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2 HISTORY

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The early years of laser hydrography have been traced by Guenther (1985). His review tracks the development of laser hydrography, now more commonly known as Airborne Laser Bathymetry (ALB), from the earliest theoretical and experimental efforts in the mid-1960's dealing with in-water lasers (Ott 1965; Sorenson, Honey, and Payne 1966; Prettyman and Cermak 1969; Duntley 1971) and the first demonstration systems capable of detecting bottom returns (Ott, Krumboltz, and Witt 1971a; Cunningham 1972a; Carswell and Sizgoric 1974) through the development of the first operational systems (Ryan and O'Neil 1980; Penny 1982; Anderson et al. 1983; Malone, Casey, and Monahan 1983; Gluch et al. 1983; Moniteq 1983b, 1983a; Calder 1980). The history was later extended to 1990 in a paper by Sizgoric, Banic and Guenther (1992). Guenther further detailed this history and provided descriptions of operational systems in the Airborne Lidar Bathymetry chapter of The DEM User's Manual (Guenther 2001), which he later updated in the 2nd Edition (Guenther 2007). This chapter summarizes and updates these reference documents.

2.1 Australia

In 1971, only about 15% of the Australian continental shelf, the critical area for safe navigation, was charted to modern standards (Setter and Willis 1994). The estimated backlog was 50 survey years using conventional ship-based acoustic equipment. Half of this area has depths less than 50 meters, and one quarter is less than 30 meters. The same year, an airborne land profiler, designed and constructed at the Weapons Research Establishment (WRE), now the Defence and Science Technology Organisation (DSTO), Adelaide, was put into service. In 1972, at the suggestion of the Royal Australian Navy (RAN) Hydrographer, Captain J.H.S. Osborne, this was further developed to profile the seabed and was first flight tested in June 1975. During flight tests in the vicinity of Adelaide, it was found that reflections from the seabed could be obtained from water depths in excess of 30 m. With such an airborne device it became possible to perform hydrographic surveying at a greatly improved rate.

2.1.1 Early systems and developments

WREMAPS I was the Airborne Terrain Profiler, mentioned above, which enabled land maps to be accurately contoured. WREMAPS I was in service for ten years with the Australian Army from 1970 – 1980. WREMAPS II was developed for the same purpose as WREMAPS I but incorporated improved technology using, for example, a pulsed Nd:YAG, frequency doubled laser. WRELADS II was in service

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for 13 years from 1974 – 1986. The research and development activity at DSTO connected with the terrain profilers (WREMAPS I and II) was a natural springboard for a Navy sponsored task – that of developing a laser airborne depth sounder. A non-scanning experimental system, known as WRELADS I was built and tested in 1976 and 1977 (Abbot and Penny 1975). The results demonstrated that a scanning system as specified by the Navy was possible and this led to the production of WRELADS II. This more advanced system with full scanning, data recording and horizontal position fixing capabilities was developed and trialed from 1979 to 1984. The trials involved 550 hours of flying in a RAAF C47 Dakota which resulted in the gathering of large volumes of data. Analysis of this data showed that over the 2-30 m range, water depths could be measured with a standard deviation of 0.3m. The horizontal positions of soundings were known within an error circle of 11 m diameter and the aircraft was navigated consistently within 30 m of track (Penny et al. 1986).

Figure 2.1.2. The RAN LADS Aircraft with HMAS Moresby and a SMB off the coast of New South Wales on the occasion of the 75th anniversary of the Royal Australian Navy's Hydrographic Service.

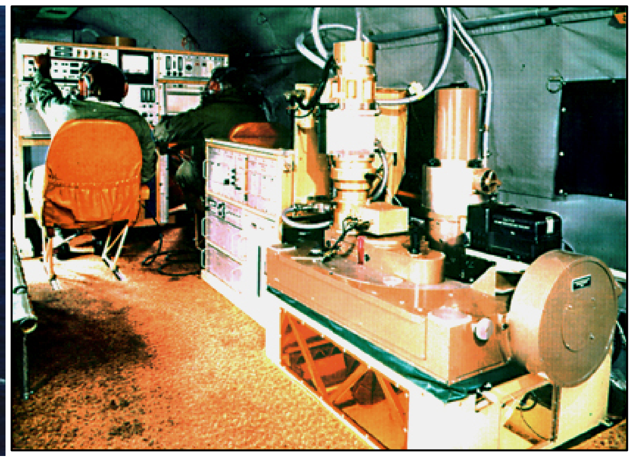

Figure 2.1.2. WRELADS II fitted to a RAAF C-47.

LADS is a product of the WRELADS programs (Setter and Willis 1994). It represents an engineered version of the experimental work, updated and integrated with all the additional features needed for a modern operational system which met the requirements of the RAN Hydrographer at that time. The contract to design, build and trial a LADS system for the RAN was awarded to Vision Systems Ltd, (VSL) in May 1989. This was to be known as RAN LADS 1. It operated a flash lamp pumped laser at 168Hz. RAN LADS 1 was accepted into Naval Service on 17 February 1993 and successfully carried out operations across Australasia internally mounted in a dedicated Fokker F27-500 series aircraft (Nairn, 1994). LADS was operated by the RAN LADS Flight unit, with logistical support from the system manufacturer, Tenix LADS Corporation Ltd. (formerly Visions Systems), a wholly owned subsidiary of Tenix Defence Systems Pty. Ltd. On one of its first RAN shakedown test flights in Spencer Gulf, LADS discovered a dangerous and previously uncharted granite pinnacle rising to an 11.9-m depth from an otherwise flat, 20-m bottom. The feature was first designated "Laser Shoal" and then, more aptly, renamed Penny Shoal, after Mike Penny, who directed development of WRELADS I and II.

In parallel with the development and support of systems for the RAN, Fugro LADS Corporation (formerly Tenix LADS) developed the next generations of LADS systems. After the release of RAN

LADS 1, the LADS Mk II system was developed, and was installed in de-Havilland Dash 8-200, VH-LCL (Spurling and Perry 1997; Sinclair 1998). This is the same aircraft that was later transferred to the RAN in 2009. This Dash 8 aircraft provided a modern aircraft with worldwide support, and qualities of speed, power, payload and endurance suitability for marine survey requirements (Sinclair 1997; Spurling and Perry 1997). The system had a a much higher pulse repetition rate and improved computer and navigation functions, operating at a sounding rate of 1 kHz and collected data to 70 m depth at IHO Order 1 charting accuracy (Sinclair, Stephenson, and Spurling 1999). The LADS MkII / Dash 8 conducted many successful surveys worldwide over the years of 1998 – 2009 operating in Europe, Middle East, North America and Australasia (Wellington 2001).

In 2008, the RAN LADS 2 System was introduced into service, providing functionality and performance improvements over the existing RAN LADS 1, whilst achieving the same standard of reliability and maintainability. The system was based upon core LADS functionality proven over the previous 15 years. It operated a diode pumped laser at 1 kHz. Initially the RAN LADS 2 system was installed in the Fokker F-27 Aircraft, but this was replaced in 2009 with the de-Havilland Dash 8-200 VH-LCL to relieve the pressure of operating with an ageing aircraft.

	ALB SYSTEM	RAN LADS 1
	AIRCRAFT	F-27 FOKKER
	PERIOD OF SERVICE	1993 to 2008 (15 YEARS)
	SORTIES FLOWN	2,232
	KM^2 SURVEYED	116,215 KM^2
	ALB SYSTEM	RAN LADS 2
	AIRCRAFT	BOMBARDIER DASH 8-202
	PERIOD OF SERVICE	Nov 2009 to Jun 2016 (6.5 YEARS)
	SORTIES FLOWN	995
	KM^2 SURVEYED	82,614 KM^2

Figure 2.1.3. Royal Australian Navy Laser Airborne Depth Sounder system statistics.

In 2009, LADS Mk3 was released into service with a new model of operation, where the equipment was mobilised to the location of aircraft of opportunity around the world, typically a Beechcraft A90, Cessna 441 or Cessna C208. The LADS Mk3 had enhanced performance over the LADS MkII and was much smaller and lighter – suitable for the smaller aircraft. The system operated at 1.5 kHz sounding rate and could now measure up to 80m depth. Incremental upgrades to the LADS Mk3 over the period of 2009 to 2015 were introduced. Significantly the sounding rate was increased to 2.5 kHz retaining the same 80m depth performance, and in 2012 a Riegl 820G sensor was integrated with LADS as a complimentary

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sensor, providing a second channel of high density 138 kHz soundings for enhanced shallow water and topography performance. In 2014 the Riegl sounding rate was increased to 250 kHz and then in 2015, the Riegl VQ-820-G was further upgraded to operate at 520 kHz. Successful surveys were conducted in Australia, France, New Zealand, Japan, Middle East, French Polynesia and Samoa with the LADS Mk3 System including the integrated Riegl sensor.

2.1.2 Current status

Early in 2016 the LADS HD system was released into service with a laser operating at 3 kHz plus new improved data processing capabilities including tightly integrated data processing of LADS and Riegl data combined, and Back 2 Base Data processing. The first survey conducted with this system was in Western Australia. Recently, in July 2016, the RAN LADS 2 system was replaced with a RAN LADS HD system operating with a sounding rate of 3 kHz. This is a customized LADS HD system installed in the Dash 8 aircraft, providing a comfortable operator console suitable for the 7hr survey endurance of the aircraft. This new capability allows the RAN to operate a more deployable model of operations where the survey team can deploy from site to site and transfer the data back to the Cairns Main Operating Base (MOB) for data processing.

Figure 2.1.4. LADS Mk II undergoing trials off the coast of South Australia, May 1998.

Figure 2.1.5. LADS HD system installed in Cessna 441 owned by Fugro.

Figure 2.1.6. RANHD installed in Dash 8 aircraft

Figure 2.1.7. LADS HD System; Change to 3 kHz

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2.2 Canada

Airborne Lidar Bathymetry has a long history in Canada. The early years have been documented very well by Guenther (Guenther 2007) and hence we will only summarize briefly here. The very early work in Canada by Optech was in some profiling efforts with the Canada Centre for Remote Sensing (CCRS) (Ryan and O'Neil 1980). The next step was collaborating with the Swedish National Defense Institute (FOA) to augment the Mark-2 profiling system with a scanning mirror (Steinvall et al. 1981).

2.2.1 Early systems and developments

In the early eighties, the ALB systems were developed beyond the experimental learning stage and into the operational regime. Optech delivered the LARSEN-500 to the Canadian Hydrographic Service (CHS) and CCRS 1985 (Banic, Sizgoric, and O'Neil 1986). LARSEN-500 supported nautical charting missions in the Arctic during the few weeks a year the region is ice free (Casey, O'Neil, and Conrad 1985). As a result of its Arctic charting missions in 1985 and 1986, it fittingly deserves recognition as the world's first operational airborne lidar bathymeter. Lessons learned from LARSEN were incorporated into the Swedish and U.S. programs that followed. FOA of Sweden sponsored the development by Optech of a scanning ALB system called FLASH-I, which was delivered in 1988 (Steinvall, Koppari, and Karlsson 1993). Also, in 1988, Optech delivered to the US DARPA an airborne lidar for the detection of mines, the ALARMS system (Airborne Laser Radar Mine Sensor), which had a very advanced pulse repetition frequency (PRF) of 10 kHz.

Other significant developments in the late eighties included the first smooth sheet chart produced by an ALB for navigation in 1988, produced for CHS by the LARSEN-500. The same year, the U.S. Army Corps of Engineers (USACE) initiated an operational ALB system to be developed by Optech Incorporated under the program name SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey). The goal of the SHOALS program was to develop a new hydrographic survey capability to support USACE dredging operations (Lillycrop and Banic 1992), and further, to transition the capability to industry so that it would be more widely available to USACE and others (Miles et al. 1994). The SHOALS system was field tested in March of 1994 at New Pass, near Sarasota, Florida (Lillycrop, Parson, and Irish 1996). The SHOALS laser pulsed 200 times per second, and was deployed in an external pod between the skids of a NOAA Bell-212 helicopter. In the late 1990's, the SHOALS laser was upgraded to 400 pulses-per-second (pps), allowing a transition from the helicopter to a fixed wing aircraft for even faster coverage rates (Wozencraft and Lillycrop 2003).

Optech delivered the CHARTS system to JALBTCX in 2003, comprising a SHOALS-1000T9, an integrated lidar system with a 1,000 pps bathymetric laser, a 9,000 pps topographic laser, and a DuncanTech (DT)-4000 digital RGB video camera with a Matrox screen grabber (LaRocque, Banic, and Cunningham 2004). SHOALS-1000 is a further generational advancement of the original SHOALS technology, based on R&D and nine years of SHOALS operations (Wozencraft and Lillycrop 2003). In 2005, CHARTS was upgraded to include a 3,000 pps bathymetric laser, a 20,000 pps topographic laser, and an Itres Compact Airborne Spectrographic Imager (CASI)-1500 (Wozencraft and Millar 2005) Optech delivered a variant of the SHOALS-1000T9 to the Japan Coast Guard in 2003. Five of these 1 kHz models were made, one of which was delivered to Fugro Pelagos. The SHOALS-1000 system's

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hazard detection capability was demonstrated to exceed IHO Order-1 in clear water, and IHO Special Order with appropriate survey planning (Yang and LaRocque 2010). Another SHOALS-3000 system was delivered to the UAE in 2010 and is still active in 2016.

The SHOALS family of systems was superseded by the development of the CZMIL system, built to have even greater depth penetration. The CZMIL system was designed at the US office of Teledyne Optech in Kiln MS (see section 1.3). Several subject matter experts from the Canadian office contributed to various subsystems of the CZMIL. The other major Canadian hardware contribution to CZMIL was the hyperspectral camera – the CASI-1500 built by ITRES of Calgary.

2.2.1 Current status

As work began on the next generation in the SHOALS family of systems at the Teledyne Optech office in the US, the Toronto office focused on smaller bathymeters that could also serve as terrain mappers. This was the beginning of the smaller, so-called "topo bathy" systems in the market. Optech had sold a large number of Airborne Laser Terrain Mappers (infrared topographic laser systems) and one of the popular ones was the Gemini. Along with the University of Houston and U.S. National Science Foundation National Center for Airborne Laser Mapping (NCALM), a green variant of the Gemini was conceived called Aquarius. This system was delivered to NCALM in 2010 (Fernandez-Diaz, Glennie, Carter, Shrestha, et al. 2014; LaRocque 2012). It was a "green-only" system which output its laser energy only at 532 nm, with a pulse repetition frequency (PRF) ranging from 33 kHz up to 70 kHz, which was a large leap forward in acquisition rate. The Aquarius system won the MAPPS Technology Innovation Award in 2011.

The current generation of shallow water mapper was made possible by the advances in fiber lasers. One limitation of the existing models was in the useful PRF. For example, the peak power of the laser in the Aquarius system would decrease with increasing PRF. Thus, its best depth performance was at its lowest PRF of 33 kHz. The newer fiber lasers did not have this restriction. In addition, while some people had combined lidar data of different wavelengths over the same area, there had never been a lidar that could collect three different wavelengths at the same time. Once again in collaboration with NCALM, Teledyne Optech completed the Optech Titan in 2014, a multi-purpose lidar useful for bathy as well as terrain mapping (LaRocque and Abdel-Rahman 2014; Fernandez-Diaz, Glennie, Carter, Shresha, et al. 2014). The depth performance of the Optech Titan is constant over its PRF of 50 to 300 kHz. It can serve as a 300 kHz shallow water mapper as well as a 900 kHz terrain mapper. The three wavelength intensity data has been very useful in enhancing bathymetry applications by helping the automatic classification of land from water (LaRocque et al. 2016). The simultaneous acquisition of three different wavelengths has also aided research on automatic land cover classification (Shaker et al. 2015). In 2015, the Optech Titan won the grand prize of the MAPPS Excellence Awards.

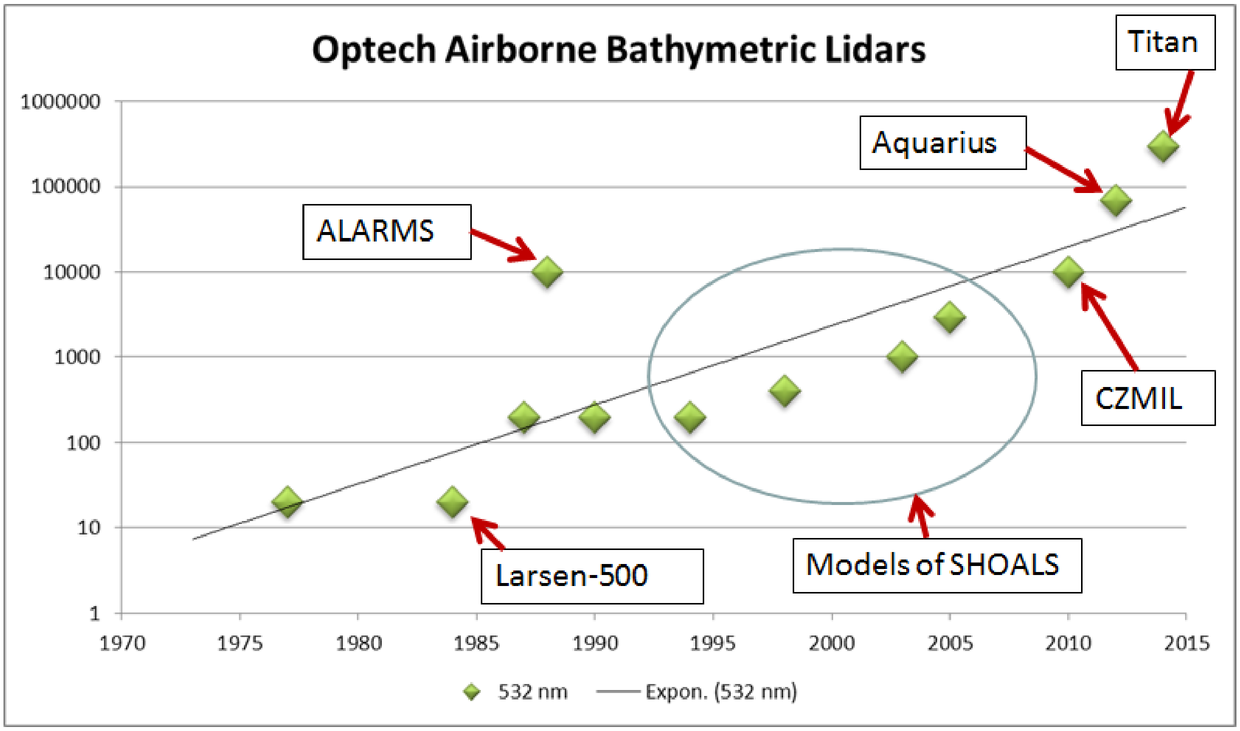

Figure 2.2.1. The evolution of ALBs in Canada. The laser PRF of the various ALBs made by Teledyne Optech is plotted on a log scale. The very early days used PRFs of 20 Hz while the latest value stands at 300 kHz for the Optech Titan.

The evolution of ALBs in Canada is illustrated in Figure 2.2.1, where the laser pulse repetition frequency (PRF) of the various ALBs made by Teledyne Optech is plotted on a log scale. The very early days used PRFs of 20 Hz while the latest value stands at 300 kHz for the Optech Titan.

2.3 United States

2.3.1 Early Systems and developments

U.S. work in the area of airborne lidar bathymetry began in the early 1960's with the concept that airborne, pulsed lasers could be used by the Navy to locate submarines. Early theoretical studies and system modeling for Naval Air Development Center (NADC) (Ott 1965; Sorenson, Honey, and Payne 1966; Prettyman and Cermak 1969) and field work (Duntley 1971) were followed by field tests of elementary bathymetric systems (Cunningham 1972b; Hickman and Hogg 1969; Ott, Krumboltz, and Witt 1971b). A system sponsored by the U.S. Air Force was successfully tested from a tower over the Gulf of Mexico (Levis et al. 1973). The Office of Naval Research (ONR), National Oceanic and Atmospheric Administration (NOAA), and U.S. Geological Survey (USGS) co-sponsored further studies of light transfer mechnisms, and development of design criteria for an airborne bathymetric system (Hickman et al. 1974; Hickman, Hogg, and Ghovanlou 1972; Hickman and Ghovanlou 1973).

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National Aeronautics and Space Administration (NASA) sponsored a symposium on the use of lasers for hydrographic studies (H. H. Kim and Ryan 1973) with contributions from NOAA, ONR, the Naval Oceanographic Office (NAVOCEANO), NADC, US Environmental Protection Agency, and the CCRS. In the next few years, further design, construction, and field testing of airborne laser systems wasconducted by NASA (H. H. Kim, Cervenka, and Lankford 1975) and NADC (Ferguson 1975; Witt et al. 1976; Shannon 1975).

Avco Everett Research Laboratory, Inc. designed the Airborne Oceanographic Lidar (AOL) for NASA (Avco Everett Research Laboratory Inc. 1975) based on design goals and user requirements in the areas of hydrography and fluorosensing developed through symposia sponsored by NASA and NOAA. NOAA Laser Hydrography Development Project (Goodman 1975, 1976) and the Naval Ocean R&D Activity field tested AOL in 1977 to assess the potential of the basic technique of airborne laser bathymetry in terms of accuracy and maximum penetration depth and to determine the effects of the numerous system and environmental parameters (Guenther 1977). Final results of the NOAA test program of the AOL, and resulting analysis of: interrelationships among system design and performance factors, corrections for environmentally-induced biases in surface and bottom returns, and depth determination algorithms, were reported in Airborne Laser Hydrography: System Design and Performance Factors (Guenther 1985).

In 1988, the U.S. Army Corps of Engineers (USACE) began the Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) program (Pope and Lillycrop 1988; Banic, Sizgoric, and Lillycrop 1990) to develop a new hydrographic capability for 40,000 km of USACE-maintained navigation channels (Guenther, Thomas, and LaRocque 1996; Lillycrop, Parson, and Irish 1996). Goals of the program were to develop an operational airborne lidar bathymetric technology, prove its application, and transition the mapping capability to the survey and mapping industry so that it would continue to be available to the USACE beyond the life of the SHOALS program (Miles et al. 1994). The SHOALS system was developed by Optech in Canada, and jointly funded by the US Army Corps of Engineers and the Canadian government. The SHOALS data processing software was developed in collaboration with Gary Guenther and based on Airborne Laser Hydrography: System Design and Performance Factors (Guenther 1985).

From its field test in 1994 to 1997, SHOALS surveyed coastal engineering projects throughout the United States, demonstrating its capability to not only provide accurate, high-resolution data for navigation channels, but also the adjacent shoals and beaches (Wozencraft 2010). SHOALS deployed in 1996 in support of a large nautical charting survey of the Yucatan Peninsula for NAVOCEANO (Irish, McClung, and Lillycrop 2000). The demonstration projects generated new user requirements that translated into a number of technological advancements including:

- extending depth measurement through the 0-2 m range, which had been prohibited by the long laser pulse and system response time, and up onto the subaerial beach (Brooks et al. 1998)
- using kinematic GPS data with on-the-fly ambiguity resolution for vertical reference, instead of the mean water surface (Guenther, Brooks, and LaRocque 1998)
- time- and geographic position-tagged analog video imagery collected concurrently with the lidar to assist in manual cleaning for the positioning of piers and other structures along the shoreline

- early work on the fusion of lidar and hyperspectral imagery for benthic classification was performed (Lillycrop and Estep 1995; Lillycrop, Irish, and Parson 1997)

USACE and NAVOCEANO formed the JALBTCX partnership in 1998 to further collaboration between the agencies in operations, research, and development in airborne lidar bathymetry (Wozencraft and Lillycrop 2006). Following its upgrade to a 400 pulse per second laser, and transition from a helicopter to a fixed wing platform, SHOALS was flown extensively for USACE projects in the US, including Alaska, Hawaii, and Puerto Rico. NAVOCEANO used SHOALS on tactical nautical charting missions in Guam, American Samoa, Hawaii, Bahamas, and Portugal. SHOALS-400 operated from 1999 to 2003. Signal processing work produced psuedoreflectance (a measure of the seafloor reflectivity) and water column parameters from the lidar waveforms (Lee 2003; Tuell and Park 2004), and produced the first hyperspectral image inversions constrained by these quantities (Tuell and Park 2004).

NASA fielded the Experimental Advanced Airborne Research Lidar (EAARL) in 2001 (Nayegandhi, Brock, and Wright 2009; Wright and Brock 2002) to map sandy beach topography, three-dimensional coastal vegetation structure, shallow bathymetry, coral communities, and near-shore benthic habitats simultaneously (Wright and Brock 2002; Brock et al. 2004; Nayegandhi et al. 2006; Nayegandhi, Brock, and Wright 2005). EAARL was the first of a new design philosophy for lidar bathymetry that uses narrow, low energy green laser pulses and narrow field of view. This design confers advantages in the areas of system size, accuracy, and resolution, but disadvantages in terms of overall depth detection capability (Feygels et al. 2003). EAARL was flown with a down-looking RGB digital camera and a high-resolution multi-spectral color infrared (CIR) camera, often in support of U.S. Geological Survey projects. EAARL operated from 2001 to 2013, surveying a number of coral reef areas in Florida and the Caribbean, rivers in the western U.S., and before and after hurricanes that made landfall in Florida in 2004 and 2005, and in New Jersey in 2012.

In 2000, NAVOCEANO undertook a sensor development effort called Compact Hydrographic Airborne Rapid Total Survey (CHARTS) based on the success of the SHOALS program (Wozencraft 2002). The goal of CHARTS was to increase the survey coverage rate, decrease the physical footprint and power requirements of SHOALS to take advantage of aircraft of opportunity, and to combine bathymetric lidar technology with topographic lidar and aerial photography. CHARTS development was jointly funded by the USACE, Canadian government and Optech. Technological advances supporting the CHARTS development in the U.S. centered on extraction of more information from lidar waveforms, and on fusion of lidar with hyperspectral imagery (Kopilevich et al. 2005; Tuell et al. 2005; Tuell and Park 2004). The NAVOCEANO CHARTS systems were operated from 2003 to 2011 in support of NAVOCEANO Airborne Coastal Surveys in Nicaragua, Haiti, Philippines, Japan, Marshall Islands, Micronesia, Palau, Northern Marianas, Guam, Samoa, Bahrain, Oman, Portugal, Israel, Morocco, and Kenya. USACE used NAVOCEANO CHARTS systems to perform surveys along the sandy coasts of the United States for its newly initiated National Coastal Mapping Program (NCMP) from 2004 to 2011.

2.3.2 Current status

Coastal Zone Mapping and Imaging Lidar (CZMIL) was fielded in 2012 to meet the requirements of the USACE NCMP and NAVOCEANO Airborne Coastal Surveys: high-resolution, high-accuracy bathymetric lidar, topographic lidar, aerial photography, and hyperspectral imagery. CZMIL was a sensor development effort in the USACE NCMP, and a partnership among the JALBTCX, Optech International in Kiln, MS (now Teledyne Optech), and The University of Southern Mississippi (USM). The design goal of CZMIL was to produce an integrated lidar, imagery sensor suite, and software package designed for highly automated generation of physical and environmental information products for the coastal zone. CZMIL was an opportunity to improve the design of current airborne lidar bathymeter hardware and software to meet the needs of the NCMP: accurate depth measurement; expanded environmental product generation by operationalizing the fusion of lidar with hyperspectral imagery (Park et al. 2010); improved performance in turbid, shallow waters (Ramnath et al. 2010); and a very fast coverage rate.

CZMIL has a unique design that combines a broad beam, or large beam divergence angle, with a high peak power, but short laser pulse, and small field of view. The 10,000 pulse per second CZMIL laser emits 2-ns-wide laser pulses and scans them across the water surface in a circular pattern using a spinning Fresnel prism. Seven small, 2-milliradian each, field of view channels spatially sub-sample each 2.8 m diameter laser spot for high resolution measurements (70 cm spacing) in shallow water and on land. A large 40-milliradian field of view channel provides maximum depth performance in turbid water, and up to 60 m in clear water. Waveforms are digitized for each receiver and receiver segment, for a total of 9 waveforms per laser pulse. CZMIL Hydrofusion data processing software can extract up to 32 returns on each waveform, up to 256 per laser shot, with separation along the slant range as little as 10 cm on land. CZMIL Hydrofusion takes advantage of CZMIL radiometric calibration and produces advanced lidar products like lidar reflectance on land and in water, water column attenuation, and water-leaving reflectance. CZMIL is integrated with a medium format digital camera, a CASI-1500 hyperspectral imager, and Applanix POS AV for positioning. The advanced lidar products and hyperspectral imagery are input to CZMIL Hydrofusion spectral optimization technique that produces land and seafloor reflectance at multiple wavelengths by fusing lidar and hyperspectral imagery (Wozencraft and Park 2013).

The current suite of USACE NCMP and CZMIL Hydrofusion deliverable products includes (Wozencraft, 2010):

- Orthorectified aerial photography
- Classified LAS files
- 1-m and 5-m Bathymetric and Topographic Digital Elevation Models (“bare earth”) and Digital Surface Models (“first return”)
- Shoreline Contour
- Lidar-derived water column properties and seafloor reflectance
- Hyperspectral image mosaics (corrected for atmosphere)
- Hyperspectral-derived water column properties and seafloor reflectance (constrained with lidar-derived depth, water column, and seafloor parameters)
- Volume change and shoreline change (using successive surveys in a location)

Advances in processing bathymetric lidar signals and in the fusion of these signals with hyperspectral imagery provide the potential to expand the NCMP product line to include images of water column attenuation, chlorophyll concentration, and CDOM concentration, and automated bottom classification (M. Kim, Park, and Tuell 2010). CZMIL has collected the sandy coastlines of the US, the major

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Hawaiian Islands, and the north shore of Puerto Rico for the USACE NCMP, and was used in response to Hurricanes Sandy (Wozencraft and Park 2013), Matthew (Virginia, North and South Carolina, Georgia, Florida), and Irma (Florida) for USACE and the Federal Emergency Management Agency (FEMA).

A significantly modified EAARL system was field tested in 2014 (Wright et al. 2016). EAARL-B is an extensive modification of the original NASA EAARL system. EAARL-B combines small and large FOVs like CZMIL, but emits much lower power (0.07 millijoules) and slightly shorter pulses (1.3 nanosecond). The outgoing pulses are split into 3 beamlets that result in 3-30 cm diameter laser footprints on the water surface, spaced 1.6 m in the along track direction. EAARL-B has 4 receivers for each laser pulse, one 60-cm FOV PMT receiver for each beamlet and another 5-m FOV PMT receiver that encompasses all three beamlets, and enables EAARL-B to see maximum depths in excess of 40 m in clear water. EAARL-B scans laser pulses across the land and water surface in a raster pattern tilted slightly forward to avoid Fresnel reflections at nadir that would saturate receivers in the aircraft. EAARL-B data are processed in the open-source Airborne Lidar Processing System (ALPS) developed at NASA and USGS (Nayegandhi, Brock, and Wright 2009). ALPS provides the capability to geometrically calibrate EAARL-B data, and apply appropriate depth-induced propagation biases to the shallow water beamlets and the deep channel. ALPS requires the user to interrogate representative waveforms in order to define a water column model for each dataset. After the model is subtracted from waveforms digitized by the system, potential bottom peaks, identified based on user-defined thresholds, are accepted or rejected based on expected bottom return characteristics like pulse width, rise time, and fall time (Wright et al. 2016). ALPS allows the user to run an Iterative Random Consensus Filter to remove noise points, and to manually delete any remaining noise points (Nayegandhi, Brock, and Wright 2009).

New sensors currently in the operational testing phase are the Arete PILLS and the Astralite, both designed to operate from UAS.

2.4 Sweden

Airborne laser hydrography in Sweden also leveraged system development capability of Canada's Optech. The driver was navigation safety. Nordstrom (2000) said it succinctly for the Swedish Maritime Administration: "the use of a helicopter-borne laser-beam system (in Sweden) is essential, especially in shallow and narrow waters in the archipelagos." In the middle 1980's, the Swedish Defense Research Establishment (FOA) worked with Optech Incorporated to develop the FLASH airborne lidar system to evaluate object detection and the performance of emerging ALB technology (Steinvall, Koppari, and Karlsson 1994).

2.4.1 Early systems and developments

The success of FLASH led to development of two identical Hawk Eye systems (Steinvall et al. 1997), largely derived from the SHOALS design, in the early 1990's by Saab Instruments AB (later Saab Dynamics AB), with Optech as the major subcontractor. The two pod-mounted systems were purchased by the Swedish Defence Material Administration (FMV) – one for the Royal Swedish Navy and one for the Swedish Maritime Administration. They were designed for helicopter operation in a Boeing Vertol and a Bell 212, and were deployed in 1994 and 1995 for the dual purposes of hydrography and submarine detection (Steinvall et al. 1997; Skogvik and Rune 2001). Two years after delivery, the Swedish

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Maritime Administration sold their system to Blom A/S, a private Norwegian surveying contractor, for use in a large survey project in Indonesia and began sharing the remaining system with the Navy. The Swedish Navy Hawk Eye system conduced navy survey operations and nautical charting missions for the Maritime Administration off the South and West coasts of Sweden, as well as in the Baltic Sea (Skogvik and Rune 2001).

Airborne Hydrography AB (AHAB) was formed as an employee buy-out of the lidar work at Saab Dynamics AB to supply state-of-the-art laser bathymetry and terrestrial systems and hydrographic laser survey services. In 2004, AHAB and TopEye AB of Sweden and Admiralty Holdings Limited in the United Kingdom formed a collaboration called Admiralty Coastal Surveys AB (ACSAB) to create and produce an ALB and topography service based around their new Hawk Eye II lidar system. Hawk Eye II Laser Bathymetry and Topography System was tested in 2005 and delivered to ASCAB in early 2006. Surveys were performed in France, Germany, Denmark, Estonia, Sweden, and the U.S.

2.4.2 Current status

Chiroptera II and Hawk Eye III are the recent shallow and deep water bathymetric lidar systems fielded by Leica AHAB in 2013 and 2015, respectively. Airborne Hydrography AB built the Chiroptera system for the University of Texas, Bureau of Economic Geology. This shallow water system was designed in the tradition of deep water systems, with multiple wavelength transceivers and waveform processing. Chiroptera was delivered in 2012. Chiroptera II, which boasts greater depth penetration capability than its predecessor was launched in 2014 with HawkEye III by Leica Airborne Hydrography AB as a modular approach to coastal zone mapping. Chiroptera II surveys over land and shallow water, while the HawkEye III surveys deeper water.

Chiroptera II comprises a green laser for bathymetry that pulses 35,000 time per second, and an infrared laser that pulses 500,000 times per second. The lasers have separate transmit and receive paths. The green laser has pulse energy of 0.1 millijoules, which is an order of magnitude less powerful than the traditional bathymetric lidar sensors SHOALS, CZMIL, and LADS. With a beam divergence of 3 milliradians the on-water laser footprint size is 1.2 m at operational altitude of 400 m. The infrared laser beam divergence is 0.5 milliradians with an on-ground laser footprint size of 0.1 m. Maximum depth penetration expected for this system is 15 m in moderately clear water. The laser pulses are scanned over the ground and water surface using a Palmer scanner which results in an elliptical scan pattern that is 40 degrees across track and 26 degrees along track, and a swath width that is 70% of the operating altitude. Chiroptera II is optionally gyro-stabilized using a PAV-100 mount and maintains a near-constant scan pattern along the flightline.

Hawk Eye III is a Chiroptera II with the addition of a separate laser transceiver for deep water depths. It has characteristics similar to CZMIL in terms of laser power (3 millijoules) and pulse repetition rate (10,000 pulses per second), but has a slightly larger beam divergence so the size of the laser footprint is also larger (4m). Chiroptera II and HawkEye III both use Novatel SPAN with LCI-100 IMU for positioning and orientation, and are operated to meet both USACE “Class 1” and IHO “Order 1” hydrographic accuracy standards for most applications. Chiroptera II is integrated with a 5 MP camera for QA/QC and may be integrated with an 80-MP RCD30 for higher-resolution imagery. Leica MissionPro and FlightPro provide mission planning and flight operations support, while Leica Survey

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Studio software and FramePro software provide lidar processing and image processing. Leica Survey Studio provides automated calibration for all three lasers (Chiroptera infrared and green, HawkEye III green), and uses all three in combination to apply the appropriate processing algorithm based on automated land/water and turbid water detection.

2.5 Austria

Having already gathered vast experience in airborne laser scanning, RIEGL entered the field of airborne laser bathymetry through a research project initiated by the University of Innsbruck in 2008. From the very beginning high resolution shallow water bathymetry was the declared target application. To this end, different technologies compared to the then established deep sounding systems were employed in many respects ranging from laser technology to scanning mechanism and receiver technology. Special focus was placed on compactness and minimizing the weight of the instrument hardware and the compatibility to RIEGL's established hardware and software solutions. Riegl teamed with the University of Innsbruck on a research project for the Bavarian Water Authority to develop and assess the capabilities of a new shallow water bathymetric lidar system (Pfennigbauer and Steinbacher 2012). This system was designed specifically to meet the inland water (riverine) mapping requirements set forth by the European Water Framework Directive and was made commercially available in 2011.

2.5.1 Early systems and developments

After a phase of research and development, RIEGL marketed the VQ-820-G in 2011. This instrument had a high pulse repetition rate (up to 485 kHz), a short laser pulse (just above 1 ns), and a comparatively small beam divergence (1 mrad). These parameters lead to high spatial resolution, but the low laser pulse energy (around 20 µJ) and the small receiver aperture (around 50 mm) limit the depth penetration to around 1 Secchi depth when operating the instrument from a flight altitude of 600 m. The laser pulses are scanned by a multifaceted mirror that describes an elliptical section across the land and water surface. The size of the laser footprint on the water surface at 400m altitude is 0.4 m and the footprint spacing is 0.2 m, up to 10 points per square meter. Furthermore, the instrument operates using only a green wavelength. The VQ 820-G utilizes echo digitization and online waveform processing (Pfennigbauer et al. 2014) techniques for real-time detection of returns on the lidar waveform, rather recording and storing waveforms for post-processing. As such, a refraction correction technique was developed using the lidar point cloud for location of the mean water surface to provide the angular and speed-of-light corrections for lidar point geolocation. The VQ-820-G was representative of a new class of ALB instruments, the so-called Topo-Bathy Laser Scanners.

The VQ-820-G was fielded in the USA for extensive coastal surveys for NOAA to update nautical charts after Hurricane Sandy, in France and Australia by Fugro, and also in central Europe by AHM and other surveying companies. AHM is a spinoff of the University of Innsbruck and another result of the research collaboration focusing on fresh water surveying. Fugro combined the VQ-820-G with its LADS deep sounding airborne laser bathymetry sensor in order to accomplish seamless surveying of the entire coastal zone using the VQ-820-G data for topography and shallow water and the LADS for the deeper regions. Extensive work was carried out with this combination. On special request of a customer the VQ-820-G has also been integrated in the Schiebel Camcopter S-100.

2.5.2 Current status

In 2014 RIEGL launched the VQ-880-G, a topo-bathy laser scanning system including an infrared channel, IMU, GNSS, and AVT 29-megapixel camera. The green channel of the VQ-880-G uses a rotating prism to perform a circular scan with an off-nadir angle of 20°. The IR channel uses a rotating polygonal mirror to perform a slightly arced scan in the center of the green's channel scan cone. This has the advantage of being able to pick up a signal from the water surface, even under unfavorable conditions. The laser has a slightly higher pulse repetition frequency, up to 550,000 pulses per second, but the pulse power and pulse width are similar to the VQ 820-G. The laser beam divergence is selectable from 0.7 to 2 mrad, as is the scan speed from 10 -200 scans/sec for the green channel. As a consequence of the scan mechanism design, the net measurement rate was nearly doubled. The VQ 880-G also utilizes onboard echo digitization, but has an add-on capability for recording all waveforms for post-processing, and is integrated with an APC 29-megapixel camera for concurrent aerial photography collection. Compared to the VQ-820-G the VQ-880-G has improved performance in every respect, most notably the depth penetration is significantly improved. Again, the first systems were deployed in the US and were later introduced in Europe.

Processing of the acquired data relies on the established RIEGL software suite for airborne laser scanning including tools for acquisition tasks like flight line planning and real-time feedback to the operator (RiAcquire), georeferencing (RiWorld), and strip adjustment, visualization, classification, and data export (RiProcessing). Water classification, water surface modeling and refraction correction are performed by the RiHydro addon.

In 2015 RIEGL announced a new concept of a laser rangefinder employing a green laser small enough to be operated from a small-scale UAV. This combination is capable of generating profiles of waterbodies. In 2016 the RIEGL BDF-1 was presented to the market as a product. The BDF-1 surveying system including IMU, GNSS, and camera has successfully been operated from RIEGL's self-developed and manufactured octocopter, the RiCOPTER. Full waveform recording of the entire range gate allows for performance improvement through pre-detection averaging (Mandlburger et al. 2016).

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