SYSTEMS ENGINEERING FOR NEXT GENERATION SPACE ENTERPRISES

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SYSTEMS ENGINEERING FOR NEXT GENERATION SPACE ENTERPRISES

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We are on the threshold of a new era of sustainable exploration and development of space. New Launch vehicles and programs such as NASA's Artemis and Lunar Gateway will change space technology and the stakes for space systems as we know them. As a result of these and other transformative changes, opportunities to launch and operate new space vehicle architectures will be unprecedented. To this end, this dissertation provides three foundational studies intended to impart rigor and systems thinking to the development and planning efforts of next-generation space projects.

1) Navigating the Policy Compliance Roadmap for Small Satellites

This study explores USA space policy and regulatory processes and how they apply to satellites not fitting the typical mold of traditional missions. It lays out a systematic way forward for small satellite mission developers and managers to navigate the approval quagmire for individual spacecraft on multi-payload launches. It also puts forth ways for approving new and expected future mission architectures and technologies. Additionally, areas are identified where there are policy and regulation gaps and "gray areas" to prepare developers and inform other stakeholders of potential issues.

2) Lessons Learned from the First Generation Interplanetary CubeSats

This study analyzes information gathered from the first sixteen interplanetary CubeSats and the unique difficulties faced by this mission type. Solutions to the specific development problems and general observations on the engineering and programmatic challenges faced by this mission

type were solicited from previous mission developers and documented. From this, development approaches are proposed to lower risk and costs for future mission developers and stakeholders.

3) Evaluating Mars Rotorcraft Development Investments

Rotorcraft can offer a new paradigm for Martian surface and atmospheric exploration missions. This study was conducted to enable stakeholders to evaluate competing research and development efforts for Mars Rotorcraft technologies. Not only for their estimated costs and system performance but also for their long-term improvement potential in the context of other ongoing developments. It does this by establishing critical metrics and relationship models for evaluating rotorcraft system and subsystem performance. Then the alignment of potential developments to the broader NASA technology goals and ways to estimate returns on investments were established.

BIOGRAPHICAL SKETCH

Aaron Zucherman received his Bachelor’s Degree in Mechanical Engineering from the New Mexico Institute of Mining and Technology, graduating with honors in 2017. Recognitions include as a 2022 Future Space Leaders Foundation Fellow and 2020 Matthew Isakowitz Fellow. Other research and career development efforts during his time at Cornell University included graduating from NASA's Planetary Science Summer School class of 2021 and contributing to NASA's Small Satellite Reliability Initiative (SSRI), the Space Generation Advisory Council's Small Satellite Working Group, INCOSE's Space Systems Working Group, and the Small Payload Ride Share Association's Multi-Manifest Design Specification (MMDS).

Dedicated to the visionaries who showed me there was no limit to the dreams I could have in the space industry:

Dr. Benjamin Malphrus

Prof. Robert Twiggs

Prof. Mason Peck

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I must express my gratitude first and foremost to Cornell University's Prof. Mason Peck, head of the Space Systems Design Studio (SSDS). I was privileged to have Prof. Peck as my advisor, his chance on me to join his program and his endless support of my research efforts, represented in this dissertation and beyond it, let me explore the limits of my curiosity. His openness to my pursuit of different areas of study while providing guidance and advice every step of the way will always inspire me and has set the course for my career. I will always be eternally thankful for his willingness to listen and seriously consider anything from my half-baked research ideas to a potential partnership for his lab while ensuring I would progress with my degree and research. Mason Peck is nothing short of a Paragon of what all Academic Researchers should aspire to.

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I want to thank my parents, Mark, and Inez Zucherman, who were always there for me, providing the support I needed to pursue my dreams and overcome hard times. Thank you to my grandparents Julia Weiss and Davina, Robert, and Patty Zucherman for their part in making sure I grow up to be a functional member of society. Finally, thank you so much to Michelle Huang for her love.

This dissertation would not be possible without the collaborators that contributed to the studies and papers published, making up the contents of this work.

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PREFACE

This dissertation is a collection of three works that individually contribute to the applied systems engineering knowledge applied to the development of specific spacecraft and space technologies. It does this by providing tailored systems engineering tools and programmatic management approaches that can be used by stakeholders to prepare for and execute the next generation of space exploration enterprises. Next generation is defined as missions and programs that utilize new technologies or architectures that diverge from the historical approaches to development. These findings aim to enable space mission stakeholders to avoid mission failures and cost overruns by utilizing the knowledge and tools provided.

Beyond the current and planned journal papers and conference proceedings, the contents and derivatives of these works have been published in various forums, including NASA's Small Satellite Reliability Initiative (SSRI) Knowledge Base and The Space Generation Advisory Council (SSGA) Small Satellites Project Group (SSPG). The SSRI Knowledge Base is an online tool that consolidates and organizes resources, best practices, and lessons learned from previous small satellite missions. Findings from this work and other efforts stemming from it were used as content for the Knowledge Base. In addition, the SSGA SSPG has taken on the project of using the findings of this work and extending it to include new developments for the 2023 International Astronautical Congress (IAC), with plans to continually update the findings to present at future IACs.

CHAPTER 1

NAVIGATING THE POLICY COMPLIANCE ROADMAP FOR SMALL SATELLITES

Summary

This section explores U.S. space policies and how they apply to satellite missions that may not fit the typical satellite mission mold. It presents a policy compliance "roadmap" for satellites from diverse agencies and identifies areas where further work is underway to address the challenges posed by the evolution of the space industry. Also, it lays out a coherent way forward for all small satellites navigating the approval quagmire and for mission managers of multi-payload rideshares who wish to smooth the path to launch approval.

Introduction

In the early days of satellite development and launch, only governments or government contractors built satellites and rockets, and, generally, each launch carried only a single payload (typically a satellite) to orbit. Today, the space enterprise encompasses many players and stakeholders, including small businesses, universities, affinity organizations, and even primary schools. In addition, the proliferation of small satellites (or "smallsats") has led to large numbers of new entrants into the space business. This has increased the number of rideshares and a paradigm where a single launch carrying a single mission or payload to space is no longer the norm.

The study explores U.S. space policies and how they apply to satellite missions that may not fit the "typical" mold on launch missions that may not have a single responsible agency. Where applicable, it outlines the processes and approvals involved in getting to space. In addition, areas have been identified where further work is required to fill in policy gaps and "gray areas" in the overall policy picture.

This study does not cover U.S. export control regulations. For more information on this subject, it is recommend reviewing the *Introduction to U.S. Export Controls for the Commercial Space Industry,* 2nd Edition, prepared by the U.S. Department of Commerce's Office of Space Commerce and the Federal Aviation Administration's Office of Commercial Space Transportation.[1]

International Treaties and U.S. National Policy and Regulations

The Outer Space Treaty of 1967 forms the basis of international space law and stipulates that the signatories "shall be responsible for national space activities whether carried out by governmental or non-governmental agencies." [1,2] It places the responsibility for operations in space on the government of the nations that fly in space and requires "authorization and continuing supervision" by that government. In the Outer Space Treaty, a nation "on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object…." This implies that the U.S. government has responsibility for U.S.-owned objects in space, regardless of whether that object is launched by the United States or by a foreign launch provider. Similarly, foreign satellites remain the property of foreign entities, even if launched from a U.S. rocket. While the Outer Space Treaty places joint liability for damage on the country "from whose territory or facility a space object is launched" as well as the country that procured the launch. This liability is only absolute for damages on Earth and to aircraft in flight. For damages in space, the launching country shall be liable "only if damage is due to its

[1]The document can be found at https://www.space.commerce.gov/wp-content/uploads/2017-export-controls-guidebook.pdf.

fault or the fault of persons for whom it is responsible"; in other words, only if the damage is due to the launching country's negligence or malicious intent.

The *National Space Policy of the United States of America* [3] also directs safe and responsible operations in space. Specific sections discuss protection of the space environment (including debris mitigation) and protection of the electromagnetic spectrum. The National Space Policy also discusses cybersecurity for U.S. space systems, which flows into lower-level guidance on cryptographic protection of space systems. Similarly, the National Space Transportation Policy [4] outlines the military, civil, and commercial launch oversight authorities. Military oversight is provided by the Department of Defense (DOD), while civil oversight is provided by the National Aeronautics and Space Administration (NASA). Commercial space transportation oversight is under the Secretary of Transportation; thus, commercial launches are licensed by the Federal Aviation Administration (FAA). These policies are often subject to change and reinterpretation based on current U.S. political leadership. The Federal Communication Commission (FCC) adopts regulations and authorizes almost all commercial space operations, including launches, space exploration, and proximity operations. It also regulates services and market access.

The Responsibilities of the Launch Provider Versus Satellite Owner

The *National Space Transportation Policy* is a document that, true to its name, mainly discusses access to space in the form of launches rather than operations in space once satellites have separated from the launch vehicle. Similarly, most of the lower-level policies (those derived from the document) demarcate the responsibilities of the launch provider and the responsibility of the spacecraft owner/operator at the point where the spacecraft separates from the launch vehicle or its upper stage.

In other words, the launching agency is responsible for launch policy and is generally not the policy gatekeeper for the satellites it launches. Without the ability or authority to enforce policy throughout the satellite's orbital lifetime, the launching agency cannot ensure compliance. Instead, compliance must be enforced through the parent agency of the satellite owner/operator. Thus, a NASA satellite launched on a DOD rocket must comply with NASA policy, not DOD policy. Similarly, a DOD satellite on a commercial launch must still demonstrate compliance with DOD policy, not commercial policy. Figure 1 illustrates the general responsibilities of mission partners on a launch mission, and Figure 2 illustrates in more detail how these policy responsibilities break down for a sample multi-payload mission.

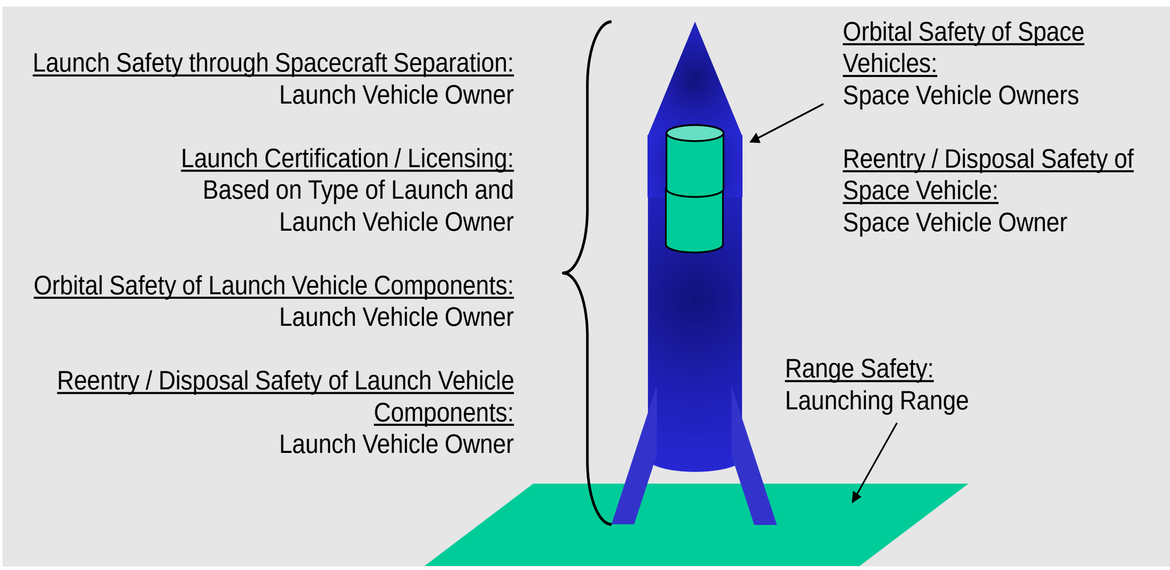

Figure 1: Policy Compliance and Safety Responsibilities for Launch Missions

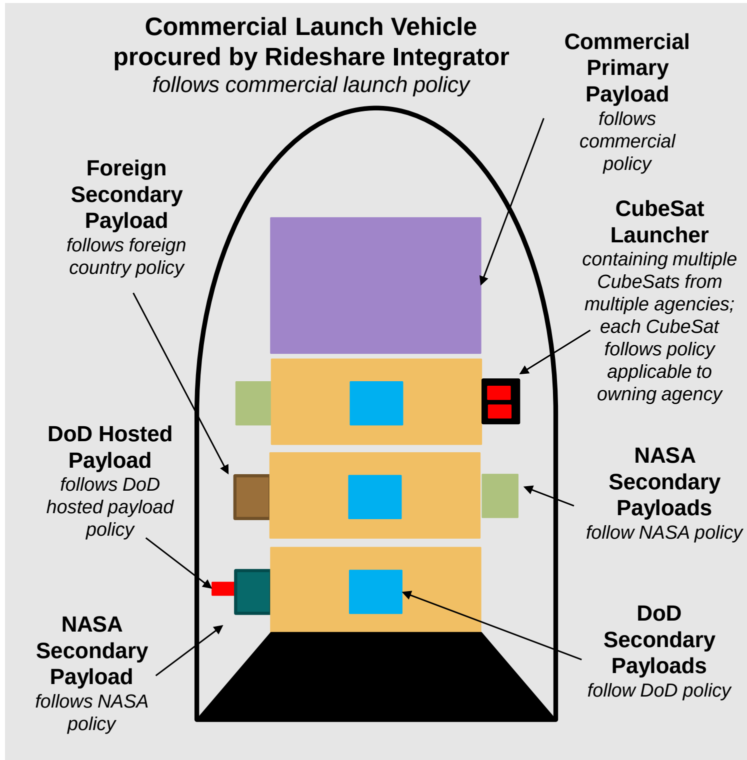

Figure 2: Rideshare Policy Compliance for Multiple Payloads

While this demarcation provides a convenient boundary for separating the responsibility of the launching agency from the responsibility of the satellite provider, in practice, the line is less clear-cut. Recent events [5] illustrate the hazards of a launch provider, leaving regulatory compliance entirely up to the satellite provider. Even though these satellites are no longer necessarily under the authority or direction of the launching agency once launched, U.S. launch providers have a strong incentive to ensure all pre-launch approvals are in place. Most launch providers now require documentation of satellite policy compliance before satellites are integrated for launch. At the beginning of a mission, it is essential to clarify this demarcation and the proper policy compliance responsibilities for all satellite provider partners. The launching agency may still “refuse service” for a satellite that does not meet specific requirements, even if those stipulations are not required by any policy outlined by any government entity.

Special Consideration for Foreign Launch of U.S. Government Small Satellites

The emergence of new commercial companies that provide launch services for small satellites has led to questions about the suitability of these launch providers for U.S. government missions. Many of these launch providers are subsidiaries of foreign companies or maintain launch sites in foreign countries. Because a body of policy and law requires U.S. government satellites to be launched on U.S. launch providers, a determination specifically for these companies is required. This is a significant requirement that spacecraft operators must plan for far in advance to comply with them.

Several U.S. laws and policies require launch vehicles for U.S. government satellites to be manufactured in the United States [3,4,6,7,8]. These laws and policy statements establish a two-part test to determine if a launch vehicle is manufactured in the United States and, thus, allowed to launch U.S. government satellites. The two tests are:

1. Is the launch vehicle company more than 50 percent owned by U.S. nationals? (Required by Title 51 of U.S. Code and Department of Defense Instruction 3100.12)
2. Are 50 percent or more of the launch vehicle components, by cost, manufactured in the United States? (Required by Title 41 of U.S. Code and the National Space Transportation Policy)

Most government launch agreements are also subject to the Federal Acquisition Regulations. Part 52.225-18 of the Federal Acquisition Regulations also defines the “place of manufacture” as “the place where an end product is assembled out of components.” This language appears to establish a third test to determine if a launch vehicle is manufactured in the United States; namely, is the product assembled out of components in the United States?

However, in August 2018, the Deputy Secretary of Defense issued a memo confirming that the two-part test was sufficient. The government typically buys a launch service (the delivery to orbit), not the launch vehicle itself. In these cases, the government does not take possession of the launch vehicle, and, therefore, the launch vehicle is not an "end product" as defined by the Federal Acquisition Regulations. The launch itself is the end product. Recently, the DOD has launched several small satellites from new commercial providers using non-U.S. launch sites, as a new normal [5]. This was done showing that some of the emerging providers meet the two-part test.

The recently released 2020 National Space Policy does appear to give new direction on government technology demonstrations or scientific payloads being allowed to fly on foreign launches [3], possibly allowing these payloads to bypass the two-part test, but it is too early to see how this change will be implemented.

What Constitutes Ownership?

Determining the parent agency of the satellite is critical to understanding the applicability of U.S. space policy. The flowchart shown in Figure 3, developed in partnership with the DOD Space Test Program (STP) and Air Force Research Laboratory (AFRL), illustrates a method for determining satellite ownership. The key consideration is "Who will have control authority over the satellite (or payload) once it launches?" Another, more direct, way to ask the question is "Who has the authority to decide when to execute the satellite's end-of-life or deorbit procedure?" If the DOD makes the decisions for all critical spacecraft activities after launch (commonly referred to as *Satellite Control Authority*), it is a DOD satellite, regardless of whether it is built or operated by a private company. Similar rules apply to NASA satellites, with the additional stipulation that NASA contracts and NASA grant recipients are also considered NASA satellites.

When using Figure 3, often the most reliable determinator of who "owns" a component or instrument is by looking to the source that provided funds to include the device or system on the spacecraft. Often, the funding body will be considered the liable owner or specify in its funding contracts who the owner of or otherwise responsible party for said device or system is. However, some satellites, systems, components, instruments, and other payloads still fall into gray areas. For example, STP frequently arranges to launch private university or small business satellites sponsored by military sponsoring agencies to the DOD Space Experiments Review Board (SERB). Some of these university or small business satellites also receive small grants from the DOD. Although sponsored by the DOD, ownership of the vehicle and Satellite Control Authority remain with the universities. These organizations are private entities, and, therefore, such payloads currently follow a commercial path to comply with policy regulations, not a DOD path.

Other "special cases," include civil government satellites that are non-DOD, non-NASA satellites such as those belonging to National Oceanic and Atmospheric Administration (NOAA). Later sections also discuss the special case of DOD satellites that are not national security space satellites, as these highlight other policy gray areas that require further clarification. However, sometimes gray areas exist to provide policy and decisionmakers with sufficient option space to accommodate new types of missions.

Once the owning organization is identified, the appropriate policies can also be identified. For example, the DOD, National Telecommunications and Information Administration (NTIA), NOAA, NASA, the FAA, and the FCC all have broad policy directives or regulations that flow down from the National Space Policy; these are discussed in more detail in the applicable sections of this chapter.

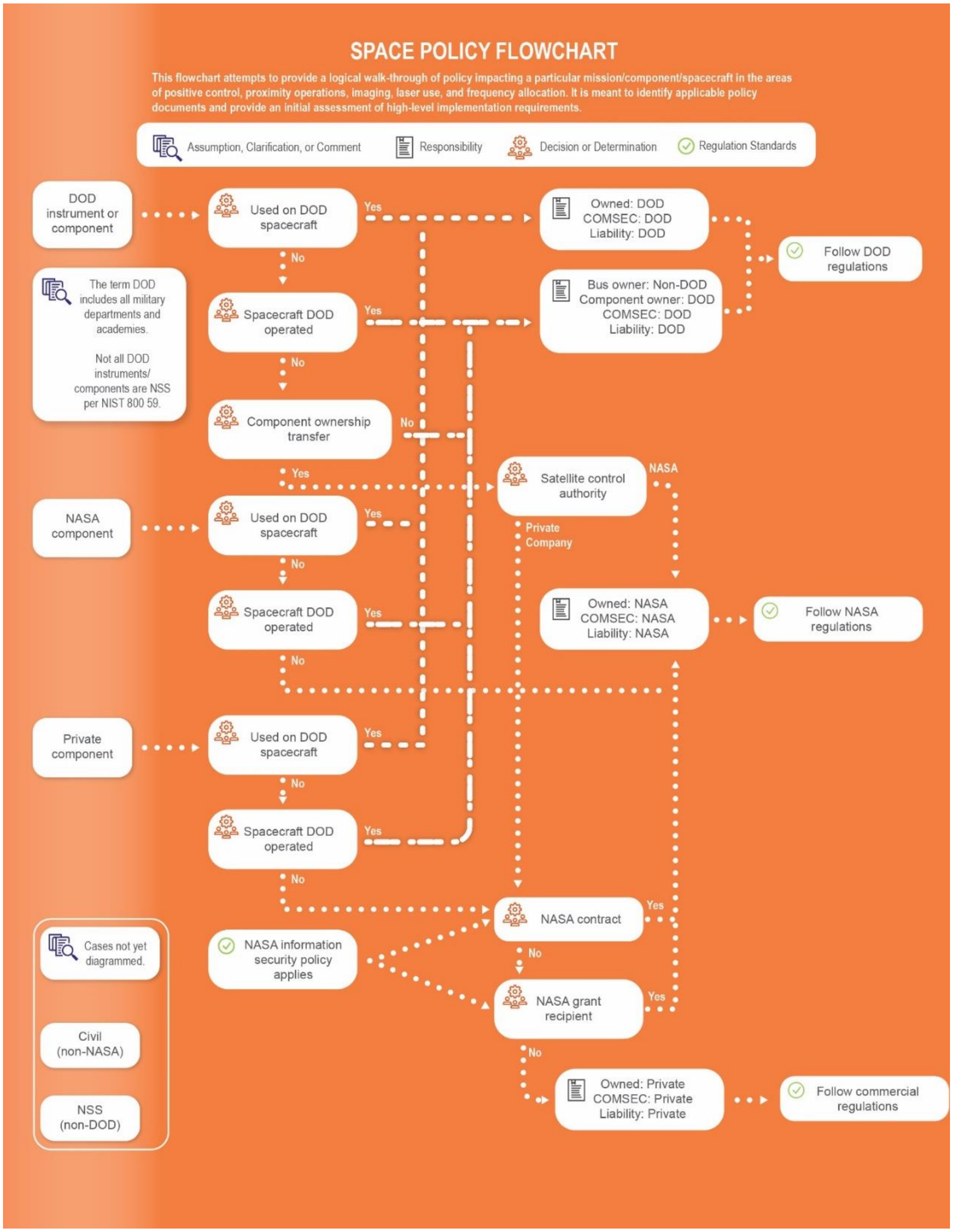

Figure 3: Flowchart for Determining Space Vehicle Ownership

Orbital Debris Policy

National Policy

As described earlier, the U.S. National Space Policy calls for protecting the space environment from orbital debris. Specifically, one of the *Cross-sector Guidelines* directs compliance with U.S. Orbital Debris Mitigation Standard Practices (ODMSP) [9] and requires "the head of the sponsoring department or agency" for space missions to approve exceptions.

The ODMSP is outlined in a document of the same name last updated in November 2019. The updated document begins with a preamble that provides an overview of the updates and discusses the motivation behind them. The first four technical sections govern debris generation, accidental explosion, minimizing the risk of collision with other objects, and disposal of space objects at the end of mission life. A new fifth section discusses special cases of space operations, including large constellations, small satellites, rendezvous and proximity operations, active debris removal, and tether systems.

The ODMSP is the source of most of the debris requirements familiar to experienced satellite developers: disposal within 25 years of the end of the mission for low Earth orbit (LEO) satellites; reentering space objects will not cause casualties on Earth; and a limit on the potential for in-space collision, debris generation, and accidental explosion. The 2019 update adds several numerical guidelines to the general recommendations, including a 1-in-1000 limit on the probability of accidental explosions, a 1-in-1000 limit on the lifetime probability of collisions with objects greater than 1 cm, and a 1-in-100 limit on the lifetime probability of collisions with objects less than 1 cm that could interfere with post-mission disposal. The new ODMSP also provides extensive guidance on post-mission disposal options and orbits and stipulates that any post-mission disposal maneuvers have at least a 90 percent chance of success. The 25-year time limit on atmospheric reentry is unchanged, but the new ODMSP encourages small satellites to have orbital lifetimes "as short as practicable." The new fifth section of the ODMSP calls attention to constellations and small satellites (as well as tether systems, rendezvous and proximity operations, and active debris removal) but does not levy any additional requirements beyond those levied in the previous four sections.

Because these guidelines are national, they apply to all U.S. missions. Exceptions and waivers to the ODMSP typically require approval at high levels and are increasingly difficult to obtain.

NASA Policy

NASA documents its orbital debris mitigation requirements in NPR 8715.6B*, NASA Procedural Requirements for Limiting Orbital Debris* [10], and NASA-STD-8719.14A*, Process for Limiting Orbital Debri*s [11]. In this last document, there are specific numeric limits to the probability of in-space collision, which mirror those included in the 2019 ODMSP. The document lists other detailed requirements for compliance with ODMSP and requires documentation of compliance in an orbital debris assessment report (ODAR) and an end-of-mission plan (EOMP). The report and plan are approved through NASA channels, and exceptions flowed up through the NASA Office of Safety and Mission Assurance (OSMA). It is worth noting that the NOAA satellites also follow NASA debris mitigation requirements [12].

NASA has also recently issued two documents governing conjunction assessment and collision avoidance. NASA Interim Directive 7120.132, *Collision Avoidance for Space Environment Protection* [13], outlines procedures for assessing and responding to the conjunction risk posed by debris and other space objects. It asks missions to document their collision avoidance practices in an orbital collision avoidance plan and, for the first time, provides guidance on thresholds for collision avoidance, suggesting teams maneuver at a probability of collision threshold of 1×10^{-4} (one in ten thousand). NASA has also released the

NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook [14], providing high-level guidance to missions.

DOD Policy

DOD Directive 3100.10*, Space Policy,* states that the "DoD will promote the responsible, peaceful, and safe use of space, including following the U.S. Government (USG) Orbital Debris Mitigation Standard Practices." [15] Department of Defense Instruction 3100.12, *Space Support,* requires that DOD missions comply with debris mitigation practices that echo the ODMSP [7]. The Air Force has implemented these two directives in several Air Force instructions, including Air Force Instruction 91-202, *The US Air Force Mishap Prevention Program* [16]. The 2020 version of Air Force Instruction 91-202 incorporates the space safety requirements formerly captured in the now-obsolete Air Force Instruction 91-217. The space safety requirements in Air Force Instruction 91-202 are similar to those in the NASA *Process for Limiting Orbital Debris*. In addition, the Air Force and Space Force record their compliance in two documents: the space debris assessment report for launch vehicles and the combined space debris assessment report/end-of-life plan for space vehicles. The format of these documents is essentially the same as the NASA orbital debris assessment report/end-of-mission plan. The Army and the Navy have relatively informal coordination processes for implementing DOD Directive 3100.10. At this time, the U.S. Space Force reports through the U.S. Air Force on policy matters related to space, and compliance processes have not yet changed to reflect the standup of the new service.

FCC Policy

Commercial satellites, defined in this case as any satellite not owned or operated by the U.S. federal government, do not fall under any of the NASA and DOD policies but must still comply with national orbital debris mitigation guidelines. The FCC currently enforces this compliance through its regulation of the nonfederal use of the radio spectrum. Title 47 of the *Code of Federal Regulations* [17] requires applicants for frequency licenses to provide information on their orbits and their plans for orbital debris mitigation. FCC regulations also require the use of disposal options and the safe management of pressure vessels at the end of life. Many commercial satellite operators use NASA's orbital debris assessment report format to document their orbital debris mitigation compliance when applying to the FCC [18,19,20].

In October 2018, the FCC issued a Notice of Proposed Rulemaking to update and expand its orbital debris regulations, outlining several potential changes to the FCC's regulations [21]. Although many of the proposed rules were compatible with the new ODMSP, many differed from it. In addition, the FCC proposed rules required maneuverability above a certain altitude in LEO, a new performance bond requirement for successful disposal post-mission, and a new indemnification requirement. Following a comment and review period, the FCC published a final set of rules on August 25, 2020, and deferred some of the more contentious issues into a Further Notice of Proposed Rulemaking [22]. The topics being tabled for further review include maneuverability above a certain altitude in LEO, post-mission orbital lifetime, indemnification, and the requirement for a performance bond for successful disposal. At the time of this study's writing, the FCC is reviewing comments from the Further Notice of Proposed Rulemaking.

FAA Policy

The FAA licenses launch and reentry operations for nongovernment launches from U.S. soil or conducted by U.S. companies or citizens. Contrary to popular belief, it does not currently oversee or regulate satellites or activities in space. FAA regulations levy safety requirements on nongovernment launch vehicles, including limiting the potential for debris generation and accidental explosions and, for reentry vehicles, limiting the potential for human casualties on the ground. The FAA, however, does not regulate the disposal of orbiting upper stages unless they plan to land on or impact Earth [23].

Policy Compliance Process

Once the owning/operating agency for a satellite is known (see Figure 3), that agency must demonstrate compliance with its parent agency's orbital debris mitigation policy. For NASA, this involves the preparation and submittal of an orbital debris assessment report (ODAR) and end-of-mission plan (EMP) per the NASA *Process for Limiting Orbital Debris*. The process is similar for Air Force and Space Force missions, which require completion of a space debris assessment report (SDAR) and end-of-life plan per Air Force Instruction 91-202. Missions without defined processes or formats for debris compliance should consider using the NASA ODAR as the template for demonstrating compliance with the higher policy. This seems to be the practice for private satellites when requesting licenses from the FCC. Launch vehicles should follow the FAA process through the "end of launch," defined by the FAA as the last exercise of control over the launch vehicle. It is important to note that exceptions to *Orbital Debris Mitigation Standard Practice* guidelines require approval at high levels, typically the head of the sponsoring department or agency. Such waivers are increasingly difficult and time-consuming to obtain, suggesting that satellite missions should conduct the required analyses early to allow time for design changes or waiver approvals, as needed.

Ambiguity, Open Questions, and Recommendations

The guidelines in the ODMSP represent one of the more well-known and universally accepted aspects of space policy, but policy gaps still exist. One of the biggest open questions is whether the FCC should be the agency to enforce orbital debris mitigation policy on the burgeoning commercial and private satellite business. The exponential growth and danger in this area may call for new authorities with greater focus to take responsibility for orbital debris mitigation.

Several items in the FCC's recent *Further Notice of Proposed Rulemaking* are concerning to many of the different types of small satellite developers (commercial, academic, etc.). Most of the small satellites and CubeSats to date have lacked significant propulsion capabilities; requiring all missions above 400 km to be capable of collision avoidance maneuvers would drive significant design changes, cost increases, and, perhaps, other unforeseen consequences. One of those concerns is linked to small satellites also lacking robust security and command authentication systems. The proliferation of smallsats with propulsion but no encryption could pose a security concern. From a research and innovation perspective, requiring satellites to provide insurance, indemnification, or bonds against successful disposal will add an additional barrier to entry for new commercial ventures and academic programs that do not have the budget to do so.

The lack of specific requirements for orbiting upper stages for non-DOD or NASA launches is a gap that policymakers must ultimately address. Currently, the FCC's proposed rules in this area differ from several elements of the ODMSP without substantial documented justification. The industry is seeking a "whole of government approach" and is pushing back on the FCC's more subjective approaches.

Spectrum Usage

<u>Summary of Applicable Policy</u>

Public law and regulations, rather than policy, provide all guidance for the assignment and usage of spectrum for satellites. The NTIA regulates frequency usage for federal agencies such as NASA and the DOD. The NTIA documents its rules and procedures in the *Manual of*

Regulations and Procedures for Federal Radio Frequency Management [25].

Through Title 47, the FCC licenses frequency use for "non-federal agencies," including private and commercial satellites. Part 25 contains commercial and remote-sensing satellite communication regulations, Part 5 covers experimental licensing, and Part 97 covers amateur communications [25]. In 2019, the FCC adopted new streamlined regulations, *Licensing Procedures for Small Satellites (Report and Order) IB Docket 18-86*, to better support the small satellite industry [26].

The FCC also serves as the United States' "notifying administration" to the International Telecommunication Union (ITU). As such, it acts as the "mailbox" for all coordination and registration correspondence to the ITU, including for federal systems. The ITU is the United Nations' "specialized agency" for telecommunications, including the international management of radiofrequency spectrum and orbital resources. The ITU has limited enforcement authority, but its 193 Member States may participate in World Radiocommunication Conferences (WRCs), a treaty conference convened every three-to-four years to revise the ITU's *Radio Regulations* [27]. Following each WRC, Member States integrate the new provisions of the *Radio Regulations* into their domestic regulations.

<u>Policy Compliance Process</u>

The NTIA is located within the Department of Commerce (DOC) and is the agency responsible for managing the "federal use" of the spectrum. Instructions for filing are laid out in the *Manual of Regulations and Procedures for Federal Radio Frequency Management*. The NTIA does not grant a frequency license but instead grants the authority to use a frequency. The Frequency Assignment Subcommittee within the NTIA coordinates and assigns radio frequencies. NASA programs work their submission through the individual center's spectrum management office and then through the NASA spectrum management office. The NASA spectrum management office then submits paperwork to the NTIA. DOD-owned missions submit through service-level spectrum management offices, which submit to the NTIA.

There are four filing stages for federal programs: (1) conceptual, (2) experimental, (3) developmental, and (4) operational. Each is explained in detail in section 10.4.1 of the NTIA's *Manual of Regulations and Procedures for Federal Radio Frequency Management* [25]. Most small satellites performing science and technology, or research and development, missions will obtain a Stage 2 experimental license. As the name indicates, operational satellites will obtain a Stage 4 operational license. Unlike the FCC, there is no requirement to conduct debris or lifetime analysis when applying to the NTIA.

The FCC is an independent U.S. government agency (overseen by Congress) that regulates interstate and international communications by radio, television, wire, satellite, and cable. Part 25 of Title 47, *Telecommunications*, in the *Code of Federal Regulations* outlines the application and filing process [17]. Most noncommercial small satellite missions will submit applications under the amateur (Part 97) or experimental (Part 5) rules. These options provide access to different frequency bands and have different requirements and limitations.

Note that authority under Part 97 is not a license for a smallsats but, rather, a permit that allows a licensed amateur radio operator (a "ham") to operate a space station (defined as being more than 50 km above Earth's surface). There are neither application nor ITU recovery fees for this type of authorization [26]. Access to frequencies allocated to the amateur satellite service is limited to amateur-related services and may not include communications in which the licensee or operator has a pecuniary interest, including communications on behalf of an employer. Additionally, for any use of amateur frequencies, missions must coordinate with the International Amateur Radio Union (IARU) and include that information in the package to the FCC. Experimental license applicants may select from a broad range of frequencies, but they are limited to noncommercial missions, receive no regulatory status, and are typically limited to two-year license terms. In both instances, the FCC suggests that missions file no later than 30 days after the launch has been identified.

Eligibility for a Part 5 experimental license is limited to “experimentation under contractual agreement with the United States Government, and [for] communications essential to a research project.” [26] Note that Part 5 specifies that spectrum is not limited to satellite use and is shared with many other experimental users. Experimental licenses are granted on a noninterference basis, and they may neither cause interference nor claim protection from interference [26].

Missions filing with the FCC must demonstrate compliance with the debris mitigation guidelines (CFR 47 25.114d(14)) [17], as described in the orbital debris section of this chapter and with other requirements specified by the FCC that go beyond the ODMSP. In addition, missions must show that they adhere to debris generation guidelines, deorbit within 25 years of end of life or move to a disposal orbit, and expect zero casualties when reentering. If missions cannot demonstrate this satisfactorily to the FCC, they may be required to carry insurance or risk not being approved to broadcast.

When frequency usage and the international coordination process are concluded as required by the ITU’s *Radio Regulations*, the operator submits its frequency assignments to the FCC liaison who files the United States’ assignments to the ITU for recording in the Master International Frequency Register. Getting a license or approval to use a frequency through either agency and completing the ITU’s coordination process takes from months to years, so missions should start working on the application and submittal as early as possible. The regulatory changes for small satellites by WRC-15 are contained in the *Final Acts of the Conference* and the *Radio Regulations* [27].

Ambiguity, Open Questions, and Recommendations

There is strict protection of the amateur frequencies from use by experimental or federal programs. This has led to some confusion in the community as to the ability to use amateur bands, particularly since, until recently, experimental or federally connected programs regularly used amateur bands. Determination has to be made whether missions that have previously used amateur bands now need to go through the FCC for an experimental frequency or through the NTIA, especially those missions run by service academies.

Additionally, there is often confusion for programs that fall into “gray areas.” For example, a university-owned and -operated satellite that receives funding from the DOD and launches on a DOD launch vehicle remains a private satellite but is sometimes directed to the NTIA for frequency approval. Occasionally, missions get different answers from the FCC and the NTIA. The future will probably bring more of these “gray area” missions, so it might be advantageous to stand up a single office at some point in time for frequency submittals. That office could then route the approvals to either the FCC or the NTIA, as appropriate to each mission.

Since the FCC updated its rules, the FCC does not specifically refer to ODMSP, though FCC rules still partially follow the ODMSP. Theoretically, there could be a regulatory mismatch between the ODMSP and the FCC rules, which could lead to loopholes or gray areas in debris mitigation requirements. If a satellite also must obtain a NOAA imaging license, which still requires compliance with ODMSP, there could be further confusion as to what debris mitigation requirements apply and who provides approval.

Optical Communication (LASERCOM)

Summary of Applicable Policy

Free-space optical (FSO) communication refers to the transmission of modulated light pulses through free space (vacuum or the atmosphere) to wirelessly transmit data for telecommunications or computer networking. The use of lasers for communication is often referred to as *lasercom*. Communication may be entirely in space (an intersatellite link) or be a ground-to-satellite or satellite-to-ground link. The technology has been increasing in popularity both due to the potential for high bandwidth and due to the limited availability of radiofrequency spectrum allocation [28].

FSO as a form of communication in the optical spectrum (typically considered greater than 3 THz) is not heavily regulated. The rationale is that emitters in the optical and near-infrared band have extremely narrow beamwidth and that space is vast, so the potential for harm is low. Nevertheless, to reduce the possibility of DOD laser projects accidentally damaging satellites, the Laser Clearinghouse (LCH) was established to ensure lasers do not negatively impact orbital assets. The LCH is tasked with providing predictive avoidance analysis and deconfliction with U.S., allied satellites, and operations for projects that utilize lasers.

Additionally, visible and infrared lasers have great potential for damage to the human eye. In the United States, the FAA regulates commercial terrestrial FSO links to prevent distraction or damage to the eyesight of airline pilots.

Policy Compliance Process

The FAA regulates terrestrial laser communications in the United States for commercial applications. Therefore, any FSO link transmitting through "navigable airspace" requires coordination with the FAA. The laser operator must submit a “Notice of Proposed Outdoor Laser Operation(s)” form found in FAA Advisory Circular (AC) 70-1B, *Outdoor Laser Operations*, along with any supporting documents. Based on that information, the FAA will issue a “Letter of Non-Objection” if it is determined that the laser system in question either poses no hazard to aircraft or that all hazards have been adequately mitigated. Otherwise, a “Letter of Objection” will be issued. This means the laser will not be allowed to operate as described, and more mitigation methods may be required before a Letter of Non-Objection is provided.

Chapter 29 of FAA Order Job Order (JO) 7400.2M, *Procedures for Handling Airspace Matters,”* contains policy, responsibilities, and guidelines for processing the notice and determining the potential effect of outdoor laser activities [29]. Compliance practices are based on standards ANSI Z136.1, *American National Standard for Safe Use of Lasers* [30] and ANSI Z136.6, *American National Standard for Safe Use of Lasers Outdoors* [31].

For non-DOD users, ANSI Z136.6 advises that lasers with a divergence less than 10 μrad or exceed a peak irradiance greater than 1 W/cm^2 above 18 km (60,000 ft) in altitude above sea level should contact LCH for screening. This screening is not required by law but still has a very high likelihood of being required by the FAA to obtain a Letter of Non-Objection [32].

<u>DOD/The Laser Clearinghouse</u>

All DOD-run or funded laser programs operating to, in, though, or from space or which are aimed above the horizon are required to conform its operations to DOD Instruction 3100.11, *Management of Laser Illumination of Objects in Space* [33], and CJCSI 3225.01, *Procedures for Management of Illumination of Objects in Space* [32]. These specify that all DOD and DOD-funded missions must coordinate with the LCH. The LCH is operated under the U.S. Space Command but coordinates with the FAA regularly.

The first step in initiating the LCH's laser registration process is for the laser operator to submit the Laser Registration Form found on the LCH website (www.space-track.org), alongside Instruction 3100.11 and CJCSI 3225.01, which outlines all relevant laser requirements and processes. Next, laser operators will be required to submit their planned laser sources, targets, and planned times of operation using LCH-provided document templates found on space-track.org. Depending on the results of the LCH's risk assessments, each laser program will be assigned a laser activity category based on criteria defined in CJCSI 3225.01. The LCH might request that the laser operator proceed with a "normalization" process prior to categorization, including changing the operating plans and system parameters.

For the next step, LCH reviews the form and provides a deterministic risk analysis, which indicates whether the laser's operation poses a threat to any space objects of interest. If the laser system is found not capable of posing a threat, it will be assigned as a "Category I: No Risk Result" and be found exempt from LCH oversight. In this case, no further coordination with LCH is required, and the owner/operator of the laser communication system can operate freely without communication with the LCH but must re-register with the LCH annually.

However, if a project's laser has the "potential" to damage a space object of interest to the LCH, it will not be given a Category I designation, and the LCH will then conduct a probabilistic risk assessment to determine whether the laser system will pose a risk to space objects of interest during its nominal operation. If it is determined that the laser's activities, when conducted from its specified location, are found to pose no greater risk to space activities than other nominal risks, as defined by the LCH, it will be assigned as a "Category II: Nominal

Risk Result.” In this case, the laser operator is only required to notify the LCH (through a method LCH determines) when it is in use. The LCH will not require any further coordination for this category unless the operator will be deliberately targeting a space object of interest. Note that if a system operates within the constraints of a “Special Use Space Range” as defined by the U.S. Space Command, it will be assigned a Category II.

If the LCH’s probabilistic analysis finds a laser system of risk higher than normal safety of flight risks, it will be designated a “Category III: Significant Risk Result.” In this case, the system will require coordination and notification with the LCH for every use. Coordination may include using LCH-provided templates and software to develop a deconfliction plan. Control measures for deconfliction may include test plans, certification memos, aircraft spotters, radar systems, automated laser shutters, and laser pointing restrictions. Plan approval may be contingent on a site visit and end-to-end demonstration. Once approved, the LCH provides an authorization letter to the mission.

In rare circumstances, a waiver can be granted by the U.S. Space Command where a laser owner is authorized to conduct a specific laser activity without the need for further coordination, notification, or risk mitigation measures for a specific period. This waiver must go through and be documented by the LCH and will only be considered after initiating the laser registration process.

The process of coordinating with the LCH can be quite lengthy and may take months. Laser operators should establish contact with the LCH as early as possible to understand the process. It may be possible to reduce the negative impact of LCH restrictions by making smart decisions early in the design and use planning of the system.

Ambiguity, Open Questions, and Recommendations

Laser communications are becoming increasingly popular for space-to-ground and space-to-space communications links, and many proliferated LEO constellations are implementing or considering laser communications links. The paradigm where each laser shot is individually coordinated and cleared with either the FAA or the LCH is unlikely to be scalable to proliferated laser communications. Owners may need to ensure their lasers are low enough power to be exempt or the coordination process may need to be automated. Future satellite systems may also need to ensure they are unlikely to be damaged by lasers beneath a certain power, as deconfliction will be cumbersome.

Policy guidelines may need to be negotiated between the FAA and LCH as space-to-ground communications systems become more common. The FAA traditionally deconflicts laser use only with airlines, and commercial providers are not required to coordinate with the LCH. In the future, the FAA may need to take on more responsibility for commercial laser communications to space. Alternatively, the FCC might ultimately decide to regulate the optical spectrum as it does the radiofrequency spectrum—though the regulation of the optical spectrum is likely to focus on the prevention of damage, rather than the deconfliction of frequencies. Although it is important to note that the FCC does not “currently” have jurisdiction over lasers and the legality of them claiming authority is not settled.

Cybersecurity/Information Assurance

Summary of Applicable Policy

Cybersecurity policy for small spacecraft is defined in a complex collection of policy documents published by the DOD, the Committee on National Security Systems, the National Institute of Standards and Technology, and other organizations. For all spacecraft used by the

DOD, a key document is DOD Instruction (DODI) 8581.01, *Information Assurance (IA) Policy for Space Systems Used by the Department of Defense* [34]. This instruction implements Committee on National Security Systems Policy No. 12, *Cybersecurity Policy for Space Systems Used to Support National Security Missions* [35]. To determine if an information system is considered national security space, refer to National Institute of Standards and Technology Special Publication 800-59, *Guideline for Identifying an Information System as a National Security System* [36].

Policy Compliance Process

Two primary areas of compliance are associated with spacecraft cybersecurity policy (although this is not exhaustive). The first concerns protection of spacecraft uplink and downlink (i.e., the requirement for encryption). The second concerns certification and accreditation requirements of the spacecraft as an information system (i.e., the requirement to receive an Authority to Operate). These are covered below.

Encryption

For DOD-owned or -controlled spacecraft, DODI 8581.01, requires encryption of uplink and downlink. This applies to all DOD satellites, including research and development spacecraft built by DOD laboratories or academic institutions. The selection and implementation of the cryptography used to meet requirements should be coordinated with the National Security Agency (NSA) early in the design phase of every spacecraft program.

Encryption is not strictly required for non-DOD federal spacecraft (i.e., NASA). However, the *National Institute of Standards and Technology Special Publication 800-53* does apply, and the criticality and sensitivity of information transmitted may lead to the selection of security controls that include encryption [37]. Organizational policies may also apply; for example, NASA Procedural Requirements 2810.1A, *Security of Information Technology*, defines information technology security requirements for NASA [38].

For commercial or private spacecraft, encryption is not typically required. However, if the DOD is “using” a commercial, private, non-DOD federal or foreign space system, DODI 8581.01 contains requirements pertaining to encryption. Depending on the criticality and sensitivity of the DOD information being transmitted, uplink and/or downlink cryptography may be required ranging from NSA-approved to commercial best practices.

In addition, some NOAA private remote sensing licenses may include cybersecurity conditions that incorporate safeguards to ensure the integrity of system operations and security of data. Early coordination with NSA NOAA is recommended.

Certification and Accreditation

DODI 8581.01 requires that all DOD-owned systems undergo cybersecurity accreditation following the *Risk Management Framework for Department of Defense Information Technology* [39]. A complete discussion of the risk management framework process is beyond the scope of this paper. However, it is worth mentioning that each DOD spacecraft program should determine who their cybersecurity Authorizing Official is early in the program. The Authorizing Official will ultimately issue the “Authority to Operate” for the spacecraft.

NASA NPR 7120.5, *NASA Space Flight Program and Project Management Requirements*, requires a project protection plan be written based on threat summaries for NASA missions [40]. NASA-STD-1006, *Space System Protection Standard*, outlines baseline standards to improve space system protection from well-understood threats [41]. NASA maintains a list of candidate protection strategies that outlines best practices for programs.

Programs each develop a project protection plan that incorporates the results of the candidate protection strategy analysis, including any requisite requirement tailoring. NASA has a standard project protection plan template available.

Commercial spacecraft have no requirements to undertake a formal cybersecurity accreditation. However, when the DOD is using non-DOD systems, DODI 8581.01 states that the Authorizing Official for the DOD organization using the system is required to perform a review of the space system's ability to meet cybersecurity requirements and accept the risk for any areas of noncompliance.

Ambiguity, Open Questions, and Recommendations

The first ambiguity has to do with whether a spacecraft should be considered DOD and therefore subject to DOD cybersecurity policy. Differing interpretations have been received, with the most stringent classifying any spacecraft receiving DOD sponsorship or funding of any nature as DOD spacecraft and subject to following all DOD policy requirements. This interpretation might have far-reaching implications. As described in the section on satellite ownership, satellites should be classified unambiguously and based on who is the owner/operator of the spacecraft. Cybersecurity policy compliance could be based on the requirements of the owner/operator organization.

A second ambiguity has to do with whether a satellite system is considered a national security space system. Not all DOD spacecraft are necessarily national security space systems. The National Institute of Standards and Technology Special Publication 800-59 has a checklist consisting of six questions to determine if an information system is a national security space system. Based on this checklist, many DOD research and development spacecraft developed and operated by military laboratories and academic institutions are not national security space systems. As such, Committee on National Security Systems Special Publication No. 12 is not applicable. However, DODI 8581.01 (which implements Committee on National Security Systems Special Publication No. 12) does not provide any provisions for non-national security space DOD spacecraft, which drives costly compliance requirements on these programs out of proportion to overall program cost and risk. DODI 8581.01 could be revised to either explicitly exclude non-national security space DOD spacecraft or to provide streamlined compliance procedures for this class of spacecraft

DODI 8581.01 provides procedures for implementing cybersecurity when the DOD uses non-DOD spacecraft. However, “use” is not well defined and subject to interpretation. It would be beneficial to expand this section of the policy to include different cases of “use” (such as hosted payloads, commercial imagery, and DOD sponsorship). Additionally, as hosting DOD payloads on non-DOD spacecraft becomes more common, cybersecurity requirements and responsibilities need to be better defined in memoranda of agreement up front.

Finally, no policy exists requiring the protection of non-DOD spacecraft command and control capability (particularly uplink encryption). This is of particular concern when the spacecraft has propulsion, or the ability to maneuver, because of the possibility of a “bad actor” gaining control of the vehicle and using it to interfere with another spacecraft. This is a significant policy hole that will become more pronounced with the increasing capabilities of small satellites and CubeSats, and especially if future FCC debris mitigation policy requires propulsion on satellites going to altitudes higher than 400 km. Policy should be established requiring uplink security on all spacecraft with significant maneuver capability. This could be incorporated into the established process for securing an FCC frequency license. Federal organizations entering into agreements with foreign spacecraft should establish this requirement, particularly when the United States is providing launch services for foreign spacecraft.

Imaging

Summary of Applicable Policy

Regulations governing remote sensing from a space platform fall into two distinct categories in the United States: Earth-imaging and non-Earth imaging. There are also two types of satellites considered: commercial (civilian) satellites and satellites owned and operated by the U.S. government. Satellites owned by DOD academic institutions are considered a subtype of government-owned satellites and fall into their own unique policy bucket. This section explores the various policies that apply to each type of satellite in each regulatory category and provides a basic understanding of how to navigate the policy compliance process.

Satellites owned and operated by commercial entities and civilian academic institutions are governed by the National Commercial and Space Programs Act [42]. This law governs Earth-imaging and assigns authority to NOAA for licensing of the same. NOAA will ensure all imagers comply with DOD and intelligence community requirements for non-Earth imaging for satellites owned by commercial and civilian academic institutions.

Government agencies currently have no requirement to obtain licensing for Earth imaging, although it is highly recommended that DOD agencies seek internal guidance. The Defense Remote Sensing Working Group manages non-Earth imaging for operational DOD systems. Experimental DOD satellites are governed by interim guidance issued by the Principal DOD Space Advisor staff [43]. This interim guidance, issued in 2015, requires DOD experimental satellites with remote sensing capability to submit test plans, data protection plans, and technical specifications of their system and payloads through the secretary of the Air Force

Space Programs (SAF/AQS) office. If it is determined that a concern exists concerning an experimental DOD satellite, the issue is automatically referred to the Defense Remote Sensing Working Group. Since this interim guidance was issued in 2015, there has been no effort to establish permanent policy or guidance. As a result, imaging approval for DOD experimental satellites remains a gray area.

In researching this topic, the author were unable to identify any NASA guidance or documentation with respect to imaging approval. All imaging devices aboard NASA satellites and missions are handled on a case-by-case basis by NASA.

Policy Compliance Process

The compliance process for commercial and civilian entities is outlined on the NOAA Commercial Remote Sensing Regulatory Affairs (CRSRA) website. NOAA recommends beginning the process with informal, nonbinding meetings between the applicant and NOAA to help inform the process and prevent rework. Interested parties can submit a licensing query using the *Initial Contact Form* found on the NOAA/CRSRA website (https://www.nesdis.noaa.gov/commercial-space/regulatory-affairs/licensing).

When an organization is prepared to begin the application process, Title 15 of the Code of Federal Regulations (CFR), Part 960, amended in 2020, establishes the rules and procedures to be followed, and NOAA provides support to ensure all the required documentation is provided [44]. All license determinations are required to be made within 60 days of receipt of a completed application unless written guidance is provided on issues that exist with the application. All licenses are valid for the system's operational lifetime unless voided through the action of the owner or operator.

Under the revised definitions in 15 CFR Part 960, remote sensing now applies only to imaging conducted when in orbit around Earth (rather than in orbit of any celestial body) and to the collecting of data that can be processed into imagery of Earth's surface features. NOAA licenses are not necessary for "instruments used primarily for mission assurance or other technical purposes, including but not limited to navigation, attitude control, monitoring spacecraft health, separation events, or payload deployments, such as traditional star trackers, sun sensors, and horizon sensors." Additionally, if a spacecraft only has instruments incapable of producing data that can be processed into Earth-surface imagery, they are not required to obtain a license.

Private entities should never take it upon themselves to determine if they need a license. All private entities must reach out to the CRSRA office at NOAA if there is a theoretical capability to image Earth with devices onboard their spacecraft. NOAA/CRSRA encourages consultation meetings with potential applicants before submitting a license application. These meetings will be informal and are not considered part of the agency record of an application.

Per the amended 15 CFR 960.6, the CRSRA office categorizes each private space-based remote sensing system it licenses into one of three tiers based on an analysis of whether the system can produce unenhanced data already available from other entities, foreign or domestic.

- Tier 1 is for systems capable of producing unenhanced data that is substantially the same as data available from other sources *not* regulated by the DOC (e.g., foreign sources) and will receive minimal license conditions.

- Tier 2 is for systems that can produce unenhanced data that is substantially the same as data available from U.S. sources that *are* regulated by the DOC (e.g., U.S.-based sources) and licensed by CRSRA.

- Tier 3 is for systems that produce data that is not directly comparable to existing systems (e.g., unenhanced data not substantially the same as unenhanced data already available), foreign or domestic. This tier may receive the most stringent license conditions.

Applicants and licensees are encouraged to provide CRSRA with new information and examples of available data using the Data Availability Notification Form. CRSRA will, as evidence becomes available, update tiering thresholds and reassess tiering of applicable licenses as necessary [55]. Tiering thresholds are found in the *Tiering Threshold Document* found on the NOAA/ CRSRA website, which is updated quarterly: https://www.nesdis.noaa.gov/commercial-space/regulatory-affairs/licensing/tier-categorization

Note that the law known as the Kyl–Bingaman Amendment (Public Law 104-201, Section 1064) prohibits NOAA from granting a license for a system capable of collecting or disseminating satellite imagery of the country of Israel at a higher resolution than is available from other commercial sources; that is, from companies outside of the United States. In a decision published in the *Federal Register* on July 21, 2020, NOAA set the current image resolution limit of 0.4 meter ground sampling distance. Most licensees abide by this requirement by onboard removal of relevant imagery (via image processing) before downloading it to the ground.

Ambiguity, Open Questions, and Recommendations

Additional or clarifying guidance related to military academic institutions, satellites that receive DOD funding, and experimental satellites has not been established since the original publication of *Policy Compliance Roadmap* in 2017 and remains an area open to interpretation.

Rendezvous and Proximity Operations

Summary of Applicable Policy

Rendezvous and proximity operations is a broad term used to describe any operations that intentionally take one satellite into the vicinity of another. Current proximity operations policy is a patchwork of policy and guidance documents across the space community. The 2019 update to the ODMSP references for the first time rendezvous, proximity operations, and satellite servicing in its new Objective 5-3; programs are encouraged to limit the probability of accidental collision and limit the probability of accidental explosion resulting from the operations. However, specific numeric thresholds for these guidelines and definitions of what constitutes *proximity operations* have not yet appeared in lower-level guidance.

As the capability of small satellite systems increases, the desire for missions to perform proximity operations becomes more of a reality. Spacecraft designers must balance the need to perform mission objectives with the safety-of-flight concerns—because of its debris-generating potential, a collision between two satellites is a concern for the entire space environment, not just the two satellites involved. Although not necessarily considered proximity operations, space safety concerns extend to formation flying missions that intend to maintain a constant relative distance to each other. NASA currently has no policy guidance concerning proximity operations. There is a policy in the DOD for the review of proximity operations missions, but this policy is not widely available. Neither the FCC nor the FAA has any policy compliance requirements for on-orbit proximity operations.

Policy Compliance Process

DOD missions intending to perform proximity operations missions must comply with DOD processes. Civil and commercial entities are currently not required to comply with any process specific to proximity operations objectives, although missions will naturally need to comply with all frequency and imaging requirements discussed above.

Ambiguity, Open Questions, and Recommendations

With the growth in capability of small satellites, there has been a surge in formation flying, rendezvous, proximity operations, and docking missions. Due to the technical challenges of performing these missions and the inherent safety of flight concerns, clarification on processes for civil and commercial entities would be beneficial. The policy should distinguish between formation flying and proximity operations and define policy guidance for each class. One possible definition for proximity operations might define proximity operations as satellites that deliberately operate within the typical screening volumes used for conjunction assessment, continuously for long periods of time. These vary but are on the order of 20 km in the along-track direction, and 1 km in the cross-track and radial directions. Missions that intend to approach other satellites or cooperatively fly within these distances might be required to develop proximity operations safety plans. For both formation and proximity operations missions, mission designers are encouraged to comply with National Institute of Standards and Technology Special Publication 800-53 and implement commercial best practice encryption on the uplink and downlink.

There are no FCC spectrum allocations for rendezvous and proximity operations, and operators must apply for Special Temporary Authority or for an experimental license, which is also temporary in nature. With the trend toward regular operations of this type of dedicated frequency allocations, long-term licensing options need to be considered.

A related issue that needs to be captured (possibly in this policy) involves cybersecurity requirements for vehicles with propulsion, regardless of their intention to conduct proximity operations. Key to this guidance might be directives based off the amount of propulsion (or “delta-V) that a space vehicle intends to carry. This should inform the cybersecurity posture of the vehicle and ground system. Care should be taken to separate policy requirements for significant translational propulsion systems from those required for simple attitude control propulsive systems.

Operations Beyond Earth Orbit/Cislunar Space

<u>Summary of Applicable Policy</u>

The number of launch opportunities for missions beyond Earth orbit is expected to grow in the coming years, given NASA’s renewed commitment to lunar exploration with the Artemis program and a new generation of heavy and superheavy launch vehicles. Additionally, the proliferation of public and private exploration partnerships, such as NASA’s Commercial Lunar Payload Services program, have the potential to involve commercial and private organizations that have never operated in this region of space before. Small satellites, traditionally confined to low Earth orbit, are increasingly being considered and used for missions beyond geosynchronous orbit [45]. This section briefly addresses policy related to operations beyond Earth orbit.

Article VI of the Outer Space Treaty requires that “[t]he activities of non-governmental entities in outer space, including the Moon and other celestial bodies, shall require authorization and continuing supervision by the appropriate State Party to the Treaty.” While the FAA has not released explicit guidelines for handling beyond Earth orbit space missions, two private lunar missions can provide insight into FAA processes for this mission type. On July 20, 2016, the FAA made a favorable payload determination for the Moon Express MX-1E mission. The FAA had determined that the launch of the payload did not jeopardize public health and safety, the safety of property, U.S. national security or foreign policy interests, or international obligations of the United States. For the mission, the FAA concluded, in concurrence with the Department of State, that the enforcement of regulations in Chapter 509 of Title 51 and other FAA regulations constitutes compliance with Article VI of the Outer Space Treaty. However, the FAA explicitly stated that these determinations did not extend to any future missions and that any future requests for a payload determination will be evaluated on a case-by-case basis. In July 2018, the FAA made another favorable payload determination for the SpaceIL Lunar Lander mission using a similar rationale.

Spectrum Usage

As part of the new FCC regulations, small spacecraft with planned non-Earth orbiting missions, such as commercial lunar missions, can file under the new streamlined process for frequency allocation and approval. Note that all spacecraft leaving Earth orbit must still receive assignment licensing with the ITU. Getting a license or approval to use a frequency through either the FCC or other agencies hinges on successfully completing the ITU's coordination process. This process can take months to years. (One cislunar operating X-band CubeSat took four years to get approval.) So, missions should start working on the application and submittal as early as possible. The regulatory changes for small satellites are contained in the *Final Acts WRC-15, World Radiocommunication conference* [54] and the *Radio Regulations* [27].

Imaging Policy

In the newly amended CFR Title 15 Part 960, NOAA-regulated spacecraft orbiting celestial bodies other than Earth are not required to obtain a license even if carrying instruments theoretically capable of producing Earth-surface imagery [44]. Nongovernment missions must still reach out to the CRSRA to get a license determination.

Planetary Protection Policy Compliance Process

Article IX of the *Outer Space Treaty* states: "...parties to the Treaty shall … conduct exploration of [the moon and other celestial bodies] so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter." [1] The United Nations Committee on Space Research (COSPAR) maintains and promulgates the internationally accepted approaches to planetary protection on behalf of Article IX. COSPAR's *Planetary Protection Policy*, last updated in March 2011, lays out five categories of missions according to the destination involved and the type of mission (i.e., orbiter, lander, and return-to-Earth mission). NASA's planetary protection requirements are founded upon COSPAR policy and fall under the Office of Planetary Protection [46]. All NASA launched or funded missions which might intentionally or unintentionally carry Earth organisms and organic constituents to other solar system bodies, or any mission employing spacecraft which are intended to return to Earth and/or its biosphere from extraterrestrial targets of exploration, must be compliant with NPD 8020.7, *Biological Contamination Control for Outbound and Inbound Planetary Spacecraft* [47].

Protection requirements are specific to the type of mission and planetary bodies visited. As described in NPR 8020.12, *Planetary Protection Provisions for Robotic Extraterrestrial Missions*, missions must meet a specific set of forward contamination (bringing something to the planetary body from Earth) and backward contamination (bringing something from the planetary body to Earth) criteria that prevents unintended encounters with solar system objects and limits the probability of contamination if encounters are unavoidable. Missions to objects of interest for origins of life (including Earth's moon) require documentation of mission trajectory and disposition of hardware [48]. The NID 8715.128, *Planetary Protection Categorization for Robotic and Crewed Missions to the Earth's Moon,* addresses the control of forward biological contamination associated with all NASA and NASA-affiliated missions intended to land, orbit, or otherwise encounter the moon [49]. Additionally, NID 8715.129, *Biological Planetary Protection for Human Missions to Mars*, and NPD 8020.7, *Biological Contamination Control for Outbound and Inbound Planetary Spacecraft,* outlines requirements to avoid harmful forward and backward biological contamination to comply with Article IX [47].

Careful mission design and planning are essential elements when considering planetary protection requirements, and consultations with the planetary protection officer (PPO) during mission development are critical in ensuring compliance with NASA policy.

Debris Mitigation Policy Compliance Process

The current ODMSP does not explicitly address debris mitigation requirements in cislunar or interplanetary space. However, NASA has required the first generation of interplanetary CubeSats on Artemis I to follow standard policies (as laid out in this paper) for debris mitigation. Although the focus of NPR 8715.6 and NS 8719.14 is on orbital debris mitigation in the near-Earth space environment, several requirements are applicable to interplanetary missions.

The requirements in NPR 8715.6 that are directly applicable for interplanetary missions include:

- Requirement 4.4-1: Limiting the risk to other space systems from accidental explosions.
- Requirement 4.4-2: Design for passivation after completion of mission operations; i.e., limit or depletion of energy sources on spacecraft at the end of life.
- Requirements 4.4-3 and 4.4-4: Limiting the long-term risk to other space systems from planned breakups.
- Requirement 4.5-2: Limiting debris generated by collisions with objects when operating in Earth or lunar orbit.

- Requirement 4.6-1: Spacecraft disposal for lunar and Mars missions is coordinated with the NASA PPO to meet the applicable planetary protection requirements per NID 8715.129, NPD 8020.7 and NPR 8020.12.
- Requirement 4.8-1: Mitigate the collision hazards of space tethers in Earth or lunar orbits.

It is worth repeating that the current OSMA position is that CubeSats 3U or smaller are automatically considered compliant with Requirements 4.4-1 and 4.4-2 due to their small size and low risk of debris generation.

Note that there are Planetary Protection considerations in NPR 8715.6A. In the event of conflicts between NPR 8715.6 and Planetary Protection requirements, the Planetary Protection requirements will take precedence. Paragraph 1.3.14 of NPR 8715.6A states that NASA's Planetary Protection Officer shall "review and concur in the final ODAR and EOMP for disposition of spacecraft on a solar system body other than the Earth." Also, Paragraph 2.2.2.4 states, "For missions traveling beyond geosynchronous Earth orbit (GEO) disposal orbits, the MDAA shall submit each draft EOMP to the NASA PPO for review, subject to NPR 8020.12."

<u>Preservation of Historic Sites Policy Compliance Process</u>

In 2011, NASA published voluntary guidelines entitled Recommendations to Space-Faring Entities: How to Protect and Preserve the Historic and Scientific Value of U.S. Government Lunar Artifacts. The One Small Step to Protect Human Heritage in Space Act, passed in December 2020, directs any federal agency that issues licenses to conduct activities in outer space (including the Department of Transportation (DOT), the DOC, FAA, and FCC) to require that all lunar activities they oversee must agree to abide by NASA's guidelines (or subsequent updates from NASA) and authorizes fines of any licensee who breaks the license terms. The law allows for exemptions (with consultation from NASA) from this requirement and calls for an international treaty consistent with this bill. So far, NASA has complied with the law through requirement 4.6-1 in NPR 8715.6.

The Artemis Accords

Drafted by NASA and the U.S. Department of State, The Artemis Accords is an international agreement that establishes a framework for cooperation in the civil exploration and peaceful use of the moon, Mars, and other astronomical objects. The agreement is meant to be "grounded in the Outer Space Treaty of 1967" to create a safe and transparent environment that facilitates exploration, science, and commercial activities for all of humanity to benefit. As of March 8, 2021, 21 countries have signed the Artemis Accords: Australia, Bahrain, Brazil, Canada, Colombia, France, Isle of Man, Israel, Italy, Japan, South Korea, Luxembourg, Mexico, New Zealand, Poland, Romania, Saudi Arabia, Ukraine, the United Arab Emirates, the United Kingdom, and the United States [51].

To date, extensive regulations and policy documents outlining how NASA and other U.S. agencies and commercial entities will implement the tenants of the Accords have not been released. Note that the Artemis Accords explicitly state that they only apply to signatory nations' civil space activities. Meaning the activities of the DOD (and the militaries of the other signatory nations) are not explicitly bound by the Artemis.

Ambiguity, Open Questions, and Recommendations

For the oversight of non-NASA-run or -funded missions, the U.S. process is not yet well established. Due to the volume of upcoming missions, it will soon become vital to determine who will be the lead organizations for space traffic management, space domain awareness, and orbital debris mitigation for beyond-Earth orbit space activities. To date, NASA is the only U.S. agency with any significant planetary protection knowledge and expertise, but it does not regulate commercial activity. Agencies such as the FCC, FAA or the DOC may ultimately need to regulate planetary protection for commercial missions.

As missions beyond Earth become more accessible to small satellites, policymakers will need to start regulating debris, particularly in lunar orbit and high-value areas such as Lagrange points. Orbits around or near Lagrange points may ultimately need to be subject to similar regulations as satellites in geosynchronous orbit, with specific slots assigned to ensure lack of dangerous interference.

Orbits in the cislunar regime are subject to high perturbations, so further study is needed to determine how disposal and operations with significantly more active missions can be done safely [52].

In September 2020, NASA and the U.S. Space Force signed a memorandum of understanding on space cooperation that more firmly pins the U.S. military to future missions in the vast region of space beyond Earth's orbit. The agreement expands long-standing NASA-DOD/Air Force space cooperation on space exploration, including cooperation on situational awareness, communications, and precision navigation. Additionally, it includes efforts to establish "norms of behavior" for activities such as moon and asteroid mining. The fruits of these efforts have yet to be widely disseminated [53].

To date, the DOD, FAA, and FCC have issued no guidance on how they intend to comply with the One Small Step to Protect Human Heritage in Space Act, Article IX of the Outer Space Treaty, or the Artemis Accords. NASA has not issued explicit guidelines on how it intends to comply with the Artemis Accords.

With its approval of the Moon Express Mission, the FAA noted, "Future missions may require additional authority to be provided to the FAA to ensure conformity with the Outer Space Treaty. Suggested language for legislative relief and the relative merits and needs has been transmitted to Congress in compliance with Section 108 of the Commercial Space Launch Competitiveness Act (Public Law 114-90). In the absence of legislative relief, the FAA will continue to work with the commercial space industry to provide support for non-traditional missions on a case-by-case basis when the law permits." [54]

Use of Nuclear Material

Summary of Applicable Policy

As more performance is demanded, regulatory implications of using nuclear systems pose new considerations for smallsats. Nuclear systems include radioisotope thermoelectric generators, radioisotope heater units, and fission reactors. To date, nongovernment entities have been contracted to fabricate parts of past launches. For example, United Launch Alliance (ULA) constructed the Atlas V rocket for the 2011 Mars Science Laboratory (MSL) NASA mission. The power source for MSL is a multi-mission radioisotope thermoelectric generator (MMRTG) with 4.8 kg of plutonium dioxide. But now companies such as BWX Technologies, Atomos, and Ultra Safe Nuclear Company are actively pursuing the development of commercial nuclear fission systems for commercial customers [55].

The policies and regulations of using and acquiring nuclear material for spacecraft are complex and lengthy. As a result, this paper does not explore the process in depth, and only the high-level compliance processes are discussed. Policies on any given mission may require coordination between and compliance to requirements from the U.S. Department of Energy (DOE), DOT, Department of Homeland Security (DHS), Nuclear Regulatory Commission

(NRC) Atomic Energy Commission, NASA, and the DOD. It should also be noted that all U.S. launches of spacecraft containing space nuclear systems to date have included technology developed and manufactured by the DOE and its contractors [56].

The U.S.'s nuclear flight safety program has existed since the early 1960s with continual evaluation from national laws, interagency declarations and international agreements and treaties like the 2019 *NSPM-20 Presidential Memorandum on Launch of Spacecraft Containing Space Nuclear Systems*, the 2020 *Pace Policy Directive 6*, *Memorandum on the National Strategy for Space Nuclear Power and Propulsion*, the 1992 UN's *Principles Relevant to the Use of Nuclear Power Sources in Outer Space,* and the 2018 International Atomic Energy Agency's *Regulations for the Safe Transport of Radioactive Material*." [57]

The Atomic Energy Act of 1954 stipulates that a "person" may not own, possess, use, or have the facilities to produce or utilize nuclear material without a license either from the DOE or NRC. The Act gives NRC the authority to license and regulate the possession, use, transfer, and transport (in conjunction with the DOT) of commercial nuclear facilities and materials (i.e., those not owned by the DOE).

<u>Policy Compliance Process</u>

DOD programs that use radioactive material and nuclear power systems in space shall follow AFMAN 91-110, *Nuclear Safety Review and Launch Approval for Space or Missile Use of Radioactive Material and Nuclear Systems* for all safety requirements, review processes, and approval processes.

For NASA-led or sponsored programs, NPR 8715.3 *NASA General Safety Program Requirements,* Chapter 6, "General Safety Program Requirements, Nuclear Safety for

Launching of Radioactive Materials," describes the requirements for characterizing and reporting potential risks associated with a planned launch of radioactive materials into space.

All government missions involving space nuclear material require presidential approval through the Office of Science and Technology Policy (OSTP). The current launch approval process is governed at a high level by the 1996 NSC-25, *Presidential Directive/National Security Council Memorandum No. 25*, the 2010 *National Space Policy of the United States of America*, and the National Environmental Protection Act (NEPA) [57].

The launch approval process for government missions with nuclear material involves three separate and somewhat concurrent reviews:

1. The mission owner prepares an environmental impact statement (EIS), or environmental assessment (EA) mandated by the NEPA.
2. The DOE performs the safety analysis and prepares a safety analysis review (SAR)
3. The Interagency Nuclear Safety Review Panel (INSRP) reviews the SAR and prepares a safety evaluation report (SER).

Based on these inputs, either the director of OSTP or the president renders approval for a launch. The process has taken an average of six years and costs over $40 million for recent missions.

The current launch approval process for any space nuclear system has only been used for government-owned and operated missions, but commercial entities have increasingly been interested in using space nuclear systems. Under 14 CFR § 415.115, FAA also has the authority to evaluate the launch of any nuclear material on a launch vehicle or payload on a case-by-case basis and issue an approval if the FAA determines the launch is consistent with public health and safety.

Ambiguity, Open Questions, and Recommendations

Specific regulatory guidance for launch of space nuclear systems is under development by the FAA, to be covered under Title 14, Code of Federal Regulations for FAA-licensed launches. PD/NSC-25 states that "[t]he head of the sponsoring agency will request the President's approval for the flight through the Office of Science and Technology Policy [OSTP]." It is uncertain if and how this could apply to commercial launches. The sponsoring agency cannot be the licensing authority; i.e., the FAA for the commercial mission. Therefore, PD/NSC-25 could only apply in the commercial context if there is some other government agency willing to act as the sponsor of the mission.

The paper titled *Evolution of NASA's Nuclear Flight Safety Program to Meet Changing Needs* was presented in November 2021 at the 11th International Association for the Advancement of Space Safety Conference. It discusses NASA's plans to update its nuclear material usage and safety policies to maintain consistency with changes to U.S. government-issued national policies that fundamentally changed the approach to nuclear flight safety for aerospace applications. As part of this evolution, NASA is factoring in an objectives-driven and assurance case mindset to develop a risk-informed and performance-based program. It also declares NASA's desire to "harmonize" its nuclear flight safety practices among the DOT, the DOD, the DOE, and the NRC, to the greatest extent practicable. These changes have yet to be implemented [56].

Policy Flowchart and Sample Walkthrough

Figures 3 through 6 summarize the policy pathways described in this paper to the extent that the author understands the existing policy framework. Starting with Figure 3, missions must first determine who "owns" the satellite to determine what policy applies. Typically, the ultimate satellite owner/operator—whoever will have satellite control authority once the satellite is operational—is the agency whose policy the mission must follow. Once mission ownership is understood, the remaining figures (Figures 4 through 6) describe the applicable policy.

For example, if AFRL builds a satellite intending to conduct unclassified proximity operations, the Air Force is the owner/operator, and the DOD policy flowchart should be followed. DOD satellites are required to abide by information assurance requirements as documented in DODI 8581.01, and even if the mission is unclassified, they must use NSA-approved encryption. Such a satellite would apply to the NTIA for frequency assignment. Since the satellite will perform proximity operations, DOD proximity operations regulations must be followed.

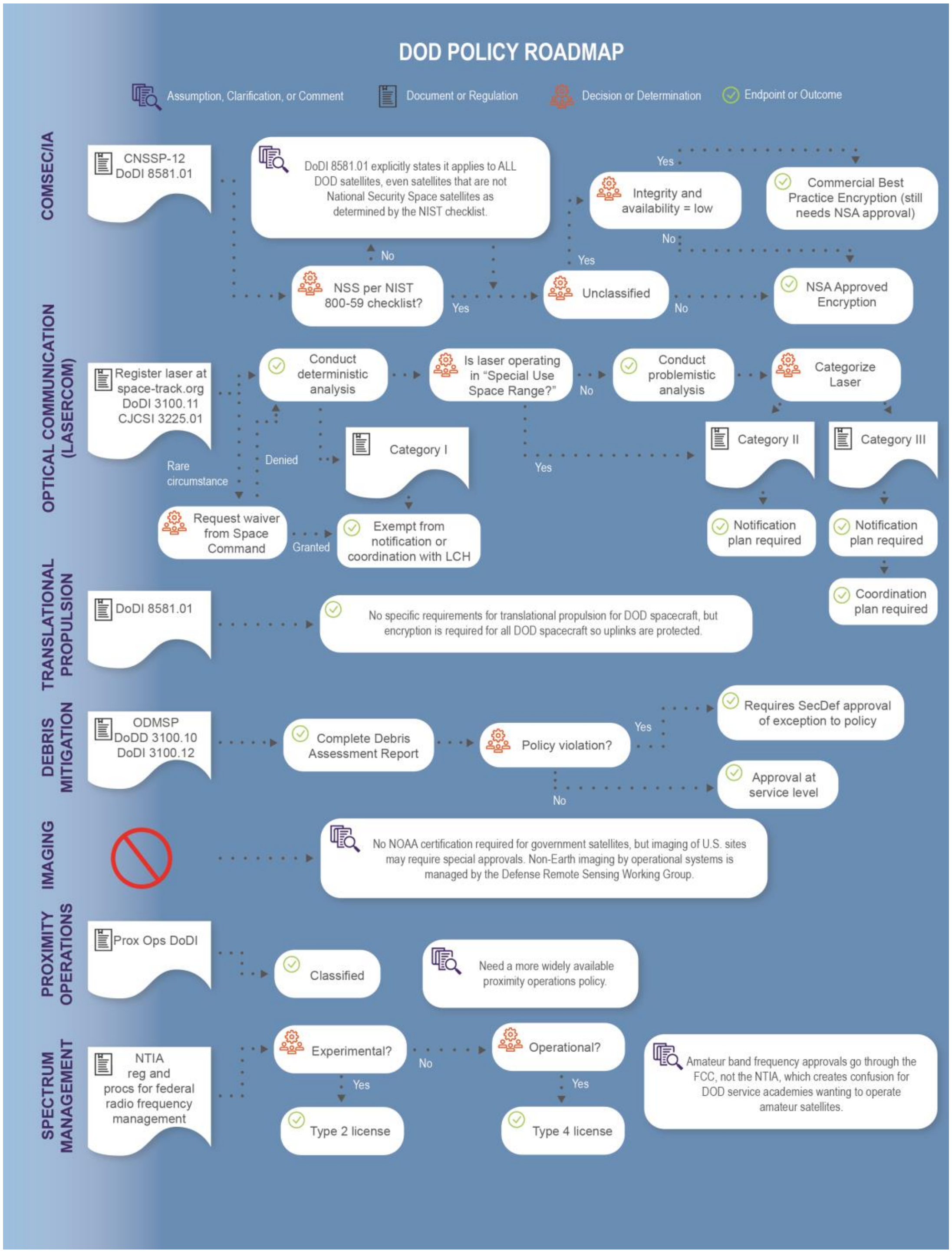

Figure 4: Policy Roadmap for DOD Satellites

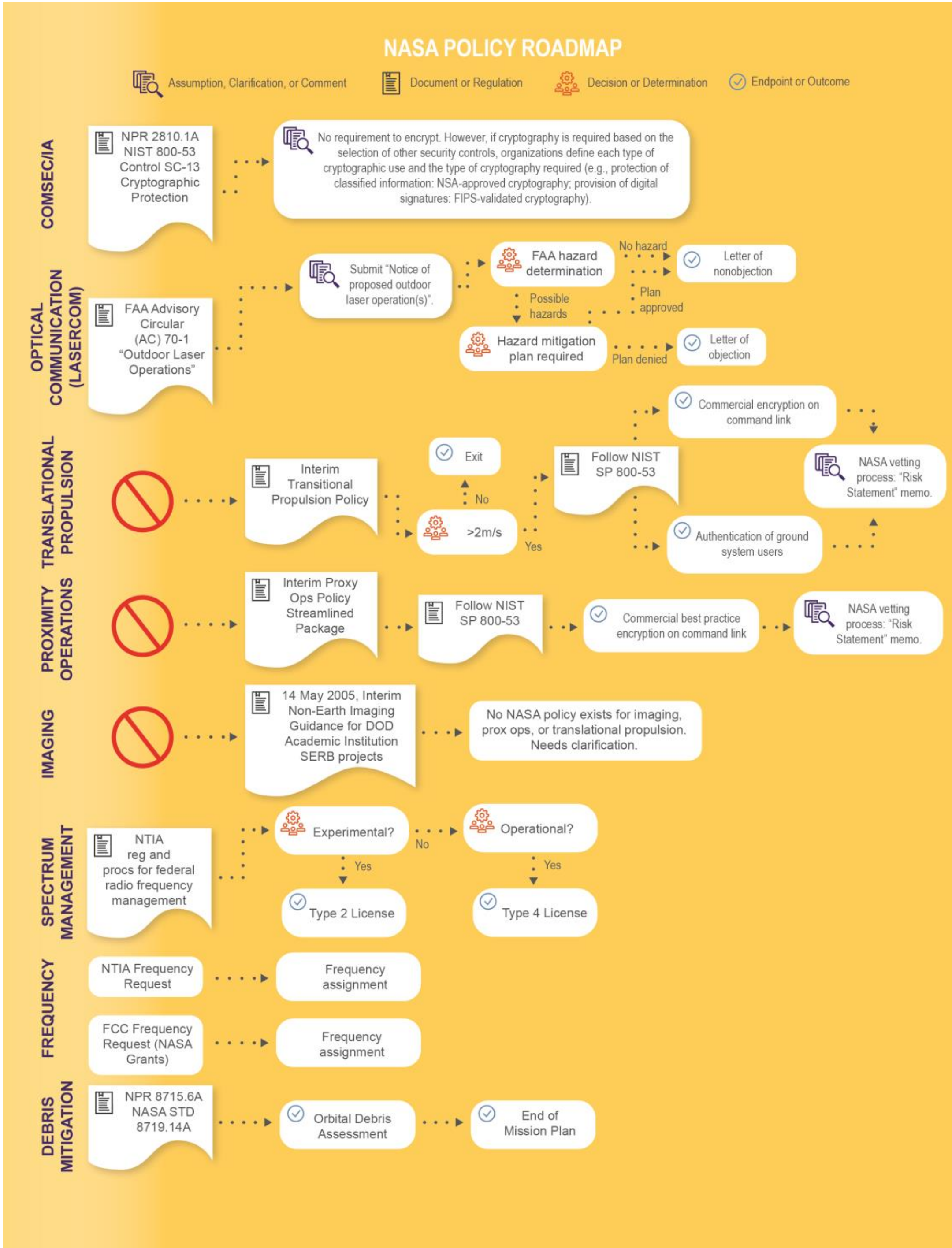

Figure 5: Policy Roadmap for NASA Satellites

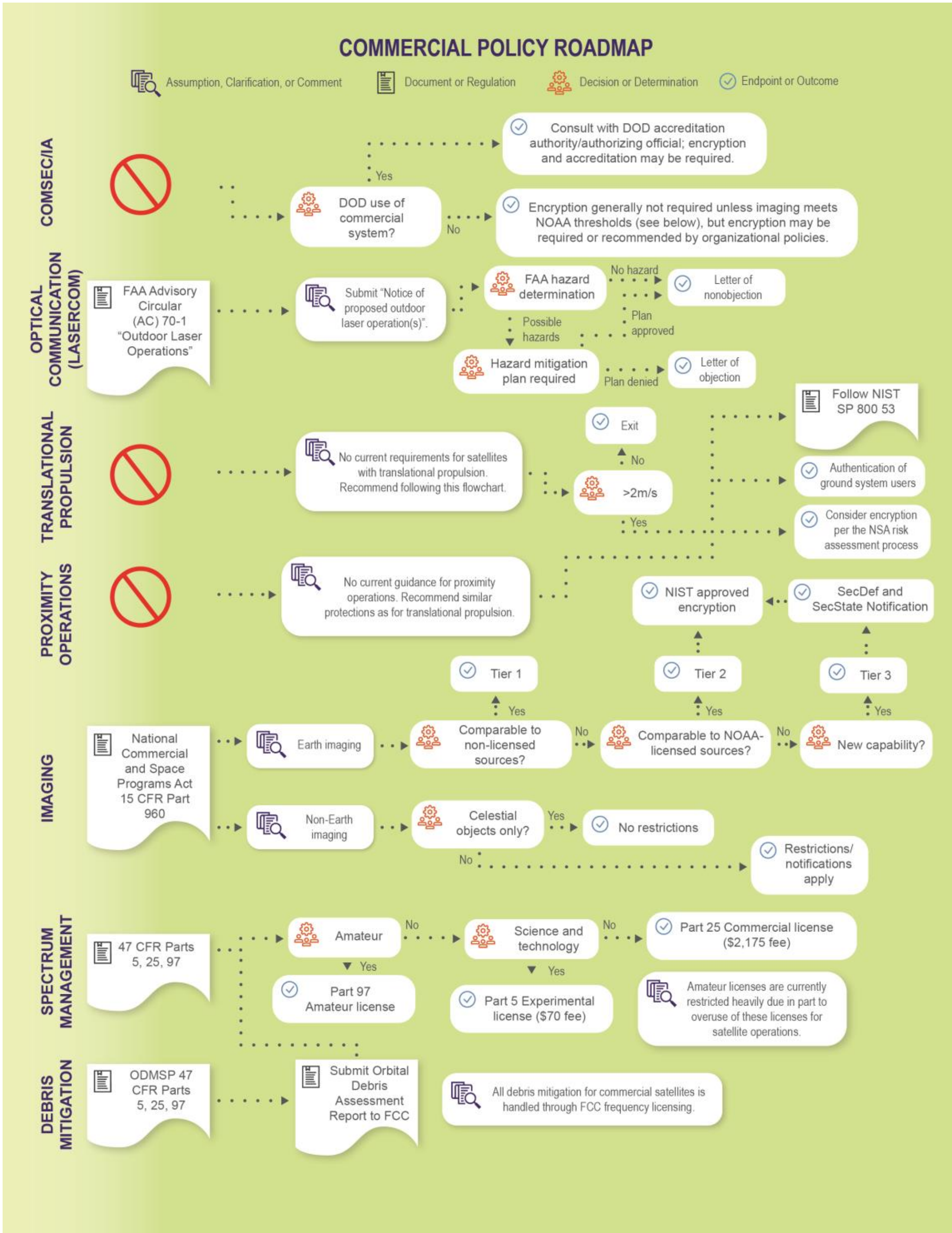

Figure 6: Policy Roadmap for Commercial Satellites

As another example, assume that a university builds a satellite capable of Tier 1 imaging and plans to do rendezvous proximity operations. They get a government organization to sponsor it to the DOD Space Experiments Review Board (SERB) for launch consideration. Even with government involvement, the satellite is still considered private and will follow the policy for privately owned satellites. The university will apply for a frequency license through the FCC and apply to NOAA for imaging approval. As part of its FCC filing, it will demonstrate its compliance with one of the respective debris mitigation regulations. As long as their imagery product does not need protecting, there are no existing regulations requiring such a satellite to encrypt its uplink or downlink, and no specific approvals are needed relating to rendezvous proximity operations.

Recent/Near Future Developments

The Small Satellite Coordination Activity (SSCA) is a DOD-level effort initiated by the Under Secretary of Defense for Acquisition and Sustainment, Ms. Ellen Lord, in 2018. The effort was started to better understand what was being done across the department in small satellites. Since 2018, a group of representatives from across the DOD and NASA have met quarterly to better understand DOD small satellite efforts and where the challenges lie. So far, there have been three phases to the SSCA. The first phase (February 2018 to July 2018) focused on data collection, the second phase (August 2018 to February 2020) focused on roadmapping, and the third phase (February 2020 to September 2020) convened eight focus groups to study challenges and make recommendations. The eight focus groups were launch, satellite vehicles, space operations and infrastructure, security, communications, remote sensing, navigation, and policy.

The policy focus group recommended including those with smallsat experience in space policy development and coordination to inform how policy affects smallsat programs. Often, policy is written with large operational programs in mind and without insight into how certain decisions (or processes) affect smallsat programs. An additional recommendation was to develop training materials to help the smallsat program managers navigate policy processes. As discussed at length in this paper, it is often hard for program managers to understand what policies they must follow and how to comply. A final recommendation was the formation of a single office at the DOD level to act as an advocate for smallsat programs and assist with policy navigation. As of the writing of this paper, these recommendations are being coordinated through the department.

On September 9, 2020, NASA and the U.S. Space Force (USSF) signed a memorandum of understanding to affirm the long-standing partnerships started under the U.S. Air Force. It also contained areas of interest for new cooperation that are relevant to smallsats. These include new rideshare opportunities, space domain awareness data sharing, and interoperability of communication systems for Earth orbit and beyond.

The Small Payload Ride Share Association (SPRSA) is leading the development of a small payload Multi-manifest Design Specification (MMDS) in support of the USSF SSC/ECL Mission Manifest Office (MMO). The ultimate objective of this effort is to create an open-source document that clearly defines the small satellite vehicle design criteria that will allow efficient integration on multi-manifested missions, including the ability to be readily moved between different launch opportunities and different launch vehicles.

Conclusion

The policy picture for today's rapidly evolving space enterprise is complex and confusing, particularly to non-traditional entrants and missions that occupy policy "gray areas." In this study, attempts to clarify the applicability of existing policy and outline a process for missions to follow to ensure compliance is done. It also highlights areas where policy is absent or unclear.

It is, however, important to remember that the policy roadmap is always “under construction” and that future changes are certainly expected. For example, with the standing of a new military service—the United States Space Force—policy roles and responsibilities are going to evolve in ways that have still not been determined. Transformation and reengineering processes will require time, broad participation, and cooperation. However, the tempo of space launches is expected to increase with several large, new constellations on the horizon. Now is a propitious time to prepare for a more crowded and busy space environment. As the space enterprise evolves, the hope is that U.S. policy will be agile enough to evolve with it to ensure access to space for all and safety in space for all.

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CHAPTER 2

LESSONS LEARNED FROM THE FIRST GENERATION INTERPLANETARY CUBESATS

Summary

Humanity is on the threshold of a new era of sustainable exploration and development of the solar system. With programs like NASA's Artemis and Lunar Gateway, rideshare opportunities for small spacecraft or "smallsats" to reach interplanetary targets will be unprecedented. However, the challenges that have to be addressed by the developers of these missions are how to meet the high-priority science and environmental survival requirements while being limited by the resources available to these missions (small budgets, relative compactness, short development timelines, lean operations, ext.). Information was gathered from the first 16 interplanetary smallsats missions that used the CubeSat form factor. This was done using several methods, including a developer's summit, interviews with mission leaders, mission surveys and a literature review. In addition, first-hand accounts from the developers of these missions on the specific challenges their missions faced and the solutions they recommended for future missions were recorded. The study also investigates the particular difficulties faced by missions of this type and their degree of impact on development. From this, recommendations for future mission developers and stakeholders to follow to lower risk and costs were created. These range from development, operation, documentation and review approaches to team composition, parts selection and qualification and shared tools and facilities.

Introduction

We are on the threshold of a new era of sustainable exploration and development of Earth's Moon and the solar system. Programs such as NASA's Artemis Missions, Commercial Lunar

Payload Services, Lunar Gateway, and other programs continue to be announced. As a result, rideshare opportunities for CubeSats and other small spacecraft or "smallsats" to reach targets that are Beyond Earth's Orbit (BEO), often referred to as xGEO (beyond Geosynchronous) or interplanetary space, will be unprecedented. CubeSat missions to these environments have already been manifested, with additional mission concepts continuing to be proposed. New organizations that have never sent spacecraft beyond Low Earth orbit (LEO) are designing spacecraft to do just that. The earliest developers of these interplanetary CubeSats continue to address the challenge of how to meet high-priority science and technology demonstration requirements with the limited resources available in the CubeSat paradigm: low-cost cap, relative compactness, higher risk, with rapid development, lean operations. Such missions are characterized by shared modeling and simulation tools and conduct only essential science measurements or demonstrations for highly focused goals.

As is the case for science and commercial applications in Low Earth Orbit (LEO), there is the expectation that utilizing the CubeSat paradigm will reduce the costs for cislunar and deep-space missions by an order of magnitude or more due to cost savings driven by each spacecraft's aggressive reduction in size and mass as well as a thoughtfully scaled-back risk posture [1]. Additionally, advances in high-performance CubeSat subsystems and science instruments are expected to enable missions with challenging planetary science objectives to potentially reach more destinations with new, novel, and targeted mission concepts and planetary science investigations [2].

However, it is important to remember that during the adoption of the CubeSat for LEO missions in the early 2000s, longtime space industry stakeholders found that traditional models, architectures, and management processes did not accurately predict or control the costs and risks associated with this new generation of smallsats [3]. Additionally, new spacecraft developers lacked a suitable body of relevant engineering and management knowledge (including engineering practices, architectures, and models) that could be applied to low-cost, high-risk smallsat missions. As a result, many CubeSat programs often operated with ad-hoc management and design approaches that did not significantly leverage established spacecraft engineering practices. The consequences were low mission-success rates and some organizations' inability to lower costs significantly [4].

In recent years, the shared body of knowledge concerning the development of reliable, low-cost smallsat missions has enabled more accurate assessments of risk and other idiosyncratic mission factors [5]. While this new body of knowledge has improved the success rate of LEO smallsat missions, mounting evidence shows these new tools will require maturation for the new class of BEO smallsat missions, just as they did for LEO assets [6]. This paper aims to accelerate the adoption and maturation of the CubeSat paradigm for BEO missions, minimize cost overruns, and avoid the high failure rates experienced by earlier LEO CubeSats.

Methodology

The Arizona State University (ASU) Interplanetary Initiative's Deep Space Summit was an acknowledgment of the need to develop a focused body of knowledge for interplanetary smallsats. It was held on October 29-30, 2021. Its goal was to engage the principal investigators, system engineers, and other stakeholders from the teams developing BEO CubeSat missions to gather their lessons learned during development. The summit engaged with teams from missions that were Post-Phase D (or equivalent) in their development at the time. The questions in the prompt were based on interviews with cost and risk analyzers, mission developers, and mission funding program directors from organizations including The Aerospace Corporation, The Jet Propulsion Laboratory (JPL), and NASA Ames Research Center (ARC) and NASA Headquarters. During the Summit, each team had a representative present an in-depth examination of lessons learned during the development of their mission guided by the common prompt. With the Chatham House Rule in effect, participants were free to use the information discussed; however, neither the identity nor the affiliation of the speaker's specific comments would revealed, to enable frank discussions. Representatives who could not attend the summit live were asked to fill out the query prompt, and then a follow-up interview was conducted to gain as much insight as possible.

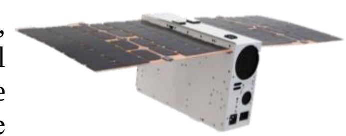
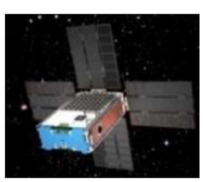
The hope is that this information can help future and ongoing interplanetary smallsat missions avoid mistakes and leverage the successes of past missions. This paper shares experiences gleaned from a diverse collection of sixteen CubeSat missions, referred to as the "reference missions" here. These spacecraft were developed by various government, academic and commercial organizations. The missions' objectives include an array of science investigations and technology demonstrations. These firsthand accounts represent rare insight into the practical challenges and opportunities of contemporary smallsat mission design and implementation. As primary-source material, these conclusions are not entirely mathematical or scientific in nature. Instead of serving as a report on a new experimental outcome, or algebraic result, for example, this paper synthesizes strategic guidance for the benefit of the current generation of smallsat engineers and program managers.

Reference Missions Overview

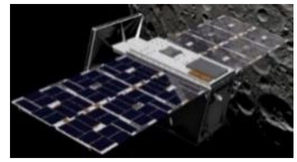
The core of missions covered by the paper is the secondary payloads planned for the first flight of NASA's SLS Rocket on the Artemis-1 (formally EM-1) Mission [7]. Three of these CubeSats (Cislunar Explorers [8], CU-E3 [9], and Team Miles [10]) are the winners of the CubeQuest Challenge, part of NASA's Space Technology Mission Directorate (STMD) Centennial Challenge Program [11]. The other missions include three led by the Human Exploration and Operations Mission Directorate (NEA Scout [12], BioSentinel [13], and Lunar Flashlight [14]), two led by the Science Mission Directorate (CuSP [15] and LunaH-Map [16]), two through NASA’s NextSTEP program (Lunar IceCube [17] and LunIR [18]) and three from among submissions by NASA's international partners (ArgoMoon [19], EQUULEUS [20], OMOTENASHI [21]). The three missions included in the present study that are not part of the Artemis-1 mission are MarCO [22], LICIACube [23] and CAPSTONE [24]. Appendix 1 provides further information on the organizations that developed the missions (the “reference developers”), their partners and other background info.

Two of the three missions in this study that did not make their planned delivery to Artemis-1 (Cislunar Explorers and CU-E3) had been assembled and completed final structural verification through a fit-check with the flight dispenser. However, they experienced late-stage hardware failures that required extensive disassembly to diagnose and repair, causing them to miss their deadline for delivery. Mission results or in-depth analysis of how the development processes affected final mission outcomes is beyond the scope of this paper.

Table 1: Reference Mission Descriptions

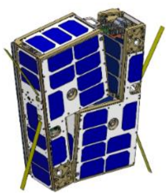
ArgoMoon	ArgoMoon will support the collection of mission data, historical records, and outreach. The mission will demonstrate advanced proximity operations around the SLS’s secondary stage, utilizing advanced image processing, autonomous tracking, and navigation technologies. After this demonstration, it will maneuver into a geocentric, highly elliptic orbit, whose apogee is high enough to allow flybys and imaging of the Cislunar environment. 
BioSentinel	 BioSentinel is a space biology mission in a heliocentric orbit that uses yeast in assays that detect, measure, and compare the impact of cosmic and solar radiation on living organisms over long durations for BEO missions to estimate and reduce the risk associated with long-term human exploration. BioSentinel will thus permit the first direct, time-resolved, *in situ* correlation of measured biological responses with physical radiation dosimetry and spectroscopy in deep space.

CAPSTONE



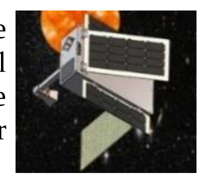
One of three reference missions to have flown by the time of this paper's publication, the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission is a 12U CubeSat mission developed by Advanced Space that will serve as the first spacecraft to enter a near rectilinear halo orbit (NRHO). The mission aims to reduce the risk for future spacecraft by validating its CAPS navigation technology and the dynamics of its halo-shaped orbit. The CAPS navigation system will measure the spacecraft's position relative to NASA's Lunar Reconnaissance Orbiter without relying on earth-based ground stations.

Cislunar Explorer



Developed by a student-staffed research team from Cornell University's Space Systems Design Studio. The mission is a technology demonstration of water propulsion, optical navigation, and UHF radio communications from beyond the moon. A 6U CubeSat system separates into two near identical ~3U smallsats with passive spin stabilization. Each incorporates commercial terrestrial components, such as commercial CO_2 cartridges for cold-gas attitude control. Each launches with ~1 liter of water, subsequently electrolyzed into hydrogen and oxygen throughout its lifetime, which provides orbit-control pulses. A Raspberry Pi based optical-navigation system autonomously determines 6DoF attitude and position. Each spacecraft is intended to use these low-cost technologies to reach lunar orbit. CisLunar Explorer is one of the missions that missed the integration window to fly on Artemis-1. The mission also hosted two different Neutron Detectors as instrument flight demos. One of the missions is to miss the integration window to fly on Artemis-1, =and is in the process of finding an alternative launch opportunity.

CU-E3

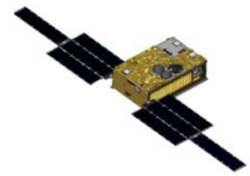


The Colorado University Earth Escape Explorer (CU-E^3) is one of the missions competing in NASA's Cube Quest Challenge. Its primary goal is to demonstrate long-distance communications from a CubeSat while in a heliocentric orbit. Its mission utilizes a low-cost X-band transmitter and a deployable high-gain reflectarray antenna. CU-E^3 .

CuSP

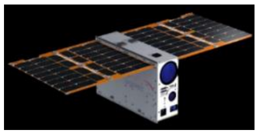
CubeSat for Solar Particles (CuSP) will study the ion populations that impact the Earth and the dynamics of particles and magnetic fields that stream from solar and interplanetary sources as a proof of concept for the feasibility of a network of stations to track space weather. One of its instruments will detect and characterize low-energy solar energetic particles, the second will return counts of high-energy solar energetic particles, and the third will measure the strength and direction of magnetic fields for contextual measurements of solar wind structures and scientific understanding of the particle data.

EQUULEUS



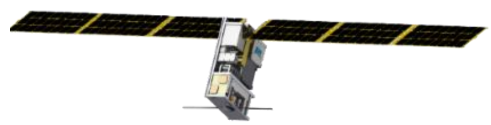
EQUilibriUm, Lunar Earth point 6 U Spacecraft (EQUULEUS)'s main objectives are to demonstrate trajectory control techniques to Earth–Moon libration orbit and image Earth's plasmasphere to study the radiation environment around Earth. The Spacecraft has three scientific missions: observe the Earth's plasmasphere, observe lunar impact flashes and measure the micrometeoroids' environment in the cislunar region. It also has a novel propulsion system, AQUARIUS, which uses water-propellant resistojet thrusters.

LICIACube



One of three reference missions to have flown by the time of this paper's publication. The Light Italian CubeSat for Imaging of Asteroids (LICIACube) is part of the NASA DART mission launched on Nov 24, 2021. It aims to document the DART probe's impact effects on the asteroid target, characterize the shape of the asteroid, and perform dedicated scientific investigations on it. The LICIACube payload includes a narrow FoV camera and a wide FoV imager with an RGB Bayer pattern filter.

Lunar IceCube

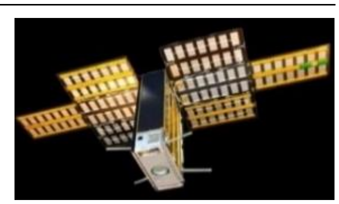


Developed by Morehead State University's Space Science Center, Lunar IceCube is a lunar orbiter with the mission to determine the abundance and distribution of the forms and components of surface water (ice, molecular water, and hydroxyl) as a function of time of day. It will do so by measuring water-related IR absorption features using a compact and cryocooled version of the OVIRS infrared spectrometer, supporting eventual sustainable human exploration and habitation of the Moon.

Lunar Flashlight

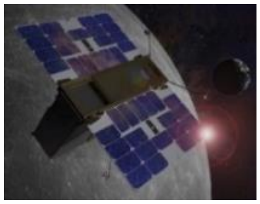
Lunar Flashlight aims to measure the composition, quantity, distribution, and forms of water and other volatiles and map its concentration in the permanently shadowed regions (PSRs) of the lunar south pole. The spacecraft carries an active laser-illumination system and a multiband optical receiver to measure surface reflectance in the PSRs. It is one of the three missions that missed the integration window to fly on Artemis-1.

LunaH-Map



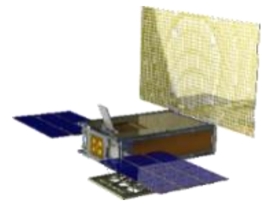
Lunar Polar Hydrogen Mapper (LunaH-Map) is a lunar orbiter that will map hydrogen at the Moon's South Pole within the permanently shaded regions. It will use a neutron and gamma-ray detector, the Miniature Neutron Spectrometer (Mini-NS), to measure the energies of neutrons that interacted with the lunar regolith. The neutron maps produced will be used to determine if water-ice enrichments are confined to permanently shadowed regions or if they extend into the subsurface in illuminated or partially illuminated regions. NASA SMD provided the estimated $15.5 million in sponsorship.

LunIR



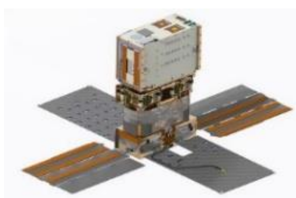
The Lunar InfraRed Imaging (LunIR), formerly known as SkyFire, is designed to perform a lunar flyby followed by a heliocentric orbit where it will assess technology solutions to issues related to transit and long-duration missions. Additionally, during its flyby, it will collect spectroscopy and thermography data using a miniature high-temperature Mid-Wave InfraRed (MWIR) for lunar surface characterization. The mission also includes a visible wavelength camera that will be used for onboard navigation processing using the moon.

MarCO



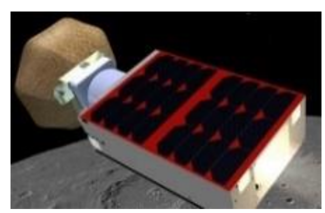
The first CubeSats to operate beyond Earth orbit, the two 6U Mars Cube One (MarCO) CubeSats launched in 2018 alongside NASA's InSight Mars lander mission. The ~$18.5 million mission comprised two identical CubeSats that functioned as communications relays for the InSight lander. The CubeSats also evaluated several miniaturized high-performance communication subsystems, including a high-gain folding reflectarray antenna and the IRIS X-Band transponder. No feedback was directly provided by the MarCO Team for this paper at the time of publication.

NEAScout



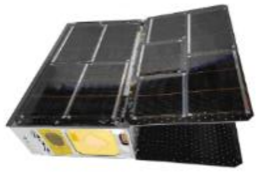
Near-Earth Asteroid (NEA) Scout will demonstrate the capability of a small and relatively inexpensive spacecraft to perform reconnaissance of an asteroid using a low-thrust solar sail propulsion system. The mission will perform reconnaissance and proximity imaging with a high-resolution monochromatic camera to characterize the physical properties of an asteroid. To have resiliency against launch delay, the NEA Scout team has been working with the astronomy community to identify new targets that can be accessed based on launch date, time of flight, and ephemeris uncertainty.

OMOTENASHI



The Outstanding MOon exploration TEchnologies demonstrated by Nano Semi-Hard Impactor (OMOTENASHI) contained the smallest lunar lander launched to date and instruments to observe the Lunar radiation environment. The CubeSat provides attitude control and thrust to maneuver itself into a Lunar intercept trajectory. The mission uses a novel approach to landing; having no initial orbit, it impacts straight to the surface after deployment. Before reaching the surface, the CubeSat spins up and deploys a 0.7 kg surface probe featuring an airbag and a solid rocket motor. The motor is fired to decrease its velocity before the probe performs a semi-hard landing on the Lunar surface.

Team Miles



Created by an all-volunteer, non-profit group of citizen scientists and engineers (Miles Space, LLC), the Team Miles spacecraft is only one of three CubeSats taking part in the NASA Cube Quest Challenge that made delivery in time for the Artemis-1 launch. The mission will demonstrate long-distance communications and deep space navigation techniques in heliocentric orbit. It utilizes a Constant Q Model H hybrid electrostatic ion thruster and will demonstrate low-thrust trajectory control techniques.

Instrument and Science Overview

The reference CubeSat missions incorporated payloads, such as spectrometers and impactors, required to operate in different cislunar and BEO target environments, as listed in Table 1, Table 2, and Appendix 1. The reference missions that reported the fewest unexpected issues during development used instruments with flight heritage in LEO on other smallsats with minimal design changes. Missions with instruments that were new, had to be adapted from larger spacecraft missions, or needed significant modification from previous versions almost universally experienced delays and cost overruns.

Table 2: Science Mission and Instruments of Reference Missions

Science Mission	**Instruments**
BioSentinel: The second payload is a physical radiation spectrometer that includes a dosimeter function to record the concurrent ambient radiation environment. It will characterize the linear energy transfer (LET) characteristics of individual radiation events in real time and measure the total ionizing dose (TID).	LET Radiation Spectrometer: single PC board TimePix-based LET radiation spectrometer by JSC-Radworks using an active chip volume of 59mL. The sensor reports radiation over the 0.2 to 300 keV/mm LET range. On-board software computes the LET value of each radiation event (particle hit) and increments the count in an appropriate bin; each of the 256 counting bins is defined by a LET width ~2.9% of its center value. The LET characteristics of a given particle "hit" are important because they describe the amount of energy the particle deposits as it traverses, e.g., a yeast cell: the units of LET are keV/mm, energy/distance.
CuSP: Measure solar particle acceleration properties of source populations in corotating interaction regions (CIR), Energetic Storm	SIS: utilizes a novel electrostatic analyzer (ESA) to measure the energy spectra, angular distributions, and the time-intensity profiles of ~3–70 keV/q H and He ions at 1/60 Hz.

Particles (ESP), and solar energetic particles (SEP) events. Study physical mechanisms responsible for accelerating energetic particles at CIR and coronal mass ejection CME shocks. Determine proton radiation levels during SEP events in the near-Earth environment. Identify suprathermal properties that could improve the lead time for predicting the arrival of strong geo-effective interplanetary shocks.	MErIT: is a modified version of its predecessor, which flew on the CeREs CubeSat. Consists of a solid-state detector (SSD) stack shielded with tungsten and aluminum. Measures the energy spectra, elemental and isotopic composition of ~2–150 MeV/nucleons and >2 MeV protons at ~8 bins/decade at 1/60 Hz.
	Vector Helium Magnetometer: is derived from a heritage line of VHMs developed by JPL and flown on numerous NASA missions that can measure magnetic field vectors at ~1 Hz.
EQUULEUS: The EQUULEUS mission has three science objectives: 1.) Observe Earth's plasmasphere, 2) Monitor the far side of the moon from EML2 to detect the flashes of light emitted by high-velocity meteoroids that impact on the moon's surface, and 3) Detect and evaluate the impact flux of micrometeoroid around the cis-lunar region by using piezoelectric dust-impact detectors.	PHOENIX: A telescope consisting of an entrance mirror, a thin metallic filter, a photon-counting device, and electronic control parts. Will observe the full view of the large structure of He^+ in the Earth's plasmasphere using the extreme ultraviolet emission from He^+ with a count rate of 3 count/min/pix/Rayleigh.
	DELPHINUS: Two cameras with the same field-of-view with an FPGA image processing board. Detects lunar impact phenomena with a duration of 10 s of milliseconds, Wavelength of 400–800 nm and limiting magnitude of 5.5 Vmag (S/N ¼ 2) for field stars 4.0 Vmag (S/N¼ 5) for lunar impact flash (18dB, 60fps).
	CLOTH: The Spacecraft utilizes a "smart MLI," which integrates thin-film dust detectors (PVDF piezoelectric films) into the inside of the spacecraft's thermal blanket, MLI (multilayer insulation). Spatial distribution and temporal variation of solid objects in the cis-lunar space from microns to 10s of cm orders. In combination with DELPHINUS, the spatial distribution and temporal variation of solid objects in the cis-lunar space from microns to 10's of cm orders will be measured.
LICIACube: Obtain multiple images of the ejecta plume around the DART impact site with a sufficient resolution to allow measurements of the size and morphology of the crater. Obtain multiple images of Dimorphos showing the non-impact hemisphere.	LEIA: A catadioptric camera composed of two reflective elements and three refractive elements. The optic has a focus between 25 km and beyond, with the detector being a CMOS sensor with 2048x2048 pixels. The latter is equipped with a Panchromatic filter centered at 650x250 nm. The primary camera will acquire pictures from a high distance providing high levels of detail in the frame field.
	LUKE: The Gecko imager from SCS space is a camera with an RGB Bayer pattern filter and focus between 400 m to ∞. The sensor unit is designed to contain the image sensor and interface with a Nano CU, and the optics consist of a ruggedized, adjustable aperture,

	lens, and spectral filters. Allows measurement of the motion of the slow (<5 m/s) ejecta to acquire images at a spatial scale better than 5 m/pixel, with the possibility to distinguish the movements of the slowest particles of the plume by the sequence of images. Allow estimation of the plume's structure, measuring the dust distribution's evolution.
Lunar IceCube: Determine the distribution of water forms and components over time to model global water origin, production, and loss on the Moon.	BIRCHES: Compact Broadband IR (1 to 4 microns to completely capture broad 3-micron band) point spectrometer with up to 10 nm spectral resolution utilizing a micro-cryocooler. IR reflectance with wavelength-dependent water components and form absorption features, with detection for >100 ppm.
Lunar Flashlight: Determine the distribution of water ice on the different surfaces in the permanently shadowed regions at the poles of the Moon.	Optical receiver aligned with lasers emitting at wavelengths associated with water ice absorption and continuum. Ratio continuum and absorption reflectance bands to quantify surface ice abundance in permanently shadowed areas at poles for > 0.5 wt.% with 1 km spatial resolution within 10 degrees of poles. Reflectance and water ice band depths will be calculated to identify locations where H2O ice is present.
LunaH-Map: Determine surface and subsurface (<1 m) water ice distribution on the Moon.	Mini-NS: The Mini-NS consists of two detectors that are comprised of four modules each. Each Module is a CLYC scintillator used to detect neutrons in the energy range of ~0.4 eV to ~10 keV that will map quantities of hydrogen down to ~50 ppm. Decrease in epithermal neutron flux (for >=20% decrease) associated with protons (ice)) (to 10's of cm depth) within ~5 degrees of poles. The goal is to map hydrogen with good statistical confidence (~20% relative) at levels as low as 0.6% water-equivalent hydrogen (~600 mg/g H).
Lunar IR: Measure the thermal environments of the moon to provide knowledge on the composition, structure, and interaction with solar particles and the lunar regolith.	MWIR: high-temperature Mid-Wave InfraRed sensor includes an integrated micro-cryocooler and a high-temperature nBn-based 1 Megapixel focal plane. During its lunar flyby, it will take IR and visible light images of the lunar surface and its environment to perform surface characterization, remote sensing, and site selection observations.
NEA Scout: Characterize the physical properties (Shape, Volume, Rotational Properties, Debris/dust field, regolith characteristics, ephemeris, albedo) of the NSA target.	High-Resolution Monochrome Imager: Utilizes an existing modular 20M pixel CMOS image sensor camera platform previously implemented on the OCO-3 mission. Images over 80% of the target's surface at <100km distance and > 30% of the target surface during closer proximities.
OMOTENASHI: Measure the radiation environment of the cislunar region.	The CubeSat's main body has an ultrasmall two-channel radiation monitor (less than 50 g per channel) to measure proton particles (Ch-1) and galactic cosmic

	ray (GCR) ions on the translunar orbit.

Technical Challenges

The reference missions identified key technical challenge areas that were the most significant drivers of unforeseen cost and schedule delays. These challenges drove systems toward larger volumes and surface areas than traditional CubeSats have attempted, often leading to the misapplication of resources during the development of the spacecraft's different subsystems. To avoid these resource issues for future missions, the reference developers offer the following observations:

Complexity-Related Challenges: Complexity by any measurement is significantly greater for this mission class than for LEO smallsats. In many cases, the design of some subsystems was found to be far more difficult because the limited volume and mass made the subsystems more complex to meet minimum requirements. Nearly all the reference missions employed or tested innovative technologies to compensate for their spacecrafts' general lack of resources or ground support. Merely integrating and verifying such systems represented work outside the scope of a "typical" smallsat mission. A continual increase in the complexity of deep space CubeSat missions can be anticipated as the proportion of science-driven requirements increases.

Payload-Related Challenges: The need to integrate several advanced miniaturized science payloads constitutes a common challenge among the reference missions. As secondary payloads, these spacecraft experience limited payload monitoring and protected environments launch providers. Specifically, thermal control and the risk of contamination before launch were significant concerns to systems with optics and biological components. Many science payloads also found meeting the mass and volume constraints of a 6U CubeSat to be difficult. Higher-performance instruments or science missions that rely on gathering large datasets, like those on missions such as Lunar IceCube and LunaH-Map, are challenged by the limited bandwidth available via ground station networks like the Deep Space Network (DSN)). Data compression and other algorithmic approaches to minimizing data throughput had to be developed and implemented to compensate.

Target-Related Challenges: Subsystem lifetime survivability issues, particularly those related to longer-term radiation exposure in deep space, are target-dependent. Most missions of this type require many months to reach their operating environment. This dependency results from the fact that many of the reference missions reach their target via low low-energy trajectories. These trajectories take significant effort to design and may exceed the capabilities of typical LEO smallsat developers [22]. The reference missions reported that most of these efforts had to be redone every time the launch date was changed. Software tools that can map low-energy trajectories simply and quickly will be vital for future BEO smallsat missions. The limited availability of uplink time for communications and position correction makes command and control a particular problem for missions of greater operational complexity, perhaps motivating the development of autonomous deep-space navigation.

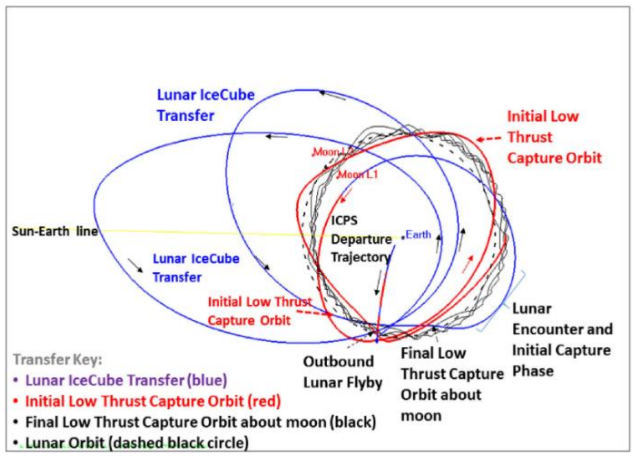


Figure 7: Approximation of Lunar IceCube transfer trajectory [8]

Propulsion-Related Challenges: More than any other subsystem, propulsion caused the most difficulties for the reference missions. Nearly all missions with high-performance propulsion systems reported development issues that caused unforeseen increased costs and schedules. Issues stemming from propulsion systems even have even caused some reference missions to fail to pass key design reviews. Three reference missions ended up switching their selected propulsion systems after PDR. CU-E3, which had no propulsion system, reported that their original mission goals were changed due to the lack of propulsion systems that could meet their requirements in a small enough form factor. The LunIR team noted that it changed its mission objectives from those in its initial proposal to make them achievable without a propulsion system due to concerns related to the TRL of systems available at the time.

Thermal-Related Challenges: Both the extremes of temperature and the duration of those extremes for interplanetary smallsats significantly exceed those experienced by LEO smallsats. Thermal control is therefore a major issue for missions of this type for three key reasons: 1) Such missions must contend with the fundamental physics of large power systems constrained by small volumes, where limited thermal mass and surface area for radiating risk high temperatures. 2) Sensitive science instruments (such as spectrometers and lasers) and high-performance subsystems (such as high-gain radios and high ΔV population systems) have unique and, in some cases, narrow operational temperature ranges. 3) Thermal control requirements for instruments often conflict with those of other subsystems (e.g.: cryogenic instruments vs. room-temperature batteries vs. hot propulsion systems).

Design and Development Lessons Learned

Certain general development approaches were most successful at controlling cost and schedule for missions of this type. Specifically, the reference missions recommended the following: 1) Maximize the use of high-reliability COTS subsystems if solutions suitable for deep space are available and 2) Design for Reliability if no acceptable COTS solution exists. Note that both approaches are constrained by cost and schedule.

Engineering contingency (sometimes referred to as margin) should exceed typical spaceflight practices to ensure CubeSats can meet objectives. Leaving at least 33% of power and 25% of mass and volume has been proposed to accommodate post-CDR design changes and to anticipate other unexpected challenges. Earlier-than-usual preparation for mass and power reduction also might be warranted as many reference designs required unexpectedly significant mass reductions and power re-budgeting.

Many missions suffered from requirements creep, causing redesigns and delays. Consequently, such spacecraft should have a finite set of well-defined features (with assured margin), including baseline and threshold designs, coming out of PDR that is fiercely defended against any change. The addition of more features, even during the beginning of the design process, should be resolutely fought against. While this principle is familiar across virtually all engineering disciplines, the less formal nature of some practices encountered in small spacecraft motivate particular attention to the issue of creep.

Organizational Lessons Learned

Organizational-related issues can be mitigated by the involvement of team members with experience on larger missions, with mutual benefit in some cases. This section summarizes general observations made by the reference missions on what made successful teams.

Having high-performing leads in small package/payload systems engineering, mission operations and ground data systems, and thermal design engineering were all agreed to be the most important to successful team organization. Furthermore, it is critical for a designated lead engineer to continue in that position for most of the mission's development. That lead should have strong systems-engineering and development-cycle knowledge and should have expertise in the most typical spacecraft subsystems.

For the Artimis-1 reference missions, a dedicated Safety Team or Safety Engineer was reported as important in managing documentation and maintaining communication with the launch integrating organizations. For many of the reference missions, the Program Manager or Principal Investigator filled this role, and it was found to be an oversize drain on their time and focus to the detriment of the missions. In the future, such requirements should be negotiated with the launch-vehicle provider, ensuring that expectations are consistent with the CubeSat mission class, thus eliminating the workload concern.

The discipline of flight software requires someone with expertise to lead and plan development. Finding such skills is especially difficult for academic missions, where the traditional computer engineering or computer science curriculum does not cover the specialized issues in developing flight software for space. Many reference developers also reported a lack of understanding of the scale of the software engineering tasks and that they failed to capture all the software requirements at the beginning of development. The development of and training on open-source and shared software tools, already underway, must be encouraged and expanded.

The effort to design a mission trajectory does not scale with the smaller size of these spacecraft. Even small satellites require a trajectory design and navigation team(s) with a similar or greater scope of work to larger exploration missions. Missions still must have a full flight dynamics team for trajectory design, exactly as for a much bigger spacecraft.

Other Key Findings

The representatives attending the Deep Space Summit discussed many challenges they faced and proposed solutions for future BEO smallsat missions. Fifteen of the most critical findings are summarized here.

1) Need for system and discipline engineers experienced with small-scope space missions

For the most part, the reference developers are the first-generation cadre of small-scope interplanetary smallsat mission developers. In many cases, their efforts created opportunities for training next-generation deep space mission developers. However, there is no clear path for future missions to leverage the expertise held by those who contributed to these reference missions for their missions. Consequently, it is recommended that NASA build on the already developing core of engineers and managers/mentors and established processes at proposing institutions ranging from NASA centers to small start-ups and universities and use them simultaneously on future projects of this nature. This approach will help alleviate turnover induced at government or corporate organizations by experienced personnel being subsumed into larger projects and academic institutions by time constraints of student availability. The involvement of members of larger missions with mutual benefit in some cases can also mitigate this issue. Special attention should be given to solving this issue for critical leads in small package/payload systems engineering, mission operations and ground data systems managers and thermal design engineering.

*2) **Enhance interplanetary mission development culture to support small scope, cost-capped opportunities***

Most smallsats, whether they orbit Earth or not, tend to not follow traditional development paths, technically or programmatically. In contrast to traditional requirements-driven missions (e.g., requirements decomposition and verification, NASA's Class A-D classification, and associated assurance practice) development frameworks, where meeting science or technology requirements is the primary metric of success. [29] Cubesat missions are more constraints-driven, where higher risk and a more flexible baseline are tradable to maintain cost and schedule constraints. These missions are also referred to as "cost-capped" as their costs are "capped" to a maximum value. "Sub-class D" is where mission requirements are considered less than those dictated in NASA's class D missions' category. However, as it has acknowledged for some time, the practice of simply assigning all cubesat/smallsat missions as sub-class D approach does not work. As a result, the "Small Spacecraft Technology Program Guidebook for Technology Development Projects" was created to provide recommended practices for the research and technology development projects sponsored by NASA's Space Technology Mission Directorate's (STMD) Small Spacecraft Technology Program [30]. While not published in time to help shape the development of the reference missions (August 2021), many of the developers acknowledge it as offering superior guidance for efficiency, best practices, and improved success of smallsat missions. Many of the recommended practices derive from lessons learned by small spacecraft developers over the course of many past projects.

*3) **Further "standardization" needs to evolve to support interplanetary CubeSats.***

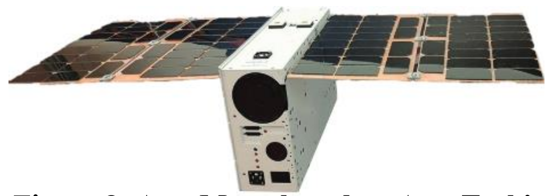


Figure 8: ArgoMoon based on ArgoTech's Hawk-6 Bus Platform [19]

Widespread standardization was not realizable in this first generation of interplanetary smallsats. Only the ArgoMoon and LICIACube reference missions shared a common bus design (shown in Figure 1), with the major difference between the two spacecraft designs being the instruments they carry. The reference developers had expressed many differing views on the appropriate degree of standardization. While no consensus was reached, the teams acknowledge that different payloads imply different subsystem requirements or at least different configurations of subsystems. They key question is how to embrace the diversity of payloads while encouraging the use of COTS and standardization. Developing a single common bus that could meet as many mission requirements and configurations as possible most likely comes with significant penalties in mass and volume if it is to accommodate a wide variety of payloads and instrument types. Therefore, multiple bus designs that could target specific target environments or payload types would enable the greatest diversity of missions of this type and potentially lower costs as well.

The ability to mix and match COTS subsystems and payloads with common interfaces and open software architectures was identified as possibly the best compromise. The industry should aim to develop several reliable, deep space-proven COTS subsystems with hardware lines and software tools matched with the most frequently visited targets and different payload types (e.g., particle analyzer, spectrometer, field detectors) with adequately standardized external constraints (volume, mass, power) to accommodate a range of payloads can be reached. Larger form factors may be required to enable more standardization for early missions.

A parallel issue of note is that miniaturized instruments suitable for future BEO smallsat missions exist but are not readily available for future missions. Many instruments and sensor designs exist worldwide as part of current and past research projects and missions. But many of these systems were built once and never thought of again. Many of these systems are owned by academic and government groups with little incentive to make copies of past work. If commercialization of these designs is not possible, funding approaches that enable groups to build many copies of useful instruments after development and store them for later missions to utilize should be explored.

4) ***Use shared tools tailored for cost-capped missions to overcome non-scalable systems of comparable or greater complexity than conventionally sized exploration missions or typical LEO CubeSat missions***

Developing new technologies or adapting even high TRL LEO subsystems for BEO missions required significantly more time and money than many reference mission developers anticipated. For the most part, direct hardware costs were still relatively low for missions to similar targets. However, costs, efforts, and time to complete program management, systems engineering, flight software development and systems integration tasks are not comparable to typical LEO CubeSats, nor do they scale in a simple way from larger exploration missions.

NASA should continue to encourage shared software tools (for modeling, testing, and data production), shared build and test facilities, and several reliable deep-space subsystem choices (computer and operating systems, communication, power, and active control systems). Furthermore, it should continue to use incentives, including funding opportunities, to facilitate the creation of such tools and approaches. It must be acknowledged that many of these tools will differ from tools already developed for LEO smallsats and will be dedicated and designed to serve smallsat missions that also leave Earth's orbit.

5) ***Expand from 6U to 12U for the standard volume for BEO missions***

Fundamental physics dictates the need for high-performance subsystems when operating beyond Earth orbit, Making operating around other planetary bodies especially challenging targets for 6U spacecraft. The reference missions surmised that most their spacecrafts were far denser (their subsystems utilizing close to all the available mass and volume available) than conventional CubeSats with the same limited external area. Thus, the reference missions had far greater challenges when designing for heat dissipation, subsystem configuration and unhindered field of view of instruments. In particular, the reference missions that required cold imaging sensors or very stable payload conditions had difficulty with the limited surface area and volume of the 6U form factor.

Future innovations may relieve some of these problems, but they will remain fundamental design issues, as discussed in [25]. It was suggested that for missions with extreme thermal control requirements, the 12U form factor, even without increasing the launch mass of the spacecraft, would alleviate much of the difficulty by providing additional surface area for radiators. Furthermore, expanding the 'standard' 6U deep space CubeSat size used by most of the reference missions to 12U would have an even greater impact, alleviating greater packing density and thus improving heat rejection for high-performance propulsion and communication systems. In addition, more surface area and less restricted field of view would be available for power, communication, thermal control, and uncontaminated fields of view for subsystem and payload optics.

6) ***Commit to a reasonable schedule to avoid severely impacting mission development***

As secondary payloads, smallsat missions tend to have launch dates or initial trajectories that are not controlled by the mission developers (as was the case for the Artemis-1 reference missions). The reference development teams found the uncertainty in the schedule of their launch vehicle was highly disruptive to planning and even changing the designs of their spacecraft. Additionally, the teams reported that many tasks, such as navigation and operational planning, had to be repeated or augmented as launch windows slipped, conditions changed, and scope increased. Uncertainty in the schedule (both pandemic and development delay driven) was incredibly disruptive for planning for all the teams. As time dragged out, the availability of personnel became more limited, and task completion slipped.

Missions must design their spacecraft to be prepared for considerable time stored by a spacecraft integrator or launch service provider on a host spacecraft or storage facility in an uncontrolled environment before launch. Commitment to specific launch dates with allowable slips agreed upon far in advance is advisable for future opportunities. In that case, launch service alternatives could be made available in a service comparable to NASA's CubeSat Launch Initiative. This would standardize rideshare and delivery to target opportunities. Also, greater communication between the primary mission and secondary payloads to where several launch windows are committed to. The other solution is to have high design margins where the spacecraft can survive the most extreme environmental conditions, with subsystems designed to account for worst-case scenarios. In the short and mid-term, the reference teams believed this approach would limit mission opportunities and significantly increase costs.

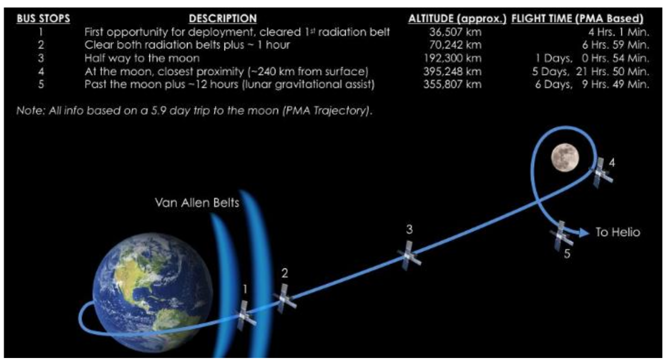


Figure 9: Representative Secondary Payload Jettison "Bus Stops" for the Artimis-1 mission. Image courtesy of NASA

7) ***<u>Provide assets to avoid severe navigation and tracking constraints during and post-deployment.</u>***

The lack of availability of navigation and tracking assets, especially for multiple secondary or multi-manifest deployments in a brief period, greatly increases the risk of mission loss for BEO secondary payloads. This aggravates the constraint imposed by the lack of onboard resources for trajectory correction, data processing and storage on BEO CubeSats. In addition, trajectory constraints and the requirements to be powered-off during launch dictate that all the reference mission spacecraft wake up lost in space and lost in time, not knowing where they are relative to Earth or Sun. Compounding these issues, most small satellite typically tumbles right after deployment. It is anticipated that most future missions will also have these constraints.

Missions must be designed to tolerate large pointing and positional errors and not knowing their own or Earth's position after powering on. Designing the power system and communications system (near Omni-directional antenna pattern, baud rate scaling) to be operational in most possible tumble orientations greatly increases survivability in off-nominal cases. The ability to orient at the beginning of the mission itself without intervention is important to minimize risk.

The reference developers acknowledged that few options are available in the short term other than the enhancement of cislunar communication assets, many already planned, should be implemented as soon as possible to reduce this 'bottleneck.' This includes upgrades to the NASA DSN and commercial ground stations.

8) ***<u>Expand the use of systems engineering approaches to assess and address risk for small-scope, cost-capped missions</u>***

The trade space for selecting and configuring features for small, cost-capped, limited-scope spacecraft is complex. BEO missions are driven technically by mission objectives, power, telecommunications, and propulsion requirements. Understanding and having clear and specific requirements for these performance metrics going into a project is key to its success. Also, many of the reference missions, in their desire to save time (or even drawing on their past experiences), did not follow standard systems engineering processes such as risk management, configuration management, and quality assurance. As a result, many (but not all) of these missions did suffer predictable consequences from omitting those processes. Many of the reference missions managed at academic institutions lacked experienced systems engineering personnel and were unaware of the processes they could use.

It is recommended that early risk assessment through trade studies of approach cost, schedule, physical resources, and impact of modification to meet threshold and baseline requirements be conducted. The "Small Spacecraft Technology Program Guidebook for Technology Development Projects" was created to provide recommended practices for the research and technology development projects sponsored by NASA's Space Technology Mission Directorate's (STMD) Small Spacecraft Technology Program [26]. While not published in time to help shape the development of the reference missions (August 2021), many developers acknowledge it as offering superior guidance for efficiency, best practices, and improved success of smallsat missions. Many recommended practices were derived from lessons learned by small spacecraft developers over many past projects.

*9) **Need to incorporate state-of-the-art technologies along with reasonable COTS to realize the potential of CubeSat class missions fully***

The CubeSat paradigm, while relying on COTS for supporting subsystems to reduce costs and to preclude 'reinventing the wheel,' should be well suited for technology demonstration missions due to more acceptable risk and will therefore be able to push forward state-of-the-art, offer improved measurement capability, and improve benefit to cost ratio for any missions. However, several reference missions experienced significant issues with COTS providers, leading to unexpected costs and delays. Including COTS components that subject to discontinuation or change without warning and inconsistent pricing

Many reference missions reported that although they used COTS subsystems developed for space, many required modifications to meet BEO mission needs. Many of these modifications had to be done by the subsystem supplier, with the mission team lacking the necessary knowledge (often a driver for selecting COTS equipment) or due to the vendor's propriety control of the hardware. The reference missions found few commercial COTS LEO smallsat component vendors willing to do custom products and services that met BEO mission needs. When they did, it came with high non-recurring engineering costs that were, for the most part, shouldered by the development teams.

It is recommended that future opportunities allow project flexibility to use high-risk state-of-the-art components (rather than preexisting >10-year-old spares) for critical subsystems are needed to lower costs. To avoid the issues of dealing with 'black boxes' from commercial vendors, it is recommended that NASA require ICDs and transparency from vendors (and continuation of the NASA Electronic Parts Program) to allow the team to plan for and mitigate any impact on the payload. In addition, it is recommended that NASA develop and test models for 'batch' parts selection and testing and payload calibration to supply to future missions.

10) ***Need for infrastructure providing resources to many small missions operating BEO***

Access to external resources, such as communication, navigation and tracking services which must serve many missions (such as NASA's DSN), is an issue for many missions and will continue to be an issue with current architectures.

It is recommended that NASA facilitate the utilization of architectures that make the CubeSat paradigm useful beyond single 'pathfinders' missions, which made up the bulk of the reference missions. Potential solutions include the development of BEO communication and navigation infrastructures that aim to enable these activities with lower resource needs from the individual spacecraft. Additionally, the paradigm where a spacecraft would deliver multiple smallsat platforms to their target trajectory or target environment would relax the need for internal resources for propulsion, communication, navigation, and tracking.

11) ***Further development needs on the first-generation miniaturized deep space radio systems.***

The RF communication systems used by the reference missions proved to have significantly greater drains on power, volume, and thermal rescores than expected. Even with flight heritage, the systems used exceeded the estimates for the resources they required. In addition, the options for communication and ranging systems compatible with the DSN were limited; as such, only 6 of the 16-reference missions did NOT use the IRIS system for their main radio. The Iris radio is a small form factor (<1U) software-defined radio developed by the Jet Propulsion Laboratory (JPL) and manufactured at Space Dynamics Laboratory [28].

More development is needed for these systems, with customer support needed to make them viable COTS solutions for many future missions. Designing, integrating, and debugging small high-performance RF comms systems require specialized knowledge. Additional support for developing competing systems would enable more flexibility for future missions.

12) ***Eliminate uncertainties in requirements scope by providing predefined and set launch service conditions.***

The Artemis-1 rideshare reference missions reported significant and unexpected design, testing and verification burdens imposed due to NASA Human Rated (Class A+) driven health and safety requirements. These requirements were generally considered out of scope, not just compared with LEO secondary payload/rideshare requirements, but with the expectations communicated when the flight opportunity was announced. Additionally, safety requirements were poorly defined initially and changed throughout the process.

It is recommended that well-defined interplanetary rideshare ICDs be provided with opportunity announcements. Additionally, programs should model their ICDs on the simplified and less stringent safety and interface requirements used on other human space missions that have proven effective. For example, the reference developers point to programs launching CubeSats from the International Space Station (ISS) as a possible reference for more reasonable requirements when incorporating cost-capped CubeSat Missions on human-rated facilities for future BEO smallsats [28].

13) ***<u>Develop more reasonable environmental requirements more typical of secondary payloads</u>***

An issue encountered by the reference developers on the Artemis-1 mission was shifting environmental requirements (e.g., the environment the CubeSats were kept in before deployment). The CubeSat missions' requirements (driven by science and technology goals) were not regarded in developing the environmental requirements of the launch environment. In the case of the SLS, due to the evolving development of the second stage where the CubeSats are stowed, these requirements would shift through the program's life.

The reference developers recommend maintaining a 'payload bay' with active environmental controls in future missions where multiple secondaries are deployed. This will be critical for limiting both the costs of the secondary payload but also in limiting the risks to the primary mission payloads in the future.

14) ***Further streamlining of licensing and certifications by the US government and international agencies is needed***

The reference developers found that the regulations and policy compliance process for BEO missions were far more extensive than they had experienced in the past and were expecting. Multiple government agencies, who often don't communicate with each other, are involved in getting final launch approval. Items like Planetary Protection, Orbital Debris Mitigation., Range Safety requirements for launch and transport requirements for an overseas launch are beyond the scope that most development teams had done for past LEO missions.

Additionally, Frequency approval for Cislunar and other BEO missions is often an unexpected labyrinth of requirements and approvals that require extensive attention to detailed requirements and time to receive full approval. Getting a license or approval to use a frequency through either the FCC or other agencies might hinge on the ITU's coordination process takes months to years (there is a case of one reference mission taking 4 years to get approval), so missions should start working on the application and submittal as early as possible.

15) ***Develop alternate build, test, and integration to minimize the impact of large-scale shutdowns***

It is important to note that the COVID-19 pandemic presented significant issues to the development of every reference mission surveyed. From 2019 onward, many teams had to operate on a limited and remote basis (in some cases, teams were locked out of their facilities entirely for months) during the extended shutdowns. Additionally, pandemic-related issues led to the part supplier/vendor issues, cost overruns, schedule delays, team turnover and other problems. In many cases, this was during critical integration and testing periods. This paper attempts to separate the effect of the pandemic from the lessons learned that are discussed.

While acknowledging the unprecedented nature of the pandemic, a possible solution to a similar situation in the future, in the case of future shutdowns, would be for teams to plan to have their facilities that have policies in place that would allow for continued use with personal protection plans (such as Personal Protection Equipment, Social distancing, etc.) in the event of a public health crisis or plan to have a back-up. Another solution would be for NASA to agree to provide support and alternative facilities in the event of a shutdown of partner facilities. Additionally, teams found that setting up remote access to test hardware for software development proved incredibly important. Teams noted that during covid lockdowns and academic holidays, remote access to development hardware allowed software development and testing to continue uninterrupted.

Conclusion

Some of the items discussed in this paper may represent known and relevant information to smallsats in LEO or larger form factors going to BEO targets. However, they were still of value and included in the paper as they represent significant issues or solutions proposed/implemented by the reference mission developers. Many of the development issues discussed in this paper could be addressed by using universally applicable solutions in next-generation CubeSat mission architectures for deep space. These solutions include next-generation infrastructure as well as standards, supporting subsystems and components. A robust transportation system designed to deliver multiple small payloads or packages to the lunar surface or orbit could alleviate the need for more capable onboard propulsion systems on compact spacecraft to achieve their orbit or landing, and thus most or all their needs for ΔV. Available ΔV could then be used for maintenance or maneuvering in orbit. Longer mission durations needed for low-energy trajectories would be unnecessary. Assets delivered to lunar orbit via this transportation system could also be used to meet navigation and communication requirements for a growing number of space missions, including CubeSats, in the cislunar neighborhood, allowing more accurate position determination and greater bandwidth availability. More information on the lessons learned can be found in the in-depth white paper developed from the complete findings of the ASU Deep Space Summit on the summit website: https://www.asudeepspacesummit.org/.

APPENDIX I: MISSION BACKGROUNDS

	Lead Developer	Sponsor/Funding Organization	Partners	Planned Launch	Mission Category	Mission Destination
Argo Moon	Argotec	Italian Space Agency / Agenzia Spaziale Italiana (ASI)	VACCO, JPL	Artemis-1	Tech Demo/ Mission Support	Proximity Ops with the ICPS, Lunar orbit
BioSentinel	NASA AMES	NASA Advanced Exploration Systems (AES)	NASA Johnson Space Center's Radworks Group	Artemis-1	Space Biology Science	Heliocentric orbit via Lunar flyby
CAPSTONE	Advanced Space	Phase III of NASA's SBIR program	NASA's STMD, NASA Launch Services Program Advanced Exploration Systems, NASA Ames Small Spacecraft Office, Tethers Unlimited, Steller Exploration, Space Dynamic Lab, JPL, Tyvak, Astra	Rocket Lab Electron (March 2022)	Tech Demo	Near rectilinear halo orbit
Cislunar Explorers	Cornell University's Space Systems Design Studio	NASA Cube Quest Challenge (CQC), sponsored by NASA's STMD Centennial Challenges Office (CCO)	National Space Society, Los Alamos National Labs,	TBD	Tech Demo	Lunar orbit
CU-E3	University of Colorado Boulder	NASA CQC, sponsored by STMD CCO, NASA's Internal Strategic University Research Partnerships (SURP)	Blue Canyon Technologies, AstroDev, JPL	TBD	Tech Demo	Heliocentric orbit
CuSP	Southwest Research Institute	NASA STMD	NASA Goddard, JPL, Blue Canyon Technologies, VACCO, Clyde Space	Artemis-1	Heliophysics Science	Heliocentric orbit
EQUULEUS	University of Tokyo	Japan Aerospace Exploration Agency (JAXA)	NASA JPL, Nihon University, The University of Electro-Communications, Chiba Institute of Technology, Hosei University	Artemis-1	Lunar Science	Earth-Moon L2 point
LICIA Cube	Argotec	Italian Space Agency / Agenzia Spaziale Italiana (ASI)	SCS space, Politecnico di Milano group, INAF, University of Bologna, JHU APL, VACCO, JPL	NASA DART (Nov 24, 2021)	Tech Demo/Mission Support	Asteroid rendezvous
Lunar IceCube	Morehead State University	NASA NextSTEP	NASA JPL, NASA Goddard, BUSEK, Blue Canyon Technologies, PUMPKIN, Space Micro	Artemis-1	Lunar Science	Lunar orbit
Lunar Flashlight	JPL	NASA AES	JHU Applied Physics Laboratory, University of California, Los Angeles, MMA Design LLC	TBD	Lunar Science	Lunar orbit
LunaH-Map	Arizona State University	NASA SMD	AZ Space Technologies, JPL, BCT NASA Ames Research Center, Radiation Monitoring Devices, MMA Design LLC, KinetX Aerospace, Qwaltec, Inc., Los Alamos National Laboratory	Artemis-1	Lunar Science	Lunar orbit

LunIR	Lockheed Martin Space	NASA NextSTEP and Lockheed Martin Space	Tyvak Nano-Satellite Systems, Inc., SpaceMicro, Santa Barbara Focalplane	Artemis-1	Tech Demo	Heliocentric orbit after Lunar flyby
MarCO	JPL	NASA JPL	VACCO, Blue Canyon Technologies, AstroDev, University of Michigan	InSight (May 5, 2018)	Tech Demo/Mission Support	Heliocentric orbit after Mars flyby
NEAScout	NASA Marshall	NASA AES	JPL, NASA MSF, NASA LRC, NASA GSFC, NASA JSC, Blue Canyon Technologies, Mountain Man Aerospace, VACCO, NeXolve Holding Corporation	Artemis-1	Small Body Science	NEA within ~1.0 AU of Earth
OMOTENASHI	JAXA's Institute of Space and Astronautical Science (ISAS)	JAXA	Kawasaki Heavy Industries, NOF Corp, Sharp, Addnics Corp, Digital Spice, The National Institute of Advanced Industrial Science and Technology (AIST) Blue Canyon Technologies, VACCO, SAFT, ENDEVCO, Koiwai	Artemis-1	Lunar Science	Lunar surface and Lunar transfer orbit
Team Miles	Miles Space, LLC	NASA CQC, sponsored by STMD CCO	ATLAS Space Operations, Destination Space, Yosemite Space	Artemis-1	Tech Demo, STEM education	Heliocentric orbit

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CHAPTER 3

EVALUATING MARS ROTORCRAFT DEVELOPMENT INVESTMENTS

Summary

Helicopters offer a new paradigm for Martian surface and atmospheric exploration. Their ability to traverse terrain quickly and reach previously inaccessible locations was proven by Ingenuity's flights over the precarious dunes of Jezero crater. However, traditional space exploration technologies, architectures and designs are ill-suited for Mars Rotorcraft developments, and there is a need to develop new ones to enable future missions. Likewise, stakeholders must be prepared to evaluate competing research and development efforts not only for their estimated costs and system performance but also for their long-term improvement potential in the context of other ongoing developments. This study enables this by investigating current and past development efforts and establishing critical metrics for evaluating rotorcraft system and subsystem performance. From these metrics, relationships and improvement potential were identified. Then overall alignment to the broader NASA technology development plans and ways to estimate return on investment values were established. This includes utilizing existing and establishing new Mars rotorcraft performance models to identify and quantify potential system-level benefits of investing in improving specific subsystem performance metrics while accounting for feedback in such a complex system. Approaches to quantifying the long-term improvement potential of competing architectures and technologies are also offered.

Introduction

With the successful landing of the Perseverance rover and its deployment of the Ingenuity helicopter (formally known as the Mars Helicopter and nicknamed Ginny), it was proven that rotorcraft flight was possible on Mars. Furthermore, by operating beyond its intended life and exploratory mission showed that similar platforms could be used for mission support and potential hosts for scientific instruments [3]. Now with the planned set of Sample Recovery Helicopters (SRH) to be hosted on the Sample Retrieval Lander for the upcoming Mars Sample Return Program, the use of rotorcraft on Mars as tools for planetary exploration is already set for launch [4]. Figure 2 shows an artist's illustration of the Mars Sample Return helicopter (SRH), highlighting the rotorcraft's wheels and sample-retrieving arm.

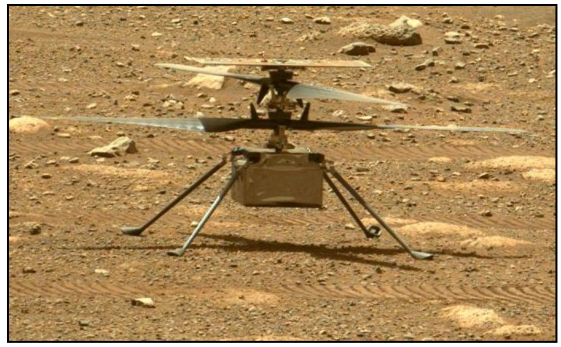

Figure 10: Photo of Ingenuity on Mars, Credits: NASA/JPL-Caltech

NASA is preparing the next campaign of landing missions to the Moon with an eye on creating a sustainable presence there and as part of a long-term plan to land humans on Mars within the next few decades. Preparing for such journeys will require testing equipment and technologies on the Moon that will be scaled and adapted for Mars *and* sending equipment to Mars for exploration and testing before humans set foot on the surface [1]. These plans will be conducted in concert with the current long-term robotic exploration plans to answer scientific questions about the origin and history of the Martian body and the solar system. The development, testing and launching of Mars rotorcraft technologies must now be factored into those plans.

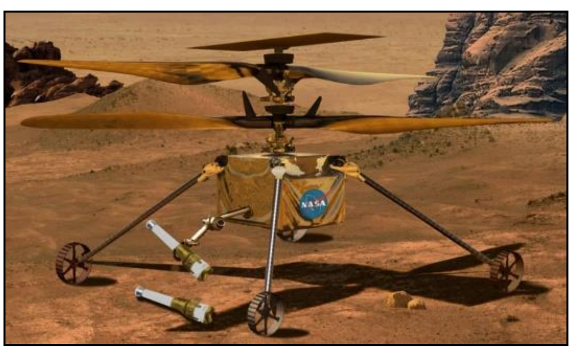

Figure 11: Model of SRH concept. Credits: NASA/JPL-Caltech

Mars Rotorcraft Advantages

For the surface exploration of Mars, rovers and landers have been the primary platforms utilized. However, these surface-locked vehicles have lacked movement flexibility and range due to constraints in the vehicles' design and the harsh Martian geography. These constraints on wheeled robots have motivated the efforts to develop powered flight technologies for the red planet [2]. Rotorcraft platforms offer three critical advantages over conventional landed assets:

1) Range and Reach: Compared to a rover, a rotorcraft significantly extends the geographic range of potential science investigations and increases the number of science targets that can be visited. Present-day rovers rarely drive more than 100 m/sol, likely requiring several years to travel 25 km, assuming the rover will have a relatively straight path with minimal detours due to terrain features. Hypothetically, a small helicopter could reach a 25 km destination within one or two months, assuming a conservative estimate of 1km/flight and <1 flight/sol, facilitating investigations spanning 100+ km across the Martian surface over a mission life. [5]

2) High Mobility in Hazardous Terrain: Rotorcraft could travel to regions inaccessible to rovers and landers. Surface types, steep elevation changes and other terrain hazards heavily restrict a rover's ability to move. Aerial vehicles can bypass impassable terrain and access most slopes, including vertical cliffs and overhangs. Potentially rotorcraft could access steep slopes made of bedrock strata, enabling measurements of time sequences of geological, geochemical, and physical processes on Mars. No longer being restricted to surfaces traversable by rovers allows exploration of new locations and features, such as subsurface cavities with openings to the surface (e.g., lava tubes, etc.). [6]

3) Planetary Boundary Layer Access: Rotorcraft enable repeated in situ measurements of the Martian atmospheric boundary layer, which extends ~5–10 km above the surface. Previously landed assets could not directly measure atmospheric properties greater than ~2 m above the local surface. Previous measurements relied on less accurate orbital assets and limited sampling during different lander and rover deployment's short entry-descent-landing (EDL) phases. Rotorcraft could extend vertical access > 5 km enabling the regional

characterization of the atmospheric boundary layer and broader measurement of vertical and lateral profiles of temperature, pressure, windspeed, dust, water, and other atmospheric content and characteristics over seasonal baselines [7].

<u>Review of Mars Helicopter Designs</u>

Ingenuity was part of the Mars 2020 mission as a "Technology Demonstrator" (i.e., no scientific instruments hosted or science objectives planned) for extraterrestrial flight whose mission was to execute up to five flights on the surface of Mars within 30 sols (i.e., Martian days) [11]. Figure 3 shows diagrams of its deployment from the Perseverance Rover and a view of some of its major subsystems. In addition to the helicopter deployment system, Perseverance had a permanently attached Helicopter Base Station (HBS) that acts as a relay between the Rover and the

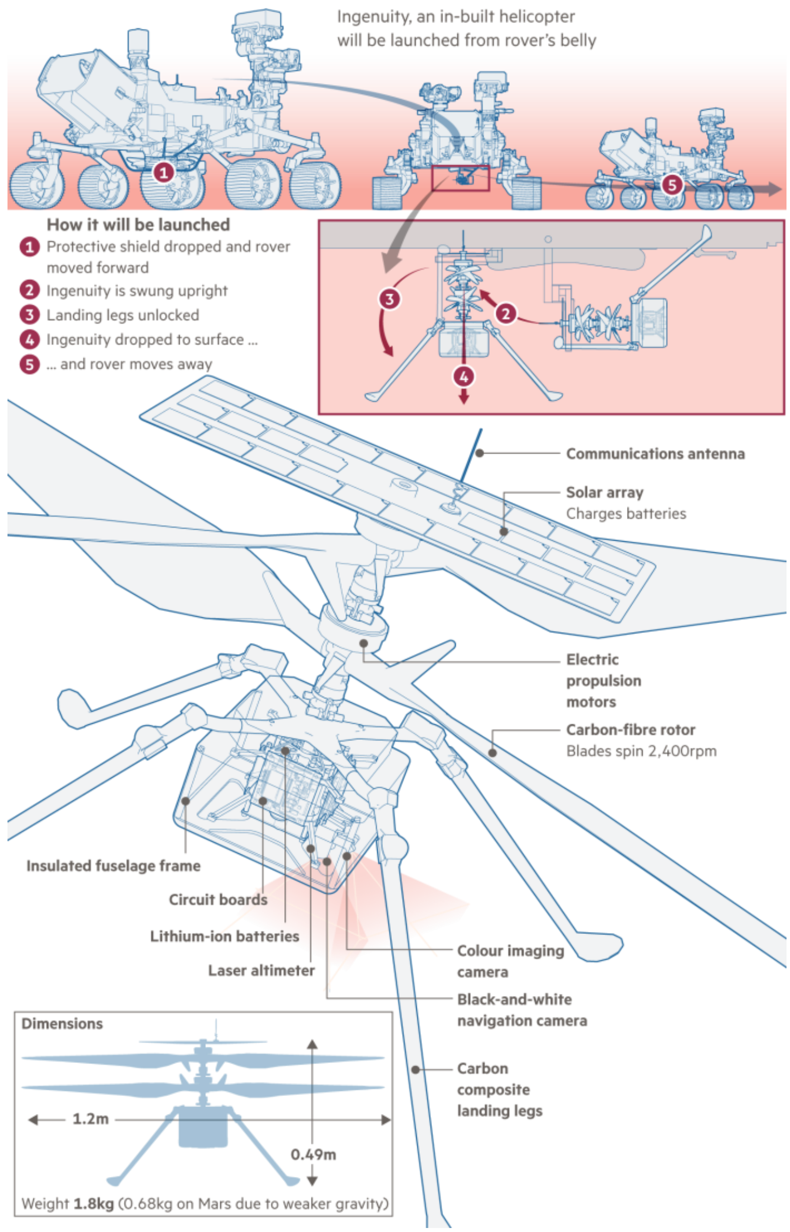

Figure 12: Diagram of Ingenuity and the Mars 2020 mission. Artist Ian Bolt, Image from Financial Times [11]

Ingenuity. Before deployment, the HBS also charges the helicopter's batteries.

With a total mass of ~1.8 kg, Ingenuity utilizes two counter-rotating coaxial rotors diameter of ~1.21 meters. Two direct-drive brushless DC propulsion motors drive the rotors. To reduce weight and maintain structural integrity, the rotor blades were built using a molded foam-core composite structure; bi-directional carbon fiber was cured around a machined foam core, yielding blades that weigh only about 28g each. Above the rotors is a solar array used to charge the battery system. The landing gear consists of four carbon-fiber legs oriented diagonally from the top of the airframe, offering a large footprint for stable takeoff and landing maneuvers. Titanium and aluminum flexures at the top of each leg offer suspension during landing [17].

Figure 13: Independent Views of Ingenuity's 6-cell Li-Ion Battery Pack with BIB (left) and Helicopter Avionics Assembly of FFB, NSB, TCB and HPB (right) mounted on test stands. [2, 21]

Commercial off-the-shelf (COTS) electronics provide guidance, navigation, and control for Ingenuity. The avionics is composed of 5 Printed Circuit boards: The Battery Interface Board (BIB), the FPGA/Flight Controller Board (FFB), the NAV/Servo Controller Board (NSB), the Telecom Board (TCB) and the Helicopter Power Board (HPB). Ingenuity's battery pack comprises six Sony SE US18650 VTC4 high-power Li-Ion cells connected in series and charged from a solar panel above the helicopter's blades. The solar panel contains 3 strings of 10 (30 total) IMM4J cells with a total cell area of ~544 cm^2. Communication is achieved with the HBS system mounted on Perseverance via a ZigBee-based radio system with a small whip antenna mounted on the center of the solar panel. The Ingenuity Mars Helicopter used the JPL-developed, open-source F-Prime flight software framework [22]. Two Inertial Measurement Units (IMUs) 3-axis MEMS device and a single Inclinometer 2-axis MEMS device are used for speed and orientation estimation. A laser range finder (LRF) is used as an Altimeter. The Navigation or NAV camera is a global-shutter, nadir-pointing grayscale imaging sensor. Visual features are extracted from the images and tracked from frame to frame to provide a velocity estimate. Included is a Return to Earth (RTE) 13 MP color camera that is pointed horizontally for imaging during flights [32].

With Ingenuity's first flight on April 19, 2021, by February 16, 2023 (666 sols), it had flown 43 times, covering 8.829 km (5.486 mi) with a total flight time of 4344 sec (1:12:24). During these flights it reached a max altitude of 14m (46 ft) and flight speed of 5.50 m/s (12.3 mph). It also demonstrated a max single flight distance of 708.91 m (2,325.8 ft) and a flight duration of 169.5 s [21]. Still functioning at the time of this study's publication, Ingenuity's mission has evolved from a Technology Demonstration to an "Operations Demonstration" Where it is acting out valuable scientific aerial exploration scenarios both independently and in concert with the Perseverance Rover. Ingenuity's activities to date. Further discussion related to the development, operations and performance of Ingenuity can be found in [3, 17, 20, 21, 32].

Figure 14: Martian rotorcraft designs (left to right): MARV, GTMARS, MEUAV, VITAS, MVHE. [8]

Beyond Ingenuity, several research groups have researched different Mars rotorcraft design and configuration approaches in the last three decades, as discussed in [2, 3, 7, 8, 9]. Some of these concepts are visualized in Figures 5 and 6. However, alongside the design of Ingenuity, this study focuses and builds on the more mature conceptual designs that have extensively published their design studies, modeling approaches and prototype performance results.

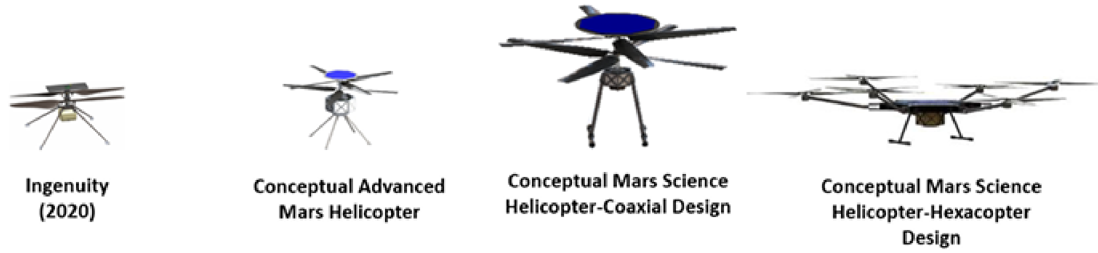

Figure 15: JPL and AMH Mars rotorcraft concepts in advanced design stages with Ingenuity for scale. [8]

These designs concepts include the work conducted by NASA Jet Propulsion Laboratory (JPL), NASA Ames Research Center (ARC), and AeroVironment, Inc on their Advanced Mars Helicopter (AMH) [10], Mars Science Helicopter/Hexacopter (MSH) [10], and Sample Fetch Helicopters (SFH aka Sample Recovery Helicopter (SRH)) [4]. The Japanese multi-university and JAXA Mars Vertical Hole Exploration (MVHE) Mission is also included in this study. Both the AMH and SFH represent iterated designs of Ingenuity, using as much of its flight heritage systems as possible with modest improvements to its sensors, avionics, composite structures, energy storage devices, larger solar arrays, and other improvements. The SFH itself is almost visually identical to Ingenuity apart from its payload (its robotic arm and wheel-based hybrid mobility system), which will enable the collection of sample tubes prepared by the Perseverance rover and deliver them to the Sample Retriever Lander as part of the Mars Sample Return Program [4]. The AMH was a joint study between NASA's JPL and ARC to develop critical technology for future generations of Mars rotorcraft. It also represents a craft that utilizes moderate technical improvements in a similarly sized package to Ingenuity to enable a science payload capability and increased hover time and range compared to Ingenuity [10]. The MSH study [8] aimed to investigate a rotorcraft capable of delivering scientific payloads in the 2-8kg range to previously unreachable areas of Mars. In the study, a rotorcraft was significantly scaled up from the current Ingenuity design, growing and changing the configuration from a co-axial rotor to a hex-multicopter design ~2.5-3m in diameter and weighing ~31kg. Scaling the coaxial configuration was considered and investigated in [8], but it was found that the large rotors of the scaled coaxial would require extensive material development or lightweight structure-dampening investments to reduce the dynamic contributions from the rotor flapping (to be discussed later in this study). The study focuses on three different configurations of the largest and highest-performance version of the MSH modeled [8]. All three designs and associated models can be considered high-fidelity, utilizing prototype measurements and verified using Ingenuity design knowledge and flight data.

The MVHE study investigated a rotorcraft designed to work with a rover to explore pit craters and certain caves [6]. As a result, specific mission objectives and performance needs differ from the JPL, ARC and AeroVironment-derived designs. In addition, the design calls for different components/subsystems crucial for its mission, such as lighting and proximity sensors, which are not considered for the other missions. Also, it does not have subsystems such as solar panels due to plans for it to be charged by its partner rover. However, it was found that the high fidelity of the published models and experiments (including on the potential aerodynamic performance of rotor blades [12]) made its inclusion valuable to this study.

Methodologies

The problem of the optimal allocation of a fixed investment budget among a portfolio of fundamental, multi-use technologies is extensive and beyond the scope of this paper. This study focuses on dividing these approaches into three broad steps. The first step is identifying the system-level areas of performance measurements and the benefits of improving the performance of its subsystems and accompanying systems. The second step is the summation of these performance-improvement potentials across several complex system architectures that share at least some accompanying systems and subsystems. Finally, methods for valuing these figures in relation to each other and other factors are conducted. This study aims to enable these approaches by providing high-level analysis and basic modeling foundations to build off. Greater information on these approaches can be found [13, 14, 15, 16]

Figures of Merit

Table 1 shows a list of Figures of Merits (FOMs) by which Mars Rotorcraft can be assessed. These FOM are the primary system-level variables to keep track of while modeling proposed technologies and calculating the potential return on investment (ROI). The FOM were selected based on criteria discovered in the following areas:

a) Information known to be inherent to designing structures and rotorcraft operating in the Martian Atmosphere.
b) Significant and repeated design variables discovered during the literature review and accounts of the Mars rotorcraft developments from JPL and AeroVironment.
c) Variables from high-fidelity parametric models performed by JPL and AeroVironment.
d) Parametric technical models based on other engineering properties.

The first 6 FOM in Table 1 are used to assess the rotorcraft at the system level. They are very similar to FOMs used to compare Earth-based aircraft, the difference being instead of being used to estimate flight performance and potential costs, they are used to estimate science return. Further investigations into return are investigated in Section IV. Rows 7 and beyond represent primary FOMs that are direct flight performance measurements and are provided as outputs from lower-level subsystem or component-level performance.

Table 2: Figures of Merit for Rotorcraft FOM

FOM	Units	Descriptions	Explanation/Notes
Payload Weight ($m_{payload}$)	*kg*	**The total mass of science instruments, excess materials, and other experimental**	**Identified as the most significant value to estimate a platform's scientific or engineering testing return potential. With greater payload mass potential proportional to the number, sensitivity, and reliability of**

		systems the craft can carry.	**the science instruments or experimental systems that can be carried.**
Gross Weight (m_{total})	kg	**The total mass of craft**	**Used as the leading indicator of total mission cost as there are not enough data or relevant models to capture costs accurately at the time of this study.**
Mission Life	$Sols$	**Number of Martian days a Platform can survive and conduct a mission**	**Used to measure the total distance potential a platform can travel over its mission life and the corresponding potential for exploration.**
Flights Per Sol (F_{sol})	$\frac{1}{sol}$	**The nominal average number of flights per Martian day**	**Flights can be constrained by performance variables such as thermal dissipation and power availability or operational constraints such as autonomous decision-making capability or communication opportunities.**
Range (R)	km	**Max distance from the takeoff site to the landing site**	**Max theoretical range and hover time are inversely proportional, but other factors like max cruise speed can limit the range.**
Hover Time (t_{hover})	s	**Max time the craft is airborne**	**Max theoretical hover time and range are inherently inversely proportional**
Cruise Speed (V_{cruise})	m/s	Max ground speed of the craft	So far, max cruise speed is expected to be constrained by sensor and software capabilities, not aerodynamic or power limitations.
Battery Specific Energy ($E_{battery}$)	$\frac{Whr}{kg}$	energy per unit mass stored by the battery	The battery capacity of the rotorcraft will be a function of how light the batteries are and how much mass can be given over to the batteries
Survival Heater Energy ($E_{survival}$)	$\frac{Whr}{sol}$	The Energy, the Thermal Control System, consumes per sol	Based on the energy needed to keep critical Electronic assemblies and batteries.
Motor Efficiency (η_{motor})	#	The overall flight efficiency of the motor and direct drive gearing/transmission	The efficiency of an electric motor changes with RPM, and loading can be averaged for operating conditions.
Flight Power (P_{flight})	W	Actual power consumed by the rotorcraft in flight	Power is primarily consumed by the rotor motor and control systems and avionics. The motor efficiency largely dictates the overall efficiency of the craft flight as drag is a relatively minor consideration in the thin atmosphere of Mars. Geared systems could allow motor efficiency increases and reduction in mass.
Rotor Figure of Merit (FM)	#	The ratio of ideal power and actual power required for a hovering rotor.	The exact value depends on rotor speed and changes with rotor pitch and orientation but is typically represented by the value at hover conditions.

Solar Array Specific Energy (E_{solar})	$\frac{Whr}{kg}$	The amount of power the Electrical Energy System can generate per kg	Current designs are single solar panels mounted with many solar cells. Deployment systems could enable more panels at the expense of added mass

Martian Environment

Table 3: Comparison of conditions on Earth and Mars

	Units	**Earth Values**	**Mars Values**
Atmospheric Density (ρ)	kg/m^3	1.225	0.01 to 0.02
Speed of Sound, (a)	m/s	~343	~233.1
Reynolds number, (Re)	#	~1,297,000	10,000 to 25,000
Max Rotor Tip speed (Mach number = 0.7, chord = 0.1 m)	m/s	238	163
Gravity (g)	m/s^2	9.807	3.721

The Martian environment imposes many challenges to achieve controlled atmospheric flight but is dominated by the extremely low density of the Martian atmosphere. Table 2 compares some of the characteristics of Earth and Mars that affect an aircraft's flight performance. The thin atmosphere (approximately 1% of that on Earth's) reduces the lift per blade area produced by a rotor. Because of the low density, the Reynolds numbers (Re) of airfoils on rotors designed for Martian operations are between 10000 to 25000, significantly impacting airfoil behavior. Low Reynolds numbers reduce the maximum lift coefficient and increase the drag coefficient of airfoils. Additionally, the corresponding lower speed of sound on Mars reduces the maximum possible tip speed of a rotor restricting its design as 0.7-0.9 tend to be the highest practical tip speed for efficient hovering [3,6].

As a result of the low atmospheric density and average temperature, low Reynolds number (Re) and high subsonic Mach numbers (M) coincide during rotorcraft flight on Mars. This unique flow combination is not encountered by rotorcraft during Earth-based flight. Leading to an optimum airfoil shape that is much different from Earth's. Studies [26, 27, 28] summarize the information available to support the selection of airfoils for a future Mars helicopter. It can be generalized that when considering aerodynamic efficiency, the need for mars helicopter rotors to be as thin as possible is much greater than their earth equivalents.

The Martian environment is also frigid, with Ingenuity's operating (flight) temperatures ranging from -40 to 80 °C and non-operating (grounded) temperatures ranging from -110 to 100 °C in the Jezero Crater region [3]. In combination with low air density, these extreme temperature limits and corresponding swings make thermal control of top concern and a complex engineering challenge to overcome. These challenges drive both the mass and the power requirements of the thermal control system.

Literature Review

A review of available literature for Ingenuity and detailed design concepts and discussions with the developers of Ingenuity was conducted to determine what areas of development would be most valuable (and what areas are currently being investigated) according to the lessons learned during these efforts. These lessons learned and solutions proposed or being investigated are summarized.

Ultralightweight rotors and vehicle hardware is the most significant enabler for successful Mars rotorcraft. Ingenuity was severely mass-constrained and only marginally power/energy constrained [3]. In fact, the specific power required to fly on Mars is similar to Earth drones [3,4]. As such, the structural mass fraction of any Mars rotorcraft will be significantly higher than Earth drones. With batteries, electronics and other subsystems representing smaller percentages of the gross weight of a Mars rotorcraft [8].

Efforts are ongoing to improve rotor performance for the low Reynolds compressible regime, and steady progress has been made. In the early 2000s, a hovering Figure of Merit (FM), or hover efficiency, of 0.40 was achievable. Fifteen years later, Ingenuity achieved FM in the

0.55 - 0.60 range. Modeling efforts show that FM > 0.60 may be feasible, and a broader range of operating thrust coefficients is possible while maximizing FM. [26]

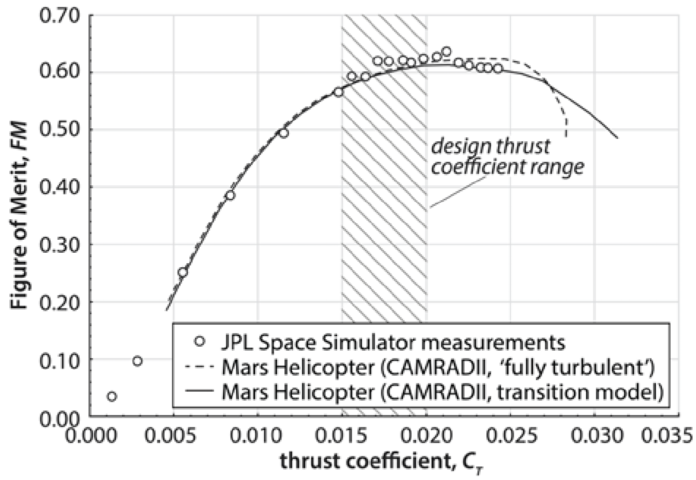

Figure 16: Hover FM of Ingenuity [8]

All optimized rotor system designs compromise structural/mass and aerodynamic efficiencies in both Earth and Mars applications. Still, the MSH and SRH models show the limited impact of aerodynamic efficiency improvements from the Ingenuity baseline compared to the far more impactful weight reduction results on the identified FOM. Due to the low air density of the Martian Atmosphere, aerodynamic loads were not significant contributors to the limiting load cases of the rotors or various structures on Ingenuity. For Ingenuity and other concept designs, the launch loads (up to 60 g's) and stiffness needs from rotation-induced flapping dominated structural design requirements rotors [3, 5, 8]. On Earth, these flapping modes are dampened naturally due to viscous air forces. However, on Mars, the low air density exaggerates modes from the flapping motion and can cause the vehicle to become unstable. Therefore, low-density, high-strength and high-modulus (high stiffness) materials are crucial to meeting inertial and dynamic loading dynamic forces. This need is expected to hold for up-sized rotors. [8, 19, 24]

The performance of Mars rotorcraft are particularly sensitive to the overall mass of the rotor blades. The study [24] shows that Mars rotor blades must weigh roughly 10 to 14 % of their equivalently sized terrestrial rotor blades. Therefore, ultra-lightweight blades are an essential design requirement for Mars rotorcraft, given the relatively large blade surface area, rotor radii and high RPM necessary to provide adequate lift to operate in Mars' thin atmosphere. For the rotors of the studied missions, the percent mass contribution of the rotor blades to the vehicle's gross mass ranges from ~10-30%.

Additionally, launch loads and centrifugal loading on the rotating hardware (rotor, hub, and control systems) increase with the size and weight of the rotor blade. The weight trends of the rotating hardware also exponentially increase with rotor length. Therefore, control system mass increases with rotor length may dictate the pursuit of alternate control systems than the servo-controlled collective/cyclic pitch link and swashplate architectures currently proposed. Architectures such as embedded Servo-Flaps and Actuators might provide a lower mass solution [4, 24].

Thermal design limits flight time and drives mass. Ingenuity's maximum flight endurance is limited by two factors: 1) the inefficient convective cooling on the surface of Mars due to the low density of the atmosphere and 2) the rise in temperature of the propulsion motor's stator due to inefficiencies during flight. Because Ingenuity doesn't have a means to directly measure temperature at the stator, a conservative flight time limit was set based on direct measurements of the initial temperature from the thermometer on the motor driver and a finite element thermal model of the motor. Additionally, the thermal control system uses over 60% of Ingenuity's energy budget to keep the helicopter's components and subsystems within allowable survival temperatures, especially during the frigid Martian nights [3]. Therefore, Sol activities, including flights and communications with the Rover, had to be planned considering battery state of charge, solar panel energy production, survival energy consumption and an activity's energy cost. Because of the limited energy budget, Ingenuity's surface operations required high-fidelity modeling for energy consumption and components temperature prediction.

Analysis of Existing Models

To study the relationship between hover time and payload to different design variables, both studies published for the SFH [4] and MSH [8] showed parametric relationships between various design variables and the FOM. The results from these studies helped determine the FOM for this study.

Table 4: SFH Simplified Sensitivity Analysis [4]

	Hover Time Sensitivity	Payload Sensitivity
Battery Energy Density	0.0262	0.0136
Rotor Diameter	0.027	0.0116
Figure of Merit	0.027	0.0116
Motor Efficiency	0.0352	0.0159
Empty Mass Fraction	-0.1245	-0.0614

Table 3 shows the outcome of a normalized sensitivity analysis (where a 1% change in the input variable results in the percent change shown) in [4] for a baseline SFH design. More info on the design assumptions for the analysis can be found in [4]. Its performance was based on the measured mass fractions and performance from Ingenuity and assumed a total mass constant at 2.0 kg and a nominal payload mass of 0.2 kg. The "Empty mass fraction" included all components except batteries, motors, and solar array, which are proportional to the power needed to fly. There are several key takeaways from [4] 's analysis. The first is that rotorcraft are severely mass-constrained, and lowering mass is crucial to increasing flight time and payload capacity. While not explicitly supported by the provided variables of the sensitivity analysis, [4] states that the battery mass is a tiny fraction of the total mass of the vehicle, and as a result, re-allocating a small percentage of the "empty mass" into the battery has a significant impact on both range and payload carrying capability, since the total mass was held constant. For these reasons, optimizing rotor and structural mass is paramount to increasing vehicle capability. While a distant second to mass, the sensitivity analysis reveals motor efficiency has a relatively high impact on range and payload performance. This is primarily due to the mass of the motor being directly inversely correlated to the power losses due to inefficiencies since the mass required to absorb waste heat is much larger than an equivalent motor operating in an Earth atmosphere.

As published in [8], the MSH design was developed using the rotorcraft design and analysis code NASA Design and Analysis of Rotorcraft (NDARC) developed by NASA AIM. NDARC has detailed performance models of the rotor, battery, motor, and other components, with the ability to include mission parameters in its analysis. The rotor performance model was calibrated from CAMRAD II calculations of hover and forward flight performance for the optimized rotors. In addition, weight models were calibrated to the actual weights of the Mars Helicopter [8].

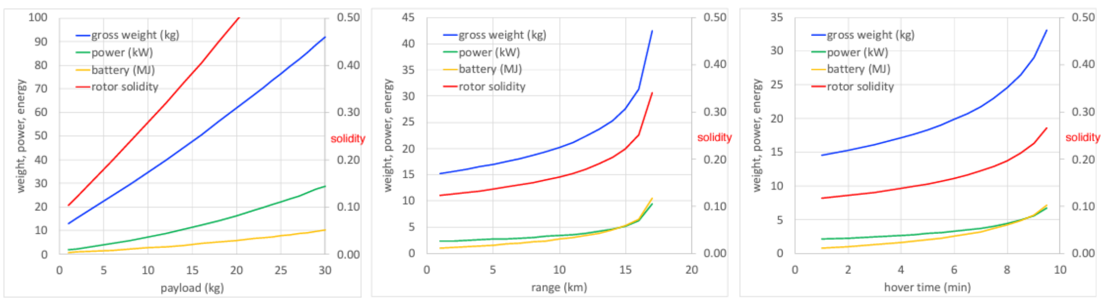

Figure 17: Influence of mission requirement on MSH Hexacopter size [8]

There are several key takeaways from the various analysis done by [8] and shown in Figure 8. First, the growth factor or d(gross weight)/d(payload) is 2.5, which is within the typical range of values for well-designed Earth-based helicopters and indicates a robust design. Second, the large solidity, σ (function of the aspect ratio and the number of blades in the rotor), implies large disk loading (the average pressure changes across an actuator disk), hence high hover power and low-aspect-ratio blades. A solidity value of 0.25 would be considered large for Earth-based rotors, thus sufficient for a Mars Helicopter. Third, the cruising speed of the Ingenuity is much lower than that of the MSH entirely due to the limitations of the craft's visual navigation system. It was assumed that the proposed navigation system of the MSH could support flight speeds up to 50 m/sec. While flying faster (the best range speed was above 50 m/sec) would reduce the cruise power, this efficiency impact on the overall aircraft's size and performance is negligible.

Other Technical Model Approaches

Design Structure Matrix Allocation

The Design Structure Matrix (DSM) shown in Figure 9 below represents the various interdependencies of the major subsystems of the Mars Helicopter subsystems and significant support systems of the entry, descent, and landing (EDL) and Mars Transfer Vehicle (MTV). The MTV is the spacecraft that hosts the EDL and Mars Helicopter from its separation from the launch vehicle and guides then releases them into the Martian atmosphere. The matrix shows which connections are physical, informatically, or whether they transmit energy (including mechanical, electrical, thermal) or mass. Each link in the matrix may have more than one form of interdependency.

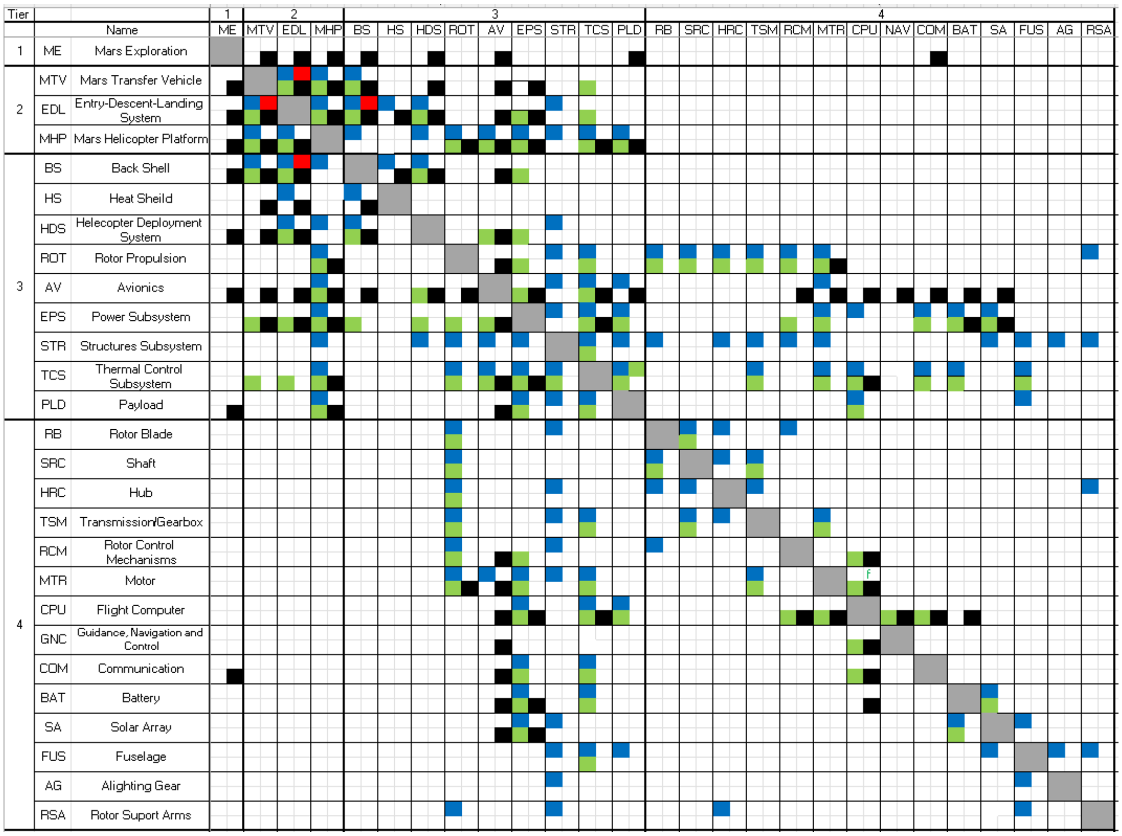

Figure 18: Design Structure Matrix. Blue represents a physical connection, Black is an information flow, Green is an energy flow, and Red represents a mass flow.

Model Equations

Using the inferences and parametric performance equation from the studies included in the literature review (especially [8, 10, 24]) and those generalized for drone and space vehicle performances (including [30, 31]), parametric relationships for the significant FOM were developed. These attempt to capture some of the complex interrelations dictating subsystem performance. Many FOM values can be found by multiple parametric equations since there can be multiple "Limiting Factors" that can act as a theoretical cap on the ultimate performance of a Mars Helicopter. This study focuses on the Limiting Factors defined by the availability of

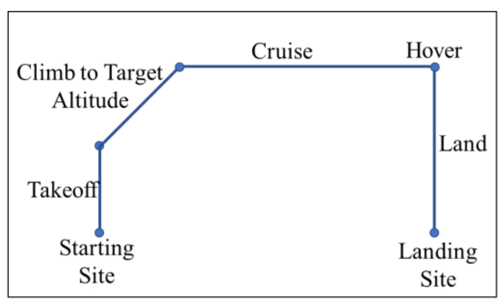

Figure 19: Generalized Flight Profile of a Mars Rotorcraft

energy in the form of battery storage and solar power generated and that of the control of the thermal. Generally, the actual value of the FOM being calculated will be equal to or less than the smallest value produced by the set of parametric equations. Figure 10 shows the typical flight profile represented in the parametric equations and generally that of the proposed missions examined with this study (with MVHE significantly deviating from this flight model). For this study, many simplifications to factors such as drag are made. Also, differences in specific performance figures for different speeds and flight segments (such as takeoff, climb, cruise and landing) and others are ignored. See Table 1 for the FOM and Table 2 for the atmospheric parameter's nomenclature.

The high-level FoM, Flights per sol, and its relations to subsystem performance can be estimated with the following relations:

$$Flights\ Per\ Sol\left(\frac{Flight}{sol}\right)$$

$$= \min_F \begin{cases} F = \dfrac{24.6583\left(\frac{hr}{sol}\right)}{t_{battery\ flight\ time}(hr) + t_{recharge}(hr)} & \text{Energy Limiting Factor} \\ F = \dfrac{24.6583\ \left(\frac{hr}{sol}\right)}{2 * t_{motor\ heating}(hr)} & \text{Thermal Limiting Factor} \end{cases}$$

$$t_{battery\ flight\ time}(hr)$$

$$= \frac{E_{battery}\left(\frac{Whr}{kg}\right) * m_{battery}(kg) * BSC_{min} - \sum_n (DC_n * E_n)\ (Whr) - \dfrac{E_{Survival}\left(\frac{Whr}{sol}\right)}{24.6583\ \left(\frac{1}{sol}\right)}}{P_{flight}\ (W)}$$

$$t_{recharge\ time}(hr)$$

$$= \frac{\left(1 - \ E_{battery}\left(\frac{Whr}{kg}\right) * m_{battery}(kg) * BSC_{min}\right) - \sum_n (DC_n * E_n)\ (Whr) - \dfrac{E_{Survival}\left(\frac{Whr}{sol}\right)}{24.6583\ \left(\frac{1}{sol}\right)}}{\mathrm{E}_{solar}\left(\frac{W}{kg}\right) * m_{solar}(kg)}$$

$$P_{flight} = FM * P_{ideal}$$

BSC_{min} is the minimum battery state of charge fraction, n is the number of power drawing subsystems, DC_n is the Duty Cycle of the subsystem n during 1 sol, and E_n is the energy consumed by subsystem n. Finally, P_{flight} is the actual power required to fly and is related to the ideal input power, $P_{ideal,}$ and overall flight efficiency, η_f (including transmission and electronic losses). While P_{flight} is not strictly directly correlated to a craft's FM, for the purpose of this study, it is assumed that the FM for forward flight and other conditions is near constant.

$$t_{motor\ heating}(hr) = \frac{C_m\left(\frac{Whr}{°\mathrm{C} * kg}\right) * m_{motor}\ (kg) * \left(T_{motor\ max}(°\mathrm{C}) - T_{flight}(°\mathrm{C})\right)}{P_{motor\ heat}(W) + P_{in}(W) - P_{Control}(W)}$$

$t_{motor\ heating}$ is the time the motor takes to reach the max temperature, $T_{motor\ max}$, the motor can get to avoid damage or degraded performance from the nominal temperature, T_{flight}, the motor should be before a flight. The value in this simplified form equals the time it takes the motor to cool from $T_{motor\ max}$ to T_{flight}. C_m is the heat capacity of the motor component. P_{motor} is the heat power generated by the motor during flight. $P_{control}$ is the heat power rejected, absorbed, or otherwise removed by the Thermal Control System. P_{in} max heat was added to the motor from other subsystems and the Martian environment. The heat power generated from the motor can be assumed to relate to the overall efficiency of the motor and the electrical power consumed by the motor P_{motor}:

$$P_{motor\ heat}(W) = \left(1 - \eta_{motor}\right) * P_{motor}$$

The Significant FOMs Hover Time and Range are found using equations:

$$Hover\ time(s) = t_{hover} = \min_t \begin{cases} t_{motor\ heating}(hr) * 60\left(\frac{s}{hr}\right) & \text{Thermal Limiting Factor} \\ t_{battery\ flight\ time}(hr) * 60\left(\frac{s}{hr}\right) & \text{Energy Limiting Factor} \end{cases}$$

$$Range\ (m) = \min_R \begin{cases} R = (E_{battery}) * \eta_f * \frac{L}{D} * \frac{1}{g_{mars}} \frac{m_{battery}}{m_{total}} & \text{Breguet Range Equation} \\ R = V_{cruise}\ \left(\frac{m}{s}\right) * \left(t_{motor\ heating}(hr)\right) * 60\left(\frac{s}{hr}\right) & \text{Thermal Limiting Factor} \\ R = V_{cruise}\ \left(\frac{m}{s}\right) * \left(t_{battery\ flight\ time}(hr)\right) * 60\left(\frac{s}{hr}\right) & \text{Energy Limiting Factor} \end{cases}$$

For the Breguet Range Equation for Electric Aircraft [30], η_f is overall flight efficiency L/D is the Lift to Drag ratio.

Establishing an accurate model for the cruising speed of a Mars Rotorcraft is difficult given the number of factors involved and the limited work on the subject that has been done. The designs examined for this study primarily assigned cruising speed as the max speed sensing capability of baselined avionics systems [3, 4, 7, 8]. No analysis provided subsystem performance relationships to cruising speed. As such, the cruising speed relations modeled for this study is a highly generalized equation attempting to capture speeds limited by the max distance a rotorcraft avionics system can react to hazards and land in a ballistic trajectory:

$$Cruising\ Speed\ \left(\frac{m}{s}\right) = V_{cruise} = \frac{S(m)}{\sqrt{\frac{2 * (A(m))}{g_{mars}\left(\frac{m}{s^2}\right)}}}$$

Where S is the max distance the navigation system can detect and react to an obstacle if the craft needs to abort a flight and land, and A is the average cruising altitude of the rotorcraft. For a light-based detection sensor, the S is a function of the speed and frequency of the light the sensor use and the size of and distance from potential hazards. It is also limited by the processing speed and method of the flight computer.

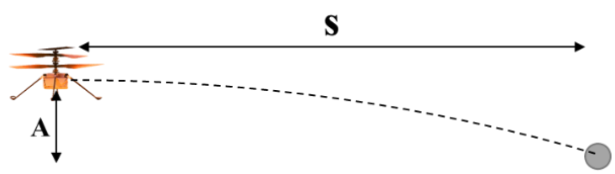

Figure 20: Diagram of sensor detection distance

For estimating the Solar Array Specific Energy Density, the ratio of the power to mass densities of the solar array is used:

$$\mathrm{E}_{solar}\left(\frac{W}{kg}\right) = \frac{Solar\ Power\ Density\ \left(\frac{W}{m^2}\right)}{Solar\ Weight\ Density\ \left(\frac{kg}{m^2}\right)}$$

The power density of the array is a function of the efficiency, number, and area of the solar cells and the solar flux that they can absorb divided by the total surface area of the solar array:

$$Solar\ Power\ Density\left(\frac{W}{m^2}\right) = \frac{\#\ of\ Cells * \eta_{solar\ cell} * Solar\ Flux_{Mars\ avg}\left(\frac{W}{m^2}\right) * Cell\ Area(m^2)}{Solar\ Array\ Area\ (m^2)}$$

The solar array weight density is a function of the number and mass of the cells and panels making up the array as well as the support structure and deployment mechanism is divided by the total surface area of the solar array:

$$Solar\ Weight\ Density\left(\frac{kg}{m^2}\right) = \frac{\#\ of\ Cells * m_{cell}\ (kg) + \#\ of\ Panels * m_{panels}\ (kg) + m_{deployment\ mechanisms}\ (kg) + m_{structure}\ (kg)}{Solar\ Array\ Area\ (m^2)}$$

Valuing Results

Performance Trajectories

Table 4 shows the FOM values that could be identified from Ingenuity and the design studies included in the study [3, 4, 5, 8, 10]. These are used to baseline the expected performance metrics of current and planned Mars Rotorcraft.

Table 5: Mars Rotorcraft Performance. Design maturities are ordered left to right from most to least columns. N/A is for Not Available or Not Relevant to the specified design.

		Ingenuity (Flight)	**SFH**	**AMH**	**MSR 1**	**MSR 2**	**MSR 3**	**MVHE**
Payload Weight	***kg***	**0**	**0.28**	**1.3**	**8**	**5**	**2**	**64.3**
Gross Weight	***kg***	**1.8**	**1.92**	**4.6**	**31.2**	**31.2**	**31.2**	**10.7**
Empty Weight	***kg***	**1.8**	**1.64**	**2**	**23.2**	**26.2**	**29.2**	**4.7**
Mission Life	***Sols***	**Plan: <30 Flight as of 1/1/23: 603**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**

Flights Per Sol	***1/sol***	**Plan: 0.167 Flight: <0.1**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**N/A**
Hover Time	***min***	**2.825**	**6**	**2**	**3.2**	**9.6**	**16**	**7**
Max Range	***km***	**0.781**	**5**	**2**	**1.5**	**4.7**	**7.8**	**0.1**
Cruise Speed	*m/s*	5.5	15	30	30	30	30	9
Battery Energy Density	*Whr/kg*	173	220	173	260	260	260	98
Survival Heater Energy	*Whr/sol*	29	29	N/A	47.2	47.2	47.2	N/A
Motor Efficiency	*%*	87.5	88.8	N/A	90	90	90	80
Figure of Merit	*#*	~0.58	0.6	0.62	0.615	0.615	0.615	N/A
Solar Array Power Density	*W/kg*	10.95	N/A	10.95	10.95	10.95	10.95	N/A

An essential part of determining the value of a development effort is to determine if its impacts on identified FOM are realistic. This study uses the design concepts to build out a set of expectations for FOM, given the maturity of the designs used. The designs were separated into three categories of maturity:

1) "Flight Designs" that have been developed and flown. This category is made up solely of Ingenuity as the only rotorcraft flown on Mars by the time of this study.
2) "Iterated Design Concepts" represent designs based on Ingenuity leveraging a sizable portion of its systems and whose models have limited scaling of Ingenuity measured parameters. These are the SFH from AeroVironment and the NASA ARC and JPL AMH concept. Some of the design changes for these concepts have been prototyped.
3) "Advanced Design Concepts" have higher performance targets and represent larger rotorcraft. The performance figures are taken from the MVHE and MSH study [8], where the three payload mass configurations were modeled for the Hexacopter design. Note that MVHE is an outlier for range due to its mission requirements only calling for short-distance flights into caverns. As a result, it has several FOM values not limited by hardware or software constraints but by lower mission requirements.

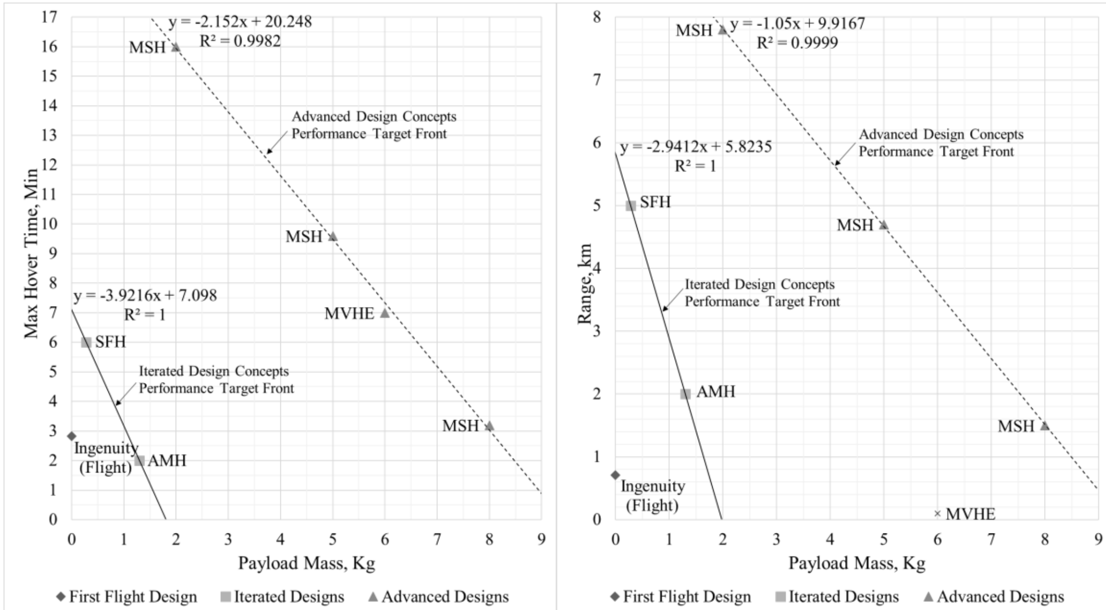

Figure 21: Hover Time and Range to Payload Mass Capacity for Mars Rotorcraft

In Figure 12, the graph shows the best relationship between the max hover time and range to the max payload of the rotorcraft designs. The performance figures form two Pareto fronts from the Iterated (solid black) and Advanced design (dashed back) Concepts. From Ingenuity performance to the Iterated Designs, the Advanced Designs all show Pareto fronts are shifting toward the top right of the chart.

Using the Pareto Shift Model [16], as demonstrated in Figure 13, potential FOM capabilities (or possibly needs) can be evaluated by the shift's direction and magnitude. In the case of range and hover time to the max payload, they can be separated by how mature the designs are. Further, the areas between can be viewed as FOM targets based on the development schedules of the proposed technology. If the FOM shift falls into the area below the Iterated Designs front, it can be viewed as having limited value and represents a performance target

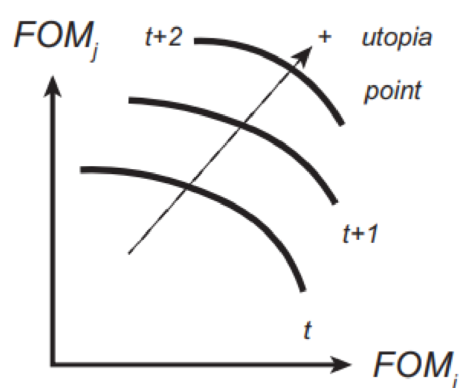

Figure 22: Technology progression modeled as a shift in the Pareto front FOM_i to FOM_j over time. [15]

enabled by current technologies. If the FOM shift falls between the Iterated and the Advanced Designs Pareto front, it can be considered a valuable mid to long-term investment. If the shift falls near the Advanced Designs, the development can be viewed as valuable long term or even transformative if the technology can be developed in the short term. Then finally, if a shift falls far beyond the Advanced Design front, the rationale or calculations behind the technology's expected performance increase might deserve further scrutiny as the technology could have an unreasonable performance expectation.

However, it is essential to note that the Pareto Shift Model is not suitable for all FOM evaluations. Some performance metrics can be restricted by considerations other than their relationship to other identified FOM. For example, the Cruise Speed for the missions studied, as graphed in Figure 14, while theoretically tied to a rotorcraft's payload and gross masses, is primarily limited by the capability of their sensors and their navigation and control systems. However, at first glance, the graph of the values looks as if they may form two Pareto fronts shifting towards the top of the chart. As such, the context of any FOM should be noted and considered when comparing improvements to existing designs.

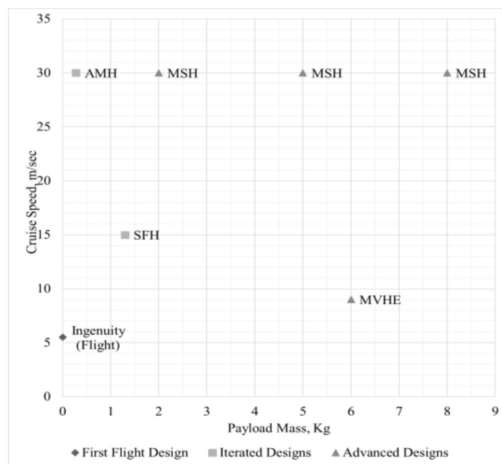

Figure 23: Cruise Speed to Payload Mass.

Table 5 shows the values or ranges of the different FOM in each design category. These figures are relatively independent of other FOM. However, they may be linked if further analysis is conducted. Similar mission design requirements may also affect other FOM. For example, the SFH, AMH and MSH all only require 1 flight every 2 sols. Thus, performance does not increase across the categories. However, increasing the Flights per Sol is a straightforward way to increase the ROI of a mission, so designs should strive to improve it. Some FoM also may not form Pareto Fronts as the advanced design may not have used higher performance systems than less advanced designs. For example, the AMH and MSH use Solar Arrays with the same Solar Array Power Density as Ingenuity. Also, the MVHE concept uses a motor assumed to be ~7.5% less efficient than Ingenuity.

Table 6: Performance Ranges for some non-Pareto Front forming FOM.

FOM	Units	Ingenuity (Flight)	Iterative Designs	Advanced Designs
Cruise Speed	*m/s*	5.5	15-30	>30
Battery Energy Density	*Whr/kg*	173	220	>260
Motor Efficiency	*%*	87.5	88-89	>90
Hover Efficiency (FM)	*#*	0.58	0.58-0.61	>0.61

It is acknowledged that while the limited data set of this study inherently limits the strength of any trends it may identify, it is important to note that most designs represented are from the organizations that developed Ingenuity and based their studies on its range and hover time performance [3, 21]. Also note that as concepts, the performance specifications from such designs are subject to change in the future as further design work increases the fidelity of performance targets. However, due to the rigorous nature of their development, they represent valid performance targets in the context of this study.

Alignment with Strategic Drivers

Linking specific system-level FOM to specific organizational objectives can be used to validate specific investments [16]. NASA's Space Technology Mission Directorate (STMD) organizes the agency's technology investments into the Strategic Framework to address its desired outcomes through technology development. The Framework is comprised of 18 Capability Areas, grouped into four categories of investment called Thrusts: *GO* (Rapid, Safe, and Efficient Space Transportation), *LAND* (Expanded Access to Diverse Surface Destinations), *LIVE* (Sustainable Living and Working Farther from Earth), and *EXPLORE* (Transformative Missions and Discoveries). Each of the 18 Capability Areas has a stated objective that works well as a strategic driver for our analysis. Strategic Targets where relevance is inferred from the capability targets, investments listed, or directly stated in the Capability Area overview on the NASA Tech Portal Framework [29]. Table 6 shows the strategic alignment to the Capability Areas with comparatively high and middle alignment to the FOM and critical subsystems identified in this study. No and Low alignment areas are excluded from the table. The Alignment score (High or Medium) and notes on why it is ranked such are listed in column 4.

Table 7: Strategic Alignment to NASA STMD Strategic Framework

Capability Areas	**Objective/Strategic Driver**	**Alignment**
LAND: Precision Landing and Hazard Avoidance	Develop capabilities to enable lighting-independent precise landing on any terrain.	**High** alignment to speed control avionics.
LAND: EDL to Enable Planetary Science Missions	Develop capabilities enabling small to large missions to efficiently enter any atmosphere within our solar system.	**Medium** alignment to hovering efficiency and thermal performance analysis
LIVE: In-Situ Resource Utilization (ISRU)	Develop scalable ISRU production/utilization capabilities, including sustainable commodities on the lunar and Mars surface.	**Medium** alignment. Enabling platform for ISRU resource scouting.
LIVE: Power and Energy Storage Systems	Develop sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.	**High** alignment to the range, mass and solar and battery specific energy.
LIVE: Thermal Management Systems	Develop thermal management technologies that enable surviving the extreme lunar and Mars environments.	**High** alignment. Thermal control is a limiting factor for hover time and highly impacts mission life and risk.
LIVE: Excavation, Construction, and Outfitting	Develop methodologies for moving regolith for in-situ purposes such as commodities extraction and constructing infrastructure like landing pads and other structures using in-situ resources	**Medium** alignment to thermal control, avionics, and rotor propulsion systems.
EXPLORE: Advanced Avionics	Develop advanced avionics to meet agency objectives, including radiation-hardened spaceflight computing technologies.	**High** alignment to the avionics subsystem, risk, mission life, and cruise speed.

EXPLORE: Advanced Manufacturing	Develop both terrestrial and in-space manufacturing technologies to make commercial and exploration missions more capable and affordable.	**High** alignment to gross mass.
EXPLORE: Autonomous Systems and Robotics	Develop autonomy and robotics technologies that enable and enhance the full range of science and exploration missions.	**Medium** alignment to risk and cruise speed capability
EXPLORE: Communication and Navigation	Develop communication, navigation, and timing approaches to support diverse asset needs, including establishing asset location in space.	**High** alignment as risk and avionics
EXPLORE: Small Spacecraft Technologies	Develop technologies for small spacecraft and responsive launch to rapidly expand space capabilities at dramatically lower costs.	**Medium** alignment to risk and avionics

Return of Investment

A return on investment (ROI) model from [15] can be used with expected FOM increases and other parameters to get a qualitative value. The model, as shown in Figure 15, can be expressed as:

$$ROI\left(\frac{Value}{\$}\right) = Prob\ of\ Success$$

$$* \frac{\Delta FOM * \sum Alignment - \ Engineering\ risk}{R\&D\ Costs}$$

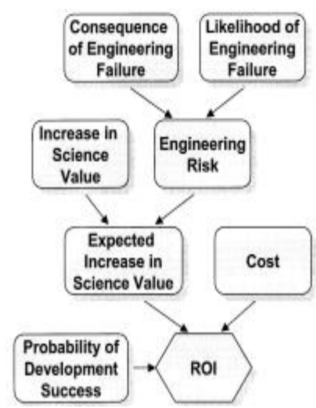

Figure 24: ROI Model [15]

The "Prob of Success" value is the 0-1 confidence assigned by the assessor that the development will likely meet the target ΔFOM value. For the "Increase in science value" in the ROI model, "ΔFOM*∑Alignment" is substituted to determine the numeral value added of a technology, where "ΔFOM" is the value of the change in the FOM being evaluated. Not for this comparison, all FOM should be normalized to each other. "Alignment" is the value related to the relative strength of the FOM to an identified alignment to a strategic driver (High-3, Medium-2, Low-1, and No Alignment-0). For technologies that have aligned to or span across multiple objective/strategic drivers (sometimes referred to as crosscutting technologies), sum the alignment scores, hence the “∑.” The “Engineering Risk” is the risk due to the technology’s use during a mission expressed as:

$$Engineering\ risk$$
$$= Consequence\ of\ engineering\ failure$$
$$*\ Likelihood\ of\ engineering\ failure$$

"Consequence of Engineering Failure" and "Likelihood of Engineering Failure" are values between 0-1 based on the consequence of the technology failing to an overall mission during operations and the 0-1 likelihood of that failure occurring. “R&D Cost” is the total estimated cost to develop the technology and to apply it to a specific mission. The process used by [14] for estimating the cost of developing new technologies (see Figure 16) includes uncertainty and an independent peer review of the estimate. It is based on interviews with technology representatives focusing on each technology's cost and performance relationships.

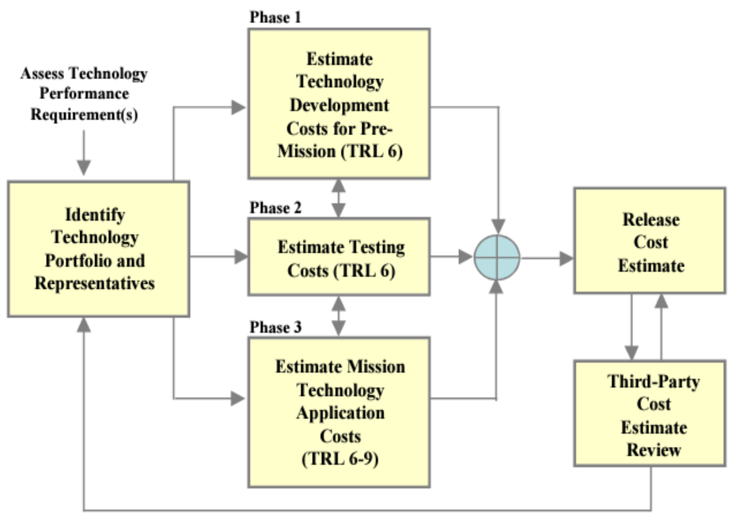

Figure 25: Process to Estimate R&D Costs [14]

Next, a qualitative measure of the ROI potential of a mission to Mars using a helicopter platform for scientific and engineering test endeavors can be defined by this relationship:

$$Mission\ ROI\ = \frac{Information\ Gathared}{Risk}$$

Where potential "Information Gathered" is estimated as a function of the payload mass and the total distance and number of flights a rotorcraft can have over its mission life:

$$Information\ Gathared = m_{payload}\ \times (R \times Flights\ Per\ Sol) * Mission\ Life$$

Risk represented as the sum of the mean probability of critical sensor, subsystem and operational failures:

$$Risk = \sum_{Sensors} \text{Mean Probability of Sensor Failure} + \sum_{Subsystems} \text{Mean Probability of Critical Subsystem Failure} + \sum_{\text{Operations}} \text{Mean Probability of Critical Operation Failure}$$

These models also represent relationships that can be used to evaluate the FOM value. Namely, lowering Risk and increasing the number of flights per sol and mission life can significantly increase ROI.

Conclusion

Development Strategy Summary

NASA already has ongoing efforts to research technologies that can increase the performance of Mars Rotorcraft, such as those outlined in [17] and [18]. These would make good candidates for the eventual evaluation of the models used and valuation approaches addressed in this study. Appendix A organizes a list of NASA technology investments into Capability Areas of the Strategic Framework. The technologies mentioned were listed on NASA Tech Portal Framework [29] as current areas identified as a need by NASA for development.

The list only contains technologies that fall into the high and medium alignment Capability Areas identified in section A

The FOMs in Table 1, the lessons learned from past developments, and the models of this and past studies show the primary need of future rotorcraft to increase capabilities are low size, weight and power (SWaP) subsystems and components. This is followed by a need for subsystems and components to have greater thermal performance either in their ability to survive extreme thermal situations (i.e., heat from the motor after long flights, Martian night cold temperatures, ext.) or improve the thermal control capabilities of the subsystems (i.e., increase subsystems ability to reject or retain heat as needed). The next need is for efficiency and power consumption improvements in the rotor propulsion and electronic subsystems.

Table 7 shows a Morphology Matrix of a few possible technology research efforts to improve the performance of Mars rotorcraft subsystems (shown in column 1), focusing on the three major areas that affect the high-level FOM: Mass, Thermal Performance, and Power Efficiency in columns 2-3. In column 4, some subsystem-specific research efforts to improve the FOMs are included.

Table 8: Morphology Matrix of Possible Improvements

Subsystem	Mass Decreases	Thermal Performance Increase	Power Efficiency Increase	Subsystem-Specific Performance Increase
Rotor System	▪ Lower mass rotor structure ▪ Lower mass dampening ▪ Lower mass rotor materials	▪ Convective cooling using forced convection in the rotor downwash	▪ Increased rotor FM ▪ Higher fidelity aerodynamic modeling	▪ Higher modulus elasticity material ▪ Higher strength materials ▪ Folding rotor design
Propulsion Motors	▪ Low mass gearing ▪ Lower mass motor	▪ Increased thermal capacity of components. ▪ Increased heat	▪ Increase motor energy efficiency. ▪ High	▪ Increase motor power /volume ratio.

	▪ Lower mass heat sink	rejection of components ▪ Motor temperature measurements	efficiency gearing system	
Avionics	▪ Lower mass electronic and sensors components ▪ Lower mass PCB substrates ▪ Lower mass harnessing and connectors	▪ Greater thermal survival range electronics ▪ Increased thermal capacity materials. ▪ Increased heat rejection materials	▪ Lower power electronics and sensors ▪ Independent air speed sensor	▪ Faster controller processing speed ▪ Faster navigation systems
Structure	▪ Lower mass materials ▪ Lower mass structural design	▪ Increased thermal capacity. ▪ Increased heat rejection	▪ Lower drag fuselage and rotor arm design ▪ Higher fidelity structural models	▪ Higher strength material ▪ Higher strength structure design
Thermal Control Systems	▪ Lower mass insolation material ▪ Lower mass heat sink design ▪ Lower mass heaters	▪ Higher-fidelity thermodynamic models ▪ The increased thermal capacity of materials ▪ Increased heat rejection material/surface finishes	▪ Low power heaters ▪ Passive heat rejection system ▪ Lower conduction insolation	▪ Deploying radiator ▪ Selective radiation system
Electrical Power System	▪ Increase battery energy/mass ratio. ▪ Increased solar cell surface. ▪ Increase operational battery depth of discharge capability	▪ Greater thermal survival range electronics ▪ Greater thermal survival range batteries	▪ Increase in battery mass fraction. ▪ Greater power efficiency and power control electron	▪ Increased solar cell energy efficiency. ▪ Increase the material strength of the solar cells. ▪ Charging by a second platform ▪ Decrease battery volume/energy ratio

Future Work

Additional parametric models for the performance of the more Mars Rotorcraft subsystems need to be created, evaluated, and published. Also, the models included in the study must be assessed for accuracy and attempts to increase fidelity should be attempted. There is a particular need for models linking Avionics and sensor performance to cruising speed and models linking the performance of the EDL, MTV, and Mars Rotorcraft Platform's subsystems. The DSM in Figure 9 shows interactions between these subsystems that could considerably impact the FOM identified in this study. Modeling interactions will be necessary for future mission design efforts and likely reveal other technology development areas of value. Figure 9 can also be used as the basis for Technology Infusion Analysis [33] and other general Technology Roadmapping methods described in [16].

There are also several inferences to the relative value of performance increases in subsystems that were not modeled or extensively examined in this study. This is primarily due to a lack of specific performance or design data during the time of this study. However, these areas must be further examined and modeled to advise on their relative improvement value compared to other investments. These areas include:

- Entry, Decent and Landing System Size and Rotorcraft Packing – Rotorcraft size will always be constrained by the available volume in the EDL delivering it to Mars. The designs investigated in this study primarily based their efforts on the assumption they will be deployed from rovers similarly sized to Perseverance or have dedicated EDL

Figure 26: Potential folding options for different rotorcraft configurations in similar aeroshells

systems based on heritage designs such as the legacy Pathfinder or Viking mission aeroshells. Heritage Aeroshells impose a maximum size envelope for the aircraft when folded/packaged in the aeroshell (2.5m was identified for the MSH in [8]) before deployment on the Martian surface. In general, investments to increase the allowable diameter and volume of EDL systems and technologies or architectures that enable a rotorcraft platform to be packaged in a smaller envelope without significant increases in mass or decreases in rotor size could significantly increase the potential their size and performance [7, 24].

- Communication Systems – While not examined in this study, the data needs of science instruments and more advanced operations will necessitate increased communication bandwidth capacity. Probably requiring increases in the communication systems' (receiver, transmitter, and antenna) mass and power consumption from the baseline performance of Ingenuity's comms system. These directly impact the FOM identified. Another consideration is that the Ingenuity and the SFH concept of operations call for communicating with a ground-based asset (Perseverance with its HBS for Ingenuity). Other mission concepts, including the MSH, involves rotorcrafts communicating directly with Mars Orbiters to relay data to Earth. This approach would enable vehicles that could scout out more complex terrains to reach different geologic features of importance. These systems would require a significantly higher gain antenna, higher power transmitters and more sensitive receivers than those on Ingenuity, SFH and MVHE. Investments in designing these systems to be light and low-power will likely represent high-value returns and may even be required for future missions.
- Instruments and Sensors – The direct performance and data gathering types represent a significant area of high-value technology development efforts that were not directly investigated in this study. Therefore, future endeavors should attempt to model the potential

return of lightweight and power-efficient instrument and sensor development efforts. Additionally, the relative value of sensor types to the unique rotorcraft mission profiles (reaching higher altitudes and different regions than rovers and landers) and the dual purpose of some sensors for science and flight performance increases should be further examined.

APPENDIX A: NASA IDENTIFIED TECHNOLOGIES

Technologies Identified in Tech Portal as Targets for NASA development.

Capability Areas	Target Technologies
LAND: Precision Landing and Hazard Avoidance	- Multi-Function Precision Landing Sensors for Robotic Missions - Precise velocity/range sensing facilitates soft landing and improves navigation - High-resolution terrain mapping hazard detection and avoidance - Plume-Surface Interaction mitigation and modeling
LAND: EDL to Enable Planetary Science Missions	- Multi-Function Precision Landing Sensors for Robotic Missions - Thermal Protection System Performance Modeling & Optimization for Robotic Missions - Static/Dynamic Aerodynamics models - Atmospheric Model Development
LIVE: In-Situ Resource Utilization (ISRU)	- Destination Reconnaissance & Resource Assessment - Site Imaging - Terrain Mapping - Instruments for Resource Evaluation - Resource/Terrain/Environment Data Fusion and analysis
LIVE: Power and Energy Storage Systems	- Reliable Rad-Hard Power Electronics - Lighter Dust-Tolerant Wired and Wireless Power Transmission - Lighter/More Efficient Solar Arrays - Low Irradiance, Low-Temperature Solar Arrays - Improved Efficiency/Durability of Thermoelectric Power Conversion - Battery Modules Thermal Survival - Low Mass Passive Thermal Control for Battery Modules
LIVE: Thermal Management Systems	- Advanced Modeling Techniques - Science Instrument Survival - Dust Tolerant Thermal Systems - Cold Tolerant Mechanisms and Electronics - Integrated Structural/Thermal Elements - Variable Heat Rejection Devices - Advanced Heat Pipes and Radiators - Advanced Cooling devices - Advanced Heat Exchangers
LIVE: Excavation, Construction, and Outfitting	- Low-Mass Rugged Robotic Platforms - Autonomy For High Throughput Operations - Wear-Resistant Materials and Wear Characterization - Long-Life Motion Parts, Including Lubricants, Motors, and Actuators - Dust Mitigation For Actuators, Seals, Joints, And Mechanisms - Dust-Tolerant Thermal Control System
EXPLORE: Advanced Avionics	- High-Performance Rad Hard Processors and Single Board Computers - Radiation-Tolerant/Lightweight Harnessing and Interconnects - Artificial Intelligence (AI) Coprocessors - Low Power Embedded Computers

	- Low-cost, Robust, High-Accuracy Data Acquisition Systems - Extreme Temperature Survival Electronics - Light Avionics Packaging and Thermal Management Technologies - Advanced Wireless Sensor Networks
EXPLORE: Advanced Manufacturing	- Low Mass, High Strength, Composites for Space Applications - Adhesive Bonding Thermosets and Welding Thermoplastics - Additive Manufacturing for Thermal Conductivity, Low-Mass, Tribological, Radiation Resistance and Other Improvements - Microstructure and defect informed predictions of damage tolerance - Process Simulation for Thin-Ply Composites - Accelerated Analytical Certification and Failure Mode Approaches
EXPLORE: Autonomous Systems and Robotics	- Efficient, Self-Adaptive and Fail-Active Autonomy - Cooperative Multi-Spacecraft System With Efficient Human Teaming - Robust Robot Mobility - Durable Self-Maintainable Robotics
EXPLORE: Communication and Navigation	- Optical Communications - Networking Technology - Planetary Surface Communications and Navigation - Position, Navigation, and Timing (PNT) - Radio Frequency - Communications
EXPLORE: Small Spacecraft Technologies	- Autonomy for Small Spacecraft and Distributed Systems - Small Spacecraft Communications - Small Spacecraft Position, Navigation, and timing capabilities - Interoperable Networking for Small Missions - Small Spacecraft Proximity Operations and Abort Systems

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