AIRBORNE LIDAR: A SURVEYING TOOL FOR THE NEW MILLENNIUM

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I. Abstract

The last few years of the 20th century have witnessed the "coming of age" of Airborne Laser Bathymetry (ALB) and its transition from research and development technology to routine operational use. Despite this transition, the technology is still generally poorly understood in the hydrographic survey community, and in this environment it has been difficult to establish a universally accepted philosophy for its use. This paper explores the strengths and limitations of the technology and relates these characteristics to several scenarios, with particular emphasis on how the use of Airborne Laser Bathymetry systems is likely to impact survey operations of the future.

II. Introduction

There has been a tendency to regard Airborne Laser Bathymetry (ALB) technology as developmental and only an addendum to multibeam echo sounders (MBES). However, as with MBES, several systems have now reached operational maturity, and it is clear that ALB has proven its worth as a survey tool for hydrographic surveys. This paper discusses the characteristics of ALB and how it can be best employed to integrate with existing survey systems.

The attraction of ALB lies in its capability to augment conventional surveys in a cost-effective manner, while operating within relatively clear, shallow-water regions that are the most costly, hazardous, and time-consuming areas for ship and boat operations. This capability is highlighted by the comparison between ALB and multibeam fitted launches which suffer from significantly decreased swath width in very shallow waters, while ALB swath width remains fixed, irrespective of depth (Fig. 1). This is particularly significant in an environment where the US Navy has vast "brown water" requirements. In addition, ALB has the ability to provide a rapid response to new survey areas measured in weeks, as opposed to months, for typical shipborne operations. In summary, Hydrographic Survey Launches (HSLs) are currently the primary platforms for surveys in depths shallower than 50m, but suffer from the following disadvantages:

A. Dependence on a Mother ship,
B. Slow coverage rates,
C. Vulnerability to damage.

ALB has the potential to overcome all these disadvantages (Guenther, 1985).

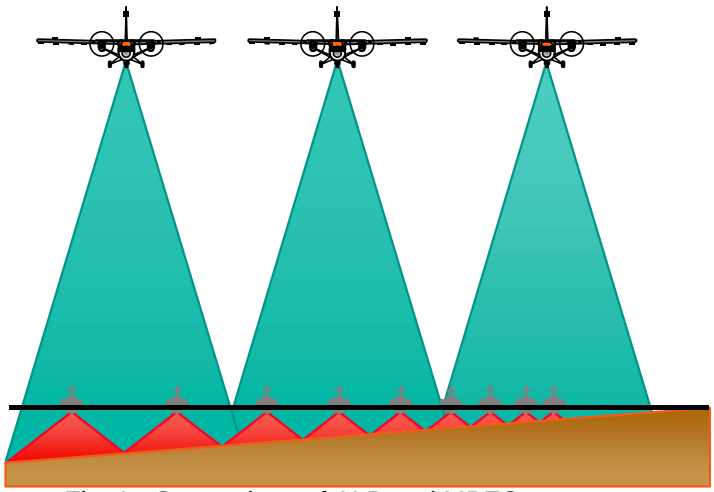


Fig. 1. Comparison of ALB and MBES coverage.

III. Principles of Light Detection and Ranging (Lidar)

All Lidar systems operate on the principle that water depth may be calculated from the time difference of laser returns reflected from the sea surface and seabed. In

[1] The Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) was established in May 1998 by the signing of a Memorandum of Agreement between the US Army Corps of Engineers, South Atlantic Division, the Waterways Experiment Station, and the Commander, Naval Meteorology and Oceanography Command.

most systems an infrared channel (1064 nm) is used for surface detection, while bottom detection is from a blue-green channel (532 nm), as shown in Fig. 2. The maximum depth measurable by a system is heavily dependent on water turbidity and can vary considerably from just a few meters in very turbid water to several tens of meters in very clear water. Water clarity is usually expressed as the diffuse attenuation coefficient K_d, which numerically is the distance over which light intensity diminishes to 1/e of its initial value. Consequently, depth performance of ALB systems is generally expressed as the product $K_d\ D$, where D is the depth.

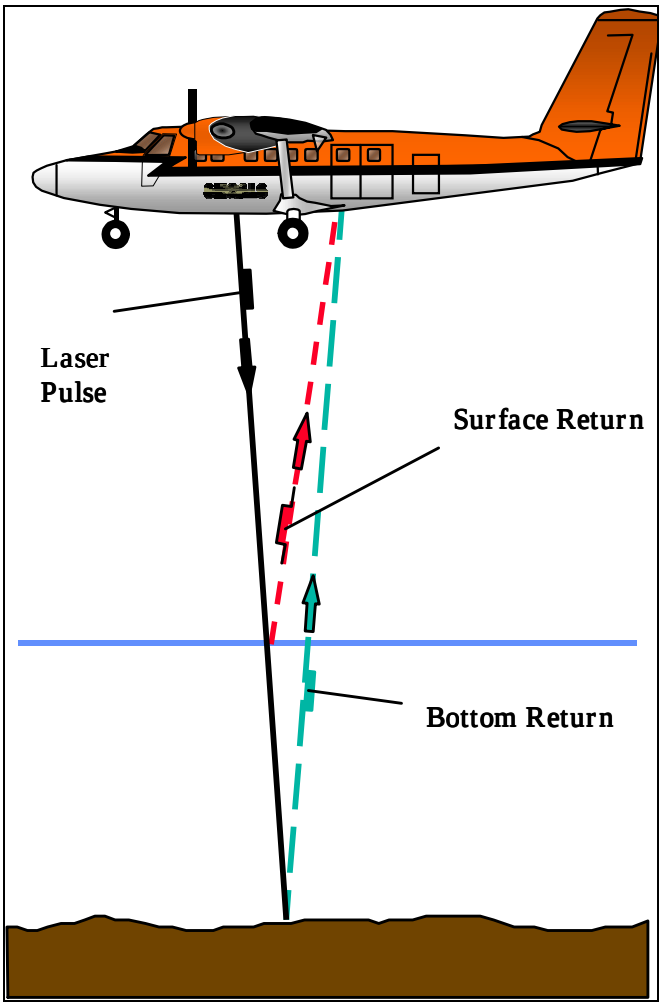
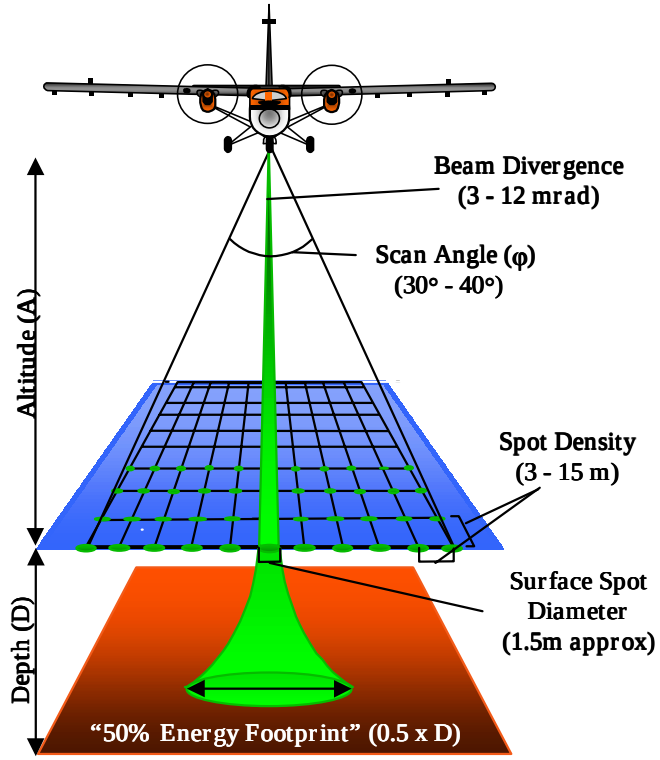


Fig. 2. ALB depth measurement.

The basic geometry of an ALB system is shown in Fig. 3, though it should be noted that the rectilinear scan pattern shown is a generalization, since many systems employ a swept arc pattern. Although source beam divergence is of the order of 12 mrad, producing a spot on the sea surface of about 1.5m diameter, the many spreading and scattering effects mean that 90% of the energy is contained within a footprint of diameter approximately equal to the depth. However, much of this energy is returned with a significant time lag and is insignificant for measurement purposes. The consequence is that a footprint with a diameter of ½ the water depth (containing 50% of the energy) is normally regarded as the "effective" footprint of an ALB system. It is important, however, to realize that illumination of the bottom does not infer detection of small targets within the footprint. For this to occur, the ratio of illuminated target area to illuminated bottom area has to be sufficiently high to enable both automatic and human recognition. To understand the reasons for this, it is necessary to discuss briefly how bottom detections are made.

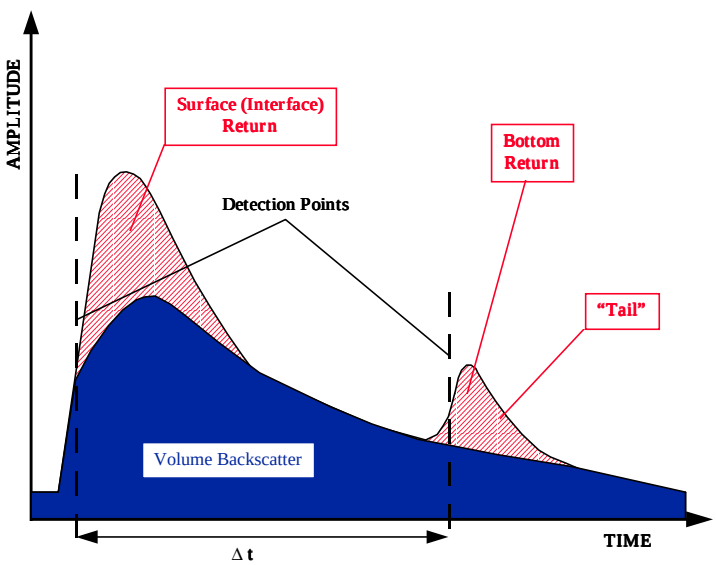


Although surface detection is usually made with the infrared channel, the blue-green channel will also detect the surface. Because of this, the generic ALB waveform is of the type shown in Fig. 4, with two distinct returns from the air/sea interface and the bottom. The asymmetry of the bottom return is a consequence of the large footprint but, as stated above, the "tail" is largely from outside the "50% diameter" footprint. Since the detection is measured on the leading "up" ramp of the waveform, it becomes clear why this scattered energy is irrelevant to the depth calculation. Present ALB systems have demonstrated capability to achieve depth accuracy standards at least as accurate as current acoustic systems (Riley, 1995) and because of this, compliance with current IHO Standards can justifiably be claimed.

Fig. 5 illustrates a typical shallow-water waveform. The bottom is saturated on the deep channel, clearly illustrating that the use of two channels is often preferred. In Fig. 6, a deep return is shown; not only does this fall beyond the maximum depth of the shallow channel, but it has a low

amplitude waveform resulting from considerable spreading of energy, which results in a large "footprint" that may get lost in noise.

Although the examples above describe the majority of cases, it is the determination of target detection capabilities that is fundamental to the characterization of Lidar as a hydrographic survey tool. The distinction between bottom illumination and confident target detection is therefore important to understand. Fig. 7 illustrates the case where there is evidence of a return above the bottom (deep channel); however, the shallow channel shows this to be a distinct and separate return, so the likelihood is that this is fish. In Fig. 8, both the deep and shallow channels show a separate return in midwater column, clearly indicating fish or other suspended material. These cases are just two examples of the problems posed in distinguishing apparent anomalies with real bottom hazards; the technology has changed, but the role of the hydrographer as an interpreter of the data has not. The situation becomes even more difficult in deep water, where a decreasing proportion of the total incident energy will illuminate small objects so they become masked by the "up" ramp of the bottom return.



IV. Hazard Detection

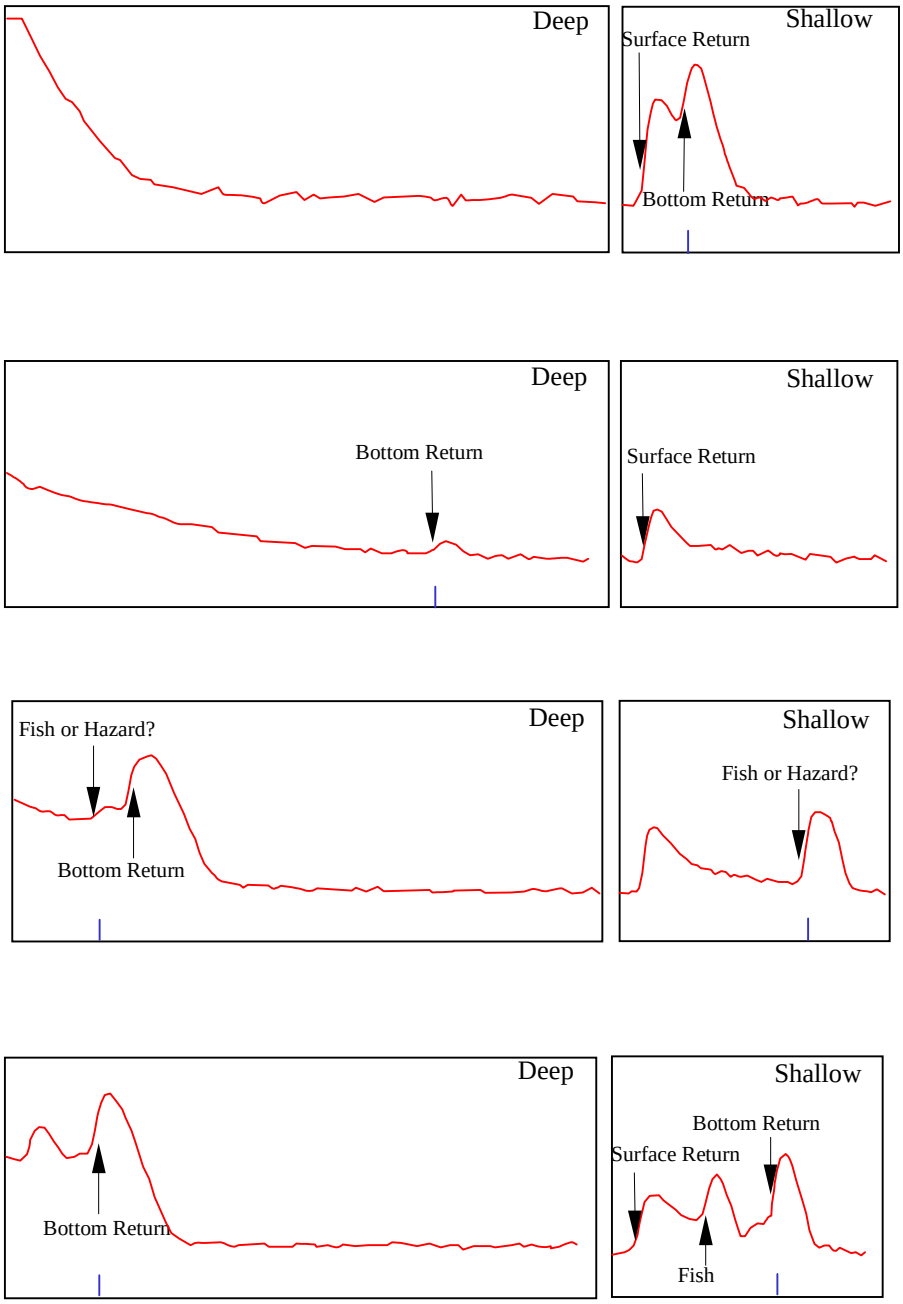
So far, only the single sounding (often known as a "shot") has been considered, and it should be clear by this point that such a situation falls short of the requirements of a hydrographic system, both in coverage and object detection. Current ALB systems employ a mechanical scanning mirror to achieve a swath, which when combined with the PRF of the laser produce a grid pattern of spots. Equally, the need for drawing a clear distinction between 100% bottom illumination and hazard detection confidence should also be recognized. Because of the need to illuminate a target with sufficient proportion of the laser footprint to result in detection, denser spacing of shots results in higher chances of detection.

This "sounding" spacing is generally referred to as spot density, and considerable debate has occurred over recent years as to optimum spot density required for hydrographic purposes. Guenther et al. (1996) highlighted this issue in a study from which Fig. 9 is developed. This is a stark illustration of the relative effectiveness of different spot densities and underlies his conclusions that "significant gains can be obtained in many cases by decreasing average linear sounding spacing to 3m." It was further concluded, "objects less than 1m high are not frequently detectable." As will be apparent from this paper, the operational benefits of ALB over acoustic systems are so compelling that the desire to replace these older systems with ALB has become extremely powerful. Consequently, the need to define the envelope of ALB capabilities is an important step if it is to replace traditional acoustic systems in legitimate circumstances. It is in this area that the most significant work in proving the efficacy of laser hydrography can be done; and while the work of Guenther et al. (1996) has been a leap ahead in the characterization of Lidar for hydrography, the process of fully characterizing ALB performance is only in its infancy. In parallel with this, we are also challenged to fully define the capabilities of our older technologies and, moreover, to be honest as to whether they actually achieve the capabilities we have so often only assumed. Most importantly for ALB, although its ability to achieve compliance on the basis of depth measurement accuracy with all Orders except "Special" (of the new IHO Standards) is assured, target detection criteria will dominate as the controlling factor over which Order an ALB survey will fall into.

V. Cost Effectiveness

Fig. 10 compares the coverage rates in differing depths of ALB to other shallow-water survey systems. While the vastly superior coverage rates of ALB over most shallow-water survey systems should come as no surprise, the relative effectiveness of ship-mounted multibeam in depths greater than 50m is evident. Consequently, there seems little to be gained from increasing the depth capability of ALB systems at present. Equally, it is worth noting that, while acoustic systems are close to maturity and therefore to their performance limits, ALB has much potential for further development and is only likely to increase its advantages.

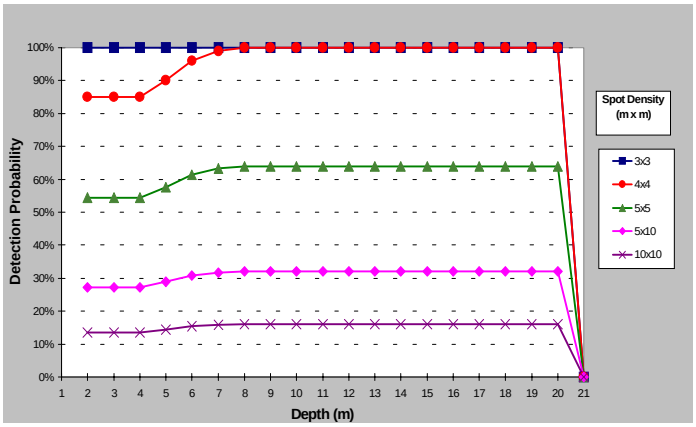
Several studies have attempted to analyze the cost benefit of ALB, the most recent of which examined several scenarios including ALB in a mutiplatform environment (Axelsson and Alfredsson, 1999). To an extent, the validity of this exercise is questionable since the comparison between a high-resolution sidescan



survey and ALB, for instance, is not a fair one. However, the utility of this is to indicate where the potential benefits of different systems are most likely to be realized. Indeed, Fig. 10 indicates some startling, if hardly surprising, features. Most notable is that ALB is at least as cost effective to run as conventional systems, while it is most economical in areas where conventional assets are least economic—in very shallow water. When taken in these terms, the new International Hydrographic Organization Standards for Hydrographic Surveys (SP 44) becomes especially significant, as it gives far more latitude for the survey planner/charting authority to choose required resolutions.

VI. Practical Applications

In July 1996, the Airborne Lidar Bathymetry Technical Center of Expertise (ALBTCX) was established by the United States Army Corps of Engineers (USACE). Its missions are to produce quality products using the SHOALS system, promote the commercialization of lidar bathymetry, and foster the evolution of airborne lidar and complimentary technologies. The ALBTCX is comprised of personnel representing the USACE, John E. Chance and Associates, the National Oceanic and Atmospheric



Administration's Aircraft Operations Center (AOC), the National Ocean Service (NOS), and Optech, Inc.

A Memorandum of Agreement (MOA) signed by the Commander, Naval Meteorology and Oceanography Command (COMNAVMETOCCOM) and the USACE in May 1998 expanded the scope of the USACE ALBTCX to a Joint ALBTCX (JALBTCX), incorporating the Naval Oceanographic Office's (NAVOCEANO's) needs into its mission and promoting the mutual leveraging of knowledge, resources, and expertise with respect to ALB and related technologies. It also serves as a vehicle to facilitate the availability of SHOALS to support COMNAVMETOCCOM/NAVOCEANO surveys. One of the primary roles of the JALBTCX is to develop the applications of Lidar technology; this has principally been achieved through operational use of the Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) system. Probably the most versatile Lidar survey system in use anywhere in the world today, it has recently undergone a major upgrade to enable it to operate from either fixed wing aircraft or helicopter. The system was installed in a Twin Otter (Fig. 12) during the fall of 1998 and has since completed projects in New Zealand, Hawaii, and the Bahamas in addition to the continental USA.

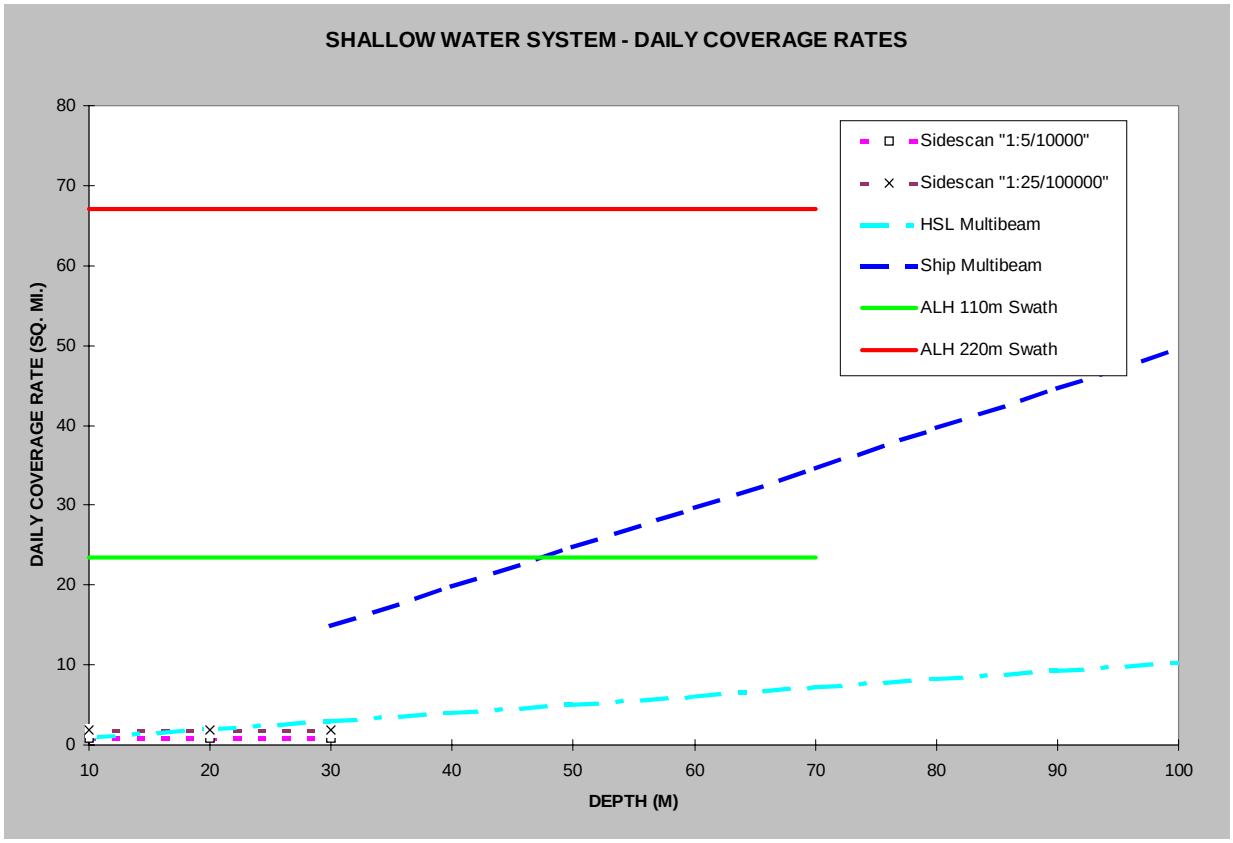
SHOALS incorporates a 400Hz laser, scanning a swath of up to 220m with a selectable spot density of 3 to 15m. Depending on selected scan width and spot density, the system can be flown at speeds up to 120kn. A single operator can operate the airborne system, but due to the extended duration of flights, usually two operators are used. Data are recorded onto Exabyte 8mm dual tape drives, which are also used for loading survey flight planning data. After landing, the data are processed by specialized postflight depth extraction procedures that calculate depths and positions, and correct for tides and waves. Automation is maximized in this part of the software so that the amount of human intervention is reduced, producing a time ratio of 1:1 with data collection. The output from the automated processor can then be accessed via a manual processor interface, that is the primary method of editing and quality-controlling the data. The final postprocessing product is an ASCII x, y, z file that can be imported into any standard CAD package for mapping.

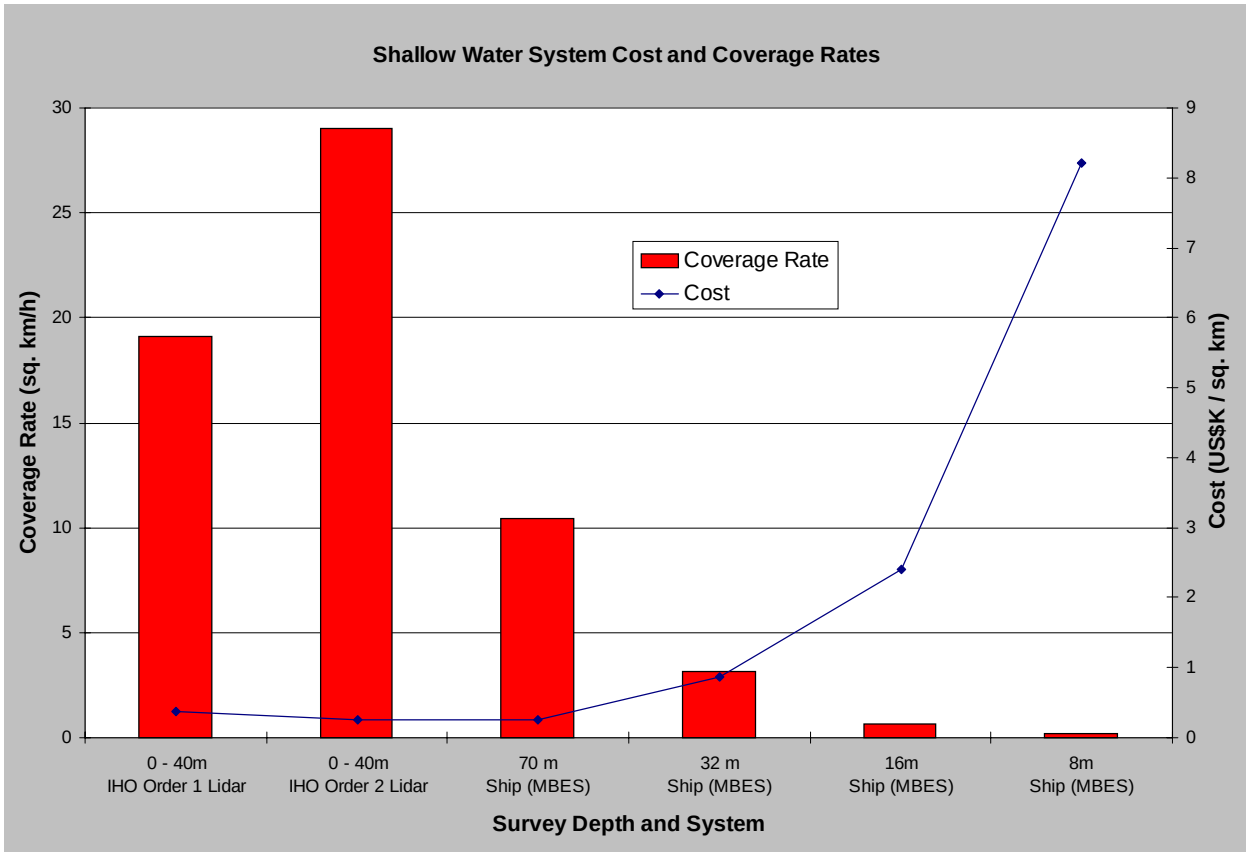
VII. Regional Coastal Management

One of the main reasons for the development of SHOALS was to conduct USACE channel condition and structure surveys and their impacts to adjacent shorelines. However these surveys have traditionally been small in scale and narrowly focused, which degrades many of the economic benefits of SHOALS. More recently, however, there has been a realization that effective management of the coastline relies on accurate, quantified characterization of a region over time. This approach allows computation of sediment volumes of smaller areas, which can then be monitored over time to establish sediment transport budgets. Traditionally the typical method of collecting survey data in and around coastal projects consists of widely spaced transects or profiles derived from conventional acoustic sounders and land leveling. The need for greater detail on the regional level is typically overlooked and often results in missing associated features that have an effect on surrounding areas. In an effort to redress this situation, the USACE has started to move toward a regionalized approach for sediment management, starting with a demonstration area in the coastal regions of the northern Gulf of Mexico. The objective of the proposed demonstration is to assess the benefits of managing sediment, specifically sand, as a regional-scale resource and to identify the obstacles that may hinder or prevent the realization of such benefits (Parson et al., 1999).

Conceptually, this approach appears to make perfect sense; however, it has become viable only as a result of Lidar technology. Because of its ability to rapidly survey entire regions seamlessly across the land/sea interface, SHOALS has become the tool of choice. The key to this has been the development of Kinematic GPS capability, which has effectively given SHOALS the ability to collect data independently of the sea surface. Consequently, all vertical elevations are directly related to the ellipsoid and are not subject to errors introduced by tidal measurements and changing datums.

As a participant in the USACE sediment management initiative, the Florida Department of Environmental Protection (FLDEP) has been concerned with the fact that almost 40% of the beaches are suffering serious erosion (Green, 1998). Using traditional methods, FLDEP has been able to survey only 4 counties each year quickly. However, in 1998 SHOALS commenced a program that will result in the entire Florida coast being mapped every 2 years, 50% each year. Elevations from 500m landward of the waterline to 750m seaward are


SHALLOW WATER SYSTEM - DAILY COVERAGE RATES
DAILY COVERAGE RATE (SQ. MI.)
DEPTH (M)
Sidescan "1:5/10000"
Sidescan "1:25/100000"
HSL Multibeam
Ship Multibeam
ALH 110m Swath
ALH 220m Swath
0
10
20
30
40
50
60
70
80
90
100


Shallow Water System Cost and Coverage Rates
Coverage Rate (sq. km/h)
Cost (US$K / sq. km)
Coverage Rate
Cost
0 - 40m IHO Order 1 Lidar
0 - 40m IHO Order 2 Lidar
70 m Ship (MBES)
32 m Ship (MBES)
16m Ship (MBES)
8m Ship (MBES)
Survey Depth and System

collected at 8m spacing; the data are then fused with aerial photography and overlaid in a GIS for presentation and analysis (Fig. 13). This represents a quantum leap in resource management that has come to fruition only because of the availability of Lidar technology (Watters and Wiggins, 1999).

VIII. Nautical Charting

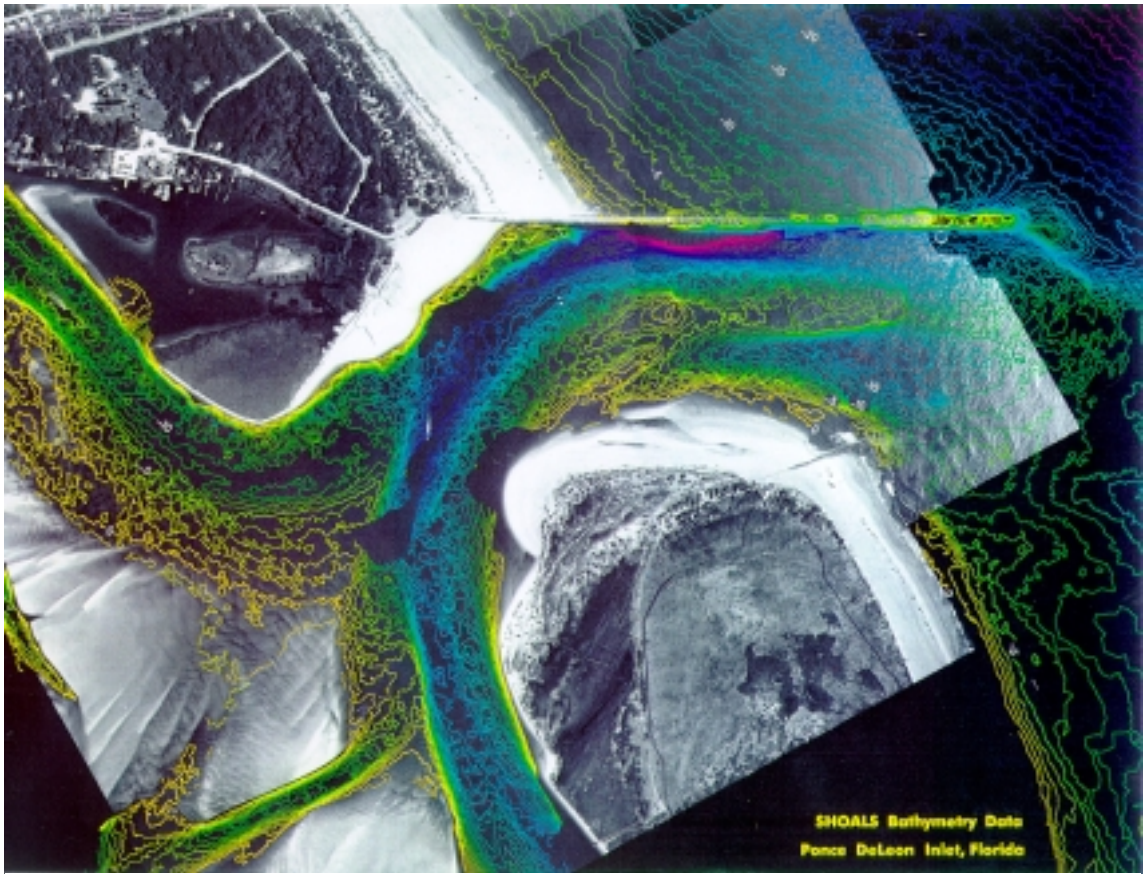
Since becoming operational, SHOALS has completed major nautical charting projects in Mexico (Pope et al., 1997), New Zealand, and the Bahamas. The survey of Snares and Solander Islands (see Fig. 14), lying 60 miles SW and 120 miles south of the New Zealand mainland illustrates the considerable benefits accruing from combining Lidar capability with conventional acoustic platforms. These sub-Antarctic island groups of Snares and Solander Islands are remote, dominated by predominantly foul weather and surrounded by pinnacles that rise unpredictably to form one of the most infamous ship graveyards in the world. In addition, both the islands are wildlife sanctuaries that attract an increasing number of cruise ships, so human impact has to be minimal. The challenge was therefore to mobilize during an extremely short weather window a survey effort that could collect a bathymetric data set in dangerous, uncharted waters and delineate inaccessible coastlines, while also ensuring the safety of survey craft operating around the islands. SHOALS was quickly identified as crucial to such a project, able to meet all the inshore requirements while also providing safe clearance for conventional acoustic platforms to work in the deeper water. The advantage of using SHOALS in an environment as hostile as the Snares and Solander Islands lies in its ability to rapidly chart shallow-water areas close to rocky coasts where conventional ship methods are difficult and dangerous (West et al., 1999).

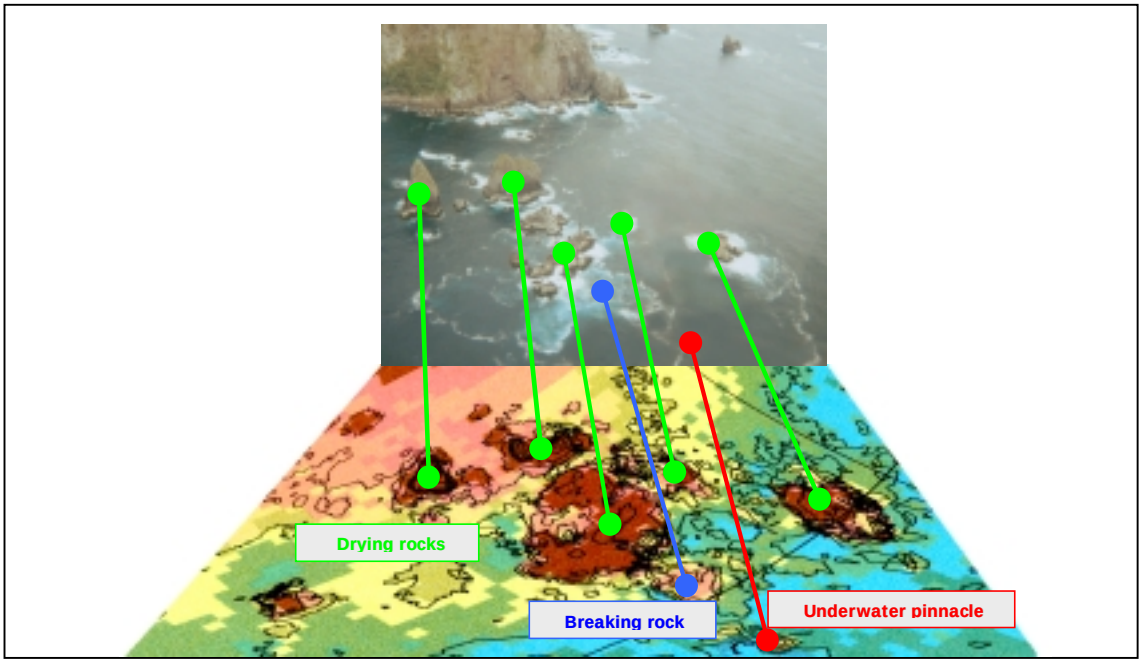
Delineating and classifying features that are anomalous to the general trend of the seabed is one of the critical elements of any nautical charting survey; this was a key role for SHOALS and one that it is optimized for. Small pinnacles, only a few meters in cross-sectional area but tens of meters in vertical extent, were commonplace. Although some of these dangers were self-evident, the more dangerous ones rose from depths in excess of 30m to within a few meters of the surface without breaking it (Fig. 14). SHOALS was therefore used to sweep many apparently deep areas with the aim of locating any rocks which posed a danger to surface navigation. Quality control (QC) of the complexes of drying and breaking rocks in the inshore zone required particular attention, as the Lidar waveform characteristics of whitewater and land are extremely similar. Integration of data sets from vastly differing sensors can be a challenge, and the value of powerful QC packages was key to reconciling the datasets. Overall, the New Zealand survey was a model of the innovative solutions that will increasingly be required by the marine community of the future. Close integration of SHOALS with conventional methods was fundamental to this.

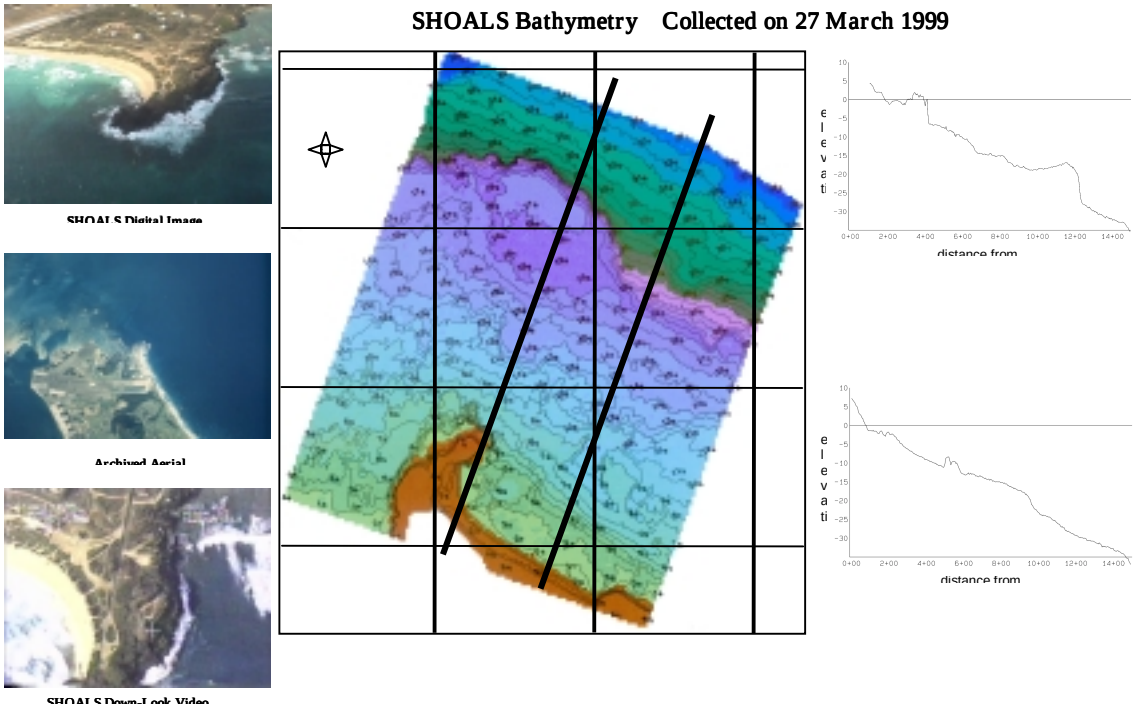
IX. Rapid Reaction Surveys

A combination of the SHOALS' features outlined in the preceding paragraphs has made it increasingly attractive as a tool for support of military operations. The ability to quickly chart an area inclusive of topographic elevations and water depths is naturally the prime attraction. However, SHOALS' potential to be significantly less vulnerable than boats to enemy activity may also prove to be important in the future. During the last years of the 20th century, there has been a shift in emphasis of naval warfare to "brown water" activities that has resulted in new shallow-water requirements being generated considerably faster than the ability of routine survey activity to keep up. Consequently, the incidence of short-notice survey requirements has increased dramatically, while at the same time the theatres have become less of a single military arm's problem and more joint in nature.

While conducting surveys in Hawaii during early 1999, two "rapid reaction" demonstration projects to illustrate the concept of Lidar support for the warfighter were undertaken. The area shown in Fig. 15 was one of these areas and comprised 1.8 sq km, which took 10 minutes to fly and one hour to map, and resulted in a data set containing 200,000 points through which profiles could be cut as required. Supporting data from the same flight came from oblique photography and grabs from the vertical video record that is always run during survey operations. Although this survey took place in highly controlled conditions, the potential for Lidar to provide a comprehensive product rapidly is clear, and for this reason the Navy will further develop this proof of concept during a NATO Rapid Environmental Assessment exercise scheduled to take place in 2000.


SHOALS Bathymetry Data
Ponce DeLeon Inlet, Florida


Drying rocks
Breaking rock
Underwater pinnacle



The need to respond rapidly to evolving situations is not just the province of the warfighter, though, and SHOALS has now become one of the USACE's primary resources in the aftermath of hurricanes striking the southern USA. For example, in 1995, a Category 3 Hurricane, Opal, struck the Florida panhandle, causing widespread damage and reshaping of coastal features. At the time, SHOALS was engaged in routine surveys in New England but received an immediate call to assess the condition of East Pass Channel at Destin. In response, SHOALS had, by 5 p.m. on the second day after call, flown the survey; maps and volume calculations were generated and delivered less than 6 hours later.

X. Conclusions

The potential benefits of ALB are considerable and will continue to open up new opportunities in fields as diverse as regional sediment management and warfighting support. In the field of conventional hydrographic survey, ALB should become the tool of choice in clear, shallow waters that are noncritical to deep-draught navigation since it will usually achieve coverage rates several orders higher than current launch methods at less cost per square mile. Therefore, deployment of a survey launch in such waters is, by comparison, a waste of an asset and should be confined to high-resolution surveys or where Lidar is ineffective. Conversely, ALB has diminishing benefits in deeper water where multibeam fitted ships become steadily more efficient. Consequently, there are limited gains associated with increasing depth penetration of an ALB beyond 50m, unless there is also an increased swath width and/or speed of operation. Route surveys where obstruction location is critical will continue to be the domain of high-resolution sidescan and/or mechanical sweep surveys. It still remains to be seen whether we have adequately defined the boundary between ALB capabilities and other surveying tools, but such characterization will to a greater extent be system specific. The result of this determination will not always be a simple and close integration of ALB, and conventional assets such as in New Zealand will often be mutually beneficial.

XI. References

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