Airborne Laser Hydrography: An Introduction

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Abstract

A review of the history of Airborne Laser Hydrography (ALH) is presented, with reference to the airborne systems developed over the last three decades. This is followed by a description of the fundamentals of the technique. The typical operational scenario is outlined and the versatility and benefits of the technology highlighted.

Introduction

The development of systems that use lasers for the sounding of depths started not long after the advent of the laser itself. The potential for these systems held great promise in the early years and we can now safely say that the promise has been delivered. There is a tremendous cost and efficiency benefit that can be derived form using these systems in conjunction with conventional techniques, especially in shallow coastal waters. These type of waters represent the most important for shipping and for territorial concerns. The coastal environment is also subject to the most variability from the weather. Hence in one sense, the job is never done: these areas must be surveyed on a periodic basis. ALH systems are well suited for this activity.

History of Airborne Laser Hydrography

Airborne Laser Hydrography (ALH), or Airborne Laser Bathymetry (ALB) as it is also known by, has been an attractive concept ever since the laser itself was invented in the early sixties. The idea of using a laser for underwater detection was confined in the early years to the problem of submarine detection (Ott, 1965; Sorenson, 1966). Hence most of this early work was classified. The first report in the open literature came from the University of Syracuse in 1969 (Hickman, 1969). In the first half of the 1970's, the work in this field concentrated on experimental profiling systems such as by NASA (Kim, 1974) and by the US Navy (Cunningham, 1972) in the USA. In Canada, the Canada Centre for Remote Sensing (CCRS) joined with Optech in profiling efforts (Ryan, 1980) while in Sweden the Defense Research Establishment (FOA) explored this area. In Australia the Weapons Research Establishment (WRE) of the Royal Australian Navy (RAN) developed a profiling system called WRELADS-1 which underwent trials in 1976/77 (Clegg, 1978).

The next step in the evolution was to move beyond the profiling mode and scan the laser beam. A joint effort by NASA, NOAA, and the US Navy produced a scanning Airborne Oceanographic Lidar (AOL) (Guenther, 1978) which remarkably is still in use today, albeit in a vastly different form from its first configuration. Experience with the AOL led to the HALS (Hydrographic Airborne Laser Sounder) program sponsored by the US Navy, the Defense Mapping Agency (DMA) and NASA (Houck, 1980). In Australia, a scanning system called WRELADS-2 was developed from the experience on WRELADS–1 and it was verified in the late 70's (Penny, 1986). Canada and Sweden cooperated with FOA augmenting the Mark-2 profiling system with a scanning mirror (Steinvall, 1981).

In the eighties, the ALH systems were developed beyond the experimental learning stage and into the operational regime. Optech built the LARSEN-500 system, sponsored by the Canadian Hydrographic Service (CHS) and CCRS (Banic, 1986). It was delivered in 1985 and is still in operation today (Hare, 1994). FOA of Sweden sponsored the development by Optech of a scanning ALH system called FLASH-I, which was delivered in 1988 (Steinvall, 1992). The HALS system was combined with a multi spectral scanner and renamed the Airborne Bathymetric System (ABS) (Harris, 1986). The ABS flew until 1988. 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). In other parts of the world, China began work on a Blue-green Oceanographic Lidar (BLOL) (Liu, 1990) and in Russia three experimental systems were in use: GOI, Chaika and Makrel-II, (Feigels, 1992).

The late 1980's saw some significant developments. In 1988, the first smooth sheet chart produced by an ALH for navigation was produced for CHS by the LARSEN-500. The same year, the U.S. Army Corps of Engineers (USACE) initiated an operational ALH system to be developed by Optech Inc. The next year, in 1989, a contract was awarded to BHP Engineering and Vision Systems of Australia to build the Laser Airborne Depth Sounder (LADS) for the Royal Australian Navy.

The decade of the nineties began with another order of two ALH systems from the Swedish Department of Defence. Saab Instruments of Sweden was the prime for this order with Optech as the major subcontractor. The Ocean Water Lidar (OWL) system, although not primarily built for hydrography was being flown in the early nineties for this application (Lutomirski, 1994). In 1993, the RAN LADS system was brought into operational use (Setter, 1994). In 1994 the SHOALS system was delivered to the USACE and also began operational surveys (Lillycrop, 1996). In 1995 two HawkEye ALH systems, similar to SHOALS, were delivered to Sweden (Steinvall, 1997).

The more recent years have witnessed significant improvements in ALH capability. In 1997, the SHOALS system developed the capability of using kinematic GPS with on-the-fly ambiguity resolution, which allowed topographic mapping over land in conjunction with the underwater mapping (Guenther, 1998). A new generation of the LADS system, the Mk II, became operational in 1998 (Sinclair, 1998). The new system has a sounding rate of 900 Hz, and is installed in a Dash 8 aircraft, which can fly at speeds of 175 knots. Also in 1998, the SHOALS system upgraded its sounding rate to 400 Hz and was installed in a Dash 6 (Twin Otter), which can survey at up to 150 knots. These systems now have survey coverage rates in the 15 – 19 nm^2/hour.

Current Status

If we restrict the count to only those systems that are primarily for commercial hydrographic purposes, there are six ALH systems currently in operation. In Canada, the LARSEN-500 is owned and operated by Terra Surveys of British Columbia, Canada. In 1995, it was contracted by the UAE for a survey that will be used for their national charting. From Australia, the LADS Mk I system is still in use by the RAN and LADS Mk II is surveying worldwide. Of the two Swedish HawkEye systems, one is still in use by the Swedish Navy; the other has been transitioned to Indonesia for the survey of coastlines. In the United States, the SHOALS system owned by the USACE and operated by John E. Chance and Associates (member of Fugro Group) is surveying throughout the US and in various parts of the world.

In addition to the countries mentioned above which have built their own ALH systems, several other countries have contracted ALH services to use the data in their national charting programs. These nations include Mexico, New Zealand, Norway, Indonesia and the UAE.

Principle of Operation

The basic principle of the ALH system is that the airborne lidar sends two laser wavelengths down to the water surface, as shown in *Fig. 1*. The water depth may be calculated from the time difference of laser returns reflected from the sea surface and seabed. In 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*. It is critical to know where the water surface is located as a reference and in the SHOALS system, there are three separate wavelength channels which can locate the surface on a priority basis (Guenther, 1994). The laser beams are either swept in an arc or in a rectilinear scan across the direction of travel with a swath width typically half of the altitude. The surface sounding density can be varied from as small as 2 x 2 meters up to 5 x 5

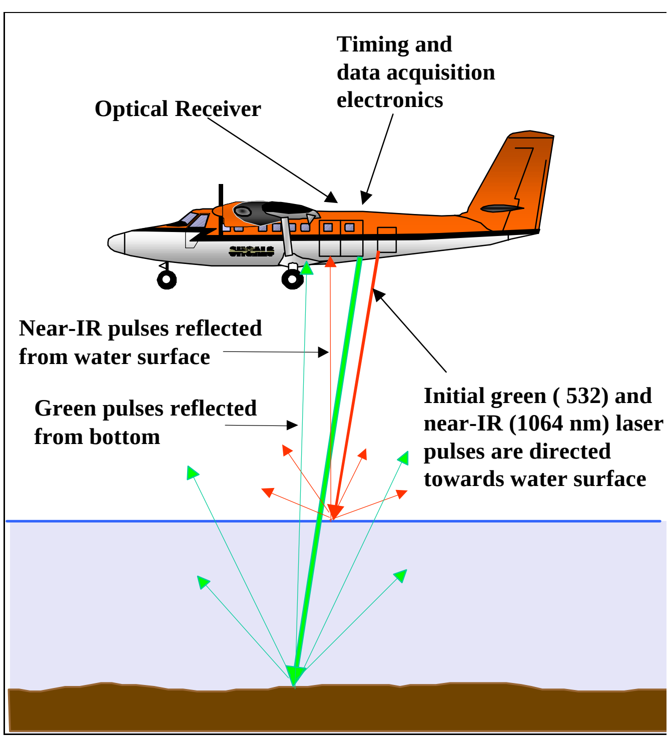

Figure 1 Principle of ALH Operation

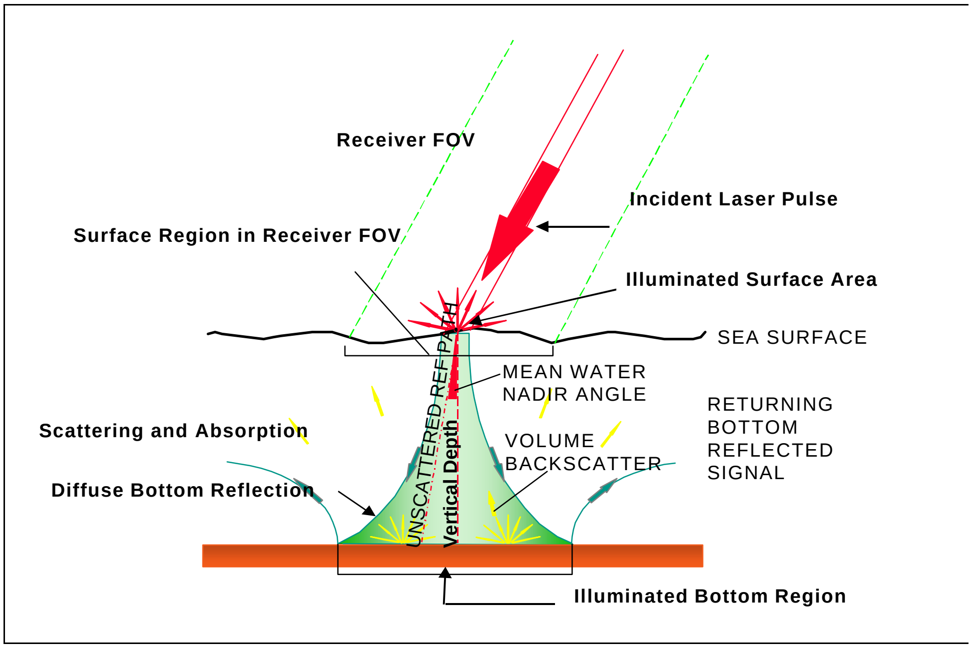

Figure 2 Geometry of Light Penetration

m spacing and higher. Since the spot size on the surface is typically greater than 2 m this implies the possibility of complete coverage of the surface of the water at high sounding densities.

The basic limitation of depth capability is the clarity of the water. Hence 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 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 ALH systems is generally expressed as the product $K_d\, D$, where D is the depth. A more practical predictor of the ALH system is the Secchi Depth. In simple terms, if a 45 cm diameter disc with alternating white and black quadrants is lowered in the water, the depth at which the disc

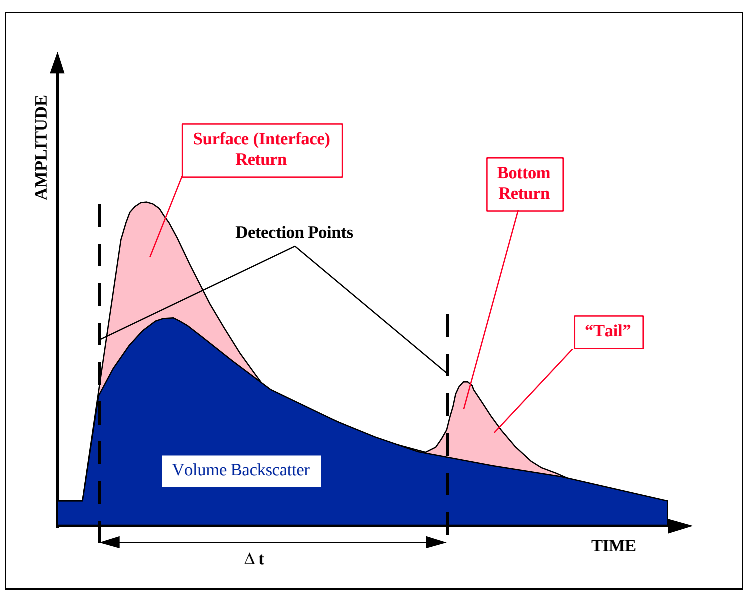

Figure 3 Generic Lidar Waveform

becomes invisible is known as the Secchi Depth. These ALH systems are capable of detecting the bottom to depths up to three times the Secchi Depth.

Although surface detection is usually made with a Raman channel or the infrared channel, the blue-green channel will also detect the surface. Because of this, the generic ALH waveform is of the type shown in *Fig. 3*, 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, 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 ALH 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.

Operational Scenario

The usual operation of an ALH system is comprised of a few steps. The first is system mobilization. If the lidar system is not on a dedicated platform then it must be mounted into the airborne platform of choice. If an installation has already been done on a particular aircraft this takes only a few hours. If the platform is new to this type of equipment, then considerably more time must be allowed for the proper approvals. The ALH system must then be ferried to the site of interest. Depending on the distances involved this can be a significant part of the cost.

Figure 4 Airborne Operator Console

The most important preparatory step is the site evaluation. It is crucial that the area of interest be examined in advance to determine if the water clarity and the intended depths are within the capability of the system. If the water clarity is too turbid, it is important to know whether this area will clear after a few days or if the water character is a seasonal one. The flexibility of these airborne systems means that it is usually possible to fly somewhere else for surveys while a particular area is clearing for a later time.

Once the system is on site and the area identified as suitable, the next step is mission planning. The desired sounding density and swath widths are preprogrammed along with flightlines that suitably cover the area. This is all done on a computer environment either from existing electronic charts or from a newly digitized form.

The collection of the data is a straightforward matter. There may or may not be requirements for ground GPS stations depending on the type of survey and its location on the globe. Airborne operation is by a single operator who monitors the data collection from a station similar to what is shown in *Fig 4*.

The final step for the production of accurate ALH depths is the post-processing. This is generally done in a dedicated work environment that either follows the airborne system when practical, or the data is sent back to a centralized processing center.

The Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) System

The remainder of this paper will discuss the benefits and versatility of ALH with reference to practical examples of projects undertaken by SHOALS, although many of

Figure 5 SHOALS Twin Otter Aircraft

these features are common to other ALH systems in existence. 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. 5)* during the fall of 1998 and has since completed projects in New Zealand, Hawaii, and the Bahamas in addition to the continental USA. Incorporating a 400Hz laser, it can scan 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 is flown at speeds up to 120 kts.

Shallow Water Capability

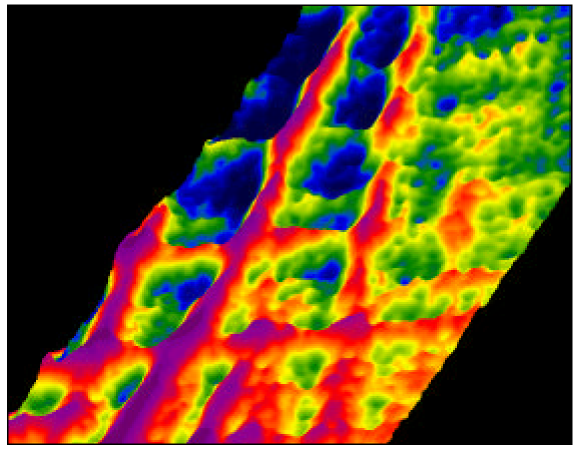

Figure 6 Intersecting Sandwave Fields

While Multibeam Echo Sounders (MBES) have revolutionized surveys in medium and deep water, they have suffered from a number of drawbacks in very shallow areas. Most significantly, their swath is greatly decreased in very shallow waters, while ALH swath width remains fixed, irrespective of depth. SHOALS normally employs a swath of 110m with a 4m x 4m spot density; this means that it is able to collect dense data sets in shallow waters that would take conventional acoustic systems many times longer to collect. *Fig. 6* is a good example of the detail that is obtainable in shallow water. This data comprises an area of approximately 1000 m x 2000 m and shows two sets of intersecting sandwaves that were detected in general depths of 6.5m during a recent survey in the Bahamas. The vertical scale has been exaggerated to highlight this structure, but the highest of the sandwaves is only 1.1m high while their width varies from 15 – 50 m.

Taking this further, it has also been possible to use SHOALS to delineate smaller area features, including several 'Blue Holes'. The data shown in *Fig. 8* is from one such case and shows the 'Blue Hole' to be about 40 m in diameter (crest to crest), with general

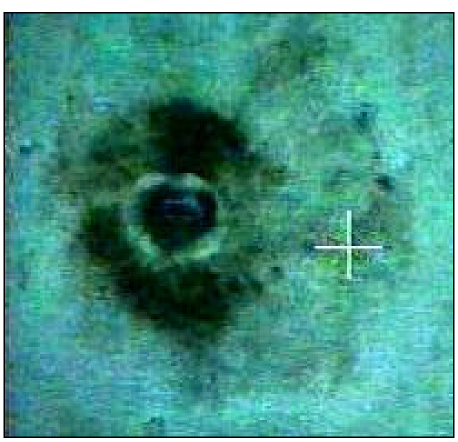

Figure 7 SHOALS Down-look Video of 'Blue Hole'

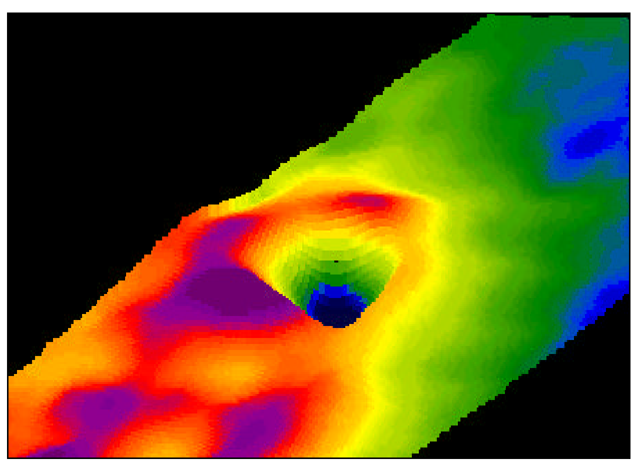

Figure 8 Blue Hole

surrounding water depths of about 3 m. The aircraft was flying from bottom-left to top-right, so the data can be directly compared with the in-flight down-look video record, which is collected simultaneously with all SHOALS surveys. In the video, the aircraft is flying from bottom to top, and the lighter right-hand side of the hole's crest is easily correlated with the yellows on the nearest side of the crest in *Fig. 8*. Also visible in *Fig. 7* are the streaks that run down-slope into the deeper water at the top-right of *Fig. 8.*

The next example shows a wreck detected by SHOALS during a survey in Mexico. *Fig. 10* clearly shows the vessel on the seabed and about 30m in length, while *Fig. 9* shows the wreck in 3D view. What is significant about this wreck is that the highest point of was located at a depth of 6.2 m in general depths of 9 m, while much of the body of the wreck had sunken into the sand and protruded less than a meter above the surrounding seabed. It should be clear from this example that lidar has a proven capability to detect small wrecks in very shallow water (West and Lillycrop 1999).

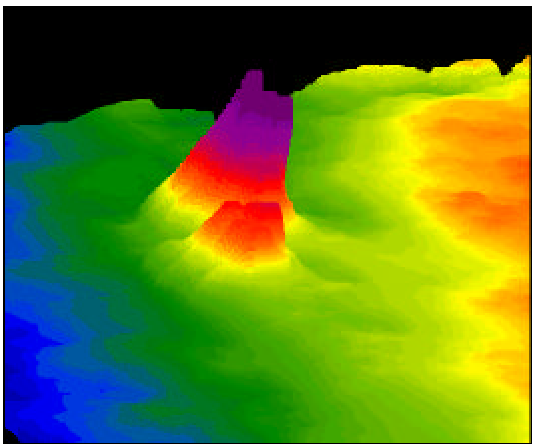
Figure 10 Wreck, Mexico

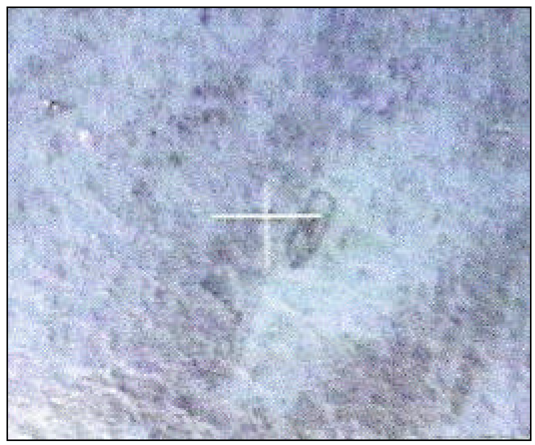
Figure 9 Down-look Video of Wreck

Safety in Hazardous Areas

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; however it is a task that often imperils the survey vessel itself. SHOALS is increasingly being used to conduct surveys in areas that are potentially too dangerous for surface vessels to operate it. One such survey was conducted around the rocky coasts of New Zealand's Sub-Antarctic Islands which are characterized by extreme surf and spray conditions as well as bottom topography which is dominated by isolated pinnacles. *Fig. 11* shows *a* typical coastal area composed of both drying and submerged rocks. The drying and breaking rocks are obvious in the photograph, but a submerged pinnacle lies to the bottom-right of the 'doughnut' shaped rock. This particular pinnacle rose from a depth of 15 m to within 7 m of the surface and had a base cross-section diameter of less than 10 m. The challenge was therefore to 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 identified as crucial to such a project (West et al.,

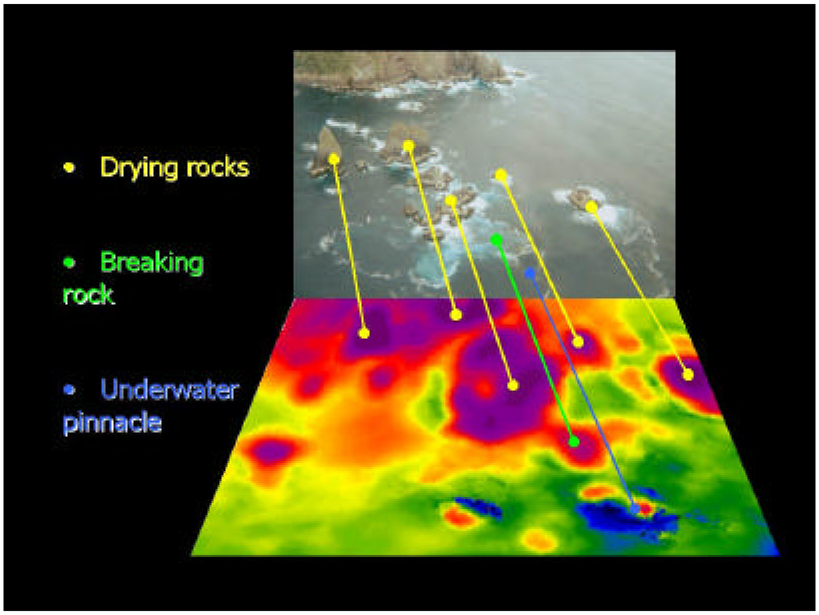

Figure 11 Shallow-water Rock Complex, New Zealand

1999), able to meet all the inshore requirements while also providing safe clearance for conventional acoustic platforms to work in the deeper water. It was therefore not only used to survey close inshore, but also to sweep many apparently deep areas with the aim of locating any rocks which posed a danger to surface navigation. The results of this survey were then passed to the Surveyor in Charge of the marine survey allowing him to plan ship and launch surveys with complete confidence that all dangers to these assets had been identified.

Rapid Response

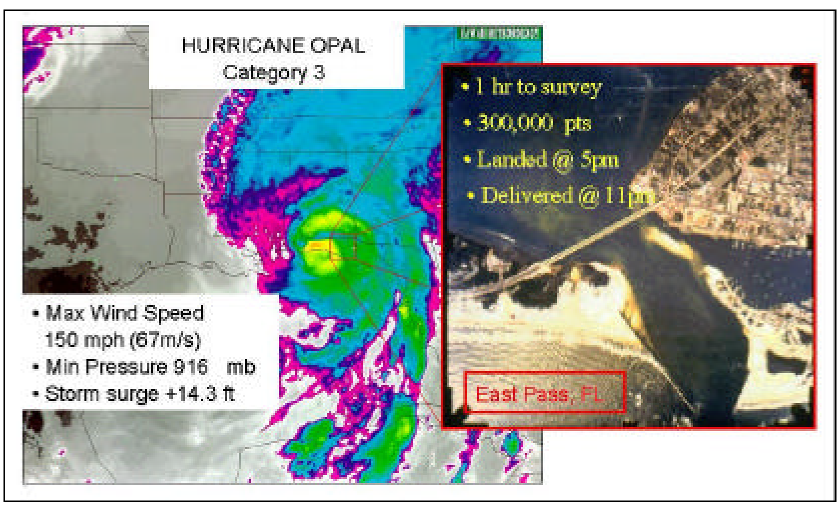

Figure 12 Post-Hurricane survey, Florida 1995

Before moving on from the above example, it is important to highlight another reason for its use in this area. The sub-Antarctic island groups of New Zealand are remote and dominated by predominantly foul weather, meaning that a major challenge was to mobilize during an extremely short weather window. The ability to conduct surveys rapidly also gives it an inherent capability to respond to evolving situations, 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 (Irish et al. 1996). 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.

Flexibility

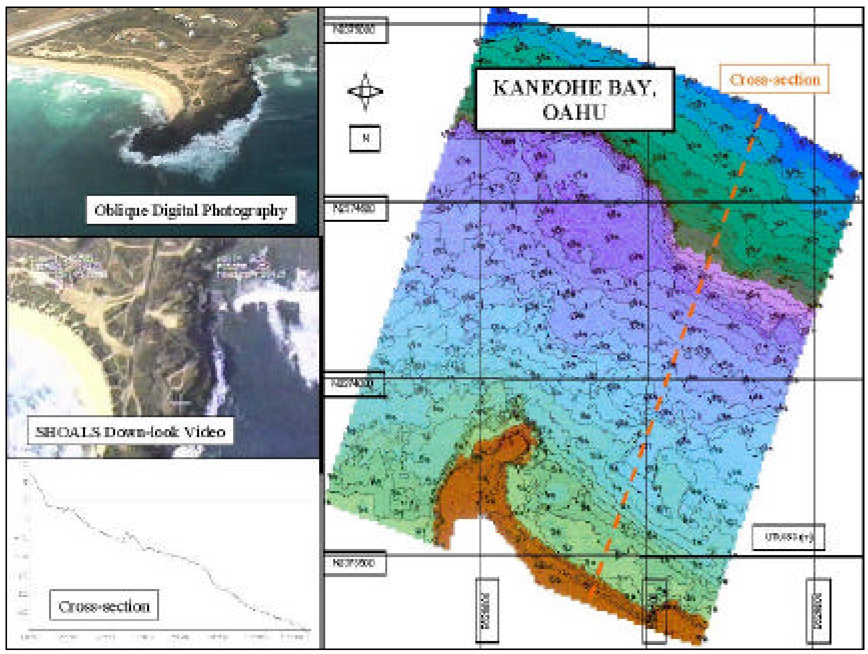

Figure 13 Composite Data Product, Hawaii

Operating from the air gives the shallow-water surveyor a new flexibility that the ship-borne hydrographers of the past could hardly have imagined. Released from many of the limitations of weather and hazards to a vessel, ALH allows the rapid and safe collection of comprehensive coastal data sets. Part of the SHOALS equipment suite is a down-look video that records imagery of the area directly under the aircraft at all times, while this is often complemented by use of oblique digital photography *(Fig. 13)*. The resultant composite of data and imagery is of immeasurable use to a wide variety of users that is diverse as the warfighter and environmentalist as much as the nautical charting authority. While these tools are standard for SHOALS surveys, there is also the potential to marry ALH with a variety of other technologies. At the most basic level this can be conventional acoustic means and the New Zealand survey illustrates the considerable benefits accruing from combining Lidar capability with conventional acoustic platforms. However, Lidar when merged with other airborne sensors presents new opportunities in fields such as coastal resource management. The USACE has started to move toward an approach that treats sediment, specifically sand, as a regional-scale resource (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

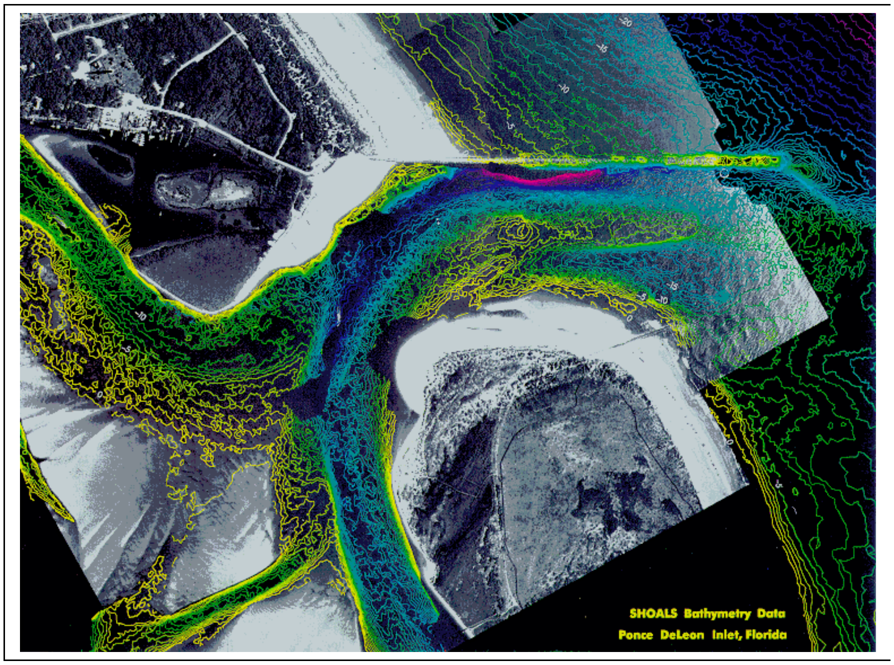

Figure 14 SHOALS Data Merged with Aerial Photography

not subject to errors introduced by tidal measurements and changing datums. These elevations are then fused with aerial photography and overlaid in a GIS for presentation and analysis *(Fig. 14)* (Watters and Wiggins, 1999). SHOALS data has also been merged with hyperspectral data in two pilot projects to map sea grass (Lillycrop and Estep 1995).

Cost Effectiveness

LADS, Hawkeye and SHOALS have all reported significant savings over conventional acoustic methods (Sinclair et al 1999), (Axelsson and Alfredsson 1999), (Lillycrop et al. 1996). Because of this, ALH is rapidly becoming the tool of choice in clear, shallow waters since it will usually achieve coverage rates several orders higher than current launch methods at less cost per square

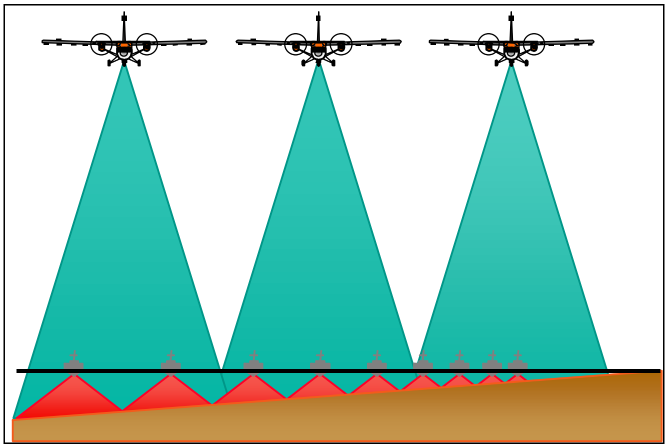

Figure 15 ALH Coverage v MBES Coverage

mile. Indeed as system capabilities increase, the economics of ALH are likely to become even more irresistible (Axelsson and Alfredsson 1999). However it is important to qualify this since MBES systems rapidly become more effective in deeper water and may also benefit in such areas from 24-hour operations. In summary, though, it is clear that ALH is most economic in areas where MBES systems are least.

Conclusion

The attraction of ALH lies in its capability to augment conventional survey capabilities in a cost-effective manner; operating within relatively clear, shallow water regions, which are among the most costly, hazardous, and time-consuming areas for ship and boat operations. In summary, survey launches suffer from their dependence on a 'Mother' ship or local operating base, slow coverage rates and vulnerability to grounding damage; ALH has the potential to overcome all these disadvantages.

The potential benefits of ALH are considerable and will continue to open up new opportunities in fields as diverse as regional sediment management and warfighting support. Development trends of ALH are already towards, smaller, cheaper and more automated systems that have the potential to be pod-mounted or even flown in Unmanned Airborne Vehicles (UAV). As a consequence, future systems are likely to be cheaper to run and offer even greater degrees of flexibility

Acknowledgements

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The Swedish Hydrographic Office and Land Information New Zealand (LINZ) have also released material for incorporation in this paper:

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