Total Shallow-Water Survey Through Airborne Hydrography

Jennifer M. Wozencraft
Joint Airborne Lidar Bathymetry Technical Center of Expertise
US Army Corps of Engineers
109 St. Joseph Street
Mobile, AL 36602 USA
Phone: (251) 690-3466   Fax: (251) 690-3464
Email: jennifer.m.wozencraft@usace.army.mil

W. Jeff Lillycrop
Joint Airborne Lidar Bathymetry Technical Center of Expertise
US Army Corps of Engineers
109 St. Joseph Street
Mobile, AL 36602 USA
Phone: (251) 694-3721   Fax: (251) 690-3466
Email: jeff.lillycrop@usace.army.mil

Eight years of SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey) operations have proven that airborne bathymetric lidar is an ideal tool for rapidly measuring shallow water depths and nearshore land elevations. The next generation Compact Hydrographic Airborne Rapid Total Survey (CHARTS) and Bathymetric And Topographic Survey (BATS) systems are fully integrated suites of airborne sensors, including bathymetric lidar, topographic lidar, and digital imagery. The flight parameters and sensor suites of the new systems are ideal for further integration with other airborne sensors like hyperspectral imagers. The new systems allow not only collection of shallow water depths, but also classification of shoreline features and shoreline position essential to a complete hydrographic mission. This paper outlines the future of airborne hydrography through a description of CHARTS and BATS. The current research and development efforts that support the creation of the new systems will result in a new era of total shallow-water survey from an airborne platform.

Introduction

The US Navy through the Joint Airborne Lidar Bathymetry Technical Center of Expertise awarded a contract through Technology Partnerships Canada to Optech, Incorporated, of Toronto, for the creation of two airborne lidar survey systems. The Compact Hydrographic Airborne Rapid Total Survey (CHARTS) system will fulfill Navy requirements for nautical charting, while the Bathymetric And Topographic Survey (BATS) system will fulfill requirements for tactical operations. Both systems will be integrated bathymetric/ topographic systems with digital imagery capability. CHARTS bathymetric component will operate at a rate of 1,000Hz, while its topographic component will operate at 10,000 Hz. BATS will operate at 400 Hz in both modes. CHARTS will collect data meeting IHO (International Hydrographic Office) Order 1 requirements and will easily fit onto most

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2002**	2. REPORT TYPE	3. DATES COVERED **00-00-2002 to 00-00-2002**
4. TITLE AND SUBTITLE **Total Shallow-Water Survey Through Airborne Hydrography**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Joint Airborne Lidar Bathymetry Technical Center of Expertise,US Army Corps of Engineers,109 St. Joseph Street,Mobile,AL,36602**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **Proceedings, Oceanology International 2002, London, England**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

photogrammetric aircraft of opportunity. BATS will meet IHO Order 2 requirements and will operate from an unmanned aerial vehicle.

The development of CHARTS and BATS relies heavily on existing SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey) system technology. SHOALS is an airborne lidar bathymeter developed by the US Army Corps of Engineers (USACE) to meet its hydrographic surveying needs. SHOALS currently collects both nearshore land elevations and water depths out to 60 m for a variety of applications including coastal mapping for sediment management, nautical charting, and coral reef studies. Design of the new systems will be an upgrade and miniaturization of current SHOALS components. Data processing algorithms for the new systems will incorporate existing SHOALS algorithms and will include more automated versions of processing tools that currently require visual inspection of individual data points.

This paper will describe existing SHOALS technology and outline the future of airborne hydrography through a description of the CHARTS and BATS systems.

Background: The SHOALS System

Eight years of SHOALS operations have proven that airborne bathymetric lidar is an ideal tool for rapidly measuring shallow water depths and nearshore land elevations. The USACE developed SHOALS to collect water depths in navigation channels for dredge payment surveys. Since its field test in March 1994, SHOALS demonstrated this and additional capability at many USACE navigation channels and shore protection projects, during nautical charting surveys for the US Navy, and during large-scale surveys for regional coastal monitoring. During this time, SHOALS algorithms have been enhanced to include a capability for measuring nearshore land elevations simultaneously with water depths.

In its original configuration, SHOALS was mounted between the skids of a Bell 212 helicopter (Figure 1A). The system itself operated at 200 Hz, with the aircraft flying at an optimal altitude of 200 m and speed of 50 m/s. These operating parameters yielded a swath width of 110 m and depth measurements spaced only 4 m apart in both the along-track and across-track directions. Overall coverage rate was 16 km^2/hour.

Figure 1. SHOALS system deployed on a Bell 212 helicopter (Figure1A) and a Twin Otter airplane (Figure 1B).

In late 1999, SHOALS was upgraded to 400 Hz and transitioned to the fixed-wing Twin Otter airplane (Figure 1B). In the Twin Otter, the SHOALS system is specially fitted over the photogrammetric window in the rear of the aircraft. The faster survey rate and flying speed increased the overall coverage rate to 25 km^2/hour and measurement spacing to 8 m. The capability exists to decrease altitude and flying speed to decrease measurement spacing when required. Typical operating parameters for this current installation of SHOALS are shown in Table 1. In this configuration, SHOALS missions became focused more on regional surveys, completing areas as large as the Hawaiian Islands, Puerto Rico and nearby islands, and the Lake Ontario shoreline in a matter of months.

Table 1. SHOALS operation and performance characteristics.

Maximum depth	to 60 m
Vertical accuracy	±0.15 m
Horizontal accuracy	
DGPS	±3 m
KGPS	±1 m
Sounding density	8 m grid (variable)
Operating altitude	400 m (variable)
Scan swath width	220 m (variable)
Operating speed	50 to 70 m/s

The core of SHOALS operations is a pulsing laser (Guenther et al. 2000, Irish et al. 2000, Guenther et al 1996). A scanning mirror directs the laser pulses in an arcing pattern on the water surface forward of the aircraft. Each laser pulse is composed of light at two wavelengths: 532 nm (green) and 1064 nm (infrared). Receivers in the aircraft detect the return of both wavelengths from each pulse. The red light reflects from the water surface ("specular interface reflection", Figure 2) while the green light propagates through the water column to reflect from the sea floor ("diffuse bottom reflection" and "reflected bottom signal," Figure 2). The surface and bottom returns are analyzed to determine a water depth for each laser pulse that is corrected for water level fluctuations due to waves and tides.

Each depth measurement is positioned horizontally based on the position of the aircraft as determined by differential, or pseudo-range, GPS techniques and the geometry of the system. During data collection, the depths are referenced vertically to the mean water level at the time of survey. They are later referenced to a known elevation on land using concurrently collected tide measurements. A video camera records each survey line and is tagged with readings from aircraft instrumentation: roll, pitch, and heading from the inertial measurement system, geographic position from the GPS, and timestamp from the SHOALS system itself. SHOALS measurements are accurate to IHO Order 1 standards, or ± 0.15 m in the

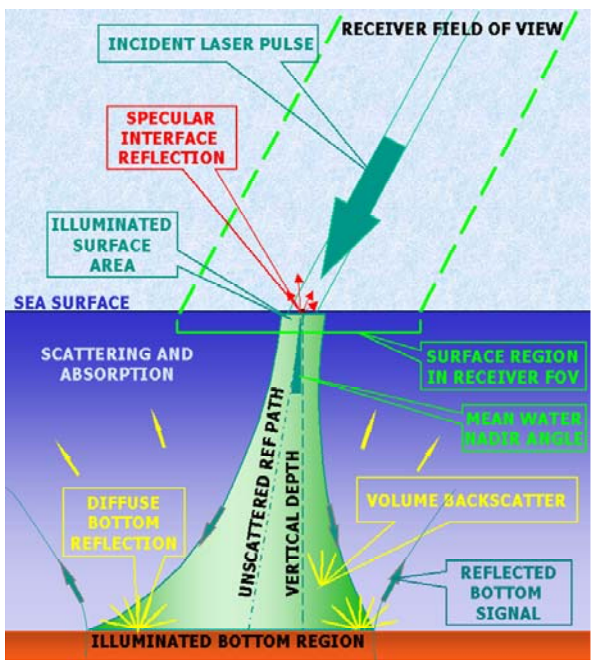

Figure 2. SHOALS operating principle.

vertical and ± 1-3 m in the horizontal (Irish et al. 2000, Pope et al. 1997, Riley 1995).

The result of SHOALS technology is an ASCII file containing XYZ data that can be imported into any CAD, GIS, or digital terrain-modeling package. An example of SHOALS data collected at East Pass, Florida, USA, is shown in Figure 3A. East Pass is located on the Gulf of Mexico coastline of the Florida Panhandle. An aerial photo of the survey area is shown in Figure 3B for reference. This data covers a 3.5 km portion of a 200 km regional monitoring project for SHOALS. Surveys of this detail on a regional scale are collected in a matter of days.

The maximum water depths detectable by SHOALS are limited by water clarity, or the amount of turbidity, in the water column. As the laser pulses travel through the water column, several processes occur that limit the amount of light to eventually reflect from the sea floor and return to the receivers in the aircraft. Light energy is lost during refraction and is scattered and absorbed by particles in the water and by water molecules themselves. In practice, this means SHOALS can "see" 2-3 times the Secchi, or visible, water depth. In the clearest coastal waters, the maximum detectable depth is 60 m.

The ability to measure nearshore land elevations was realized during the first year of operations. When a laser pulse strikes land, the red surface return is strong enough to saturate the receiver in the aircraft. Saturated returns were considered bad until processors noted that the green bottom return was reporting reasonable (though negative) land elevations in this situation. In light of this realization, the algorithms were updated to ignore the saturated IR return and accept the land elevation based on the mean water level calculated from water depths near that data point. With the new processing tool, on-land elevations falling within ½ swath-width from the water's edge are reported with accuracy, increasing SHOALS survey capability to include beaches and beachfills, nearshore and shore-normal structures, and sea-surface piercing features like rocks and breakwaters.

The capability to measure land elevations was further augmented in 1997 with the implementation of carrier-phase, or kinematic, GPS techniques. Kinematic GPS post-processing gives the altitude of the aircraft relative to temporary base stations operating at the time of survey. Including the vertical position of the aircraft in SHOALS data processing eliminates the need to collect concurrent tide measurements. With the vertical reference included in the aircraft position, land elevations could be extended beyond the ½ swath width required when using only differential GPS, increasing SHOALS survey capability further to include more landward coverage of beaches and coverage of completely land-locked areas. SHOALS topographic capability is limited by the configuration of the system, specifically a minimum 2-m laser footprint at typical operating parameters.

During nautical charting missions, SHOALS has demonstrated many advantages over traditional survey methods in shallow water. Operating from both the Bell 212 and the Twin Otter, SHOALS has played an instrumental role in nautical charting missions offshore of Cancun, Mexico, for the Mexican Navy; south of New Zealand for the Royal Australian Navy; and for the US Navy on the Great Bahama Banks, and around the major Hawaiian

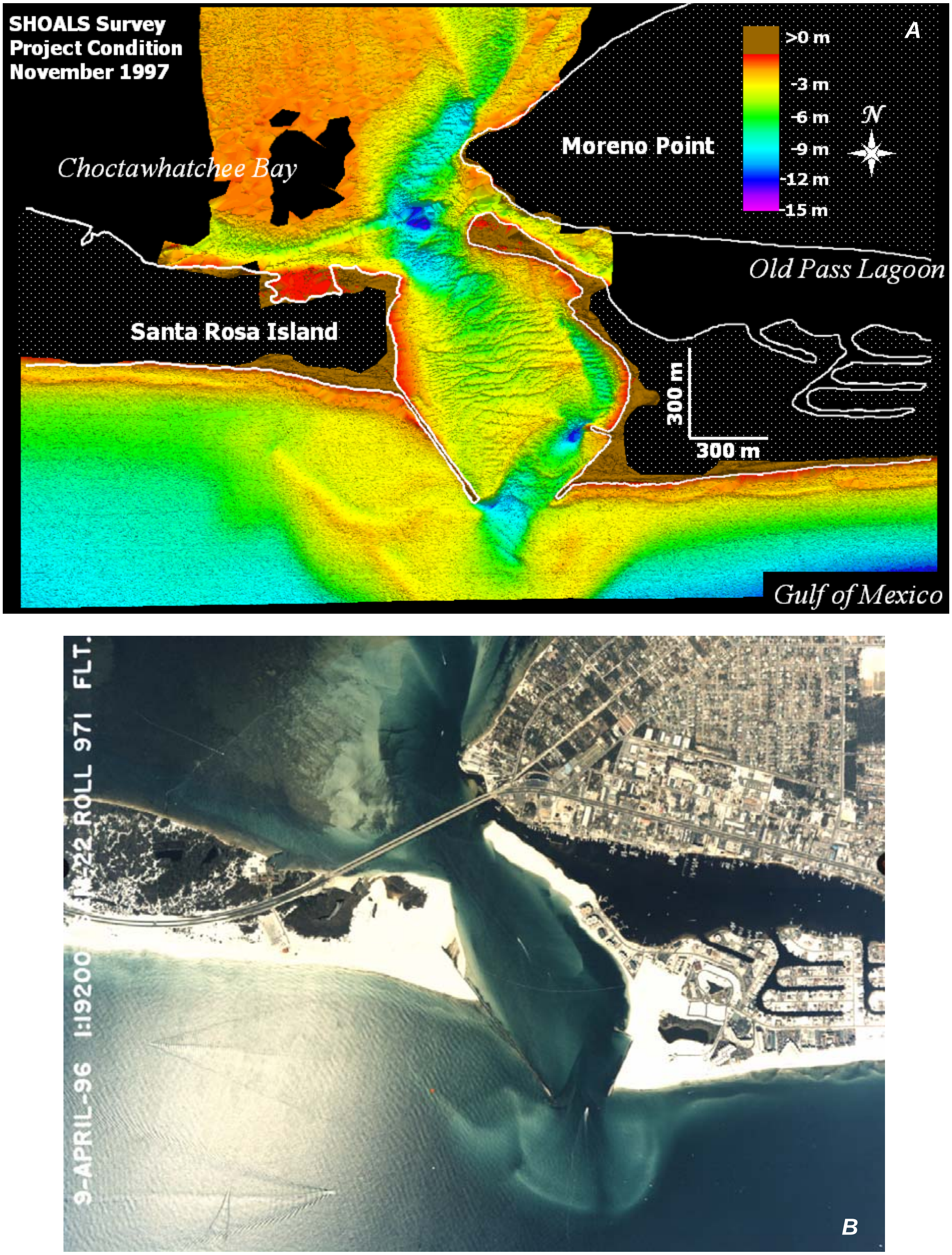

Figure 3. East Pass, Florida, USA. Figure 3A is a 3D rendering of SHOALS data collected at East Pass in November 1997. Figure 3B is an aerial photo of East Pass.

Islands, Guam, and Saipan. Many advantages of the SHOALS system are derived from its operation from an airborne platform. SHOALS has a very rapid coverage rate. SHOALS swath width remains constant as water depth decreases, so SHOALS coverage rate remains constant as water depth changes. Areas hazardous to surface-borne survey vessels, like coral reefs, protruding rocks, and previously unsurveyed shallow waters, are safely accessible to an airborne system. In addition to collecting water depths in navigable depths, SHOALS collects depth measurements in the 0-2 m range and land elevation measurements. SHOALS video provides a visual record of surf conditions and land features useful to identification of anomalous returns in the data and providing a record of conditions at the survey site.

CHARTS and BATS

SHOALS performance through many nautical charting missions precipitated a JALBTCX contract for two new airborne lidar bathymetric systems for the US Navy. CHARTS and BATS represent a new generation of airborne lidar hydrographic systems. Development for the new systems centers on miniaturizing components of the lidar bathymetric sensor and reducing the expertise required for system operation through automation of existing flight planning and data processing tools. The new systems will provide enhanced video capability with the integration of digital imagery and will afford new opportunities for fusion with additional airborne sensors. Performance characteristics of both systems are summarized in Table 2.

CHARTS will fulfill NAVO requirements for coastal mapping and nautical charting. The CHARTS system will consist of a 1,000 Hz bathymetric lidar. The added value of concurrent topographic and bathymetric collection by the SHOALS system led to integration of a topographic lidar operating at 10,000 Hz in the new system. The bathymetric and topographic components will have separate lasers, but share receivers to reduce hardware requirements. CHARTS will be capable of operating in two modes: the hydrographic mode, which is the mode in which SHOALS currently operates at all times, and a topographic mode. In topographic mode, CHARTS will operate strictly in the infrared wavelengths and have no hydrographic capability. CHARTS will not operate in both modes simultaneously

The increased pulse rate of the CHARTS system will in turn increase allowable aircraft speed, and therefore will also increase survey coverage rate. Increased aircraft speed will enable integration with sensors that are flown at higher speeds. For example, concurrently collected hyperspectral imagery can delineate/quantify environmental parameters like sea bottom type and sediment concentration. The CHARTS system will also have an enhanced down-looking video capability. Digital imagery collected during a survey will be tagged with time and geographic position to provide a visual record of environmental conditions at the time of survey for later use in identifying coastal features or anomalous returns. The digital imagery is a value-added georeferenced imagery product that will accompany the lidar bathymetric and topographic data.

Additional development for the CHARTS system focuses on a capability to install and operate the CHARTS system on most photogrammetric aircraft of opportunity. Some example aircraft are shown in Figure 4. The CHARTS system will be a more compact version of the SHOALS system, even with the added topographic capability, so that it will fit easily in most commercially available aircraft. The specified maximum total weight for the CHARTS system is 210 kg. Design of CHARTS casings and fittings will be compatible with a variety of aircraft.

Figure 4. Photogrammetric aircraft of opportunity for CHARTS missions.

BATS will fulfill NAVO requirements for tactical operations. The BATS system will essentially be a much more compact and automated version of the current SHOALS system. It will retain many of the operating parameters of existing SHOALS technology including 400 Hz operating speed, flight speed, and swath width approximately equal to ½ altitude. Topographic capability will only include that currently available using saturated IR returns or

Table 2. Performance requirements for CHARTS and BATS systems.

Parameter	**CHARTS Requirements**	**BATS Requirements**
Depth Measurement	To 50 meters	To 30 meters
Maximum depth	Kd>3.0 (daytime)	Kd>2.5 (daytime)
Minimum depth	To as shallow as 0.1 meter	Less than 1 meter
Operational Altitude	Hydro: 200 m < alt < 400 m; Topo: 300 m < alt < 700 m (10kHz)	Hydro: 200 m < alt < 400 m; Topo: 300 m < alt < 1,000 m
Aircraft Speed	125 to 175 knots (nominal)	40 to 80 knots (nominal)
Laser spot spacing	2x2, 3x3, 4x4, 5x5 meters	2x2, 3x3, 4x4, 5x5 meters
Scan swath width	70% of the altitude	Half the altitude
Vertical accuracy of Soundings & Elevations	IHO Order 1	IHO Order 2 (hydro) Dependent on VTUAV GPS (topo)
Horizontal positional accuracy of Soundings & Elevations	IHO Order 1	Error not greater than ± 10 meters, with 95 percent probability (P-code).
Laser Operation	Hydrographic >1,000 Hz (nominal) Topographic >10,000 Hz (nominal) Operate at same altitude	Hydrographic >400 Hz Topographic >400 Hz Operate at same altitude
Laser Energy	5 mJ nominal	>3 mJ nominal
Post Processing and Validation	Depths – 1.0:1.0 (processing:collection) Hazards and obstacles – 1.0:1.0	Depths - 0.5:1.0 (processing:collection) Hazards and obstacles – 1.0:1.0
Video Record	Digital. Time & position tagged color video	Digital. Time & position tagged color or night video
Airborne Sensor Weight	210 Kg or less	100 Kg or less

kinematic GPS. Like CHARTS, BATS will incorporate an enhanced video capability through integration of digital imagery capability. BATS will be integrated with digital color or nighttime video. Each video frame will be referenced to the survey by time and geographic position. This value-added product will again provide a visual record to aid in identifying coastal features and anomalous returns, as well as provide a sample of environmental conditions at the survey site to the war fighter.

A major component of BATS development is capability for deployment on an unmanned aerial vehicle (UAV). The UAV selected for the BATS system is the Northrup-Grumman Vertical Takeoff and Landing UAV shown in Figure 5. This capability requires fully automated sensor operation with remote controls, a very compact and lightweight sensor, and an in-flight data relay system. The specified maximum total weight of the BATS system is 100kg. An additional requirement for the BATS system is highly automated processing algorithms that decrease processing time for bathymetric data to ½ the time required for data collection. For example, recent work has improved the capability of the SHOALS system to more accurately discriminate between land and water returns in the presence of whitewater (Sosebee 2001).

Figure 5. Northrup-Grumman Vertical Takeoff and Landing UAV for BATS deployment.

Conclusion

The development of CHARTS and BATS represents a generational advancement in the state-of-the-art in airborne lidar surveying. The advancement relies heavily on lessons learned through eight years of operation and continuing development of the SHOALS system. The integration of bathymetric and topographic lidar with digital georeferenced imagery capability in the CHARTS system will provide a full description of the coastline and upland topography, nearshore water depths, and any hazards to navigation in a survey area. Increases in operating speed realized in the new CHARTS system will allow integration with other airborne sensors like hyperspectral imagers. The more automated BATS system will provide a new asset for measuring bathymetry, nearshore topography, and imagery of hostile territory. The current research and development efforts of the JALBTCX to support the creation of CHARTS and BATS will result in a new era of total shallow water survey from an airborne platform.

References

Guenther, G. C., Cunningham, A. G., LaRocque, P. E., and Reid, D. J. 2000. Meeting the accuracy challenge in airborne lidar bathymetry. Proceedings of EARSeL Symposium 2000. Dresden, Germany.

Guenther, G. C., Thomas, R. W. L., and LaRocque, P. E. 1996. Design considerations for achieving high accuracy with the SHOALS bathymetric lidar system. SPIE: Laser Remote Sensing of Natural Waters: From Theory to Practice. 15: 54-71.

Irish, J. L., McClung, J. K., and Lillycrop, W. J. 2000. Airborne lidar bathymetry: the SHOALS system. PIANC Bulletin. 2000(103): 43-53.

Pope, R. W., Reed, B. A., West, G. W., and Lillycrop, W. J. 1997. Use of an airborne laser depth sounding system in a complex shallow-water environment. Proceedings of Hydrographic Symposium XVth International Hydro Conference. Monaco.

Riley, J. L. 1995. Evaluating SHOALS bathymetry using NOAA hydrographic survey data. Proceedings, 24th Joint Meeting of UJNR Sea-Bottom Surveys Panel. Japan.

Sosebee, C. R. 2001. Improvement of the land/water discrimination algorithm for the US Army Corps of Engineers Scanning Hydrographic Operational Airborne Lidar Survey System. Masters Thesis, Cornell University.