Airborne Laser Bathymetry: A Tool for the Next Millennium

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Abstract

Airborne laser bathymetry (ALB) is a swath surveying technology for shallow coastal waters that is complementary to conventional multi-beam acoustic systems. Its ability to survey with high coverage rates, high sounding density and good accuracy makes ALB an effective tool for many hydrographic surveying applications. ALB surveys remote and shoal-infested regions safely, easily and efficiently. An additional advantage offered by Optech's SHOALS system lies in its capability for continuous surveying of the water bottom topography through the shoreline and up onto land.

This article addresses the technology and utility of this established and proven, but often misunderstood, hydrographic surveying technique, and discusses several interesting and unique applications where it has demonstrated its merits, with examples drawn from SHOALS, Optech's commercially available system.

INTRODUCTION

Hydrographic surveying and nautical charting play a vital role in the safety of navigation in coastal areas, and are thus essential to world maritime commerce. However, the status of hydrographic surveys and nautical charting world-wide is usually quite poor. As a result of the United Nations Convention on the Law of the Sea (UNCLOS), coastal states will be responsible for surveying and charting their Exclusive Economic Zones (EEZ). This is a monumental task for all coastal states, but particularly for those with enormous coastlines, such as Canada with over 200,000 km.

The above requirements must be met by technology that can provide nearly 100% bottom coverage and cover large areas quickly. Multibeam swath acoustic systems now provide virtually complete bottom coverage, and are ideal in deeper waters where their swath coverage is large. In shallow coastal waters of less than 50 m, however, even these systems become less cost-effective since their swath width is typically limited to about twice the water depth and they are vulnerable in shoal-infested waters. Moreover, these systems cannot survey up to the land/water interface, and certainly not onto the adjacent land itself.

Fortunately a recent technology, Airborne Laser Bathymetry (ALB), has developed into an ideal complement to acoustic swath mapping in shallow coastal waters, and has now been proven to be operationally viable. ALB is analogous to acoustic depth measurement, but uses light instead of sound (Figure 1).

As an airborne technique it has several advantages over ship-based systems:

1) it surveys at aircraft speed;
2) its swath width is independent of water depth;
3) it can survey effectively in shallow and shoal-infested water; and
4) it can survey both land and water at the same time, with continuity through the shoreline.

By delivering these benefits, ALB will speed up the survey tasks that fall under the current mandate of international hydrographic agencies, produce significant savings in the cost-per-unit-area surveyed, and drastically simplify a range of other coastal survey applications that can be crucial to coastal states.

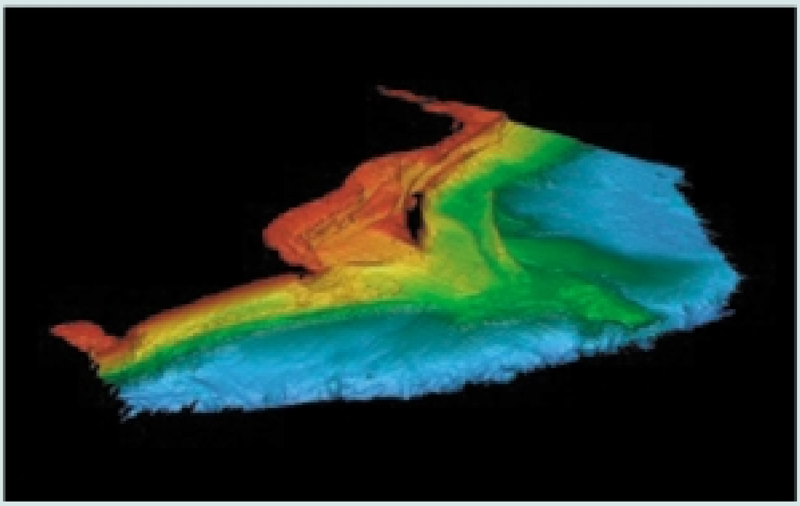
THE AIRBORNE LASER BATHYMETRY TECHNIQUE

The light detection and ranging technique (lidar) accurately determines water depths by measuring the time

Figure 1
System Concept for Airborne Laser Bathymetry

Figure 2, SHOALS in Flight

Figure 3a, Yucatan Survey Area
Figure 3b, Yucatan Survey Depth Data



of flight of two laser pulses at different wavelengths: one travels through the air-water interface to the water bottom, while the second pulse is reflected from the water surface. An optical receiver on the aircraft detects the pulse reflections from both the bottom and the water surface. The water depth is determined by the elapsed time between these two reflection/scattering events, after accounting for the system's operating geometry, propagation-induced biases, and waveheight and tide effects.

In operation, successive laser pulses are scanned sequentially across the water surface to produce, when combined with the aircraft's forward velocity, a swath of nearly evenly spaced soundings. The horizontal coordinates of the soundings are determined from the aircraft position, altitude and attitude, the direction of the laser beam with respect to the aircraft, and the measured water depth.

THE SHOALS SYSTEM AND ITS CAPABILITIES

SHOALS (Scanning Hydrographic Operational Airborne Laser Survey) is a successor to Optech's first airborne laser bathymetry system, the LARSEN 500, which was developed for the Canadian Hydrographic Service. The LARSEN 500 has been in operation since the mid-1980s on all three coasts of Canada and internationally in areas such as Indonesia, Barbados and the Middle East. It was used to produce the world's first nautical chart based on airborne laser data.

SHOALS is a fully operational commercial system, the latest generation in a series of such systems produced by Optech over the past 15 years. It meets International Hydrographic Organisation (IHO) Order 2 requirements for accuracy: its depth measurement accuracy is better than 20 cm, and its horizontal position accuracy is better than 1.5 m when using the latest positioning technology.

SHOALS determines the mean water surface elevation, and corrects individual depth soundings for wave height effects and long-period swell. These depths are then referenced to the local tide measurement. With the recent implementation of kinematic GPS positioning with on-the-fly ambiguity resolution (KGPS/OTF), the collection of tidal data is no longer necessary. SHOALS soundings and land elevations can be processed without being referenced to a local water surface.

The SHOALS minimum depth capability was originally limited to about one metre. However, with the recent implementation of a special "shoreline depths" processing mode, SHOALS can now provide continuous topographic and bathymetric mapping through the shoreline from water onto land.

Turbid water, weather-related phenomena and bottom structure can limit SHOALS depth determination. The typical maximum depth capability is 40-50 m in clear ocean waters, 20-40 m in coastal waters and less than 20m in more turbid inland waters. High surface waves, heavy fog and precipitation, and sun glint can reduce depth penetration and measurement accuracy. Heavy bottom vegetation and "fluid mud" may limit system performance as well.

SHOALS takes advantage of recent advances in laser, computer and positioning technologies to provide a compact, self-contained system that can be installed into an aircraft of opportunity, either fixed-wing or helicopter, for example a Bell 212 helicopter (Figure 2).

The SHOALS laser generates short pulses of light at two wavelengths (green and infrared). As the aircraft flies along its pre-defined survey flight line, a programmable scanner sweeps laser pulses across the aircraft track, producing a nearly-uniform, high-density distribution of laser spots on the water surface. A video camera also records the area being surveyed.

The scanner compensates dynamically for the roll and pitch of the aircraft to generate straight swaths of laser soundings and eliminate potential gaps in collected data. By programming the scanner, the operator sets the laser sounding density and swath width. When combined with aircraft altitude and speed, this produces very useful trade-offs between sounding density and the area coverage rate. The density can be as high as a 2 x 2 m grid, providing 100% bottom coverage at lower area coverage rates; conversely, with a lower sounding density, the area coverage rate can be much higher, more than 50 km²/hr.

SHOALS uses differential GPS (DGPS) to provide positioning information to the aircraft in real time. Inertial reference and GPS systems record the aircraft altitude and attitude to produce accurate real-time and post-processed sounding positions.

A dedicated, VME-based, airborne computer handles all data acquisition, control, and real-time processing and display functions. A ground-based computer system generates all flight survey parameters. It also handles the automatic processing and manual editing (if needed) that transform the raw survey data into XYZ data suitable for geographic manipulations, analysis and interpretation. The final output is a fully-verified database of soundings.

SHOALS RESULTS AND ACHIEVEMENTS

To illustrate the benefits of airborne laser bathymetry, the results of typical surveys are described below for the SHOALS system delivered to the U.S. Army Corps of Engineers (USACE). This SHOALS system has conducted more than 200 surveys in the USA and Mexico in the four years since its field verification, with total area coverage of more than 2750 km². Each survey addressed a specific objective, such as nautical charting, hazard identification, hurricane and coral-reef damage assessment, beach nourishment, sea-grass delineation, erosion monitoring and military applications.

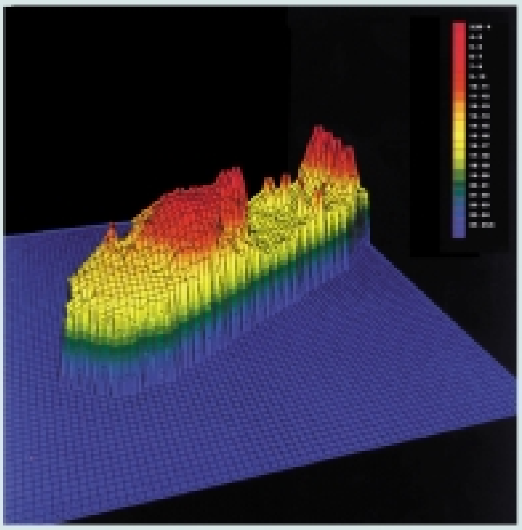
(a) Nautical Charting and Navigational Hazard Identification

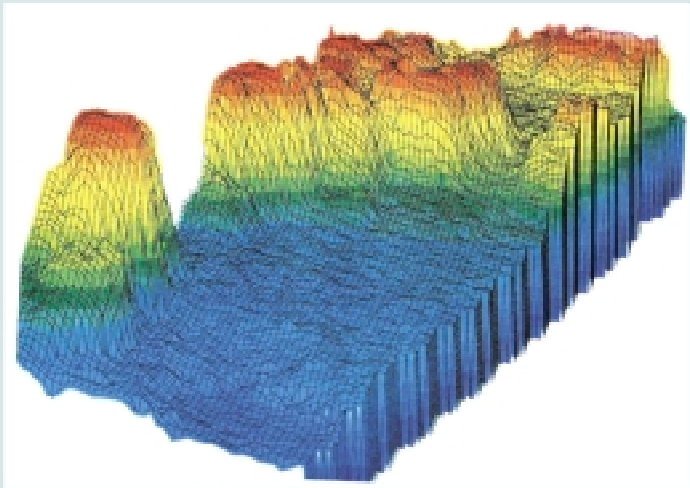
The largest single mission for SHOALS was a nautical charting operation conducted over three months in early 1996 off the Yucatan Peninsula near Cancun, Mexico. SHOALS surveyed approximately 800 km² with a 4 x 4 m sounding density, producing more than 100 million individual soundings and providing complete bottom coverage in all but the shallowest waters. A map of the surveyed area shows a sample of the SHOALS-derived, colour-coded depth data (Figures 3a and 3b). The sheer volume of raw lidar data collected (~12 Gbyte/day) presented a considerable data handling challenge. This project demonstrated the system's ability to collect, process and integrate large volumes of high-resolution data from many separate missions seamlessly. SHOALS also located and mapped a previously uncharted shipwreck.

The system's ability to identify navigational hazards was confirmed in the Baltic. The system used in these cases is a close derivative of SHOALS, Hawk Eye, procured by the Swedish Hydrographic Department. Hawk Eye located and mapped a sunken cargo vessel in waters of 25 m (Figure 4a). The ship was located near a shipping channel in the Baltic Sea with its topmost portions only 3 m below the surface, a potential navigation hazard. The excellent resolution of the data can be seen in features such as the wheelhouse structure, and the tailfan and winches near the ship's stern.

Hawk Eye also mapped shoal-infested waters in Braviken Bay, Sweden, a lengthy, painstaking and potentially dangerous task for conventional ship-based survey methods. The excellent three-dimensional resolution of shoals was obtained in less than 10 m of water, with shoal heads less than 1.5 m deep (Figure 4b).

The system's ability to detect underwater hazards was further illustrated using a 10 x 10 m platform located





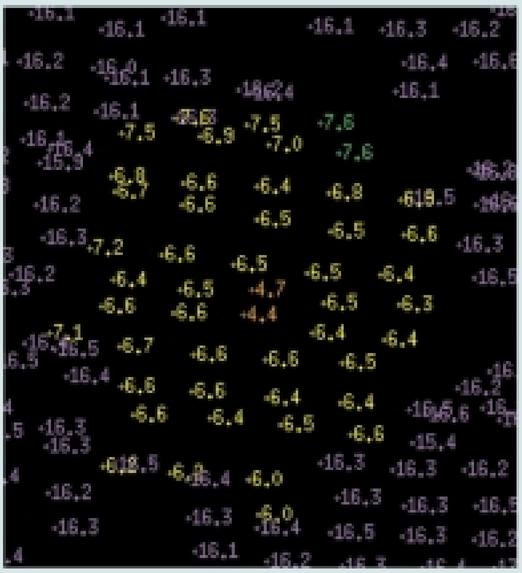
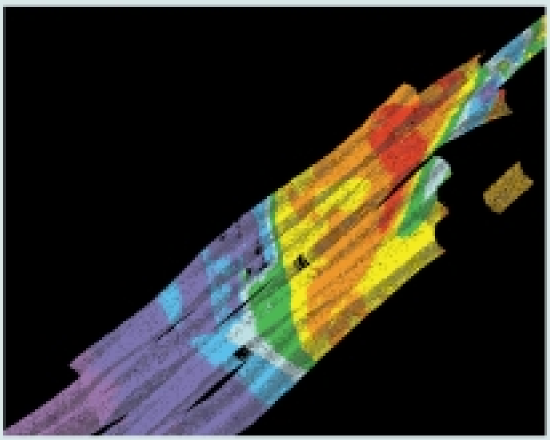
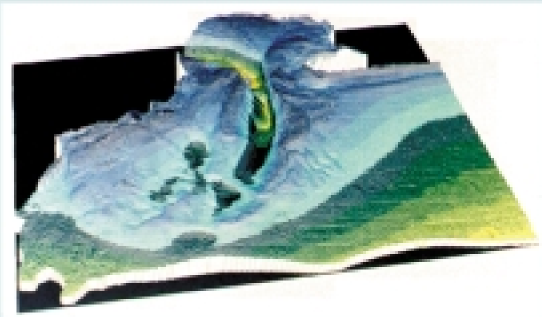


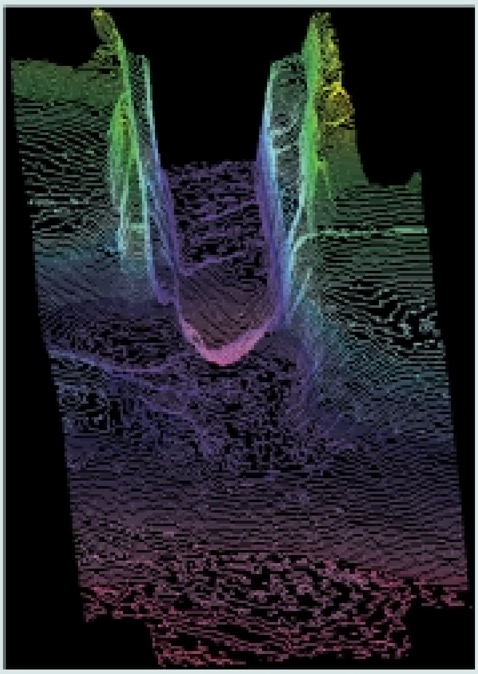
Figure 4a
Sunken Ship in the Baltic Sea

Figure 4b
Shoals in Braviken Bay, Sweden

Figure 4c
Identification of Navigation Hazards







6.5 m deep in waters of about 16.5 m. The platform outlines are easily distinguished from the sea bottom (Figure 4c). Most notable are two depths (4.4 m and 4.7 m) in the centre of the platform, which represent soundings against a 1 m^3 cube located 1 m above the platform. This clearly shows the system's ability to resolve small submerged objects jutting up from the adjacent bottom.

(b) Navigational Channel and Harbour Inspections

Because of its high-density sounding rate and its ability to map shallow water and adjacent land, SHOALS is well suited to survey navigational channels and harbour structures. Florida's New Pass Channel has been surveyed by SHOALS five times over 32 months to assess continuing changes in its channel structure. This detailed monitoring has enabled coastal engineers to construct a precise, three-dimensional model, and to quantify sediment transport through the area. The total surveyed area is more than 30 km^2, representing three million soundings surveyed in a total of less than 12 hours. The results of one survey (Figure 5b), along with an aerial photograph of the survey area (Figure 5a), are shown.

The high-resolution SHOALS data acquired here also delineated the area mined for a neighboring beach restoration project. It highlighted the system's ability to acquire large amounts of data in shallow water of less than 2 m, where conventional survey technologies are limited.

SHOALS has also been used to survey tidal inlets in New Jersey (Figure 5c) and Florida (Figure 5d). Each survey was completed in a few hours and provided complete, high-resolution coverage of the entire inlet system and adjacent beaches. This has enabled engineers to quantify channel dredging requirements, above- and below-water jetty conditions, scour at the structures, and dry-beach and near-shore morphology. Particularly interesting at Great Egg Harbour Bay is the contrast between the very uniform and flat offshore area and the ebb shoal area, as well as the cloverleaf-shaped erosion feature at the channel inlet (Figure 5c).

(c) Coastal Engineering Applications

Since SHOALS acquires high-density soundings both in water and on land, it is ideal for monitoring the beach and nearshore in dynamic, irregular regions. Florida's Longboat Key, near New Pass Channel, has also been surveyed five times since 1994. The results of one survey are shown (Figure 6a). SHOALS data from these surveys were used to monitor the dispersal of over 2 million m^3 of sand deposited on Longboat Key in 1993 as part of a beach restoration project. The data proved that the beach material was being redistributed within, but not being removed from, the area.

SHOALS can also provide a rapid but accurate indication of emergency damage. In October 1995, after Hurricane Opal (Figure 6b), SHOALS was used to assess post-storm damage. Ten days after the storm, SHOALS carried out a 2.6 km^2 survey of East Pass consisting of 300,000 soundings gathered in less than an hour. By the end of the day, data processing had been

Figure 5a
Aerial Photograph of New Pass Channel, Florida

Figure 5b
New Pass Channel survey results

FIgure 5c
Tidal Inlet of Great Egg Harbour Bay, New Jersey

Figure 5d
Tidal Inlet of Lake Worth, Florida

completed, hard copy charts produced, and quantitative estimates made of the dredging required and the damage to jetties and similar structures (Figure 6c).

A third example of a coastal engineering project is a 9 km stretch of beach along Lake Erie, Pennsylvania, which is protected by 55 detached offshore breakwaters. Traditional shore-normal profiles used survey rod and level to wading depth, and a ship-based acoustic depth sounder further offshore. Apparent anomalies in the breakwaters at deeper depths typically required time-consuming inspection by divers. By contrast, SHOALS surveyed the entire region, with a sounding density of 4 x 4 m and over 1 million soundings, in less than two hours. Three of the breakwaters are illustrated (Figure 7a), showing both land and below-water topography. Also revealed was a previously undiscovered geologic fault line.

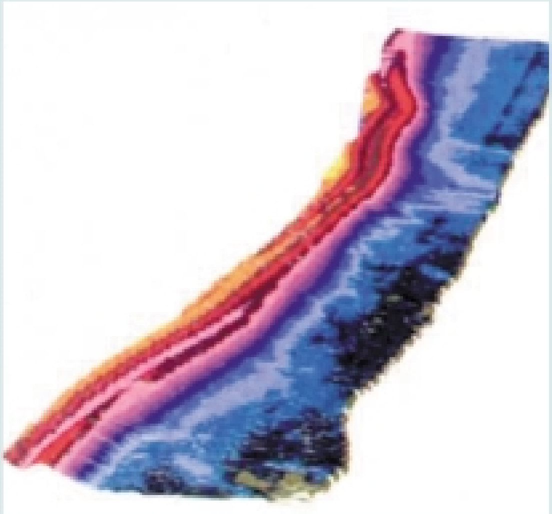
A SHOALS survey of Fort Pierce in 1997 illustrates the usefulness of KGPS/OTF positioning when applied to high-resolution coverage of the upland beach and dune system. A map of the inlet and beaches derived from SHOALS data and seen from offshore shows the two jetties near the top, extending off-shore on either side of the navigation channel (Figure 7b). The beach/dune system, in blue, is aligned along both sides of the channel. This survey quantifies several inlet features such as coral reefs, rock outcrops, the rock-blasted channel, navigation jetties, shoal features, and the beach and nearshore morphology.

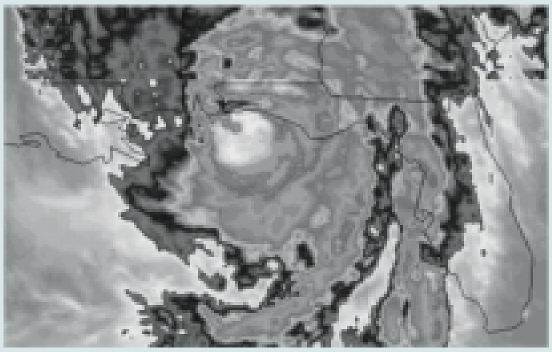
(d) Very Shallow Water and Land Survey Capabilities
A significant advantage of airborne laser bathymetry is its ability to survey very shallow water (<5 m) through the shoreline and up onto land (topographic elevation). There is no degradation in vertical accuracy, no change in sounding density, and no adjustment in aircraft track to match the shoreline direction. As an example, the central area of Florida Bay is characterised by an extensive network of mud banks, cuts and basins – all consisting of water depths between 0.5 m and 3 m that had never been properly surveyed. SHOALS laid bare this complicated subsurface structure with a three-hour survey of more than 450,000 depth soundings. In the results (Figure 8), individual sounding swaths can be distinguished. Of particular interest is the central (black) region with depths of less than 0.9 m.

SHOALS' ability to measure continuously through the air-water interface was also shown at Presque Isle (Figure 7a), where both the blue below-water and the green above-water structures of the breakwaters are accurately measured. Similarly at Fort Pierce (Figure 7b) the highly-structured topographic elevations representing the beach/dune system are shown by the blue areas bordering the navigational channel and shoreline. With KGPS/OTF positioning, land surveying independent of the water bodies has been easily demonstrated.

FUTURE DEVELOPMENT

With the introduction of airborne laser bathymetry, hydrographic surveying clearly has a brighter future, particularly in light of the challenging requirements now being imposed by UNCLOS. The achievements of Optech's SHOALS system confirm the advantages of this technology in the nautical charting of large areas and in other coastal and onshore surveying applications. Airborne laser bathymetry is not meant to displace the traditional acoustic technique by any means, but rather to offer a more cost-effective solution in relatively shallow coastal waters. In that respect it should be viewed as complementary to acoustic multibeam swath surveying.





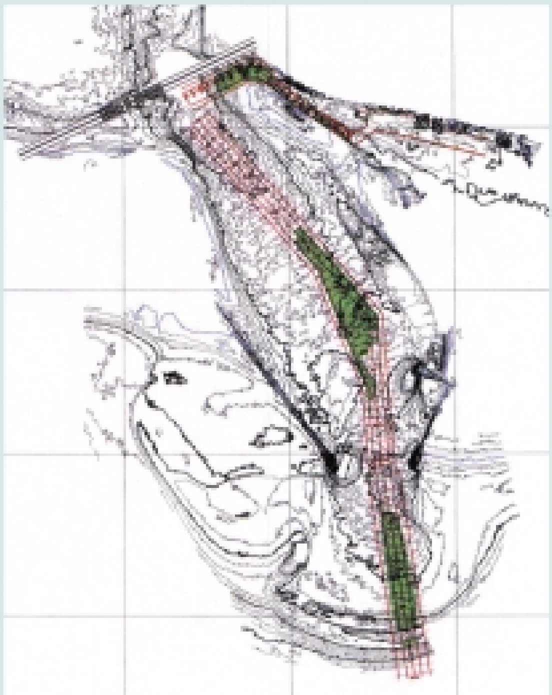


Figure 6a
Longboat Key, Florida

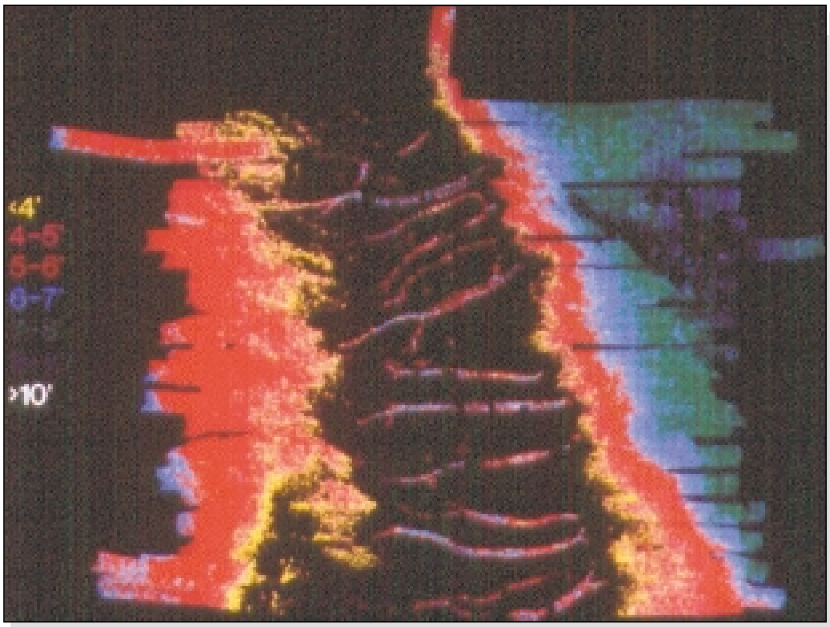
Figure 6b
Satellite Image of Hurricane Opal, October 1995

Figure 6c
Chart of East Pass Dredging Estimates

Figure 7a, Presque Isle Breakwaters

Figure 7b, Fort Pierce Jetties

Figure 8, Little Rabbit Cuts, Florida Bay



Over the last four years, as the capabilities of the SHOALS system have increased and been refined, the range of practical applications has likewise increased. This trend is expected to continue. The rapid technological advances in laser systems and computer hardware/software are improving system performance and reliability while reducing system size and weight. The system and operating costs are also shrinking, with operating costs for large surveys expected to be as low as US $300 per km^2, or less than 1 cent per sounding.

SHOALS is currently being upgraded to double its data acquisition rate, thereby improving its performance in several ways. A higher data acquisition rate enables the survey aircraft to fly higher and faster, with a corresponding increase in swath width and area coverage rate at the same high sounding density as before. Increased coverage also reduces the surveying cost per square kilometre. Advances in the post-flight processor are speeding up data processing, producing robust algorithms that can handle data acquired in a wider range of environmental and operational conditions, and opening up the processed data to ever more modern visualisation techniques. With the SHOALS system, airborne laser bathymetry is indeed beginning to lighten the burden of surveying and charting EEZs.

ABOUT THE AUTHORS

Dr. John Banic, the Manager of the Marine Survey Division at Optech, has been working in the field of airborne lidar bathymeters at Optech since 1983. He has been Project Manager for the development of three major lidar bathymeter systems, each for a different application.

Dr. Grant Cunningham, a member of Optech's Marine Survey Division, is a physicist who has most recently been working on theoretical aspects of algorithm development for the post-processing system used with Optech's lidar bathymeters. He has also recently conducted a feasibility study into novel applications of these systems.

IF YOU HAVE ANY ENQUIRIES REGARDING THE CONTENT OF THIS ARTICLE, PLEASE CONTACT:

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