the one that automatically determines caltarget regions.

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20 Park Doing (2004) provides another example of lab hands at the synchrotron laboratory who experience a similar agnosticism towards the experiments they facilitate; in Doing’s case, however, the “magic” was in the hands of these operators, whose intuition for the machine was credited as a particular kind of expertise granting political status within the lab.

21 March 5, 2006.

22 March 2, 2006.
So while calibrators may display different degrees of knowledge about the program, the technology remains somewhat blackboxed, despite access to its coded scripts being available for consultation.\textsuperscript{23} Calibrators are content to let the computer run through its image transformations, limiting their interventions to those visual inspections that are deemed to be “what humans do better than machines”. In general, then, human judgment is enlisted in the calibration process, but is tightly trained, circumscribed, and limited by the opacity of the coded algorithms.

\textit{Digital Discipline}

The next step of the calibration pipeline is entirely digitally achieved. The calibrator types a command at the IDL prompt and is asked to enter their name before the computer takes over. Producing scrolling text on a Linux terminal screen, the actual program is invisible to the common CCC member, who is instructed to:

Read a book … get a snack … ie. this may take a while. But … don’t go to far. \[sic\]\textsuperscript{24}

While CCC members may be nursing a cup of tea, tending to their homework or reviewing data from the other Rover as this program runs, this does not mean that users are passive with respect to software. All the calibration routines were produced in-house by expert programmers who continue to be senior members of the CCC: they were written in the IDL programming language, commonly used by astronomical

\textsuperscript{23} The software was written in-house by a graduate student on the mission who has since left the lab, but who also wrote a program that can display all MER software scripts upon request. In practice, however, this program is very rarely consulted, as many CCC members either do not know enough IDL to ‘read’ the scripts, or were the authors of the scripts themselves.

It is also interesting to note that IDL is not the only programming platform available for image processing, but is the variety often preferred by astronomers: scientists on the mission may use the in-house Pancam software but more often use tools with disciplinary or institutional affiliation, such as ENVI (preferred by orbital image processors), ISIS (produced by the US Geological Survey), or ArcGIS (preferred by geographers), or even Photoshop. Due to different standard routines available in each software package, scientists spend much of their time exporting and importing data from one program to another to take advantage of different digital tools. Data products produced by other team members with alternate affiliations and software may often be welcomed with amazement and appreciation of deep skill, although these products were produced through simple routines.

\textsuperscript{24} Pancam Calibration Procedures: 7.01.
image processors, to accomplish the particular goals of calibration as a routine practice. This means that the exactly repeatable scripts act on and transform the images according to a pre-established value of what a reliable image ought to look like. Further, in a software environment, a piece of technology works on a digital artifact (such as a .JPG file), which only exists within that technological environment, to change it into something else. The image, not the machine or the software, develops and changes under the force of this script. Thus assumptions of what makes a good image are encoded directly into the image data as the original pixels are disciplined into calibrated values.25 The raw images are drawn as cleaned images, a standardized view of Mars.

How are the pixels digitally disciplined? Using the identification of caltarget regions, the program corrects each image according to two constants: a “lab” and a “field” value. The first is a radiance constant (RAD), determined in the pre-flight testing period “to estimate the radiometric conversion coefficients on Mars … to determine the camera responsivity, and assuming a ‘typical’ Mars radiance spectrum as output.”26 The second is a constant generated by the comparison between the values of the identified caltarget areas with their expected values (IOF). Thus images are adjusted according to both the crew’s pre-flight expectation of what Mars ought to be like, as well as an in situ calculation of what Mars is actually like on any given day. The result is a duplication of each image through the calibration pipeline, into images disciplined to two different calipers: one with metrics generated in the lab and constant across all images, and the other generated in context in order to eradicate that context from its digital form.

25 This discussion of discipline is indebted to Lynch (1985b).

26 Bell, et al. (2006): this source also includes technical details as to how this was achieved. RAD files are often preferred by the atmospheric scientists on the team, as they preserve the measurement of how many photons actually hit the CCD in situ, and the effects of dust scattering from the atmosphere. As mentioned in the previous chapter, one scientist's artifact can be another scientist's data.
Essentially, then, a calibrated image has been operated upon by a software script to first identify, then subtract the effects of the atmosphere from the scene. Such a procedure is common in astronomical image processing, where ambient radiometric indications of the location- or time-specific nature of the observations may be removed to get a more object-oriented image. Pixel mathematics are common in a variety of forms in image processing: for example, the standard routine of “flatfielding” divides images by shots of neutral backgrounds -- the night sky, or the dome of an observatory in which a telescope is housed -- from an image so as to correct for any irregularities on the CCD itself. Images can then be “normalized” by multiplying them by an average value derived from the flatfield image. Although it might be strange to think of Mars without dust in the atmosphere (or divided by the sky), for the geologists on the MER team this dust scatters the light so as to compromise the ability to measure a rock’s individual reflective properties, and presents an aspect of Mars that must be tamed before it can be subject to scientific analysis. Thus *drawing* the image *as* trustworthy means drawing the dust or other changeable features *out*.

In spite of the popular revolutionary rhetoric surrounding the novelty of digital tools with their limitless possibilities, the regime of the software script enforces even more heavily the social construction of scientific facts. Scripts digitally alter image data such that the resulting calibrated image possesses all the virtues of a trustworthy datapoint. The result is an image that is changed, on the one hand, so as almost to believe that the camera itself had been physically adjusted before it began to record images of phenomena. On the other hand, the result is also an image that encodes into...

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27 Constructing dust and even sunlight as artifactual recalls Lynch’s (1985a) ethnomethodological study of the construction of artifacts through work and talk in a biology laboratory. Of additional interest are discussions of programmed corrections to observations in Lynch & Edgerton (1988) and Lynch (1991a). I am thankful to Jim Bell and Kjartan Kinch for their explanations and demonstrations of flatfielding.
its very pixel composition what it means to be “calibrated”. The software code that transforms the images one by one actively adjusts images such that they conform to the MER scientists’ ideals of what makes an image reliable, data-worthy, or a scientific observation. That ideal is one in which the situated nature of the image must be effaced: for IOF images especially, ambient local radiance is extracted, the image is automatically flat-fielded, and images are made translatable across locations, times, viewers and contexts on Mars. Thus individual images are drawn as trustworthy, standardized, comparable datasets, as a view from nowhere produced by a “modest witness.”28 Further, how the image is drawn as -- that is, the delicate balance of mechanical operations and human judgment -- is equally important for the status of the image as evidentiary, ripe for scientific analysis. If Mars is to “speak for itself” through these images it must be unencumbered by its dusty atmosphere, its distant sunlight, or sometimes even its robotic observer.

The Value Of Routine

Once the calibration routine is complete, calibrators open the duplicated images in their image viewer and conduct one more visual inspection to be sure that nothing has gone wrong during the process. Here the original version of the image becomes a familiar point of reference, meant to help the calibrators to check the new images against their memory of the old images.29 Further, four more graphs pop up, plotting pixel values in both the RAD and the IOF images and offering a visual comparison to twenty images from the previously calibrated set: calibrators must also visually inspect these graphs to be sure that no single image has an outrageous or confusing plot, out of line with the average values in both the current and past suites of

28 On the view from nowhere, objectivity and modest witnessing, see Haraway (1991, 1997).

29 As a participant observer, I have noticed that the calibrated images do not look all that different from the uncalibrated images. Sometimes they are noticeably lightened, but I still do not feel I could detect if an image had been calibrated or not simply by visual inspection.
images. This can be a visually taxing process. For example, “Tau” sequence images of the sun produce sharp peaks in pixel values because of the brightness of the majority of the image, and calibrators must scroll through lists of file names and pictures to be sure that each pixel peak indeed corresponds to a shot of the sun, or similarly, that low pixel values correspond to a night sky routine.

Very rarely is it apparent that something has gone wrong with the calibration scripts, so instructors and co-calibrators usually encourage team members to treat this stage as routine. When I asked another calibrator about her appraisal of the values on the graph, she said “I don’t know why. … They’re asking me to do it so I learn how to do it.” This emphasis on executing the routine can sometimes lead more senior calibrators to discourage neophyte calibrators from treating something they don’t understand as a problem. For example, I once noticed some missing values and questioned my graph, but it was an uphill battle with another CCC member in the room to spend the extra time tracing which images had data loss, find out why it had occurred, and note that loss in the log. This team member insisted that it was not worth wasting my time -- or, more importantly, the time of the senior members of the MER team who would read my report and need to review the files -- on a trivial error. I wondered at the time why this might be: was it just that this team member was tired after a long session of calibrating, late for class, or even a poor calibrator? The last option seemed particularly unlikely due to their extensive coding experience and their long history with the team. I noted the problem in my log anyway, but soon received a reply from the head of the CCC, indicating that this was a known error, and thus not really a problem after all. The next time I saw the same irregularity, I could dismiss it as a nominal anomaly too.

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30 March 2, 2006.
This incident demonstrates the acquisition of expertise as a calibrator. Adherence to routine is not necessarily indicative of laziness or of ignorance: just like knowing what computers and humans are good at doing, knowing just what degree of precision in image maintenance is required, and how much is undue attention to unimportant details, is derived from experience, knowledge of the camera and code, and practicing the routine itself. Thus routine-ness itself becomes one of the virtues of calibration, as it demonstrates expertise with the system and its nuances. This knowledge enables the calibrator to recognize a true anomaly or problem -- “strange stuff” -- when it does finally arise. For example, a few weeks later I noticed another problem with my calibration procedure. Rather than dismiss this with false confidence or fear of alarming my superiors, the above incident prompted me to report this error as well -- I was thanked for noticing a “real” problem. Accumulating knowledge of “nominal anomalies” thus establishes the boundaries of normalcy in calibration such that the routine can continue to be completed with regularity, focusing the attention of the team supervisors on new errors instead of known problems; and such that the calibrator can demonstrate and apply their honed judgment when faced with future trouble spots. Thus who the image is drawn by retains importance even in the phase of calibration, as such skill is the hallmark of a trustworthy operator who can produce trustworthy results.

Should all go well, as it usually does, the calibrator has only to enter a few more small commands in order to upload the corrected images to JPL and email a copy of their report textfile to the entire Pancam team. Calibrators see a “Done!” on their screen, to which they usually breathe a sigh of relief and gather their things to race to an impending class. The entire process, run side by side for both Rovers, takes three to four hours. But mission scientists consider this time commitment essential to providing them with trustworthy images of Mars. The camera’s data results have been
disciplined to approximate how the camera itself might have behaved had it been adjusted for local conditions. These local conditions are not the planetary geologist’s concern: they are considered artifacts that must be removed from the data, or at least aspects of Mars that must be tamed or factored out in order to ‘do science’ on Mars.

**Inscription And Objectivity**

Collins, Pinch and others have used the example of calibration to show how scientific knowledge is necessarily socially constructed: no matter how rigorous the “test of a test,” calibration relies on the community’s assumption of what constitutes evidence of a phenomenon in the first place. In the context of controversy, therefore, critiques about instrumental calibration can take on heightened significance. But we might derive further conclusions from a study of instrumental calibration. In the case of the Pancams, the work of calibration stands as an actor’s solution to the trouble with digital images. The image processing techniques discussed in this chapter constitute no less a kind of *drawing as* than Susan or Ben’s colorful transformations. This time, however, the data is drawn as tamed and disciplined as it is stripped of unwanted characteristics while heightening valued features. It further reveals the anxiety associated with digital imaging and the processing techniques of pixel-pushing; in the face of the malleability afforded by these digital tools, calibration is one way to ensure that the image is *drawn as* something credible, a trustworthy representation of the Martian surface?
An interesting facet of this case study is the contrast between the status of the raw images versus that of the calibrated ones. NASA posts all the raw image data on its Rover website, but the calibrated versions are released several months later. As my instructor explained, if anyone else tried to do photometry or spectral analysis with the raw images, their results would be flawed -- even though these images constitute first-hand witness reports, the closest thing to a trustworthy inscription produced by an inscription device on the mission. Such an account adds nuance to the story of the transparency of inscriptions, wherein we might otherwise have claimed, with Latour, that image data produced directly from instruments are trusted as the object “speaking for itself”, effacing the processes of its production (Latour and Woolgar, 1986; Latour, 1990). Indeed, as discussed in the Introduction, the narrative of the Pancam is one of the direct self-registration of natural effects -- photons onto a CCD plate -- to produce an image that is simultaneously numerical and pictorial. But inscriptions from the camera must be consistently monitored and modified or else they cannot be taken as “the thing itself”. In traditional laboratory environments, where experimental apparatus can be massaged during set-up and even during experiment, such activities might be subsumed under a general heading of technical competence, but this example -- a non-experimental field site wherein the alien and remote environment demands active calibration -- highlights just how essential calibration is to producing trusted results. Only when images are calibrated can mission scientists see this data as

31 All raw images can be viewed at [http://marsrovers.jpl.nasa.gov/gallery/all/](http://marsrovers.jpl.nasa.gov/gallery/all/), while calibrated images are released to the public on the Planetary Data System in 3-month packets. Caltarget images are available for download, but the scripts that enable their interpretation and calibration are not publicly released, prompting much discussion among amateur sites as to how to calibrate the newest images themselves. This may seem counterintuitive at first: surely these images are too raw for public consumption and present a vulnerable side of the Rover program. However, the policy accomplishes the dual goals of upholding the norm of communalism, while still restricting access to the calibrated images to a core set, bounded by the MER team, who “certify new knowledge” (Collins, 1985, p.143) about Mars. Even among this core set, however, a 3-month turnaround for public release of calibrated images is considered extremely fast, as many high-profile space missions guard their data closely until their team has amassed enough publications; in such an environment, the early decision to release the Rover team’s images as soon as they hit the ground was considered a rare gesture and has influenced other missions since then. I discuss this topic further in Chapter One and Chapter Eight.
evidence, uninhibited by instrumental artifacts or observer bias. The story of the instrument’s “hand and eye” seamlessly recording “the things themselves as they appear”\(^{32}\) is incomplete without calibration.

Further, the calibration process is emphatically not effaced from the story of the image’s production, but is rather talked about and referred to as the routine procedure that gives the image its moral and epistemic status.\(^{33}\) CCC members are far from being “invisible technicians” (Shapin, 1989): rather, calibration of the Rover images takes place in the middle of the Cornell lab, commands to image the caltarget are scripted daily into uplink instructions, and mission scientists routinely acknowledge the Cornell Calibration Crew’s efforts as central to the mission. The persuasion that the image is a direct registration of natural effects and a seamless frame for witnessing cannot, in fact, be effected if “all sources of persuasion seem to have disappeared” (Latour and Woolgar, 1986, p.76): because calibration is so essential to the trustworthiness of the data, the story of calibration must instead be told and retold. It is not simply the process of inscription that prompts a story of transparent access to the phenomena under study, but rather the continuous taming of the observational field, effected by corrective software and human judgment in concert, that enables the instrument to vanish from the witness account.\(^{34}\) This elimination of variables from the Martian field, combined with the digital inscription of ideal conditions and reliable imaging practices onto the very images themselves,

\(^{32}\) The reference here is to Hooke (1665), although this commonly-held value for the relationship between instruments and images dominates the development of graphic instruments, of which the photograph is one. See Brain (2002), De Chadarevian (1993).

\(^{33}\) Lynch (1991b) discusses the “moral and epistemic status” of photographs and diagrams, especially as they are presented as a pair. It is worth noting here that the calibrated image follows Lynch’s suggestion for the digital image: it is more trustworthy and taken as truthful because it has been subject to the purification regime of calibration.

\(^{34}\) See Shapin and Schaffer (1985) on “virtual witnessing”, the literary technologies that enabled far-flung members of the early Royal Society to feel as though they were present at an experiment or demonstration.
ultimately enables the team to trust what their instrument tells them. Calibration disciplines the Rovers’ robotic eyes such that Mars can “speak for itself”.

The combination of human and machine operators in crafting reliable inscriptions points also to a possible new chapter in the story of objectivity as explored by Lorraine Daston and Peter Galison. In two papers and in a recent volume the authors discuss the observational and moral cultures of objectivity in the nineteenth and twentieth centuries, respectively: mechanical objectivity, in which the impartiality of the mechanical inscription device mirrors the disciplined and impartial scientist-observer (Daston and Galison, 1992), and judgmental objectivity, in which an experienced eye is employed to transform the singular into the universal or to bring out relevant features (Galison, 1998; Daston and Galison, 2007). But in the digital world of the Mars laboratory, these modes are fluid. People are called upon to intervene and exercise judgment at various stages of the calibration routine, and computers are called upon to reproduce routinized scripts, reinforcing a sense of objectivity through balancing what humans and machines are each “good at doing”. Further, digital procedures inscribe judgments about singularity and universality onto the image; the software treats as artifactual certain aspects of the imaged object that give it a situated nature, such as local atmospheric conditions, and attempts to produce an image in which only the properties specific to the imaged object itself are relevant. Finally, the black-boxed software script and the robot in which the cameras are embedded reinforce the mechanical qualities of impartiality and distance. Thus the Pancam’s calibration routine is both “hands off” and “hands on”: both trained eyes and impartial circuit arrays are essential to the production of what are considered trustworthy, calibrated images. Drawing as practices are invoked to produce “the image of objectivity” even with digital artifacts.
Certainly other modes of working with instruments to produce reliable reports of natural phenomena require a similarly careful arrangement of humans and machines in practice. But as Daston and Galison explore in their studies of scientific atlases, the changing *story* of what makes an observation objective, with what particular arrangements of humans and machines and what resulting moral and epistemic requirements of the human observer, produces different practices and identities alongside the production of scientific images. What may be unique in digital era is a dual and sometimes even conflicting invocation of both human and machine expertise, producing a mixed morality and even a cyborg identity for the scientist.35

In this and the previous chapter, I have described the pixel-pushing activities of scientists and calibrators as they work with digital images to *draw* them as legible and trustworthy. But images of Tyrone or Cercedilla are not simply products of robotic interactions on Mars: they are also and especially the products of human interactions on Earth. In the following chapter I move to describe these interactions in the context of the planning meetings for each Rover to show how images are drawn as documents of consensus building within the particular organizational structure and rituals of the Rover team.

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35 The cyborg has been well-discussed in STS as both a historical and theoretical object: see especially the “Cyborg Manifesto” in Haraway (1991).
CHAPTER 4: “ARE YOU HAPPY?”

IMAGE PLANNING AND RITUAL INTERACTION IN THE SOWG

“JPL, are you on the line?”1 The sound of ringing telephones punctuates the darkened room at Cornell University, where a group of MER team members gather around a conference table on the fourth floor of the Astronomy building. Screens are everywhere: a ring of computers line the room with official signs on them reading “Pancam PUL” and “Pancam PDL,” a large hanging screen on one wall displays a projection of video conference activities,2 and it seems like everyone in the room also brought their laptops. Visible on the projector, team members at the Jet Propulsion Laboratory file to their seats in comfortable chairs around a U-shaped table in a bright, spacious room with a model Rover in the center, facing a series of screens onto which shared images are projected and distributed online. The teleconference line beeps as team members telephone in from their offices, cars or coffee shops around the world. This is the daily Science and Operations Working Group meeting -- the “SOWG”3 -- at which the scientists and engineers on the team come together to make decisions about what the Rover should do the next day: what the team calls “tactical” planning.

While the Rovers do have some capacity to drive autonomously, they do not conduct science or see by themselves. Instead, they receive detailed instructions daily from their human team on Earth about where to go and what to do. And while MER

1 A common opening statement at the beginning of SOWG proceedings, indicating that the meeting is about to take place. Descriptions of and quotations from SOWG interactions in this chapter were transcribed during SOWG meetings observed between 2006-2008.

2 As the institutional home of the Principal Investigator and the Pancam Payload Element Lead, Cornell University is one of the few spaces connected by video feed to the SOWG meetings. Only Washington University in St Louis, home of the deputy Principal Investigator, and the Jet Propulsion Laboratory in Pasadena, home of Rover operations, regularly participate with video feeds.

3 Pronounced ‘sōg’.
team members often joke about the “keys to the Rover”, it can take up to 20 minutes for a signal to reach the planet. Thus there is no joystick that controls real-time operations on Mars: the team communicates with the Rovers only once a day, sending one to three days’ worth of commands at a time (“uplink”), and simultaneously receiving the data from the Rover’s successful activities the day before (“downlink”). As a team member explained to me, “We’re working on the Martian Night Shift.”

The SOWG meeting, usually convened once daily for each Rover, is the place where scientists and engineers must balance several competing pressures and produce a plan for both Rover’s activities on Mars for the following Martian day, called a “Sol.” The goal of the meeting is to produce a daily plan that will be uploaded to each Rover, indicating a sequence of observations and drive directions that will direct its activity on Mars. To that end, conversations are conscripted to carefully manage Rover health and actions by monitoring the space available in the robots’ flash memory, fluctuations in solar power (called “Tau”), and safety. Because surface situations may change daily and new scientific questions may arise on the spot, a daily approach to surface operations is essential, and detailed planning is required to ensure that the Rover wakes up to a complete list of requested activities, compiled and negotiated on a day-to-day basis, with no bytes to spare.

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4 Rover artificial intelligence is limited to auto-navigation around features in the Martian terrain that they might judge insurmountable in situ. This has been subject to upgrade over the course of the mission due to new software uploaded to the Rovers -- as team members put it, “our Rovers are getting smarter.” The emphasis on human actors is particularly important to Bill Clancy (2006), who argues that calling the Rovers “robotic geologists” obscures the human element of the mission.

5 Interview, Mark, February 15, 2007.

6 Tau is technically a measurement of how much dust is in the atmosphere, what atmospheric scientists call “optical depth.” On the Rover mission this is measured by taking pictures of the sun with the Panoramic cameras. As scientists know how bright the sun ought to be in these photographs, they compare how much its brightness is reduced to characterize the dust in the atmosphere and estimate solar power levels. Tau graphs are presented at the outset of every SOWG meeting I have attended.
With its tightly sequenced and adhered-to combinations of reports, discussions and statements, the SOWG meeting can be fruitfully analyzed sociologically as a highly refined ritual interaction that organizes social activity on Earth even as it achieves the goal of producing robotic activity on Mars. The relationship between ritual and social order have long been topics of interest for sociologists; in particular, Emile Durkheim’s discussion of the production of social order both through the division of labor (Durkheim, 1933[1893]) and the performance of religious rites (Durkheim, 1915[1912]), and Erving Goffman’s (1967) framing of face-to-face interactions as ritual productions of social order may both provide useful points of departure for the analysis of a meeting like the SOWG. On the one hand, attention to the reciprocal relationships that arise due to the division of labor among team members (Durkheim, 1933[1893]) or the performances of those relationships inherent to social structure through ritual activity (Durkheim, 1915[1912]) provides a way to view the activity of Rover Planning as essential to the construction and maintenance of a collective team identity. On the other hand, Goffman allows the sociologist to move away from Durkheimian structuralism to locate “the action” that constructs such social order at the moment of face-to-face encounters. This requires considering how individuals produce social order in those local interactions that comprise “the labor”, and noting what resources are available to them to do so: such as maintaining “face”, deferring to others, or producing appropriate responses to standard questions or phrases (Goffman, 1967). As I will describe, the ritual character of the SOWG makes available certain resources and interactions to team members as they work together on

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7 Despite Durkheim’s importance to Goffman’s work and to Symbolic Interactionism more generally, it would be a stretch to suggest that these two social theories can be seamlessly combined. My emphasis here is on Goffman’s approach to the unit of individual interactions as constitutive of and derived from social order, and the Durkheimian theme of solidarity as it is composed of the performance and division of labor, and ritual enactments. However, as an STS scholar I reject Durkheim’s positivist and progressivist stance, and would be loath to suggest that the MER team is more or less “primative” or “elementary” as a social group.
a daily basis, reinforcing the MER team’s commitment to peaceful consensus. Because images on the Rover mission are produced through these ritual interactions, they are constitutive of and reflect this social order as well.

The ritual pattern of SOWG interactions thus enforces and reproduces the local norms that govern participation on the MER mission. Alongside tracking robotic memory and watt-hours, participants on the teleconference line must keep track of immediate and long term scientific goals on the surface and manage competing requests for robotic activities from members of the science and engineering sides of the Rover team. Activities are traded and negotiated within a language of accounting for robotic resources; and while certain sequences of talk are tightly reproduced as part of the order of the meeting, during the time in the meeting when activities are open to discussion, participants appeal to certain resources that both allow for local positive face-work and maintain the social order of the mission team. This is perhaps most evident in the ritual closing statements of the SOWG meeting, wherein the plan cannot be approved and proceed to implementation until all team members at the SOWG achieve consensus, a moment they signal at the end of the meeting by declaring, one at a time, that they are “happy” with the plan.

Examining talk with, about, and for images in the context of the SOWG meeting reveals the practical work through which images from the Rover mission are constructed, prior even to their inscription, as part of the daily operation of the spacecraft and consensus politics of the Rovers’ human team. Following images as they are planned, accounted for and negotiated in the SOWG meeting, I show how Rover images are the products and currency of practices of social negotiation within a tightly-honed structure of engagement. I begin with a description of the SOWG meeting framework, goals, and roles that team members regularly assume to support

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8 On inscriptions see Latour (1990).
the local politics of consensus with its associated norms for interaction. I then show four resources that involve images and image planning within this social context: the appeal to constraints of robotic time and disk-space, the patterns of negotiation between team members, the use of images to manage disagreement, and an appeal to aesthetic considerations. I next briefly discuss a rare example of a breach in the SOWG to further elaborate the role of images in achieving unity of purpose and direction among the team and their Rovers. Exploring this collaborative activity achieve through teleconferenced and networked interactions locates “where the action is” within the digital topical contexture\(^9\) of twenty-first century space exploration, demonstrating how knowledge of Mars is constructed by means of the practical, social management of visual technologies, and how the same management of these visual technologies also constitutes management of the team.

**Into The SOWG: “A Finely Tuned Little Dance”**

“Can I get a roll call on the Meet-Me line?” asks the SOWG Chair, kicking off the meeting precisely on the hour as usual. Remote participants state their names on the teleconference (“Meet-Me”) line as the engineers file into their seats in the room reserved for Rover operations at NASA’s Jet Propulsion Laboratory in Pasadena. The back row is usually reserved for the Rover Planners, specialist engineers who are responsible for producing the code that drives the Rovers. A Mission Manager is also in the room, an engineer who maintains oversight over the Rover’s operations for the day, as well as an engineer whose sole focus is the basic status of the Rover, keeping track of its changing solar power situation or communications needs. Around the room are blue placards that identify the liaisons from each of the Rover’s Athena suite of instruments: the Pancams, the MiniTES, Mössbauer, Microscopic Imager, APXS, and

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9 The digital “topical contexture” is contrasted to the optical ‘topical contexture’ in Lynch (1991a) as the somewhat virtual space in which work with digital instruments, instead of optical instruments such as microscopes, is accomplished.
RAT. The chairs behind these placards are empty as their occupants now dial in from around the country. They are responsible for the current status of their individual instrument, including whether or not yesterday’s sequences ran to completion or sent back any data (“downlink”), and are also responsible for coding the instructions for the plan that will be sent up to the Rover at the end of the day (“uplink’’).10 Also at the virtual table are the mission’s Participating Scientists and members of their groups of staff or graduate students who maintain close involvement with the mission. All attendees at the meeting share online access to documents posted on a secure networked site and to a live video feed from JPL showing the SOWG room and two screens with either relevant Powerpoint presentations or Maestro, the Rover’s in-house science activity planning software (Figure 27).

In Chapter One, I described the Rover team as attuned to a consensus model of operations, wherein principles such as data sharing or speaking up to question assumptions are encouraged by a flattened hierarchy and collaborative relationships among members. But this does not mean that a meeting like the SOWG is a free-for-all: conversely, the SOWG’s goals, structure and roles are explicit and closely adhered to by team members. The purpose of the SOWG meeting is to host daily “tactical” discussions, which the team identifies as pertaining to the here-and-now of daily operations on Mars: i.e. what the Rover should do tomorrow.11 This requires

10 Most of these instrument liaisons combine both downlink and uplink responsibilities; only the Pancams have distinct uplink and downlink liaisons due in part to the volume of data that must be managed.

11 In contrast, “strategic” discussions about longer term goals, hypotheses and required observations, and drive directions for the Rovers are hosted in another forum, typically the End of Sol meeting. I will discuss this further in the next chapter, but it is worth noting here that a distinction between the two types of conversation is tightly drawn. When a team member brought up a possible approach to Victoria Crater during a SOWG meeting, another shook their head over the muted microphone, “you don't talk about strategic issues in tactical meetings.” Such breach of tacit protocol “only makes the SOWG Chair grumpy” and usually requires the SOWG Chair to intervene and put things right again; but it also reveals to the analyst the importance the team accords to maintaining these categories, procedures and ways of interacting to govern and manage their activity planning and their internal relations.
producing a plan for the Rover’s activities the following day that balances the health and operational concerns of the Rovers, such as conserving its power or taking care not to cause damage, with scientific concerns like conducting observations or experiments. Team members talk about this in terms of managing “Rover health” alongside “squeezing out every last possible bit of science” from the vehicles. But the SOWG also requires achieving consensus by the end of the hour, when all participants at the meeting must assent to the day’s plan. This requires balancing competing science or operations needs of team members, maintaining strong working relationships between them, and keeping the peace in the case of disagreement. Referring to both the tightly-honed structure and the need to satisfy multiple different groups and interests, one team member described the meeting to me as, “a finely tuned little dance that we do.”

Figure 27 A photo of an early SOWG meeting, when team members were co-present in the SOWG room at JPL. The Rover planners are usually seated in the back row; scientists serving as uplink and downlink leads are in the front rows. Courtesy NASA/JPL-Caltech.
The structure of the SOWG includes tightly-delineated roles for participants that include specific domains of tasks and responsibilities. One scientist I spoke to, James, described this structure as arising from the testing phase of Rover operations, in which it became clear that for the team and the Rover to operate together successfully, “you need some degree of organization, and there are crucial positions that need to have folks with skills associated with them:” this required “the right partitioning of assignments” among people on the team.\textsuperscript{12} Thus meetings begin with a “roll call” to hear who is participating today, but this also serves as a “role call” as participants state which operational role they are responsible for today. Each Science Theme Group -- Atmospheres, Geochemistry, Geomorphology, etc -- designates a member to be present at the SOWG to represent their group’s interests, concerns, or requests. Each instrument also has a Payload Uplink Lead and a Payload Downlink Lead (PUL or PDL), who closely follows the conversation and asks questions along the way to make sure that they understand what activities are requested of them and can ask questions of the requestors before they spend the remainder of the day writing the code for that operation. In addition to these specific liaisons, team members can also assume roles designed to think holistically about the operation of the Rover and the team in concert. The Keeper of the Plan (KOP) is in charge of entering commands for observations into the Rover’s software, called \textit{Maestro}, in sequence and as decided by the entire team. A Documentarian keeps careful record of each observation, who requested it and why, and ensures that all commands and requests issued at the beginning of the day are accounted for by the end of the day. An engineer at JPL is responsible for thinking about how all the commands sequenced by different operators will interact with each other, so that no observation or move will contradict or ‘fault out’ another. And a group of scientists are designated as Long Term Planners (LTP),

\textsuperscript{12} Interview, James, June 21, 2007.
whose job it is to stay attuned to the issue of long term strategy: keeping the bigger picture in mind while the daily meeting focuses on the immediate concerns of Rover operation. 13

Finally, the meeting is presided over by a SOWG Chair, a position that rotates among a select few on the team. These are chosen by the Principal Investigator for their ability to manage complex negotiations and achieve consensus while still maintaining the general “happiness” of the team. During pre-flight tests, the PI and Deputy PI noted that certain members of the team were especially good at balancing the demands of not only the scientific and technical goals of the robotic investigation, but also the social cohesion of the team. The roster of SOWG Chairs includes members of the MER team who have had experience leading missions, such as on Pathfinder or Viking, and the PI and Deputy PI, but it also includes scientists who are new to mission participation. The role has been described to me in various ways, but all team members essentially concur that “not everybody’s suited to be a SOWG Chair.” A SOWG Chair himself, James explained the role as a question of balancing the short and long term aspects of the mission, as well as the scientific and engineering considerations:

Well I guess the most important thing is to keep things within reasonable range. The science teams can easily spin into a tight kind little small loop where they'd like to get down on their knees with a magnifying glasses and explore Mars. The problem is it's not very efficient. So trying to get a rhythm where you cover some distance, stop and do scientific analysis and observations and then cover some more distance has been the toughest thing…

13 Each of these positions are normally accomplished remotely: that is, the Doc, KOP, Chair and LTP lead are rarely, if ever, in the same physical room at the same time. This has not always been the case, however: the SOWG meeting was conducted in person in the first 90 days of the mission, when each sequence had to be hand-written and scientists and engineers alike were suffering from the permanent jet lag of Mars Time. See Tollinger et al. (2005) for more on the changes in SOWG structure.
The other thing is trying to make sure that you can dovetail the engineering and the science requirements, so it requires enough knowledge of the engineering limitations …\textsuperscript{14}

But alongside these balancing acts, many MER team members impressed upon me the importance of ensuring the values of the mission such as openness and communalism, were adhered to. \textit{Listening} is most frequently listed as one of the key factors in the making of a good SOWG Chair: not only listening to members’ statements, but also and especially allowing opportunities for people to voice alternative opinions or to question assumptions. “It could be that person is only right ten percent of the time,” said William, another SOWG Chair, “but if it’s that ten percent, then you’d better be listening.” Another team member explained to me that one of their colleagues would not make a good SOWG Chair because they “didn’t listen.” Listening is important, James explained, because it enables “buy in” to the plan at the end of the day, making everyone feel like a valued participant in the process:

… at the end of the meeting you want to people to have a sense of ownership of the plan, that's why I kept asking at the meeting, are there any other comments, are there any other comments? … It's the whole empowerment thing, the team needs to feel like they're part of the process, and they're getting their two cents in and we're doing the right thing and we'll get the other stuff that we can't get [today] as part of the future [plans] … That's the most important thing. Because if you wait to the end [of the meeting] and everyone comes in with their own discipline-oriented or pet peeve kind of things then it's chaos, total chaos.\textsuperscript{15}

\textsuperscript{14} Interview, James, June 21, 2007.

\textsuperscript{15} Interview, James, June 21, 2007.
Managing and avoiding this potential chaos and distributing a sense of empowerment was also stated as an important job for the SOWG Chair. Michael said laughingly, “The SOWG Chair’s role is basically to Xerox and get coffee until all hell breaks loose.”

SOWG Chairs and other team members alike often describe the role as being “the grown-up in the room,” or making sure the team wasn’t “operating without adult supervision.” Such descriptions are not related to a sense of the team as immature, but rather highlight the Chair’s responsibility for keeping the team on track and on task through the course of the meeting, while keeping the peace and staying fair-minded in times of squabbles. This managerial aspect of the role appeals in particular to the younger scientists who are invited to assume the position: as one such scientist explained, “I’m ambitious … I want to run my own mission someday.”

She admitted that managing so many different (and often famous) personalities, having to make difficult calls and build consensus, and making a decision about what the Rover should do was daunting at first, but also exciting and felt like good “on the job training” for the next stage of a successful planetary scientist’s career.

The SOWG Chair must, through the course of the meeting, move the team from an analysis of the downlinked data indicating where the Rover is and how it is doing, to a plan contingent upon that analysis that will be uplinked to that Rover at the end of the day for execution over the next Sol. That is, during the SOWG meeting for each Rover, the team together evaluates the local situation of that Rover based on image and other data, and from there derives a careful plan for upload and execution that takes these local factors into account. The process is based on experience in the Operational Readiness Tests for the Rover, the pre-flight testing period in which the

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16 Interview, Michael, June 12, 2007.

17 Personal Conversation, September 16 2008.
team initially learned to work together, as well as on MER team members’ experiences on previous missions. As James continued,

There are kind of two ways to do the plan. One is that you send Atmospheres guys, the geochemists, the geologists, the whatevers off separately to come up with their druthers and then you make sure that it fits. It won't fit. And there will be hard feelings. The other is that you start off with a strategic [long term] plan that people have bought into, and then you give them realistic constraints as a group, and then help them develop a tactical [day’s worth of activities] plan that fits into the strategic plan … And where peoples' observations can't be fit in, you develop a Liens List and make sure they understand that we're gonna get to them.¹⁸

This description implicitly describes previous and even concurrent missions. In telescopic astronomy, high energy physics, or even unmanned space exploration, the valuable commodity of spacecraft or instrument time may be partitioned out to different groups of scientists in order to conduct their own experiments: thus getting “beamtime” (Traweek, 1988) or a few days at a synchotron (Doing, 2004) enforces and enables particular patterns of interaction between scientists and with their instruments. My own experience with other spacecraft teams would also indicate that this method of collective planning is far from the usual practice of partitioning segments in an orbit to disciplinary working groups with particular science questions, as on Cassini, or using a software program to decide which observations, submitted by different instrument teams, will fit together into a daily sequence, as on MRO. But the division of labor -- the responsibility for each instrument and group planning -- that James describes resonates strongly with the kind of system that Durkheim suggests produces “organic” solidarity (1933[1893]). That is, the intensity and directness of the

¹⁸ Interview, James, June 21, 2007.
relationship between human and robotic team components produces a deeply-felt
sense of reciprocity, strong social ties, and collective unity of purpose or even opinion.
It is perhaps unsurprising, then, that James here draws a tight association between the
structure of the team and its planning process, and the MER team’s values for
interaction such as unity, cordiality, collaboration, communication, and maintaining
strong working relationships between disciplines. Performing the ritual of the SOWG
with its associated roles and patterns of interaction on a daily or thrice-weekly basis
thus reflects, expresses and projects both these local norms for interaction and the
team’s sense of solidarity.

To establish a collective point of departure, the SOWG meeting starts with
ritual presentations that the team believes will set them up to achieve a cohesive plan
at the end of the day. A series of routine reports at the outset updates everyone in
attendance -- whether in the room at JPL, in their car in Arizona or at their kitchen
table in Ithaca -- on the Rover’s status such that the entire team shares the same
situated view of the Rover’s location, health, and specific challenges: the team cannot
end up in the same place if they do not at least start from the same place. Achieving
this local stance from which to begin planning is accomplished through a combination
of verbal reports and image dissection by the SOWG Chair and the LTP lead. An
initial, very brief statement from the SOWG Chair sets the stage for the Sol:

We can see the rock target and again correct me if I’ve got any of this wrong,
but it looks like we’re at Cape Faraday, a small rock shown here. It is reachable
and it is RAT-able, and just to remind folks the importance of making this
measurement … is that we got a very unusual chemical composition last time
we imaged at a trench and we want to find out if we’re seeing … a correlation
between this rock and the … high magnesium sulphate composition.19

19 Opportunity SOWG Sol 933, September 13, 2006. Note that “RAT-able” means that it is
deemed safe to use the Rock Abrasion Tool (RAT) on the target.
At the outset of this meeting we see the SOWG Chair informing the team where the Rover is, what it is doing there, and why it is there. In another example, the Chair reminds the team of the previous day’s failed observations and the ‘tactical situation’ for the Sol they are currently planning:

We had an IDD [robotic arm] fault when we went to [use the Microscopic Imager] … . It looks like we got a bunch of MIs that were not anywhere near the target and are still out of focus … . So my plan for today is to actually recover the MI … and then put in some IDD diagnostics, then bump back and look at [the target] with Pancam … . That’s a summary of the current tactical situation this morning.\(^\text{20}\)

Emmanuel Schegloff has described how formulations of place and location both establish a shared geographical location and identify membership within a conversation.\(^\text{21}\) As the LTP lead summarizes the local situation around the Rover, they orient the team within the Rover’s frame of reference to establish a shared virtual location with the Rover on Mars, despite the fact that team members may be physically located in different rooms or if they have just come off shift on the other Rover, as is frequently the case. Such talk and frequent use of the term “we” (instead of “us” and “them”) also identifies all the participants on the line as members of the unified mission team, engaged in a collective process. Further, ascribing team-selected names to features around the Rover according to the running naming scheme makes for a shared sense of familiarity with the alien environment. Statements such as “we’re at Cape Faraday,” or “we’re moving from Emma Dean to Duck Bay,” therefore, do not imply impersonal geographical points on a map, but serve as a shared local

\(^{20}\) *Opportunity* SOWG Sol 1102 March 1 2007. The IDD is the Rover’s arm (Instrument Deployment Device).

\(^{21}\) On formulations of place and membership categories, see Schegloff (1972). I return to this point in more detail in Chapter Six. On “we” and articulations of membership, see not only Schegloff (1972), but also Sacks (1992) especially lectures II.3 and III.8.
nomenclature among members of the team. Thus the ritual of summarizing the “tactical situation” at the outset of the meeting upholds team norms by supporting the group’s collectively-oriented structure.

Following this brief introduction, the Long Term Planning Lead (LTP) associated with the Rover gives a report that places the robot within the context of the Martian landscape and the team’s longer-term objectives. Images are central to this discussion. The LTP report is often an image-laden PowerPoint presentation, updated daily, wherein several key slides may stay embedded in the presentation for days on end. These images are typically familiar from a past LTP report or a recent science meeting (discussed in the next chapter), and are used to remind the team where the Rover is, which science targets are of importance in the scene, and what overarching goals must drive the formulation of the plan. For example, Spirit’s LTP lead put up a slide showing the East side of Home Plate, the area the Rover was exploring, annotated with arrows and labels to indicate where the Rover is, what it has already accomplished, and what it has left to do:

The second slide will remind you what we have been doing, give you some context … [we are located] between those two green arrows which define the existing Pancam coverage, so we've already imaged from position labeled “first” and we hope we are at the position labeled “second” which we hope will enable us to finish off that gap, and we expect to turn around and take images of Mitcheltree Ridge and then finish off the observations of Mitcheltree Ridge before driving up the onramp … . We're about four meters from the outcrop that we wanted to image and so the idea was to bump forward maybe two or three meters so that we can get better images and MiniTES observations.

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22 LTP leads typically occupy their role in shifts of about two or three weeks at a time.

Similarly, on approach to Victoria Crater, Opportunity’s LTP lead kicked off his presentation with a panoramic view of the Crater freshly downlinked from the Rover’s Navigation Cameras, and a view from orbital imagery to give the team a sense of “where we currently are” and “where we’re heading” (Figure 28):

This is the map view image from where we currently are, and we are at that open green dot, and our target is that light green dot at ‘Duck Bay’ … I put the light green dots to give you a sense of where our target is, where we’re heading on Monday.

Figure 28  Orbital imagery used for approach to Victoria Crater, annotated to identify “where we currently are and where we’re heading.” Opportunity LTP Report September 22, 2006. Used with permission.

Similarly, on approach to Victoria Crater, Opportunity’s LTP lead kicked off his presentation with a panoramic view of the Crater freshly downlinked from the Rover’s Navigation Cameras, and a view from orbital imagery to give the team a sense of “where we currently are” and “where we’re heading” (Figure 28):

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24 Spirit and Opportunity are located on different sides of the planet, and both have their own separate SOWG meetings. There is little standardization of LTP reports between the two both sets of PowerPoint presentations have stabilized into two slightly different documents. On Spirit, for example, long term planning objectives are more often displayed in a graph or table, and there is always a graph of current data volume and power; while on Opportunity these are usually displayed as units on a different slide. While it is beyond the scope of this paper to explore this topic further, it is worth noting that this difference in LTP report format may reflect the differences between the two Rovers and their respective teams, who are often said to have different personalities.

In both cases, the use of annotated images and the use of the pronoun ‘we’ in these presentations give the team a highly situated view of Mars, a shared visual sense of their surroundings and their possibilities, and establish group membership around and through the Rover. I will return to the importance of this language in the following two chapters. For the purposes of the present discussion, however, these images and conversation about them at the outset of a meeting enable a distributed team to become localized, brought together at a specific point on Mars to witness their surroundings through the Rover’s “eyes”, sharing a sense of their situation before they begin to plan further observations.

One final crucial piece completes the LTP report: a summary of solar energy fluctuations and the status of the Rover’s flash memory. Based on this information, the LTP lead offers a recommendation to the SOWG Chair: a limit of how many bits can be in the day’s plan. This can be anything from 30 to 350 megabits and changes daily depending on factors that range from local dust storms to the location of the communicating satellite as it passes overhead. The number is a critical piece of information, as SOWG Chairs must then attempt to fit requested observations into that recommended bit count. This may involve merciless cutting or smooth finessing in the sixty minutes to come, as will be discussed below.

Before proceeding to an open call for observation requests, this big-picture view of the Rover’s location and situation is complemented by specific reports from each instrument and from the Rover Planners to build a picture of the Rover’s “health.” Each of the Payload Downlink Leads or instrument liaisons reports to the team how their specific instrument is doing, which observations were successful and which require repeating, and how ‘healthy’ the instrument is. The Microscopic Imager PDL might say:
MI is healthy, we received eighteen full frame thumbnails…

And shortly thereafter, the Pancam PDL:

It appears Pancam is healthy from telemetry data but we have not had any new products [images] down since [Sol] 940.26

Such reports inform team members of the status of completed observations, as well as any issues the instruments might be facing on any given day, such as dust contamination or instrument malfunctions. Over the course of my fieldwork, a report from Rover Planners – the engineers who drive the Rovers – and other engineering personnel was added to the SOWG roster of reports. This was suggested by an engineer at JPL as a good way to maintain “cohesiveness” between the science and operations sides of the mission by keeping all team members informed -- not just those directly responsible for producing Rover code -- about the status of their vehicle. For example, as one Rover Planner reported:

We did get the final state of the Rover just before the [satellite] pass which shows that we … have reached our target, we are in a good state.27

Following these status reports an engineer also displays on a shared screen a rough outline indicating when the Rover must “sleep” or “nap” to recharge its batteries, when it must communicate with the Earth based on satellite passes overhead, and what time is available to the science team to request observations. This outline, called “the skeleton,” presents a frame into which all planned Rover activities must be adjusted or fit. Commenting on the relationship between the skeleton and the Rover’s scientific command software, Maestro, one team member explained to me, “Maestro is the science plan… The skeleton is the Engineering constraints that gives us the time and energy in which we have to do our science.” For example, the Skeleton for the day


may show that the Rover wakes up at 10AM (Mars time), has two hours available “for science” before it must check in with its relay orbiter, Odyssey, flying by overhead; it then must take a “nap” to recharge, “wakes up” at 2PM and has enough energy to drive 20 meters to its next target site, leaving only 20 minutes “for science” at the end of the drive before it has to “go to sleep” overnight at 4:30PM. Thus technical issues such as the health and status of the Rovers and their instruments are expressed at the outset of the meeting as the required activities for operations, around which any scientific observations – shorthanded as “science” – must be planned.

The balance of rigid elements around which Rover activities must be planned with the local, situated view afforded by updated statements of the Rover’s current status draws attention to how the SOWG ritualized an exercise of what we might call “situated planning”. This recalls Lucy Suchman’s (1987) classic distinction between “plans” and “situated actions”: the former being artificial intelligence models requiring a complete a mental model of the world within which to plan interactions, the latter being context-dependent interactions characteristic of human activity. Suchman’s formulation gave rise to an area in artificial intelligence research aimed at developing agents whose activities were derived from local contexts of interaction, an approach which may have influenced the design of the Rovers’ own AI systems. What is interesting here is how the Rover team combines these approaches -- the regimented structure of detailed planning with the flexibility of local interaction -- in the production of highly local, situated and short-term plans for the Rover on a regular basis. Far from providing conflicting input on Rover activity, however, the combination of the situated approach with the process of planning is unified under the organizational rubric of consensus-building through carefully-managed social negotiation.
In the process of setting up the SOWG meeting we see a clear articulation of roles on the mission and the social structure for interaction in which they are embedded. As each member speaks up with their required report in sequence, they both inform the meeting participants as to the Rover’s location, establish a unified membership category and outlook, and enact the local norms adopted by the team. These introductory presentations also provide specific parameters that become resources for managing the open discussion of specific observations that will ensue – from vehicle health, location, available bits and duration of time available to science, to who is on the line today and the requests or concerns they will bring to the table. It is worth noting also that team members rotate regularly through these roles, enabling an opportunity for fresh eyes on a problem or time to resolve any conflicts between team members as they arise in the process of planning before these have the opportunity to become personal. Images are conscripted into this activity with talk that places the team in the same situation, at the Rover’s location, prepared for the work of moving together through consensus planning. As the LTP report and the skeletons leave the screen, the Keeper of the Plan loads their view of Maestro, the Science Activity Planner software, to the remote display for all to see and the Chair opens the floor to requests for observations.

Working With Images In The SOWG

Crafting a plan for each Mars Exploration Rover is a dynamic, collective and carefully managed art that must take many factors into account. Unlike lander or orbiter missions, where observations may be planned weeks in advance, the contingent and local nature of the Rover allows team members to take into account errors or fortuitous discoveries as they go along. But laced into this scientific and technical explanation are the team’s values for collaboration and consensus building. This can perhaps best be seen, again, through contrast with other spacecraft teams and their
process of planning. On the Viking lander, for instance, the decision of what pictures
to take was made by the imaging team alone. A specially-printed pad of paper showing
the view of Mars from over the lander’s deck was circulated to the imaging team
members, who would draw a box on where they wanted to request an image (Figure
29). This piece of paper would then be handed to an engineer, who would code the
instructions for the image and monitor its acquisition over the course of several weeks.

Figure 29 Viking Imaging Team planning paper. Scientists on the Imaging team
would color in areas to request a picture, and hand the paper to an engineer to
develop and transmit the appropriate code.

In contrast, however, the Rover team treats observation planning as a collaborative
activity that involves not only scientists and engineers, but also all kinds of scientists,
not just one or another team. Scientists are loosely grouped into Science Theme
Groups (STGs) who share common research questions, such that they may craft
together a list of observations that their discipline finds salient. But during my
observations of the team these groups -- Atmospheres, Geochemistry and Minerology,
or Geomorphology -- did not function as competing political units, as they might in a
group with a more “mechanical” division of labor (Durkheim, 1933[1893]). They were rather visible as a roster of “Leads” who could be called upon to speak up for one or another scientific perspective during a meeting, although participation at the meeting was not restricted to these STG Leads.

Thus image planning in the SOWG presents an interesting site for the exploration of scientific representation as “ordinary action” (Lynch, 1993), for several reasons. First, the activities at the SOWG constitute the “everyday” work of conducting science on Mars. While operating a robot on another planet is recognized by all to be exceptional, it is also intensely routine and practical. Activities, roles, hierarchies, and even particular conversations are enacted daily through video and teleconference links. This is where the ground is laid for the achievement of both the “science” and the “operations” goals of the mission. But the robotic pressures of power and bits are matched by the social pressure to achieve consensus on a single plan to upload by the end of the day. This highlights some of the complications of human-machine operations, but also lays bare some of the social, technical and visual tools that team members employ to gain assent for their observations, conscript viewers to their perspective, and team-build at the same time. Images in their interpretation and planning play an essential role in this process.

Most interesting for the study of practical work with images in science, the remote and collaborative nature of the mission requires scientists and engineers to be especially verbal and visual about their interactions with images. Interpretation relies upon extended conversation, negotiation, and a range of activities employed to craft images from the ground up, to recruit other team members to see the same thing or agree to the same course of action. Ultimately only one set of observations can be uploaded to the Rover at the end of the day, so each team member is challenged to express and effectively communicate their need for and interpretation of images to
their distributed colleagues, who are separated by physical distance, virtual documents, and home disciplines. Further complicating the issue is the fact that, while each participant in principle has the same level of access to mission materials through networked sites and video links, in actuality each has varying degrees of access, types of documents (static or refreshing), and people with them as they work together in this collaborative and virtual project. Thus planning for imaging is a practical activity that enlists a variety of sociotechnical resources, including previously-taken images. In this section I will describe four ways in which planning observations are enmeshed in and arise from within this sociotechnical system.

Making An Observation “Fit”

The overriding consideration when planning observations of Mars in the SOWG is, “Will it fit?” What an observation must “fit” into is a changing target of recommended bits, watt hours, and timing based on changing conditions on the Martian surface. The solar-paneled vehicles may have lots of energy to power observations during summer days when the sun is high, but during the winter or during a dust storm these levels may become dangerously low.28 The time of sunrise, sunset, or communication with an overhead satellite can also affect how much time is available for an observation. And the satellite’s position is also important as it dictates how much data the Rovers can send back to Earth. After all, the Rovers are equipped with flash memory systems that can only permit so many ‘bytes’ to be collected and stored at a time. After a particularly good satellite pass or during a sunny summer’s day, flash memory can be fairly empty, and SOWG Chairs may simply open the floor to the scientists to suggest observations. For example, Sol 1010 on Opportunity was jokingly pronounced by the SOWG Chair as “Christmas for Atmospheres” as an

28 During the dust storm of 2007, for example, Spirit only had enough energy to ‘call home’ with a single beep a few times a week, and could not even take pictures of the sun as the sky was so obscured its sun-locating program could not locate it.
atmospheric scientist, the only scientist who had called in to the meeting that day, added request after request; and upon capping the day off with a ‘cloud movie’ observational sequence it was proclaimed “Atmospheres Gone Wild!”

By the time team members show up at the SOWG meeting, too, a draft plan is usually available, cobbled together from observations on the “Lien List” (the list of requests held over the longer term) or based on ongoing discussions on the team. As one KOP announced at the outset of a set of observation requests:

The remote sensing activities on this sol are mostly things that I just made up yesterday out of thin air kind of guessing what people might like to do … so the idea behind that Cape Desire thirteen filter [Pancam observation] is that this would be a … full color let's-look-at-the-stratigraphy-layer of the far wall … to get color variations … [and] I put in two [MiniTES] stares on Cape Desire …

The MiniTES PUL replied enthusiastically to this statement:

This is exactly what we were going to request. I was going to send an email to [today’s KOP] yesterday and then I noticed it was already in the [plan].

These occasions aside, requesting images usually involves an “advocate” on the team, someone who can speak to exactly what the observation is, what it requires, and why it is needed. This person can email the KOP before the meeting requesting an observation of a particular target of interest, named and identified on previous images, or simply speak up during the course of the meeting to make a request, as MER team members are always encouraged to do. The following scientist’s request for an observation is an excellent example:

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29 Opportunity SOWG Sol 1010 November 26 2006. The Rovers do not have movie cameras on board, but scientists may request rapidly-shot frames of the same observation to assemble into a ‘movie’ on Earth; this is particularly useful for analyzing drift direction of Martian clouds or the formation of dust devils.

I’d like to advocate for one of these quick L2 R2 pans… If there’s a hole in the [Sol] 957 plan we should put it in there. It is on the order of fifteen minutes and something like under twenty megabits.31

Note how the scientist articulates exactly what he wants and when he wants it: a panorama with the second filter on the left Pancam and the second filter on the right,32 only fifteen minutes long and twenty megabits in terms of memory, and which he believes can be easily placed into an existing ‘hole’ in an upcoming sol plan. Presenting an observation with a description of what it is for, and how many bits and minutes it will require, helps to determine whether or not it should go into or stay in the plan. However, in addition to covering the technical and scientific concerns, one scientist informed me that sounding enthusiastic was also helpful, as in the following early morning exchange:

Chair (addressing Atmospheric Sciences Theme Group representative):
Atmospheres, do you want that observation?
Scientist: Yeah we're ecstatic [sounds flat].
Chair: Do you want it or not?
Scientist: Sure. Is it a question that we're arguing over it?
Chair: No, it's yours, dude. Just wanted you to show a little more enthusiasm.
Scientist: I haven't had coffee yet! [laughter]33

31 *Opportunity* SOWG Sol 954-956 September 29 2006. Note that these requests do not come out of the blue: they usually have a heritage in the weekly science meetings, discussed in the following chapter.

32 As described in the Introduction, filter wheels in front of the Pancam lenses can rotate to present thirteen different views of the Martian terrain attuned to different wavelengths of light. Left and right filters are prefixed “L” or “R” with the filter number, i.e. “2” or “7”: i.e. an observation with the common combination L257R1 uses the left second, fifth, seventh and first on the right filters. I will discuss the use of these filters in Chapter Two.

“This whole thing is negotiation,” the same scientist had earlier insisted to me after a meeting had ended, explaining that success at requesting observations was contingent upon being “good at the give and take.” Negotiation with and about images is a consistent feature of SOWG talk; performance of this negotiation with a positive or upbeat tone is seen as consistent with the proper way to maintain face and social order while managing competing observational requests.

To meet daily bit quota, especially if there is a drive involved or solar power is low, the team together accounts for every piece of data requested from the Rover. No observation can be made willy-nilly, and no time should be left over with nothing for the Rover to do. The terminology is indeed one of accounting: Chairs speak of “tallying” bits and “bookkeeping” observations. When disk space on the Rover is tight, therefore, all requests are be subject to detailed scrutiny by the Chair in order to make sure that bits in the “bit bucket” are “bookkept.” This results in the strategic “trimming” of observations to fit the amount of time, bytes and watts that the Rover has available for the day. The observation’s advocate may be required to stick up for a request or identify just what exactly can be cut should there be too many bits in the eventual plan. In such cases, if the advocate has not already clarified the purpose of the observation, the SOWG chair will usually ask exactly what the image is for, in order to better tailor the observation to that need. For example, faced with a request for a Pancam observation using the left and right cameras, a SOWG Chair tried to articulate what exactly the observation was for:


35 Garfinkel (1967), of course, has much to say on the subject of “accounting” for ordinary activity. The SOWG meeting can be seen as an elaborate networked social setting for the structured ‘accounting’ for each Rover’s practical activities.

Chair: So lemme ask about these Pancams. What you got right now is a Pancam L7 R1 two by one [frame mosaic]… I think what we want them most for is … identifying with confidence where there is exposed rock.  

Identifying what the image is for permits the SOWG Chair and image advocate to trim the image to just its predicted context of use in order to conserve bits. Trimming the image resolution (measured in bits-per-pixel) requires walking the line between staying under the bit limit, and producing an image that is actually legible. For example, in this case the camera operator and the scientist negotiate the trade off between how many bits they can spare for the day’s plan, and how high the resolution must be in order to get adequate resolution to see anything in the image at all:

Camera PUL: To get the best focus, going with three [bits per pixel] is the best bet, if we can afford it.

Scientist: If you do need to drop back to one [bit per pixel], the 20 millimeter is the best position.  

The result of this trimming in negotiation is that the images of Mars taken by the Rover are often constructed for a particular purpose from their very inception. I will return to the implications of this activity for image processing and knowledge-making in later chapters.

In addition to image resolution, while the Panoramic Cameras have thirteen filters, these are not all regularly used. Rather, scientists must decide exactly how many they need for their observations and often be satisfied with no more, no less. For example, while driving towards the feature Home Plate, a geologist requested a thirteen-filter observation of a strange feature in a rock along the way, which the Chair held up to scrutiny:

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Chair: Cynthia, that's great that you have this observation in there to look at this [ridge in the rock], it's potentially a really interesting target, but I guess I'm just wondering what's the rationale for thirteen filter rather than L257R1 LOCO [Low-Compression] … if you’re trying to characterize the dust …?

Cynthia: No, I guess I'm curious to see if it's something different. So well I guess it doesn't have to be thirteen filter.

Chair: Would you be happy also with an L257 R1? Just if we are tight on bits.

Cynthia: Yes I guess that would be fine.

Here the Chair “trims” the proposed observation from using all thirteen Pancam filters to only using four (the second, fifth and seventh on the left Pancam and the first on the right) with low image compression. Lest this seem like wheedling someone out of their observation, note that built into the code of social interaction around negotiation is the ability for scientists on the team state to outright whether or not such a change would cripple their observation. Scientists are very comfortable in doing so. In this case, another scientist spoke up to clarify whether or not Cynthia actually needed all thirteen filters and whether or not the trade was a good one:

Alexa [to Chair]: This is Alexa, I'm just wondering what is L257R1 going to reveal in terms of differences, what would you predict? … Cynthia wants to find out if this is different spectrally than the surrounding, and I'm trying to get at if it's dustier. What are we going to be seeing, what's different?

Cynthia: I want to get a sense of whether or not it's the same composition and maybe go visit this thing at some point.

Chair: I think an excellent example of what L257R1 can reveal is [the targets] Montalvo and Riquelme. We imaged those with L257R1 and you can see very clearly the color and texture differences … we have a long track record of using these filters to distinguish between different units.
Alexa: Okay then.

Chair: And I want to emphasize the textural.

Alexa: I'm all for texture.\textsuperscript{39}

Advocacy -- explaining what each team member wants and why -- enables scientists to propose and defend their observations against cutting in a manner that preserves the team’s collegial approach to planning. Further, a cut or trimmed observation is never presented as a failure or a personal catastrophe for the team member who proposed it. Observations that cannot be performed on a given day are relegated to a “Liens List,” a reminder of “to-do’s” that is presented in LTP reports until the observations are accomplished. In the above case, while the observation has been cut, the interaction represents what the team would consider a successful negotiation and proper performance of team membership: the Chair has clarified that the limited filter set can still accomplish its advocate’s scientific goals, the observation has been trimmed so that the science fits into the day’s recommendation, the scientists Alexa and Cynthia voiced their concerns and a potential misunderstanding between the Chair and the two scientists has been verbalized and resolved. As for the resulting data that is ultimately taken on Mars, transmitted to Earth and analyzed, the purpose of the observation is built into the image from the ground up, ultimately delimiting and prescribing its possible transformations and scientific analysis. Thus such images are, very literally, socially constructed: built up bit by bit through interaction and negotiation among members of the team.\textsuperscript{40}

\textsuperscript{39} \textit{Spirit} SOWG Sols 1118-1120 February 23, 2007.

\textsuperscript{40} The idea of science as socially constructed is foundational to Science Studies. The Sociology of Scientific Knowledge (SSK) championed by authors such as Shapin and Schaffer (1985), Collins’ (1985) Empirical Program of Relativism (EPR), Berger and Luckmann’s (1966) Social Construction of Reality, and Pinch and Bijker’s (1987) Social Construction of Technology (SCOT) are notable contributions to that perspective, just as Hacking’s \textit{The Social Construction of What?} (2000) provides a valuable critique. Rather than a derogatory statement about “extra-scientific” social and political commitments this paper joins these texts in discussing social construction as an achievement, requiring work to generate a shared understanding of the natural world.
Another requirement alongside bit and time allocation that requires finessing are those images associated with driving. Driving the Rover, in theory, requires a navigation camera mosaic of the Rover’s prospective drive direction, images along the way to ensure that it is proceeding at the right pace and direction, and images taken at the final location, including a picture taken just before completing the drive so that Planners know what is underneath the robot in order to deploy its arm.\textsuperscript{41} This means that should a drive be included in the day’s plan, the Rover Planners must also request any and all of these images to support that drive. These images can be “bit-heavy,” taking up much memory, but are considered “mission critical.” They are therefore given high priority for acquisition and downlink to Earth so that they will be available to the SOWG by the time of the next meeting, usually the next day, for the purposes of immediate drive planning. These images may even require higher resolutions that can bump other scientific observations off the activity plan, as in the following exchange:

SOWG Chair: We got some pretty challenging driving ahead of us and if we got only two sols to get those images down then we can go with more images, lower compression ratios, more bits per pixel, just give the Rover Planners better quality products so that they can do what we’re gonna ask them to do on Monday.\textsuperscript{42}

In another case, a SOWG Chair realized late in the meeting that while they had planned for many scientific observations, they had not put in the images necessary for the drive:

SOWG Chair: Given that we've got to do a short bump [i.e. drive] … do we already have the drive direction Pancams and navcams that we need to plan that drive?

\textsuperscript{41} For more details on driving images, see Maki et al. (2005).

\textsuperscript{42} Opportunity SOWG Sol 953 September 28 2006.
Rover Planner: Nope.

SOWG Chair: I was afraid you'd say that.

Rover Planner: We can possibly get by without the navcams but we can't get by without the Pancams and we probably should get the navcams.\textsuperscript{43}

The result of this exchange was cutting the scientific activities planned for that Sol to make room for the images necessary for the drive.

In practice, however, such images are often managed alongside the science requests and are therefore not always set in stone. When the terrain appears predictable or if the Rover Planners are set to drive the Rover a long distance, the scientists may request of the Rover Planners that they take lower quality images in exchange for extra bits “for science”. The crunch can be severe enough as to obtain only minimal rear-looking and low-quality, highly compressed “drive direction” images. Still, when the terrain is more complex, the imaging required by the Rover Planners can be so intensive as to require cutting scientific observations. When an SOWG Chair observed that the recommended bit count for the day was used up before they could even get to science but began putting in optimistic observations just in case, a team member explained off-microphone that it didn’t mean the science would necessarily get done: “the science will just get cut downstairs [when and where the Rover Planners plan the drive]… Too bad, isn’t it?”

The trade-off between scientific and driving observations throws into relief a relationship that MER team members believe requires constant management: that between scientists and engineers. Stories abound on the MER team about fractured relationships between the two camps on previous missions, and about the importance of paying attention to methods of communication between the two sides of the mission. Here the limited number of bytes and watt-hours in a plan can serve as a

\textsuperscript{43} Opportunity SOWG Sol 1075 January 31 2007.
resource to manage relations between the two groups. If the Rover can only permit a
certain number of bytes in a plan, and the plan requires drive images in order to get to
where the scientist wants to get an observation, then the Chair can appeal to the needs
of the Rover to pacify the advocates of the competing observation. Similarly,
generosity on the part of the scientist or the engineer in terms of offering up ways of
trimming their own observations builds rapport between both sides of the team,
goodwill that is often repaid in kind with similar generosity in later meetings. Thus
policing the bit quota is used as a resource for managing both proposed observations,
and the team members who proposed them.

Rover health more generally can also be called upon as a resource in the
pressure of SOWG decision-making. At the time of my fieldwork, the Rovers were
already running hundreds of days over their recommended limit, and the team treated
the threat of Rover death as imminent. As a result, a common argument in favor of an
observation is that the team will not get another shot at this target, that image, or this
location. In one case, as someone suggested a three filter instead of a thirteen filter
Pancam observation, the SOWG Chair declared, “I don’t know what the science
objective is for it … but I’d hate to see us drive away from this spot and whoever it
was who wanted this doesn’t [get it]…”44 Thus instead of cutting the observation, the
Chair kept it in the plan. In another case, a mission scientist urged the team not to go
“throwing away a drive sol” on a panorama of Victoria Crater in the interest of getting
to the rim faster and seeing more. When his colleague protested that, “driving away
from this pan[orama] would be nuts,” he explained, “I like imaging probably more
than, just as much as anybody, believe me; I’m just worried that we’re going to run out
of Sols at the end.”45 Ultimately, the Chair decided that the cost of days it would

45 Opportunity SOWG Sol 953 September 26 2006.
require to take the panorama was “more than counterbalanced by the quality of the scene in front of us,” and continued with the observation. Such examples reveal how SOWG Chairs are required to make decisions about imaging based on the pressure of doing it right the first time, with no chance to go back and possibly no opportunity to go forward. But it also shows how the threat of Rover death can be used as a resource on the team to make decisions, support or justify a proposed plan of action, or assuage a team member’s concern about their observation. After another such decision cut short an observation in favour of driving onward, a team member turned to me and explained, “This is Mars, we're only here once, you know.”

**Imaging As Resource And Strategy**

Whether trimming observations to make way for other scientific or technical constraints, appealing to Rover death or selecting targets with team members, the work involved in planning images is a complex management not only of Rover bytes and power but also of the team. After all, concerns over which observations to cut and which to keep, or over which target to observe and which to neglect, have a social as well as a scientific and a technical dimension. Cutting one scientist’s observation in the interest of another scientist’s observation could imply a value judgment about their science, but cutting an observation because of the importance of Rover health, safety, or resource management provides an effective neutral ground from which to organize observations, as noted above. Another effective observation-“killing” strategy that can both save face and save bits is to move the observation to the following day or later in the week, at a time when it can be given priority and executed properly. The team therefore keeps an active “Liens List” of observations that need to get done in the short term, whether because they are an observation requested on a repeated basis (like atmospheric argon measurements), an based on seasonal variations on Mars (like dust

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devil observations), or left over from a previous negotiation in which one scientist’s observation didn’t “fit” and had to get cut. Most scientists are satisfied with this change, as they say they prefer getting their observation done right to getting it done at all. While it is very rare that a “killed” observation request is ever taken personally, more offensive would be killing a specific scientist’s observations in the aggregate. Paying attention to whose observations are consistently moved or changed is important in order to smooth over potential sources of tension. For example, when a scientist’s observations were put off for several meetings in a row and his voice on the line began to sound testy, the SOWG Chair used humour to diffuse the situation, promising to bring him flowers at the upcoming Team Meeting. The Chair then made the scientist’s observations the entire focus of the following day’s plan.

Thus the management of images and other observations can be an important resource in maintaining the peace among team members and achieving consensus at the end of the day. For example, when facing a controversy about what the Rover should do, a common strategy for preserving consensus is for the SOWG Chair to declare a paucity of information in the images to make an informed decision. The next step of Rover progress, therefore, changes from whether to choose one or another drive direction, to one of what further images are required to make the decision, or where the Rover should drive to in the interim in order to get more visual data about which plan to adopt. For example, on final approach to Victoria Crater there were many vivid discussions in both science and tactical meetings about which way to drive around the rim. The decision that was eventually imported to the SOWG, however, was described by the LTP lead as follows:
On Friday we start the drive towards Victoria Crater rim. We might not be close enough to see far enough to make any decisions but the next drive which we’ll plan on Monday … [will bring us to] a good place to have a look at Victoria crater and to decide which way to drive from there.\textsuperscript{47}

At a Team Meeting in February of 2007, too, the team rounded up a discussion of where to go into Victoria and how to get on top of Home Plate with a similar deliverable: drive to a new point and make more observations from there until the path becomes clear, or evolves further. Similarly, a heated discussion about where Spirit should spend its third winter on Mars involved an either-or argument that was said to require further imaging in order to resolve; I will discuss this case further in the following chapters.

Operational and scientific reasons aside, such a move buys team members some time to build consensus outside of the structured meeting format, such as through emails and other off-line conversations. This has the benefit of allowing them to get away from the limited personae of an authoritative or demanding “voice on the line” and pick up the discussion in different formats and locations. By the time the group reconvenes, tensions may be soothed and a decision may be achieved. For example, while it seemed ambiguous from far away which direction to go around Victoria Crater, once the Rover approached the rim I was surprised to note that the drive direction decision was “magically” resolved offline before the downlink of the new spectacular panorama from Duck Bay, the first point of access to the crater. The plan was to drive to Duck Bay and image both promontories on either side of the Rover, in order to decide among the two. The argument was made that if Opportunity moved clockwise to the Cape Verde, it could better image Cabo Frio, the opposing promontory, and then another decision could be made as to whether to turn back and

\textsuperscript{47} Opportunity SOWG Sol 954-956 September 29 2006.
drive counter-clockwise. But as more views opened up to Opportunity’s left on Cape Verde, the discussion of drive direction had evaporated from the SOWG.

It may indeed be the case that the team does not have enough information to make an informed decision at the time, particularly with respect to the trafficability of the terrain. But several points here reveal the roles of image management in mission planning. First, imaging and an appeal to further imaging can be used in the practical management of the team to attain consensus. Like agreeing to cut an observation to a limited set of filters or placing a target, the decision to put off a decision until there is more visual information also constitutes a successful moment in the mission, another point where consensus is achieved. Second, and interestingly for the study of imaging, there is a shared idea, or perhaps an ideal, on the team that images relay information, and that further imaging will generate more of this information upon which to base an increasingly informed and unified opinion. But such information cannot be gleaned unless the images are disambiguated through a process of collective interpretation. For the purposes of deciding what the Rover should do at the end of the day, everyone must see and subscribe to the same plan laid out in them. Thus as these images evolve in interpretation they become the mechanism for achieving consensus, and the record of that same achievement.

One place to observe this process in action is in the selection of targets: the things the team would like the Rover to observe or the places to which they would like to drive. Aside from atmospheric observations of the sky, the majority of the Rover’s observations are usually directed at a location on the Martian surface that the team member has determined as interesting based on their analyses of previous image data. Such points are called ‘targets’, and are assigned names from a pre-circulated list for identification. The scientist may then click on a Pancam or Navcam image in the Rover’s activity planning software to define and identify a target both so that the
software can determine the right commands to issue, and so that the other members of the team can see where that target is located on the surface. Thus images are intimately tied to targets both in their discernment and in their execution (Figure 30).  

Figure 30 Identifying targets both for the Rover and the Rover team. Pancam True and False colour images are annotated to show the targets Nancy Warren, Virginia Bell and Innocent Bystander. Image inset bottom left shows the location of MiniTES stares on the targets. LTP presentation, Spirit SOWG June 27, 2007. Used with permission.

Placing a target is sometimes an individual affair: scientists may do this at their leisure in their remote versions of the Rover software, and target names are either emailed to the KOP or assigned at SOWG meetings. But when targets must be negotiated as a group, the process of identifying which region to target displays an interesting combination of visual analysis, social convention, and technical action. For example, in this case, only a single Microscopic Image could be obtained of a set of clast nodules that the team found interesting. The discussion between the scientists Susan, Judy, Louise, and Thomas, the Rover Planners Jane, Mark and Kwame, and the

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48 For more on targeting, see Powell et al. (2006).
SOWG Chair reveals that the selection of targets requires coming to consensus about how to interpret the image:

Jane: I sent an email with the [annotated images] to [today’s KOP] … With Judy and Louise we discussed three potential targets … Judy and Louise think that maybe the Target 3 [is best] … I prefer Target 1 but I think that in the work volume [the area where the Rover can reach] Target 1 is the only one reachable, can you confirm that? … But Judy thinks that Target 3 on that side are the cleanest nodules … The rationale for Target 1 is the density and diversity of nodules, Target 2 is because of the drift … and she thinks it looks cleaner, just visually, I don't think we have any other data.

Chair: Okay, Mark and Kwame, do we have any reading on the feasibility of going to any of them?

Mark: Kwame is looking at the details. To our eyeballs it looks like either of them should be reachable.

Chair: Okay, so we have a difference of opinion… [Judy and the Chair are at the same location; she shows the Chair an image of the three target zones]

Ben [on the line]: Judy and Louise thought that Target 3 should go first.

Chair: So it's kind of two to one in terms of the Clast Mafia…

Jane: Right. It's fine with me, both have the same information.

Chair: Okay if we went to number three is there any other dissent or discussion needed?

Jane: And you would set up the 1x1 [Microscopic image] over the big nodule?

Chair: Yes. Going once, three times, done.\footnote{Spirit SOWG Sol 1100-1101, February 5 2007.}
Arriving at a shared visual analysis of the image on which the MI target is placed is key in this exchange, as the scientists and engineers attempt to locate a target that the Rover can reach and that would be useful for scientific purposes. Judy thinks her target “looks cleaner, visually,” while Jane judges hers to be “the only one reachable” but opens that statement up to her colleagues with a “can you confirm that?” Even Mark and Kwame “eyeball” the image to judge reachability. Judy shows the Chair the image of the three targets and points to each of them as they are discussed, as the two are present at the same location. The Chair uses humour to lighten a potentially tense situation, referring jokingly to the “Clast Mafia,” and Jane concedes her selection of Target 3 with, “It’s fine with me” and “both have the same information” as it became clear that a two-to-one vote would decide the target. And once the target is placed, it demonstrates that the team has agreed that this particular area is of interest for some further Rover work, in this case a Microscopic Image (Figure 31). The resulting MI picture is thus the visual sign of a moment of consensus in the meeting: a moment when several team members came to see the same thing in the image (Target 1 as the best reachable target of interest). As the target is placed in the Rover command software, the moment of consensus around the target is translated into practical action on the surface of Mars: the acquisition of Figure 31.

Another example further reveals other aspects of image planning that can be used as a resource for building consensus. Reviewing the downlinked images from Opportunity, a SOWG Chair, was struck by a strange feature on the surface. She marked it as a target and suggested that she would like to image it further as part of the
day’s plan, then chose to “open this up to the SOWG” for further input. One scientist concurred that, “it's an odd looking thing and given that we don't see many of these kinds of things it's probably worth looking at …” But another had a radically different reading of the picture, suggesting, “it could be something that fell off the IDD [robotic arm] and is on the surface now or it could just be some bizarrely shaped crack or a dibbit or something that's reflecting the sun in a strange way …” This scientist’s recommendation was to pursue the observation only “as long as those measurements would be useful for sort of generic outcrop observation; if it doesn't turn out to be something useful feature, like if it just turns out to be a trick of the light.” Further discussion revealed that the outcrop in which the feature was embedded was not a useful thing to look at, but a few team members continued to be intrigued by the feature. The Chair eventually ruled, “I’ve heard a lot of different ideas and I haven’t heard consensus,” so “I’m going to declare victory and say that that’s what we’re going to do.” The observations proceeded as she suggested at the outset (Figure 32).
This example presented an ambiguous feature that could have turned out to be either a “trick of the light” or a target of scientific value, and thus while the requested observations could easily have proven to be frivolous it might also present an opportunity for what the team would call “high science returns.” While it turned out to be the former, the Chair’s decision responds to a division of opinion among team members over whether or not an observation was worth keeping by choosing to perform the observation just in case. This ensures that team members can agree to the plan at the end of the day: those who championed it are happy with it because it is in the plan, and those who thought it would be useless could at least recognize the value of letting other scientists request observations. If all that happens is that new images fail to be of scientific interest, at least those members of the team who advocated the observation will still feel listened to. Thus the image is deemed be worthwhile because it will either reveal something interesting on the surface of Mars, or its very activity will support the principle of engaging team members with Rover activity by enacting the norm of listening to everyone’s input and accommodating all requests to the extent

Figure 32 "An odd looking thing." Left: Pancam L4 image, Right: close-up with Microscopic Imager, Opportunity Sol 1103. Courtesy NASA/JPL/Cornell and NASA/JPL/USGS.
possible. The Chair’s reference to “declaring victory” here is also indicative: this does not mean that she feels she is victorious in winning an observation over their opponents. Rather, it is a term SOWG Chairs frequently use at the end of a meeting to indicate that the team has come to consensus or coalesced around a decision, and that there is closure regarding whether or not the observation will be performed.

A similar method for resolving conflict was employed at a Team Meeting at CalTech where a drive scenario presented as crucial by both the Principal Investigator and the Rover Planners alike was contested by a scientist who requested further observations of a nearby feature before the Rover could move. The Principal Investigator invited comments on his drive proposal, saying “I wanna hear everyone express their view,” asking the dissenting scientist in particular to present his case with a PowerPoint slideshow to the team, and requesting other comments and discussion from the scientists and Rover Planners in the room as usual. But the conversation was cut unexpectedly short when a troupe of musicians descended upon the room to take up their rehearsal booking: the Rover meeting had run into overtime. Forced to close the discussion in haste, the Principal Investigator declared that the scientist’s observations would be performed as he requested before the Rover moved. Although unusual in terms of the need for the PI to “call it” before consensus had been fully crafted among the team, the decision conformed to the local value of listening and performing scientists’ observations whenever possible, thus continuing scientists’ sense of engagement and empowerment. To soothe any tensions that might have erupted during the meeting, the PI sought out the scientists who had spoken in favor of the observation and the engineers who had expressed concern about the necessity of the drive and asked them to work together before the next SOWG meeting to craft the observation sequence.\footnote{Team Meeting, January 13 2009.}
There is no right or wrong answer about where to drive the Rover or what images to take, although the team believes that there are better and worse scientific criteria for making decisions about observations, and that any decision that puts the Rovers in physical jeopardy must be avoided at all cost. But most questions do not have a simple yes or no answer. For example: can *Spirit* climb on top of ‘Home Plate’, and if so how should it try to get there? Can *Opportunity* descend into ‘Victoria Crater’, and if so what route should it follow? Such questions depend on how the team collectively interprets the images that return from the planet and comes to a consensus decision. In the midst of more heated exchanges, then, the SOWG Chair is not only responsible for making tough decisions as to what to put into the plan and what to take out: more importantly, they are also expected to quell arguments before they can get heated or personal. Techniques for team management in these cases vary from Chair to Chair: some take a vote, or “go around the room” to hear other voices in the discussion. Opening the conversation up to a plurality of views turns the situation from an accusatory one-on-one argument into a more general discussion in which dissent may be better negotiated and depersonalized. As one experienced SOWG Chair expressed above, it is most important for resolving controversy that everyone’s comment, concern, or potential observation be heard, whether or not it is eventually taken. Another frequent SOWG Chair tactic is to hear arguments from two or more sides, and then to offer a judgment on the decision. While arbitration has its value in moderation, used too extensively it could easily allow disagreements among the team to brew by forming factions or breeding discontent with a SOWG Chair. In such cases where tough judgment calls need to be made, one team member explained that it helped her to remind herself what the Chair was like “in person” instead of just on the teleconference line. After all, these situations are made more precarious by the team’s distributed locations, their necessary reliance on telephone and email conversations,
and the pressure to curtail discussion to resolve a plan within an hour. Authority in this case is not necessarily granted through hierarchical distance between SOWG Chairs and other team members; on the contrary, should the SOWG Chair simply become a disembodied “voice on the line” issuing commands to team members, this would be rejected as a violation of the team’s sense of co-operation and fair play. A degree of familiarity and connection through close working relationships online and in-person can help conflate role distance and bolster working relationships under the MER team’s collective model.\footnote{A Goffmanian (1961) sense of Role Distance may not apply in the context of the MER team’s distributed model of operations. Team members report that working relationships are not helped by professional distancing strategies (as in the case of the doctor-patient relationship). In the MER case, trust derives from interpersonal relationships that support the working relationships, as it reminds the participants of their colleagues’ human identity in the face of constant computer-mediated-communication in which nuances of personality and intentionality may be lost.}

*Postcards And Dinosaur Bones*

Observations do not simply have to be “scientific” or “technical” in order to make it into the plan, however. On rare occasions, another kind of appeal can be successfully offered as a reason for an observation. The following exchange between the SOWG Chair, the Pancam PUL, two scientists and the Mission Manager took place on a Sol when *Opportunity*’s power was high and memory banks were low:

SOWG Chair: Something I've been wanting to do for a long time at Victoria Crater is to take some Pancam imaging … with the sun low in the sky. There's really-- there might be some science that would pop out of this, but think of all the pictures that you've seen of the Grand Canyon an hour after sunrise or after sunset with all those long shadows from those promontories. I'm curious to see what the crater looks like at that time of day … maybe take a few minutes to get a really spectacular image. Just sort of a postcard.

Marc (Scientist): Sounds pretty.

Sam (Scientist): Could become the [NASA] Image Of The Week.
Chair: This is … something that we're doing sort of for fun, who knows maybe something good will come out of this but I'd like to try this if nobody objects … suppose we did a 2x1 red-green-blue, everything one bit [per pixel], how long does that take at sixteen megabits?

Thomas (Pancam PUL): [consults computer] About five minutes.

Chair: How much duration can I have for this, guys?

Mission Manager: However much you need.

Chair: Alright so I want five hours, now tell me what you really want.

Mission Manager: [laughs] I mean, within reason. I'd put an upper cap of – if it's over 15 minutes.

Chair: Let's bookkeep this for now … as a Pancam 4x1 one bit per pixel L257. And if we have to change that we will [downgrade it]… And Thomas, you and I will just look at where the shadows are supposed to fall and find the prettiest place to do it… Thanks, everybody.52

On first glance it is tempting to view such interruptions in routine as abuse of the SOWG Chair’s power: they can even convince the final arbitrators of the plan’s viability – the Mission Manager and Long Term Planner -- that their observation should occur regardless of duration and bits consumption. But this is not the case. Other team members may request similar observations, although they usually require the Chair’s buy-in to make them happen. And scientists on the team do not consider these breaches of the regular rules to be problematic, disruptive, or outside the Chair’s authority: as one scientist shrugged ambivalently when such an observation went through, “She’s the chair, if that’s what she wants to do, that’s fine with me.”

Nor, however, is this a case of simply accepting an observation because it is “pretty” or potentially “beautiful.” Although this consideration does come into play when crafting an image, especially one that is likely to move into the public sphere (as will be discussed in Chapter Eight), they do not on their own constitute a weighty enough argument for the consumption of bits and power. Instead, successful justifications of such costly observations to the Sol’s plan most often appeal to the team’s sense of exploration, adventure and curiosity on the Martian frontier. The value is not placed on routine or planned activities, but on discovery due to noticing and pursuing the unexpected, arousing and satisfying curiosity, and appreciating the sublime complexity of the field setting. Such observations present a different kind of science than the careful, directed activities that often characterize the laboratory setting. This is not just field science: it is the science of adventurous exploration. The idea of driving that “depends on what we see!” and looking out for “targets of opportunity” or finding a “dinosaur bone” can inspire the team to lay bit counts aside in favour of an extraordinary opportunity to probe an alien terrain that they may never

53 Lynch and Edgerton (1988, 1996) discuss the importance of aesthetics in astronomical image processing in two papers based on observations in the late 1980’s of the Harvard Smithsonian laboratory. Aesthetics are often a consideration when planning a panoramic view, suggesting a potential observation, or appreciating the spectacle of the latest downlink. But in the face of bit constraints and mission time, superfluous observations are considered superfluous. On a number of occasions, observations that are simply “pretty” are turned down as they do not present a scientific benefit to the team.

54 The development of the field sciences in early twentieth century America and their relationship to laboratory-based models of scientific work is eloquently explored by Kohler (2002). The Rovers, as usual, present a challenging case as the field is simultaneously remote and virtually present, the laboratory is often located ‘inside’ a computer, and the scientists who populate the mission hail from both lab (chemistry) and field (geology) disciplines. I discuss this further in Chapter Seven.


56 Targets of opportunity are defined by the team as potential sites of interest, usually located along a drive path, that deserve closer inspection but usually only become apparent at the last minute (i.e. during a drive). A mission scientist defines a “dinosaur bone” as “a mythical discovery that will force the science team to stop in the middle of the drive” (Landis, 2004), but this myth is invoked in practice as well: i.e. when referring to the discovery of a particular kind of geological structure, an LTP lead declared, “That's sort of our dinosaur bone … This is the kind of stuff we need to go after.” (Opportunity SOWG Sol 958)
visit again. The SOWG Chair must therefore nurture a talent not only for tough
accounting, but also for responsibly championing those observations that promote this
value of the excitement of field exploration. After all, periodic observations of
aesthetic or sublime interest satisfy the drive for a sense of exploration among team
members. Such images remind team members not of the mundane every-day nature of
doing focused science on Mars, but return them to the ‘big picture’ of their collective
position on Mars and the importance of unity of purpose on this alien planetary
frontier. And as the postcard developed into a high resolution black and white
panorama, it came to be known as the “Ansel Adams” image, taking on a sense of the
sublime and untouched natural landscapes that enticed adventurous Americans to the
frontiers of their country: an element of Martian imaging I will discuss in the final
chapter of this dissertation.

But I also want to draw attention to the phrase, “for fun.” Although under
tremendous time pressure and public scrutiny, part of keeping everyone “happy”
requires not only staying attuned to scientific and operational constraints, but keeping
the enterprise engaging. Talk and action about “fun” is also a resource in this
interactional environment attuned to maintaining the “happiness” of team members.
Even during the stressful period of deciding where Spirit should drive at Home Plate, a
team member characterized his colleagues as “driving around and having a great
time.” When charged with a difficult piece of Rover planning requiring custom
sequencing, I witnessed a team member walk away from the table at the end of the
meeting singing aloud, “I get to plan a custom sequence, do-de-do-de-do!” Laughter
often rings out on the line, scientists whoop and cheer as new images come down from
the Rovers, and team members regularly leave the SOWG meeting with comments
like “This is one kickass mission!” One light-hearted exchange about approaching
and conducting scientific observations on a kind of rock called a cobble is typical for
its jovial framing, poking fun at exactly the combination of serendipity and flexibility that characterizes the daily situated planning process. Here, the Chair has decided based on an engineering appraisal that the Rover cannot drive towards a cobble that members of the team have noticed for analysis, although a scientist still tries to squeeze in an observation that would capture the cobble nonetheless:

Scientist: Could we take a second [picture] at higher fidelity and put it at lower priority?
Chair: We can, but we probably won't see it [because it’s too low priority].
Scientist: We could bump it below those hazcams [in priority] …
Chair: Guys [laughs], we are not doing an approach to a cobble on this drive!
The chances that we're gonna wake up with the perfect cobble for IDD work in front of us are pretty slim …
Scientist: … I'm just saying if you keep making statements like that pretty soon we're gonna be betting beers.
Chair: [Laughs] Okay you got yourself a beer bet then.

The playful ‘bet’ never materialized, but such banter lightens the mood in the virtual room and affirms members’ engagement with the Rover and each other.

As already stated, at the end of the SOWG meeting the Chair always asks, “Are you happy?” of each liaison on the line in turn -- instrument operators, the Rover Planners and other engineers, and the Science Theme Group leaders. This is the final opportunity for each of these members to speak up with questions that might help them fine-tune their observations, or remaining concerns about any aspect of the process. When these issues are aired and addressed, the usual response to “Are you happy?” is a chorus of “I’m happy” from each member on the line. The phrase, in context, means something closer to “I’m satisfied,” demonstrating that all the participants on the line have had their questions answered, and that they feel that their
opinions have been heard. But the phrase has become so common that it is often subject to joking: team members might vary their response with “I’m ecstatic!” and the TAPSIE, an engineering role on the team, often replies with “TAPSIE’s hapsie!”

Such ritual statements serve on the one hand as closing statements for the SOWG, an indication that the planning process is over and the next stage of Rover sequencing can begin. But as interactional sequences they also articulate the social order of the mission, serving as shorthand for team members to assert their continued engagement with the mission. This sense of solidarity, again, resonates with Durkheim’s theories of ritual performances as important for building and sustaining collective self-image (1915[1912]). Participation in this question and answer sequence is important, as the ritual chorus of “I’m happy’s” articulates the operational structure of the team and individuals’ sense of membership within the community.

When Things Go Wrong

In this game where observational time and size are often tightly constrained and consensus is sought all round, an ethnomethodological approach suggests noting when exceptions occur and exploring their value for the construction of a normalized account of shared activity. Breaches of the SOWG structure or role outline can cause strain on mission team members; for example, when scientists do not suggest their observations at the right time in the meeting. Observations that come in after the plan has been settled, all the bits accounted for and all “I’m happy’s” stated could still be considered, but half-heartedly and usually with sighs off the microphone. When team members get this timing wrong -- for example, requesting a new observation

57 Garfinkel’s (1967) breaching experiments, for example, attempted to force moments of alteration in patterns of exchange in order to probe the underlying rules to everyday sense-making.

58 Muting the microphone on the teleconference line can allow streamlined conversation at the meeting, but it can also permit occasional expressions of frustration to happen off-line. This resource is used by team members so that they do not disrupt the disciplined cordiality that governs interaction on the mission. I must report, however, that such expressions are rare and relatively contained: I did not witness muting the microphone to develop a faction and rally local support for an observation, or to discuss another scientist’s requests in a derogatory fashion, for example.
without waiting to see if it has already been placed in the Sol’s plan or not -- their colleagues find their behaviour frustrating and it can amount to loss of face. While never directly expressed, the time to request observations that have not been emailed in advance is after the Chair’s summary, the LTP report, the instrument health reports, and the skeletons; and before the final readout of the plan and request for verbal assent from each instrument PUL, when the discussion is closed. Adherence to roles is also important, as one scientist discovered when he tried to interpret a possible drive path from the available imagery, and a Rover Planner interrupted with, “If I could just interject, I think it might be wisest to leave the science to the scientists and leave the engineering to the Rover Planners.” When the scientist tried to protest, the Chair shut off the conversation politely but abruptly with a “No, [scientist], please.” Such examples demonstrate the importance team members place on the ritual character of their SOWG interactions and the management of labor among team members, such that role- and rule-following is bound up in producing their collaborative outlook.

I have only witnessed one case where the SOWG broke down, and this breach was instructive for what it reveals about the importance the team places on their values of listening, communication, and role- and rule-following. In March 2007, *Spirit* was driving away from the white patch of soil, Tyrone, towards the feature called Home Plate, a region about the size of a football field with a unique topography visible from orbit. On the way, however, the scientists were requesting images of other light-toned materials, and had begun to make some important discoveries about different kinds of rocks in the region that betrayed high silica content. Looking over the downlinked images from the previous week, one of the scientists on the team circulated an email to some of his colleagues with an image attachment; on the image he circled the target areas he was interested in observing in order to further a hypothesis about the silica-rich rocks. This would require putting off the drive onto Home Plate for another few
days, substituting instead a drive towards one of the relevant targets where the Rover could return observations using Pancam and MiniTES. As everyone assembled on the SOWG line on Monday morning, the LTP lead mentioned in their report that a rich discussion had taken place over the weekend involving new potential observations. This seemed to set the stage for a discussion of how to drive towards the targets. But then a Rover Planner spoke up to talk about how to get onto Home Plate. The SOWG Chair of the day engaged with the Rover Planner, asking for input on the “Philosophical Question” about the priorities for observation on top of Home Plate.

At this point, I noted in my fieldnotes, the lines of communication in the meeting started to diverge. The scientists on the line started to sound antsy: after all, since they had decided to look at local rocks for the day and put off the drive to Home Plate, this sounded like a strategic discussion instead of a tactical one, and thus out of place in a SOWG meeting. As a result of this disengagement, side conversations developed and several questions posed on the line went unheard and unanswered. In addition, new restrictions in response to a recent security breach at JPL meant that a new phone line and phone system were installed, and participants were for the first time asked to state their names as soon as they dialed in. Thus the meeting was interrupted repeatedly as the Mission Manager tried to figure out who was on the line to satisfy local security requirements. Throughout the confusion, both scientists and engineers spoke of “the drive” without articulating exactly where the Rover was driving. At the end of the meeting when the KOP suggested reading out the plan before asking for everyone’s assent, the SOWG Chair said, “No, I’ve been having a look over it myself and it looks fine.” When the team hung up a local member worried that their colleagues were “sort of assuming that because [they] understood something, everyone understood something.” The voices on the line must have sounded different than usual, as my field notes record that the Principal Investigator -- although not
participating in this particular meeting -- came into the room from his office across the hall looking “worried” several times. At the end of the meeting, when I asked what went wrong, a team member offered, “I think it’s a bunch of people not normally working together, it’s Monday morning, people seemed like they were foggy, they’re doing things they wouldn’t normally do, it just felt disjointed to me.”

This could simply stand as an example of people being “off their game” as some team members accounted for the unusual meeting after it had ended. But it had consequences for the operation of the Rover and for the unity and “happiness” of the team. As the images came down the next day, they showed the Rover perched on the edge of Home Plate, poised to ascend to the top. Emails flew around the science team listserve: the scientist who had identified the targets was confused as to why the Rover was on top of Home Plate already, but the Chair and Documentarian thought that the drive had executed as planned. The Principal Investigator even asked the sociologist present at the meeting asking for “any idea of what went wrong here?” As everyone dialed back to the subsequent SOWG meeting, the mood was tense. The Rover Planners seemed unaware of the confusion and launched into a description of how they planned the next drive to place Spirit firmly on top of Home Plate: the goal which, as they understood it, the scientists had been pushing towards for months. But when a scientist started to ask them how soon they could get the Rover down from Home Plate and back to where it was the day before, the Rover Planner making the presentation faltered. “I’m sorry, I can’t make out what you’re saying,” she said.

About fifteen minutes into the meeting, with confusion still reigning, the Principal Investigator requested to speak up with “Can I try for a second?” His request was welcomed with a tone of relief and a “yes please!”


60 S. Squyres to J. Vertesi, Email correspondence, March 27 2007.
What I’m seeing here is a little bit of a disconnect between what the science team, some of them, are saying and what the Rover Planners are focusing on. The science team has a great deal of interest, some of them at least, in some outcrops that are not on Home Plate; the Rover Planners seem to be very focused on how to get on to Home Plate. We want to get on to Home Plate eventually, but I think we need to listen hard to what some of the scientists wanna do before we do that and come up with an appropriate plan that achieves the necessary science before we actually get on to Home Plate.61

Instead of accusing one or another team member of not doing their job properly, the PI’s language is vague in describing what “some” scientists and Rover Planners want. He also reminds the team of first principles in the performance of their ritual planning. There is a “disconnect” -- the kind of thing that MER communication should avoid. This is, further, a “disconnect” between the scientists and the engineers, a zone that the team both believes is rife for tension and prides itself on its ability to overcome. The PI articulates, as he sees it, the goals of both sides, and states an order in which both of those activities could happen that would satisfy both sides. He also invokes the value of listening (i.e “we need to listen hard”), which team members accept and expect as the conduit to good science. And while his comments are usually met with respect across the board and are heavily weighted in group decision-making, when he offered his opinion he did not attempt to overrule or take over from the SOWG Chair, but rather played the part of one of the meeting participants, even suggesting an observation later in the meeting. In the thirty minutes that followed, the discussion adopted an intense clarity as each side presented their concerns, goals and assumptions, looking for points of compromise or a “location that we can achieve those multiple goals.” By the end of the meeting, the Chair recapped the conversation

and ended by asking if everything was understood: “So, do the Rover Planners have a better idea of where we’re driving and what we’re doing? I believe we have an idea of what our goal is, that is what we were looking at in the pictures of [the previous Sol].” The meeting even ended with a joke: when the Chair announced the name for the new target, the scientist who had originally proposed the observations quipped, “But ‘that outcrop’ was working so well!” This comment, referring to the ambiguity of language that got the team into trouble in the previous meeting, was met with laughter all around on the line.62

Ultimately, the team coalesced around a plan that would take images from the Rover’s present position to help with future drive planning, then descend from the “onramp” to Home Plate to the place where the scientists wished to conduct further investigations before returning to the “onramp” later in the mission. This decision led Spirit to what the scientists believe are its most significant discoveries to date. But several issues are worth noting in the analysis of this singular ‘breach’. One is that the language of consensus and inclusion can itself be invoked as a resource when things go wrong. Thus comments about the meeting use expressions like, “not to point fingers or anything” or “potential misunderstandings” which aim to sort out what went wrong without placing blame or ostracizing a team member. The focus thus moves to collective rallying to improve the situation. The PI’s response to the situation was indicative: as he said, “I'm not pointing any fingers here, or looking to blame anyone for anything. It's just that it's part of my job to keep everyone happy, and when something like this happens, it's helpful to me to understand why it happened.” His response in terms of maintaining a hands-off approach, not disciplining the SOWG Chair or taking the reins himself, was also indicative of the importance of maintaining the fragile state of the team’s “happiness.” Overriding the immediate

miscommunication is the concern to strengthen the team, understand the situation and overcome it by addressing the problem in such a way as to avoid future miscommunication and to “keep everyone happy.”

This is not a one-off response to a singular problem but an approach to problem-solving practiced across the mission. When in June 2007 two faulty instructions were sent to the Rovers by mistake, the program’s manager at JPL called for an “operational stand-down,” canceling all operations for two days and requiring Rover staff to take a break. He then scheduled an “All Hands” meeting for a few days later, inviting all members of the Rover team to attend, and opened the floor for an opportunity to discuss existing processes, problems that people had noticed and ways that they could be fixed or addressed. In his opening statement he reiterated the team value that all team members were at the table together as equals, as he recounted a story about the Japanese automobile industry:

In Japan, anyone on the assembly line can stop the process. They have these cords at every station and the entire assembly line can stop instantly…. That wasn’t present in the US automotive industry … people didn’t feel they had the power, the authority to do that, and it’s that kind of thinking that I want to make sure all of us, every one of us, has. … We all share … a responsibility to the health and safety of the rovers, and we should all be willing and motivated to ask that question, to raise our hand and say I don’t know, I don’t understand that. … You all have the power and the responsibility to hold the process if you have any questions or concerns or just need extra time to work through something.63

The PI’s opening comment also underlined this authority invested in all team members, including the science team, saying “if you see something that looks funny

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63 “All Hands” Meeting, June 29, 2007.
you are empowered just like everyone else to pull the cord, to ask questions … it applies to everybody as part of the process.” He also advocated a return to first principles, as he found the operations process “a little more casual than it used to” be. More rigour in following the process, the rules and the roles, he believed, would return team members to the level of operations where “we’re like a fighter squadron at the top of our game.”

The importance of the ritual and its requisite division of labor was thus re-affirmed. The rest of the meeting lasted two hours, and elicited comments from many engineers and scientists on the line. Several changes were implemented as a result of the discussion, including a Role Call at the top of SOWG meetings, and a quarterly Stand Down for All Hands meetings to keep on top of the process. At time of writing, the most recent Stand Down included a video to further cement the connection between solid communication on well-functioning teams that speak up to question authority, and the avoidance of disasters: a NOVA television special on the Columbia Space Shuttle disaster.

Figure 33 "Silver lining" navcam image of cross-bedding at Home Plate. Spirit Sol 1148, Courtesy NASA/JPL-Caltech.

64 “All Hands” Meeting, June 29, 2007.
But another interesting issue arose from the tense SOWG meeting I witnessed. After the meeting ended I suggested that it was unfortunate to lose a day of driving and science due to the misunderstanding. But the PI remained upbeat and enthusiastic and countered my concern. “Note the silver lining stuff!” he exclaimed, pointing excitedly to the Navcam image that Spirit had acquired at the end of the troubled drive, at the edge of Home Plate (Figure 33). The image showed the fine stratigraphic layers at the edge of Home Plate stretching off into the distance, which those geologists focused on rock morphology would soon see as a tantalising clue as to Home Plate’s formation. The Principal Investigator continued:

This is one of the most amazing images of cross bedding we’ve ever seen on this Rover! [The Chair] gets it but if [his colleague, a geomorphologist] were on the line he’d be jumping up and down. This is one of the more important Pancams we’re gonna take and it’s gonna be splayed across the page of some journal or scientific magazine and it was completely fortuitous, we didn’t go looking for it… Exploration is like that.65

The miscommunication didn’t result in catastrophe. The Rover was not lost or broken, and the day’s activities were not wasted. Team members laughed as they signed off, promising to renew their commitment to work more closely together and to more clearly articulate their goals even as they joked about their mistake. And the Pancam panorama that was acquired as a result was indeed displayed in a scientific journal as supporting evidence for Home Plate’s hydrothermal origin.66 The premature move to the top of Home Plate was recast as a happy accident, while the use of local resources such as an appeal to listening and role-following assured the team’s

65 Personal Conversation, March 31 2007.
66 See Lewis et al. (2008).
continued “happiness” and orderly interactions. Exploration on the Mars Rover Mission, as the PI put it, “is like that.”

**Conclusion**

Chair (PI): Hey, hey guys, when you get a chance to look at [this image] of Cape Verde, it is just stunning. It is absolutely stunning.

Background: “Whoop!” “Oh my gosh!” “Ahh!”

Pancam PUL: I'm surprised we could get a color panorama that quickly…

Chair: Oh my goodness gracious golly gumbo this is great.

Pancam PUL: Yeah, yeah, I can't believe it, we're there.

Chair: Yeah, yeah it's just--

PUL: You know what I mean, I think we can declare victory.

Chair: Yeah, yeah, we made it. That was, that was a beautiful, beautiful job yesterday by everybody, just spectacular.67

The room at Cornell is crowded and the mood in the SOWG is jubilant: *Opportunity* has just arrived at Duck Bay on the edge of Victoria Crater after a year-long trek through the Meridiani dunes. As the SOWG Chair pulls up image after image of the closest promontories, Cape Verde and Cabo Frio, the team on the teleconference line chatters excitedly about what they see, what features are geologically exciting, where they might drive, take pictures and deploy the IDD next.

The view from Duck Bay (Figure 34) is not only dramatic, it is also the culmination of a detailed series of plans and negotiations. It took thousands of images to produce this single view – not only the individual frames that make up the panorama, but a digital trail of images that were displayed, annotated, dissected,

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planned, disputed, and ultimately agreed upon. The Duck Bay panorama, like the vast majority of images on the mission, was first elaborated from a map view of the crater, was then proposed as an observation, calculated and accounted for, was approached through a drive and finally requested as a navcam mosaic before being used to target filtered Panoramic camera observations. And in addition to recording these activities around a multitude of contributing images, the image is also testimony to a complex achievement of group consensus produced through adherence to ritual interaction. After all, at the end of the previous SOWG, the Chair was required as usual to call on every representative in the virtual room to ensure that each observation had their support. Only when a chorus of “yeses” and “I’m happy’s” ensued from Science Theme Group leaders to PUL’s to the Mission Manager could the request for these images be coded and sent to the Rover. Only then could they be downloaded to the “oohs” and “ahs” of the team, and displayed in color at a NASA press conference a few days later. And only then could these pictures begin to circulate among the team as the subject of further discussions and analysis in order to decide what to do next.

The usual understanding of the popular expression – a picture is worth a thousand words – is misleading. Pictures do not speak volumes for themselves, but as they must be planned, negotiated, annotated, discussed, transformed, and spoken for, we might say that thousands of words go into crafting them. Rover images are the product of daily negotiations and interactions, scripted and improvised, between this group of distributed scientists and engineers. From the ground up, images are drawn
as records of this ritual achievement as they are requested, accounted-for and obtained. They may also serve as a platform for future accountings, as the mission builds daily and iteratively upon past observations and experiences. But further, each image is a record of an SOWG meeting in which the observation was collectively approved by the MER team, each of whom declared their solidarity before the commands to take the picture were coded and uploaded to the Rover. Images are thus both the product and the currency of this observational accounting embedded within this organizational structure, the performance of its rituals and its associated consensus structure. How Rover images are drawn as from the beginning is bound up in their immediate, situated purpose as well as in the interactions of the MER team.
Assembled on a teleconference line for their weekly End of Sol meeting, the conversation among MER scientists becomes particularly animated when they turn to a picture of their Rover’s location taken by the high-resolution camera in orbit on the Mars Reconnaissance Orbiter (Hi-RISE). The scientists are trying to agree about how to drive Spirit to the southern edge of Home Plate as quickly as possible so that they can, from there, move on to a location where it will be safe to spend the next winter and from whence they can access an intriguing site to the south, Von Braun. One scientist, a member of Spirit’s Long Term Planning (LTP) group, opens the conversation by directing his colleagues to the presentation made by another of the LTP leads: this is an orbital image of Home Plate, drawn upon using arrows, circles and lines generated in PowerPoint in order to demonstrate a multiple-stage approach to exploring Home Plate. This scientist hopes that by looking at the image together it will “mak[e] sure we have agreement with the LTP and SOWG chairs,” and allow them to point out the locations “where there might be some controversy” about how best to get there. “I hope there’s no controversy,” replies another LTP lead pointedly, “we really want to get to the southwest corner of Home Plate as soon as possible.”

Having outlined the dual goals of a strategy for Spirit and controversy-free discussion, the scientist presents “a chart that tries to carefully map out the drive times” and marks on the orbital image how long it will take to get from point to point to arrive at their goal location. The drive times will be important for elaborating “what would be a reasonable set of science objectives that could be accomplished reasonably within a twenty-sol block” around the necessary drive sols. Identifying what is
“reasonable” involves balancing scientific goals with operational constraints such as drive times, power, and Spirit’s capacity to manage slopes and soils with its broken wheel. Another scientist on the line confirms that the Rover Planners are engaged in visual analysis of the orbital and Rover-based images to “look at the evidence and see what we’re up against” in terms of generating driving projections; the engineers will report back to the scientists as soon as this task is complete.

Turning to what science they want to do along the way, team members recommend Pancam images, MiniTES observations and APXS measurements; another advocates a less pressed-for-time approach as “a defensible objective from the point of view of field geology”; and a third scientist wants to know “what happens if we get there sooner or get there later?” At the end of the conversation, having compiled a list of science requests that could be accomplished during the drive and avoided controversial encounters and are therefore considered “reasonable,” one of the LTP leads refers to the orbital image on screen and requests of his colleagues, “I would just suggest that we annotate this diagram in some way … to capture what you’re saying.”

The result of this discussion of images is more images: drawn on, marked up, colored in, then presented at SOWG meetings in the routine LTP report and circulated online among the team.

Knorr-Cetina and Amman (1990) have analyzed collective image interpretation and sense-making conversation in the laboratory to demonstrate “image analyzing shop talk” and enhancement techniques required to “fix visual evidence” in autoradiographs. Rudwick (1976) has pointed to the importance of “visual languages” in geology and other sciences to depict objects of analytical interest to one’s colleagues in the context of establishing disciplinary methods and objectives. In this chapter I focus on two related aspects of the combination of talk-about-images and

\[1\] End of Sol meeting, September 19, 2007.
techniques of visual annotation as they are practiced on the Mars Exploration Rover Mission. First, I show how annotating digital photographs reveals a technique of visual parsing, isolating relevant features and drawing attention to them to develop, capture and reproduce local visual knowledge. Thus annotations present an interpretation of Mars, drawn onto the images in question in another variation of drawing as. I then show how these annotated images record moments of collective agreement in the ongoing planning of Martian operations, resolving local controversies and reflecting and projecting the team’s politics of consensus with its associated norms and interactional practices. Thus not only do annotated images reveal a process of visual knowledge-making: they record the team’s politics of knowledge-making as well.

**Visual Parsing And Recording Interpretations**

Before demonstrating how annotations present particular interpretations of Mars I wish to briefly explain what the hypotheses that inspire these interpretations are about: that is, what scientific questions the Athena Science Team hoped to answer with their Rovers at Home Plate and at Victoria Crater. One area of interest is a study of each area’s stratigraphy. As craters carve out a deep hole in what is otherwise bedrock, geologists find them particularly exciting as opportunities to examine which layers of rock are available to viewing. Many elements are of importance here, such as distinguishing layers from each other by locating their “contacts”, determining the depth and range of each layer to say something about how many years it took to develop, and examining the changes of elemental abundances these layers to say something about the environment in which they were deposited. Geomorphologists are also interested in discerning if there is any visible direction of rock formation, evidenced by lines and striations in the rock, as this can also give clues as to deposition. Such analyses form the crux of the investigations at Victoria Crater, the
deepest crater *Opportunity* visted to date, and require much high resolution Pancam imaging. These images are usually taken at particular times of day to take advantage of lighting conditions that produce slight shadows between layers: scientists analyze the geometrical properties of these shadows to make claims about the size and shape of the layer components. The spectrometers on *Opportunity* have revealed that most rocks on Meridiani Planum have similar geochemistry, so they are therefore often deployed in close analyses of individual crater layers, rocks that could be crater ejecta (such as Cercedilla), and meteorites under study strewn around the crater’s rim.

Stratigraphy is also important to an analysis of Home Plate, an odd-looking plateau on the surface of the ancient and deep Gusev crater which betrays a bowl-like curvature. Here the discernment of different layered units is examined not to explore the history of the planet’s formation, but to say something more local. The layering at Home Plate could be due to its former activity as a hotspring, which would have laid down chemically-rich layers of rock in a geologically short period of time. This would be an exciting claim, as geothermal hotspots on Earth are often teeming with microorganisms. To nail down whether or not Home Plate was once a hotspring and if so, what kind of aqueous environment it was and whether or not it could have supported life, MER scientists must be able to describe the chemistry of its rocks and the extent and complexity of this chemical layering. Close examination of images of these rocks and layers can also help to determine the depositional environment that would cause their exhibited morphology. The entire suite of Athena science instruments is regularly deployed in order to build up evidence for these claims: as the PI often puts it, this constitutes “hitting Mars with everything we’ve got.”
Drawing and other image work has been central to the geological sciences since their inception in the late eighteenth and early nineteenth centuries, as Martin Rudwick has documented. Indeed, Human Factors researchers who studied the MER team during the Primary Mission phase, when they were collocated at JPL, were surprised to witness Athena scientists printing out images and drawing on them, and therefore provided the scientists with a long table upon which they could lay printouts of recently acquired images and gather around them to discuss their interpretations.\(^2\)

But, as mentioned in Chapter Four, because the MER team is now remotely located and meetings happen largely by teleconference, observations have to be articulated in order to be shared. A kind of visual parsing therefore takes place, a practice analogous to that of grammatical parsing\(^3\) in which discrete elements of an image are identified and analyzed within the image frame, and voiced over the teleconference line. Because all team members on the line may see a copy of the same file posted to a document sharing site but cannot always see changes made to that file in real time, parsing requires some complicated verbal work to enlist other viewers to ‘see the same things’ in the image. Team members refer to familiar shapes -- in one meeting a scientist claimed, “You can see it’s almost like a mini donut just to the left of the target”\(^4\) -- or to structures within the image, such as rocks or shadows, as in this conversation about Figure 35:

\(^2\) I am grateful to conversations with NASA Ames Research Center ethnographers Roxana Wales (now at Google) and Chin Seah for a discussion of how scientists worked with images during the Operational Readiness Tests and Primary Mission.

\(^3\) Parsing means to break sentences down into discrete elements and analyze each word as to its role in the sentence, i.e. is it an article, a verb, what tense, etc.

I find it most convenient to use the shadow as a guide, so starting from the right side of the shadow there’s a place where there’s kind of two notches in the left of the shadow and then another notch to the left of that…\(^5\)

Similarly, when clustered around a shared videoconference display in which one user alone has control of the image, others may direct their attention through reference to their mouse pointer: such as, “The target is literally just a dark chunk off the left of your arrow there,”\(^6\) or, “The target is about ten meters away from this if you see my pointer,”\(^7\) or even, when directing someone else’s pointer: “The second possibility would be that there, stop moving [your cursor], up at the top, no, to the left … There.”\(^8\) These statements orient many disparate viewers within the same image, using features such as “the dark chunk,” “a mini donut,” pointers, or also, frequently,

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\(^6\) _Spirit_ SOWG Sol 1063 December 27 2006

\(^7\) _Spirit_ SOWG Sol 1094 January 30, 2007.

\(^8\) _Opportunity_ SOWG Sol 931-932 September 5 2006.
the o’clock system or azimuth degrees. Shadows and cracks, which may themselves be the object of scientific interest, are also used as “guides” in this manner.

But simply directing a colleague’s attention to an element in the scene is not enough: one must also indicate an analytical reason why this object in the scene ought to be noticed or considered salient. For example, in this case, a scientist indicates that his eyes see a geological unit, inviting others to see that part of the image as the same thing by drawing upon the image with “a dashed yellow line”:

[This slide] shows the Sol 1002 Navcam, a pair of Navcams put together, and I’ve noted in a dashed yellow line the location where at least my eyes see this thin laminating unit that is one of the targets.9

The scientist here uses dashed lines to indicate where “my eyes at least see” a stratigraphic layer of interest at the edge of Victoria Crater so that the vision can be shared, inspiring the rest of the team to see the area as a layer as well; the image in Figure 36 is similarly engaged for a possibly identified section at Home Plate. These annotations can also be used to share a sense of drive direction and possible next sites of scientific analysis. Similarly, another scientist uses degrees and dots to “encode a suggestion” into the image, demarcating noteworthy features:

Three sort of suggestions that are encoded into this image are, one where we drive, and I put a little blue dot there that is out about 145 degrees in the orientation of this image … also there are two sets of features there that have been suggested from Pancamming, one is the far wall and there are also some rather interesting near field surface textures there.10

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In both cases, these scientists use annotations on the digital image file -- drawing lines and dots onto them -- to record their interpretation of the image related to driving or morphological features. Such interpretations are not even limited to a single image at hand, but can serve to tie images together as depicting the same type of thing. For example, one scientist, Bob, presented one of his colorful images of the rim of Victoria Crater at the weekly End of Sol meeting, drawing the team’s attention to what he identified as distinct layers using Greek lettering:

I was just looking through some of the recent color images we have of Cape Saint Vincent and noticed something interesting … I labeled them the alpha beta and gamma layers… . I wondered if anyone else has noticed this?\textsuperscript{11}

\textsuperscript{11} End of Sol Meeting, April 4 2007.
Annotating these units with Greek letters adds two layers of interpretation. On the one hand, it distinguishes the units from each other, and from other features visible in the image. But on the other hand, these letters correspond to three similarly-labeled colored units found at a previous crater that *Opportunity* examined before arriving at Victoria (Figure 37). Bob thus visually demonstrates through cross-referenced annotations and image talk that these units are *the same type of thing* and sets up a *seeing as* experience at Victoria to support a coordinated analysis of the crater’s layered units.

This brief discussion should serve to indicate that both talk about and drawing onto images constitute important image-related work on the mission. On the one hand, annotations provide a kind of visual parsing that directs a community of observers to focus on a particular aspect of an image. On the other, it can be used to inscribe the kind of visual coding practices articulated by Goodwin (1994) and management of analytical graphic space (Lynch, 1990) into the image itself. Annotations thus function as a *drawing as* practice that directs collective attention and encourages others to *see*...
that object as the same kind of thing that the author suggests: a laminating unit or related stratigraphic section. Thus an interpretation is written onto the image in the form of annotations, as writing on images, drawing on them, drawing out relevant elements of the scene, inscribes an analysis onto the alien landscape. Such images thus provide an interesting case of drawing as, and the analyst may trace along with the scientist what is known about the region through their annotations. But it is worth noting that this epistemological work does not occur in a vacuum. I turn now to a discussion of how annotations are put to use in the scientific and strategic decision-making contexts of the mission.

“Building Your Geology Around You”

A powerful example of a technique that involves drawing interpretations onto images are geological maps. As already mentioned, Mars Rover scientists are by and large not astronomers, but planetary geologists with a heritage in the practices of terrestrial geology. This heritage extends to common terrestrial mapping techniques that imprint the geologists’ interpretations of a region onto that space by coloring on a map. Taking a photograph from the air or from the ground, the geologist will synthesize observations of those locations, interpret these observations, and then color in the image in various shades to represent different geological units. Not only do these colorations record and present scientists’ interpretations of the region; they also aim to present or facilitate the development of a coherent story about the geological history of the region.

First developed on Earth as a technique of image analysis, geological mapping has since been applied to planetary bodies across the solar system. The technique essentially involves close visual inspection of a site, perhaps through fieldwork or perhaps through aerial surveillance, and on top of a photograph of that area, tracing out the zones, rocks, or other characteristics that have different geological
characteristics. For example, such a map could identify categories like “regolith” or “contacts” between two different geological units. Beyond simply identifying areas, another MER scientist impressed upon me, a geological map must “tell a cohesive story” about that region. Taken together, the identification of different units or rocks should enable a geologist to identify the processes or periods of deposition -- for example, of each rock layer -- to build up a narrative about the history of the area under scrutiny. Thus geological maps are excellent examples of image annotations as they inscribe scientists’ judgments about classes and categories of objects or hypotheses about that region’s geological history directly onto the image of the region.\textsuperscript{12}

Joseph, an Athena Science Team member, regularly produces geological maps of the region around \textit{Spirit} (Figure 38). As Joseph put it, the geological map shows “a sort of x-ray vision version of the landscape in which everything is colored according to your hypothesis.”\textsuperscript{13} As he presented one such geological map at a Team Meeting, he went through all the steps of visual parsing, identifying features verbally and through annotations, referring to false color and other observations that identified units as distinct and/or related, then coloring regions in over top of the base image. These verbal and visual moves ensured not only that his colleagues could identify the same features in the region, but also that they would see them as the kinds of things he saw them as, and grasp the story he was trying to tell about the region. The parsed landscape is presented as a defacto object, and natural classes and categories are revealed.

\textsuperscript{12} The classic text on geological mapping in planetary astronomy is Greeley and Baston, 1990. Extending their terrestrial techniques and authority to other planetary bodies, the US Geological Survey now produces geological maps for many other regions in the solar system. I am grateful to conversations with Jeff Moore, Don Wilhelms, Ken Tanaka, and Larry Crumpler on the topic of geological maps.

\textsuperscript{13} Team meeting July 7, 2007.
“Coloring according to your hypothesis” can also serve an ongoing purpose as grounding for active fieldwork in a region, enabling scientists to keep track of hypotheses as they go along. In fact, geologists are often taught to keep notebooks of evolving hypotheses about the region they wish to map as they conduct their fieldwork. Joseph called these “sketch maps;” presenting one to his team-mates he was clear about the iterative relationship between fieldwork and practices of drawing:
The idea is that the sketch map is something you sketch out in your field notes as you’re working along, you’re mapping and modifying it as you’re actually doing it, and you update your hypotheses… presenting to yourself hypotheses about what you’re seeing. … A field map is a step in that process as you map out what you think you’re seeing… [it’s] a field-based best estimate of geologic units at any given time … putting [your interpretations] into the base map and then building your geology around you.¹⁴

As the relevant classes of objects develop through iterative observations, scientists develop and record a more global scene in their local environs on in geological map, alongside a way of seeing that impresses itself on the field. As it is represented, it is re-observed in the field as the mission continues: recall here the scientist who labeled layers of the crater to relate them to a previous observation.

An implication of this use of annotations is the uptake of a representational convention as an object proxy. As a particular color comes to identify a particular geological aspect, such as geochemical properties or a stratigraphic section, new objects begin to be referred to by their false color. For example, when searching for a piece of ejecta accessible to the Rover on the rim of Victoria crater, Ben Quinn said, “we want something big and dark purple.” He thus requested Pancam images in that day’s plan, using particular filters that would allow him to locate such material because “what we wanna use this [image] for is to just be able to pick out the dark purple and reds.”¹⁵ Nothing on Mars is purple to the human eye: what Ben is referring to is purple in a conventionalised false color algorithm that emphasizes a rock property that he wants to examine further. The result of this search was the Rover’s approach to the rock target Cercedilla, and Ben’s analytical work discussed in Chapter Two.


Similarly, crater layers become identified as alpha, beta and gamma, referring back to the previous scientist’s visual claims, and potential drive surfaces are referred to as “red” or “green” if they can be driven upon or not. This metonymy here links a representational convention to its object, enabling it to be taken as that object, such that the annotation or other identification becomes not just the marker but also the inherent characteristic of a class of objects.

But singular visions must be approved by the entire team before they can be accepted as factual interpretations. Thus annotated images that propose an interpretation of the Martian surface can become of heightened importance when an interpretation is held up to scrutiny. For example, at an End of Sol meeting Stewart, a scientist who specializes in geomorphology and stratification displayed to his colleagues a newly-downlinked, high-resolution, black and white (single filter) Pancam image of a cliff face in Victoria Crater, annotated with lines to demarcate what he distinguished as different units in the cliff. He proceeded to parse the image verbally for his colleagues to direct their attention to the lines traced across the illustration (Figure 39):

These are tall cliffs, we’re probably getting ten to twenty meters of exposure on the cliff, and in this view of the west face of Cape Verde we can see what looks like a massive unit overlain by the breccia of the [crater’s] ejecta blanket, and then underlain by something that looks thin bedded and quite particulate. And then if you stretch [i.e. increase contrast on] that image what you can see is again that there is a well-defined thin bedded facies and one of the questions we ask is … can you see that, and so far we don’t know, we don’t have data for the outcrop yet…16

16 End of Sol Meeting November 29 2006.
Figure 39 Two R2 Pancam frames stitched together to show the promontory at Victoria Crater (Cape Verde) under discussion. Annotations unavailable. Opportunity Sol 973 976 & 977. Courtesy NASA/JPL/Cornell.
Using visual and verbal tools this scientist draws the Martian terrain according to his hypothesis to present to his colleagues. He first employs the geological standard of drawing lines across orbital or ground images to demarcate different units laid down through different processes through the ages, and labels each of these strata with their geological name (breccia, thin-bedded facies) to generate a narrative about the crater’s formation. Joseph called this kind of drawing “a very useful process because otherwise you have no way of knowing where this [geological] contact is in this image, but now [i.e. once it is annotated] we know where it is.” Putting the annotation before the image itself thus reveals hidden features in the landscape; the lines on the image then direct the MER team members’ attention to these and enable them to see them, too, as the units this scientist has identified.

Simply presenting an annotated image does not mean that the image is now closed to interpretation, however. At the same meeting, another scientist who specialized in geomorphology, William, interrupted his colleague to challenge his annotations:

The way this slide has always been labeled has been massive above, massive below and then thin bedded facies. But you gotta keep in mind that this was shot from a considerable distance and the resolution for a lot of our layering was really on that scale. So what I really wonder is if what you labeled as massive is really massive, and that if we had a vantage point that was closer we wouldn't see that there was some finer scale bedding in that stuff … I think that if you look at the images of the other side of Cape Verde … I think what you’ll see is that in fact … at more or less the same stratigraphic level of what you labeled as massive, there is some layering visible. We got two things working against us here: one is the resolution and the other is that it’s in shadow. And I
really question the massive nature of that *vis a vis* what we've seen other places … my suspicion is that there’s a lot of fine layering that you simply can’t see.\textsuperscript{17}

Note that Stewart tries, using words and an annotated image, to articulate what can be seen, while his challenger focuses on what cannot be seen to argue that such markings are premature. However, consistent with consensus-building and “keeping the team happy,” William does not direct his challenge against his colleague’s expertise. He uses phrases like “my suspicion” and “what I really wonder” to position his interruption as polite, disinterested discussion, and expressions like “things working against us” to attribute his colleague’s potential misinterpretation to Martian conditions and insufficient information. He also blames poor lighting conditions, poor resolution, and conflicting data as compromising the ability to safely make the visual claims his colleague submits.

To resolve this disagreement, both scientists planned an extensive image campaign that could address these shortcomings and permit better identification of the characteristics of this cliff face. The team’s stratigraphic geomorphologists and their graduate students planned several suites of images over the coming year, imaging at specific times of day to get the best lighting and shadowing conditions for photogeology, planning Pancam images in the highest resolution possible, and shooting photographs of many different cliffs around Victoria Crater to see if these layers were visible with consistency around the entire crater. A year later, *Opportunity* even drove into Victoria Crater in order to get even closer images of the cliff face and to place the IDD on these rock layers to more precisely characterize them. Again, like the example of circumnavigating Victoria Crater discussed in Chapter Four, controversy is resolved through an appeal to more, or better observations. But further, this example serves to note that annotations must be collectively discussed before they

\textsuperscript{17} End of Sol Meeting, November 29, 2006.
can be collectively adopted, and that these discussions may lead directly to a request for further imaging or other experiments from the Rovers on Mars.

_These Images Are Our Maps:_ Annotating For Operations

Placing these images into an operations context, annotations gain an additional layer of meaning: as William explained it to me, “these images are our maps.” Drawing onto images, or drawing out features from them for attention, helps to plan the Rover’s future path at each stop where images are taken. Such parsed visions of Martian terrain can then present paths for movement, points for interaction on Mars or blank spaces in the map to fill in.

Consider the following case, in which a scientist uses parsing and pointing to submit a proposed observation to his colleagues on the SOWG line. Gesturing with his mouse to locations circled on a shared navigation camera image, he not only postulates what these different elements might be, but also proposes a set of instrumental activities with the Rover’s IDD:

It isn't often that we have a chance to do this on Spirit but I'd like to go back to the last slide and solicit input from the SOWG about which of these two targets we'd like to approach …. it seems like the darker stuff is potentially more contaminated with sand and will be more difficult to get an IDD on … the lighter spot marked by the oval there is perhaps more likely to be able to use the RAT on … maybe if we start on the light stuff it it'll help us find a good place to do the dark stuff …

As discussed above, circling and gesturing enables others to see the “darker stuff” in this image as significant, and identifying “dark stuff” also provides a map and a name for interacting with the material. Also implicit in these identifications is a call to discussion about the validity of the scientist’s claims, and an open question as to

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what the Rover ought to do (i.e. drive or use an instrument) on these new and unusual features in the landscape. Considerations such as power and bits will play into the resulting observations, as discussed in the previous chapter, but the image here takes on another valence as a method of conscripting this team members’ fellow scientists to assent to an operation.

This kind of activity is regularly seen when deciding upon targets for interaction. Because the Rovers’ activity planning software, *Maestro*, did not originally permit sharing or storing targets locations, team members turned to tools at hand such as PowerPoint and Photoshop to place arrows, circles, or colored dots onto images to locate their preferred target locations. They then circulated a screen shot among the team to project and record the placement of an instrument or drive path. In fact, instrument operators regularly demand screenshots from scientists during planning meetings so that they know where to place the requested observations. In this exchange a scientist and an instrument operator use a red circle to communicate the location of a proposed observation:

Scientist: “This looks like the red circled area that I sent out.”

PUL: “I put the target squarely on the red circle that you sent out.”

This is also regularly done by Rover Planners for the sake of communicating drive planning:

Here are some of the various path options, I sort of overlaid them on top here along with our science targets …

Such visions of the landscape can also present points for negotiation, as targets can be moved or traded like SOWG observations. For example, countering a proposed targeted observation by one of his colleagues, a scientist proposed:

I think what we might want to do is to take your [annotated] position three and your [annotated] red dot and shift both of them to the south a bit.\textsuperscript{20}

Placing red dots, instrument targets, or other annotations onto an image projects an interaction with the landscape, and later comes to record where those interactions took place (Figure 40).\textsuperscript{21} In these cases, annotating brings other team members into the same vision of the landscape as prepared for a particular kind of interaction.

![Figure 40 Red dots on a navcam image indicate MiniTES stares at those locations. Image Credit: NASA/JPL/ASU.](image)

\textsuperscript{20} End Of Sol Meeting, June 12 2007.

\textsuperscript{21} Red and blue dots placed on screenshots are regularly used in both planning and recording MiniTES operations. A scientist will send the MiniTES PUL a screen shot image with labeled red dots on a Navcam or Pancam image to show where to place the observation; within their software, the MiniTES PUL will closely approximate the location of the screen-shot dots with fresh blue dots in order to provide the pointings to the MiniTES on Mars; then a MiniTES worker will create a screenshot JPG of that operations software image to record the location of the targets for the sake of recording them in the Planetary Data System. I am grateful to interviews with several MiniTES PULs for their descriptions of this work.
On the one hand, these images are instrumental in communicating between the scientists who design the experiment and the engineers who implement it -- instrument operators use these marked up images to point their instruments. MER team members refer to the co-ordination of “red dots” and “screenshots” in order to be sure that both the scientist who requests an observation and the instrument operator who will deliver it are “on the same page.” Failure to implement an observation correctly is often ascribed to failed visual communication. For example, when a difficult maneuver on the target rock called Gerturde Weise failed, the SOWG Chair explained to me, “I would maintain that the reason we didn’t crush [the target] is because we didn’t have a good idea of where we were. … We couldn’t visualize it…”

But on the other hand, as Rover operations have to be assented to by the whole team; these images turn individually-selected targets placed on an image into a collective or shared vision of the landscape, conscripting viewers into that consensus moment over which observations to make. As activities, targets, and object identities are written onto an image and circulated; presented as arising naturally from the terrain, these images help to craft and sustain a shared vision of Mars among MER team members. Annotated images thus function to unite the team behind a particular vision of Mars and commitments to planned activities. This aspect of annotations is most evident when team members call such images into question. For example, when a particular annotated image (Figure 41) was presented in an SOWG meeting, one of the scientists spoke up to articulate his dissent:

Scientist: I'm still struggling to understand where we're going and what it is we want to achieve …

Chair: Okay let me recapitulate what we're trying to do … [we are taking more Pancam images to] characterize geometry, cross bed and textures along that

\[22\] Spirit SOWG Meeting Sol 1234-1236 June 22 2007.
east side of Home Plate. So I would say that we probably have one or two more locations in which to do that, and if we get a really good drive next time maybe it will be one …

Scientist: There was never any discussion of what kind of coverage are we trying to fill in … I saw two arrows drawn [on the image] and we arrived at a second arrow and I don't know if we're going to drive further.

Chair: The discussion all along was to drive back up to the location where the angled cross bedding is and fill in from there.

Scientist: I think those arrows were drawn pretty haphazardly without any discussion of where we are going and what we might be doing.

Chair: Whether we are at the first arrow or at the top of the second arrow, that's not the point … The point is we want to complete an imaging sequence somewhere between those two arrows.

![Annotated image presented at SOWG proposing Pancam observations](image)

**Figure 41** Annotated image presented at SOWG proposing Pancam observations. Used with permission.
Scientist: We already have Pancam coverage … How good do we need to do this? Why can't we do the imaging from this location and then … be done with it? …

Chair: Well, certainly we will be getting images from this location: the pre-drive remote sensing block is certainly supposed to be getting images of this section …

Scientist: I at least don't see that … . We can see looking back from that location on top that [Sol] 773 Pancam contains that outcrop that we're trying to drive to. We've already got [a picture of] it.

Chair: Yeah, but that’s too far away to do [analyze] the geometries …

Scientist: I guess this is where the minutiae of how much we need to do comes in … but in a tactical reality [i.e. of time and bit constraints] we can't do Pancam plus MiniTES and get good results …

In this case, the discussion centers around differing interpretations of an annotated map displayed in the Long Term Planning report, which presents an approximate location for this imaging campaign. But the discussion concerns a disagreement over the scientific objectives in the region around the Rover and how well those objectives have been satisfied. It is worth noting here that one of the interlocutors specializes in spectroscopy while the other is often more concerned with geomorphology: the two sides of geology that often come into conflict about what to observe and how to observe it. The Chair is interested in imaging this side of Home Plate to characterize its stratigraphy; the scientist is interested in collecting the spectral signatures of the silica-rich rocks in the area in question. Both are trying to say something about the depositional environment at Home Plate, but both also worry that the other’s observations would place their own in jeopardy due to the constraints of

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23 Spirit SOWG; date withheld.
Rover bits, time and power. The scientist therefore points out that the Rover already acquired Pancam at this location which the Chair counters as unsatisfactory due to distance, while the Chair describes the “minutiae” of thorough spectral readings on every rock in the area to support his interest in better imaging. Given this rift, the scientist points out that the annotated image meant to direct Rover activity in this area does not record a discussion in which consensus was reached over which observations to take. The Chair explains that there was indeed a discussion which the image is meant to capture, but the scientist accuses his colleague of annotating haphazardly -- that is, without the discussion that usually anchors such annotations.

The accusation of haphazard image annotations that do not present a consensus agreement or capture a discussion is of real concern to the SOWG Chair, as it could imply that they are not proceeding with the best information or in the interests of the whole group but are rather following another agenda. The Chair therefore attempts to clarify with reference to previous conversations: parsing the image anew, pointing to other observations in the plan, and explaining the scientific reasons for obtaining another set of images. Ultimately he conforms to the interactive procedures shared by the Rover team and articulated in the previous chapter to build agreement and attempt to accommodate the scientist’s observation requests as soon as possible.

This moment draws attention on the one hand to the explicit relationship between annotating and interacting: the image proposes a specific observation of the terrain and thus implies activity in its very construction. Its negotiation is thus a negotiation not about visual interpretation, but about what the Rover is about to do on Mars. But on the other hand, it reveals the social context of these images’ circulation and their valence in the local consensus culture. The image is not technically inaccurate in terms of how it interprets the Martian terrain: the scientist and his students who put it together spent a lot of time to ensure that the Pancam projections
over the orbital terrain were perfectly aligned and draped over the orbital projection. The accusation leveled here is that the image is invalid because it presents an imminent observation that captures what one scientist wants to do but not what all the scientists agreed to do.

As previously mentioned, MER scientists often resolve such conflicts by appealing to more imaging. If they cannot agree on what they are seeing together and what to do about it, then they at least agree that they need more information to make the path or interpretation clear. Thus they move quickly from challenging an individual’s interpretation to asking each other, “are there any observations we could make that would nail that down?” in order to diffuse disagreement before it can erupt into divisive controversy. This is even appealed to in advance with respect to very long-term planning; discussing the approach to Home Plate in a Science team Meeting, an LTP lead presented an annotated image that proposed moving only as far as a projected reconnaissance point, saying, “As soon as we get up there, we take an image so we know what we’re gonna do [when we arrive] at the top.”

Annotations And Long Term Planning

Aside from the day-to-day tactical operation of the Rover or scientific discussions, annotated images are also employed in long-term strategic planning. These are slightly different than the daily driving maps (detailed later in Chapter Six) that are constantly updated with the Rover’s position on a daily basis. Rather, these images anchor and record projective discussions about what the Rover ought to do over the next few weeks, and are produced in the strategic discussions called Long Term Planning, usually hosted at End of Sol meetings (Figure 42).

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24 End of Sol meeting, September 13, 2007.

Long Term Planning (LTP) leads regularly put orbital or ground-based maps in their presentations to facilitate conversations about strategic goals for the Rover. In one case, an LTP lead even insisted on it, saying: “It may be more useful for the discussion to keep the map up on the screen. … We need to converge towards some kind of priority …” Team members ask each other, “Which of these is our next objective? This, this or that?” They use this conversation around a suite of images to converge on a plan for the next round of activity.26 The result of these conversations is annotated images that capture the conversation using arrows, boxes, circles and question mark. These images are then imported into LTP lead presentations at the

26 Such conversations usually happen virtually although I was privileged to witness one in person, pictured in Figure 42.
opening of every SOWG meeting to make sure that everyone is still on the same page. Circulating thus, they become part of the local political economy of images that reinforces a consensual understanding of Mars and collective decision-making about where the Rover is, what it is looking at and what the team has decided to do about it.

As they evolve and change, these images present a trace of a moment when the team reached consensus in an ongoing conversation about their environment and interactions with it. As one LTP lead put it,

The approach we usually take and it’s been very fruitful, is that we have a strategic plan, and then as we approach [our target] that plan evolves … As we approach and acquire our remote sensing data it may be that … the strategic plan goes out the window.  

Representations of Mars are thus progressively modified and changed as the Rovers go along, reflecting evolving local conversations and the push and pull between tactical and strategic planning. The images are rarely viewed in series, but rather replace each other with new iterations every time a new decision is made or a Rover drives further. However, viewed in series with the benefit of hindsight, the analyst is presented with an evolving story of the mission, the crucial features at each moment faced in the terrain and the dividing decisions that needed to be overcome.

An example of this evolving story is the suite of many images of the Home Plate region that circulated between Winter Haven 2 and Winter Haven 3 (approximately, throughout the Earth year 2007; Figure 43). Using a single orbital image taken by the Hi-RISE orbital camera in October of 2006, scientists drew and redrew projected paths, targets, locations, and proposed phases of exploration. When one such set of annotations was presented at an End of Sol meeting in January 2007,  

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27 End of Sol meeting, January 24, 2007.
Figure 43 Three iterations of the Home Plate planning map, End of Sol June 27, July 18, and September 12, 2007. Courtesy David Des Marais.
the LTP lead called it a “Draft Strategic Plan… the emphasis here is on draft” but noted that it encompassed “a fair number of inputs from a fair number of perspectives.” He introduced the orbital image as “the background map, the base map of a lot of what we’re going to present here” and “the traverses that Spirit is doing now ….” Marking up sections of Home Plate as Phase I, Phase II and Phase III to capture “an approach to thinking about the exploration of Home Plate, sort of in time sequence,” the LTP lead drew several possible trajectories for the Rover: the preferred one moving “clockwise around home plate ending up sort of at six o’clock [the position, not the time]” and the backup “trying to get around Home Plate going up in the top in a counter clockwise position.” Already incorporating “a fair number of perspectives,” the image also generated a lively discussion. One scientist suggested that Spirit “just go around Home Plate, to heck with the top, and just get on with the West side,” while others debated the importance of investigating the Eastern or Northern rim. A slope map was projected alongside the annotated image to demonstrate “the source of our optimism” that the Rover could make it on top of Home Plate. Ultimately the scientists agreed to discuss specific objectives on a Science Theme Group level to best inform the observations Spirit would need to take at each step.28

Yet another iteration of this diagram was circulated following a discussion at the Team Meeting in February 2007 -- the same meeting at which Susan Lee reported her results with Tyrone, also in the Home Plate region. All agreed at this meeting that it was time to move quickly through the Eastern rim area of Home Plate and to aim for getting the Rover to the top of Home Plate within four weeks: this was recorded in annotations on the image. But yet another image was devised following the discovery of high Silica rocks in the area, which the team then nicknamed Silica Valley. This

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map outlined a revised geological sketch for the region as well as projected drive targets and directions, showing no intention of moving on to the top of Home Plate until Silica Valley was well characterized and explored. And yet another circulated image devised after the July 2007 Team Meeting captured the team’s desire to move away from Silica Valley and up onto Home Plate as quickly as possible. By the fall of 2007, the pressure to move the Rover as close to a Winter Haven position as possible prompted the End of Sol discussions that opened this chapter.

In each case, the annotated orbital maps become the subject for discussion as the team members try to articulate what they should do next, but they also reflect agreed-upon decisions for activities undertaken by the whole team. Indeed, following these kinds of decision-making discussions, LTP leads will often take the lead on putting together an annotated image to circulate that reflects the conversation. After an End of Sol, for example, an LTP lead put forward the suggestion “that we annotate this diagram … in some way to capture what you’re saying,” while in another case, following an intensive discussion about where to drive, a scientist requested an annotated image, asking the LTP lead in charge of the discussion, “Can you send out a description of this, just so we’re all on the same page?” Thus the case of many iterative images of Home Plate does not present a failed instance of annotations to project careful team planning, or of a failure of the team to stick to their plans; rather, each iteration of the image captures a consensus moment in the evolving story of the mission, and the team’s flexibility in planning around unexpected discoveries.

The importance of these images as records of ‘being on the same page’ is reflected in their use in LTP reports at the beginning of SOWG meetings. Annotated images that result from End of Sol LTP discussions are regularly included in these daily reports in order to remind MER team members of the interpretations of images.

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that they collectively attained and that should guide their daily work. The importance of using these images in LTP reports cannot be understated: they anchor the team at the beginning of the day and provide continuity between shifting mission personnel rosters or Rover locations, and bridge End of Sol with SOWG discussions, thus linking strategic (long term) and tactical (daily) decision making. And once they have been placed into an LTP report, these anchoring images usually stay in that report as a “handover” from the last meeting until they become outdated and must be replaced with a new image that records a new conversation or the new location of the Rover.

Indeed, so standard is this routine of placing images into the LTP reports to keep the team conscious of their evolving location, goals and decisions that a false image was once traced in LTP reports for up to a week before it was removed. This was an image of the Rover’s “odometer,” created by one of the team members using Photoshop to commemorate Opportunity achieving her 10-kilometer mark. The image used a black and white Pancam image of the Rover deck and placed a 4-digit odometer at 9,997 embedded in the solar panels, dangerously close to rolling over to 0,000. The Rovers were never equipped with odometers, but the image was imported into the LTP reports as a visual joke and remained there for several days. This image’s inclusion in the LTP reports was not due to the fact that certain team members were not familiar enough with the Rover’s technical plans to recognize the joke, but rather because the image was still such a powerful reminder of the team’s achievement to date that it deserved inclusion in the LTP reports alongside other annotated reminders of collective achievement.

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30 On the analysis of scientific humor see Mulkay and Gilbert (1982).
Long Term Planning conversations around images may become particularly heated when disagreements erupt over where the Rover should drive -- not necessarily tactically in terms of daily negotiation of driving parameters, but strategically in terms of longer term directions and goals. For example, when it was discovered that Spirit could not make it to the Southern edge of Home Plate and then towards a Winter Haven site to the South from there in time to survive the Martian Winter, the discussion shifted towards deciding whether to spend the winter on the South Promontory or the North slope of Home Plate. The South Promontory presented a new vista over what the scientists called “the Promised Land,” an area ear-marked for exploration to the South of Home Plate (Figure 44), while the North represented a return to a known area, as Spirit had spent a previous winter there (and, importantly, survived). An End of Sol discussion was especially designated by the P.I. “to get the issues on the table as to the scientific merit” of either site. Each scientist employed a variety of annotations, visual and verbal parsing in order to make their case for one or another winter haven site as presenting compelling questions for the Rover to answer in situ.
As one of many examples, Joseph presented an iteration of his “regional overview geo-sketch map,” like the one in Figure 38, to make a case for a move to the South Promontory region of Home Plate. Joseph’s annotations identified the “basic stratigraphy” of the region, including the location and characteristics of the units the Rover had already examined and where those could be identified in current imagery. Moving from what was known about the region to what was not known about the region, he then identified unusual layers and bedding directions in the few available images of the South, and pointing to the question marks on his geological map, he asked, “What is that Ridge on the South Edge of Home Plate?”

My interpretation, and this is the term ‘interpretation’ – that’s what basically you go to places to look at things to see if your interpretation is correct or not – is that the top of that ridge is in some parts covered in bits and snatches of the upper unit of Home plate. If so that would be the furthest from Home plate we've seen this upper Rogan unit, and of course knowing its orientation and the attitude of the bedding would be rather critical to understanding how Home Plate was basically formed in the first place, so there’s basically a crater formed and with a rim of Rogan-like material, or whether there’s a Rogan material draped over a crater that’s formed, there’s also the nature of that unconformity between the Rogan unit and the underlying material. So seeing that up close would be really useful to do.\(^\text{32}\)

\(^{31}\) In other published work I have commented on the “Here Be Dragons” approach to map interpretation: in that case, the London Underground Map. While in both cases the question marks represented areas that the map-maker had not yet visited, in the Tube case this was cause for potential confusion and perhaps caution, while in the Rover case it is an exciting example for potential exploration. See Vertesi (2008a).

\(^{32}\) End of Sol Meeting October 30 2007. Rogan is a target name for a rock representing a geological stratum of interest composing Home Plate. Consistent with other targets in the area it was named after a baseball player in the American Negro League to celebrate the United States’ Black History Month.
Joseph’s annotated image presented both what was known about Home Plate (using strokes of color overlaid on the image to identify regional units) and what was not known (using question marks). As he told it, the point of annotating these images according to his interpretation was to direct attention to unknown features and provide the context for observations that could test his hypothesis (according to which the landscape was colored) about the distribution of the Rogan unit at Home Plate. This hypothesis relied upon previous observations of this layer, believed to be deposited while the area was hydrothermically active. Pinpointing exactly where else such material could be found in the region would enable the geologists to make claims about the extent, activity and characteristics of the ancient hotspring.

Annotations related to the Rover’s ability to drive were also deployed in decision-making. A Rover Planner, Sarah, presented her perspective of the same region using the same images (i.e. the orbital image and Figure 44). Using verbal parsings, cursor moves, and red patches over areas that were considered impassible for the Rover, she presented a different interpretation:

The possibility of using [South Promontory] as a Winter Haven is significantly reduced in my opinion given this set of images … The drive up to the end of this outcrop is full of fairly large rocks although it looks flat. [dragging her cursor between red splotches on the image that indicate undriveable areas] There is a path through there that we think if we constrain things very tightly we could get to the edge of that outcrop … The problem occurs when we hit the outcrop… If you look at the close up imagery that we have now [displays an image colored in to show various degrees of slope], I can't really find any way that we could park and get any more than 22 degrees slope … From all the
imagery that I've seen … I can't demonstrate with any level of confidence that we actually can reach that parking place for the last segment of that drive.  

Unlike the scientist’s map, the areas in the image that the Rover Planner identified as ‘unknown’ were not calls to exploration, but were annotated as areas that must either be avoided or characterized more precisely with additional imaging before a safe drive could be guaranteed. Twenty-two degrees of slope would not be enough to sustain Spirit through the winter, and the path to that north-facing area would constitute difficult driving for the five-wheeled Rover. The two perspectives on the same region offered incommensurable conclusions about where the Rover should drive, one presented by a scientist and the other by an engineer. Thus the same set of images can support multiple interpretations, revealing as much about the roles and associated concerns of different team members as they do about the Martian landscape. The Rover Planner’s colleague Mark noted “of these options the North side of Home Plate is from the engineering perspective the better choice, but I understand this is not just an engineering decision.”

In this case, the PI suggested that the Science Team consider these findings preliminary, and continue with their presentations regarding the scientific rationales for moving South or North. Political implications were also deeply considered, as scientists on the line debated whether they should try to move South as it meant they could “continue to explore and not retreat to places we’ve been before” or whether such a move signaled a “transition from bold to suicidal.” But the Rover’s failing capabilities remained the primary consideration. “We’re talking about climbing ten to fifteen degree slopes as if we know we can do it,” Mark worried aloud as his scientist colleagues pored over slope maps “looking for … a way there [South].” “Obviously we don’t want to commit suicide,” a scientist assured him. “Whatever we decide as a

33 End of Sol meeting, October 30, 2007. The remaining quotes in this section are from the same meeting and the following one in November 2007.
project, we have to decide soon … [we have to] get moving fast,” warned a SOWG Chair. With so many interpretations and considerations flying around and pressure to “decide soon” mounting, a scientist finally gestured to the HiRISE image on which so many plans had been recorded and asked, “Can you annotate [this] in some way to indicate what’s interpreted and what’s real?”

After “an agonizing evaluation,” as the Mission Director called it, he and the Principal Investigator announced a decision to move North, much to several of the scientists’ dismay. It is worth noting that the scientists were split between going North and going South, and that the decision was recognized all along to have to come down to trafficability and to political factors (which will be discussed in more detail in Chapter Eight). Some of the scientists were dismayed at how the decision was made: without a consensus moment in which they were involved, but in a meeting between the mission directors and the Rover Planners with no further input from the science team. Here the all-important resource of Rover safety was brought in to force a decision where consensus was impossible. But even after the decision was announced -- usually when team members know that the discussion is closed -- a scientist spoke up to question it, asking how it had been decided and why, and suggesting that the scientists had been “railroaded” into a decision. What this scientist seemed to object to the most was not being heard in the final analysis and having to go along with a plan they had not agreed to. The team’s anxiety here was due to not being able to find common ground between scientific and engineering interpretations of an image, with implications for the Rover’s activities, and thus being able to continue with consensus derived from collective agreement. As another scientist resignedly put it in response to the decision based on Rover survival, “Reality sucks sometimes.”
Conclusion

This chapter has shown how visually parsing an image with annotations can present an aspect of an object to others for appraisal and interaction, and record a moment of agreement among mission team members. The map-like quality of these images becomes especially apparent in an operations context, where they may not only represent a scientific interpretation of Mars but may also hold direct implications for interaction with the surface, whether as maps showing where to (or not to) drive, geological maps indicating which question marks to characterize next, or screen shots depicting instrumental targets. Again, this kind of drawing as is central to mission operations; when an observation of a rock target failed because no screenshot was precirculated, I witnessed the SOWG Chair wonder aloud, “Why was I so confused [about that observation]?” When I asked if it was perhaps because there was no visual to accompany it, he vigorously agreed. “If there were a visual it would have been completely obvious,” he said.34

But drawing an image as a record of collective interpretation must also be placed in the context of consensus management on the team. As images are annotated by individuals, they are also submitted to and discussed by the team so that they come to represent a collective interpretation. They thus enable others to see the same features as the same kinds of things. Further, these annotations may transform an image into a collective map that is used to plan Rover operations on a daily basis, from which the code that tells the Rover how and where to drive, take a picture or another observation is directly derived. Thus these images do not simply record an epistemology of Mars. They also represent a social achievement within a micro-political system that ultimately informs that epistemology.

34 Opportunity SOWG Sols 1128-1129 March 27 2007.
It is analytically interesting here to witness images whose representational quality is based on how well it represents the group that constructs it, not only the object it purports to represent. While we tend to think of representations as standing between an observer and the world, they also represent an observer’s epistemological work in the world. Images on the Rover mission may be presented in order to propose a hypothesis or an interaction, but they must also be crafted in such a way as to generate a shared vision within the team. Thus annotating images is a practice through which MER scientists fashion themselves as a member of a collective that demands a particular moral and political conduct. The externalized retina (Lynch, 1990) that is produced through these images is simultaneously graphic, spatial and collective, belonging as it does to the Rover’s vision as it is interpreted and animated by a team.

While images may make a case for a specific observation or drive, these images generally function in a consensus-based context that is less adversarial than typical studies of visual rhetoric may document. It is one thing to trace an image’s “pattern of intention”, as Baxandall (1985) claims, when in an argument. Maria Lane’s work on the competing maps of Mars in the nineteenth century and my own work on maps of the moon in the seventeenth century both demonstrate how specific representational decisions function in the context of controversy to propose how an object like Mars or the moon should be understood (Lane 2005; Vertesi 2007). But while local disagreements may arise, the team uses images and talk about images to quell these disagreements before they can become heated. Questions of each others’ representations are framed as attempts to better represent collective decision-making. Delimiting controversy here may explain a relative uniformity of visual modes to discourage incommensurability, as well as the easily moved and removed digital markings painted over an image on Powerpoint.
Such methods and resources for interaction do not mean that the image has no politics: rather, *drawing as* here is about sharing a vision, recording and reminding team members of the importance of their collective management. The annotated images that persist in archived LTP reports, End of Sol presentations and Team Meeting slides not only direct the Rover and situate the team on Mars, they are also a reminder of moments of agreement achieved in End of Sol meetings, reminding the scientists of their belief that the collective and co-operative nature of their vision is what will guarantee the best possible decision-making and the best possible science on Mars. In the next chapter I follow up on this and other image work related to Rover driving to further elaborate this connection between *drawing as* and the cohesion of the Rover team.
On the other side of the planet from Home Plate, *Opportunity* has spent almost a whole Earth year exploring Victoria Crater. Proceeding clockwise around the rim, the Rover drives up to each ledge in turn and snaps high-resolution Pancam panoramas, producing what the team regularly heralds as “spectacular” images. The gaping vista of the crater with its rippled dunes at the centre opens beyond towering promontories and rocks cobbled at the rim like dragon scales. “Who would ever have thought we would ever take a picture of Mars that looks like that?” the PI gasps when yet another image of a cliff face, Cape Saint Vincent, comes down from the Rover. He points at the dusty rocks imaged by *Pathfinder* on the wall in the MER lab at Cornell. “Up until now, *that* was the most exciting view of Mars anyone had ever taken.”

The high resolution Pancam image of Cape Saint Vincent is indeed a far cry from the dusty, rock-strewn vistas witnessed by *Viking* or *Pathfinder*. But it is also an image that the team will use to inform their decision about how and where the Rover should drive around or even try to enter Victoria Crater. Several state borders away, in a Geographical Information Systems laboratory at a large public university, MER Participating Scientist Tom Chin’s graduate students and staff are analyzing Pancam images for this task. The images must be mined for topographical data in order to plan for *Opportunity*’s ingress into Victoria Crater. To do this, image processors rely on the Pancam’s stereo capability, and use the parallax between images taken by the right and left Pancam eyes to generate a three-dimensional sense of the terrain. But when characterizing an object as large as Victoria Crater, the team does not rely simply on

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1 Personal conversation, End of Sol meeting, March 28 2007.
the 30cm displacement between the two cameras: they also drive the Rover several feet, taking pictures from two displaced locations to produce what they call Long Baseline Stereo imaginge. As Tom explains,

Long Baseline Stereo is very important for this mission, because our Rover only has thirty centimeters of … base [between the Pancam’s eyes] … but [to analyze the crater] the base is too small. You can’t make a Rover that wide! You have a Rover drive five meters here and five meters there, you can get a longer base. When you look at two pictures with wider angle you get a higher degree of accuracy.

Over several months at Victoria, Opportunity takes pairs of high resolution Pancam images of the crater from each of the promontories, taking one image from one location and then driving five meters or so and taking the second image in the stereo pair from there (Figure 45a). These images are then numerically analyzed to generate a three-dimensional sense of the terrain. By selecting common points shared between the two images -- for example, a rock visible in both images -- and comparing the differences between these tie points due to the parallax caused by stereo vision, the computer can generate topographical a model of the surface of Mars. This data is used to build a terrain mesh, a Digital Elevation Map (DEM): a three-dimensional model of the surface of Mars upon which the same images can then be “draped” to give an immersive view of the Rover’s environment, like “skin on the texture map” (Figure 45b). As Li Bo, one of Chin’s students put it, “They cannot let the Rover go somewhere with no measured points.” After all, when driving the Rover, “we do not need this two dimensional, we need a 3-D view.” Pointing to the map he is producing of slopes around Duck Bay, he says, “This slope map will be very helpful for these operations guys.” But the decision about how and where to drive in to the crater will be made at the SOWG meeting the next morning, so Chin’s lab is buzzing to get the
Figure 45 Above (a) Planning image for Wide Baseline Stereo imaging at Victoria Crater. Image credit: Mapping/GIS lab, OSU. Below (b) Using tie points between Long Baseline Stereo images, Chin's laboratory generates a slope map and “drapes” an orbital colour image overtop to produce a three dimensional view used for planning Opportunity’s drive into Victoria Crater.
image processed in time. “Tomorrow at 9 o’clock it’s gonna be useful,” says Li Bo, “otherwise it’s not gonna be used.”

So far, this dissertation has analyzed various kinds of talk about Rover images and ways in which the raw digital data can be varyingly construed in order to reveal different details about Mars. This talk and image work has centered around such issues as planning observations, cleaning and calibrating data, and ‘doing science’ with digital images -- drawing Mars as composed of different materials, as dusty or clean, as trustworthy images. But this work with images of Duck Bay reveals yet another way of pixel-pushing Rover image data more common to the operations side of the Rover mission. The aspect that must be acquired and transmitted here with its various constraints and possibilities is not one that reveals spectral or morphological properties of Martian rocks and soil, but rather one that focuses on where and how the Rover can drive. Chin and Bo’s vision of the Martian surface, including the transformations of Rover image data that they project on the screen for the rest of the team to see, draws Mars as tangible, interactable terrain.

Although the Rover Planners, the specialist engineers who drive the Rover, are most skilled at seeing and drawing Mars in this way, such expertise is shared in various degrees and kinds by instrument operators and even, to a certain extent, scientists throughout the team. But this tangibility and interactability is tied to a particular kind of expertise about the Rover: it requires knowing how the Rover moves, navigates, and interacts with the terrain in order to inscribe these images with the point of view, possibilities and limitations of the robotic body. That is, Mars is drawn as tangible and interactable for the Rover. The team calls this, “Rover trafficability.” Thus each member of the team, in order to make decisions about how and where to drive or in order to program their instruments to conduct an observation, must learn how to see Mars from the Rover’s point of view. A Pancam PUL put it best:
“When you work with the team for a long time, you sort of learn to see like a Rover.”

This chapter will articulate what it means to “see like a Rover” in terms of the practical image interpretation activities, embodied vision, and teamwork this requires. I begin by discussing common ways drawing Mars as trafficable, demonstrating how learning to “see like a Rover” is a success statement related to the acquisition of a particular shared skill. “Seeing like a Rover” therefore recalls the kinds of seeing as practices that both inform and are informed by practices of drawing Mars as Rover-trafficable terrain. But as Rover operators and scientists learn to see like a Rover, they also learn to move, feel and be like a Rover, emphasizing an often deeply physical and even physiological connection to the Rovers on Mars. In the second section of this chapter I show how these complementary practices are part of visualizing Mars, indicating a central role for embodiment in image interpretation and interaction. Finally, I place these image-making, interpreting and embodied practices in the context of consensus operations to explore what work “seeing like a Rover” does for the team.

**Drawing Mars As Trafficable Terrain**

A new team member’s first introduction to learning to “see like a Rover” is usually exposure to Hazard Avoidance Camera (Hazcam) images. The four Hazcams, mounted under the Rover deck and looking down between the Rover’s front and back wheels, have a fish-eye lens that enables the robots to record in a much broader view of the horizon, up to 120 degrees (Figure 46a). Correcting a fish-eye distortion to a rectangular image frame is an easy accomplishment on most image processors, but rather than correct the optics to a human frame, scientists and engineers alike speak of acquiring the visual expertise of working with these images uncorrected, adapting

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2 Jude, personal conversation, September 2006.
their eyes to this way of viewing the Martian surface. In the course of my research, many scientists expressed to me different explanations of how one should approach a Hazcam image; one referred to a pre-flight photograph taken with the same lens (Figure 46b) that assisted him in learning “how to see” with the Hazcams:

For me, I need pictures like this [points to a Hazcam photo of people in a lab on Earth] to make the correction… this [points to a Hazcam image from Mars] sort of looks normal, but it’s being warped and distorted.

Should a Hazcam image be displayed in an SOWG or End of Sol meeting, scientists will often verbally remind their colleagues that they are looking at a Hazcam image and thus the optics are distorted: that the cameras are very close to the ground, and as MER scientist Pierre Lefebre often jokingly puts it, “objects in the mirror are closer than they appear.” But this reminder is not so much a caveat as it is an invocation of shared knowledge and tacit skill. Scientists share a (perhaps apocryphal) story about a reporter for a major newspaper who, upon seeing the Hazcam images posted online at the JPL website shortly after the Rover’s arrival, publicly commented that Mars had a sharper curvature than Earth. Thus developing and invoking others’
visual fluency with the Hazcams is a way of identifying a fellow team member who has a developing intuition for the Rover’s eye view of Mars.

This particular distortion enables the Rovers and their human team members to look out for driving hazards in the local environment. The Rovers are equipped with artificial intelligence to compare stereo Hazcam images and evaluate whether or not a rock in its path is too large to drive over; if so, the Rover can modify its course somewhat to avoid this hazard, overriding its instructions sent by its human operators. As they drive, the vehicles periodically take pictures and analyze them before moving ahead. As Mark, a Rover Planner, put it:

For one thing the Rover’s view of the world when driving is very much like your view of the world if you imagine yourself trying to make your way through a dark cluttered room with nothing but a flashbulb. So you can kind of take a picture in the world and you can get a sense of where there’s a safe path and you walk a little way along that safe path and you pop the flashbulb again … That's one of the ways in which the Rover sees the world when it's driving. Other times it just does this [he throws his hands in the air]: “Alright, I'm going to just go where you [Rover Planners] tell me.”

Just as the Rovers’ software actively looks out for hazardous elements of their terrain in order to safely execute driving instructions, a parallel sensitivity to the Martian terrain is adopted by Rover Planners, who are responsible for coding those instructions. These specialist engineers are particularly adept at identifying rocks, slippery soil, sand traps, and other potential obstacles in the images that return to them that would be likely to trip up a 5-foot tall, six-wheeled Rover out in the wilds of Mars.³ An important step in this analysis is the ability to see two-dimensional Pancam,

³ It is worth noting that this skill has changed somewhat since both Spirit and Opportunity broke their right front wheels. Now, Rover Planners are acutely aware of what would trip up a five-wheeled Rover, and have developed a deep physical sense of how Spirit as opposed to Opportunity would handle a particular terrain.
Navcam or Hazcam images in three dimensions. In order to do this, many Rover Planners put these images into stereo projections, called *anaglyphs*. They load two pictures of the same scene, one taken by the Right camera and the other taken by the Left camera, and combine them in an image processor to make a 3-D projection in which one image is colored red, the other is colored blue, and both are offset from each other by a certain degree consistent with stereo vision (Figure 47). Anaglyphs do not look like much when viewed on a screen, but once the scientist or engineer dons red-blue 3-D glasses, the scene acquires depth.

Figure 47 Stereo anaglyph of small crater with *Opportunity* Navcams. Note red and blue associated with stereo projection. Courtesy NASA/JPL-Caltech.

Anaglyphs are employed across the mission for different reasons: for example, scientists frequently use them to get a sense of the texture or the morphology of a rock or surface feature under examination. But engineers parse anaglyph images in very different ways. Mark explained the value of the three-dimensional view as one that
engaged his kinesthetic sense for the terrain, making elements “pop out” to get a “better sense of the size and slope”:

In 2D you can’t really get a sense of, is this a big ridge? … even when you get the numbers the numbers don't really tell the whole story … there's something to be said for engaging your own kinesthetic sense … . If you take a look at this in 3D, you can see how it now kinda pops out at you, how this terrain is kind of undulating … where I could see kinda that there was a ridge here [in 2D], this is now [in 3D] giving me a much better sense of the size of that ridge and the slope of that ridge, and you can get a sense of there’s terrain blocked behind the ridge so that you're not looking at something small but at something that’s big enough from your current perspective …

This language strongly recalls that of the scientist, like Ben or Susan, engaging in *drawing as* to make particular features “pop out” in false color. In this case, the aspect that needs to be acquired is one of extreme attention to obstacles: the Rover Planner must *see* Mars as strewn with potential obstacles that must be avoided. And as he verbally parsed the image with me, Mark pointed to rocks and dunes strewn across the field, “evaluating them as obstacles”: “these two here are obstacles, this one here is definitely an obstacle, this stuff here is probably okay although we should stay away from them with a five wheeled rover…” Parsing an image in this way, the Rover Planner not only demonstrates a kind of professional vision (Goodwin, 1994) in his attunement to driving hazards. He talks through how the Rover’s own artificial intelligence is also taught to examine a terrain, and an understanding of how the Rover would need to interact with the field and how to keep the vehicle safe. Visually parsing the terrain in this way and verbalizing what he can see, Mark demonstrates his ability to see like a Rover.

Seeing like a Rover means acquiring an aspect, a deep attunement to hazardous elements of the terrain: to this extent it is a kind of seeing as experience with related drawing as practices that place rocks and other drive hazards in the perceptual foreground. But it also requires the acquisition of the Rover’s frame of reference, how the Rover represents and visualizes Mars, much like learned familiarity with the Hazcam images. After all, the Pancam images are taken from only five feet off the ground, and from a stereo position 30 centimeters apart; this presents a difference to human stereo vision accomplished by a six foot tall human engineer whose two eyes are offset by only about 10 to 15 centimeters. Scientists and engineers alike continually remind themselves that ‘seeing like a Rover’ involves this important change in stereo vision. When I suggested putting Cercedilla into stereo to look at its morphology Ben insisted that because the rock was so close to the Rover, the anaglyph would be too wide-set for him to see anything, and Pancam operator Liz regularly puts her hands up to either side of her face to approximate the distance between the two Pancams when planning images of a close-by target (Figure 48). Thus Seeing as becomes “seeing like”: seeing from a different subject position, seeing from within the body of the Rover.

Just as seeing as is interlaced with drawing as -- practical activities of image construal that present a particular aspect of the Martian terrain to the viewer -- acquiring the aspect of seeing like a Rover is also facilitated, expressed and developed
by crafting views that display this point of view. For example, anaglyphs are routinely made by Microscopic Imager operators in order to present as detailed a textural view as possible at a close-up range. Unlike the other Rover cameras, there is only a single MI, and so stereo views generated by offset cameras are impossible. Instead, the camera takes a ‘stack’ of images by moving slowly towards the object that requires imaging, taking three, five or seven pictures along the way. Because the MI has a fixed focal length, zooming in by moving the camera closer means that the chances of getting at least one image with good focus is increased. But the stacks are also used to generate anaglyphs, as a photograph from each position generates a slightly different view of the target from a different depth that, when compiled, can give a sense of the object’s three-dimensionality. In order to be compiled, however, the computer must recognize common points between the image stacks so that the images can align correctly. Thus the MI operators spend several hours of their shift manually locating up to five “tie points” between images in an MI stack: that is, identifying the same region, sometimes even down to single pixels, that are shared between images (Figure 49a). One MI operator I observed explained how he picks points that he “can identify
pretty easily… points that are kind contrasty.” He thus looks for shadows, highlights, or unusual features in the image, starting in the upper right corner of the image and spiraling clockwise around the perimeter into the center and choosing up to five points in a single image; he then loads two other images from the same stack and must locate those five points in those images as well (Figure 49b). This work is time-consuming, visually taxing and sometimes mysterious, as once the tie points are manually selected the computer program will “go and crank for a few minutes or so” before generating the anaglyph. Thus the program is blackboxed and often finicky. When I asked him why one of the anaglyphs he made didn’t align very well, the operator shrugged. “I might have picked crummy points, or it might be Monday,” he offered.

Like the Microscopic Imager anaglyphs, Long Baseline Stereo image analysis also takes a considerable amount of work and specialist vision. In Tom Chin’s GIS lab, graduate students are hard at work identifying tie points between images, pointing to and coloring in matching rocks across stereo or other pictures by hand to identify them to the computer as ‘the same thing.’ One student, Ying, was busy tying points between orbital images and Rover images of Mars in order to generate maps of the Rover’s location: as she put it,

I’m doing it by hand, manually. I look at an image and judge whether it’s the same.5

Her colleague Yao, was tying points between two images of the same location taken by an Earth-based Rover, viewed in stereo. He described his project as,

First, generate anaglyphs [stereo], use experience to find identical rock… if you look at the same thing for many, many times you will see the same thing.6

5 Interview, Ying, June 26, 2007.
6 Interview, Yao, June 26, 2007.
This language again is reminiscent of the scientists’ characterization of their work with digital images, requiring looking, judging, using experience and looking at the same thing “for many, many times.” Yao stared intently at his screen, explaining to me as he clicked on bushes and rocks to identify them for the computer as the same object (Figure 50):

Figure 49 Above (a) Microscopic Imager anaglyph image. Courtesy NASA/JPL/USGS. Below (b) MI operator looks for tie points between three MI images in a stack to produce an anaglyph.
This bush is in this track and over here this bush is also in this track. And there, there is a black rock in front of the bush, and this image is looking backward so this black rock should be behind… In Mars data it’s very difficult to find the same points: the rock [he makes a fist to indicate the rock] is very small, and second it is very far away. I learned from [Li Bo] that some students had spent one day to find no points!\(^7\)

Work like Yao’s and Ying’s is an essential component to the digital work of drawing Mars as trafficable terrain, in order to “see like a Rover” and analyze the topography to prepare for a drive. The resulting images will prove crucial to deciding where and how Opportunity can safely descend into Victoria Crater.

While the Microscopic Imager anaglyphs and Pancam Wide Baseline Stereo observations require much in the way of human image interaction in order to produce stereo views, other engineers and scientists use software to automatically locate “tie

\(^7\) Interview, Yao, June 27, 2007.
points” between stereo images. But while entirely digitally effected, the steps in this process can again be cumbersome in terms of human manpower. Sometimes the software identifies tie-points incorrectly, requiring manual correction and cleaning of the image. For example, it is very difficult to teach the software to tell the difference between the Martian sky and the Martian ground. One image processor informed me that often “the software will find a tie-point in the sky,” but when trying to correct this with some kind of optimization program he realized that there was no predictable way to identify the horizon, as it was not always straight or even a regular color. A computer scientist on the mission was working on precisely this problem, and demonstrated for me his own program for producing 3-D views that began with the systematic removal of the Martian sky from his input image data (Figure 51). As with the examples from the scientific side of the mission, drawing as is just as much a question of circumscribing which features are salient and of interest as is it a question of drawing certain features and details out of the picture altogether.

Figure 51 Removing the sky from the image can avoid the computer error of seeking “tie points” in the sky.
On the one hand, DEM data can be used to create spectacular vision of Mars; draped with Approximate True Color Pancam or orbital images, highly specialized image processors use DEM to create dramatic “fly-through” movies that simulate soaring above the Rover landing sites or even Valles Marineris. While I have seen this work accomplished by scientists, it is also performed by engineers at JPL in facilities similar to those of a Hollywood studio where the processing lab equipment, techniques and even personnel overlap with the film industry. But on the other hand, DEM data is crucial for Rover mission operations. It is frequently imported directly into the Rover Planning software, presenting a virtual reality world in which operators have a sense not only of what it looks like around their Rover but also, importantly, the undulations of the terrain (Figure 52). Special versions of this software exist for those who operate the Pancams or other instruments; using DEM data, the computer can instantly color a patch of a Navcam image to show where the Rover can reach in order to place an instrument, or place a colored block over the Martian terrain to show where a Pancam

![Software used to plan Rover drives imports image-derived digital elevation data as a "terrain mesh" and overlays navcam images to create a virtual reality space for drive planning. Figure 3 in Maki et al (2005).](image)
image will eventually be taken. While I was restricted from witnessing first hand how users interact with this software, team members report that they use these tools regularly and rely upon them daily to model how and where the Rover can drive or place an instrument.

In addition to programming the Rover, image-derived topographical data are often used for the human side of decision-making. DEM maps can be color-coded to show which areas are safe for Rover wheels in order to make decisions about where and how the Rovers should drive. For example, working with image-derived slope data for Victoria crater Li Chen generated a color-coded slope map so that the team could analyze trafficability and plan a drive into Victoria (Figure 53). He explained:

This is the contour map to show people the [slope] … . This red color and this orange color it is not safe to drive.

Engineers also frequently combine DEM data, parsed stereo anaglyphs, and their own professional vision to create what are colloquially called lillypad maps. These images are created digitally and physically by drawing on existing images to create annotated representations of the terrain showing where it is safe for the Rover to drive and where it is optimal to soak up solar energy. Coloring a region in green and coloring hazardous or poorly lit areas in red, the Rover is said to “hop” from green patch to green patch like a frog in a lily pond. Lillypad maps are also sometimes used to show where the slope faces the sun, to show good spots to stop in order to soak up power. This technique proved so pervasive that it is built into Rover flight software routines: the Rover activity planning software also regularly produces lillypad or lillypad-esque visions of the surface that are captured in screen-shots and circulated among team members when planning a drive.
As team members learn to see like a Rover, becoming familiar with the Rover’s-eye view of Mars and developing an ability to parse it with respect to Rover trafficability, the judgments they make are captured or even extracted from image data to create new visualizations, which circulate, encode and represent and communicate these parsed terrains. Stereo image work such as DEM, Long Baseline, and even MI stacks permit seeing like a Rover, showing relevant details that permit decisions about Rover driving, operation and safety. Like the Galileo example in Chapter Two, these
images also encourage future visions of the terrain. *Seeing like a Rover* encourages drawing Mars as a Rover map, which again encourages *seeing like a Rover*.

There is also a direct relationship between how these images are parsed and represented, and subsequent decisions for driving in addition to standing as annotated records of decision-making discussed in the previous chapter. It is important to note here that the slope and DEM maps of Victoria crater generated from Pancam images in the GIS lab were credited by an SOWG Chair as instrumental in “nailing down the slopes and the ingress routes,” as upon examining the maps the team chose to change their opinion about where and how to enter the crater. Lilypad, hazcam, and anaglyph images are used to assess obstacles, slope and drive direction, and like such iconic images as the London Underground Map these images have appreciable effects on how an object is talked about, interacted with, and moved about in (Vertesi, 2008a). Indeed, this kind of pixel-pushing image work is precisely what allowed Sarah, in the previous chapter, to dismiss South Promontory as a Winter Haven in spite of compelling scientific reasons to travel there. Using stereo anaglyphs to make terrain features “pop out” in 3-D, Sarah could assert that “although it looks flat” the drive to the outcrop was “full of fairly large rocks.” Using Pancam stereo image data she showed a lilypad map to trace a possible path to the South Promontory, but then reviewed the underlying DEM data and judged that there were no slopes nearby that would give the correct angle for the Rover to soak up power-generating sunlight. Thus her conclusion: “From all the imagery that I've seen … I can't demonstrate with any level of confidence that we actually can reach that parking place for the last segment of that drive.” Seeing like a scientist, South Promontory was compelling; but seeing like a Rover, it was impassible.
“My Body Is Always The Rover’s Body”

The question of whether or not these visualizations really capture what it would be like to “see like a Rover” is not the subject of the present discussion. More interesting is how these acquired visual skills and representational conventions are discussed and explained as though they constitute a human acquisition of robotic characteristics. This skill is not only enacted through drawing and talk but is also physically performed through gesture and movement that writes the Rover onto the human body.

Recent work in Science and Technology Studies is beginning to explore the importance of the body to visualization, expanding on themes in the phenomenology of perception (Merleau-Ponty, 1962[1944]) to discuss how molecular biologists contort their bodies to get a feel for the shape of a protein (Myers, 2008) or how doctors practicing minimally invasive surgery speak as though they are embedded within the surgical site at the location of the camera (Prentice, 2005). Similarly, Rover team members take on attributes of their robotic proxies both as an essential part of their work and as explanatory narratives about their experiences on Earth. Seeing like a Rover quickly becomes feeling and being like a Rover, and possessing and enacting the embodied skills of seeing like a Rover contributes to an affective sense of intimacy with the robots as team members daily “look through their eyes” at the Martian surface.

This embodied interaction begins at the level of talk about the robotic body, ascribing human characteristics to the Rovers. While lacking a humanoid shape, various parts of the Rover are verbally related to human body parts and actions. For example, the Panoramic Cameras are regularly referred to as the Rovers’ “eyes,” the hazard cameras aimed at the wheels show “what’s under our feet,” while the Instrument Deployment Device (IDD) is “the arm” and its four instruments are
described as “fingers.” The Rovers “talk” to Earth via communication antennas, “sleep” at night, “wake up” and “take a nap” at certain times, “stare” or “look” at targets on the surface regularly throughout the day. These active verbs describe technical activities but also reinforce an experiential dimension of these processes consistent with human experience.

Consistent with studies of domestic robots like Roomba or AIBO (Friedman, 2003; Sung, 2007) the Rovers have quite different personalities, ascribed to their different experiences on Mars. Spirit is often described as the “Little Rover That Could” or “our blue-collar Rover,” while Opportunity is described as privileged: as one team member recounted,

Opportunity’s sort of the glamour girl, she went to Mars to find water and she sort of fell into a hole and opened her eyes and there’s evidence of water. And Spirit is a little more hard-working, a little more hard-nosed. She went all this way to find water and she got there and there’s no water, and she could have given up at that point but she’s not the kind of Rover to go three hundred million miles and then give up so … she gets to the Columbia Hills … the size of the Statue of Liberty… she’s only meant to be on flat terrain and she manages to figure out how to climb this hill and along the way finds the evidence she looked for … I love this Rover!^8

Spirit is also described as the “Problem Child”: many of her parts failed on initial testing on Earth, while on Mars she is subject to continual trials from dust storms to mountainous terrain to sand traps. In alternative accounts, team members ascribe personalities to the Rovers based on the shifting teams of scientists and engineers who animate them. Such accountings of the Rovers’ activities bring the robots to life as parallel yet distant members of the Mars Exploration Rover team

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^8 Interview, Rover Planner, February 15, 2007.
alongside their human co-workers. One MER team member, part of the Miami First Nations community, described to me that in the Algonquin language the Rovers have *animacy*, not so much a sense of agency as an inherent “life force”:

> It [animacy] essentially is an extension of us. Other things don’t have it. Cars don’t have it, trains don’t. It’s not a possessive language, it denotes what something *does*, not what it *is*.  

Ascribing human characteristics to machines and other inanimate objects has been well described in both psychology and in studies of human-robot interaction (see for example, DiSalvo, 2002; DiSalvo & Gemperie, 2003). But interestingly, here the projection does not only run one way, as the humans on the mission learn, imitate, and demonstrate what it is like to be a Rover on Mars. I have elsewhere called these practices *technomorphism*, drawing attention to the purposeful, practical activities and discourse that humans may perform in order to relate to a specific device.  

One aspect of this practice is a developing intuitive sensibility to what the Rover might see, think, or feel on a given day, usually related to specific activities that must be planned. For example, Panoramic Camera operators are highly attuned to the sun’s position on Mars throughout the day, attributing their heightened sense of light and shade to seeing with the Rover’s “eyes.” A Rock Abrasion Tool operator talked about his instrument as the Rover’s “sense of touch,” describing the output graphs of RAT drill intensity as descriptions of how the Rover “feels out the rock.” Mark confessed to me that, when planning a drive, “I have frequently tried to put myself in the Rover’s head and say, what do I know about the world…” He then elaborated by describing the differences between himself and the Rover:

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10 Vertesi (2008b). *Technomorphism* may also recall Caporeal’s *mechanomorphism* (1986), which refers to the philosophical position of the human-as-machine (a dominant metaphor in cognitive science and artificial intelligence).
…the Rover has senses that we don’t have … the Rover sees stuff that we
don’t see, it sees into wavelengths that we don’t see, it never really sees the
world in color but it can see parts of the spectrum that we can’t.\textsuperscript{11}

In enumerating these differences Mark describes how he must be differently
sensitive to Mars in order to interact with it through his Rover proxy, and how he must
even use himself as proxy for the Rover. He often used the word, “kinesthetic” to
describe his affinity for the Rovers, placing emphasis on his body as a site of Rover
experience. His colleague, Jordan, a Mission Manager, used another evocative
expression to relate sensitivity to the Rover’s own experience to a physical sense of
his own body:

You just have more of an intuition as to how, like, I don’t know if this is a good
example or not but you know as you get older you know how your body works
… you know you feel differently [today] as opposed to yesterday … Operating
the vehicle like after a while you get an idea of like, the Rover did this
yesterday so I know what it’s going to feel like and to be like tomorrow.\textsuperscript{12}

Enhancing this intuitive and embodied connection are a set of practices that,
taken together, become a kind of physical calculus for working through Rover motions
and activities on Mars from a distance. For example, team members regularly employ
a variety of paper tools at hand, usually paper, when planning operations. The Rover
Planner with an interest in kinesthesia once developed a set of paper tools that could
mimicked the degrees of force the Rover could use on Mars, so that his colleagues
could get a sense of what the Rover’s experience “felt like” in their own bodies. Ben
has a piece of paper cut out in the shape of a Pancam frame that he lays over his screen
to get a sense of what a proposed observation will capture, while Jude recalls how she

\textsuperscript{11} Interview, Mark, February 15, 2007.

\textsuperscript{12} Interview, Jordan, February 15, 2007.
and her PUL colleagues “used to put post-it notes on our foreheads so we could know how the [Pancam] frames would turn out” by imagining these squares projecting out from their foreheads into the imagined Martian world around them. Pancam operator Liz has been known to print out Hazcam pictures and place them around her screen so that she can get a better sense of where and how to plan a difficult observation when pointing the camera “between my [the Rover’s] feet.” (Figure 54)

As these latter examples suggest, such practices enact an elision between the human and the robotic body. Gestures also play a key role in this elision. When one scientist proposed a new maneuver in an SOWG meeting, another in the room used his wheelie chair to work through the move as it was being described; similarly, a Rover Planner confessed that he and his colleagues “used to talk about how the Rover was going to go by scooting around in our chairs, in part because we had a poor understanding about how the commands worked … .” When discussing Pancam observations operators and scientists alike put their hands up to either side of their face, as discussed above (Figure 48), to emulate the Rovers’ wide-set eyes. Team
members regularly manipulate their shoulders, elbows and wrists to mimic the robots’ range of motion, and when estimating their position they splay their arms out to either side to imitate solar panels and tilt their bodies to approximate the Rover’s pitch and yaw. Indeed, one of the most common gestures on the mission is that of using one’s own arm to demonstrate how the Rover deploys its IDD, colloquially called its “arm.” This is practiced across the mission by scientists and engineers alike whenever a move is discussed.

The use of the arm as an IDD is not primarily a communicative gesture, as it is performed regardless of whether or not anyone is actively watching the person making the gesture, who may not be visible on teleconference lines. However, it does communicate a kind of expertise, a demonstration of intuition and feel for the Rover. As one Rover Planner put it,

When we're training new Rover drivers we can really tell that they get it when you start talking about moves with the IDD and they start moving their own arm to kind of show you what they mean, and they say you know we're gonna swing this to the left and then move their elbow [moves his elbow to the left].

The elision between the human and the robot body can be so complete that many of the team members I interviewed expressed that their eyes have “become Pancam, or Navcam.” Another put it more succinctly: when seeing like a Rover, “I am the Rover. I am the Pancam.”

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14 Interview, MiniTES PUL, June 6, 2007.
15 Jude, personal conversation. The use of the pronoun “I” and the implied switch in subject position between a scientist and an object of scientific study has been documented by Ochs et al (1996). In their study of a physics laboratory, the team of linguistic anthropologists analyzed talk about particles, including a conversation in which a scientist speaks from the point of view of his particle in the phrase, “When I come down, I’m in the domain state.” A similar empathetic switch in subject positioning is clearly at work in the Rover team as members’ talk and gesture puts them into the Rovers’ positions on Mars. I am grateful to Charlotte Linde for this connection.
An empathetic sense of what it feels like to be a Rover, to see and move like a Rover, is an integral part of operating the vehicles. After all, acting out a Rover’s pitch, yaw and angle to the sun is important for estimating whether or not the Rover will project too much shadow into a prospective image, for example. This is how Liz articulates her activities when planning a Pancam image. In a complex association of speech and gesture, the latter indicated in italics in the quote below, she associates her body with the Rover’s, piece by piece:

My body by the way is always the Rover, so right here [touches chest] is the front of the Rover, my magnets are right here [touches base of neck], and my shoulders [touches shoulders] are the front of the solar panels and that's [leans forward, splays arms out behind to either side] the rest of it, so I have all kinds of things sticking up over here [gestures to back], um [laughs]. But when I'm taking a picture of the atmosphere then it helps me to kind of look up [looks up], being the Rover, and this is the front of me [touches chest] and then I put my head up [puts head up, looks back and forth] wherever, to whichever vector I'm looking at …

Liz regularly transforms her body into the Rover’s body in order to plan her observations. As she later articulated, it helps her not only for planning, but also for problem-solving in a fast-paced environment, when there is no time to complete complex calculations but there is only time for intuition. As she explains,

In order to be fully prepared for my job … I need to literally be that vehicle. That’s what all the visualization software I use is about … For me, it’s all about intuitively being able to make decisions, because you’re gonna be getting questions on the fly and you’re gonna have to answer them on the fly. You’re not you, you’re the Rover… You’re thinking for the vehicle… I think

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16 Liz, interview, February 1, 2008.
of myself as the Rover so I can call the shots. I need to know where I am as the Rover. It’s a huge, huge part of my job.\textsuperscript{17}

Liz’s experience is by no means unique. Through talk and gestures such as these the human team members take on the Rover’s unique body and senses when they interact, or speak of interacting, with Mars. And this embodied connection does not stop with simply operations planning, but rather extends as a sympathetic experience or a narrative for the experiences of the human team. For example, seeing like a Rover through stepping into their robotic bodies requires assuming the vehicles’ weaknesses and ailments as well. When the Rovers are “healthy” or “sick,” human team members on Earth may exude energy or tense up. Jude explained to me that when something is not right with the Rover, “We feel it in our bodies.” During the dust storm in the summer of 2007, team members were very much on edge, perceptibly anxious about whether or not their Rovers would survive. One articulated a comparison independently drawn by several team members:

It’s like if your grandparent is sick and in the hospital and there’s nothing you can do about it. You just have to trust that the doctors are doing all they can.\textsuperscript{18}

Such tension and emotional intensity could simply be excused as extreme sensitivity to the difficulty associated with operating a remote spacecraft under severe Martian conditions. However, these affective states are often tied, for team members, to their robots’ experiences on the Red Planet. These form a narrative the can be used to make sense of human experience on Earth. For example, as one scientist recounted,

\textsuperscript{17} Liz, personal conversation, February 6, 2008.

\textsuperscript{18} MER team member, personal conversation, July 15, 2007.
I was working in the garden one day and all of a sudden, I don’t know what’s going on with my right wrist, I cannot move it -- out of nowhere! I get here [to the SOWG meeting], and *Spirit* has, it’s right front wheel is stuck! Things like that, you know? … I am totally connected to that gal [*Spirit*]!\(^{19}\)

This scientist accounted for her injury in a cause-and-effect manner: what happened to the Rover on Mars certainly, inexplicably affected her body even without her consciously knowing it. And this phenomenon is not limited to scientists or to female team members; a male engineer told me a similar story:

> [I]nterestingly, I screwed up my shoulder… and needed surgery on it right about the time that *Opportunity*'s IDD started having problems [with a stiff joint], and I broke my toe right before *Spirit*'s wheel [froze], so I'm just saying, maybe it's kind of sympathetic, I don't know, [laughs] I mean I don't think there's any magic involved or anything but maybe it's some kind of subconscious thing, I don’t know.\(^{20}\)

Such stories demonstrate the very physical and often uncanny connection that is often described or exhibited by Rover team members as they work with their robots, even at a distance of millions of miles. The physiological experience that accompanies such talk suggests a further area for analysis as, after all, physicists’ talk about being an atom in the domain state (Ochs et al., 1996) is different than sympathetically *being* in the domain state. Even as an ethnographer on the mission, I can report a different bodily experience that feels almost like a particular kind of posture or stiffness associated with working with *Spirit* versus working with *Opportunity*, although the experience is difficult to articulate verbally. The intensity of the embodied experience

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\(^{19}\) Interview, MER scientist, May 25, 2007.

\(^{20}\) Interview, Rover Planner, February 15, 2007.
is such that team members regularly compare the experience of operating Rovers on Mars to simply “being there.”

Members of the team do talk about the Rovers as their proxies, or their way of being on Mars, as Bill Clancy has well documented (Clancy, forthcoming). A suggestive analytical connection here is in the literature on the phenomenology of perception, in which proxies are well-discussed. Rejecting the mind-body dualism perhaps made most famous by Descartes’ “Cogito ergo sum,” Merleau-Ponty in his classic work, *The Phenomenology of Perception (1962[1944])*, instead suggests the importance of the body to human experience and understanding. The external world is “not so much copied, as composed” (p.9) by embodied sensation; and as sensing beings humans are “are caught up in the world and we do not succeed in extricating ourselves from it in order to achieve consciousness of the world” (p.5). For Merleau-Ponty, “The theory of the body is already a theory of perception” (p.203). Far from enabling us to break free of this local and embodied perception to achieve a mechanical and more objective vision of the world as it truly is, Merleau-Ponty declares in an oft-cited analogy that instruments act as a kind of proxy, an extension of human senses and the human body:

Learning to find one’s way among things with a stick, which we gave a little earlier as an example of motor habit, is equally an example of perceptual habit. Once the stick has become a familiar instrument, the world of feelable things recedes and now begins, not at the outer skin of the hand, but at the end of the stick … the stick is no longer an object perceived by the blind man, but an instrument *with* which he perceives. It is a bodily auxiliary, an extension of the bodily synthesis. (p.152)
The Rovers certainly act as robotic proxies through which the human members of the team can experience Mars. But this example may challenge the analyst to extend the phenomenological concept of the proxy. For it is not just that the Rovers are the human team members’ proxies: rather, the embodied elision between human and machine through gesture and language would indicate that the human members of the team step into the Rovers’ bodies in order to experience Mars. They take on the body of the Rover with all of its attributes. As one scientist explained to me, on the one hand the “Athena payload is embodiment of a geologist on the Earth,” but on the other hand in operations one must “think like you’re in the body of the Rover.”

The stick does not just become part of or an extension of the blind man, but the blind man also becomes part of the stick, projecting himself into it and taking on its kind of experience of the world as his own direct experience. His instrument-enabled experience transforms him into a cyborg body, such that it makes little sense to talk of a proxy as though it is an external thing through which one can experience the world. Embodiment is a two way street.

Recent work has extended phenomenological arguments to the social studies of science by showing the centrality of the body to scientific practice and understanding. Natasha Myers’ study of a molecular biology laboratory, for example, focuses on the physical calculus that biologists employ while working with digital, virtual models of proteins:

As [the scientist] tells the story, she contorts her entire body into the shape of the misfolded protein. With one arm bent over above her head, another wrapping around the front of her body, her neck crooked to the side, and her body twisting, she expresses the strain felt by the misshapen protein model. (Myers, 2008, p.62)

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Similarly, Rachel Prentice’s (2005) work on minimally invasive surgery cites a surgeon who, while operating on an arthritic shoulder and looking at the screen in which the video feed is projected, says, “actually I would say I am sitting on that piece of anatomy, or rather that you are floating around, swimming around in the [joint].” This chapter joins these studies in emphasizing the importance of embodiment to perception even when working with virtual models, visualizations and video or other camera feeds. Finally, we might also associate the importance of embodiment to *seeing as* and *drawing as*. For as Merleau-Ponty suggests, as knowing and embodied subjects in the world, composing the world as we see it, embodied vision remains a question of distinguishing foreground from background. In a passage reminiscent of the discussion of *seeing as* in Chapter Two, the philosopher claims:

> Even if I knew nothing of rods and cones [i.e. how the eye ‘technically’ works], I should realize that it is necessary to put the surroundings in abeyance the better to see the object, and to lose in background what one gains in focal figure, because to look at the object is to plunge oneself into it, and because objects form a system in which one cannot show itself without concealing others. More precisely, the inner horizon of an object cannot become an object without the surrounding objects’ becoming a horizon, and so vision is an act with two facets. (p.67-8)

The body with its senses and mobility within an environment, as Merleau-Ponty argues, is an essential part of this perceptive practice. He is not alone in this argument: a recent monograph in the philosophy of science also associates the importance of mobility and interaction in the world with perceptual arrangement and Hanson’s concept of *seeing as* (Radder, 2006). Acting or being like a Rover and bodily practices such as gestures and empathetic affect are also part and parcel with “seeing like a Rover”.
**Drawing As And Seeing As In Context**

So far in this dissertation I have repeatedly shown that images and planning observations are used as resources to manage team relations in a consensus-based environment. I wish to further elaborate this issue here by extending the conversation on embodied perception to the social context of such activities. That is, I ask what work does *seeing like a Rover* -- including *drawing as*, narrative, and gesture -- do for the team in the context of mission operations?

As described in Chapter One, the Mars Rover Mission operates by consensus: every scientist and engineer around the table at the end of a planning meeting must agree to the plan. Keeping the team together in a unified view of Mars is thus important for maintaining this working atmosphere. Significant to this discussion is the fact that members of the MER team are encouraged to think of the Rover as a single, unified instrument, mirroring their unified stance on Earth. This holistic approach to the Rover has made space for feats of improvisation that were not anticipated uses of the vehicles: using a wheel to dig a trench, or using the Microscopic Imager to take a picture of the MiniTES mirror. The PI has often emphasized to me that this approach maintains the positive spirit of collaboration, allows the team to think creatively and interdisciplinarily, and results in what they characterize as “the best possible science.”

The visual and gestural techniques under discussion in this chapter reinforce this aspect of the Rover team’s operations as they build and reinforce an elision between the human and the robotic body, strengthening commitment to the Rover as a unified tool at the head of a unified team. But as these gestures and stories build a connection between the human body and the Rover’s body, they also contribute to a strong interconnection among team members. This is especially apparent in the

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22 Squyres, Personal conversation.
language used to describe the Rovers on the mission, which elides the human and robotic aspects of the team seamlessly under the pronoun, “we.” The vast majority of the time, especially when discussing operations, team members use this pronoun to describe their Rovers. The language in the LTP reports at the top of the SOWG meetings reinforces this positioning, as discussed in Chapter Four, as LTP leads pronounce statements like the following:

We expect to turn around and take images of [the target] … We’re about four meters from the outcrop that we wanted to image and so the idea was to bump forward maybe two or three meters so that we can get better images and MiniTES observations.

The “we” here refers to the Rover. The pronoun persists outside of the context of the SOWG meeting. Returning to Sarah’s decision against using South Promontory as a Winter Haven, the pronoun “we” sometimes refers to the Rover Planners, but more frequently refers to the Rover:

There is a path through there that we [Rover Planners] think if we constrain things very tightly we [Spirit] could get to the edge of that outcrop… The problem occurs when we [Spirit] hit the outcrop… if you look at the close up imagery that we [Rover Planners] have now I can't really find any way that we [Spirit] could park and get any more than 22 degrees slope … From all the imagery that I've seen … I can't demonstrate with any level of confidence that we [Spirit] actually can reach that parking place for the last segment of that drive.

23 The present study does not include the primary mission, but Bill Clancey’s forthcoming monograph based on earlier research suggests that this is a long-standing practice. When anthropomorphizing the Rovers or discussing their activities in public, team members use the pronoun “she”: consistent with nautical terminology. But “she” or even “it” are rare within the operations context. The insiders’ term “we” is consistently used.


In each of these examples, too, the use of “we” is punctuated with interpreted visions of the Martian terrain. Indeed, the drawing together of visual resources and embodied talk is particularly evident as a resource for consensus-building in situations of controversy, where team members are divided over a course of action. Recall that Sarah used slope maps, lillypad maps, and other visual tools to not only draw but also demonstrate her conclusions to the team, inspiring them to adopt her vision of seeing like a Rover and see South Promontory as impassible. Similarly, when attempting to promote a move to more silica-rich materials to the southeast of Home Plate, a scientist attempted his own visual analysis of the terrain at hand. Presenting an image that he had marked up to include a possible drive route, the scientist claimed, “based on your [the Rover Planner’s] presentation the other day, you showed one onramp [to Home Plate] that does look unapproachable or difficult, but what I was trying to show with these images … was an alternative that I wondered if you guys have looked at as well.” The Rover Planner, Kwame, countered that his team had “looked at all the southern approaches [to Home Plate] and we don’t think they’re viable.” But instead of turning the situation into a question of a scientist’s image interpretation versus an engineer’s image interpretation, he invoked the team’s technomorphism and the singularity of any robotic vision of Mars. After all, there is only one robot at each location, and there can only be one robotic interpretation of the terrain. Kwame therefore invoked the imperative of protecting the body of the Rover, “We don’t want to get stuck somewhere we cannot recover.” Resolving the conflict at hand, a second scientist jumped in to the conversation to suggest a third option, a middle ground that was both “reachable” for the Rover and presented the kinds of features his colleague was so interested in seeing in the southeast.26

Using “we” reinforces team members’ embodied connection with the distant Rover. But it also reminds individual scientists and engineers that they are part of a team who together animates the Rovers and that they have a responsibility to their teammates as well as to the Rovers. And the emphasis on the robotic singularity means that there are not as many Rovers or instruments as there are team members; rather, there is only one robotic body that team members must inhabit in order to experience Mars. So when they move their bodies like a Rover’s and see through the Rover’s eyes, team members reinforce and enact these values of consensus, unity of purpose and tools, despite the large distances that separate them.

Two comparisons here may illuminate the interrelatedness of these activities. The first derives from Durkheim’s description of social order and solidarity arising from ritual practices, as described in Chapter Four. Drawing upon anthropological literature of the day, Durkheim (1915[1912]) characterizes “elementary” religions as concerned with the management of totem animals, plants, or other protective forces. Totems and their management, according to Durkheim, serve structural functions in their societies, as their characteristics and associated rituals assert the local culture’s categories and structures, such as social hierarchies or divisions between the sacred and the profane. Care of the totem requires adherence to elaborate rituals that perform the social order of the group, and gathering in “effervescent” assemblies that include dancing or other gestures in which members of the group may imitate the object that brings them together. Given the carefully-adhered-to structure of the SOWG meeting, the emphasis on solidarity and unity through consensus-building, and the series of gestures and activities that elide the Rover’s body with those of their team members, it may be useful to consider how the Rover also serves a function as a totemic object. Such a consideration may point to the connection between the unity and solidarity of the group as achieved through interaction rituals like the SOWG, and how the Rover
draws together individual energies to inhabit the robotic body as a collective “we”. It also suggests why the preservation of the Rover demands (and sometimes achieves) sacrifice of individual scientific interests to support the collective goals of the team through an emphasis on Rover survival, making an appeal to Rover death such a powerful resource on the team. I will return to this idea below.

Another comparison drawn from the history of science further elucidates the importance of the robotic body, especially its optical technologies, to consensus-building and the values that animate the Rover team. Noel Malcolm (1998) has discussed the work of Jesuit natural philosopher Jean-Francois Niceron, whose catoptric anamorphic lenses could pull together a unified image from several discrete components. The optical device in question was something of a reverse kaleidoscope: that is, instead of fracturing a unified scene, the glass would unify elements from a fragmented scene into a new, singular image (Figure 55). Niceron gave examples such as images of the twelve disciples that when seen through the lens composed the face of Christ, or ten past Popes who together comprised the face of the newly appointed (and perhaps hotly contested) Pope. Such a device made a political statement about the legitimacy of the Pope by associating him clearly with a lineage of approved Popes, just as it made a theological statement about the truth of the apostles’ witness in their composition of Christ. In the same spirit of *ex pluribus unum*, Malcolm turns to the frontispiece to Hobbes’ *Leviathan* (1660), to show how many tiny bodies of subjects make up the body of the King, granting legitimacy to his power (Figure 56). Such a depiction reinforced Hobbes’ political point of the importance of surrendering individual power and authority to the King’s body in the interest of preserving the State. Ronnie Lippens extends this argument to show how Hobbes’ pictured Leviathan stands for the kind of “bureaucratic *machinerie*” that can artificially produce unity out of fragments (Lippens, 2006, p.14-15). Subjects give their authority to the King to act
Figure 55 Many popes combine through the use of a optical device to produce the face of Christ. Fig. 50 in Niceron (1638).

Figure 56 Frontispiece to Leviathan shows the king’s body composed of his subjects’ bodies. In Hobbes (1660).
on their behalf as a “sovereign machine,” the “engine” (Lippens, p.15) of their unified *Body Politick*, and they in turn are complicit and implicit in all that he does.\(^{27}\)

Similarly, through the resources of optical instruments and robotic machinery, the embodied visualization activities associated with *seeing like a Rover* bring together disparate members of the Rover team into a single collective body: that of their Rover. Thus these technomorphic practices of speaking, gesturing and seeing function as a political resource, contributing to the success of the mission by bringing team members together in the body of the Rover, such that they, like the King’s subjects who compose him, are implicit and complicit in all that their robot does. *The Rover’s body is a body politic.*

Team members’ sympathy for the robotic body affects mission operations on the level of both the Rovers’ activities on Mars and on the level of the team’s organization and commitment to the mission and to each other. For example, the experiential sense of physical interaction with Mars gives team members the confidence to push the boundaries of Rover operations beyond their original technical specifications; the Rovers have descended into craters and climbed mountains, team members have gestured with their feet, arms and eyes to suggest digging trenches with the Rovers’ wheels or using the Microscopic Imager to take a picture of a problematic component on the Pancam mast. But making novel suggestions for Rover activities requires a perfected sensitivity to the balance between the Rover’s resilience and its fragility, intuited through embodied experience. Thus this uncanny sympathy for the Rover’s experience can provide creative possibilities for operations unforeseen in the robots’ design.

\(^{27}\) On this topic see also Hobbes (1660), Schaffer (2005).
An embodied sense of the Rover’s experience also animates a spirit of perseverance in the face of adversity. Even as parts of the Rovers start to break down, the team maintains a fierce connection to their robots rather than abandoning them as faulty tools. For example, when Spirit’s right front wheel stopped working, the Rover Planners started to drive Spirit backwards, dragging the stuck wheel behind. In this make-do arrangement, the Rover serendipitously turfed up the white soil at Tyrone, later recognized as one of the most significant finds of the mission. Within days of this momentous discovery, team members stopped referring to “our crippled Rover” and started calling the bum wheel, “our trenching tool.”

This sensitivity is heightened and rendered more urgent through an appeal to robotic death. The Rovers have outlasted their 90-day warranty by over fifteen hundred sols and are certainly fragile vehicles -- especially for those who knew them through their construction, who built, designed and cared for them before their launch. However, in the multiple extended missions that have evolved since then, a routine pattern of operation has developed with a constant level of excitement and wonder. Still, for some members of the team robotic death remains a constant threat. They invoke a need to consider “what do we need to do before we die” when the team must come down to a pressing decision about where to drive or what observations to make. The resort to this appeal underscores the urgency or severity of the decision, but it also underscores the importance of maintaining an extraordinary level of service to the Rover and to ones’ teammates. This was elaborated by an engineer at an All-Hands meeting following two human errors on the mission:

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28 Even during their development phase, spacecraft cannot be left unattended but require constant supervision, even overnight. Several team members volunteered for this night shift activity, often called “babysitting.” One MER team member recalled how babysitting for the Mars Polar Lander, with which she was involved, built up her affective relationship with the lander.
[At the beginning of the Mission] there was sort of this culture of curiosity combined with paranoia and everyone was on their game … As people have been cycled in and out of MER … we have new people and I kind of get the feeling that they don't have the fear [we had] … It’s more of a video game for a lot of people, it's kind of cool … it's sort of abstracted a little bit … They may not be as connected to the fact that the Rover is only one day away from we're never going to hear from it again … any thing we could potentially do could end the whole game …

Death thus becomes a resource for team members wishing to inspire renewed commitment to the team. A fragile totem, the Rovers not only require constant care and attention but also require that their caregivers work together flawlessly to ensure their survival. When they encounter difficulties, the geographically disparate team unites in their grief or their concern for their vehicle: after all, the Rover’s body is their body too. This may be an important, yet under-considered, aspect of affective computing, as it reminds individual scientists and engineers of the technomorphized, intimate association with the Rover and thus ensures their continued complicity in its actions and communal success.

**Conclusion: Seeing Like A Rover**

As this chapter has shown, the ability to make decisions about where the Rover can drive is bound up in embodied practices of *drawing as* and *seeing as*. *Seeing like a Rover* begins with a sensitivity to Mars as tangible and interactable on a Rover scale, and the representations of the Rovers’ environment that the robots themselves use to make driving decisions. This awareness of the trafficability of a terrain is a kind of professional vision usually associated with Rover Planners, whose specialist conventions for representation are attuned to the aspect of driving hazards. Just as

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29 All Hands Meeting, June 29, 2007.
scientists draw Mars as composed of hematite or as silica-rich, honing in on one aspect of the terrain and drawing out others, engineers and others with an eye to operating the vehicles draw Mars as tangible and interactable, as terrain, as a map. Alongside these practices of visual construal are embodied gestures that elide the human and the robotic body at a distance of millions of miles. Human operators account for and make sense of the terrain around the Rover by enacting its interactions with Mars in their own bodies, taking on robotic characteristics and acquiring a performed sensitivity to robotic vision and movement. Embodied practices are not only essential for image interpretation; they provide the cyborg body with which it is possible to see as, to make sense of the Martian environment. As this sensitivity extends to all aspects of robotic experience on Mars, the Rover is not simply a proxy for extended human senses or an anthropomorphized agent; it is a body politic in which team members come together, reinforcing a value for teamwork in consensus operations. Thus seeing like a Rover -- seeing Mars as a Rover would, drawing the terrain as trafficable, and the talk and gesture that are inherent to an embodied understanding of seeing and drawing Mars -- is a social and political practice, enacting a body politic and the social organization of the human team.

Understood in this way, the intersubjective activities of seeing like a Rover are an essential part of team dynamics. The drawing, gestures and talk associated with this kind of visualization do not simply make an image of the Rover’s position on Mars interpretable (as Morana Alač, 2008, has shown with her study of gesture and digital images) and do not simply exhibit a proxy approach to working with a distant tool. They are essential to planning remote operations by building a connection between the team members’ bodies and the Rover’s body (see also Alač, in press), and crafting social ties between team members on Earth. Imaging that places the observer behind the Rover’s eyes is part and parcel of this process of building empathy and intimacy
between team members and their distant robots. This activity brings team members together in the body of the Rover, a single object to which they are all physiologically committed, in which they are all at the same time present, reinforcing the team’s solidarity and complicity in the Rover’s activities. In this effervescent state they are enlisted, they are loyal to the Rovers and to each other, they are present together on Mars, and the Rovers are the engines of their body politic. The stance of the virtual witness in these panoramic views of the terrain invite the viewer to inhabit this robotic yet collective body, coming together as a “we,” and this reinforces and perpetuates the disciplinary politics of operating on this consensus-based team.
Following the discovery of the salty soils at Tyrone, the team commands *Spirit* to drive backwards towards Home Plate, dragging her stuck wheel behind her and taking Pancam and MiniTES observations of every white patch of soil she encounters along the way. As the Rover approaches Home Plate the team makes another discovery: at Tyrone, the soil contained a significant amount of sulphur, but the small cobbled rocks scattered over the ground only a few meters away indicates over 90% silica content in MiniTES measurements. As the Rock Abrasion Tool on *Spirit* has already been grown down on hard, volcanic rocks encountered early in the mission, the team opts for crushing one of the cobbles with the Rover’s own wheels in order to reveal its internal structure and chemistry. The Microscopic Imager pictures display a texture that many team members recognize as a sinter, made on Earth from deposits in hydrothermal springs, and the scientists examining the spectrometers’ readings identify the rock as kind of opaline quartz. The energy on the line is suddenly electric: after all, many opaline sinters on Earth are formed by microbial processes. As the teleconferencing scientists at the End of Sol cautiously trade theories about how such sinters could form on Mars, my field notes record the first use of the word “biology” since the beginning of my observations.

A week later, I sit in the office of Mars Exploration Rover scientist Sam Barton at a NASA Research Center. Sam recalls for me the day in 1985 when he received his copy of the *Whole Earth Review* with a picture of San Francisco swarmed by flying saucers on the front cover. “The headline read, *The end of photography as evidence of anything*,” he remembers, and laughs, “it was all about of course this new application
that a company called Adobe was developing called Photoshop, and they illustrated how fast and trivially easy it was to make pictures of anything … [such that] unless someone handed you really a negative of something you shouldn’t trust it [photography] any longer.”¹ A former member of the US Army, by 1985 Sam was settling into a career as a planetary geologist. He found the Whole Earth’s headline ironic, not the least because digital photography and other computational remote sensing tools had, he believed, transformed his field from one of speculation into “science.” Before digital photographs, Sam explains to me, planetary geologists in the past engaged in what he pejoratively called “lookiloo” analysis: that is, “looking at pictures and making up stories.” At the time, the pictures were usually orbital images taken by vidicon tube cameras on board Viking or Mariner, and the stories were assumptions about the geological processes at play on the surface of the planet, extrapolating a hypothesis from limited visual data based on an approximation to a familiar structure or process on Earth. “People got whole papers published this way,” Sam laments. In contrast, he explained, the Galileo mission to Jupiter and the Mars orbiter missions of 1997 and beyond sent back digital images taken by CCD cameras that could be correlated with topographical data derived from an on-board laser altimeter. According to Sam, this presented reams of new and trustworthy information with a whole new status to the planetary science community. The entirety of what was known about Mars was suddenly up for grabs. As Sam delicately put it, “What we learned from Mars in the 90’s is: we were full of shit.”

Planetary geologists regularly credit digital photography, along with associated techniques and instruments such as laser altimetry and spectroscopy, as nothing short of revolutionary in terms of their understanding of distant worlds. But Sam’s description of lookiloo highlights a tension inherent in working with digital image

¹ The quotes in this paragraph are from my interview with Sam, May 24, 2007. The article in question is Brand (1985).
data: on the one hand, image manipulation is an essential part of doing science with this data, but on the other hand the very fact of this malleability leaves such images open to suspicion. If images can be drawn as at will, what is to stop them from being drawn as anything? Or, as the Whole Earth Review put it: how can digital photographs be “evidence of anything”? Just as Chapter Three explores the work of calibration to produce a trustworthy base image for scientific analysis, this chapter inquires into the construction of trusted evidential reports based on “pixel-pushing” Rover data.

In doing so I rely on work by sociologist of science Trevor Pinch’s study of neutrino and solar ablateness detection in physics, which argues for the analyst’s attention to the “externality” and “evidential context” of scientists’ observational reports (Pinch, 1985). Pinch observed that scientists moved along a “chain of interpretation” (p.8) from seeing “splodges on a graph” to “seeing Argon atoms” to “seeing neutrinos.” At each point in the chain, the degree of externality in the observational report becomes increasingly distal, incorporating a different evidential context. Pinch then asserts that scientists who contested the findings of the solar neutrino group did not deny that their colleagues saw splodges on a graph, or even Argon atoms, but rather denied the publishing group’s ability to make the more distal interpretative move towards declaring that they saw neutrinos: that is, they denied the degree of externality evidenced in the published observational report. According to Pinch, such an analytical orientation to observation usefully recasts the tired

2 While it is beyond the scope of this dissertation to compare image manipulation practices and moral codes across fields, it is important to note that the subject has also been hotly debated in microbiology: under the heading, “Why is it wrong to ‘touch up’ images?,” Rossner & Yamada (2004) state the following:

“If you misrepresent your data, you are deceiving your colleagues, who expect and assume basic scientific honesty—that is, that each image you present is an accurate representation of what you actually observed... Manipulating images to make figures more simple and more convincing may also deprive you and your colleagues of seeing other information that is often hidden in a picture or other primary data.” (p.11)

The strong moralistic language in this statement (e.g. “misrepresentation,” “deceit,” “honesty,” “deprivation”) clearly demonstrates the importance of the issue, although what exactly counts as “misrepresentation” in the face of digital practice requires several pages to articulate.
philosophical debates over what kind of “theory” “observations” are “laden” with, as sociological questions about how and when scientists appeal to or attempt to change the evidential context of their observational reports. It also allows the analyst to examine what resources such as trust, responsibility, or data management are employed to support evidential claims in the face of challenges of underdetermination: that is, the choice of only one of an infinite number of possible hypotheses to explain a single observation. After all, Pinch reminds us, “arguments over observations center not so much on the reliability of scientists’ sense perceptions, but rather on the reliability of the practices and assumptions that went into the observation process” (1985, p.8).

Pinch’s analysis is instructive here for analyzing how scientists on the Rover mission appeal to the trustworthiness of their observational reports even as they actively manipulate the very data that constitutes their observations of Mars. Of importance here is the actor’s category of “constraints:” locally-approved criteria that must be satisfied before the scientist can change evidential contexts for their observational reports without being accused of “lookiloo.” In this chapter I will first discuss the MER scientists’ use of the term “constraints” within the context of externality of observational reporting. I then describe the characterization of the digital image as a mathematical entity and the appeals scientists make to “constrained” interpretation and manipulation of digital images. Next, I show how studies of and experiments on Earth can be called into play as “constraints” upon interpretation that can justify more distal changes in evidential context as a result of scientists’ Earth-trained judgment. Finally, I discuss two cases in which scientists become caught between these two constraints to show their conflicting management in practice.

3 The Duhem-Quine thesis in the philosophy of science draws attention to the problem of under-determination in theory-choice. Both philosophers demonstrate that hypotheses cannot in and of themselves be falsified as they rely upon a chain of assumptions that cannot be individually tested; removing even one link in the chain can invalidate a scientific claim. See Quine (1951).
Constraints, Underdetermination And Externality

The concept of ‘constraint’ is a belabored one in Science and Technology Studies. A long-standing debate between Andy Pickering and Peter Galison on the topic makes clear the complexities of invoking constraints in any analysis of scientific practice. Galison’s description of constraints as “creat[ing] a problem domain, giving it shape, structure and direction” (1995, p.22) implies that naturally-given factors shepherd and influence the growth of scientific knowledge alongside scientists’ given beliefs about physical laws or instruments. Pickering, in contrast, asserts that such a view can only be retrospective; material and cultural resistances encountered in “the mangle of practice” may be variously flexible but “there is no especially informative pattern to be discovered about what changes and what does not” (Pickering, 1995, p. 207). Reviewing the published conversations between these analysts and others reveals that the debate about “constraints” is a debate about the potential limits of a constructivist approach to the analysis of scientific practice.

My discussion of constraints in this chapter should not be interpreted as making a claim to demarcation criteria around or within science. I do not attempt to construct boundaries between contexts of discovery and justification, external and internal factors in scientific discovery, experiments that end and those still in progress, social construction or the resistance of reality. What I do want to do is to show how, in the face of ambiguous data, underdetermined explanations, and possible accusations of over-manipulation, MER team members do draw these boundaries in their discourse about and their practices of image analysis. “Constraints” are therefore here described as an actor’s category: a term used by the scientists I observed to describe several related practices in their digital image work. The resulting discussion of the “constraints” leveled upon drawing as practices should not be taken in a philosophical vein -- that this or that kind of manipulation guarantees the right kind of representation
and interpretation -- but instead aim to describe this community’s local way of accounting for their activities with digital images in the process of making community-sanctioned knowledge about Mars.

With the partial, local view of Mars that the Rovers provide and digital image data vulnerable to being cast as “evidence of anything,” MER scientists invoke “constraints” as a way to cut down the number of possible interpretations of a phenomenon and delimit their interpretations to fewer possible theories. This is visible in terms of how scientists on the MER team talk about “constraining hypotheses.” For example, examining results from Spirit’s spectroscopic observations that revealed a high level of titanium in some of the local rocks, a scientist exclaimed, “We gotta constrain what’s going on here!” In this context, “constraining what’s going on” meant providing a credible explanation for the observation by limiting interpretative flexibility and taming the degree of underdetermination inherent in the hypothesis. The scientist’s colleague agreed, exhorting his fellow team members to look for a hypothesis that was “really well constrained.” Such a hypothesis might involve one or more observations that the Rover could perform that would enable the scientists to discriminate between possible interpretations of the phenomenon at hand. It might also involve invoking observations from multiple instruments: arguing for a Mossbauer spectrometer reading on a target that had already been examined by APXS, one scientist reminded his colleagues, “when you have both instruments on the same target you have the ability to constrain things ...” Thus constraints are called upon to narrow in on a story about the Martian observations that the community believes will be credible, to allow for a change in evidential context for an observational report. For example, following the titanium case, the team decided that to “constrain a

4 Team Meeting, July 7 2007.

5 Team Meeting, February 14, 2007.
depositional hypothesis” -- that is, narrow down their interpretations of the titanium readings to a story about the deposition of titanium in a watery environment -- they should take spectral readings of a nearby rock to see if it had a similar composition. Reporting on the readings when they were received from the Rover, the same scientist expressed that he was “struck by the difference” between the two samples; the inconsistency was such that he claimed, “For me, right now the titanium story doesn’t really constrain anything.”6 That is, titanium content alone could not delimit the possible interpretations of his visual data such that deposition was the only possible way it could have been present. Explanations of “what’s going on” can only judged credible when they are tightly coupled to a restricted chain of reasoning that allows for limited degrees of inference. The hypothesis must narrow down, not open up, from an observation to an explanation.

Constraints as invoked with respect to hypotheses allow MER scientists to make what they consider to be valid moves along a chain of interpretation to incorporate greater degrees of externality.7 But moving from “We see white soil,” to “We see two kinds of salts,” to “we see two layers of salty deposits,” to “we see evidence of past hydrothermic activity” requires the incorporation of many resources and appeals to tightly couple the relationship between one evidential report and another more distal one. Central here is a discussion of practices of data management, manipulation, combination and interpretation which are said to provide suitably constrained interpretations of visual data. After all, moving between degrees of externality requires an appeal to the “reliability of practices” (Pinch, 1985).

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7 Note that in the solar neutrino case, Pinch often uses terms such as “distal” and “externality” quite literally, referring to the distance between the argon tank and the sun in the description of an “observation” of solar neutrinos. I take a less literal tack here, using such terms to denote the analytical distance along a chain of reasoning from an initial observation to an observational report.
For the scientists I observed, both the language of constraints and the practices enlisted in their enactment are related to anxieties about the nature of knowledge production on their mission. Located in the space between increasingly external observational reports, “constraints” negotiate the fine line between what these scientists believe to be valid image manipulations and interpretations, and what they accuse of being unsupported interpretation or “lookiloo analysis.” Put differently, what Mars Rover scientists describe as limitations on or resources for their image interpretation and manipulation says something about how the community makes knowledge from digital image work.

**Digital Practices**

Bob Glover’s decorrelation stretches are legendary among the Rover scientists. No other images on the mission so vividly recall the hypercolor palette of Andy Warhol, and his images make visible even the slightest difference between units or soils. When they heard I was studying images many mission scientists helpfully suggested that I meet with Bob to learn how he produces such fascinating images; I therefore set up a visit and planned on spending two days at his office in a lively university town in the United States to get a sense of his approach to image work. But when I arrived and asked him to demonstrate his technique, Bob seemed perplexed. He started his image processing program on his computer, loaded a set of Pancam images, and then said, “I just push this button.” Upon clicking upon a built-in function, the Pancam image turned into a brilliant decorrelation stretch with the colors that unmistakably marked it as one of his images. While I was at first disappointed that this unique production could be ascribed to a built-in software function, I quickly learned that for Bob, what was important was that the button initiated a coded script that applied a precise mathematical formula to the images he had selected. Thus these
images were not transformed or interpreted willy-nilly, but precisely disciplined, maintaining a persistent underlying mathematical integrity to the original dataset.\(^8\)

A year later as I was reminded of this interaction when I was putting together a paper that included one of Bob’s characteristic images, but realized that I did not have his permission to publish it. When I contacted another member of the team who frequently works with Pancam images to ask about how to get his permission, I was instructed to just credit it “the usual way,” with the tagline “NASA/JPL/Cornell.” I insisted that this was very clearly Bob’s image, and recalled my conversations with him about the values of artistic production in science and even the possibilities for gallery exhibitions of some of the more striking pictures. But the other scientist insisted in return that “anybody could have made that image,” and then suggested that if I was still concerned about it, that he could recreate the image on the spot and give me permission to publish that instead. I must have seemed taken aback by this offer, so he elaborated further. What made Bob’s work scientific was precisely this ability to recreate the image. Because his image was a combination of particular filters governed by a mathematical formula, it was and should be replicable. Indeed, Bob’s images’ very status “as evidence of anything” depended on their ability to be precisely recreated at will by any other interested scientist.\(^9\)

Scientists across the mission repeatedly expressed to me that this virtue of replication was one of the features that makes their work with digital images scientific, as opposed to “lookiloo”. This is perhaps unsurprising given the importance of replication to the experimental sciences. Studies of the early Royal Society have noted the epistemic value placed on repeatable experiments as tests or demonstrations of natural phenomena, often contrasted with “monstrous” or one-time cases that tested

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\(^8\) Interview, Bob, June 4 2007.

The limits of nature. The practical difficulties with replication have been explored in the sociological work of Harry Collins (1985) and in efforts to replicate historical experiments, such as in the work of Otto Sibum (1995); these scholars have shown that experimental replication demands a high degree of tacit skill, such that it can be impossible to replicate experimental results even given the most detailed instructions. But despite the fact that it may be nearly impossible to achieve and rarely practiced, studies of cases such as the Cold Fusion debate (Collins and Pinch, 1993) suggest that experimental results are subject to discredit if they are unable to be replicated.

But just because they appeal to replication does not mean that Mars Rover scientists actually replicate each other’s work as a way of fact-checking or confirming an experiment. This is especially clear with respect to those occasions when similar techniques are exerted over the same image data with slightly different results. For example, the Geographical Information Systems (GIS) laboratory at Ohio State University and the Jet Propulsion Laboratory’s image processing center (MIPL) both create Rover transit maps, and both Bob Glover and Ben Quinn create decorrelation stretches (Figure 57), but the resulting images are openly acknowledged as not exactly the same. One can see details in Bob’s images that one cannot in Ben’s and vice versa; in fact, when they discovered that they were both working on Cercedilla, Ben and Bob exchanged decorrelation stretches as an opportunity to discuss what “popped out” in each image. Similarly, techniques for locating the Rover based on orbital GIS data practiced at OSU versus Rover odometry practiced at JPL each have advantages and disadvantages depending on the slip of Rover wheels or the availability of orbital co-

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10 On the ‘experimental life’ see Shapin and Schaffer (1985) and a volume on The Uses of Experiment (1989, ed. by Gooding, Pinch, and Schaffer) to name only a few studies. The ideal of ‘nature as she always is’ contrasts with nature as she is subject to occasional distortion: see, for example, Daston and Park (1998).

11 This issue came to a head in the contested replication of Isaac Newton’s prism experiments (as related in his Opticks), discussed by Schaffer (1989) and critiqued by Shapiro (1996).
ordinates. This results in different maps being taken up and used at different times for different purposes. Replication may also occur for disciplinary or institutional reasons, as some scientists are more comfortable using geographical information system software, like ARC-GIS or ENVI, than astronomical image processing software, like ISIS (developed by the USGS for planetary studies) or IDL (preferred by astronomers), depending on what they were trained with and what software their institution provides.

Figure 57 Decorrelation stretches of nearby areas at the edge of Victoria Crater produced by Bob (left) and Ben (right).

This kind of replication is not seen as creating an inconsistent picture of ‘what is really going on’ on Mars. Nor is it taken as an indication of one scientist’s inferior skills compared to another’s, or as a crucial experiment that might disprove a theory. Instead the resulting images are folded into the tactical and strategic contexts of the mission as further pieces of the puzzle to be grappled with. To the team, slight differences in these drawing as practices draw out slightly different details and taken together, present additional tools with which to problem-solve. Li Chen, a computer scientist on the mission engaged in making terrain models, explained this as a question of bringing together different strengths, each arising from different disciplinary perspectives, software suites, and interpretations:
Joseph looks at the images and interprets the rocks very well, he is a geologist. I am not, I'm an engineer. He's good at the tactical, we should go here, we should go there. That we [my software team] can't do. He doesn't have the tools we have, the software. Peter, he's a geologist … he doesn't have the math models and software we have.12

The maps Li generates reveal a software engineering perspective of Mars, which has the advantage of mathematical modeling over Joseph or Peter’s maps, but the disadvantage of little geological interpretation. The question here is not one of replication and induction as experimental virtues, as what matters here is not whether or not the construction and manipulation of Pancam imagery is actually repeated by other scientists. Rather, it is a question of generating different epistemological inroads for understanding Mars.

Although replication is not a feature of experimental or observational practice, it is nonetheless invoked as a constraint upon interpretation, arising from a commitment to the mathematical nature of the image data. Manipulated images can be replicated, MER scientists explain, because they were created in the first place by a mathematical expression: a function applied to a range of numerical pixel values. If they cannot be replicated, then that is because the underlying mathematics has been tampered with in an unpredictable way -- and the interpretative leap from the raw-data observation to the manipulated and thus more distal observational report cannot therefore be considered credible.

Consistent with the constraint of mathematical reasoning, many pixel-pushing practices invoke mathematical expressions related to geometry, functions, integers and operations. Pixels are added and subtracted, multiplied or divided, and may also be subject to complex equations or derivations. For example, when filters are combined

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into a new and colorful image they are said to constitute an Image Cube (also spelled Qub or Qube), in which the three dimensions of the cube are the height of the image frame, the width of the image frame, and the number of combined filters (Figure 58). Scientists thus speak of ‘slicing through’ an image cube to get a spectrum at any given point, or performing other geometrical transformations upon this Cube. Bob impressed upon me the importance of computing Eigenvalues, an expression derived from matrix algebra to determine the vector relationship between pixel values as they are plotted in multi-dimensional space. Indeed, when Bob used the term ‘image space’, he didn’t mean the space within the visible image frame, but rather referred to a multi-dimensional graphical plot of pixels, like a histogram in 3D; this image space could be digitally “rotated” in order to determine what groupings the pixels fell into and which were outliers from these groups, indicating a difference in spectral composition (Figure 59). Demonstrating his simulation software to me, Sam’s graduate student showed me a list of numbers on his screen, calling them “a quantification of what our eyes are seeing.” He claimed that tabulating statistics on these numbers added
robustness to his interpretation of the resulting images, saying, “Your brain is really good at saying that's wrong or that's good but when you're publishing a paper you want it to be … more robust.”

This approach to image manipulation as requiring mathematical integrity can be taken to interesting extremes: while interviewing Michael Jensen about his work on Martian images, he showed me a picture he had taken (and subsequently altered) of a Greek temple in Athens on a recent business trip:

You can never get these pictures without you know, people in ‘em … So I decided that we’d go ahead and get rid of these people [in the foreground] … Well it’s a very organized scene, there’s a lot of structure in here, so I basically built a little model of gravel and sand, and pasted it in there and randomized it and changed the spatial frequencies until it had the same texture …

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13 Interview, Bob, June 4 2007.

14 Interview, Michael, June 12, 2007.
Even with his personal photos, Michael did not use idiosyncratic tools to touch up his images willy-nilly, but rather employed a hand-written computational algorithm to alter the picture in a precise, replicable way according to mathematical principles (Figure 60).

Inherent in this talk and action with digital images is a belief in an underlying mathematical rigour that lends trustworthiness and evidential status to the resulting images. Such a feature must be preserved in any movement along the interpretative chain of reasoning, and provides a constraint in practice upon Rover scientists’ image manipulations. This constraint recalls the necessity for “traceable” inscriptions that Latour notes in his study of scientists in a rainforest, who note every sample and observation in their logbook as these samples move from object to inscription to allow others to “go back to each data point in order to reconstitute its history” (1995, p.161). It also restricts scientists to only those types of image manipulations that can be replicated, mathematically described or generated. So this constraint upon image interpretation as it is enacted in practices of image work not only disciplines the *image* into a trustworthy document as it is *drawn as* to incorporate an interpretative move: it also disciplines the image processor as they draw.
Arguably, the current state of digital imaging codifies a longstanding set of practices concerned with quantifying the qualitative aspects of visual data. Before the introduction of digital images, techniques of photogrammetry were acutely developed using analog tools to apply measurement strategies such as triangulation between stereoscopic photographs to orbital images to determine, for example, the height or depth of a feature of the terrain (Figure 61). While photogrammeters used ever more refined stereoscopic instruments to measure their photographs, other techniques drew upon contour mapping to derive quantities from their data. For example, conducting his study of cloud cover on Mars in the 1969, Dr. William McKinney of the Lowell Observatory in Flagstaff began his observational work by placing successive sheets of plastic on top of Percival Lowell’s Albedo Map of Mars, at the time the standard cartographic base for such work. The first layer placed a semi-transparant grid over the map; on successive layers of plastic he noted, with tally-marks at first and then tallied into a final number, the number of days he observed cloudiness in that small section of Mars over a period of several months. McKinney tallied these marks into numbers in the next layer of plastic, then laid a layer overtop on which he drew contour lines around areas with similar numbers. These contour lines were eventually

Figure 61 Figure from a 1961 textbook on photogeology showing how to use stereo apparatus to determine topography. (Miller, 1961)
abstracted from the numerical data that was, quite literally, behind them and published as the results of his observations (Figure 62). While a laborious process, this technique ensured the ability to, traceably (literally), derive quantitative data from qualitative observations, and then to synthesize that data into a schematized representational form. In that sense it is not far removed from the underlying strategies and stories behind pixel-pushing. Another fine example of this charting practice is in the possession of one of the Payload Element Leads. Produced by his graduate advisor, one of the original *Viking* team members, the map uses numerical printouts from the *Viking* orbiter indicating surface temperatures as a base: the scientist then meticulously drew contour lines around regions with similar temperatures, then colored these delineated sections in with a color scale ranging from blue for cold to red for hot, eventually resulting in a temperature map of Mars that would be published at the 2\textsuperscript{nd} International Conference on Mars.

Figure 62 Four layers of transparent plastic laid over an Albedo Map (shaded area) of Mars: the yellow and white graph, tally marks for days of cloudiness observed, a number for the sum of the tally marks, and contour lines. Lowell Observatory Archives.
Recalling the scientist mentioned above who required Mossbauer in addition to APXS measurements to provide a constraint upon his interpretation of the rock he was studying, another practice that is often observed on the MER mission is one of combining data sets from different instruments, spacecraft or scales. MER scientists call this activity “co-registration.” The scientists I interviewed explained this activity as due to “a desire maybe to see different things at the same time,” and another explained it as a function of “context visualizing, using data to give you confidence in other types of data.” It is especially common to co-register spectral and pictorial data sets, such as readings from MiniTES and Pancam or from orbital spectrometers like THEMIS, OMEGA or TES and cameras like HiRISE and MOC.

Here it is worth noting that there is in practice little distinction made between cameras and spectrometers in terms of the perceived interchangeability of their data products. When I asked Bob to explain the difference between a spectrometer and a camera he explained that they were often interchangeable labels: after all, cameras like HiRISE and Pancam provide spectral datasets, they just do so in the visible range of light, unlike TES or MiniTES, which take readings through infrared and thermal sensor bands. The primary difference is seen to involve a trade-off between spatial versus spectral resolution. Most scientists chose a camera filter that can provide a high-resolution base map upon which to co-register other observations, such that at least one dataset in the combination provides the essential spatial, locational, and geomorphic as well as spectral data. For example, the Pancam, HiRISE or Mars Orbiter Camera can provide a picture of the visible features, which would then be co-registered with invisible features provided by other instruments, such as spectral bands.
in the infrared.\textsuperscript{15} Co-registering data in this way is said to help constrain interpretations: although alone, each individual data set could support a variety of interpretations, taken together they may point to only one or two shared hypotheses.

While the technique might vary with each kind of data or software platform, the basic process is the same. First the scientists must convert the two kinds of data into mutually understandable data formats. This can be as simple – and as time consuming – as opening the two files in two respective software suites and ‘exporting’ the data to a third file format, readable by a third software suite. Second, the scientist must correlate the data through some element that is mutually shared: for example, a co-ordinate system. A scientist trying to project MiniTES data onto NavCam images must first correspond, through a co-ordinate system, \textit{where} those MiniTES stares are located relative to or within the NavCam frame. Similarly, combining spectral or infrared data obtained in orbit with a picture of that area also requires knowing exactly where that spectral data came from, so that it can be co-ordinated with the orbital picture. Finally, the data must be displayed in a format that reveals the relevant dimensions of information, such that a MiniTES-NavCam image pair might show both the location of the MiniTES stare on the Martian terrain \textit{and} the reading that the MiniTES actually got from that location (Figure 63).

\textsuperscript{15} Interestingly, when creating their industry-standard maps, the US Geological Survey and others rely increasingly upon thermal data to provide this base map. Despite the fact that the THEMIS orbital instrument only measures thermal emissions spectra, i.e. the infrared and non-visible range of light, it presents a good balance between orbital coverage and resolution upon which to co-register other datasets. This is possible because different features on the Martian terrain retain and reflect heat differently; rocks are typically cooler during the day but retain their heat at night, while sand is typically hotter during the day and cools quickly at night. By comparing daytime and nighttime infrared readings, this instrument team can provide essentially a ground map of topographical features derived solely from infrared detection. Such an example further blurs the already blurry distinction, in practice, between spectrometers and cameras.
Let’s return to Bob’s desk for an example. Bob is trying to make a case for a landing site for the next generation of Mars Rovers (Mars Science Laboratory) and is therefore working with orbital imagery to make the case that the region he is interested in may present evidence of past water activity. To do this, he wants to combine orbital images from HRSC, the High Resolution Science Camera on board Europe’s Mars Express Orbiter, with images from OMEGA, a spectrometer on board the same orbiter (Figure 64). Or as he puts it,

I had mapped out … from this data set … the various features such as the hydrated stuff that shows that 1.9 micrometer band [the water signature] … . What I’m gonna try to do is be able to overlay that, those mineralogical interpretations onto this multispectral data.¹⁶

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¹⁶ Interview, Bob, June 4, 2007.
He chooses these data sets for three reasons: one, because it provides coverage of the part of the planet he is interested in; two, because he wants to be able to correlate the detection of water, a spectral signature, with its spatial location on the planet; and three, because the views of the planet are complementary, one with “much higher spatial resolution but lower spectral resolution” and the other with “higher spectral resolution but lower spatial resolution.” Bob will eventually use ENVI, a software program, to combine these two sets of data through “reference from input geometry”: using the latitude and longitude measurements encoded in the image to create a correspondence between them. But the file formats are not compatible with ENVI yet. First he must open them in their respective software suites and export them to file formats that can be opened together in ENVI. He selects the filters that are close to where water signatures show up to export. Then with the two datasets open in ENVI, he must get the data to correlate. He does this by projecting both sets of data onto the same orthographic map of Mars, so that the two data sets appear one on top of

Figure 64 On his computer screen, Bob spatially correlates the 1.9 micrometer spectral band from OMEGA (in pink) with an orbital image from HRSC.
the other. In the resulting image, HRSC provides a sense of context, the pictorial features of the terrain, while the OMEGA data shows up in variety of colors painted across the scene. Looking at this data in this way, Bob notices that the areas that show a lot of the 1.9 micrometer water signature align along topographical features visible from space, the flatlands around the ridge of a crater. This leads him to not only know where those water features are located on Mars, but also to make a claim about where they come from and their relationship to the crater and other local features.

Because scientists’ decisions about which pieces of data to combine is directed by their interest in ‘seeing new things’ or making features ‘pop out’, as discussed in Chapter Two, choosing which pieces of data to combine can be a powerful way to draw as. But co-registration, as a kind of drawing as practice, provides a built-in constraint upon interpretation that allows the resulting image to stand as “evidence of anything.” Sam, for example, repeatedly stressed to me that the Laser Altimeter aboard the 1997 Mars Orbiter (MOLA) was invaluable as it provided topographical data that could had previously been inferred from the visual data from orbit (Figure 65). The
MOLA dataset was considered so fundamental to understanding Mars that another scientist I interviewed referred to it as “the control for the planet.”\textsuperscript{17} Sam’s graduate student, David, suggests that the only way to discern the topography on Mars before MOLA was available was from “inferences”:

You could make inferences like, well this is a huge crater so it’s probably really deep and these are mountains so they’re probably high, but nobody really knew that this dichotomy was so pronounced that you had this like, lowland here and this highland here.\textsuperscript{18}

Indeed, the visual appreciation of images alone had several problems. The possibilities for interpretation were on the one hand, limitless, as “lookiloo” looking could suggest any number of stories to support any number of hypotheses about what was going on in the picture. But on the other hand, the possibilities for interpretation were also limited: after all, before MOLA data, there was no way to quantify the dichotomy between the highlands and the lowlands. To that extent, combining visual with altimetric data to provide “the third dimension” revealed otherwise indiscernible features as they ‘popped out’ of the new dataset. Further, it could also quantify what could only otherwise be inferred from visually-derived hypotheses about features such as water-produced features such as gullies and run-off. As Sam put it, the “The stories are quantifiable, [so] the hypotheses aren’t so poorly constrained.” An appeal to this mathematical aspect of the data was believed to support the analytical move from “seeing a line” to “seeing a gully” to “seeing a deep gully” -- to, potentially, “seeing a deep gully formed by water run-off.”

\textsuperscript{17} Note that this scientist uses the term “control” in the experimental sense, as in a “control group” that grounds an observation.

\textsuperscript{18} Interview, David, May 24 2007.
Thus combining datasets, MER scientists believe, enables them to narrow down on a hypothesis through a confluence of factors derived from multiple corresponding -- and agreeing -- datasets. No wonder that more than one graduate student on the mission is engaged with combining ground-based Rover data with data from the orbiting Mars Express Context Camera and the Mars Reconnaissance Orbiter High Resolution Camera “to better constrain” her hypothesis. The commitment behind this constraint is a belief that the datasets would not co-register were there no naturally existing correspondence between them -- and were this naturally existing correspondence not altered in the course of data manipulation. As one scientist explained, “you can’t make a mosaic unless all your pieces are from the same puzzle.”

This pixel-pushing practice thus supports a correspondence theory of representation at the same time as it is believed to constrain interpretations of an imaged object.

Here again, we see a relationship between constraints and self-restraint, a disciplining of the individual scientist along with their data. Speaking with Katie, a graduate student on the mission who was engaged in co-registering Rover-derived data with orbital data, I asked her if it was possible to just do a visual comparison between the two sets of images to align them; she strongly objected:

Visually it really doesn’t work, actually. Because they’re in completely different scales, so you really have to [do the comparison] mathematically, and it’s much more scientifically rigorous to do it that way, anyway… because if you look at two images and you say, oh these two look the same, you can’t really, it’s hard to get that published… scientists are like, “that’s subjective! They might look the same to you but they might look completely different to

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19 Team Meeting, February 14 2007.
somebody else!” Science has to be backed up by… statistically significant results in order to make sure that you’re making the right interpretations.  

Katie begins by explaining that a mathematical approach to her co-registration problem is essential for the result to be considered “scientifically rigorous.” This rigor is then associated with the difficulties of publication and the complexities of subjective observation. The appeal to mathematics, to rigor and statistics, supports her analysis as “the right interpretation,” allowing her to make suitably constrained changes in evidential context for her results. But Katie’s language of subjectivity, publication, peer evaluation, rigor, and “the right” interpretation also invokes the scientific person, the practices and identity of the responsible scientist whose interpretations can be trusted and who she hopes to become. The constraint upon pixel pushing enforced by mathematics also shapes and constrains the pixel-pusher’s identity as a responsible scientist. 

In a related case, Sam spoke of the rhetorical importance of quantitative explanations as providing evidence that peer communities of scientists can trust as suitably constrained interpretations. He recalled a situation in which climate modelers, who worked with simulation software, were at odds with geologists, who visually interpreted image data, over how to model the environment of early Mars. 

There were a number of reasons why people were so sure that precipitation and runoff weren’t happening was because [the atmospheric modelers] couldn’t make it work. Geologists could only offer a qualitative explanation [based on image interpretation, but the modelers would say] … you can’t show us any evidence for that, you just sort of handwave at your pictures … . You had all

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20 Interview, Katie, June 21 2007.
these climate modelers armed with numbers and physics against all these geologists armed with only our pictures…

The interpretation of gullies and runoff looked suspiciously like ‘lookiloo’ looking at first, and the mathematical model was believed over the visual. But once MOLA data was combined with visual data from orbital instruments on Viking and Odyssey, the geologists had the quantitative measurements to back up their visual interpretation and enable a move from “we see pictures” to “we see gullies.” At this point they could charge the atmospheric scientists with believing too much in their quantitative model, and not tempering this approach with caution and visual experience. “We went [back] to the climate modelers and said, now it’s your problem,” Sam recalls.

An interesting counter-example might be illuminating here, as it provides an alternative view of working with Rover data that purports to be unscientific without appeal to constraints of any kind. In a visit to the Cornell-based Mars Exploration Rover team, the owner of a fan website displayed spectacular images of the Martian terrain generated by his group’s own, home-built software tools. The language he used to describe these images, however, invoked the artistic, the aesthetic and even the fraudulent. For example, he introduced an image as “stuff that you guys wouldn’t put together as a public image because it doesn’t make sense, but then again it’s pretty, so why not?” Discussing an animation program for building 3D images he called it “not easy for a temperamental artist like myself.” His images added clouds, ducks, and model Rovers into the field of view, and even when an image appeared seamless he confessed it to be “a complete fraud” because there were “bits of horizon missing so I just added a few more.” In another case he digitally stitched together Navcam and

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21 Interview, Sam, May 24, 2007.
corrected Hazcam images into a mosaic, calling it “really, really cheating … you [scientists] sure as hell can’t get away with this but we [laypeople] can.”

The discussion of cheating here should not be interpreted as illegitimate activities with these images; the presentation was well received, with the delighted and amused scientists in the room even asking what they could do to better supply the group with images suited to their purposes. But if the webmaster had stood before the scientists with the same images and claimed to be ‘doing science’ with the same images, the mood in the room might have been different. His language and description of his own pixel-pushing activities point to a different persona: as a self-professed artist, he can take liberties with visual data, and in creating his images -- importantly -- replication or adherence to mathematical principles are emphatically not virtues. In this case, the irrepli
cability of his image-making techniques and his pictures’ inability to be combined with other datasets is a marker of individual skill and creativity. This stands in contrast to the approach required of the scientist, where replication, mathematical functions and the superimposition of other data sets affirm the integrity of the interpreted image and, by implication, the pixel-pusher who crafted it.

It is also worth noting here that the co-registration of data has a political as well as a mathematical and moral dimension. After all, Bob’s attempt at co-registering HRSC and OMEGA data was not entirely successful. After two hours of working with the data sets, opening them in three different image editors, and performing various transformations, the two data sets still would not align. Cursing at his screen, Bob explained the problem to me as one of international politics:

Part of the problem with these planetary data sets is this HRSC data is in a fundamentally different projection than the OMEGA data is … they [the OMEGA team] actually provide these images that show the latitude and

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22 Cornell Astronomy Colloquium, June 20, 2008.
longitude information for each pixel, but it’s in a different type of projection than the HRSC data is... The HRSC was built by the Germans and the OMEGA was built by the French, and you know how well they get along.\textsuperscript{23}

Despite their co-location on the European Space Agency’s Mars Express orbiter, the two instruments’ different co-ordinate systems for Mars based on historical and nationalist reasons leads Bob to a scientific impasse.\textsuperscript{24} While he could massage the data in such a way as to force it to coregister, these changes would not be mathematical or replicable. Publicly presenting the not-quite-coregistered images to his colleagues at the Seventh International Conference on Mars a few months later, Bob admitted this issue, identifying the problem with aligning the two datasets as not due to his deficiency or to Mars’ irregularity, but instrumental inconsistency. As he put it, “it’s great to have all this data, but of course not all data sets are inherently registered, so you have to do some gymnastics sometimes.”\textsuperscript{25}

\textit{Mars Analogs}

In a science that depends upon interpretation and extrapolation of image data of distant environments, planetary geologists self-impose limitations on their \textit{drawing as} activities to constrain their interpretations. Asking “is it repeatable?” or “is it combinable with other data sets?” places restrictions on data manipulation such that the resulting images, \textit{drawn as} to incorporate a broadened evidential context, can be taken as “evidence of anything.” But a quantitative approach is not the only constraint

\textsuperscript{23} Interview, Bob, June 5, 2007.

\textsuperscript{24} In the case of HRSC and OMEGA this politics may be due to different national borders, but proprietary data rights can also limit a scientist’s ability to co-register data sets, such as in the case of the laser altimeter and orbital camera, two instruments on board the Mars Global Surveyor orbiter. Given, also, the differences between minerologists and geomorphologists in the planetary science community, aligning both sets of data -- spectral and visual -- can make a case that appeals to both sides of the divide. This gives increased significance to the decision to treat the instruments on board the Mars Exploration Rovers as a unified suite of instruments that permits the integration, comparison and co-registration of data across instrument teams. Such a move allows embeds the team’s values for constrained scientific analysis in the Rover’s very construction.

\textsuperscript{25} Fieldnotes, Seventh International Conference on Mars, Pasadena, CA, July 9, 2007.
that can quell the accusation of “lookiloo” looking: another important piece of the puzzle is appeal to experience and judgment gained from working with Mars-like environments on Earth. For the Mars Rover scientists, experience is derived not only from experience with the interpretation of images, but also and especially from experience gained in the field. This kind of experience is called into play when justifying the robustness of an interpretative claim about the Martian environment, drawing Mars as Earth-like in the process.

“The field” has an intriguing status within the practice of planetary geology. While the Rover scientists talk about wanting to “get their boots dirty” by stepping into their Rovers’ tracks on Mars, none of them have physically been there. Instead, the Rover scientists make use of field or laboratory studies on Earth that they consider analogous to the sites they are examining on Mars: in a curious juxtaposition to the digital nature of Rover data, these Earth-bound sites are called “Mars Analogs.” As described in Chapter One, the use of Earth-based fieldwork has been an essential part of any planetary geologist’s training from the early history of the field. Similarly, field techniques such as geological mapping must be practiced on Earth before they can be applied to extraterrestrial sites like Mars or Europa. As Don Wilhelms explains in Greeley and Batson’s classic Planetary Mapping (1990), translating Earth-based experiences to other planets is complicated by the fact that while maps of the Earth moved from ground-based surveys to the contextual “synoptic” view provided by

26 Maria Lane (2005) also notes the importance of ‘going into the field’ to early observations of Mars; this largely consisted of parties of astronomers going to remote sites from which to better view Mars through their telescopes due to the variations of atmospheric depth and opacity and light contamination from cities. At the Lowell Archives I examined a suite of evocative letters between the Slipher brothers as one was sent to Chile with delicate new filters through which to observe and photograph the canals. Typical of field accounts, these letters were as rife with descriptions of local people and customs, the difficulties of travel and requests for news from home as they were replete with technical descriptions of ongoing observations.
aircraft and satellites, planetary images have the opposite approach, moving from fly-by images, to images from orbit, to ground-based Rovers. It is generally recommended that the eye of the planetary mapper be trained from terrestrial experiences, as this is how young planetary scientists can best acquire expertise about how what is on the ground is seen from space. This training involves ‘reading’ orbital images, drawing on them to transform them into maps identifying particular types of terrain, stratigraphic layers or mineral deposits, and taking these orbital images into the field, walking carefully around the area on Earth to better understand how what is on the ground is seen from space (Figure 66). As Stefan Helmreich (2009) has claimed in his analysis of astrobiology, through these practices the Earth becomes something

Figure 66 This classic photogeology textbook asks students to draw onto stereo aerial photographs to identify features in the landscape caused by glacier erosion. (Miller, 1961)

27 The purported value of this synoptic view is heavily critiqued in Science Studies, especially by feminist scholars: Donna Haraway calls it “the god-trick of seeing everything from nowhere.” (1991, 189).
more than itself, a representative of ‘planets’ more generally as a category, and
laboratory through which we can explore what planetary environments might be like.\textsuperscript{28}

The Mars Rover scientists employ particular parts of the Earth as Mars-Analog
sites, and both refer to and visit them relatively regularly. These include Rio Tinto in
Spain for its high-iron and highly acidic groundwater, elevated ultra-dry deserts in
South America, and research in Antarctica or the high Arctic. These Analogs are not
meant to fully replicate or provide a simulated Martian environment. Instead, the
language of analogy invokes another constraint upon the interpretation of digital
image data. For example, a meteorite expert used “samples we have in our labs” to
develop a hypothesis about how particular meteorites on Earth -- and by extension,
one under discussion on Mars -- undergo changes when exposed to water (July 8
2007). Another scientist pointed to the distribution of meteorites on Antarctica as a
case study that would enable the scientists to “confirm or refute the ‘strewn field’
hypothesis [on Meridiani] …[and] assist in confirming the meteoritic character of
Santa Caterina [a rock target].”\textsuperscript{29} And a senior scientist and respected planetary
mapper insisted to his colleagues at a Team Meeting, gesturing to the ripples in the
Martian terrain visible in an orbital image of Mars, “Of course if we’d seen this image
on Earth there’d be no question that this would be formed by water.”\textsuperscript{30} In these cases
interpretations of terrestrial materials suggest, support or challenge various
interpretations under consideration about Mars.

\textsuperscript{28} I am grateful to Professor Helmreich for allowing me to read these chapters before their
publication.

\textsuperscript{29} End of Sol May 23, 2007.

\textsuperscript{30} Team Meeting, February 13, 2008.
The case of the silica sinters at Home Plate is revealing for how the scientists use knowledge of analog sites to constrain interpretations of Rover data. One of the first discussions about the oddly textured rocks *Spirit* discovered near the Tyrone area, which revealed upwards of 90% silica content in spectral analysis, was whether or not the silica was a coating or an actual constituent of the rock. If it were a constituent of the rock, one could say that the rock was built up by silica deposited within a hot spring environment; if it were a coating, it might be a remnant of some transformation to the rock’s surface effected by steam or some other kind of hydrothermal system. One of the scientists, Nick, suggested that the silica was a kind of deposit called a sinter, and produced two possible hypotheses for the rocks’ formation as “distinguishable from one another as a function of silica content as a function of depth.” But another interjected that his second hypothesis was not necessarily “unique,” claiming, “you can see in Hawaii for example, there are coatings of opal and silica that are sitting on top of [the grains that make up the rock].” That is, the grains that make up the rock could themselves be coated with silica, not just the exterior of the rock itself, and this would be indicative of yet another geological process. Thus the depth of silica presence within the rock could not constrain his hypothesis, could not allow him to move to an observational report with a more distal evidential context. Another scientist agreed, “I have exactly that from Hawaii… where I scooped up sand and [examined it] under a microscope,” to which another assented, “the Hawaiian silicon coating is a classic.” Interestingly, this talk about Hawaii is actually talk about Mars, providing the constraints for what the silica readings at Home Plate could mean. Ultimately, another scientist spoke up, “the presence of silica does not constrain a depositional environment … Silica is just too complicated, too ubiquitous to nail it down…. .”

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31 End of Sol May 16, May 23 2007
that could have produced this rock was one in which deposition was taking place; moving from “we see silica” to “we see sinters formed under a past depositional environment” would be judged an invalid move.

The conversation then centered around what features the science team could look for that would “constrain a depositional environment,” in order to generate a series of observations that the Rover and human team on Earth could accomplish that would help to nail the hypothesis down. The outcome of this exchange about Hawaiian rocks was a series of observations on Mars to see whether the rock was made of silica all the way down, including crushing a sample with a Rover wheel to analyze its interior with Microscopic Imager pictures. Scientists also turned to other Analogs in which silica deposits existed to look for clues in the Rover’s wider context. At a Team Meeting several months later, Gwen put up Powerpoint slides of sinter systems on Earth in Wyoming and Nevada; she then suggested she would “go back and get started on this again,” this time at a “terrestrial analog site… in my back yard, Lake Tahoe…”

Experiments conducted on Earth are also called upon to support, constrain, or open up a particular interpretation of the Martian case in question. These are not the product of knowledge of a field site, but are rather produced in a laboratory, often altered to approximate some aspect of Martian conditions. Indeed the majority of Mars Rover scientists maintain both active digital laboratories in which they perform data processing or operational duties and analog laboratories of all shapes and sizes which sport equipment from spectrometers to wet labs, pressure chambers to chemical apparati, to sandboxes with simulated Martian soil which churn under surplus Rover...
wheels. Susan Lee, for example, has several laboratories under her care: one in which she builds new spectrometers to test and eventually propose to upcoming missions, the other in which she performs chemical experiments to approximate weathering conditions on Mars. Susan used this laboratory to constrain her interpretations of Tyrone’s changing soils: or, as she put it, “to be sure this change is real.”

We need to be sure this change is real, so I checked several factors… One possible change could be the dehydration of hydrous salts… I did an experiment starting with seven water ferric sulphate …

The experimental results suggested that ferric sulphate could change, and determined under which conditions the results she saw in the Pancam spectra might be effected. Calling upon the laboratory data to constrain her interpretation of the Pancam spectra, Susan could therefore move from an observational report about “seeing changing histograms” to “seeing the dehydration of hydrous salts.” Describing the experiment to me in a later interview, Susan called it “observation and laboratory experiment put together, and some common knowledge.”

While Susan works in her chemistry lab to constrain her drawing as activities with Pancam data of Tyrone, MER scientist Pierre Lefebre tends to a suite of greenhouses on the roof of his institution’s Astrobiology center in which he studies “synthetic microbial communities.” In the greenhouse are rows of flat red rocks, cordoned off into squares and submerged in bubbling liquid (Figure 67). Pierre explains the experiment:

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34 Team Meeting, February 14, 2007.
The cyanobacteria that live in these [here, analog] mats are just excellent examples of ecosystems that go back close to three billion years ago. That’s exciting for two reasons. It’s an obvious target to study to help us interpret what we see in the rocks … this is probably a theatre in which a lot of early evolution occurred…. This is the microbial analog of a tropical rainforest.\textsuperscript{36}

In Pierre’s words, growing cyanobacteria to approximate an early Earth environment can “help us interpret what we see in the rocks.” That is, appealing to these Earth-bound, 21st century experiments can “constrain” a scientist’s interpretations of ancient materials. As the tanks churn around us Pierre

Figure 67 Flats of cyanobacteria in a greenhouse in an astrobiology laboratory simulate an early Earth environment.

\textsuperscript{36} Interview, Pierre, May 24, 2007.
enthusiastically relates how, by fostering these ecosystems, his research group can then “tease apart the history that’s recorded in these things” to better understand how life on Earth arose. This is one of the main research tracks of the NASA Astrobiology program, but Pierre also suggests,

… Even that focus on early Earth is very relevant to Mars because … the most habitable environments on early Mars could have been at a time when life was developing on the Earth, so what we learn about the earliest history of the biosphere on the Earth is directly relevant to what we might expect or look for in these ancient rocks on Mars.

Many layers of analogy animate this work. Growing these cyanobacteria on rocks from material gleaned from the salt flats in southern California, the laboratory uses contemporary materials to approximate early Earth. This analog early Earth can also be seen as an analog for early Mars. And as he describes the system of cyanobacteria, brine shrimp and growing crystallized rocks, Marc refers continuously to the analogy of a rain forest: identifying the “canopy,” the “animals,” the “food chain,” and the “diversity” of the organisms living in the “ecosystem” in each tank.

But further, each of these analogies can be called upon as a constraint upon interpretation of Martian data, by providing experimental results from Earth-based chemistry, geology or microbial life that can support expanded evidential contexts for Martian observational reports.

Collecting rock samples on Earth is another important aspect of Rover work on Mars. When I visited the meteorite laboratory at the Smithsonian Natural History Museum in Washington, DC, the Rover team scientists there brought out a few small

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39 He does, however, suggest that this analogy is somewhat misleading: “To be historically proper you should say that a forest is analogous to this [cyanobacteria-filled vats] because this came first!”
samples of meteorites believed to be Martian rocks, including the famous ALH84001 described in Chapter One. But even without access to rocks from Mars (which may be contaminated from their forced ejection, journey to Earth and exposure to the Earth’s atmosphere and biosphere) scientists turn to samples of the minerals they see on Mars collected on Earth. Both Ben and Bob were quick to pull out their field samples of terrestrial rocks that betrayed some kind of similar quality, whether in mineralogy or

Figure 68 Drawers of rock samples collected on Earth support field science on Mars.

texture, to the ones they were observing on Mars. During my visit to the US Geological Survey offices in Flagstaff, one of the MER scientists took me on a day trip to the Grand Canyon, where he described the geological features to me through Martian eyes: the diagonal sectioning on the canyon walls were analogous to the layering patterns at Victoria Crater, while the fine dust on the trail was like the dust on Spirit’s solar panels. When another scientist I visited opened drawer upon drawer of carefully collected samples from field sites on Earth, explaining to me that he liked to “get samples, get things in my hands,” (Figure 68) I asked if this made the kind of
science he did on Mars seem somehow poorer, not as textured or somehow real in comparison. He disagreed: “Even if I can’t get samples [from Mars] in my hands, they’ve [the Rovers] done a good job.”

As the Mars Rover scientists move back and forth between their digital experiences of Mars and their physical experiments on and interactions with Earth, this complicates the border between the lab and the field and allows for some mobility of techniques and interpretative frameworks between the two. Scientists are simultaneously in the field and the lab whether they are at their desks or immersed in an analog environment. When Pierre is in his wet lab or Nick is at his spectrometer, they are by simulation “in the field” on Mars; when Ben is at his desk manipulating an image so as to see something new, he is also “in the field” on Mars; similarly, when Gwen is “in the field” at Lake Tahoe or Yellowstone she is also “in the lab” in the sense that the environment she seeks to understand (Mars) is only being partially simulated (on Earth). After the discovery of the ‘blueberries’ on Meridiani, graduate students at Cornell flooded their Athena Science Team advisor’s office with hundreds of spherical hematite concretions collected in Utah in celebration, effectively turning the office into “the field” on Mars. And it is noteworthy that the Principal Investigator regularly dresses in jeans, a plaid shirt and cowboy boots, giving the impression (and often expressing aloud) that he is ready to pick up his hammer and walk out into the field, right into the images of Mars on his screen. Such analog work builds a repertoire for Mars, through experience on Earth, that can be called upon to support hypotheses and interpretations of the Martian environment.

40 Interview, Bart, June 20, 2007.

41 I am indebted here to Robert Kohler’s (2002) description of field biology’s appropriation of laboratory-inspired techniques in the scientization of field science.
Constraining The Scientist

At a Team Meeting in July 2007, Susan was again on the agenda to discuss her preliminary Pancam results on a target other than Tyrone. I recalled that in her presentation in February, Susan had appealed both to the mathematical transformations of Pancam data with decorrelation stretches and histograms, and to experiment with ferric sulphates on Earth to constrain her hypothesis about the history of Tyrone. But when Susan presented her study of another feature at the team meeting in July 2007 and this time only presented Pancam spectral work, her conclusions were met with skepticism by her audience of fellow teammates. In the question period following her talk, Bob accused Susan of “over-interpreting,” saying, “I know some of the spectra you're showing in the visible near-infrared had that pretty steep slope so those were obviously dust-affected.” His challenge was rooted in his sense of the field environment: as he saw it, Susan was interpreting her spectra without considering the practical field context in which they were embedded, such as which minerals would be seen together and how much dust-contamination that might imply. Fresh out of his own laboratory, Nick asked Susan, “Are there any lab data … that support or sort of suggest what that feature is attributable to?” Such questions, amid others from the audience, revealed a discomfort with appealing to the mathematical side of the image alone with equations and transformations of image data.42

This exchange exemplifies the importance of counterbalancing an appeal to both kinds of constraints in interpretation: the digital and the analog. Going too far on the judgment side of things becomes a question of “lookiloo” looking, but going too far on the computational side can also place the scientist into a situation of circular logic with no window onto reality. Thus both methods of constraint-generation are

42 I caught up with Susan following the presentation to see how she was feeling, and if the questioning by Bob, Nick and other senior (male and female) scientists on the mission was discouraging to her. I was surprised to note that she seemed enthused about their feedback, as it gave her an idea of what further work she needed to do to better constrain her hypothesis.
often called upon in practice, such that each acts as a constraint upon the other. Too much reliance on visual interpretation from experience in the field on Earth can be challenged if there is no digital data to support such interpretation. But as one Athena Science Team member put it, “Bright kids can make computers sing and dance, now they have much better technical skills, but what they don’t have is 25 years of being in the field.”

Similarly, David articulated that he needed to be cautious in presenting data from his simulated model of Mars as an interpretation of the Martian environment, “Computers only do what you tell them to do.”

However, the importance of balancing these kinds of constraints when promoting an observation to a different evidentiary context can also place scientists in a complex bind with respect to their data and to their interpretations, as it did with two scientists -- Nick and George -- who work with the MiniTES spectrometer. The MiniTES instrument is a thermal spectrometer that picks up in the infrared shortly after Pancam’s filters leave off. Like the elision between the cameras and spectrometers discussed above, the MiniTES is compared in some respects to the Pancam, with each “pixel” containing an infrared spectrum of that location on the surface, and when I interviewed one of the principal engineers on the instrument he likened the MiniTES detector to an eye. Like the Pancam, MiniTES collects data through different filters, also called bands, but sports 167 of these bands instead of only 13, which is what generates such detailed spectra (compare to the Pancam spectra Ben works with in Chapter Two). And instead of capturing a wide range of photons that can be displayed as a picture of the field, the MiniTES captures data from only a

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43 Interview, MER team member, June 7, 2007.

44 However, the computational can also be called upon to provide elements of ‘experience.’ When questioning whether or not the bright band around the rim of Victoria crater could be ascribed to a water-line, a team member suggested something of a digital experiment. One of his colleagues had written a program that would fill any given volume with liquid: he suggested that his colleague should take the pictorial data of Victoria Crater, generate a 3-D volume, and “fill it with water,” digitally. This was promised to provide evidence as to whether or not the band was consistently located the whole way around the rim, constraining the hypothesis about a water-filled Victoria Crater.
small, focused spot on the Martian surface: this operation is called a “stare.” The standard display of MiniTES data is as a rather noisy graph, and its operators fondly call it a “squiggly line instrument.” But while the MiniTES provides data that is highly numerical, its operators insist that its “interpretation of these squiggly lines is as much an art as a science.” One must therefore develop a “feel for the spectra.”

The “squiggly lines” that the MiniTES generates are the product of “seeing” a number of different kinds of minerals on the surface of Mars, each with its own unique spectrum that when combined with other minerals or varieties of minerals, produces a new and unique graph. The question for the scientist is, what combination of spectra from which configuration of minerals would combine to create exactly this particular squiggly line, with peaks and dips in these regions? Unmixing or analyzing these spectra into their component parts is called deconvolution or sometimes, spectral mixture analysis (SMA; Figure 69). Spectroscopists examine hundreds of samples of mineralogical spectra to learn which peaks to expect and what such peaks might correspond to in terms of mineralogy (recall here the “blueberry finder” curve on Pancam). Nick explained to me that being a good spectroscopist required having:

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45 This “feel for the spectra” is not limited to MiniTES. Sitting in on a training session where a MER scientist was instructing an undergraduate student on deconvolving spectra from a different spectrometer, I witnessed her frustration as she went back and forth between how the software was deconvolving her spectra, and how she was supposed to interpret it. When the computer presented one possible combination of mineral components that could make up her spectrum, she exclaimed, “it’s wrong! I know what it’s supposed to be!” and later called the computer “completely useless,” finally accepting a computationally-derived deconvolution with, “it’s the closest thing that this [software] and I actually agree on.” Still, her intuition for the spectra was not yet perfectly honed. She told me that water bands were “characteristic,” making quotation marks with her fingers to indicate irony, while she was told that these bands would be easy to spot, they weren’t really in practice. Finally, when I asked her how to read a spectrum, she laughed and said, “[The scientist] tells you how!” indicating the importance of her advisor’s considerable expertise in interpreting the computational products. Indeed, when he sat by her side and helped her to find the mineral jarosite in a spectrum, he said under his breath, “I can almost taste it.”
…a photographic memory of these shapes, recognizing curves and features as shapes, being able to discern features and remember comparable ones … I can tell by eye my brain can do this better than a computer.46

Nick finds this system compelling for being able to “read” a spectrum on the fly. This is particularly important in the day-to-day operation of the Rover, where there is no time for the lengthily deconvolution that could give precise measurements but there is a need for tactical interpretations that could suggest an imminent Rover drive or the use of other instruments. Further, the very fact of the dips, shoulders and spikes in the graph indicate that some mineralogical phenomenon is present. As Nick insisted, “the spectra don’t lie. You can interpret them differently but, I have this squiggly line, they’re either there or they’re not.”47

46 Interview, Nick, June 6, 2007.
But while the fact of the squiggly line -- like the “splodges” of the solar neutrino detector graph -- is rarely contested, moving from this observational report to a more distal one with a different evidentiary context proves challenging. George, Nick’s former doctoral advisor, expressed to me the value of his and Nick’s honed “feel for the spectra”. As he put it, “I can look at a spectrum and say, that looks like a Wishbone Class spectrum, it’s got three features here …”\textsuperscript{48} That is, for Nick and George, moving from “we see a squiggly line” to “we see three relevant features in this squiggly line” to “we see a Wishbone Class rock” is a matter of knowledge, experience and skill. But George found it extremely frustrating when trying to present his work to his colleagues. When he tried to direct their attention to the tiny, diagnostic peaks and shoulders in a graph, they were transfixed by the large swoops and dips which he knew from experience to be unimportant or even artifactual. He could not even get them to move from seeing the squiggly line to seeing relevant features, let alone seeing them as evidence of anything.

In an attempt to convince his MER peers to pay attention to these tiny details, and to teach them how to read the spectra, he tried cutting out huge patches from the graph, only presenting the parts that were relevant to discussion. But this selectivity seemed disingenuous to him, recalling his frustration with the limitations of qualitative photogeology (the same “lookiloo” looking that frustrated his long-time colleague, Sam). George therefore turned to the quantitative side, looking to build a home-grown software suite that could deconvolve the spectra more perfectly and thus mediate this anxiety. Equipped with spectral libraries (atlases of spectra from known minerals on Earth provided by the home institution or by national organizations like the USGS or the Smithsonian), the software could factor known curves out of the MiniTES graph to

\textsuperscript{48} Interview, George, June 7, 2007.
determine which minerals were present and in which quantities. But even George’s computational deconvolution program generated skepticism. While the program could provide a suggested interpretation for an existing curve, it often returned improbable combinations of minerals, such that the George would have to issue the contradictory claim, “it’s a good fit but I don’t know what’s real.” The computer could also present too fine a level of detail. George recalled:

I’m trying to get across this deconvolution and I gave this talk and people just glazed over … . They’re going, well wait a minute, 3% Microcline and 2% Siderite and 2% Bronzite and 1% Hidenburgite and 1% this and 1% that, and everyone in the audience was like, I don’t believe that, there’s no way you got the sensitivity to actually see 2%. So this figure convinced people that, you guys don’t know what you’re doing, instead of like wow, we’ve got this great instrument we’re getting these cool spectra we can see all this neat stuff, it had the exact opposite effect of, I don’t believe any of these numbers, therefore I don’t believe anything you’re telling me.

Precision is not always a virtue. Indeed, this story recalls the reception of Lavoisier’s chemical measurements to several decimal places that so offended his colleagues in England and Scotland, who found such attention to insignificant figures detracted from rather than supported his argument (Golinski, 1995; see also Wise, 1995). In a similar vein, when George started rounding numbers up and dumping any

49 This turn to the quantitative is not extraordinary given George’s specific and deeply considered ideas about scientific image-making, especially with respect to the use of color to display thermal data and public understanding and potential misinterpretation of images, issues I will return to in Chapter Eight. George is a tremendous fan of Edward Tufte, author of *The Visual Display of Quantitative Information*, who he met at one of the latter’s public lectures. At the time, Tufte expressed frustration with NASA’s use of false color imaging. George recalls his visual hero saying something to the effect of, “If it’s art it’s okay, if it’s science it should have a scale!” In each of his images that we viewed together, George pointed out to me that they always include a scale. The scale and the analytical rigour it entails are indicators, for George, of a process of image-making that can be considered scientific and not misleading.

50 Interview, George, June 7, 2007.
mineral that registered under 5% into a category called “other” in an attempt to “make these data intelligible and interesting,” he was further frustrated to find that his colleagues merely wanted to add up his percents and challenge him as to the remainder. He then tried just mapping mineral abundances on a Navcam mosaic, but that produced skepticism as well. As he said,

I found myself constantly struggling with, if you showed the spectra half the audience would fall asleep, if you showed this colored map the audience would be like, how do you know these colors mean anything, and unfortunately we ended up arguing about the spectra instead of the big picture … 51

George’s frustration here illuminates how the Mars scientist can get caught between different levels of externality in their observational reports. George cannot just present the final result -- the Navcam mosaic -- without his colleagues questioning the evidential context of his claims. But he also cannot present his base observation of the spectral graph to his peers for their interpretation, as they lack the ability to read it. Here the dual constraints of mathematics and intuition combined constrain the scientist along with his data, such that no move among distal observational reports can go uncontested.

When I visited Nick, he was beginning a set of laborious Mars Analog observations that had him both excited and cautious. The observations were aimed at alleviating the keenly-felt underdetermination of a fraught hypothesis based on MiniTES observations: that of the possible detection of past life on Mars. Nick’s honed skills of spectral deconvolution had led Spirit to one of the most significant discoveries on the MER mission to date: a patch of silica-rich sinters in an area near Home Plate that the team nicknamed Silica Valley. Reviewing the spectra that returned from the patch of soil Gertrude Weise, Nick noticed a small “bump” in the MiniTES

51 Interview, George, June 7, 2007.
spectrum around the 8 micron region (Figure 70). Nick’s expertise led him to identify this bump in the spectrum as relevant data in the first place, as signal instead of noise. In our interview he points it out to me in the middle of the squiggly line, directing my attention with gestures at the screen,

It starts to have this feature here [points to a part of the spectrum] … it’s what a spectroscopist would call a shoulder … by the time you go to these siliceous sinters with their very distinctive texture, what I’m discovering is that that shoulder turns into a fully resolved minimum, an absorption minimum there [points to the 8 micron spike in the spectrum] … 52

Figure 70 MiniTES spectra and annotated navcam locating Gertrude Weise. A red vertical line on the graph marks the “shoulder” of interest.

52 Interview, Nick, June 6, 2007.
In this observational report Nick moves quickly from identifying a “feature” as a “shoulder,” then as “an absorption minimum,” with its implicit identification as a measurement of the quantity and quality of light the object reflects. And even identifying a “feature” is an achievement requiring skill: when I locate another spike in the spectrum, he dismisses it: “That’s in the lab, that’s an artifact that wasn’t removed, so that’s a total garbage thing.”

Silica has many different crystalline forms, corresponding to different formational processes, and these each produce different “squiggly lines” on MiniTES observations. Nick used a combination of his computational resources and his experience with spectrometers to identify the kind of silica that would produce the 8 micron feature. At first he thought that the peak was due to quartz, but loading up the spectrum for quartz from his spectral library, the visual comparison revealed a difference. Again in our interview, he loads the two spectra side by side, that of quartz and that from Gertude Weise on Mars, and makes similarity and difference judgments based on the two squiggly lines:

This peak [on the quartz spectrum] is what I was thinking I was seeing in this spectrum [Gertrude Weise], so I thought this black peak [quartz] is this purple peak [Gertrude Weise] but it’s shifted so there’s no way that it’s due to quartz.

However, Nick recalls, when he loaded the “lab measurement” of “classic amorphous silica,” he detected a match between the location and pronounced nature of the bump on both spectra. Describing the connection to me, he appealed to what he knew about amorphous silica from fieldwork on Earth: “you can go to these fumerole environments in Hawaii and see this … effect on basalts,” he explained, “[fumerole
environments] leave behind a spectrum that looks like that [Gertrude Weise].” 55 The Gertrude Wiese spectrum was also, curiously, similar to spectra obtained from small, scattered, clumpy rocks that the team called “nodules”, strewn in the area. It is worth noting here that certain types of amorphous silica are formed, on Earth, under biological conditions: some types of opal, for example, can be formed biogenetically, unlike quartz which is crystalline. At this point, Nick’s observational report -- and achievement -- had changed from “a feature” embedded in a squiggly line, to “an absorption minimum” via experience with spectral readings; from there to “a silica rock with an amorphous, not a crystalline structure” via the constraint of mathematical and experiential judgment of comparative spectra; to “a rock produced on Mars under fumerole conditions like those in Hawaii on Earth.” The next step was to be able to either prove or deny the claim that what was visible in the Gertrude Weise spectrum and others like it was “evidence of past biological activity on Mars” (Table 1).

In the months that followed this initial discovery Nick resorted to further combinations of the techniques described above to constrain the hypothesis about the biotic origin of the silica deposits. He mathematically “cleaned” the spectra from Mars with algorithms that could account for dust, compared and computed with spectra from his spectral libraries. He co-registered MiniTES stares with Navcam and Pancam images to show exactly where the high silica readings were coming from on the surface. This work was complemented by extensive laboratory studies of terrestrial silica samples, which Nick credited as “absolutely essential to understand what I’m seeing”56 on Mars. Consistent with the collective approach of the Rover mission, Nick did not work alone: Gwen sent him spectra from sinters that she had collected in the Yellowstone area, and another MER scientist, Allan, sent him boxes full of silica sinter

55 Interview, Nick, June 6, 2007.
56 Interview, Nick, June 6, 2007.
Table 1 Comparing externality of Rover observational reports with the solar neutrino case. Note that movement between degrees of externality requires drawing and related work with digital or analog materials as described to counter underdetermination or accusations of “lookiloo.” Adapted from Pinch, 1985.

<table>
<thead>
<tr>
<th>Degree of Externality</th>
<th>NEUTRINOS</th>
<th>TYRONE</th>
<th>SINTERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>High externality</td>
<td>“Solar neutrinos”</td>
<td>“Salts deposited by hydrothermal activity”</td>
<td>“Amorphous/Opaline silica produced in fumerolic environment”</td>
</tr>
<tr>
<td>Increased externality</td>
<td>“Argon atoms”</td>
<td>“Ferric Oxide”</td>
<td>“Silica sinter”</td>
</tr>
<tr>
<td>Low externality</td>
<td>“Splodges on a graph”</td>
<td>“Two kinds of white soil”</td>
<td>“A feature in the 8 micron region”</td>
</tr>
</tbody>
</table>

Table 1: Comparing externality of Rover observational reports with the solar neutrino case. Note that movement between degrees of externality requires drawing and related work with digital or analog materials as described to counter underdetermination or accusations of “lookiloo.” Adapted from Pinch, 1985.
deposits that he had collected in the field. When we met for the first time Nick had just received this box of samples; we sat together in his laboratory as he loaded the rocks one by one into the MiniTES-like spectrometer that he had built as a graduate student, attempting to build a spectral library of different kinds of Earth-bound amorphous silica deposits to compare to the Martian examples (Figure 71).

This laborious process did produce some of the experimental results that Nick needed to add “robustness” to his interpretation of the silica sinters. In a presentation at the Team Meeting in July of 2007 he brought together spectra from “Mars, Earth-Hawaii, and Earth-Yellowstone” to show a “very robust and undeniable… match in this 8 micron feature”\footnote{Team Meeting July 7, 2007.} between the Yellowstone and Martian examples of sinter.

Figure 71 Placing sinter samples into a laboratory spectrometer to better “understand what I’m seeing” in MinTES spectral results from Mars.
deposits. At the following meeting six months later, he again went “from Mars to Earth” and showed the “very interesting, very rich spectra from Mars” alongside the ones he had generated with his spectrometer in the lab. Nick declared this a case where there was a “beautiful … synergy” between the lab environment and the field site on Mars, strengthening his appeal to laboratory-based constraints on interpretation. Other team members explained to me that this case redeemed the MiniTES’s as a trustworthy instrument, before then seen as suspect due precisely to this requirement for a “feeling” for the instrument as well as the considerable (and ongoing, at time of writing) difficulties with calibrating out the changing effects of dust on its readings. In this case, MiniTES appeared to be leading the way. At SOWG meeting after SOWG meeting, Nick reported on completed MiniTES stares of sinter-like rocks around Spirit to build up a map of their location at Home Plate, and requested further stares of other nearby objects for completeness. The observations were prioritized and delayed Spirit’s ascent onto Home Plate for several weeks.

Nick’s attempt to properly constrain his hypotheses and avoid accusations of underdetermination required a labor-intensive and time-consuming attempt to collect and compare the spectra of silica rock samples, both on Earth and on Mars, to the MiniTES spectrum of Gertrude Weise. A single example of amorphous silica that was biotic in origin that did not display the 8-micron feature would falsify his hypothesis. Until that sample was found, however, the measurements continued in earnest, and even lent a positive air to the interpretation. “The more of these measurements we make,” said Nick, “the more difficult it is to come up with an abiotic way to make this feature, the more compelling it is.” Pointing to an opaline sinter plot scrawled across his screen as the rock sample sat a few feet away in the spectrometer, he explained,

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58 Team Meeting February 12, 2008.
“This is currently the best fit to what we see on Mars, so that allows me to tell people that this opaline silica story is the best most consistent fit to MiniTES.”

But alongside the hard work of constraining the interpretation of MiniTES data acquired on Mars, was a sense of constraint felt by the scientist caught between degrees of externality. Given the controversies over ALH840001 and Viking’s results, Nick and his MER colleagues were all-too aware of the enormous implications of announcing any discovery of life on Mars, prematurely or otherwise. As he transferred rock samples from their heated chamber to his spectrometer, Nick explained:

I’m trying to do this myself, to be very dispassionate about it, because on the one hand it’s like, shit, have we discovered life on Mars? On the other hand it’s like, come on, it’s not that easy. I totally subscribe to [Carl] Sagan’s classic quote that extraordinary claims require extraordinary evidence…. This is an extraordinary case. The evidence is compelling so far, but it’s not extraordinary.

Nick appeals to intensive laboratory work, a sense of dispassion and a requirement for extraordinary evidence in an attempt to either affirm or deny the next step of the interpretative chain. After all, moving from observational reports of graphic traces to the evidentiary context of life on Mars would generate no end of contestation among Mars scientists, especially as it relies upon interpretations of an instrument’s readings that pose challenges for communication with colleagues. “People are gonna think you’re crazy!” Nick exclaimed, revealing the precariousness of his situation: any scientist who would attempt such a claim without “extraordinary evidence” would be accused of “looking at his squiggly lines and thinking he sees bugs!”

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59 Interview, Nick, June 6, 2007.
60 Interview, Nick, June 6, 2007.
61 Interview, Nick, June 6, 2007.
As an ethnographer I have no doubt internalized much of the combination of excitement and discomfort I witnessed on the team during this period. I cannot pretend to write about this episode as if talk of life on Mars is “just talk,” with no implications for the actors involved or for their broader community. The tone of conversation I witnessed was measured and cautious, indicative of the high stakes involved in exploring such a hypothesis. After all, not only Nick’s credibility but that of the entire MER team was on the line. The team did not announce the potential implications of this investigation outright: no discovery was made, after all. The eventual conclusion was that the 8-micron feature was an effect of the spectrometer’s viewing angle, and presentations of the results were therefore limited to lower-level hypotheses in the chain of interpretation. A paper presented at the Seventh International Conference on Mars offered the modest and constrained observation that the material in question was compared to fumerole deposits in Hawaii, and that the material “has a really nice match to opaline silica.” The MER team subsequently published a paper about the investigation in *Science*, “Detection of Silica-Rich Deposits on Mars,” under the reputable first authorship of the PI and Co-PI (Squyres et al., 2008). The paper only made the case that the spectra and their link to hydrothermal conditions were “important for understanding the past habitability of Mars because hydrothermal environments on Earth support thriving microbial ecosystems” — but it was printed in a special issue on “Microbial Ecology.” Perhaps other experts within the Mars community picked up the hint: after all, shortly thereafter, a group unassociated with the MER team published a paper in *Icarus* (the journal of planetary science) under the title “A multidisciplinary study of silica sinter deposits with applications to silica identification and detection of fossil life on Mars.” That paper, too, would not assert that silica sinters could stand as “biomarkers” but only as evidence for “the existence of pre-biotic conditions on Mars” (Preston et al., 2008).
There are several aspects of this episode that I want to draw attention to for what they imply about the complexities of knowledge-making with Rover data, visual or otherwise. The first is the management of a variety of constraints upon interpretation. The MiniTES spectra require, on the one hand, a complex and expert approach to their interpretation involving both the mathematical and experiential constraints common to data interpretation on the MER team. But the necessary appeal to both the mathematical and the experiential and the high degree of specialized skill required to read the instrument’s results puts the scientist in a bind as he or she attempts to make the interpretative move between evidential contexts. George’s experiments with different formats for his results attests to the frustration of presenting observational reports, and Nick’s Sisyphean task of spectra collection placed him in an exciting albeit highly vulnerable position with respect to generating less underdetermined results, requiring intensive hours in the laboratory day after day.

Related to this issue is that of disciplining the scientist. Ethnomethodologist Harold Garfinkel’s “breaching experiments” made much of the assertion that many rules that we take for granted as constraints upon behaviour, such as the rules of chess or answering questions with other questions, are not so much natural constraints as they are socially produced and enforced (Garfinkel, 1963, 1967). The “constraints” that scientists associate with interpreting their data similarly act as constraints upon their behavior. We might also talk about this relationship as a question of discipline. Picking up on Foucault’s (1977) discussion of bodily discipline as productive of social order in the prison, the army or the schoolhouse, Michael Lynch also discusses the role of discipline in image work in the laboratory, disciplining both objects of analysis and the scientists who analyze them (1985b). Daston and Galison (2007), too, make much of the category of the “scientific self,” crafted through disciplined adherence to shifting values and practices associated with “objectivity.”
Such perspectives resonate with Nick and George’s stories. As the scientists attempt to rigorously constrain their hypotheses, they are restricted from making particular analytical moves or pronouncements. This restriction is bound up in the wider social implications of presenting underdetermined claims that the wider community believes to be unfounded and methodologically invalid, to be sure; but it also requires the scientist, uncomfortably, to confront the community’s anxiety about the status of their collective knowledge-claims. If on the one hand, scientific hypotheses can only be validated by narrowing down interpretative flexibility, delimiting possible interpretations of underdetermined data, but on the other hand, the data that returns from the Rovers is always, to a certain degree, underdetermined and requires manipulation in the process of its very analysis, then the scientist may become trapped in between evidential contexts in their observational reports. Constraining hypotheses constrains the scientist as well.

Further, the ability to claim a discovery moment in such a case is also a complex task. In their ethnomethodological analysis of the discovery of an optical pulsar, Garfinkel, Lynch and Livingston (1981) closely analyze an audio-taped exchange among the astronomers in the observatory to examine how they come to agree that they have made a discovery that they can announce publicly. The MER team’s potential discovery claim is similarly fraught: at what point does seeing rocks like Gertrude Weise become “seeing a silica sinter”, or “seeing evidence of past life on Mars?” The increasingly distal evidential context of the observational report is critical to generating a discovery statement, but this underdetermined context can only be arduously achieved, if it can be achieved at all. Such an achievement requires the dogged practical work of justifying distal observational reports through appeals to digital and analog work, in order to present *drawn as* images that can be *seen as* “evidence of anything” and avoid an accusation of “lookiloo” analysis.
Despite these appeals to constraints and disciplined behavior, however, the status of remote observations of a distant planet remains tenuous at best, requiring a substantial dose of hubris. After all, working with images or even with analog materials in an Earth-bound laboratory can only allow for limited moves in degrees of externality from observational reports to evidence. In the words of Sam Barton:

You need to go see how it really works. If you think you can just look at a picture of a planet and make out its geology then you aren’t approaching your field with sufficient awe … . What you’re proposing to do should be extremely intimidating and you should probably accept that you’ll probably get most of it wrong, and probably get all of it wrong.62

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62 Interview, Sam, May 24, 2007.
CHAPTER 8: “SURVIVING BOTH PHYSICALLY AND POLITICALLY”
THE POLITICS OF THE MARTIAN PICTURESQUE

It was a difficult decision to send the ailing Spirit to the North Side of Home Plate, where the Rover had already visited several hundred sols before, to survive the winter. But as the MER team assembled for their End of Sol meeting to start Long Term Planning for Spirit’s third winter on Mars, they were met with more troublesome news: the next generation Rover, Mars Science Laboratory, was incurring significant budget overruns. Based partly on MER’s success, MSL was a flagship mission, the category reserved for the most significant of NASA projects, and was due to be launched in 2009.1 Despite having two operational robots on Mars and a recently-arrived orbiter that was sending back spectacular pictures of the surface, the Mars Program’s response was to cut budgets across the board. A MER administrator on the line at the End of Sol meeting made it clear that the team had other imperatives aside from simple bodily survival:

Every mission is going to be held to a very high standard in terms of the quality of the science … It's not enough that we keep the Rover alive, it's more important that keep pushing hard and getting science that is new …… I can say with pretty high degree of certainty that if we were to take that kind of approach [and retreat to the North Side] we would have the keys to the Rover taken away from us because we're not being efficient scientifically.2

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1 MER is not a flagship mission; as described in Chapter One, it was proposed under the Mars Program based on the new Discovery-class missions implemented by NASA in the late 1990’s. These missions have different sources of funding within NASA, different organizational structures (single versus multiple PIs, for example), and different budgetary ranges. At time of writing MSL has been delayed to 2011 with implications for the operational budgets of MER, MRO, and other missions.

2 End of Sol, October 17, 2007
Seeing like a Rover, the MER engineers had made the point in their image analyses that driving to Von Braun or South Promontory would mean certain death as Spirit’s electronics would freeze en route. But driving backwards to the North would also mean certain death through the denial of mission funding. That is, NASA would “take the keys to the Rover away” from the team. This placed the Rover’s survivability in as dangerous and volatile a terrestrial climate as Mars could ever offer: the uncertainty of public funding. Reviewing their options, Sarah made an insightful comment. “We need to be aggressively productive during this time in order to survive both physically and politically,” she said.³

So far, I have discussed the Rover mission with respect to how images are crafted for different purposes by the men and women who operate the vehicles and conduct scientific investigations with the Rovers’ results. However, the Rovers are also embedded in an extensive network involving congressional patronage and accountabilities to other organizations and groups. In this chapter, then, I wish to articulate another way in which Mars is drawn as: this time as a public, shared vision according to internally-developed conventions for representing the Martian landscape. I call this convention “The Martian Picturesque.” Invoking a particular aesthetic with the accompanying phrase, “This is what it would look like if you were standing on Mars,” the Martian Picturesque enables team members to draw Mars as a postcard or as a public space, with implications for the Rovers’ “political survival” on Mars.

I am inspired in this analysis by two analyses of landscape imagery: one in astronomical image processing, the other in the politics of representing territory. The first is Elizabeth Kessler’s recent dissertation on the role of the sublime in Hubble Space Telescope imagery (2006). Her analysis of the color palate, framing, lighting and other compositional elements in awe-inspiring pictures such as the Pillars of

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³ End of Sol, November 17, 2007; emphasis mine.
Creation (the Eagle Nebula) is informed especially by the adoption of nineteenth-century European notions of Romanticism into the landscape painting traditions developed in the American West during the frontier era. I will borrow this attention to the role of the aesthetic to develop a particular and local “Spacescape” which tames an alien vista, renders it familiar and inviting, and even places the observer on Mars.

Secondly, I am informed in my discussion by Denis Cosgrove’s challenge that we regard landscape as symbolic of particular political relationships and social relations:

The argument here is that the landscape idea represents a way of seeing -- a way in which some Europeans have represented to themselves and to others the world about them and their relationships with it, and through which they have commented on social relations. (Cosgrove, 1984, p.1)

As Cosgrove suggests, representations of landscape produce and reproduce ways of seeing -- in my terminology, drawing as in order to see as -- that inscribe social values and political concerns onto the landscape. The Martian Picturesque is just such a drawing as convention that employs a particular landscape aesthetic, color palate and stance of its observer, operating from within a network of public patrons and an American imaginary about exploration. In this chapter I will first discuss the team’s patrons and their double-consciousness of these publics as evidenced in image-planning; I will then discuss the crafting of the True Color Martian aesthetic; and will finally locate the production of these images within the politics of the team and the Rover’s own “political survival.”

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4 See also Greenberg (2004) on the Pillars of Creation.
The Tensions Of Patronage

Before analyzing the specific elements of the Martian Picturesque’s aesthetic, it is worth exploring which “publics” the Rover team implies when they craft these images. I discuss here three different kinds of audiences for the Rover mission that are considered during image planning: NASA, the larger Mars science community, and an amorphous general ‘public’. Each brings associated tensions that an appeal to the Martian Picturesque attempts to surmount.

NASA

The Rovers’ direct patron is the National Aeronautics and Space Administration (NASA), which through its Mars Exploration Program has funded past missions such as Pathfinder and Mars Polar Lander. In 1997 the agency chose to fund Steve Squyres’ Athena Science Team to fly not the single Rover he had proposed, but two identical copies, to bolster NASA’s chance of at least landing a single Mars mission. The mission was supposed to last 90 Martian days and at time of this dissertation’s submission has lasted upwards of 1700, requiring repeated appeals for extended mission funding. But with each funding extension there is cause for nail-biting as well as celebration. After all, NASA did not expect to be funding MER for over five years, and continuing to fund the Rovers alongside other missions such as Mars Reconnaissance Orbiter (arrived 2006), Phoenix (arrived 2008) and Mars Science Laboratory (at time of fieldwork, delayed from launch in 2009) places a considerable strain on the Mars Exploration Program budget. No one at the time of budget writing expected these costly missions to overlap; nor did the many MER scientists who committed to participating on later missions in sequence, only to find them running in parallel. Many of the Rover scientists and engineers must therefore

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5 I am privileged to witness a side of the mission that is not necessarily public; therefore, my comments in this chapter are restricted to the Team’s own construction of the public and values for the Martian aesthetic. For a discussion of public response to Rover imagery, see Rice (2008).
juggle multiple commitments to concurrent projects in their everyday work, whether they drive the MER Rovers and conduct testing for MSL on alternate weeks, or whether they hang up from an SOWG meeting only to call in to HiRISE or Phoenix telecoms.

At the same time, MER team members are constantly aware of the potential funding axe and accusations of inutility that might mean “political death” for their vehicles, and often exhort each other to “give the taxpayers their money’s worth on this Sol” as they put together complex and chock-full daily plans for observations. Unlike most scientists in the United States, the PI of the Rover mission is often asked to report directly to the U.S. Congress on his team’s activities and scientific discoveries to justify the continued public expense of operating the Rovers, estimated in June of 2008 to be $20 million per year. Internally, this shoe-string budget places high demands on MER scientists and engineers, who must continue to perform with exactitude and finesse in order to remain NASA’s “poster child” mission and guarantee continued public support. But even this appeal will no doubt come under threat when the Mars Science Laboratory rover begins operations in 2011.

This pressure of continued NASA patronage creates several sources of tension within the mission. A significant example is the pressure to conduct exploration, which sometimes comes into contradiction with “doing science”. The Rovers are billed as “robotic geologists,” and when characterizing a new region it is perfectly common for geologists to “walk the contacts,” returning over and over again to areas they have already been to build up a more precise geological map of the area. However, faced with spending the winter on the North Side of Home Plate, it was considered a sign of poor scientific efficiency to return to an area that Spirit had already visited. The pressure to continue to explore, to see new things, to pursue the horizon can thus impact on conducting a thorough scientific study of a region -- and impact the kinds of
data and images returned from the Martian surface. As a graduate student on the mission stated in frustration during the Winter Haven talks, “They’re the Mars Exploration Rovers, not the Mars Redundancy Rovers.”

Institutional politics also affect all aspects of spacecraft operations, from hardware to software, from mission personnel to the visualizations they produce. Despite its status as a public agency, NASA should not be thought of as a single, unified system but instead as composed of different institutions, each with different relationships to the agency and to each other. For example, the strict division between manned and unmanned exploration at NASA results in different centers with different focuses, such as JPL for managing robotic exploration and Johnson for commanding the space shuttle, with research facilities like Ames or Langley designated “centers of excellence” in other applied fields such as systems design or aeronautical testing. When President George W. Bush announced in 2006 that NASA should send a manned mission to Mars by 2020, this statement boosted funding to NASA centers that focus on manned spaceflight, but devastated centers for robotics expertise like JPL, where the Rover operations team lost many of their colleagues in the resulting layoffs.

Changes in leadership at NASA Headquarters can also create uncertainty, as long-planned missions are canned to make way for new directors with new proposals, timelines, and budgets. As described in Chapter One, such a change was responsible for the truncation of the MESUR project and the adoption of the Faster Better Cheaper motto in the 1990’s; for the cancellation of orbiters and landers in 2001 and the selection of the Athena Science Payload to fly in 2003. And ongoing positioning for contracts within the agency feeds longstanding inter-institutional quarrels. For example, Pathfinder was originally proposed as the first of the MESUR missions by NASA Ames Research Center as a way of leveraging their existing mission operations
assets and developing expertise in Mars Exploration for the agency at their Center. But JPL was awarded the contract for *Pathfinder*. Emotions remain strong about this incident, which a few Ames personnel I spoke with still describe as JPL “stealing” their mission. To be fair, JPL’s status as a NASA contractor creates local institutional pressure to compete for contracts in order to stay central in spacecraft operations -- or witness the loss of their laboratory due to lack of incoming funds.

Thus another tension on the MER mission is that of managing institutional boundaries, even while the team attempts to maintain a unified stance and “see like a Rover.” Mission resources such as images are often called into play in this management. For example, visualization experts at Ames were asked to contribute to the MER mission by developing modeling software (a tool called Viz) that could produce 3-D environments in which to plan Rover operations (Figure 72). But JPL built their own software and integrated it into the Rover planning tools shared by team members. Despite this, certain MER team members located at Ames continue to use

Figure 72 Building a three-dimensional model of the Martian terrain in Viz.
Viz. The *Phoenix* mission, run out of the University of Arizona, also uses a version of Viz; this choice is not insignificant given that some members of the Mars science community I spoke to described *Phoenix*’s headquartering location, at a University, as related to tensions surrounding the mission’s autonomy. Just as ArcGIS or IDL create images within disciplinary boundaries for geographers or astronomers, visualization software can also enforce institutional boundaries and political commitments.

This example demonstrates how visual resources can be harnessed to manage insider and outsider status, even within a single mission. This can sometimes result in what appears to be a reduplication of efforts, but which is actually an attempt to achieve different institutional aims and adjust boundaries for different institutional needs. For example, the raw images that return from the Rovers are processed at an image processing facility at JPL before being posted for team members to access, but they are also downloaded to local servers at universities affiliated with the mission for processing. The technical differences between these kinds of processing are relatively minimal, but the social distinction is significant: images located on JPL servers require JPL-managed clearance to access while images located at a university server do not. JPL-managed servers are also export-controlled assets, thus imposing limited involvement for foreign nationals. But locating raw image data products (which are not in and of themselves subject to export restrictions) on servers at universities with public mandates subjects those images to different institutional pressures: such as that of providing educational opportunities for all students without discrimination on the basis of nationality. And research scientists at universities also maintain a strong commitment to broadened participation in their activities, whether by recruiting graduate students or maintaining ties with national and international communities of

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6 This is not an insignificant hurdle. At the time of my fieldwork, instituted changes in the JPL badging policy became the subject of a lawsuit brought forward by its employees for violation of privacy. MER team members at JPL and other participating institutions were affected by this policy.
scientists. Were these images not doubled on university servers, essential mission work such as Pancam calibration, the production of DEM and Rover location maps, or even basic scientific examination as proposed by the participating scientists could not take place at their institutional locations.

This discussion of NASA politics is important for understanding the context in which images of Mars are produced. On the one hand, public funding for the mission places demands and restraints upon the mission that the team is expected to satisfy. On the other hand, competing institutional pressures and inter-institutional infighting produces an environment in which managing this patronage is a complex and even contradictory venture. Yet another community to which the MER mission is accountable also presents complex and competing tensions: this is the larger community of Mars scientists.

Mars Scientists

At the Seventh International Conference on Mars in July of 2007, scientist after scientist from institutions in North America, Europe and Asia presented their hypotheses about the Red Planet. The colorful images that lit up the screen were transformations of data not only from MER instruments, but also and especially from the orbiters circling overhead, presenting spectral readings, geomorphological interpretations, coregistered overlays, and mineral abundance plots. Sitting in the packed auditorium among so many unfamiliar faces, it was clear that the scientists who participate in the MER mission are only a subset of the broader community of planetary scientists who study Mars. They are also not the only group involved in ongoing NASA mission planning and management: aside from other contemporary missions like Phoenix, Mars Global Surveyor or Mars Reconnaissance Orbiter, scientists from around the world regularly participate in NASA’s Mars Exploration
Program Advisory Group (MEPAG) to advise the agency on which missions to fund that would aid this wider scientific community.7

Viewed in this broader context, MER data is a rich, localized dataset that contributes to overall understanding of Mars. Indeed, Rover data is repeatedly invoked as a “ground truth” datapoint to be used alongside data from orbital instruments such as the American HiRISE camera or France’s OMEGA spectrometer on the ESA’s Mars Express Orbiter. Many graduate students on the MER mission are engaged in exactly this project as their doctoral work, digitally coregistering orbital spectral data with data acquired from Spirit and Opportunity; MER’s MiniTES is purposefully similar to the orbital instruments TES and Themis so as to provide comparable datasets; and cooperative observations in which the surface-based spacecraft looks up at the same time that the orbital spacecraft looks down are becoming increasingly popular since MRO’s and Phoenix’s arrival on Mars. Thus it is no wonder that MER scientists are concerned with “generating a really good dataset for the community to mine,”8 as one Pancam operator told me, and this legacy aspect of MER observations can be deployed as a decision-making strategy on the mission.

An oft-repeated adage on the mission is that MER scientists are so concerned with the everyday operation of the spacecraft that they don’t have time to “do science” to a greater degree than what is required for daily tactical decision making. Recall, for example, that Susan explained she finally had the time to work with Tyrone imagery because Spirit was immobile during the winter. Team members hope that future scientists will be presented with an enormous archive of their collected data, with which they will have the time and leisure to do more and better science away from the

7 I was privileged to observe a MEPAG general meeting at the 7th International Conference on Mars in July of 2007, and at the MSL landing site meetings in September of 2008. Minutes and reports from the MEPAG committee are available at http://mepag.jpl.nasa.gov.

8 Interview, Simon, October 5, 2007.
pressures of daily operations. So faced with a difficult decision to make or a choice among observations, MER scientists will often ask each other outright on the line, what would our colleagues expect us to get here? What will people need in the future in order to “do science” in this area?

MER team members’ concern for accountability to this community is reflected in their aggressive data release policy. As described in Chapter One, previous missions saw raw and calibrated data jealously guarded by different instrument teams, pored over for science results for publication before their release to the public. *Mars Global Surveyor* and *Pathfinder* proposed releasing data to the public NASA Planetary Data System [PDS] in six month intervals, under the assumption that six months was enough to clean and validate the data, with few images or other results released as publicity items. In contrast, all raw image data on MER is released to the public as soon as it is assembled from downlink for visual inspection, and calibrated datasets are released to the PDS every three months. This gesture, MER scientists believe, represents their openness and accountability to their broader community, and it has led to a considerable change in how mission data is made available to the public: HiRISE proposed to be “the Peoples’ Camera” with opportunities for the general public to request observations, and the *Phoenix* mission’s Twitter feed brought hundreds of thousands to follow the spacecraft’s experience as though it were one of a close friend.9

But this arrangement reveals another tension in drawing Mars as a public space. The Rover missions are narrative missions that have unfolded over time. The Rovers’ daily operations rely on the team members who are in the meeting room and the changing location of the Rover on Mars. Thus the “story” behind any particular

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9 See HiRISE’s “philosophy” for “the People’s Camera” online at [http://marsoweb.nas.nasa.gov/hirise/public.html](http://marsoweb.nas.nasa.gov/hirise/public.html) and Phoenix’s popular Twitter-feed at [http://twitter.com/MarsPhoenix](http://twitter.com/MarsPhoenix) which in mid-November of 2008 after the mission’s end had 39,348 subscribers.
observation is complex, contingent, local, and evolving. It can be extremely difficult if one is not in the room to know where the Rovers are, what they are doing and why. This problem is magnified if one wishes to seek a particular observation that may or may not have been taken on a given day.

Many team members I interviewed see this problem as largely one of data management. The scarcity of data available on Mars in the 1970’s and 1980’s has turned into a “data glut” or “cascade” that is too overwhelming for any individual to manage, they explain. Several strategies have developed to address the issue for the audience of Mars scientists. One of these is the MER Analyst’s Notebook, an online tool developed and maintained at Washington University St Louis, a participating Rover site. The Analyst’s Notebook is an integrated web-based interface that draws together all images, instrument reports and documentation, site maps and other location information to present a unified approach to locating Rover data products. As the tool’s creator explained to me in an interview, the Analysts’ Notebook arose early in the mission as the result of the FIDO Operational Readiness Tests, as an attempt to categorize all the data acquired by the test Rover, FIDO, organized by “sites.” But with so much data to load and visualize over an over-extended mission timeline, wherein numbered mission “sites” are in the hundreds, the MER Analysts’ Notebook can be a clumsy tool: my own attempts to use it have been met with frustration and most of the team members I interviewed admit that they do not use it.

Rather, science and operations team members usually have their own, idiosyncratic methods for retrieving MER data that rely on the visual memory they have built up of Rover locations and the stories of back-room discussions. One team member described this as a question of the pressure of time, combined with the necessary “feeling” associated with daily practices of “seeing like a Rover” that enable data interpretation in the first place:
I kind of have heard people [outside the mission] complain. But it’s hard. It’s not the fault of the people who are on the mission. We are too busy, we are doing what we can do… as quick as we can. It’s very open, it’s much better than the Europeans, than Japanese, India, China, but still there’s limitations, people only have limited time… [There’s] some kind of a feeling, you cannot get it from the outside, you need to be in front of a computer looking at data day by day, then when someone mentions a name and you know immediately where that’s located and what’s around them, but for outsiders, they have to look through lots of images … It’s harder because you’re not inside. You’re not in the field.10

Once again, it is difficult to access or even know that data is there if one is not a member of the team, engaged in seeing like a Rover, and virtually co-present with the Rovers in the field. And without knowing how the team was interacting with Mars, accusations can fly as to why certain observations were or were not acquired. For example, at the Seventh International Conference on Mars, I only witnessed one paper that used MER data that was not presented by MER team members, which attempted to use chemical data to reclassify some of the rocks at Gusev crater based on a classification system published by the MER team (Squyres et al., 2006). While the response from the MER team members was encouraging, their questions revealed that the paper reviewed issues they had already considered, and that it lacked a deeply situated knowledge of their data. When the presenter called for another sample similar to that acquired at the rock Fuzzy Smith, a team member explained, “we only got one shot at [Fuzzy Smith] and kept looking for another example.” This MER team member also explained that “Silica is not totally new to us,” that the questions raised by the presenter were under discussion “even back at [the earlier target] Paso Robles,” and

10 Interview, MER scientist, June 18, 2007.
that some experiments had been done to test various hypotheses about the source of the silica readings. When the presenter suggested that the rock called Good Question presented an outlier example in the Independence class of rocks, the team member clarified that the name was due to a joke at the SOWG meeting and did not relate to the nature of the material under study:

[The KOP asked,] ‘What should we name it?’ And [Sam] said ‘Good question,’ and the person on the computer typed it in [the audience laughs]… In fact this sample is 54%. It’s not Independence Class because it has far too little aluminum.\footnote{This comment and others in this section are from the Seventh International Conference on Mars, July 10, 2007.}

Later in the conference, another non-MER team member suggested in response to a MER team member’s presentation that,

There is controversy over the interpretation of these structures … How do you actually interpret the structures you mentioned? … In a lot of the MER images that are distributed on the web, there are structures where if you were taking images from two different angles of a structure it’s very hard to in great detail figure out what the geometry is.\footnote{Seventh International Conference on Mars, July 12, 2007.}

The scientist then stated that she would “very strongly support … more attempts to get geometry” and imaging “techniques to do a much better job” of obtaining stereo images of sedimentary structures, and proposed that if MER could not do that then she would do her best to make sure it could be done on MSL. The MER PI was invited to respond directly, and he opened his comments with an attempt to diffuse the tension: “I agree with you completely, and that’s a great thing to try to do that, and we’re of course limited by what geometries Mars gives to us… .” First drawing attention to the complexities of Rover planning and the uncertainties
associated with operating on Mars, the PI then shifted focus to *Opportunity’s* ongoing project at Victoria Crater to acquire high resolution stereo imaging of the crater’s promontories. As he described the modeling processes that would map out the crater’s stratigraphic layers in more detail, he made it clear that there was indeed an interest in “getting geometries” as evidenced at the other Rover site, where there was clearly significant “geometry” to “get,” but also assured his colleague that his team would do all they could do to better satisfy her needs.

Another MER team member also offered a comment, first thanking his colleague for her “plug” for the “valuable” work that his collaborating laboratory was already doing in characterizing structural geometries through three-dimensional image analysis. He too emphasized the difficulties of situated planning, based on his experience as a SOWG Chair:

> It’s not trivial that this [imaging] happens, we have to sort of think about it very carefully in the science strategies. For example when we were encircling Home Plate we were designing our drive and imaging campaigns very carefully so that we can see each individual exposure of the outcrops as we were going round, and we were not driving past any imaging locations … so it is very important to pay attention both to the designing the operations … so yeah, it’s not trivial …\(^\text{13}\)

The scientist’s description of the contingencies of planning reveal another complication involved in interpreting MER data. As described in the previous chapter, the ongoing articulation of hypotheses results in observations that aim to constrain one or another interpretation of the data. Thus when a group of non-MER scientists presented an alternative interpretation of the hematite concretions on Meridians Planum at the Lunar and Planetary Science Conference (Burt et al., 2006), MER

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\(^{13}\) Seventh International Conference on Mars, July 12, 2007.
scientists countered that the interpretation in question had already been considered by the team, and that observations were performed to constrain this hypothesis and rule out the interpretation that the other scientists presented. While this meeting took place before my fieldwork, a MER scientist later recalled for me the mixed feelings of many of the Athena Science Team at LPSC that year as they tried to balance the appearance of openness with an appeal to insider knowledge. However, this scientist suggested that for a few of the MER scientists at least, believed that a staged intervention was unnecessary, as the claims would be judged by a larger scientific community, and judged poorly on scientific grounds. Thus while data may be released promptly and is in principle inherently mobile, available to be shared and worked with by other scientists, the deep embeddedness of the mission team at the time of data acquisition continues remains crucial to its interpretation. This may be the reason why the MER team believes that they have never been “scooped” on a discovery by other scientists, despite their open data policy. It may also explain why the replication or refutation of published results is difficult to achieve from outside the MER community.

The above examples reveal how working with Rover data enlists both a strong affinity for the Rover’s evolving experience of Mars, and intuition for the Rovers’ instruments that is a honed skill acquired through extensive experience. In addition to the imagery, another instrumental example is the MiniTES, which is subject to shifting dust and atmospheric conditions. As one team member who worked closely with MiniTES complained, “Everything we get with MiniTES it’s like, well I’m not even sure this spectrum is right …” This scientist explained,

14 MER scientist, personal conversation.
They’re complicated enough instruments that there aren’t many people who use it outside of the research group … People just feel like, oh it’s this really complicated thing and I’m really not going to get this right … . The techniques become very home-grown …

MiniTES does tend to be operated and interpreted by a limited community; while scientists like Nick have such strong intuition for the spectra that they can interpret the data “on the fly” to provide input into mission operations in real time, another team member noted that “Only the MiniTES team can look at MiniTES. Then we hear the report directing where to go.” Changing atmospheric conditions at both landing sites also require changing dust-correction algorithms for the instruments on both Rovers: at time of writing there was still no viable correction for Opportunity’s spectra, while Spirit’s MiniTES was so besieged by dust that in an attempt to save power in an unexpected dust storm in late 2008 the instrument’s heaters were turned off, potentially sacrificing the instrument to save the Rover. Alongside MiniTES, the APXS, Mössbauer, and RAT data also require very specialized competency with the instrument in order to interpret their spectra or lists of numbers. This instrumental expertise combined with the difficulty of locating information or accessing a special narrative presents a challenge for presenting an open and accountable mission to the community of Mars scientists who might not work directly with the Rovers but who consider its data their own.

16 MER scientist, personal conversation.
“The Public”

The data returned from the Mars Rovers should not only give rise to knowledge and understanding among experts, however. “People should be able to get up in the morning, get their coffee, log onto the internet and see what’s happening on Mars today,” the Principal Investigator often explains when asked about the MER mission’s daily release, upon downlink, of image data from the Rovers’ nine cameras. Regardless of whether or not this is actually so, MER team members believe that an audience of amateurs and the generally interested international public is following their every move on Mars. But, leaving raw data open to public interpretation can be a dangerous move -- for how do you teach them to interpret it? A MER team administrator recalled this as one of the key concerns surrounding the open data release policies:

We had a lot of internal debate about success criteria, about public outreach, about proprietary periods, all that stuff. I distinctly remember discussion about gee, what if we post these things and somebody decides they see a face on Mars, or some kind of nonsense like that. I said, that's a risk, but on the other hand I think it's a risk worth taking. Because it's the scientists who will have the knowledge to really interpret this and who will be the ones up in front of the cameras after they've had a chance to look at the images, to stand up front and say this is what you're seeing. … When we got around to the images for Spirit and Opportunity, it was a deliberate decision first on the part of headquarters … the program office and the PI to post these immediately so that we could build the momentum of public engagement.¹⁷

The “momentum of public engagement” would have to be balanced by the expertise of public scientists who could interpret the images, provide a seeing as experience for the audience of amateurs. Indeed, team members have often been called upon to quell such “momentum of public engagement” when it does get out of hand. Early on in the mission, an amateur on the internet noticed what looked like a rabbit in a MER photo, and it required intervention by the team to calm the storm that brewed in public fora on the internet as the meme spread. In 2008, an individual interpretation of a false color image of a rock was trumpeted by international media as the discovery of a sasquatch or female figure on Mars. Team members who know how to see like a Rover due to everyday interaction with the vehicle and its visualizations are often at a loss to explain to an amateur audience why such an interpretation is impossible: their visual expertise at this point is a deeply tacit kind of knowledge. And team members point to other public misinterpretations of images, such as the face on Mars or the controversy over evidence of life discovered on the Martian meteorite ALH84001, with which they have been involved, as points of tension between the open attitude towards public involvement and potential misunderstandings that may develop and spread.

The possibility of being watched at any given moment and being misinterpreted in their observations inspires a kind of Panopticon mentality, a double consciousness on the team that occasionally surfaces during planning.18 In one instance, the Opportunity team planned an early-morning observation of a comet from Meridiani Planum. The observation required waking the Rover up early and pointing

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18 Bentham’s panopticon is discussed by Foucault in his Discipline and Punish (1977) as an example of prison architecture that enables the watchman to observe all prisoners at any time, while no prisoner can confirm precisely when he or she is being watched. Prisoners thus discipline themselves to conform to expectation or standards of behaviour even when they are not, strictly speaking, actively being watched. Just as the Panopticon serves “to induce in the inmate a state of conscious and permanent visibility that assures the automatic functioning of power,” (p.201) the consciousness of visibility that Rover team members exhibit also maintains power relations between the team and their patrons, the widely-defined “public”.
at a region of the sky during sunrise, not too early but not too late, so as to catch a
glimpse of the comet: a tricky observation. After detailing the features of the
observation, the SOWG chair intervened when it came to giving the images a special
file name, saying:

I'm not putting ‘comet’ in the name because what will happen is this will
actually end up on the Pancam [web]site and the people who follow along on
what we do … I don't want them to look at this and think it's a comet [in case
we don't see it].\textsuperscript{19}

It may be true that in case the observation failed (which it did), the Chair did
not want the team to look incompetent to their public observers. But more importantly,
the possibility for misinterpretation of the image, for amateurs to think they see a
comet in an image in which there is no comet, constitutes a greater danger.

Aside from “the public,” an actor’s category referring to an amorphous but
extensive international community, there is a particular group of amateurs who do
watch the Rovers on a regular basis and whom the team are well aware of: this is the
community on www.unmannedspaceflight.com. The approximately 1500 members of
this active online forum discuss \textit{Spirit} and \textit{Opportunity’s} daily activities, trade home-
made algorithms for making their own True Color images and trade thoughts and
opinions as to what the team’s rationale is for taking particular actions on Mars. The
MER team is well aware of this community; the PI has met with its webmaster on a
few occasions to answer the forum’s questions about the mission, and when \textit{Spirit} had
been on Mars for two Martian years, a birthday card arrived at the Cornell
headquarters addressed to \textit{Spirit} from “the folks at unmannedspaceflight.com,” and the
model Rover in the local Mars lab sported a colorful “I am 2!” pin from then on
(Figure 73). Some team members occasionally check in on the forum’s postings to see

\textsuperscript{19} \textit{Opportunity} SOWG, January 2007.
how they are being interpreted, although they usually restrain themselves from interfering with this external conversation.\textsuperscript{20} They do, however, try to guess at how the online group or other publics will respond to particular activities. A scientist once cautioned a colleague in a Team Meeting to be careful about releasing an observation in case observers “will think it’s a duck talking to a flamingo or something.”\textsuperscript{21} This statement is not a joke at the public’s expense, but rather reveals the real tension inherent in the management of public interpretation of images, as one in which it is difficult to maintain expertise at image interpretation and manage these images’

\textsuperscript{20} As my subjects explained, sometimes the temptation to say something is too hard to resist. One team member, after reading a heated conversation about whether or not the team would take a particular observation, left a cryptic posting suggesting that the questions would be resolved with tomorrow’s downlink.

\textsuperscript{21} Team Meeting, July 6, 2007.
underdetermination when the public is meant to “see for themselves” and join the adventure of making discoveries on Mars. Thus the MER team watches their watchers and maintains a double-consciousness about what their amateur public will think of their activities.

But this watching reveals an important way in which work with images can assuage some of these tensions. When the online forum’s webmaster came to Cornell to give a talk to the Astronomy department about his work, the Principal Investigator of the MER mission exuded enthusiasm. After a talk in which he exclaimed “sweet!” and “cool!” at every turn, he exclaimed,

I can't tell you how thrilled I am at what you guys are doing. When we made the decision years ago to throw all our images out there it was exactly so you guys could do what you're doing, to follow along … do something of substance with them…

The webmaster replied simply, “Once those images hit the web, I couldn’t not play with them!” But the “something of substance” that the web participants are praised for doing is very different than the work that MER team members accomplish with their images. When the webmaster revealed that it took him thirty-six hours to process an image of Mars, the PI pressed, “I know why we do it [work with MER images], why do you do it?” The webmaster’s reply is illuminating.

I guess, take your explanation, why you do it? You do the good science and you do the exploring. We can't do the science but we can do the exploring … so we can be right there with you.

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22 Cornell Astronomy colloquium, June 20, 2008.

23 Cornell Astronomy colloquium, June 20, 2008.
Rover Planners might *draw* Martian features as hazards for Rover interaction and MER scientists might *draw* these same features as betraying morphological or mineralogical distinctions, but this webmaster appeals to different aims in his pixel-pushing. And unlike amateurs who might dangerously *see* Martian features as ducks, faces, and sasquatches, the PI characterizes his work as doing “exactly” what the MER team had hoped the public would do: to *draw* Mars and *see* Mars as a shared site of exploration and experience. The emphasis on “being right there with you” echoes the team’s publicly-stated emphasis on producing images that show “what you would see if you were standing on Mars.” Taken together, such statements present a use for Mars Rover images that employs this sense of shared exploration in order to manage the complexities of public patronage, involvement and accountability.

**The Aesthetic Of The Martian Picturesque**

As we have seen, NASA, the Mars science community and the amateur public are powerful patrons that the Rover mission must appeal to in order to ensure continued relevance and funding; yet each present inherent challenges and tensions that must be surmounted in order to fulfill this appeal. This is the background against which we must place the Rover team’s continued exhortation that their public release images present “what it would look like if you were standing on Mars.” Like Galileo’s emblems, the True Color high resolution panoramas, often artistically framed shots with Rover tracks snaking off into the horizon, naturalize a relationship between the patronage community (the Medicis, or NASA) and the science (the lodestone or astronomy, or planetary exploration) done in their name in order to continue the patronage relationship that supports these activities. Essentially, naturalizing a particular vision of the Martian landscape through the development and release of a

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24 This statement is so ubiquitous in the mission’s public release documents that it is difficult to provide a definitive citation, but see especially Bell (2006) and [http://pancam.astro.cornell.edu](http://pancam.astro.cornell.edu) (accessed November 18, 2008).
specific Martian landscape aesthetic naturalizes, domesticates and shares America’s presence on Mars. This is what I call the Martian Picturesque, a visual convention of panoramic vistas characterized by the use of True Color and reference to American frontier and other wilderness imagery.

True Color Visions

A central component of this landscape aesthetic is the adoption of a palette referred to as “Approximate True Color” (ATC). As previously discussed, Pancam images are black and white as they are taken through various filters that limit the range of light wavelengths received by the CCD. Combining three or more of these black and white images through the red, green and blue channels of an image processing software suite will transform these images into color. I have argued above that the ability to transform images into false color and manipulate them in a variety of ways, resulting in no one “best” image but rather images that reveal different aspects of Mars for different purposes, is essential to scientific work with images. Indeed, many scientists on the mission insist that presenting Mars the way the human eye would actually see it presents no scientific advantages. After all, the Pancams’ sensitivity to light frequencies extends slightly into the infrared and ultraviolet to enable a wider range of features to be seen or discriminated in the Martian landscape through false color processing. But in terms of True Color products, as George once put it,

Okay we know Mars is red, we get it! Seeing more natural Mars colors isn’t helping, I’m not learning anything. Seeing Bob Glover’s decorrelation stretches? Okay, now I’m learning something new…

Public release images have been discussed by Michael Lynch and Sam Edgerton (1988, 1996), whose interviews with image processors at the Harvard Smithsonian revealed the complexities of managing color images in the context of

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25 Interview, George, June 6, 2007.
both scientific publication and public release. Here, the price of full color printing inspired greyscale palettes in professional journals, but “natural” or enhanced colors were preferred in popular magazines, which an informant derided as “a cheap way of dressing up the presentation” and “a distraction” from “the science”. Kessler’s work with Hubble Heritage (2006) also reveals how public-release images placed on the Hubble website are brightened for heightened sublime effect as opposed to those used for publication, wherein a subdued palette is preferred. For the MER team, public release images are usually True Color visions of Mars, whose limited palette and tailoring to a human eye on Earth present Mars as accessible, local and tamed.

As much a construct as false color, True Color is not without its own controversies and differences in approach as to how it should be produced. “Approximate True Color” (ATC) in fact refers to a specific algorithm developed by the Pancam group at Cornell to imitate how they think that the human eye, with its special sensitivity to light, would reveal the Martian landscape were it located on Mars. George, at least, challenged this vision:

[The Pancam Lead] always wants to make Mars images look dark because if you were there you’re farther from the sun so it’d be dark… It’s the gloomiest saddest most depressing [view] you could imagine … If you were on Mars, your eyes adapt. Yes, Mars is darker but my eyes would adapt because my pupils would dilate. So why are you making it gloomy when it doesn’t have to be? … Even with visible imagery there’s real differences of do you make it look exactly like you were standing there or make it look something like, okay I’m attracted to this image, I want to look at it, I want to peer into the shadows…

26 Lynch & Edgerton, 1988, p.194.
27 Interview, George, June 6, 2007.
This statement reveals how ATC images require choices about how to construct an image that is “true to the human eye,” and how variable these choices might be. But it also shows how this appeal to accuracy is embedded within an appeal to public interest, as this statement also reveals the ultimate purpose of images: their drive to attract the public. An appeal to the human eye is a means to this end.

These public visions are time-consuming and demanding to produce, and require their own processing algorithms distinct from “doing science”, producing drive maps, or calibrating. Early in the mission, mosaics were stitched together one frame at a time through image processing software, and True Color images were produced by hand-coding the appropriate transformations and making adjustments by hand in software. These processes have mostly been automated since then to ensure a more unified view of Mars across the board. But important decisions must be made as these views of “what you would see if you were standing on Mars” develop. For example, sometimes the algorithm results in an image that doesn’t look quite right, and must still be adjusted by hand. In one case, I witnessed a Pancam mosaic-maker shake their head at an image that came through the software pipeline, saying, “It's too red!” and opening Photoshop to adjust individual properties until Mars was less “red.” As another example, when taking a panorama the Pancam must snap one frame at a time at a rate of 2 minutes per shot. This means that by the time the camera physically rotates from the left side of a panorama to the right, several hours if not days may have transpired. In the meanwhile, brightness and contrast of the Martian sky and terrain have shifted from frame to frame, such that different panels of the mosaic may present different colors for ground and sky. To minimize the discrepancy, Pancam operators who plan out these mosaics use physical calculus maneuvers and software to maintain acute awareness of the location of the sun relative to the Rover and the landscape throughout the day. Still, however, patchiness in the resulting pan is common. The
mosaic maker may adjust the frames such that the ground is a consistent color, then select the color of the sky at one point in the image and paint it over the rest of the sky in the scene, creating a uniform sky and ground. While in any production of the image for scientific purposes, painting over a scene would be seen as an interpretative intervention, in this case it is seen as staying true to the original data; because the sky value is an actual pixel value from the sky, as one mosaic maker explained, “you’re not inventing values” (Figure 74).

Pancam is not the only instrument that appeals to a landscape aesthetic: MiniTES has also adopted the panoramic and True Color techniques to display their data. As one of the MiniTES operators explained, MiniTES faced a significant problem with public outreach because it was “a squiggly line instrument”: “it’s hard to get people to love MiniTES,” he sighed. Again, the team turned to images to bridge this divide and engage this public. While MiniTES data is primarily exchanged among team members as complex graphs, the team adopted its method of planning observations by placing a red or blue circle (footprint) on a Navcam frame, to public release images which use black and white Pancam mosaics and overlay colored circles ‘on top’. Colors may correspond to elemental abundance, as in the case of Eagle Crater at Meridini, or temperature, as in the case of Spirit’s landing site at Gusev (Figure 75).28 This use of the Pancam panoramas to place other instrumental data directly addresses the problem described above of data retrieval. After all, whether on the team or not, the display of compiled data as tied to a specific location on the landscape aids in knowing that that dataset exists and being able to find it.

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28 This produces some complications in interpretation. For example, the PEL prefers blue to indicate less abundance and red to indicate abundance, and applies this across the board. But hematite is usually depicted as blue in the standard false-color stretch that reveals blueberries, described above in the Introduction and Chapter Two. In the case of images of Meridini, one wants to read blue patches as ‘hematite’ and red patches as ‘no hematite’, instead of vice-versa.
Figure 74 360° Panorama at Husband Hill. Note uniform sky colour, askew stance of the Rover mast relative to the frame, and tracks. Courtesy NASA/JPL/Cornell.
As mentioned above, George has a developed sensitivity to the aesthetics of data display. According to him, data released to the public has “gotta be pretty but it’s also gotta be intuitive.” The team has therefore hired an artist to work with TES and Themis data produced by his research group and transform scientists’ images such that they captivate the public. The data that the orbital TES instrument reveals is thermal, not visual, and the team could adopt any palette to depict its concentrations or absence. Like Kessler’s Spacescapes these images tend to have a heightened contrast in their color palette, although lately the team has made an uncomfortable discovery: public enthusiasm for their images is greater when they release them with a Mars-like palette, i.e. browns, oranges, reds and butterscotch. In our interview George pointed to the tension this presents as an ethical dilemma: “Your eyes can’t even see these wavelengths… Should we be putting Mars-like colors on something that’s infrared data?” The appeal of True Color, of “what it would look like if you were standing on Mars”, even transcends to the depiction of invisible data, revealing along the way the choices that produce and the responsibility that accompanies such visualizations (Figure 76).29

In addition to True Color, images that address the question of “what it would look like if you were standing on Mars” also betray elements of a frontier and wilderness narrative in their framing and composition. As detailed in Chapter Four, the pressures of time, bits funding and energy are too great to allow spurious use of precious Rover imaging resources, thus requiring that a successful image request be accompanied by a detailed scientific or engineering rationale. But in this time and bit-
conscious environment, exceptions exist. Here I wish to return full circle to a moment that was cited in Chapter Four, in which the SOWG Chair proposes what was later known as the “Ansel Adams” panorama:

Chair: Something I've been wanting to do for a long time at Victoria Crater is to take some Pancam imaging … with the sun low in the sky. There's really--there might be some science that would pop out of this, but think of all the pictures that you've seen of the Grand Canyon an hour after sunrise or after sunset with all those long shadows from those promontories. I'm curious to see what the crater looks like at that time of day … maybe take a few minutes to get a really spectacular image. Just sort of a postcard.

Marc: Sounds pretty.

Sam: Could become the [NASA] Image Of The Week.

Chair: This is … something that we're doing sort of for fun, who knows maybe something good will come out of this but I'd like to try this …

In proposing this observation, the Chair draws an alliance between the aesthetic and the public. Note that the Chair is not proposing a scientific observation: although “some good” might come out of it, neither science nor operations are the image’s primary function. He also invokes traditions in American Western landscape photography, citing postcards of the Grand Canyon, and after the meeting a team member laughed that the Chair was “playing Ansel Adams.” The proposed image is meant to be “spectacular,” “a postcard”; or as the Chair put it later, “it’s not science, but it’ll be cool!” Finally, the audience for this image is not the team itself. It will not be subject to Bob or Ben’s decorrelation stretches, matched with tie points to deliver

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31 This particular image was eventually shot in black and white in a high contrast filter to highlight the early photographic effect, and was soon known as “The Ansel Adams Pan.” Ansel Adams features in Beth Kessler’s study as well: the HST Hubble Heritage project includes an Ansel Adams section featuring black and white Hubble images.
Digital Elevation Models, or used to plan targeted operations. Instead, it is meant to be
released to the public, to be promoted to NASA's webpage for an Image of the Week,
something as iconic as photos of the Grand Canyon, inspiring Americans with an
awareness of their new frontier. In this moment, the American public and the aesthetic
are rhetorically intertwined and realized through the planning and execution of the
photograph (Figure 77).

The frontier narrative of the spacescape that characterizes the Martian
Picturesque is evident in many of the images produced on the mission for public
consumption. Countless images show rover tracks receding into a distant horizon
reminiscent of wagon-wheels on a pioneer trail (Figure 78) and the award-winning
promotional animation for the Rover mission produced by a then-student on the
mission depicts the Rover descending from its landing module onto the Martian terrain
and driving off into the sunset in a move reminiscent of a cowboy in a Western
movie. Such framings are not accidental. Pancam operators -- many of whom are
accomplished amateur photographers and artists -- have been known on occasion
when planning mosaics to “push for more frames [single images] to make it prettier.”
One Pancam PUL, Thomas, explained that if he thought that the imaging sequence
needed “one more frame to make it prettier” he would simply ask on the SOWG line if
that was okay “within the limits of our resources,” and it was generally approved.
“Making it prettier” involved largely thinking about how the individual Pancam
images would stitch together to create a larger picture. For example, Thomas
suggested, if two scientists suggested two observations of two separate objects that

32 The animation is available for viewing at http://www.maasdigital.com/gallery.html
(Accessed November 18, 2008). The Rover enjoys several sunsets on its landing pad before exploring
the alien terrain, and it drives off into the sunset around 8 minutes 24 seconds into the clip. The Walt
Disney 2006 feature film, Roving Mars (Butler, 2007), relies on similar imagery in computer-produced
animations to highlight the Rovers’ experiences as explorers on another world.
Figure 77 Self-assembled frames of the Ansel Adams Pan. Note long-shadowed promontories, attention to light and shade, and rover tracks. Courtesy NASA/JPL/Cornell.
were close to the surface and involved the same exposure, he might suggest an additional frame to “make a nicer picture because it’s all together.” Similarly, an image of a particular rock target might be enhanced by an adjacent frame that could give a greater sense of the context around the rock. Thomas might also suggest a particular time of day or combination of filters to capture qualities of the light and offer and “improvement” on the requested image. “Generally everyone wants the prettier image but within constraints,” he offered. “I do it to make it look nice, and generally the

Figure 78 A combination of rover tracks listing to the right, the framing of the ridge and True Color sky and ground make for the Martian Picturesque. Courtesy NASA/JPL/Cornell.
scientists care about that too.” Indeed, the Pancam Payload Element Lead often expresses being moved by “the sheer absolute phenomenal beauty of the scene” and at a promontory on Victoria Crater he requested an observation as a result, saying “that’s obviously not a scientific driver but something that’s always in the back of our minds.”

This appeal to American landscape photography, aesthetic choices and skill in the act of photographing the “phenomenal beauty” of Martian scenes is not limited to the Rover mission. In a 1979 letter to the photography critic at the New York Times, the Viking Image Team’s deputy leader berated the journalist for ignoring the detailed attention to planning and aesthetic considerations that the imaging team effected in the daily use of their camera. The letter is worth quoting at length:

… on the second question you raised of “automation,” I must take strong issue with you. Except for the first few images, none of the [Viking] Lander camera photographs were automatic in the sense I believe you mean. Even the first few shots, which were "preplanned" and part of the initial computer load, did what Ansel Adams would have done if he had arrived with his camera at the lander site. Namely, look around the panorama to determine the most exciting use of film and time, calibrate the camera to avoid exposure errors, correct color balance, and adjust focus and tripod tilt. All other images were the result of intense human interaction involving all the normal choices, scenes, framing, resolution, color, exposure, etc. Did it matter that our triggering cable was 100 million miles long and was electronic rather than mechanical? … I can assure you that humans were very much involved in the choices and moved by the landscape they were observing.34

33 Interview, Thomas, October 5, 2007.

Almost thirty years beforehand, the *Viking* team members invoked similar considerations. Note the attention here to excitement and to active intervention with the camera, to the aesthetic “choices” involved in photographing another planet and to the emotional response of the team to the environment around the lander. Ansel Adams, too, is conspicuously present as not only one of America’s great nature photographers, but also and especially the photographer of the country’s dramatic and sublime landscapes that inspired the environmental and preservational consciousness of the mid-twentieth century.

References to American landscape and frontier imagery are pervasive, but this is not a view from nowhere or a God’s-eye view. Instead the viewer is very clearly situated: on Mars, copresent with the Rover. The location of the viewer in an aesthetically beautiful landscape with a scene laid out around them thus recalls the *picturesque*, a popular convention of eighteenth century landscape painting, which these twenty-first century pictures of Mars invoke and renew.\(^{35}\) Mostly associated with the English or pastoral landscape, the picturesque usually stood in contradistinction to the sublime, which aroused passion in the observer with its emphasis on the terrible and awesome aspects of nature. Instead, the picturesque presented a more attractive scene, one that was usually calm, peaceful and even charming, elevating everyday scenes into those of gently pleasing beauty. The picturesque places particular emphasis on arranging the landscape around an observer who is embedded in it at a particular location. Indeed, one must be in the right spot on the ground to enjoy the picturesque view, to have the elements of the countryside arrange themselves just right around the viewer. This view differs from, for example, the perfect geometry and symmetry of seventeenth century gardens, meant to be surveyed from a balcony looking out over palace grounds, portraying the harmony and

\(^{35}\) My description of the picturesque and the sublime is indebted to Burke (1759), Cosgrove (1984), Cunningham (1996), Mukerji (1997) and Stockstad (1995).
hierarchy of the universe and man’s dominion over it as natural properties.\textsuperscript{36} In the picturesque the scene is typically more askew. The observer is embedded in, not omnisciently gazing over, the landscape from a single subject position. Further, the viewer is not meant to be so overwhelmed with their surroundings that the view is both terrible and awesome, as in the sublime; nor is the viewer observing from a God-like perspective. Instead the viewer is embedded in a scene that is peaceful, understandable, tangible, and occurring in a precious place and time.

Such conventions resonate in the True Color panoramas produced by the Mars Exploration Rover team. The appeal to “what you would see if you were standing on Mars” in Approximate True Color crafts the experience of the alien world on a human level. Where sublime landscape painting would employ extremes of light and color to emphasize the emotional impact of a scene, the relatively monochrome palette of the Martian picturesque aims not to overwhelm the viewer with trepidation but to present them with familiarity. Embedded on the Martian terrain, the Pancams present a vision of Mars that makes human presence and our virtual witnessing of Mars from Earth appear natural and seamless. The situated nature of the robotic viewer in Martian picturesque imagery is often highlighted by foregrounding a panorama with splayed Rover solar panels, or framing tracks visible in the sand, reinforcing the position of the subject observer as rooted in the scene and producing the sense of the landscape as slightly but charmingly askew, a “found” moment in an untouched space. Not only is this a pristine environment explored for the first time, not only is this the new frontier, but it is a familiar and down-to-earth space, beautiful but quaint, alien but tangible.

\textsuperscript{36} European gardens of the period were also sculpted to reflect the ideals of the picturesque in their construction, such that view points within the garden would offer the vision of what appeared to be a perfectly composed landscape painting. Fashionable English grounds were sculpted by such architects as Capability Brown to include perfectly placed knolls and valleys, faux Greek temples and soft willow trees that encouraged specially arranged vistas from particular points of view, while Marie Antoinette’s “English Garden” at Versailles also betrays an escape from the symmetrical geometry of the King’s garden, best surveyed from a single focal point on the Royal balcony, with the Queen’s arranged vistas framing rolling hills, sloping pond banks and even a faux English hamlet.
But the Martian Picturesque draws inspiration not only from the perfectly sited picturesque landscape but also from American traditions of photography, such as the sublime views of natural landscapes such as Yellowstone or the Grand Canyon, or nostalgic views of the Western frontier. These aspects appeal on the one hand to the “exploration” side of the mission, which may come into conflict with the steady and slow work of science and Rover management as described above. But they also presents a familiarly American view of the Martian landscape, informed by American landscape photographic traditions such as those produced by the oft-invoked Ansel Adams (Figure 79). Images of Victoria Crater, combining a sublime sensibility with Rover tracks wheeling off into the horizon, in particular appeal to this formulation of
Mars as like the American wilderness. And the images are participatory: transforming Mars into a vision you would see if you were there inspires the viewer to put themselves in the scene at the point of the camera’s lens. They invite the viewer to step out into the frame, into the Rover’s tracks so often visible in the scene. As Mars is reproduced according to the conventions of the Martian Picturesque, it is *drawn as* the new American frontier.

**The Martian Picturesque In Context**

The stance of the observer in the Rover’s tracks at America’s new frontier, and the transformation of Martian imagery into a color palette that appeals to the human eye combine to craft a particular kind of virtual witnessing experience for the viewer. A crafted and intentional image feels like an individual observation, and the alien planet is rendered familiar and knowable to distant human observers. Unlike the *seeing like a Rover* skills possessed by team members, such Approximate True Color, carefully framed and crafted scenes anthropomorphize the Rovers’ vision, transforming Mars onto a human scale. Taking these color panoramas provides a visual narrative for the mission, bringing a shared visual experience of the Rovers’ journeys on Mars to outsiders, whether amateurs guessing as to their purpose or scientists attempting to use ground-based measurements in their work. What political and social relations are embedded in this symbolic landscape? How do these representations of Mars assuage the political tensions surrounding images described earlier in this chapter, and reflect and project the social relations discussed in this dissertation?

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37 At time of writing, America is the only country with robotic spacecraft on the surface of another planet. It would be interesting to compare, in future, representations of planetary landscapes made by other cultures with a different, yet similarly culturally entrenched, vision of landscape: for example, might the Japanese culture of rock gardening or the Chinese landscape painting tradition provide an interesting counterpoint in their visions of planetary terrain?
The most obvious function of these images is as public relations documents, images that remind the public -- and Congress -- of the continued value of their exploration. In their study of the Harvard Smithsonian Lynch and Edgerton (1988, 1996) relate how image processors described such images as part of the “dog and pony show” and distinct from the scientific production of their laboratory. While Rover team members too may find little scientific value in how these images are specifically construed, they believe these images are essential to their continued public support and interest in the mission. As George said to me, matter-of-factly,

How many people know we have a spacecraft around Saturn? No one, maybe one out of ten people on the street know about Cerassini. But how many people know we have two Rovers on Mars? I’ll bet you nine out of ten people know that, and it’s because of the images.38

The Pancam Payload Element Lead was similarly direct in his astronomy course lectures, once declaring: “It would be a crime against humanity to send a spacecraft without a camera.”

Images also stand in as a measurement of mission success: they are the most easily perceived and shared “deliverable” of the mission. This was articulated by the Science Team responsible for the Pathfinder mission when their imaging payload was threatened by budget cuts in 1994. In a protest letter to NASA Headquarters, they said,

… try to imagine two successful Viking landings on Mars in 1976 followed by no images, no samples and no sample analysis to test the hypothesis for life on Mars. Try to imagine the successful landing of Apollo 11 on the Moon with only voice communication - no pictures, no samples and no televised "first step." It is important to recognize that images from the surface of Mars will

38 George, personal conversation, June 6, 2007.
prove success to the American public (and Congress) and provide them with tangible results they can comprehend…39

Here pictures of Mars taken by a robot are equated with the world-famous televised landing on the Moon and Viking lander pictures in terms of their scientific and emotional impact. The pictures themselves are said to “prove success” and provide “tangible results” that taxpayers can “comprehend” by simply seeing them. Surely the team here does not mean that taxpayers will see the pictures and be able to judge for themselves the geology of the scene around them. Rather, the sharing of the imagery is itself a “tangible result.”

The “result” here is somewhat complex. At first glance, it is obvious that the use of frontier imagery appeals to an American congress, public and NASA alike with a shared cultural understanding of these images as standing for the greatness of their nation and their accomplishment. Such visions of Mars domesticate the planet and naturalize continued support and patronage of the mission. But perhaps more subtly, the Martian Picturesque images are also aimed at reproducing the Rover team’s own value of unit, invoked here as a kind of overcoming of differences in the face of the exciting, open frontier terrain. Bob asserted this connection when discussing what he felt was the importance of the mission:

… doing planetary and space exploration I think really helps society, giving us a frontier, a place to push our boundaries … The problem with American society is we don’t have a frontier anymore so we’re turning on each other…40


40 Interview, Bob, June 5, 2007.
While frontiers also stand as places of confrontation between cultures, indigenous or otherwise, or as spaces of violent conflict, Bob describes the Martian frontier as a place that requires the maximum human creativity and ingenuity to manage the difficult terrain, and thus an essential contribution to maintaining a harmonious “American society”. This idea of the image of the Martian terrain as a place where people come together to push their boundaries and achieve new heights is enforced in how such images are used as a resource within the team to achieve or record consensus. For example, large scale Pancam panoramas stand as a kind of landmark for the team members, a record of a significant achievement and teamwork. Liz explained that these mosaics function “to mark a significant location, to record an incredible view … but each one of them also tells a story…” This is particularly true of the largest panoramas, which are usually commissioned by the team at moments when they achieve a Long Term Planning goal, often overcoming obstacles en route: for example, the Husband Hill Pan, taken when Spirit made it to the peak of the Husband Hills after a long, arduous and uncertain journey, or the Duck Bay Pan, taken when Opportunity finally arrived at Victoria Crater after trudging through the Meridiani dunes for over a year. These panoramas, released to the public, provide an overall sense of place in which other Mars scientists might begin to associate local observations. They also project the sense of group accomplishment achieved through overcoming adversity at the alien frontier.

Also, as already discussed, the very act of taking a panorama may be embedded in a moment of controversy among the team, such that the image can be used to resolve disagreements over where to drive next. In order to achieve consensus over which way to drive around Victoria Crater, for example, the team resorted to a well-honed tactic: drive to the decision point, take a panorama, and that should make

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41 Liz, personal conversation.
the path clear. So while the Duck Bay Pan was released to the public with great fanfare at a NASA press conference in which both the Pancam Payload Element Lead and the Principal Investigator were flown to Washington DC to present the Approximate True Color rendering of Duck Bay, the panorama was planned within the team to both commemorate their arrival at Victoria and to resolve a disagreement over which way to proceed around the crater.

Contributing to and record of this consensus, again, is the visual presentation of the team’s unified stance and view of the Rover as a single instrument. In this respect the location of the observer is critical. The stance of the observer in the Martian Picturesque as embedded in the Martian landscape became clear to me when the Pancam Payload Element Lead presented the Duck Bay Panorama at the NASA press conference in September 2006. In addition to the panorama, he also displayed a version that placed a Rover in the scene, “for scale.” Looking at the image of Duck Bay with a Rover placed atop Cape Verde, however, was a disorienting experience. I realized that every time I was looking at a panorama, I was used to looking at it through the Rover’s eyes at the terrain. With the imposition of a “Photoshopped” Rover on the scene, suddenly I was standing on Mars alone, looking at the Rover looking at the scene.42

The cognitive dissonance I experienced at this shift is a reminder of the importance of the observer’s location. It is not simply that the viewer is invited to step into the frame and observe Mars from upon its surface: in these images one is asked to join the body politic of the team and to observe Mars from within the body of the Rover. Thus these images present something of a public opportunity to “see like a Rover”. Such a vision requires less tacit or embodied sense of the robot’s experience

42 This technique is often used in nature documentaries, meant to place the viewer in the action. On filmic techniques in science documentaries see Mittman (1999).
as adopted by team members, but still permits the opportunity to build an attachment to the robotic observer through which they are able to witness the scene.\footnote{43}

Here we might take the opportunity to comment on Shapin and Schaffer’s concept of “virtual witnessing” (1985), used to discuss how Robert Boyle’s descriptions of experimental apparatus in the early Royal Society served to bring distant members into the room, allowing them to witness a carefully crafted and staged experience from afar. Certainly the Martian Picturesque convention allows the general public to become virtual witnesses, and in doing so brings these groups together behind a singular vision of the Martian surface, building rapport for the mission with its patrons. Subsequent discussions of virtual witnessing in STS have focused more on what is being witnessed, and how this is arranged for the observer. However, it is also important to note the stance that the witness is encouraged to take can also accomplish social work for the experimenter. *Where* one is asked to witness from is often as important as *what* one is asked to witness.

Their scientific virtues aside, True Color images play a significant role in the continued success of the Mars Rover Mission through their positioning as circulating objects that entice and enlist external viewers into support of the mission. Through the use of Approximate True Color, frontier resonances, and view from behind the Rovers’ eyes such images *draw Mars as* a new frontier, at the same time as putting the viewer within arm’s reach of this other planet. The standpoint of the virtual witness is thus a political stand -- it unites multiple bodies in the body of the Rover alongside those of the team members committed to the mission. These images then, don’t just invite the viewer to imagine themselves standing on Mars and perhaps become an astronaut someday. They invoke the excitement of the “postcard” from another planet.

\footnote{43}{It is worth noting that students on the Pancam team have experimented with image processing algorithms that adjust the point of view from five feet above the Martian surface to about ten inches taller, thus eliminating the need for outsiders to learn the skills necessary to see like a Rover but still making it possible for the outsider to stand with the robot and its human team on Mars.}
as they invite the viewer to imagine themselves present in the body of the Rover; to join the team in this social, political and technical arrangement; to foster an emotional connection to the Rovers by looking out through their eyes at the terrain --- such that ultimately, these viewers become as committed to the Rovers as the team is to their patrons. These visions make the public complicit in the Rover’s experience of Mars, invite their patrons into a position sympathetic with the Rovers and thus encourage support for their continuing program of exploration. In these ways, with an appeal to “what your eye would see,” the Martian Picturesque present “postcards from Mars” that aim to draw together a variety of publics to which the MER team are indebted and accountable, and to efface some of the critical tensions inherent in ensuring these communities’ continued support.

**Epilogue**

While it is beyond the scope of this dissertation to show how these images are received and whether or not the crafting of the Martian Picturesque is effective in achieving these aims, a recent near-death experience for *Spirit* may provide at least indirect evidence that images from the Mars Exploration Rover mission have established strong relationships between various public stakeholders and the Rovers themselves. In March 2008, NASA’s Associate Administrator for the Science Mission Directorate’s office issued a letter to the Mars Program denying requests for increased funding. In the light of the major overruns incurred by MSL the Directorate announced the importance of withholding more funds because of the need to support not only Mars, but also Outer Planet Exploration. The Administrator’s decision to level this playing field was not surprising, given his responsibility to the Outer Planets community and his position as co-PI on the *New Horizons* mission which was, at that time, wrapping up an encounter with Jupiter and heading towards Pluto. The Mars Program Office could not support the needs of MSL, MER and MRO with the amount
of money now in hand. A letter was issued to the Rover team indicating that they had to cut $4 million from their current fiscal year’s operating budget and up to $8 million for the next year; a similar letter gutted the resources of the Mars Reconnaissance Orbiter. Reviewing their options for a 20% cut to an already shoestring team, the MER Principal Investigator responded with a public announcement that there was no way to operate two Rovers: they would have to shut Spirit down. The mood was glum as the changes were announced on the SOWG line and broadcast through press release. It seemed the Rover had survived physically, but not politically.

By noon on Monday, March 24, the announcement hit the major press websites. On Monday afternoon websites from cnn.com to space.com to physicstoday.org teemed with outraged comments from “the public” – those users who had indeed followed the mission through its images from Day One. The webmaster of unmannedspaceflight.com contacted the MER team to reiterate his community’s continued support for the mission and offer any help through letter-writing or other activist activities that could reverse the funding decision. CBS ran a story detailing “THE OUTRAGE FROM SCIENTISTS TO SWITCH OFF SPIRIT AND RUN OPPORTUNITY EVERY OTHER DAY”44 while a commentator on spacepolitics.com simply stated, “I would venture to guess more people could name both rovers on Mars than could name a single member of the current astronaut corps.”45 The website io9.com, frequented by science fiction fans, posted an article about Spirit’s “death sentence by the U.S. government,” claiming, “To say that this is a tragedy is an understatement.” Next to the blog post, above the 37 comments, was an image of Rover tracks snaking off into a Martian horizon, captioned as “a picture Spirit took of


45 http://www.spacepolitics.com/2008/03/24/mars-rover-funding-cuts-will-there-be-a-backlash/
its own tracks in the dust.”\textsuperscript{46} Across a myriad of internet sites, images in the convention of the Martian Picturesque cropped up next to the brief headlines and blog comment tirades.

The story moved too quickly for mainstream media. As the Cornell team made their way home on Monday afternoon Eastern Time the question had already been raised as to whether JPL would stand idly by to watch their prized mission canned by a Headquarters decision. By Tuesday morning, NASA Administrator Michael Griffin announced that the budget letter would be rescinded: NASA would not kill one of the Rovers. On Wednesday morning, NASA announced the Associate Administrator’s resignation. “Did the internet just accomplish something?”\textsuperscript{47} mused one blog commenter when the story made its way to universetoday.com.

If “the internet accomplished something” that afternoon, it was as the space for “the public’s” overwhelming response to the Rovers’ political plight. It was also the space in which over four years of images were publicly released straight from the Rovers’ cameras to individual desktops across the country, and images of the Martian surface made legible and mobile as Approximate True Color renderings of the distant world. As a result, the “public” that the MER team so frequently invokes had come to see the Rovers as their own, develop a relationship with them and their journey, and experience a sense of co-presence at the new frontier. Four years of drawing Mars as a political space, a public landscape, a frontier that could unite Americans and world citizens at its border, was in no small way responsible for the public reaction, and perhaps also Griffin’s quick action to rescind the letter.

\textsuperscript{46} http://io9.com/371700/spirit-the-mars-rover-left-to-die-before-its-time  March 25, 2008 Tuesday 10:00 AM EST.

“We’re planning with a lighter heart than I expected,” the Chair exclaimed at the SOWG meeting that Wednesday morning. MER scientists cheered the reinstatement of their funding on the teleconference line: *Spirit* had survived yet another near-death experience -- this one, political, not physical. But before getting down to the business of the day, the Principal Investigator piped up on the line with a reminder of the robot’s precarious position on both planets, and the team’s responsibility to each other and to their robot. His voice was at the same time relieved and cautious: “The only thing I would add is, we don’t know what’s gonna happen next, so live for the moment. Get all you can out of this Rover today, guys.”48

48 *Spirit* SOWG March 26, 2008.
This dissertation opened with the question, *How does practical image craft construct meaningful, workable relationships with an alien planet?* Although we often believe representations to stand between an observer and the world, this study of the Mars Exploration Rover mission demonstrates how such images also represent an observer’s work in the world. Conducted with materials ready-to-hand and with robots millions of miles away, this work is at the same time practical, technical, social and epistemological as it makes Mars available for interaction.

As I describe in Chapter One, the Rovers were constructed to render Mars legible to a particular community of observers, whose local solution to the problem of social order enabled the conduct of team science and the crafting of knowledge of Mars. This resulting “form of life” (Shapin & Schaffer, 1985) with its associated norms and resources infuses the practices of Rover science and operations such that the management of the Rover and the management of the team are the same activity. As described in Chapters Two and Three, scientists use digital processing software to reveal various aspects of an image suitable to their local purpose. Their *drawing as* exercises with digital materials can direct future visions of Mars and can be called upon to tame alien data and render it trustworthy at a distance.

In Chapters Four, Five and Six I elaborate the relationship between *drawing as* and social organization. As products of the interaction ritual of the Science and Operations Working Group meetings, images are negotiated, crafted, trimmed and ultimately assented to by the team, asserting their solidarity; annotated images from End of Sol meetings and Long Term Planning meetings similarly document this
collective positioning and decision-making on Mars. The images further locate the team within the robotic body politic such that they together “see like a Rover.”

Finally, image work also reveals local anxieties about the status of the team and their knowledge-making. Construed as experiments, imaging and associated *drawing as* practices can support a range of underdetermined hypotheses, giving rise to attempts to “constrain” interpretation through appeals to digital and analog resources, as shown in Chapter Seven. And as Mars is *drawn as* a public space through the use of Approximate True Color panoramas, I show in Chapter Eight how the resulting “postcards” address the troublesome question of accountability to Congress, to a broader community of scientists, and to various publics. Those interactions that render Mars workable and meaningful to its Earth-bound observers are embedded in the many images produced by the Mars Exploration Rover Mission: from the raw frames freshly downlinked to the internet, to the Warholesque false color prints in scientific journals, to the fold-out panoramas in coffee table books.

*Drawing As: A Synthetic Perspective*

This study thus presents several issues of interest for scholars in Science & Technology Studies. The first is a synthesis -- or perhaps a drawing together -- of existing formulations about images in science into a suggestive way to think about image work as simultaneously the site and document of knowledge production in the sciences. Even as scientists employ and invent visual languages for categorizing objects of interest (Rudwick, 1976), they exert their professional vision over the image (Goodwin, 1994) and inscribe their discrimination of categories and meaning into the image itself. To do so with credibility requires an appeal to historically specific formulations of objectivity (Daston & Galison, 1992; 2007) such that the image can be *drawn as* trustworthy and *seen as* “evidence of anything” (Brand, 1985). This process requires exerting discipline both over the pixels in the image, and over the pixel-
pushing scientists themselves (Lynch, 1985b), conscripting eyes, hands and machines in careful co-ordination to produce trusted images and communities of scientists alike. With each twist of the story-line, however, the action may be increasingly distal analytically from the observation’s original evidentiary context (Pinch, 1985).

Finally, in exploring how scientists draw a natural object as an analytical object, *drawing as* also permits a move away from the troublesome question of what constitutes the “theory” in “theory-laden observation” towards a praxiological orientation, including the work of producing such images and the images’ implications for future observations and interactions (Hacking, 1983; Vertesi, 2008a). After all, *drawing as*, as opposed to *seeing as*, is a material practice, taking place in public space with graphic materials. It inscribes traces of the object’s analytical production (Latour, 1995) into the image, documenting scientists’ work “in action” with the visual data they interpret. It is therefore not only a practical activity available for accounting, but also an activity that leaves graphic traces even as it shapes how objects are appreciated, interacted with, and seen.

*Historical Applications*

This synthetic orientation for *drawing as* begs the question of the applicability of the analytical frame to other studies of scientific visualization. Although my study focuses on a site of digital image work, I use the term *drawing* to emphasize thematic continuities between practices of representation across different historical periods and media. Like Mars Rover images, Galileo’s cratered moon or Lowell’s Mars criss-crossed with canals are also examples of *drawing as*, inscribing categories and distinctions into the image of the object and embedding a way of *seeing as* -- an appreciation of an aspect of the object -- into its representation. Similarly, previous studies of images in the history of science such as representations of nebulae (Schaffer, 1998), cosmological systems (Kemp, 1996) and various other astronomical
phenomena (Lynch and Edgerton, 1996) describe how theoretical claims and analytical distinctions about kinds of objects and their meanings are drawn into images of the day. *Drawing as* is not unique to astronomy, however. Eighteenth and nineteenth century anatomical illustrations can be analyzed for traces of historical orientations towards gender and sexuality (Schiebinger, 1991; Cartwright, 1995); geologists in the nineteenth century draw debates about catastrophic change into their paleontological images (Rudwick, 1992); and even Feynman diagrams express elements and changes in theoretical physics (Kaiser, 2005). In these cases, and in others, modes of seeing are impressed onto the surface of the canvas and are taken up with the image and the object as matters of fact.

*Digital Ethnography*

In addition to this historical orientation, *drawing as* opens up questions for S&TS about work with digital images. Although much of “where the action is” has moved to the screen, to computational algorithms, or to teleconference lines, in this virtual space images require work to make them present, accountable and traceable. The externalized retina (Lynch, 1990) does not disappear from the laboratory but continues to be highly situated, implying shared modes of viewing and confrontation with an alien frontier. The practices that comprise this digital visual work have been particularly well-documented in studies of false-color, image composition, and gesture while working with brain imaging technologies (Alač, 2008; Beaulieu, 2001 & 2002; Dumit, 2004; Joyce 2008) although their applicability in the practice of planetary science has received limited attention (with the notable exceptions of Lynch & Edgerton, 1988 & 1996 and Kessler, 2006). In addition to these studies, it is worth noting that the ability for the same image to be combined and recombined in so many different ways, and for these images to be brought into conversation with one another, allows for an opportunity to witness *drawing as* in various places and stages of action.
This may afford access to multiple partial perspectives (Haraway, 1991; Longino, 1990; Traweek, 1992) and possibilities for exhibiting and addressing incommensurability (Kuhn, 1962; Hanson, 1958).

*Drawing As and the Social Life of Spacecraft*

If *drawing as* constructs knowledge of Mars for the MER mission members, however, it does so only so far as it is embedded in the social order adopted and reinforced among team members that is essential to knowledge-making: the “form of life” in which science is conducted, observations are produced and hypotheses gain validity (Shapin & Schaffer, 1985; Wittgenstein, 1953). Thus, this dissertation suggests, work with Rover images *draws* the scientists of the MER team *as* members of a social and political body exhibiting expressions of solidarity around a collection of shared values. The MER community’s solidarity is mediated, expressed, and exhibited in the production of their images; these images at the same time provide a focus for the team’s communal *seeing as* practices which tie them to the Rover and to each other. Understood in this way, the practices of *drawing as* produce the intersubjective activities of *seeing like a Rover*, supporting the team’s interaction rituals and political structure.

It is not known if members of instrument teams on orbiters or other robotic teams with different arrangements of actors employ or respond to images in the same way: in future work I aim to better characterize comparative politics of visual production among robotic spacecraft teams. But recalling Liz’s assertion that, “After those Rovers leave Earth, the team is all we’ve got,” it is at the very least clear that images of Mars produced by the Mars Exploration Rovers reveal as much about the Rover team as they do about the Red Planet.

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By November of 2008 *Opportunity* had successfully exited Victoria Crater and the team set their sights on a larger crater several kilometers to the south. Although farther away than the robot’s entire odometry to date, the team began planning a long series of drives that would put the Rover at the crater in an Earth year or two. MER team members who were also members of the *Mars Reconnaissance Orbiter*’s camera team requested high-resolution images of the terrain from their orbiter to craft terrain meshes and create the three dimensional images necessary for “seeing like a Rover.” Purposefully recalling Captain Cook’s ship in describing their own voyage of exploration, the team submitted a name to the International Astronomical Union for their new objective: Endeavour Crater.

On the other side of the planet in the Martian spring, *Spirit*’s power levels finally rose to the point where the Rover Planners felt comfortable driving her away from her much-discussed Winter Haven location at the North end of Home Plate. But *Spirit* had only moved a few inches when a localized dust storm engulfed the Rover. The team moved into emergency mode: *Spirit* was instructed to shut all but essential heating operations down, possibly sacrificing the MiniTES instrument to the Martian cold, and to only send a single “beep” home to Earth at a pre-appointed time if she survived over the next few days. The mood was tense as scientists and engineers waited anxiously for a sign from their vehicle. MER scientists with connections to the MARCI weather instrument on board the *Mars Reconnaissance Orbiter* sought coverage of the weather system over *Spirit* to produce estimates as to when the storm would recede. MER engineers stayed up on Mars time until the early hours of the Earth morning to oversee the issuing of Rover commands and check for a reply. The polar lander *Phoenix* had sent its last signal only the weekend before and the *Phoenix* team had just announced the death of their spacecraft; the Rover team prepared for the worst, should *Spirit*, too, never call home again. “Like concerned parents,” said the
Project Manager in a NASA press release, “if we can stay in communication with the rover, we are in a better position to help.”¹

A press release issued the very next day recorded the cheers and shouts of “She’s talking!” that echoed through the Rover control room at JPL when Spirit’s lone beep was received on schedule.² The Mission Manager’s report that circulated to the MER team and the public that week also conveyed the team’s relief and pride:

We still have a lot of work ahead of us, but continue to be amazed by the incredible resiliency of this vehicle. She is a true testament to the team that designed and built her and those that have and continue to operate and support this magnificent rover.³

APPENDIX A: ROVER TRAVERSE MAPS

*Spirit Traverse Maps*


*Spirit* landed in Gusev crater on January 3, 2004 at the Columbia Memorial Station at the upper left corner of the image. After briefly visiting Bonneville Crater, the Rover drove across the crater floor to climb the Columbia Hills, on the right side of the image, where she spent her first winter on Mars. From there *Spirit* proceeded south to the area called Home Plate, pictured in detail on the following page. Fieldwork for this dissertation project took place during *Spirit*’s exploration of Home Plate.
In the image from the orbital HIRISE camera one can see the distinctive shape that gives Home Plate its name. To the right is Mitcheltree Ridge; the area of activity west of it is Silica Valley, the location of the silica-rich Innocent Bystander and Gertrude Weise. The extent of Spirit’s tracks to the bottom right of the image is Tyrone: under the yellow traverse lines the white soil can be seen from orbit. South Promontory is to the bottom left, and Winter Haven (“WH3”) is at top left.
Opportunity Traverse Maps

Figure 82 *Opportunity* Regional Map: Meridiani Planum. Image Released December 29, 2008. Image Credit: OSU Mapping and GIS Laboratory/NASA/JPL/Cornell/University of Arizona/Malin Space Science Systems.

*Opportunity* landed January 24, 2004 in Eagle Crater on Meridiani Planum and has since explored a variety of craters in the area. Fieldwork for this dissertation project took place as the Rover explored Victoria Crater.

*Opportunity* arrived at Victoria in September 2007 at Duck Bay and proceeded clockwise around the crater to the dust streaks on the upper right of the image. This close-up of the rim of the crater taken by the HIRISE orbital camera is annotated with the names of the promontories and the Rover’s tracks up to Sol 1188 (end of May, 2007). Based on imaging conducted at the promontories *Opportunity* returned to Duck Bay and entered the crater there. Cercedilla is located on the edge of Golfo San Matias near the Cape of Good Hope, upper right. The Rover is visible in the orbital image on the promontory at Cape Verde.

All traverse maps in this appendix are publicly released and available online at http://marsrovers.jpl.nasa.gov/mission/traverse_maps.html
WORKS CITED


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