Future Advancements in Airborne Hydrography

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The airborne lidar bathymetry (ALB) systems operating in the world today are the products of Canadian, Australian, United States, and Swedish government programmes, and these governments have been primarily responsible for defining the user requirements. ALB systems of the current generation have matured, and the services of several are now available from industry. With up to eight years of successful operations, including thousands of hours of experience in logistics, data collection, data processing, and product generation, the latter three national governments are currently re-evaluating their needs and formulating more ambitious ALB requirements that go well beyond the current capabilities. Serious consideration is being given to defining where the technology and systems must be in five to ten years to meet anticipated needs in areas such as nautical charting, port and harbour mapping, coastal zone management, coastal engineering projects, and military rapid environmental assessment for site characterisation.

Vision

ALB systems in each of the above countries were developed upon different survey requirements and programme goals. Each programme has travelled a different path, and each has experienced different successes and problems, but representatives of these programmes have discovered that they all share a similar vision for the future (Lillycrop et al., 2001). Industry will be quite challenged to meet these new requirements for enhanced data collection capabilities, lower unit cost, size constraints, and the ability to integrate with complementary sensors.

The future of airborne lidar bathymetry is now envisioned within the broader context of airborne coastal mapping and charting. Because lidar bathymetry has matured into a viable operational technology, it is now possible to propose a more complete coastal mapping and charting capability that includes collecting land and water elevations, imagery, navigation aids, land-use features, and environmental characteristics from a single flight and platform. The power of such a capability will be in the ability to collect more information from the air and the synergy of the measurements. Flying areas each year allows accurate calculations of change, and, over time, rates of change. This is critical in monitoring short-term storm impacts and long-term physical and environmental variations.

One significant step is the fusing of hydrographic and topographic lidars with digital imagery to create the Compact Hydrographic Airborne Rapid Total Survey

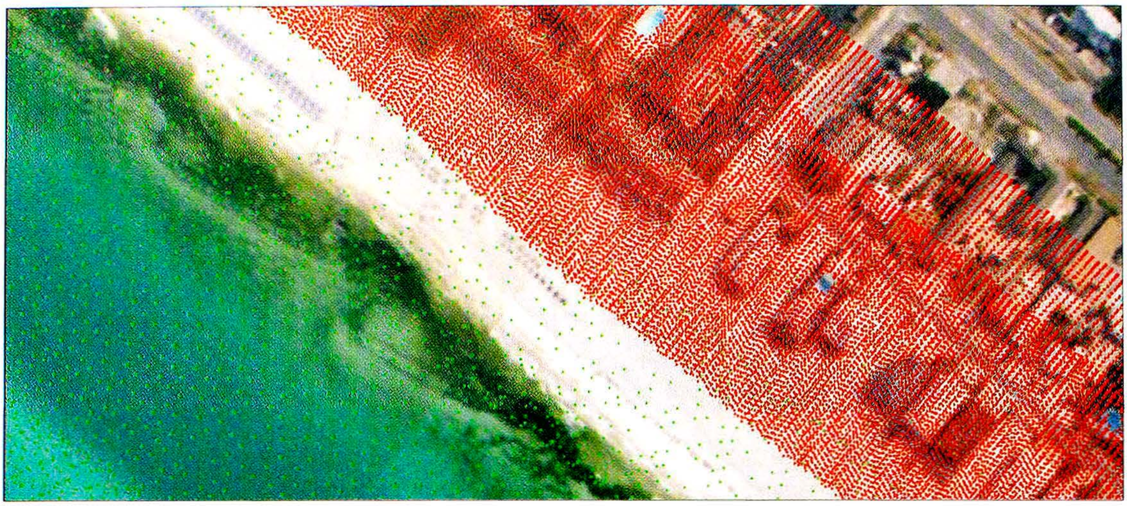

Figure 1a: Fusion of hydrographic and topographic lidar data with imagery: data points

(CHARTS) system (West et al., 2001b). Elevations from topographic and hydrographic lidars will overlay high-resolution digital still imagery. Included in the design is the ability to share the inertial navigation and GPS data with other potential sensors such as a passive hyperspectral scanner. In this configuration, a single airborne platform will be able to fly a suite of sensors to rapidly collect a wide range of accurate coastal measurements. Since the sensors are co-located and use the same positioning and attitude data, combining the results will be straightforward and provide valuable synergy. A simulated product, created from existing, non-simultaneous data sets, is shown in Figures 1a and 1b. Figure 1a shows dots representing locations of lidar measurements, and Figure 1b shows contours of the associated measurements referenced to a common datum. Dots and contours overlay aerial photography from the Florida Department of Environmental Protection taken west of the Panama City Entrance Channel, Florida in 2000. The width of the figures is 450 m. In both figures, green represents data from the U.S. Army Corps of Engineers (USACE) Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) system, and red is from the Optech Incorporated Airborne Lidar Topographic Mapper (ALTM). The SHOALS contours at 1m intervals were collected in June 2000, while the ALTM contours at 0.305m increments are from June 1996. New construction can be seen on the land as differences between image detail and contours.

Figure 1b: Fusion of hydrographic and topographic lidar data with imagery: elevation contours

Such information is required by the U.S. Army for coastal monitoring and for logistics of over-the-shore operations, by the U.S. Navy for collecting nautical charting and environmental data, and by many other federal, state, and local government agencies for coastal zone management. These data, either alone or fused, will provide high-density measurements both above and below the water to produce a more complete and consistent map of the coast based on a common datum (Parker et al., 2001). As an example, the hydrographic lidar can provide calibration information for the analysis of multispectral imagery to delineate bottom types (Lillycrop and Estep, 1995) and water clarity. The topographic lidar can provide vegetation elevations to support land use characterisation of the digital or multispectral imagery.

Background

Airborne laser (or lidar) bathymetry is a technique for measuring the depths of moderately clear, near-shore coastal waters and lakes from a low-altitude aircraft using a scanning, pulsed laser beam (Guenther, 1985; Guenther, 1989). It is also known as airborne lidar hydrography (ALH) when used primarily for nautical charting. The term 'lidar' is an acronym that stands for LIght Detection And Ranging, but, as with 'sonar' and 'radar', it is in such common usage that it has become a word in its own right and needs no longer to be capitalised. The principle of operation is based on the estimation of depth from precise measurement of the time difference between the received components of each laser pulse as it is partially reflected from the water surface and from the sea bottom (Figure 2). The location of each sounding is determined by using one of several highly-accurate forms of GPS to position the aircraft along with carefully-measured beam pointing and aircraft attitude information. The maximum operational depth depends strongly on water clarity and can be in excess of 50 metres. Other environmental factors that can cause problems with ALB surveys include rain, fog, low clouds, high winds, high waves, surf zone, heavy sun glint, very steep bottom slopes, and kelp beds (Steinvall et al., 1994; Guenther, 1985; Nairn, 1994). A wealth of detailed technical information on ALB is provided in Guenther et al. (2000). Practical matters are covered extensively in Guenther (2001).

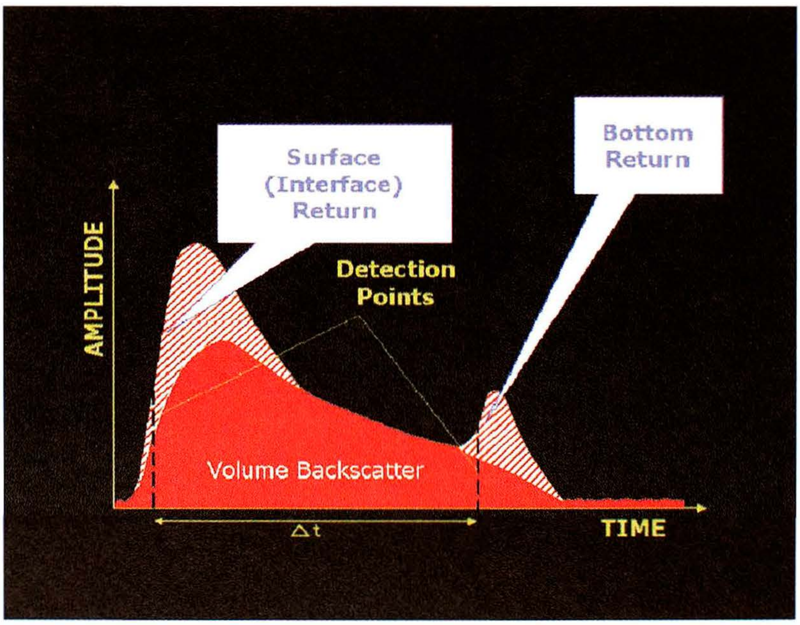

Figure 2: Schematic lidar waveform with key elements

The concept of ALB grew out of efforts in the mid 1960's to use the newly invented laser to find submarines (Ott, 1965; Sorenson et al., 1966) and as an 'airborne laser fathometer' (Sorenson, 1966). The seminal paper confirming the ability to perform near-shore bathymetry was written by Hickman and Hogg

(1969) based on work done at the Syracuse University Research Center. Critical phenomenological vertical-accuracy considerations were identified during the testing of the NASA Airborne Oceanographic Lidar (AOL) operational bathymetric prototype (Guenther and Goodman, 1978; Hoge et al., 1980) and ameliorated as a result of subsequent analyses and simulations (Guenther, 1981; Guenther and Thomas, 1984; Guenther, 1986). In 1985, the Canadian LARSEN system, designed with the goal of surveying in the Northwest Territories during brief ice-free times, became the world's first operational airborne lidar bathymeter (Casey et al., 1985; Casey and Vosburgh, 1986). In Australia, the successful testing of the WRELADS II prototype (Penny et al., 1986) led to the development and fielding of LADS (Penny, 1992; Setter and Willis, 1994) and LADS Mk II (Spurling and Perry, 1997; Sinclair, 1998). The successes of the AOL and LARSEN designs led to the development and fielding of SHOALS in the U.S. (Lillycrop et al., 1994; Lillycrop, et al. 1996; Guenther et al., 1996) and Hawk Eye in Sweden (Steinvall et al., 1994; Steinvall et al., 1997). A comprehensive history of ALB developments and detailed descriptions of all current systems are presented in Guenther (2001).

The primary advantages of this technology are that it provides:
- The ability to perform surveys accurately and quickly, in both large and small project areas, in a more cost-effective manner than traditional waterborne methods (Enabnit et al., 1978; Sinclair and Spurling, 1997; LaRocque and West, 1999)
- The capability to survey where it would be difficult, dangerous, or impossible to use water-borne techniques (Graham et al., 1999)
- The facility to simultaneously survey the sea bottom, the adjacent beach, and coastal engineering structures (both above and below the waterline) (Guenther et al., 1998; Mohr et al., 1999)
- The mobility to perform yearly monitoring of dynamic areas and rapid assessments of seasonal change (McClung and Douglass, 1999) and storm damage (Irish et al., 1996; Irish and Truitt, 1995)
- The capacity to quickly complete surveys during favourable environmental windows in areas which are unavailable to traditional techniques for long periods due to conditions such as ice cover (Vosburgh and Banic, 1987)

A bonus is that several of these requirements can sometimes be satisfied simultaneously (Ebrite et al., 2001).

Based on many years of operations of the five current systems, ALB has proven to be an accurate, cost-effective, rapid, safe, and flexible method for surveying in shallow water and on coastlines where sonar systems are less efficient (LaRocque and West, 1999; Wellington, 2001; Skogvik and Axelsson, 2001; Ebrite et al., 2001). Applications for bathymetric data such as traditional nautical charting, monitoring engineering structures and the movement of sand (Wozencraft and Irish, 2000), environmental protection, and resource management and exploitation are expanding rapidly. In Figure 3, the navigation channel, jetties, and offshore area at Fort Pierce, Florida have been accurately charted in a few minutes

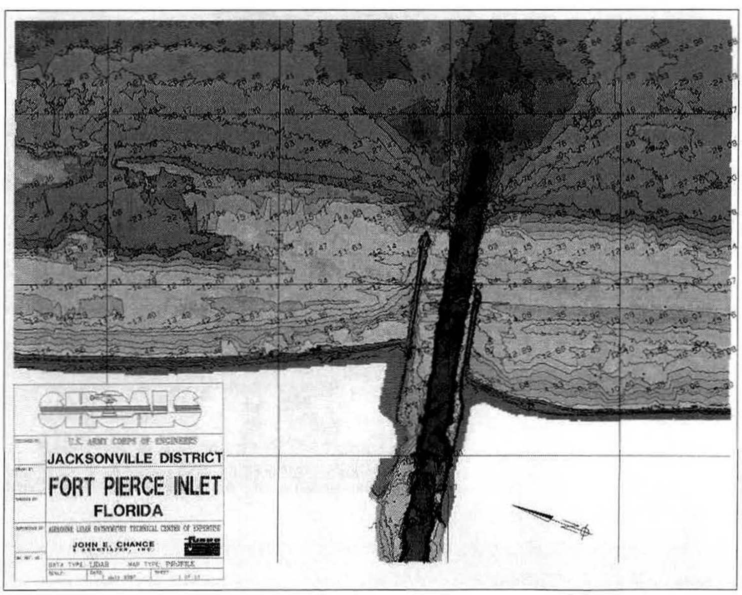

Figure 3: SHOALS airborne survey of Fort Pierce, Florida inlet

of flight time. The growth in the recognition, utilisation, and demand for ALH and ALB surveys has become explosive around the world and is beginning to outstrip availability.

A great deal of care, time, and money has been put into the design, construction, testing, calibration, and operation of the present ALB systems to ensure that they meet the accuracy standards of the International Hydrographic Organisation (IHO) (Guenther et al., 2000). The costs of operations for all current ALB systems are reported most often as 15-30 per cent of the standard survey cost, depending on location, depth, and survey density. Soundings are densely spaced, typically on a 4-5 metre grid, within a wide swath under the aircraft, whose width is roughly half of the altitude. Gross coverage rates as high as 64 km^2/hour (19 nmi^2/hour) are reported (Sinclair, 1999a). The major limitation is water clarity. Extremely low bottom reflectivity can occasionally be a problem. For areas with very clear water, the advantage of surveying a wide swath at aircraft speeds can be obtained for depths as great as 50 metres or more. Only in this way can the enormous survey backlogs of many countries (UN, 1989) be significantly reduced in a timely manner. The fact that airborne lidar can also measure land topography and survey simultaneously on both sides of the land/water boundary (Guenther et al., 1998; Irish et al., 2000) is highly beneficial and attractive to coastal engineers. Figure 4 presents a graphic comparison of lidar and multibeam sonar operations in shallow water.

The next-generation systems described below, which are presently being constructed according to the above Vision, are derived from the USACE SHOALS system (Lillycrop et al., 1997; Guenther et al., 1998; Brooks et al., 1998). SHOALS is a government-owned, contractor-operated bathymeter. It is a semi-portable system that can be either hung from the aircraft in an external pod or mounted internally. It can be installed in aircraft of opportunity that have an appropriate external port. SHOALS was initially developed for surveying the condition of navigation channels, but quickly evolved into a nautical charting and coastal zone mapping system as well. It is owned by the USACE and employed in co-operation with the U.S. Naval Meteorology and Oceanography Command (CNMOC) and the U.S. Naval Oceanographic Office (NAVOCEANO) under the auspices of the Joint Airborne Lidar Bathymetry Technical Center of eXpertise (JALBTCX) in Mobile, Alabama, USA. It was built and is maintained by Optech Incorporated (Toronto,

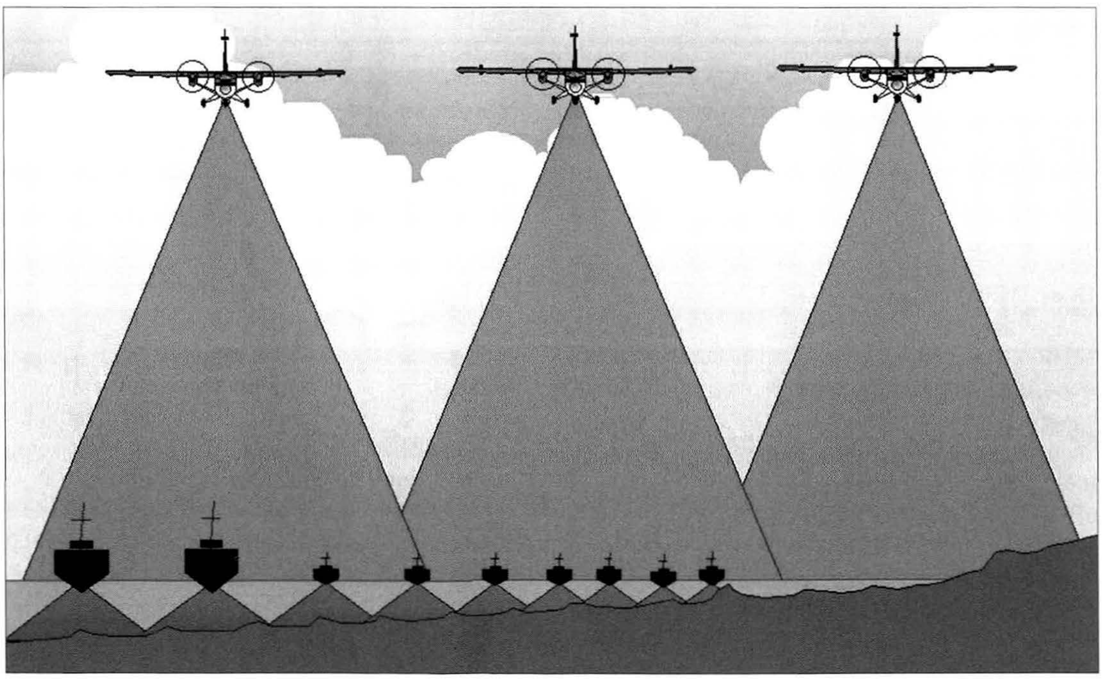

Figure 4: Depiction of lidar and multibeam sonar operation in shallow water

Ontario, Canada). Field operations are conducted by Fugro Chance (formerly John E. Chance & Associates), Lafayette, Louisiana, currently in a deHavilland DHC-6 Twin Otter aircraft provided by Kenn Borek Air Ltd. (Calgary, Alberta, Canada) of recent Antarctic rescue fame (Figure 5).

Since the initiation of SHOALS survey operations in early 1994, eight successful field seasons have been conducted, and over 400 projects have been surveyed for a variety of sponsors, around all continental U.S. coastlines (Irish and White, 1998; Irish et al., 2000) including the Great Lakes (Mohr et al, 1999), and around the world (LaRocque and West, 1999). Notable survey locations include Mexico (Pope, et al., 1997), New Zealand (Graham et al., 1999), Bahamas (West and Lillycrop, 1999), Portugal (Lillycrop et al., 2000;

Figure 5: SHOALS system in Kenn Borek deHavilland DHC-6 Twin Otter

West et al., 2001b), Puerto Rico (West et al., 2001a), Florida (Irish et al., 1995; Irish et al., 1996; McClung, 1998; Watters and Wiggins, 1999), Lake Tahoe (West et al., 2001a), the volcanic island of Montserrat, six Hawaiian islands including Molokai (West, 2001), and the Pacific islands of Guam, Saipan, Tinian, and Farallon de Medinila. The system has recently surveyed in Honduras, Alaska, and California for a variety of customers.

User Applications

Airborne lidar bathymetry is an accurate, capable, and highly cost-effective alternative to traditional, waterborne sonar in areas with appropriate depth and water clarity. With the production of high-density, three-dimensional digital bathymetric data, it offers a number of important products, services, and applications in coastal waters. Under appropriate circumstances, finished survey products may be delivered within 24 hours (Sinclair, 1999b; Lillycrop et al., 2000). ALB is often optimal in relatively shallow areas where sonar is less efficient. It can also survey safely in areas where sonar cannot, including, for some systems, above-water structures and dry land. ALB is, however, not a substitute for sonar because ALB surveys are limited by water clarity and depth. Furthermore, it cannot be expected to detect one-hundred per cent of bottom hazards with size on the order of a one-metre cube (IHO 'Special Order') unless an expensive, unusually high-density survey is conducted. It should be noted, however, that this is a difficult and expensive task for modern sonar systems, as well. Regions where ALB and sonar capabilities overlap are thought of as areas of co-operation rather than of competition.

Operational ALB systems have been and can be deployed to locations around the globe. Applications for ALB (Cunningham et al., 1998; Sinclair, 1999b; Irish et al., 2000; Wellington, 2001; Guenther, 2001) include bathymetric surveys of large offshore coastal areas, islands, coral reefs, navigation channels, lakes, ports and harbours, shore protection projects such as jetties and breakwaters, beaches, shorelines, mud banks, and dredge disposal sites. Surveys have been completed economically and safely in disparate areas. These include everything from large, relatively shallow, mostly flat areas with sink holes and patterns of sand waves (Figures 6), as in the Bahamas (LaRocque and West, 1999), to complex areas composed of myriad small islands, channels, and shallow banks, as in Norway (Sinclair, 1999a) and Sweden (Skogvik and Axelsson, 2001), to deeper, rocky areas rife with pinnacles which pose a serious danger to surface vessels (Figure 7), as in New Zealand (Graham et al., 1999; Sinclair, 1999b). Large, stable regions, such as coral reefs, can be surveyed one time only, while rapidly changing areas like the sandy coast of Florida, 40 per cent of which is suffering serious erosion, may be surveyed every year or two to monitor change (West and Wiggins, 2000b).

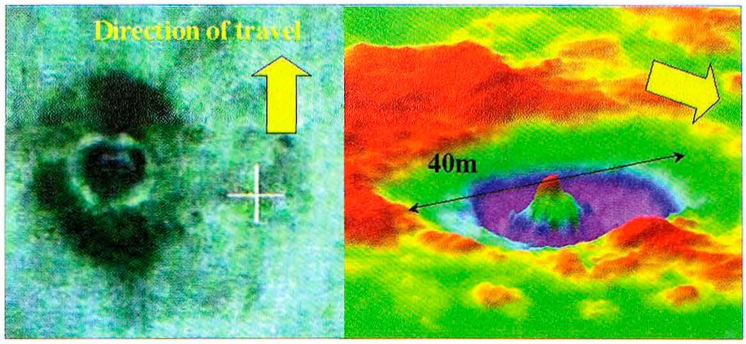

Figure 6a: Sink hole approximately 30 m in diameter in Bahamas

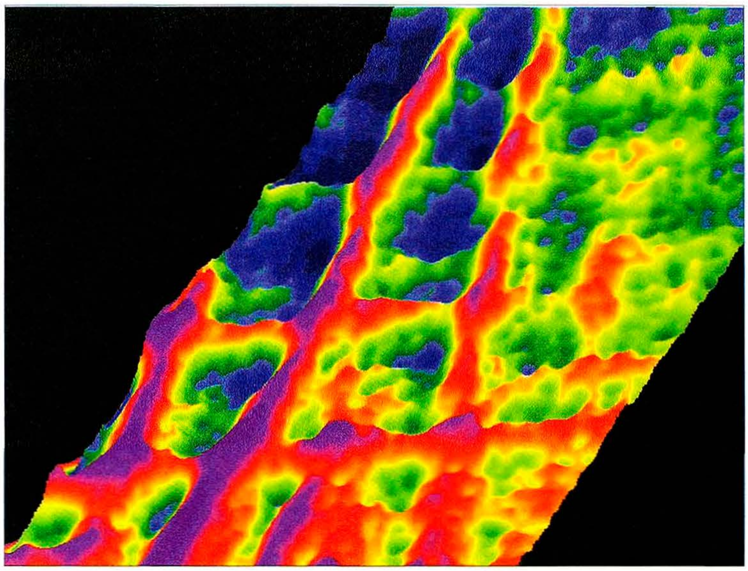

Figure 6b: Complex 1-m high sand wave pattern in Bahamas

The overall status of hydrographic surveying and nautical charting worldwide has been rated in the range from 'poor' to 'fair' (UN, 1989). Conversely, the use of coastal areas by commercial and recreational concerns is growing at a rapid pace. Large-scale nautical charting has been the chief survey requirement for most of the airborne lidar survey systems. This is due to the enormous backlog in the production of modern charts needed for safe navigation worldwide (Setter and Willis, 1994; Nordstrom, 2000; Featherstone, 2001). A large percentage of the backlog areas is in relatively clear, shallow waters (less than, say, 50 m) which are well suited for ALB. This mission requirement is not likely to diminish over the next 20 years because even though thousands of square nautical miles have been surveyed with LARSEN, LADS, SHOALS, Hawk Eye, and LADS Mk II airborne lidar bathymetry systems (Guenther, 2001), many more times this area is in critical need of surveying. ALB is particularly important for use in complex coastal areas because of its cost, speed, and safety. Nordstrom (2000) said it succinctly for the Swedish Maritime Administration: "the use of a helicopter-borne laser-beam system is essential, especially in shallow and narrow waters in the archipelagos."

Perhaps one of the more rapidly growing survey requirements is for large regional surveys to map and monitor the conditions of coastal shorelines (McClung, 1998; Watters and Wiggins, 1999). This is particularly true along sandy shorelines that are subjected to severe storms. Additional applications include such tasks as support of oil and gas exploration and production (Sinclair, 1999b), baseline turning point and Exclusive Economic Zone (EEZ) delimitation (Sinclair, 1999b), design and evaluation of coastal engineering structures for shoreline stabilisation (Mohr et al., 1999; Irish and White, 1998), marine resource and coral reef management, storm surge modeling (West and Wiggins, 2000a), resolution of historic bathy/topo shoreline inconsistencies (Parker, et al., 2001), submarine pipeline planning and construction, low impact surveys in ecologically sensitive areas (West et al., 2001a), and rapid shoreline assessment for tactical military operations (Lillycrop et al., 2000).

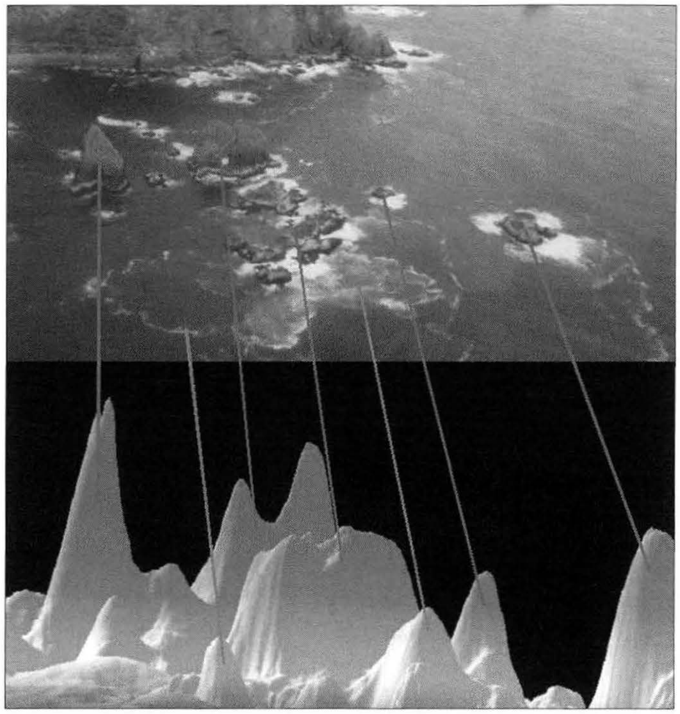

Figure 7: Graphic display of SHOALS airborne survey on dangerous rocky shoreline

The Challenge

The missions described above are expected to continue to be the primary applications over the next ten years. At the present time, there are two general philosophies of system configuration in terms of aircraft size and utilisation. One approach is to use a large, high-performance lidar system in a dedicated, long-range aircraft. In this way, the system can be flown directly to any location in the world within a few days. Long sorties may consist of lengthy surveys if flown at a location near the airport or shorter surveys performed at remote locations. This also provides the operational flexibility to transit to a distant alternate survey area in response to local environmental conditions. It is expected that there will be continued demand for services from such systems. Few such systems, however, will be needed. The second approach is the proliferation of smaller, portable, shorter-range systems that can be installed in local 'aircraft-of-opportunity'. These have the advantage of lower cost, the ability to fly from smaller and less developed airfields, and the potential for greater acceptance as a general survey tool by both service providers and clients.

The consensus opinion of government and industry representatives is that major emphases in the future will be on smaller size and lower cost for the lidar sensor and associated electronics, potential for use in smaller aircraft, greater flexibility in the use of aircraft-of-opportunity, more sophisticated automated data processing with integrated survey planning, and utilisation of more off-the-shelf equipment for easier maintenance (Lillycrop et al., 2001). These characteristics will reduce the survey cost per unit area by reducing the initial investment, flight costs, field crew size and training, and manual data processing complexity.

The second part of the challenge is to provide a wide range of additional capabilities and products. More information about the environment should be extracted from the raw lidar return signals to better quantify the physical characteristics of the survey area and add value to the existing bathymetric products. Once the cost has been expended to operate the aircraft for lidar elevations, valuable additional environmental characterisation can be obtained at a very low cost if appropriate software algorithms are available. The ability to use multiple lidars, and lidar in conjunction with complementary sensors such as multispectral and hyperspectral imagers, to produce a broader range of information and products will lead to new applications and missions. There are undoubtedly other sensors that lidar could complement to improve the ability to rapidly and accurately characterise and quantify the coastal zone. The potential applications are broad, but require ALB systems that are small, flexible, relatively inexpensive to purchase and operate, and easy to operate and integrate with a variety of other techniques.

Driving Factors

There are two types of ALB customers - - system customers who wish to own and operate their own systems and survey customers who wish to contract for surveys. The first category includes both government agencies and private companies. The latter ranges from national governments with huge survey backlogs and multi-million dollar budgets to local governments or private entities with a small budget and a little project. There could be a very large number of the latter if costs are attractive, and knowledge and availability of the technology become widespread. With few exceptions, the needs of this diverse customer base are very similar.

One of the primary reasons for the development of ALB systems is their significant cost advantage in shallow water. In the past, there may have been only one way to conduct a survey. Today, a hydrographer has choices. There may be more than one method possible for solving a given survey problem, and after accuracy, cost must be one of the most important considerations. The true costs associated with surveying in general are highly dependent on location and geography. Flat, smooth, nearby coastlines like the Gulf Coast of the U.S. are cheaper to survey than the remote, rocky coastlines of Alaska by a factor of two or three. According to a recently published report (Featherstone, 2001), the cost of waterborne sonar hydrography, averaged over a number of different areas, some easy and some hard, varies from US\$ 4,400/km^2 for NOAA surveys to over twice that much for contract surveys. Modern hydrographic surveying is clearly a very expensive and labour-intensive task. This is one of the reasons for the large hydrographic backlogs being experienced by many countries (UN, 1989). Although it offers many adjunct capabilities that are utilised and appreciated by a variety of customers, the primary reasons for the use of ALB are its ability to perform hydrographic surveys much more rapidly and at a much lower cost per unit area.

Costs can be broken down into two main categories: initial system and upgrade costs, and operations and maintenance (O&M). If a typical lidar system surveys, say, 5,000 km^2 per year for ten years and incurs certain additional costs for technology and software upgrades, the amortised system cost today will be roughly US\$ 70/km^2. The cost of future systems is expected to be even lower when they are produced in greater numbers. Lidar survey O&M costs depend strongly on project characteristics. Survey scenarios and costs can vary widely. The characteristics with the largest effects on costs are project location (in the world, and relative to the nearest airport), project size, horizontal density requirements, survey accuracy 'order', the possible requirement to resolve all questionable points by reflying, the physical shape of survey area and if it includes surf zone or high cliffs, the positioning method employed, and extant environmental conditions on site. Many of these same factors apply to sonar costs. The O&M cost ratio between ALB and multibeam sonar depends very strongly on the survey depth, the lidar survey density, the pulse repetition rate of the airborne system, and the location of the survey. For most practical cases, a realistic factor is between 3 and 10 in favour of ALB for depths under 50 metres. Regardless of the exact numbers, it is quite clear that ALB offers a significant cost advantage.

A detailed cost model comparing lidar and sonar for a large, complex survey area has been published by Axelsson and Alfredsson (1999) of Saab Dynamics AB with input from the Swedish Hydrographic Department. The survey logistics are broken down by depth range and associated accuracy requirements. The ALB values are for a proposed 1,000-pulses per second (pps) system mounted in a helicopter. It is surmised that these values are for 'local' surveying and do not include transit or mobilisation costs from a distant location. The cost ratios vary from 2.5 to 43.5 in favour of lidar, depending on depth and accuracy requirement, with larger values in shallower waters. Lidar costs are predicted between US\$ 210 /km^2 and US\$ 378 /km^2 for IHO Order 1 and Order 2 surveys at depths between 4 and 32 m. These values are lower by a factor of from two to four compared to current practical experience. Prices charged will also vary according to risk, rate of recovery of initial investment, and profit margin. A more comprehensive description of cost considerations can be found in Guenther (2001).

For some applications, the high coverage rate of lidar, and associated reduction of the survey backlog, may be as important as the cost savings. Since 1994, the Royal Australian Navy LADS system has covered the same area as the remainder of the Australian Hydrographic Service's six survey ships combined and utilised a small fraction of the manpower.

The vision for future ALB systems is driven by the following hypotheses.
- All customers desire more affordable ALB systems and surveys
- Most survey customers do not have large enough requirements or budgets to justify the purchase cost of a system
- Most potential system customers wish to operate systems in smaller aircraft to reduce overall operating costs, because aircraft costs are the dominant cost in ALB operation
- Systems of the future must be extremely flexible to meet the varied and changing requirements of the survey community
- Lessons learned from existing systems and programmes must be incorporated, and preferably automated, into the new ALB systems
- Compact Airborne Laser Terrain Mapping (ALTM) systems, adapted for operation on small photogrammetric aircraft-of-opportunity and providing accurate, high-density terrain elevation data, are enjoying worldwide success. This implies the existence of a large potential user base and acts as a role model for more complex ALB systems
- Expectations of the international hydrographic community are shifting towards higher standards for hydrographic mapping, including nearly 100 per cent bottom coverage and the ability to detect small features on the bottom
- Many survey customers would be able to make use of value-added products related to environmental characterisation
- Military organisations desire to put even smaller systems (generation-after-next) into unmanned airborne vehicles for covert operations

It is envisioned that in the future, as with ALTM systems now, the majority of ALB systems will be procured by aerial survey companies which will then provide survey services to clients as required. A minority of systems will be purchased by government agencies who will want to own and operate their own equipment. Many government agencies will make use of contract surveys.

Performance Characteristics

New advancements in ALB technology and software algorithms will be able to provide the user with a combination of increased capability, improved performance, new products, and lower operating costs in a smaller package than has been available with earlier-generation ALB systems. As performance improves, the locations and types of applications will increase. It is crucial to remember, however, that the accuracy and water penetration capability of existing systems has been hard won and must not be compromised in new systems for the sake of cost and size reductions. An ineffective or marginalised system is not a bargain and is not acceptable. Standards must be maintained, and lessons learned must not be forgotten.

To support the applications described above, the ALB systems of today must evolve. This section lists some of the desired performance characteristics and identifies key focal points for research and development to provide the changes needed to enhance today's sensors and systems. Until these characteristics are adopted by industry, government programmes will be the only method of evolving airborne lidar hydrography. If these criteria are met, the entire survey community, both industry and governments, will add ALB to their capabilities. Only then will systems mature and evolve based on the needs of the many.

Platform and Logistics

Size and power requirements of existing ALB systems make them somewhat platform-specific. For systems not intended to be operated from a dedicated aircraft, achieving an airborne sensor design that is fully platform-independent will allow the use of aircraft-of-opportunity. To increase operational flexibility with respect to mission type, sensor fusion, and survey cost, most systems of the future will be small, portable, and modular in design. Regardless of application, these three criteria will ensure that future systems can utilise standard photogrammetric aircraft of opportunity (including utility helicopters), be easily shipped worldwide to utilise these aircraft, and be capable of operating integrated with other sensors. A smaller sensor may be operated from a smaller aircraft, thus reducing the cost of hourly survey flight operations. Reduced costs for sensor mobilisation and demobilisation will also be realised. The size must also be reduced so that lidar can become a viable sensor for Unmanned Aerial Vehicles (UAV). This is important to the military of the future, one that must project itself in a moment's notice around a region or around the world.

Existing systems require several specially-trained personnel to mobilise them into the aircraft. Once installed, they require complex procedures to calibrate. Future systems, as a goal, should require fewer and less-specially-trained personnel to mobilise equipment and initiate survey missions. Targets for size and training requirements should be similar to those for acoustic multibeam survey systems. System maintenance should be modular and self-diagnosing to reduce the amount of training required of the field survey crew. Finally, the level of automation versus operator control must advance such that the system itself is capable of monitoring the progress of the mission and assessing the quality of the data to reduce the needed expertise level and workload of the operator, or in the case of a UAV application, to operate autonomously.

Lasers

Since airborne lidar bathymetry began, a primary performance metric has been laser pulse-repetition rate. Faster lasers are very desirable. Higher sounding rates will allow even greater area coverage rates, with associated reduction in survey cost, and/or denser coverage. Higher area density, particularly to achieve 100 per cent overlap at the surface, would improve the detection probability for small objects on the bottom. Along with high repetition rates, the pulses must have sufficient energy and narrow temporal width. Diode-pumped, solid-state laser technology has advanced to the point today where pulse repetition rates of 1,000 pulses per second, with appropriate characteristics, are achievable in a relatively compact laser system. In the future, there are expectations for yet higher repetition rates and narrower pulse widths. The limitations then may shift to digitizers, associated electronics, computers, and data management and quality control procedures that can keep up with the data rate. As such performance improves, however, it will still be desired to maintain system compatibility with smaller aircraft of opportunity. As pulse rates increase, in conjunction with the need for the same pulse energy, average power requirements would naturally increase. It will be important to find compensating efficiencies to prevent this. For the distant future, tunable lasers (wave-length and energy) capable of adjusting to maximise performance under given environmental conditions could improve maximum depth performance and possibly extend the locations and missions where ALB systems are capable of operating.

Technology

In current systems, many components are custom or in limited availability. This can lead to maintenance and support problems as the system ages. In future systems, maximum use should be made of commercial off-the-shelf components. For platform-dedicated systems, which can be larger and more expensive, the ultimate performance envelope can be extended with the use of cutting-edge, highly sophisticated components regardless of size. Portable systems of limited cost and size will be built to meet but not exceed ad hoc operational requirements. The sophistication in this case will be in miniaturisation.

In order to achieve the above goals, recent and upcoming advancements in several key areas of ALB technology will be utilised. In addition to the lasers already discussed, these include the following.

- Lightweight and compact optical scanning systems are now becoming available that can provide the high scanning rates required by future ALB systems. The scanner must be flexible, programmable, and capable of operating in a variety of configurations to match the survey requirements. This might involve altering sounding density in the range between 1 m and 10 m. This and other mission survey parameters must be able to change for each survey line
- Compact, commercially available waveform digitisers on one board are needed that provide 1-ns time bins (without the need for interleaving) at kilohertz repetition rates with at least ten-bits of amplitude resolution
- Significant advances have been made in the development of compact inertial measurement systems that are now integrated with GPS. Future systems should be capable of using a wide range of different positioning systems such as GPS, P-code GPS (PGPS), differential GPS (DGPS), and kinematic GPS (KGPS)
- High-pulse rate ALTM systems using KGPS will provide ALB systems of the future with enhanced capabilities for terrain mapping and allowing mapping of coastal areas on both sides of the land-water interface at appropriate densities to a common datum
- Computer technology has taken enormous strides with the development of new functional boards and faster processors, which will provide tremendous increases in data acquisition and data processing speeds. Fewer computer boards will be required for airborne data acquisition and control. This computing power will also be harnessed by incorporating sophisticated software and algorithms to provide increased automation in both airborne operations as well as post-flight data processing
- Light-weight, flat-panel displays are replacing the large, heavy computer monitors used for operator displays in earlier-generation systems
- Geo-referenced digital imagery and digital video are highly desirable features that will be incorporated into more of the ALB systems of the future
- Developments in compact narrow-band optical filters will be closely monitored because these can improve the signal-to-noise ratio, and hence the maximum depth penetration capability, for daytime operations

The above technological advancements, when simultaneously incorporated into future-generation ALB systems, will yield a powerful combination of superior performance in a miniaturised package.

Ground-based Processing

Survey operations, including survey planning, data acquisition, and data processing, will become faster and more automated, thereby providing the user with a quicker turn-around and reducing the number of personnel required to support system operations. Software and algorithm development to provide more automated data processing is essential in making ALB a mainstream hydrographic tool. Minimising hydrographer interaction through streamlining and optimising ALB data processing will increase data throughput and provide greater uniformity in final products. Improved algorithms are needed for the complex surf zone and land/water interface where large areas of white foam and suspended solids complicate depth measurement and shore-line differentiation. Delineating where the land ends and the water begins, whether for coastal zone management or military rapid environmental assessment, can be very difficult and time consuming. An accurate, repeatable, automated methodology is required and should be achievable with more-aggressive use of existing raw data. In addition, a variety of new, sophisticated data processing options could be used to meet application and mission-specific goals.

Some existing ALB systems appeared before conventional shallow-water acoustic multi-beam survey systems became wide spread, but this acoustic technology has already significantly helped ALB. Shallow-water multibeam echosounders can produce more data than ALB systems, and this has caused a boom in tools to manage, edit, and visualise large spatial data sets. These tools, and their successors, can be integrated into future ALB systems in order to improve depth extraction and processing efficiency. Today, many weeks of special training in lidar technology are required to learn to process data accurately. Only through an integrated approach that automatically processes ALB data by considering raw lidar signals, nearest neighbors, and statistical variations simultaneously with survey mission parameters and historic survey data, can the amount of additional training be reduced and a typical hydrographer conduct ALB processing. To maximise the incorporation of ALB into commercial visualisation and editing packages, an open architecture must be adopted by the lidar manufactures so that existing software manufacturers and universities can evolve this capability.

New Systems: Near Term

The design and construction of a number of new-generation systems are currently underway. These will be smaller, more capable, more flexible, and less expensive to operate than current instruments.

SHOALS-1000

SHOALS-1000, representing a new generation of smaller, lighter, more flexible, full-capability, portable ALB systems with multi-sensor fusion capability, is currently being built by Optech Incorporated. In early 2001, the Japan Coast Guard (JCG) placed an order for the procurement of a SHOALS-1000 ALB system whose delivery and commissioning will be in the summer of 2003. The intended platform is a Beechcraft 350 aircraft. The new SHOALS-1000 family will be much more compact and roughly half the weight of the current SHOALS and will be initially capable of 1,000 soundings per second with upgrade capability to 3,000-pps. A digital still camera will provide overlapping, high-resolution imagery time-correlated to laser pulses. The basic transceiver design continues the extremely-successful SHOALS hardware configuration. Significantly, it will require no increase in overall aircraft power requirement for a 2.5x increase in pulse-repetition rate. The sounding density will be selectable from a 2-m, 3-m, 4-m, and 5-m spacing. As with SHOALS, the depth and position accuracy will satisfy IHO Order 1 (S44, 4th Edition). Extensive modular construction will improve field maintenance logistics.

Compact Hydrographic Airborne Rapid Total Survey (CHARTS)

In January 2001, the USACE JALBTCX announced plans to initiate development, in co-operation with the U.S. Navy, of a new family of ALB systems (West et al., 2001b). The first of these, the Compact Hydrographic Airborne Rapid Total Survey (CHARTS), incorporating a 1,000-pps laser for bathymetry, will be the logical successor to SHOALS for nautical charting and coastal mapping. CHARTS is a member of the SHOALS-1000 family with many of the same specifications and characteristics. One additional requirement is the inclusion of an integrated, low-energy, 10,000-pps IR laser transceiver to provide the option of a much higher density, non-simultaneous topographic capability over land. Orders for the procurement of CHARTS, and the related BATS system described below, were placed with Optech Incorporated, in conjunction with Technology Partnerships Canada through the Canada Defense Development Sharing Agreement (DDSA). Design and fabrication are underway, and delivery is scheduled for late 2003.

CHARTS will be a highly-automated system with lower operating costs than current systems. The smaller size and 210-kg total weight will enable it to operate from a wide variety of available photogrammetric aircraft-of-opportunity such as the Cessna 310, Aero Commander, Piper Navajo, and many others including military airframes. It will include all the capabilities currently operational on SHOALS and be capable of rapid response worldwide. The system will be completely portable via commercial transport to the project location and designed to allow system installation to be performed on an available aircraft at the survey location. Installation in a photo-camera mount will be possible. CHARTS is being designed to enable flight planning, data collection, processing and analysis, map generation, and data backup to all be performed in the field. Vertical and horizontal accuracy will be IHO Order 1 or better.

Bathymetric And Topographic Survey (BATS)

CHARTS' sibling, the highly-compact Bathymetric And Topographic Survey (BATS) system, will also be supplied by Optech Incorporated under the Canada DDSA. While SHOALS' involvement in NATO's Linked Seas

2000 exercise in Portugal (Lillycrop et. al, 2000; West et al., 2001b) was highly successful, leading one U.S. Navy observer to comment that: 'SHOALS put the 'Rapid' in Rapid Environmental Assessment (REA)', the current generation of systems is clearly not deployable to a hostile environment. BATS is specifically designed for tactical operations from an unmanned aerial vehicle (UAV). It will be compatible as a modular mission payload (MMP) for the Navy's new Vertical takeoff and landing Tactical Unmanned Aerial Vehicle (VTUAV) which has an Initial Operational Capability date in FY-03.

BATS will support the needs of the Navy, Army, and Joint Commands, including Special Operations and Joint Logistics Over The Shore. It may perform covert/overt reconnaissance and site characterisation surveys in relatively clear, shallow waters and adjacent coastal land areas, and rapid-response surveys in littoral areas of high or emerging importance. BATS will soon become a key component in successful military operations requiring rapid collection of bathymetric and topographic data over large areas.

BATS will be smaller than CHARTS, half its weight, and have a lower power requirement as a result of a lower, 400-pps pulse-repetition rate. It will also incorporate an autonomous operation capability and highly automated on-vehicle data processing to permit telemetering of preliminary data. Although these additional limitations will clearly be challenges, they are realistic goals since BATS is intended as an REA tool and will be designed to achieve only IHO Order-2 hydrographic accuracy and more-restricted depths from a slower platform. It is being designed to enable flight planning and data collection, processing, analysis, and data fusion with other technical data to be accomplished in the field. BATS is scheduled for delivery in 2004.

Future Capabilities

A comprehensive ALB system of the future could embody a variety of potential capabilities. Added features may include bottom and water-column characteristics, hydrodynamic characteristics, and feature imaging. Airborne technologies and data processing algorithms have demonstrated the potential to measure or infer such parameters as water clarity, bottom type, water wave properties, and surface currents. More detailed interrogation of raw ALB waveforms to extract value-added information may provide an independent means for quantifying certain environmental parameters. Integration of ALB with existing operational sensors such as geo-referenced digital imagery and topographic lidar will meet additional data requirements. Multi-sensor data fusion with ALB may provide the most efficient and reliable means for mapping additional environmental parameters.

Added ALB Products

Water Clarity

There is much more information contained in the digitised and recorded raw green lidar return waveforms than only water depth. The development of algorithms to extract value-added information from on-wavelength returns is possible for applications such as the quantification and three-dimensional mapping of various water clarity parameters and associated environmental factors. This has been a popular topic since the availability of practical lasers in the late 1960's, particularly due to military applications. The literature abounds with hundreds of highly technical and increasingly sophisticated references dedicated to theoretical studies and field measurements, from surface vessels and aircraft, of the propagation and scattering of light in hydrosols (see, for example, numerous volumes from the biennial Ocean Optics conferences published by SPIE). A great deal of work is also reported in the Soviet literature (Bunkin et al., 1984; Vlasov, 1985). Of greatest interest for this application is the solving the so-called 'inverse' problem, i.e., estimating the parameters from the measured light field, rather than predicting the effects of the parameters on the light field. It should be noted, however, that from a practical point of view, much more effort and funding is put into off-wavelength (fluorescence) and passive multispectral techniques because of the benefits these offer, particularly for living resources. The chief advantage of a lidar system over passive techniques is related to its ability to penetrate much deeper and to estimate the parameter depth profiles.

From depth resolved green pulse returns, the optical diffuse attenuation coefficient can certainly be estimated (Gordon, 1982; Billard, et al., 1986; Steinvall et al., 1992), and water clarity parameters, such as some form of scattering coefficient, may be possible (Reuter, 1982; Phillips et al., 1984; Billard, 1986). For some users, mapping the three-dimensional distribution of a parameter may be of more value than its precise value. Such applications have been discussed by Hoge et al. (1988), Feigels and Kopilevich (1993), and Feigels and Kopilevich (1994). The spatial concentration of suspended materials could be used, for example, to evaluate dredging operations or measure the impact of effluents on a region. Systems have also been designed for the detection of fish schools (Murphree et al., 1974; Kronman, 1992; Churnside et al., 1997), but that type of operation would require dedicated missions and probably not be conducive to simultaneous operation with a bathymeter.

Wave Spectra

In order to calculate accurate depths, the wave heights about the mean water level at each pulse location must be measured (Thomas and Guenther, 1990). These estimated wave heights are presently not being used as value-added products by the operational bathymeters. This should change. The size and direction of waves is important for many coastal engineering applications such as measuring sediment transport rates and in military operations such as determining limiting conditions for safe ingress and egress routes. Early one-dimensional experiments with airborne profiling lasers were carried out by Ross et al. (1970), Schule et al. (1971), Liu and Ross (1980), and McClain et al. (1982). Spatial and statistical wave height characteristics including the two-dimensional vector wave-number spectra can be obtained from a scanning system. These dynamics can be obtained with airborne topographic lidar systems (Hwang et al., 2000), and the results could also easily be reported for ALB missions.

One difficulty which requires careful attention to detail is the fact that the waves and the aircraft are both moving and at very different rates and directions. The sampled wave heights are thus neither synoptic nor stationary, and special algorithms are required to provide a useful product (Walsh et al., 1985). One possible drawback with the present scenario is the spatial data density. The 4-m spacing typically used by today's bathymeters may not provide sufficient sampling density for many wave applications. If future systems have higher sounding densities, the wave-height products would be of greater value. It should be noted that wave heights over the entire swath under all environmental conditions can only be reliably measured at infrared or red (Raman-shifted green) wavelengths by systems with scanned collinear green and infrared beams (Guenther et al., 1994).

Multi-sensor Fusion

More information than is currently collected is needed to better quantify the environment. With integration and fusion of data in Geographical Information Systems (GIS) becoming increasingly common, the value of multi-sensor systems is apparent. The move towards open architecture and non-proprietary data formats enables an operator to select from a variety of commercial software packages for processing and quality control. Lidar sensors will be combined with other airborne sensors on a single airborne platform because of the resulting economy in simultaneously collecting information from many sensors. More importantly, the synergy between synoptic or near-synoptic products can provide environmental information that neither sensor alone could produce. For example, lidar and geo-referenced digital photography are currently combined in the venerable LARSEN system (Quinn, 2000) operated by Terra Remote Sensing Incorporated (Sidney, British Columbia, Canada). The ALB systems of the near future, such as SHOALS-1000, will be capable of sharing a single airborne platform with a variety of complementary sensors. Proof-of-concept studies and tests have successfully brought together ALB with topographic lidar and ALB with hyperspectral imaging (Borstad and Vosburgh, 1993). Other possibilities include ALB with airborne electromagnetic sensors or with IFSAR.

The use of lidar provides the unique ability to survey ground elevations at the same time as depth soundings, thus integrating land and water measurements in the same data set. Land elevations are being collected on a regular basis by some existing ALB systems, but the pulse repetition rate of current bathymeters is not as great as desired for land operations, and they consequently lack the horizontal resolution necessary to fully define topographical features such as small structures, dune lines, seawall break points, and other fine detail. High-resolution renderings of these shore-line structures and coastal features provided by existing ALTM systems are capable of being merged with ALB underwater data, thus producing a seamless product. The solution has two approaches depending on where you start: add topographic capability to a bathymeter or bathymetric capability to a topographic system. The merging of a combined terrain and bathymetric lidar system with a geo-referenced digital camera would create a powerful data collection tool with numerous applications. Further addition of hyperspectral capability would complete the picture and provide capabilities not yet contemplated. Several current examples of sensor fusion follow.

Multiple Lidars

Combinations of independent bathymetric and topographic lidars on one platform are being planned. The CHARTS system, for example, has been specified with a requirement for independent high-rate topographic lidar capability to sample land elevations at a higher rate than the water depths. The two sensors will not operate simultaneously, but will be able to be interchanged from flightline to flightline. Similarly, Optech Incorporated is currently planning a low-energy, several-thousand-pps lidar-bathymeter option as an add-on module to augment their current 33,000-pps ALTM land survey system. This is intended for use in adjacent clear coastal waters to 10-m depths and will provide the capability for integrated land and water measurements. As above, operations will be non-simultaneous but interchangeable from flightline to flightline.

Bathymetric Lidar with Geo-referenced Digital Imagery

Digital, geo-referenced imagery has been used traditionally as a base photograph on elevation and depth contour plots. With the use of GIS software, elevations and imagery can be integrated, possibly with other data, to yield more-interesting displays and more-sophisticated and valuable products. Existing lidar data have been used with separately-collected aerial photographs or even satellite imagery, but precise geo-rectification of the individual products can be a serious problem. When imaging ability is deployed on the lidar aircraft to collect simultaneous data, this synoptic information can be more accurate, more meaningful, and less expensive. LARSEN, for example, is currently making extensive use of this feature to provide products such as mapping of shorelines, coral reefs, and fish habitats. Flying with Terra Remote Sensing's proprietary VideoMap imaging system, the LARSEN bathymeter has provided the Coastal Zone Management Unit of the Barbados Government with lidar, geo-referenced video, and ortho-rectified still images, all of which are combined with sonar data, to provide a complete solution for shipping and navigation, shoreline erosion, and coastal features (Quinn, 2000). More ALB systems are needed with this facility. The digital imagery from CHARTS may be fully rectified in the future.

Bathymetric Lidar with Multispectral or Hyperspectral Scanner

Multispectral and, more recently, hyperspectral imagers are perhaps the most valuable of all remote sensing tools for both land and water. World-wide attention was drawn to them with the satellite launches of LANDSAT in 1972 and the Coastal Zone Colour Scanner in 1978 (Austin, 1979). These increasingly capable tools are being used from satellites and aircraft to discern a myriad of environmental parameters. Extremely sophisticated algorithms have been developed and proofed to estimate everything from crop health and the location of minerals on land to many physical, optical, and biological parameters from the sea. There is no room here to delve much deeper, but innumerable books, journal articles, and conferences have been dedicated to this very broad subject (see, for example, Volume II of ERIM, 1998).

Several facts are worth mentioning. The radiances measured at various wavelengths from shallow water by imagers can be used to estimate approximate depths (to a maximum depth of somewhat less than one Secchi depth) (Lyzenga, 1978), but even with sophisticated algorithms these depths are not reliable and do not meet IHO requirements (Fay and Miller, 1990; Morel and Lindell, 1998). These same high-density depths from the imager, however, can be accurately calibrated with the simultaneous use of a low-density lidar bathymeter in a so-called 'active-passive' mode (Cooper, 1981). This capability was further demonstrated in a test in which the Compact Airborne Spectrographic Imager (CASI) was successfully flown simultaneously with LARSEN (Borstad and Vosburgh, 1993).

The multispectral radiances measured by the scanners, if processed with appropriate algorithms, can provide the ability to map a wide variety of aquatic features such as oil slicks, near-surface fish schools, bottom types, sea grass, coral and other benthic plants, phytoplankton in the water column, and suspended sediment plumes, to name only a few (Quinn, 1992). As with estimated depths, however, when radiances are used to estimate many environmental characteristics, assumptions must be made, and an uncertainty or ambiguity exists in the results if the bottom depth is unknown. Again, the active-passive combination of a bathymetric lidar with the imager provides a major synergy that permits significant improvements in the accuracy of the products, both quantitative and qualitative, that can be derived from the imager. For example, lidar depths were used to calibrate multispectral imagery in the Environmental Research Institute of Michigan (ERIM) M8 scanner (Lyzenga, 1985). Two additional examples are provided by Hoge et al. (1986). In a later experiment, SHOALS depths were used to calibrate CASI multi-spectral imagery collected on a separate flight (Lillycrop and Estep, 1995). It was determined that it is possible to classify and map bottom types in gross terms (i.e., sand, sea grass, mud, etc.), but more research and experimentation are needed.

There is currently a great deal of interest in the mapping, monitoring, health, and conservation of coral reefs (McManus and Noordeloos, 1998; CRTF, 1998). It is expected that an active-passive approach could provide accurate, high-resolution information on characteristics such as coral reef location, health, and speciation which neither sensor alone could produce.

There is much important and interesting work to be done in environmental characterisation and mapping. Active-passive sensing will be a dynamic area of research in the future if compact, inexpensive, portable ALB systems are available. Both sensors involve very complex technology and algorithms, and there are numerous technical, scientific, and financial challenges that will have to be met.

Conclusions

The quantum leap from sound to light has been made. The first steps have been taken with excellent and exciting results. As of spring 2002, five systems are presently engaged in ALB operations -- three of these full time. Several of the current-generation bathymetric systems have been operating successfully for over eight years for diverse applications. The accuracy, capabilities, and cost-effectiveness of these novel bathymeters are now being widely recognised and respected by the user community, and demand for contract surveys and new systems is increasing rapidly.

New systems are under construction, and prospects for expanded services, greater flexibility, new products, and reduced costs are very positive. Many of the continuing technical developments outlined here are not simple, and some will not be easy to achieve. Most exciting is the prospect of extracting more information from co-located synergetic sensors. The parallel challenge will be in further educating government hydrographic surveyors and survey companies regarding the numerous benefits of these systems. The time is ripe for ALB to be further integrated into the survey community.

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References

Austin, R.W., 1979. Coastal zone color scanner radiometry, *Proc. SPIE Ocean Optics VI, Vol. 208*, 170-177

Billard, B., 1986. Remote sensing of scattering coefficient for airborne laser hydrography, *Appl. Opt. 25*, 13, 2099-2108

Billard, B., Abbot, R., and Penny, M., 1986. Airborne estimation of sea turbidity parameters from the WRELADS Laser Airborne Depth Sounder, *Appl. Opt. 25*, 13, 2080-2088

Borstad, G.A. and Vosburgh, J., 1993. Combined active and passive optical bathymetric mapping: using the LARSEN lidar and the CASI imaging spectrometer, *Proc. 16th Canadian Symposium on Remote Sensing*, June 7-10, Sherbrooke, Quebec, 153-157

Brooks, M.W., Culpepper, E., Guenther, G.C., and LaRocque, P.E., 1998. Advancements and applications of the SHOALS laser bathymetry system, *Proc. ION GPS 98*, Institute of Navigation, Sept. 15-18, Nashville, TN, 8 pp

Bunkin, A.F., Vlasov, D.V., Mirkamilov, D.M., and Slobodyanin, V.P., 1984. Airborne laser probing of turbidity profiles and mapping of phytoplankton distribution, *Sov. Phys.-Dokl., 29*, 11, 932-934

Casey, M.J., O'Neil, R.A., and Conrad, P., 1985. The advent of LARSEN, *Proc. Canadian Hydro. Conf.*, Halifax, N.S., 7-12

Casey, M.J. and Vosburgh, J., 1986. Chartmaking with LARSEN, *Canadian Surveyor*, 40, 3

Churnside, J.H., Wilson, J.J., and Tatarskii, V.V., 1997. Lidar profiles of fish schools, *Appl. Opt. LP, 36*, 24, 6011-6020

Cooper, M.T., 1981. An active/passive multispectral scanner for airborne hydrography, *Proc. 4th Laser Hydrography Symposium, ERL-0193-SD*, Defence Research Centre Salisbury, Sept. 30 - Oct. 3, 1980, Salisbury, South Australia, 305-335

CRTF, 1998. National action plan, The U.S. Coral Reef Task Force (CRTF), Executive Order #13089 on Coral Reef Protection, President W.J. Clinton

Cunningham, A.G., Lillycrop, W.J., Guenther, G.C., and Brooks, M.W., 1998. Shallow water laser bathymetry: accomplishments and applications, *Proc. Oceanology International: The Global Ocean*, March 10-13, Brighton, England, Vol. 3, 277-288

Ebrite, S., Pope, R.W., and Lillycrop, W.J., 2001. A multi-agency solution for coastal surveys – SHOALS in the Pacific, *Proc. Oceans 2001*, MTS/IEEE, Nov. 5-8, Honolulu, Hawaii

Enabnit, D.B., Goodman, L.R., Young, G.K., and Shaughnessy, W.J., 1978. The cost effectiveness of airborne laser hydrography, *NOAA Technical Memorandum NOS 26*, National Oceanic and Atmospheric Administration, Rockville, MD, 56 pp

ERIM, 1998. *Proc. 5th Int'l. Conf. on Remote Sensing for Marine and Coastal Environments*, ERIM International, October 5-7, San Diego, CA.

Fay, T.H., and Miller, H.V., 1990. Bathymetric analysis of 'in-water' upwelling radiance data, *Proc. SPIE Ocean Optics X, Vol. 1302*, 641-654

Featherstone, S., 2001. NOAA is sinking, *Boating, 74*, 2 (February), 150-155

Feigels, V.I. and Kopilevich, Yu.I., 1993. Remote sensing of subsurface layers of turbid sea water with the help of optical lidar system, *Proc. SPIE*, Vol. 2048, 34-42

Feigels, V.I. and Kopilevich, Yu.I., 1994. Applicability of lidar remote sensing methods for vertical structure investigation of ocean optical properties distribution, *Proc. SPIE, Vol. 2258*, 449-457

Gordon, H.R., 1982. Interpretation of airborne oceanic lidar: effects of multiple scattering, *Appl. Opt. 21*, 16, 2996-3001

Graham, T., Smith, K., Spittal, J., and West, G.R., 1999. Improving the efficiency, safety and economy of the New Zealand national nautical charting program through the integrated use of the SHOALS system in a multi-sensor survey, *Proc. U.S. Hydrographic Conference*, April 26-29, Mobile, AL, (paper 9-5 on CD), 11 pp

Guenther, G.C., 1981. Accuracy and penetration measurements from hydrographic trials of the AOL system, *Proc. 4th Laser Hydrography Symposium, ERL-0193-SD*, Defence Research Centre Salisbury, Sept. 30 - Oct. 3, 1980, Salisbury, South Australia, 108-150

Guenther, G.C., 1985. Airborne laser hydrography: System design and performance factors, *NOAA Professional Paper Series*, National Ocean Service 1, National Oceanic and Atmospheric Administration, Rockville, MD, 385 pp

Guenther, G.C., 1986. Wind and nadir angle effects on airborne lidar water surface returns, *Proc. SPIE Ocean Optics VIII, Vol. 637*, 277-286

Guenther, G.C., 1989. Airborne laser hydrography to chart shallow coastal waters, *Sea Technology*, March, Vol. 30, No. 3, 55-59

Guenther, G.C., 2001. Digital Elevation Model Technologies and Applications: The DEM Users Manual, D. Maune, ed., American Society for Photogrammetry and Remote Sensing, Chapter 8: Airborne lidar bathymetry, 237-306

Guenther, G.C., Brooks, M.W., and LaRocque, P.E., 1998. New capabilities of the SHOALS airborne lidar bathymeter, *Proc. 5th Int'l. Conf. on Remote Sensing for Marine and Coastal Environments*, ERIM International, October 5-7, San Diego, CA, Vol. I, 47-55. [reprinted in 2000, *Remote Sens. Environ. 73*, 247-255.]

Guenther, G.C., Cunningham, A.G., LaRocque, P.E., and Reid, D.J., 2000. Meeting the accuracy challenge in airborne lidar bathymetry, *Proc. 20th EARSeL Symposium: Workshop on Lidar Remote Sensing of Land and Sea*, European Association of Remote Sensing Laboratories, June 16-17, Dresden, Germany, EARSeL eProceedings No. 1, 2001, 1 – 27

Guenther, G.C. and Goodman, L.R., 1978. Laser applications for near-shore nautical charting, *Proc. SPIE Ocean Optics V, Vol. 160,* 174-183

Guenther, G.C., LaRocque, P.E., and Lillycrop, W.J., 1994. Multiple surface channels in SHOALS airborne lidar, *Proc. SPIE Ocean Optics XII,* Vol. 2258, 422-430

Guenther G.C. and Thomas, R.W.L., 1984. Effects of Propaga-tion-induced Pulse Stretching in Airborne Laser Hydrography, *Proc. SPIE Ocean Optics VII, Vol. 489,* 287-296

Guenther, G.C., Thomas, R.W.L., and LaRocque, P.E., 1996. Design Considerations for Achieving High Accuracy with the SHOALS Bathymetric Lidar System, *Laser Remote Sensing of Natural Waters: From Theory to Practice,* V.I. Feigels, Y.I. Kopilevich, Editors, Proc. SPIE, Vol. 2964, 54-71

Hickman, G.D. and Hogg, J.E., 1969. Application of an airborne pulsed laser for near-shore bathymetric measurements, *Remote Sens. of Env.,* **1**, Elsevier, New York, 47-58

Hoge, F.E., Swift, R.N., and Frederick, E.B., 1980. Water depth measurement using an airborne pulsed neon laser system, *Appl. Opt. 19,* 6, 871-883

Hoge, F.E., Swift, R.N., and Jungel, J.K., 1986. Active-passive ocean color measurement: two applications, *Appl. Opt. 25,* 48

Hoge, F.E., Wright, C.W., Krabill, W.B., Buntzen, R.R., Gilbert, G.D., Swift, R.N., Yungel, J.K., and Berry, R.E., 1988. Airborne lidar detection of subsurface oceanic scattering layers, *Appl. Opt. 27,* 19, 3969-3977

Hwang, P.A., Wang, D.W., Walsh, E.J., Krabill, W.B., and Swift, R.N., 2000. Airborne measurements of the wavenumber spectra of ocean surface waves, *J. Physical Oceanography,* Vol. 30, November, 2753-2787

International Hydrographic Organisation, 1998. *Special Publication 44,* 4th Edition (April)

Irish, J. L., McClung, J. K., and Lillycrop, W.J., 2000. Airborne lidar bathymetry: the SHOALS system, *The International Navigation Association, PIANC Bulletin, No. 103,* 43-53

Irish, J.L., Parson, L.E., Lillycrop, W.J., 1995. Detailed Bathymetry of Four Florida Inlets, *Proc. 1995 National Conference on Beach Preservation Technology,* Florida Shore and Beach Preservation Association, January 25-27, St. Petersburg, FL, pp. 243-258

Irish, J.L., Thomas, J.E., Parson, L.E., and Lillycrop, W.J., 1996. Mon-itoring storm response with high density lidar bathymetry: The effects of Hurricane Opal on Florida's Panhandle, *Proc. 2nd Int. Airborne Remote Sensing Conf.,* June 24-27, San Francisco, CA., Vol. III, 723-732

Irish, J.L. and Truitt, C.L., 1995. Beach Fill Storm Response at Longboat Key, Florida, *Proc. 1995 National Conference on Beach Preservation Technology,* Florida Shore and Beach Preservation Association, January 25-27, St. Petersburg, FL, 103-117

Irish, J. L. and White, T.E., 1998. Coastal engineering applications of high-resolution lidar bathymetry, *Coastal Engineering, Vol. 35,* Nos. 1-2, 47-71

Kronman, M., 1992. Lidar: laser technology could revolutionise aerial fish finding, *Nat. Fisherman, April,* 40-42

LaRocque P.E. and West, G.R., 1999. Airborne laser hydrography: an introduction, *Proc. ROPME/PERSGA/IHB Workshop on Hydrographic Activities in the ROPME Sea area and Red Sea,* October 24-27, Kuwait, 16 pp

Lillycrop, W.J. and Estep, L.L, 1995. Generational advancements in coastal surveying and mapping, *Sea Technology*, 36, 6, (June), 10-16

Lillycrop, W.J., Irish, J.L., and Parson, L.E., 1997. SHOALS System: Three Years of Operation with Airborne Lidar Bathymetry - Experiences, Capability and Technology Advancements, *Sea Technology*, June, Vol. 38, No. 6, 17-25

Lillycrop, W.J., Irish, J.L., Pope, R.W., and West, G.R., 2000. GPS sends in the marines: rapid environmental assessment with lidar, *GPS World*, 11, 11 (November), 18-28

Lillycrop, W.J., Johnson, P., Lejdebrink, U., and Pope, R.W., 2001. Airborne lidar hydrography: requirements for tomorrow, *Proc. Oceanology International*, April 3-5, Miami, FL, paper 5-7, 9 pp

Lillycrop, W.J., Parson, L.E., Estep, L.L., LaRocque, P.E., Guenther, G.C., Reed, M.D., and Truitt, C.L., 1994. Field testing of the U.S. Army Corps of Engineers airborne lidar hydrographic survey system, *Proc. U.S. Hydro. Conf. '94*, The Hydrographic Society, April 18-23, Norfolk, VA, Special Pub. No. 32, 144-151

Lillycrop, W.J., Parson, L.E., and Irish, J.L., 1996. Development and Operation of the SHOALS Airborne Lidar Hydro-graphic Survey System, *Laser Remote Sensing of Natural Waters: From Theory to Practice*, V. I. Feigels, Y. I. Kopilevich, Editors, Proc. SPIE, Vol. 2964, 26-37

Liu, P.C. and Ross, D.B., 1980. Airborne measurements of wave growth for stable and unstable atmospheres in Lake Michigan, *J. Physical Oceanography*, 10, November, 1842-1853

Lyzenga, D.R., 1978. Passive remote sensing techniques for mapping water depth and bottom features, *Appl. Opt. 17*, 3, 379-383

Lyzenga, D.R., 1985. Shallow-water bathymetry using combined lidar and passive multispectral scanner data, *Int. J. Remote Sensing*, 6, 115

McClain, C.R., Huang, N.E., and LaViolette, P.E., 1982. Measurements of sea-state variations across oceanic fronts using laser profilometry, *J. Physical Oceanography*, 12, November, 1228-1244

McClung J.K., 1998. High density lidar data: A monitoring tool for East Pass Florida, *Proc. 5th Int'l Conf. on Remote Sensing for Marine and Coastal Environments*, ERIM International, October 5-7, San Diego, CA, Vol. I, 75-82, [reprinted in 2000, Remote Sens. Environ., 73]

McClung, J.K. and Douglass, S.L., 1999. Observing changes in an ebb-tidal shoal, *Proc. 4th International Symposium on Coastal Engineering and Science of Coastal Sediment Processes*, American Society of Civil Engineers, June 21-23, Long Island, NY, Vol. 1, 734-749

McManus, J. and Noordeloos, M., 1998. Toward a global inventory of coral reefs (GICOR): remote sensing, international co-operation, and Reefbase, *Proc. 5th Int'l. Conf. on Remote Sensing for Marine and Coastal Environments*, ERIM International, October 5-7, San Diego, CA, Vol. I, 83-89

Mohr, M.C., Pope, J., and McClung, J.K., 1999. Coastal response to a detached breakwater system; Presque Isle, Pennsylvania, USA, *Proc. 4th International Symposium on Coastal Engineering and Science of Coastal Sediment Processes*, American Society of Civil Engineers, June 21-23, Long Island, NY, Vol. 3, 2010-2025

Morel, Y.G. and Lindell, L.T., 1998. Passive multispectral bathymetry mapping of Negril Shores, Jamaica, *Proc. 5th Int'l. Conf. on Remote Sensing for Marine and Coastal Environments*, ERIM International, October 5-7, San Diego, CA, Vol. I, 315-324

Murphree, D.L., Taylor, C.D., and McClendon, R.W., 1974. Mathematical modeling for the detection of fish by an airborne laser, AIAA Journal, 12, 12, 1686-1692

Nairn, R., 1994. Royal Australian Navy Laser Airborne Depth Sounder, The first year of operations, *Int'l. Hydro. Rev., Monaco, LXXI(1)*, 109-119

Nordstrom, G., 2000. The Swedish Hydrographic Service on the eve of a new millennium, Integrated Coastal Zone Management, *Spring Edition*, 37 - 40

Ott, L.M., 1965. Underwater ranging measurements using blue-green laser, NAVAIRDEVCEN Report No. NADC-AE-6519, Naval Air Development Center, Warminster, PA (CONFIDENTIAL)

Parker, B., D. Milbert, R. Wilson, K. Hess, J. Bailey, C. Fowler, D. Gesch, and R. Berry, 2001. A Tampa Bay Bathymetric/Topographic Digital Elevation Model With Internally Consistent Shorelines for Various Datums, Proc. Hydro 2001, The Hydrographic Society, *Special Pub. 42*, March 27-29, Norwich, England, Paper 11, 11 pp

Penny, M.F., 1992. LADS, the Australian laser airborne depth sounder, part 1, *Proc. Int'l Hydro. Symp., Monaco*, II-5, 9 pp

Penny, M.F., Abbot, R.H., Phillips, D.M., Billard, B., Rees, D., Faulkner, D.W., Cartwright, D.G., Woodcock, B., Perry, G.J., Wilsen, P.J., Adams, T.R., and Richards, J., 1986. Airborne laser hydrography in Australia, *Appl. Opt. 25*, 13, 2046-2058

Phillips, D.M., Abbott, R.H., and Penny, M.F., 1984. Remote sensing of sea water turbidity with an airborne laser system, *J. Phys. D: Appl. Phys.*, 17, 1749

Pope, R.W., Reed, B.A., West, G.R., and Lillycrop, W.J., 1997. Use of an airborne laser depth sounding system in a complex shallow-water environment, *Proc. XVth Int'l Hydro Conference*, April 21-22, Monaco, 10 pp

Quinn, R., 1992. Coastal base mapping with the LARSEN scanning LIDAR system and other sensors, *Fifth Biennial International Hydrographic Conference*, National Ocean Service, Feb 25-28, Baltimore, MD, 219-221

Quinn, R., 2000. Bathymetry with airborne lidar & videography, *Backscatter, (Alliance for Marine Remote Sensing Association), Volume 11*, 2 (April), 8-17

Reuter, R., 1982. Lidar investigations of hydrosols: notes on the determination of scattering matrix elements, *Appl. Opt. 21*, 3762

Ross, D.B., Cardone, V.J., and Conaway, J.W., 1970. Laser and microwave observations of sea-surface conditions for fetch-limited 17 to 25-m/s winds, *IEEE Trans., GE-8*, 326-336

Schule, J.J., Simpson, L.S., and DeLeonibus, P.S., 1971. A study of fetch-limited wave spectra with an airborne laser, *J. Geophysical Research, 76*, 18, 4160-4171

Setter, C. and Willis, R.J., 1994. LADS – From development to hydro-graphic operations, *Proc. U.S. Hydro. Conf. 1994*, The Hydrographic Society, April 18-23, Norfolk, VA, Special Pub. No. 32, 134-139

Sinclair, M., 1998. Australians get on board with new laser airborne depth sounder, *Sea Technology, June*, 19-25

Sinclair, M., 1999a. Airborne laser bathymetry in 1998/1999, *EEZ Technology 4*, 2, 69-72

Sinclair, M., 1999b. Application of laser airborne depth sounder for EEZ delimitation and management, *EEZ Technology 5*, 2, 95-99

Sinclair, M.J. and Spurling, T., 1997. Operational laser bathymetry in Australia, *XVth International Hydrographic Conference*, International Hydrographic Organisation, 21-22 April 1997, Monaco, Session IV, 4.1-4.17

Skogvik, J. and Axelsson, R., 2001. Experience and results from Swedish laser surveys and post-processing of laser bathymetry data, *Proc. Hydro 2001*, The Hydrographic Society, *Special Pub. 42*, March 27-29, Norwich, England. Paper 20, 13 pp

Sorenson, G.P., 1966. Proposed airborne fathometer system for high-speed offshore beach mapping, *Technical Note*, Stanford Research Institute

Sorenson, G.P., Honey, R.C., and Payne, J.R., 1966. Analysis of the use of airborne laser radar for submarine detection and ranging, *SRI Report No. 5583*, Stanford Research Institute

Spurling, T. and Perry, G., 1997. A new generation laser airborne depth sounder, *XVth International Hydrographic Conference*, International Hydrographic Organisation, April 21-22, 1997, Monaco, Session IV, 1.1-1.16

Steinvall, O., Koppari, K., and Karlsson, U., 1992. Experimental evaluation of an airborne depth sounding lidar, *Proc. SPIE Lidar for Remote Sensing, Vol. 1714*, 108-126

Steinvall, O., Koppari, K., and Karlsson, U., 1994. Airborne laser depth sounding: system aspects and performance, *Proc. SPIE Ocean Optics XII, Vol. 2258*, 392-412

Steinvall, O., Koppari, K., Lejdebrink, U., Winell, J., Nilsson, M., Ellsen, R., and Gjellan, E., 1997. Theories and experience of the Swedish airborne laser system, *XVth International Hydrographic Conference*, International Hydrographic Organisation, April 21-22, 1997, Monaco, Session IV, 3.1-3.23

Thomas, R.W.L, and Guenther, G.C., 1990. Water Surface Detection Strategy for an airborne laser bathymeter, *Ocean Optics X, Proc. SPIE, Vol. 1302*, 597-611

UN, 1989. Status of hydrographic surveying and nautical charting world-wide, *4th United Nations Regional Cartographic Conference for the Americas*, January 23-27, 81/INF/9

Vlasov, D.V., 1985. Aerial laser sounding on the upper layer of the ocean, *Bull. Acad. Sci. USSR: Phys. Ser., 49*, 3, 433-442

Vosburgh, J. and Banic, J., 1987. Airborne laser surveys of the Northwest Passage, *Proc. XIIIth Int'l. Hydro. Conf.*, Monaco

Walsh, E.J., Hancock, D.W., Hines, D.E., Swift, R.N., and Scott, J.F., 1985. Directional wave spectra measured with the surface contour radar, *J. Phys. Oceanogr., 15*, 566-592

Watters, T. and Wiggins C.E., 1999. Utilisation of remote sensing methods for management of Florida's coastal zone, Proc. *U.S. Hydrographic Conference*, April 26-29, Mobile, AL, (paper 9-3 on CD), 7 pp

Wellington, M., 2001. The Laser Airborne Depth Sounder (LADS) – a broad range of applications, *Proc. Hydro 2001*, The Hydrographic Society, *Special Pub. 42*, March 27-29, Norwich, England, Paper 19, 11 pp

West, G.R., 2001. In deeper waters, *POB (Point of Beginning)*, 26, 7, 22-26

West, G.R. and Lillycrop, W.J., 1999. Feature detection and classification with airborne lidar – practical experience, *Proc. Shallow Survey-99*, Australian Defence Science and Technology Organisation, Oct 18-20, Sydney, Australia, Paper 3-4, 8 pp

West, G.R., Lillycrop, W.J., and Pope R.W., 2001a. Keeping a low profile – using airborne laser bathymetry in sensitive hydrographic scenarios, *Hydro INTERNATIONAL, 5*, 4 (May/June), 28-31

West, G.R., Lillycrop, W.J., and Pope, R.W., 2001b. Utilizing airborne lidar bathymetry technology for rapid environmental assessment, *Sea Technology, 42*, 6 (June), 10-15

West, G.R. and Wiggins, C.E., 2000a. Airborne mapping sheds light on Hawaiian coasts and harbors, *EOM (Earth Observation Magazine), April, Vol. 9*, No. 4, 25-27

West, G.R. and Wiggins, C.E., 2000b. Airborne lidar bathymetry in the management of Florida's coastal zone, *ICZM, 2*, 2, 69-73

Wozencraft, J. M. and Irish, J.L., 2000. Airborne lidar surveys and regional sediment management, *Proc. 20th EARSeL Symposium: Workshop on Lidar Remote Sensing of Land and Sea*, European Association of Remote Sensing Laboratories, June 16-17, Dresden, Germany, EARSeL eProceedings No. 1, 2001, 28-38

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John R. Banic received a PhD in Physics in 1982, from the University of Toronto. He has been with Optech Incorporated for nearly 20 years, working primarily on the development of airborne laser bathymetry systems. Over that time, he has been involved in system design and testing, project management, and business development. Dr. Banic was Project Manager for the development of several systems for Canadian, Swedish, and U.S. Government agencies. He is currently Program Manager for the development of next-generation systems for the U.S. Navy and Japan Coast Guard.

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