MEETING THE ACCURACY CHALLENGE IN AIRBORNE LIDAR BATHYMETRY

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ABSTRACT

The essential qualities for a successful airborne lidar bathymeter are accuracy, capability, and cost effectiveness. Over the past twenty five years, developments in lasers, optics, electronics, and computers have made it somewhat easier to construct viable airborne lidar systems with varying purposes, and an increasing number are being constructed. Fewer than ten airborne lidar bathymeters exist in the world today, however, because of limited demand and because of the fact that it is still very difficult to meet the above three requirements, particularly the first. It is not hard to get answers from a system. It takes a great deal of understanding and effort, however, to obtain results that will meet international accuracy standards and the operational requirements of the typical customer.

The primary considerations in the design, construction, and operation of an airborne bathymeter must be data quality and depth measurement accuracy. Both the physical environment and system hardware components contribute many error sources that must be overcome. This requires thoughtful hardware and software system design and construction, as well as the prediction, modelling, and application of appropriate correctors. Operational procedures for quality control, calibration, and maintenance must be established and followed. In this paper, we describe the large number of hardware design features, software algorithms, bias correctors, displays, and operational procedures that have been developed to provide the basis for a system which will meet required accuracy standards while maintaining efficiency and cost-effectiveness.

The above features have all been incorporated into the U.S. Army Corps of Engineers SHOALS operational airborne lidar bathymetry system. SHOALS has been operated, from both a helicopter and a fixed-wing aircraft, to meet a wide range of survey requirements in categories such as charting, dredging, coastal engineering, resource management, modeling, and reconnaissance. Although SHOALS hardware was designed ten years ago, that design has been demonstrated to be optimal through seven years of successful field operation covering a wide range of sponsors, requirements, locations around the world, and environmental conditions. The SHOALS post-flight data processing software suite has provided high accuracy, performed flawlessly, and been regularly upgraded to improve utility and efficiency. The overall system design has proven to be very flexible, and a number of new features and capabilities have been added in hardware and software in response to customer requirements. In this paper, we will describe hardware and software design philosophy and critical design considerations. We discuss in detail how a large number of potential or realized error sources, inherent to airborne lidar hydrography systems in general and for SHOALS in particular, have been overcome.

INTRODUCTION

Rationale

Airborne laser (or lidar) bathymetry (ALB) is a technique for measuring the depths of relatively shallow, coastal waters from the air using a scanning, pulsed laser beam (1-3). It is also known as airborne lidar hydrography (ALH) when used primarily for nautical charting. Typical applications include bathymetric surveys of federal navigation channels, large offshore areas, ports and harbours, shore protection projects such as jetties and breakwaters, coral reefs, beaches, shorelines, and dredge disposal sites (4,5). Topographic surveys above the water surface can be conducted simultaneously, as needed. Data are also acquired for storm surge modelling and for monitoring sand as a local resource. The primary reasons for pursuing this technology are that, for such areas, it provides:

A) the ability to perform surveys quickly, in both large and small project areas, in a more cost-effective manner (6-9);
B) the capability to survey where it would be difficult, dangerous, or impossible to use water-borne techniques (10);
C) the facility to simultaneously survey the sea bottom, the adjacent beach, and coastal engineering structures (both above and below the waterline) (11, 12);
D) the mobility to perform rapid assessments of seasonal change (13) and storm damage (14, 15); and
E) 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 (16).

Experience with SHOALS has shown that, for appropriate and properly planned projects, the cost of ALB is from one-fifth to one-half that of waterborne techniques, depending on the logistical situation. Similar cost benefits have also been found in Sweden (17) and Australia (18). Furthermore, ALB provides unique survey opportunities, capabilities, and products, in shallow water and across the land/water boundary, which would be worth having even if they cost more. Figure 1 presents a graphic comparison of lidar and sonar operations in shallow water.

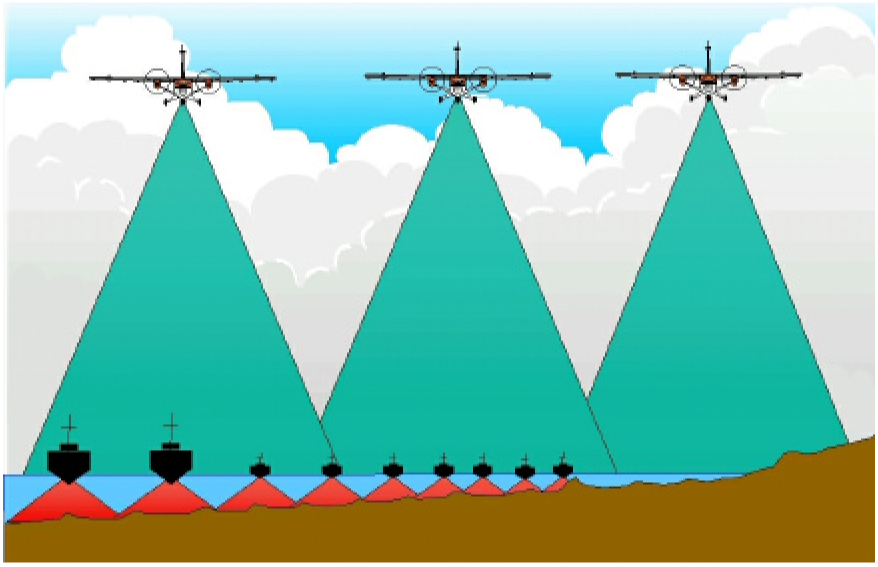

Figure 1: Depiction of lidar and multi-beam sonar operation in shallow water to emphasize lidar capabilities and efficiency.

Airborne laser bathymetry is an established operational technique which has been proven to be an accurate, efficient, cost-effective, safe, and flexible method for rapidly charting near-shore waters, adjacent beaches, and coastal engineering structures. On the other hand, ALB remains a state-of-the-art technique that requires knowledgeable implementation and is far from mature. New capabilities continue to be attained, and new products are produced.

History

The concept of ALB grew out of efforts in the mid 1960's to use the newly invented laser to find submarines (19, 20). The seminal paper confirming the ability to perform near-shore bathymetry was written by Hickman and Hogg (1) based on work done at the Syracuse University Research Center. In the early 1970's a number of first-generation airborne lidar systems were successfully tested by the U.S. Navy (21-24), by the National Aeronautics and Space Administration (NASA) (25), in Canada (26, 27), and in Australia (28). Much of the early work in the Soviet Union (29) and in Canada (30) was ship-borne. Several symposia, co-sponsored by the National Oceanic and Atmospheric Administration (NOAA) and NASA, were convened to establish user requirements and design goals for the use of the second-generation NASA Airborne Oceanographic Lidar (AOL) for hydrography (31, 32). Successful field testing of the AOL was conducted in 1977 (33-35). As a result, the existence of environmentally-induced biases in both surface and bottom returns was discovered (36). Other second-generation systems were built and tested in Canada (37), in Australia (38, 39), and in the Soviet Union (40). The Canadian system, augmented with a scanner, was also tested in Sweden (41).

In the 1980's, the Larsen-500 (42, 43) was developed in Canada, and, based on surveys performed in the Northwest Territories, became the world's first operational ALH system (44-47, 16). Testing of the Australian WRELADS II was completed (48), and construction was begun on the operational version called LADS (49, 50) for the Royal Australian Navy. Design and testing of a number of systems such as the U.S. Navy HALS (51, 52) and the Swedish FLASH (53, 54) continued. Three multi-purpose research systems (GOI, Chaika, and Makrel-II) were actively tested in the Soviet Union (55-59), and work was also conducted in China on their BLOL (60). In 1988, the U.S. Army Corps of Engineers began the SHOALS program (61, 62).

In the 1990's, systems became operational in Australia (LADS) (63, 64), the United States (SHOALS) (4, 65-67) and Sweden (Hawk Eye) (68-70). LADS is flown in a dedicated Fokker F-27 fixed-wing aircraft. SHOALS originally operated from either of a pair of NOAA Bell 212 helicopters, while two Hawkeye systems were borne in several different types of helicopters. The Canadian Larsen-500 system continued to perform in several fixed-wing aircraft (71). Late in the decade, the LADS II system, with a much higher pulse repetition rate than its predecessor, became operational in a Dash 8 aircraft (72-74). SHOALS added the capability of using kinematic GPS (11); this permits topographic mapping over land to be conducted in conjunction with bathymetric missions. The pulse repetition rate of SHOALS was doubled (75), and the system was transitioned from the helicopters to a Twin Otter (Dash 6) fixed-wing aircraft. Several additional nations, such as India and Japan, are expressing interest in purchasing systems, and a number of others, such as Mexico, New Zealand, Norway, Indonesia, and the United Arab Emirates, have contracted surveys with the above systems.

Concept

Airborne laser bathymetry is a comparatively young and growing discipline which depends on state-of-the-art engineering in areas of lasers, optics, and electronics. The general technique of ALB (2, 33, 35, 76) involves the use of a pulsed laser transmitter with both green and infrared (IR) output beams. Green is selected for sea bottom detection because that is the wavelength which penetrates typical coastal waters with the least attenuation (77). Infrared light penetrates very little and can be used for detection of the sea surface location. Depending on system design, the IR beam may be nearly collimated and scanned collinearly with the green beam, or it may be broader and constrained at nadir. Red energy generated in the water from green-excited Raman backscatter (78) immediately beneath the air/water interface may also be used as a surface return when its arrival time is properly corrected to the interface (79). The transmitted laser pulses are partially reflected from the water surface and from the sea bottom back to the airborne receiver. In effect, distances to the sea surface and bottom can be calculated by measuring the times of flight of the pulses to those locations and knowing the speed of light in air and water. Water depths are determined from the resulting time differences and corrected for known errors such as electronic delays. A conceptual green lidar return waveform, as seen in an airborne receiver, is shown in Figure 2.

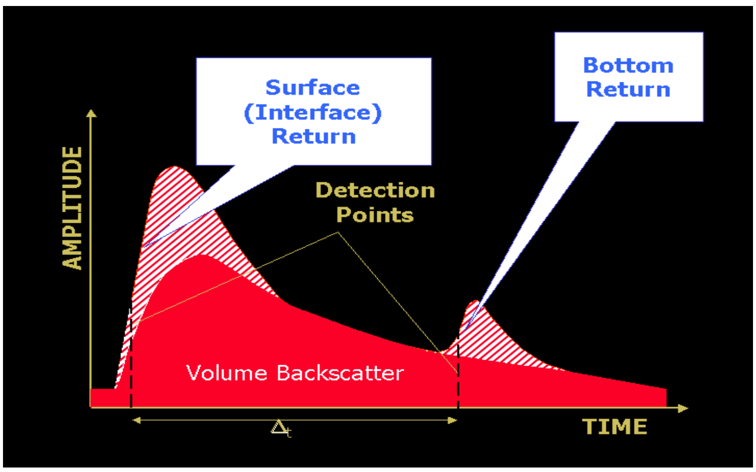

Figure 2: Schematic green lidar waveform showing the three principle signal components.

The green and IR beams are purposely expanded to a diameter of at least several meters at the water surface in order to achieve eye safe operation. More beam spreading is caused by the optical effects of waves on refraction angles at the water surface. In all but very shallow water, however, most of the beam spreading occurs in the water column. Although laser beams are commonly envisioned as being highly collimated with a small cross section (as they are in space or over short distances in air), this is not the case in water. Here, scattering causes even the narrowest beam to expand into a cone whose interior angle and cross section increase significantly with depth. Related propagation-induced depth measurement biases must be corrected (80). The resulting net expansion in irradiated bottom area is beneficial to the detection probability for significant bottom features (81) but, as with broad sonar beams, can be detrimental to depth accuracy when high-relief features are present.

The receiver consists of a telescope, various optical filters and field-of-view controls, light detectors, amplifiers, analog surface detection logic, and analog-to-digital converters (a digitiser). The receiver, system control logic, and tape storage are all operated under computer command. Because of the complexity of the environment and of the interactions of the lidar beam with the environment, it has not been possible to calculate all depths with high accuracy and reliability in real time. Approximate depths are calculated in the air for quality control, but precise depths, involving more-detailed calculations and a limited amount of manual intervention for difficult cases, are determined via post-flight processing of stored waveforms.

Typical aircraft altitudes are in the 200-500 meter range. An optical scanner provides coverage of a broad swath under the aircraft track. Scan patterns vary from system to system; both semi-circular and rectangular are in use. The maximum scanner nadir angles in use are 15-20 degrees; this leads to surveyed swaths with widths roughly equal to one half of the aircraft altitude. Larger angles would cause unacceptably large pulse timing errors in both surface and bottom returns due to the more extreme geometry. Coverage is dense; surveys for most systems are done with soundings spaced on a 4 or 5-meter grid. This density is achieved with laser pulse-repetition rates from 400 to 1000 pulses per second. If a programmable scanner is employed, higher sounding densities can be achieved for special purposes, for a given altitude and pulse-repetition rate, by reducing the swath width. Conservative gross coverage rates, for the case of a 100-kt speed and a 110-m swath width, for example, are on the order of 5000 m^2/sec. The net rate achieved depends on factors such as the swath overlap and the fraction of time spent in turns. In this example, for a 6-hour mission (a typical day's work) with a 65% on-line fraction, about 70 km^2 would be surveyed. With a wider swath and/or a faster aircraft, even higher coverage rates could be achieved at this sounding density. The limiting factor is the laser pulse-repetition rate.

Although ALB is most frequently used alone to good advantage, it is generally complementary with surface-borne sonar bathymetry techniques. Lidar systems, with swath widths nearly independent of depth, are very efficient in relatively shallow waters. Multibeam sonar systems, whose swath widths decrease with decreasing depths, are more efficient in deeper waters. Because of depth, water clarity, safety, or weather limitations, a survey area may break down naturally into regions best served by airborne and water-borne approaches (10). ALH can also be used safely for survey planning, prior to a sonar survey, in order to delineate dangerous areas and features that might imperil the survey vessels (82). Airborne lidar is not a replacement for sonar; it is a new tool that can be utilized with great cost and coverage benefit under the proper circumstances.

Limitations

<u>Water clarity</u>

The most significant limitation for ALB systems is water clarity, which limits the maximum surveyable depths (33). The maximum surveyable depth is the greatest depth, at a given time and location, for which depth measurements can be obtained whose accuracy meets obligatory standards. This requires that the bottom-return signals be reasonably strong and free from excessive noise.

This depth will be somewhat less than the greatest depth from which weak, noisy lumps of bottom-return energy are visible to the human eye in the signal waveforms. The maximum surveyable depth depends on a number of system hardware, software, and logistic parameters as well as on environmental conditions. The former include such items as green laser pulse energy, receiver optical bandwidth, aperture, and field of view, optical system efficiency, electronic noise figures, and flight altitude. The latter are primarily water clarity and bottom reflectivity. Of the environmental factors, water clarity is by far the more important because it enters as a negative exponential factor, while bottom reflectivity is a linear factor.

For a typical, eye-safe system, maximum surveyable depths range from greater than 50 meters in very clean offshore waters to possibly less than 10 meters in murky near-shore waters. For extremely turbid conditions, surveying may not be possible. As a rule of thumb, one can expect successful operations to depths between 2 and 3 times the Secchi depth. [The Secchi depth is an old and intuitive water clarity measure which is the depth at which a standard black and white disc, deployed over the side of a boat, is no longer visible to the human eye. (83)] The Secchi depth is not a particularly good predictor of performance, however, because its relationship to the proper optical parameter, the diffuse attenuation coefficient, varies with the scattering-to-absorption ratio (84). The factor of two applies where the water has a significant amount of absorption (which reduces energy), while the factor of three is appropriate for waters dominated by scattering (which redistributes energy). The ratio of absorption to scattering in seawater depends on the amount of dissolved organic material in the water and on the quantities and types of suspended organic and inorganic particulates. This varies strongly with location, season, tidal cycle phase, and weather.

In the more specific terms of ocean optics, the water property which most nearly dictates the received bottom-return pulse energy in a well-designed ALB system is the diffuse attenuation coefficient, K, at the green laser wavelength. The concepts surrounding various measures of K are far too complex to describe here (85, 86), but in simple terms, K is the exponential factor by which the downwelling vector irradiance of the incident light field, at a given wavelength, decreases with increasing depth. The bottom-return peak power, typically used in ALB pulse detections, decreases slightly more rapidly than pulse energy with increasing depth due to pulse stretching caused by scattering (2). The value of K is very different from the so-called beam attenuation coefficient, c, which is the sum of the scattering and absorption coefficients. For a well-designed system, c is not a good measure of the maximum surveyable depth. [The ratio K/c, is always less than unity and for green light typically ranges between one-sixth and one-half for coastal waters. It depends strongly on the scattering-to-absorption ratio of the water column (87), often expressed in terms of the so-called single-scattering albedo, and also, to a lesser extent, on the scattering phase function (2).]

If the receiver field of view (FOV) is sufficient, at the given altitude and depth, to integrate a major fraction of the returning bottom-reflected energy, the system attenuation coefficient for pulse energy, k, will approach K. If the FOV is insufficient, k tends toward the larger value of c (88), and a potentially severe depth penalty will result. For a well-designed system, the maximum surveyable depth for a given water clarity can be expressed approximately as n/K, where n is a constant. For typical, eye-safe ALB systems, under customary operational circumstances, the value of n will be around 3.0 to 3.5 for daytime operation and perhaps 5 at night (2). In other words, if, for example, the water clarity can be expressed in terms of a value of $K=0.1\ m^{-1}$, then one would expect to be able to survey to a depth of 30-35 meters during the daytime. The daytime value of n depends on the optical filter bandwidth of the system and on the extent of sun glint present during operations. Nighttime operation would be preferred from a performance standpoint, because the shot noise associated with the ambient, reflected solar background in the optical filter bandwidth is absent. Flying at night for extended periods, at low altitude over water, near land, is not, however, particularly desirable from a safety point of view, and is hence not the customary mode of operation.

In many areas, if the water is too dirty for a survey to be successfully performed on a given day, it may only be necessary to return to that site at a different tidal phase, or several days later, to find acceptably clear water. This is one of the logistics factors involved in survey planning for ALB systems. Given that many government agencies involved in bathymetric surveying have a large hydrographic backlog in areas with moderately clear waters, as well as the need for periodic monitoring in sites with dynamic bottoms, there is more than enough work within these water clarity limits for a number of ALB systems (89).

Small object detection

The use for which airborne lidar is not appropriate is in proving, beyond any doubt, that a navigation channel is free of small objects on the bottom with a size on the order of a 1-meter cube. The problem is that it is either difficult or impossible, depending on which part of the laser beam hits the target, to resolve the small target return in the presence of the much stronger and immediately following bottom return. To be confidently detected, the small target must be in the part of the illuminated bottom area closest to the aircraft where the light path-lengths are shorter than those for the remainder of the bottom return energy. The detection probability for small objects can be increased by greatly increasing the survey density, but this technique would not be foolproof and is not economically viable. In general, objects with larger surface areas and smaller heights are well detected, as are objects with smaller areas and larger heights (81). This is true because the target returns for such cases are better separated from the bottom returns. Modern channel clearance surveys, such as done by the U.S. National Ocean Service, for example, require waterborne sonar using both multibeam and side-scan technologies. ALH is not a substitute for side-scan sonar. Its spatial resolution is not as good as for modern high-frequency sonars, and, as noted above, some small targets may not be detected, even if illuminated.

THE CHALLENGE

The accuracy standards generally accepted for hydrography are established by the International Hydrographic Organization (IHO) in Monaco and disseminated in Special Publication 44. In its simplest form, the vertical accuracy requirement for shallow water hydrography can be paraphrased as a total of ±25 cm (one sigma) from all sources, including tides. The operational production of reliable ALB depths accurate to these IHO standards involves detailed understanding of the characteristics of the laser and optics, of the data collection electronics, and of a number of physical interactions between the laser beam and the environment. Each of these factors contributes important error sources that must be ameliorated. The development of a system must begin with proper hardware and software design in which all major error sources are recognized and minimized so that flight data have desirable characteristics and all necessary system outputs are available and unambiguous.

There is a danger to believe that, if a generic water lidar system can detect bottom returns, it can be used as a hydrographic system. That is not necessarily the case, because one of the biggest problems that must be solved in the design of a bathymetric lidar involves the accurate and reliable determination of the location of the air/water interface for each laser pulse (79). For reasons which will be detailed, the use of green surface returns alone is not an acceptable solution. It is necessary to have surface channels for at least two widely-separated, non-green wavelengths, such as red and IR, in order to maintain the highest accuracy for every laser pulse, to not restrict the operational envelope, and to cover full ranges of water depths and environmental constraints.

A second major problem that must be solved is the handling of the more than six orders of magnitude of amplitude dynamic range between strong water interface returns and weak bottom returns. That difference, which occurs in only a matter of tens or hundreds of nanoseconds, must be handled by the detector without anomalous effects and must be compressed into the useful input range of the digitiser, which is typically only two or three orders of magnitude.

The laser transmitter is one of the most critical system components. The requirements for an ALB laser in terms of pulse energy, pulse-repetition rate, pulse width, and reliability under field conditions seem to be little easier to achieve with today's technology than they were 25 years ago. Appropriate lasers have continued to be not generally available off the shelf.

HARDWARE CONSIDERATIONS

The design of an airborne lidar system is a highly complex undertaking involving lasers, mechanics, optics, detectors, electronics, and computers. Many of the design decisions are interrelated in an intricate web (76). There are a number of problems to be solved and a variety of ways to approach their solution. It is imperative that these decisions be made correctly and in a consistent manner because many become irrevocable. In this section, we will list a number of desirable features that such a system should have, and the associated rationale. The goals are to meet accuracy standards, to minimize sensitivity to unavoidable environmental effects, and to produce a compact and cost-effective system with a flexible operational envelope.

Laser

A green beam is required for bottom detection; an IR beam is commonly used as part of the surface detection strategy. The need for both green and IR wavelengths is met by using an IR laser, typically Nd:YAG, with a frequency doubler. The laser is pulsed because the distances are inferred by measuring the round-trip flight times of the laser pulses. [A continuous-wave (CW) heterodyne approach is being studied (90) but has not been fielded.] A pulse-repetition rate of at least 400 pulses per second is needed to provide sufficient sounding density for typical swath widths at fixed-wing aircraft speeds. Relatively narrow pulse widths are needed to provide required timing accuracy and resolution of shallow depths; a pulse width of under 7 ns is desirable. Such a pulse, with a typical risetime of 6 ns, can provide sub-decimeter measurement precision when used with an appropriate digitiser and leading-edge detector (91).

Although depth penetration increases marginally with higher pulse energies, one primary requirement is that the system must be eye safe at operational altitudes. The scanned beam can only be expanded to a diameter of 2 - 3 meters before geometric effects begin to cause accuracy problems. For this case, the maximum eye-safe energy density at the water surface limits pulse energies to values on the order of 5 mJ. While reliability and long lifetime are very important, another critical characteristic is stability. Key parameters which affect depth measurement accuracy, such as pulse width and rise time, must not vary significantly on a pulse-to-pulse basis or with laser tuning parameters such as temperature, pump current, and pump pulse width, or with aging.

Measurements

A great deal of attention, during both design and operation, must be paid to the precise and accurate measurement of times and angles. Optical and electronic time delays through the system, both fixed and variable, must be carefully determined, and errors must be either eliminated or calibrated and corrected in software. Typical examples are signal transit time variations in a photomultiplier tube as a function of high voltage and in a logarithmic amplifier as a function of signal amplitude. All inputs related to aircraft attitude and location must be temporally deskewed and appropriately interpolated. Computer latencies must be well understood and carefully handled. It is important to design the system such that any correctors are small so that errors in the correctors do not have a substantial impact on overall system performance. Timing calibration must be measured and corrected to sub-nanosecond accuracy.

System installation angles, aircraft orientation angles, and the resulting beam nadir angle in the world frame, must be known to high accuracy for every pulse because their effect is magnified by the aircraft altitude. For example, at a 400-m altitude and with a nominal 20-degree nadir angle, a system angle error of 0.05 degrees (<1 mrad), which equates to a nadir angle error of 0.10 degrees, would yield a 25-cm error in the vertical height of the aircraft. This would be unacceptably large for many applications. It is desirable to limit system error components to about 5 cm and thus system angle errors to about 0.01 degrees. Because such angles are too small to measure directly in the aircraft, this can only be accomplished by applying an inverse algorithm to flight data collected occasionally for the purpose of angle calibration. Finally, precision, repeatability, and absolute accuracy of time and angle measurements must be checked on a regular basis through monitoring overlap areas between swaths, flying cross lines, and by performing occasional intercomparisons against independent standards.

Water surface detection strategy

One of the first questions asked during system design is: “Can we build an accurate ‘all-green’ ALB system?”, i.e., a system which uses only green laser light and which will meet IHO depth accuracy standards over a full range of depths and environmental conditions. The simple answer is “no”. There are two reasons. The first reason is that it is necessary to accurately estimate the pulse transit time to the air/water interface for a large fraction of the laser soundings. This is true if the mean water interface is the original depth datum, and it is also true if measurements are made with respect to the ellipsoid, because of the speed of light difference in air and water. In very shallow water, because of the finite pulse width, strong green bottom returns can swamp associated green surface returns so that they are unusable for surface detection. The minimum depth at which pulse separation can be achieved decreases as the pulse width decreases, but if one wishes to go to zero depth, this is moot. A second reason would apply even if shallow depths were not required; it is more complex and is presented as follows.

Green “surface” returns are a problem. As illustrated in Figure 2, a green “surface” return is a linear superposition of energy reflected from the actual air/water interface and energy backscattered from particulate materials in the volume of water just under the interface. The interface component signal amplitudes, which depend strongly on the beam nadir angle, wind speed, and the specific irradiated wave slopes, have a huge standard deviation (92). They can and do vary by orders of magnitude from pulse to pulse, while the volume backscatter amplitudes, which depend primarily on water clarity, are much more constant. For beam nadir angles in the 0-20 degree range, individual interface return amplitudes may be much stronger or much weaker than typical volume backscatter return amplitudes on a statistical basis. Each green “surface” return may thus be virtually a pure interface return or virtually a pure volume backscatter return, but they generally fall somewhere between with a “mixed” character (93). This is termed the "surface uncertainty" problem.

In time, both signal components begin at the instant when the leading edge of the laser pulse reaches the water surface, but from there they rise at different rates. The volume backscatter return derives solely from particulate backscattering in the water column under the interface. Its rise time, which depends mostly on incident pulse shape and duration and on water clarity, is significantly longer than the rise time of the interface reflection which mirrors the transmitted pulse shape, modified by off-nadir geometric stretching. For clear water, the peak of the volume backscatter return occurs at the same time as the tail end of the interface-reflected pulse (94). For any useful measure of pulse timing, the measured arrival time of a typically “mixed” green “surface” return will thus be from an indeterminate distance under the water interface, and it will consequently be in error. For currently available pulse widths, the time difference between these two inseparable components is far too large to permit the use of this combined green return of ambiguous origin for surface timing (36). For example, the depth error associated with the time difference between an interface return and a volume return in $K=0.1m^{-1}$ water, for a 7-ns pulse width and a leading-edge, half-peak-height pulse location algorithm, would be on the order of 35 cm (94).

It has recently been determined that, for practical values of beam nadir angle and surface laser spot diameter, the time difference between interface and volume detections does not go to zero as the laser pulse width is reduced to zero (95). The reason is related to the oblique geometry with a non-trivial time difference across the laser footprint. This causes a net delay for volume returns even for delta-function source pulses. A minimum laser spot diameter on the order of 2 or 3 meters is needed both for eye-safe operation and to provide satisfactory surface return probability. A beam nadir angle of 15 or 20 degrees is needed for an economically sound swath width. Consequently, the surface uncertainty problem cannot be solved by using an extremely short laser pulse, if one becomes available.

For these reasons, a system with only a green receiver is unacceptable for hydrography. Receiver channels at one or more additional wavelengths are required for surface returns. The use of green surface returns in a multi-channel system remains subject to significant environmental limitations.

Theoretically, it is possible to derive relatively accurate surface times from the limited set of green pulses whose character is clearly dominated by either interface character or volume character. In the latter case, a predictive bias corrector would be applied to correct the measured time from the volume to the interface. It is very difficult in a noisy environment, however, to determine if the detection point for a particular pulse is dictated by interface character or volume backscatter character. It has been reported that it is operationally feasible to use a limited selection of green surface returns, which have been identified as interface returns through an unspecified algorithm, for surface detection to augment the information from a broad, vertical IR beam (96). As has been seen, however, this recognition may be somewhat arbitrary, and its use may not cover the full desired operational envelope -- particularly for cases of low wind. More importantly, the depth measurement error is larger for the many pulses whose green surface returns cannot be used because they are not dominated by interface character.

Infrared surface returns have the advantage that the interface reflection component dominates. The IR volume backscatter is considerably weaker because of much higher attenuation in the water at this wavelength (97), and it consequently arises from a region so near the interface that it would not cause an unacceptable timing error in the event that it was detectable. Under calm wind circumstances, however, both IR components can become undetectably weak in clear water for the typical beam nadir angles used by an ALB system. Additionally, the IR returns can arise from false targets above the surface such as spray, birds, and low-lying mist (“sea smoke”). Because of these problems, an IR channel alone is not a completely satisfactory surface detector. This is also true for a broad, vertical IR beam which does not properly sample longer water wavelengths, as noted by Billard (96).

It is a great advantage to have a surface channel tuned to the green-excited water Raman backscatter wavelength in the red portion of the spectrum (79). This is an inelastic scattering process that arises from a vibrational mode of the O:H bond in water molecules (78). It yields a relatively weak return (compared with the green and IR) which, with a high-gain, low-noise channel, is useable for altitudes up to at least 400 meters. Because this return arises solely from volume excitation under the interface, there is no interface component, and its origin is unambiguous. It can be used for surface location by applying an appropriate bias corrector to translate its arrival time to the predicted location of the interface. The major benefit is that these Raman returns will be present regardless of wind speed and sea-surface wave slopes. Also very useful is the fact that they do not arise from spray, birds, or sea smoke, and they have a relatively small amplitude dynamic range. In very shallow, clear water, these surface returns may, however, be contaminated with bottom reflected red energy. Such returns must be discriminated against. A red channel will also detect the broad-band, green-excited fluorescence (from dissolved organics, various pigments, and the chlorophyll tail) present within its optical filter bandwidth. This can be beneficial, as extra signal, if the source is in the water, but, as above, can be a problem if it arises from the sea bottom.

Depths can be calculated for a limited fraction of pulses whose surface returns are not detected but whose times to the mean surface can be predicted based on a mathematical model of the water surface (96). Depth errors for such pulses are related to the physical wave height, however, and can be larger than desirable for higher wave heights. In order to be able to handle all environmental circumstances and provide fully reliable, accurate, false-alarm free surface location for nearly every pulse, a receiver should have surface channels at both IR and red (green-excited Raman) wavelengths. This provides the added benefit of constant intercalibration between the two surface channels.

Surface return detections will generally be used by system hardware to trigger the digitiser at a time appropriate for approximately aligning the surface return waveforms in the digital record. They can also be used in the estimate of approximate depths in real time. For these purposes, even the less accurate green surface return can be used. Since none of the three channels, by itself, can be guaranteed to provide the needed surface location times over the entire range of operating altitudes and environmental conditions, a prioritised "cascade" logic can be used. An example might be called "R-I-G" in which the Raman channel is the first choice due to its insensitivity to surface conditions and to its immunity from false targets. If the Raman signal does not exceed a preselected threshold, the logic looks for an IR return. If neither Raman nor IR returns are detected, the logic defaults to the green channel. It is also possible to use "I-R-G" logic or to lock the hardware surface detection to a single, selected channel.

Handling amplitude dynamic range

The amplitude of an interface return from a mirror-like, near-nadir reflection can be as large as 2% of the transmitted beam energy. This is a very strong signal, indeed. The light pulse in the water is attenuated exponentially, based on water clarity, over the round trip path to the bottom and back. Only a very small portion of the transmitted energy is reflected from the bottom and returned to the airborne receiver. A bottom return with a useful signal-to-noise ratio may be six or seven orders of magnitude weaker than the noted interface return. This amplitude range can occur over the very short time span of a few tens or hundreds of nanoseconds. This is a severe challenge for the receiver. If the dynamic range capability of the receiver is a limiting design factor, then either weak signal performance will be compromised in one or more channels or saturated waveforms may result.

Typical approaches involve strategies such as logarithmic amplifiers, variable-gain photomultiplier tubes (PMT's), limiting the minimum beam nadir angle, and using two green channels with high and low gains. There is no single or best solution; using a combination of several techniques, each of which handles a portion of the range, is customary. Great care must be taken in the application of these often nonlinear methods, however, because they may introduce undesirable side effects such as variable time delays which, if not corrected, could cause depth measurement errors. A logarithmic amplifier has the advantage of being a static component whose gain and transit delay vary only with signal strength and not as function of time as well. Other techniques such as crossed polarization and optical centre blocks are less desirable because of insertion loss and waveform distortion, respectively.

Beam nadir angle

The nadir angle of the scanned beam is a powerful independent variable which has a significant effect on surface return amplitudes, propagation-induced depth measurement biases, variations in propagation-induced depth measurement biases with unknown water clarity parameters, and small-target detection probabilities, among other things. Consistent arguments can be made for each of these items that it is preferable to keep the nadir angle nearly constant at "larger" values in the 15 to 20 degree range (2). This can be accomplished by directing the beam ahead of the aircraft in a section of a semicircular arc. If a programmable scanner is used, a small, purposeful variation of about 1.5 degrees in the nadir angle at the ends of the scan lines can be used to provide loops whose purpose is to prevent pulse pile-up and keep the sounding spacing near the desired average. The scan pattern for a nearly constant nadir angle is illustrated in the colour-coded depth map of Figure 3. On the left, at a small scale, are the ends of five overlapping swaths of SHOALS data flown in alternating directions. The depth scale on the far left is in meters. On the right is part of a larger scale "zoom" window which shows the sounding pattern for small sections of three swaths. As can be seen, coverage is dense and uniform. There is no inherent need for a rectilinear scan pattern.

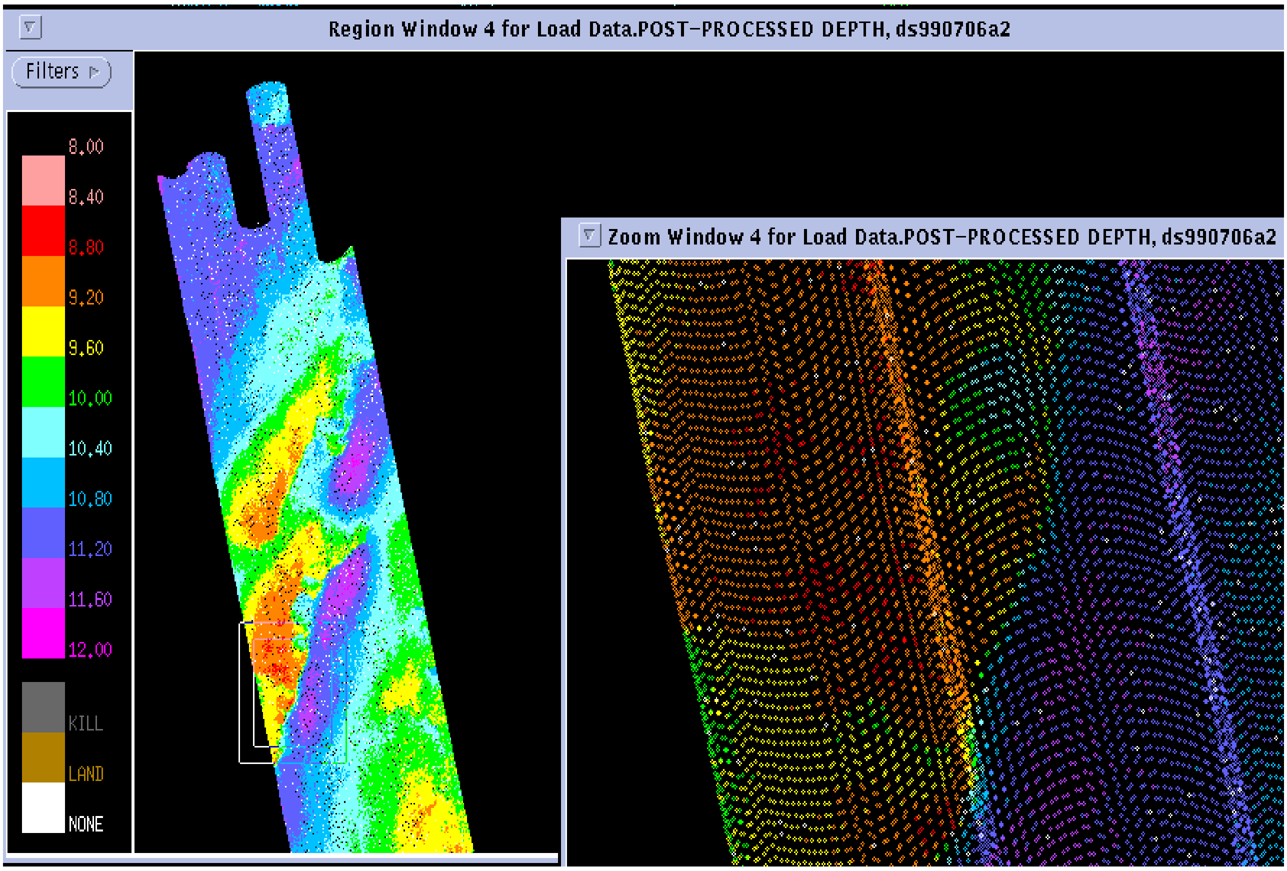

Figure 3: Example of intersecting scan patterns (flown in opposite directions) with nearly constant nadir angle.

Sea surface interface reflection amplitudes and their dynamic range increase rapidly as the beam nadir angle decreases, particularly for lower wind speeds (92). Limiting the nadir angle to larger values is an effective method of decreasing the overall amplitude dynamic range that must be handled by the receiver optics and electronics. A major benefit of this approach is the fact that this reduces the dynamic range not just for one channel, but for all channels. If smaller nadir angles are avoided, the IR channel, for example, given a limited dynamic range, can be made to be highly sensitive to detect very weak returns.

The very strong interface reflections that frequently occur near nadir can cause PMT-related problems in several ways. Even if the tube is gated off, strong input light levels can cause a build-up of space charge around the photocathode. This can affect output signal levels, linearity, and bandwidth and can be deleterious to performance or even damaging to the tube. Another problem often seen as a result of overly strong input signals is the appearance of "afterpulses" at a delayed time after the impulse. These are false signals generated within the tube itself, and a software trap may be necessary to recognize and remove them (64). Although this problem depends somewhat on the type of PMT used, a system with a nadir angle of no less than 15 or 20 degrees is far less likely to experience such a difficulty. In a system that uses smaller nadir angles, unexpectedly large surface returns may result in saturated waveforms (96). The use of such distorted waveforms for depth calculations is not recommended.

The green light beam in the water spreads out because of the effects of surface waves and of scattering from organic and inorganic particulate materials. Scattering is generally the dominant effect. The complex phenomena involved are diagrammed in Figure 4. The beam spreading is both spatial and temporal and affects the arrival time of the bottom return at the receiver. The basis for timing measurements for the slant path to the bottom is the so-called "unscattered ray". Scattering causes both "long" biases due to increased photon path lengths and "short" biases due to the fact that a significant amount of energy is scattered into the "undercutting" region in the direction closer to the aircraft than the unscattered ray. The resulting net depth-measurement bias must be predicted by modeling and the prediction applied as a corrector to the raw measured depths. The results of Monte Carlo simulation studies of underwater light propagation (2, 98) indicate that propagation-induced depth measurement biases vary with nadir angle, depth, and water clarity parameters and exhibit larger magnitudes near nadir. A more important factor, from the point of view of bias correction, is that variations in these predicted biases, as a function of unknown water optical properties, are minimized for nadir angles in the 15-20 degree realm. For these angles, the use of bias correctors globally averaged over a wide range of typical parameter values is acceptable, and no water clarity estimates are needed from the lidar data. These angles provide a cost-effective swath width and do not cause unacceptable geometric effects. As a result of fixing the nadir angle at a value such as 20 degrees, the nadir angle ceases to be a source of variation in propagation-induced bias calculations, and the resulting biases are relatively small, predictable, and have only a weak dependence on depth. This is not the case for smaller and variable nadir angles.

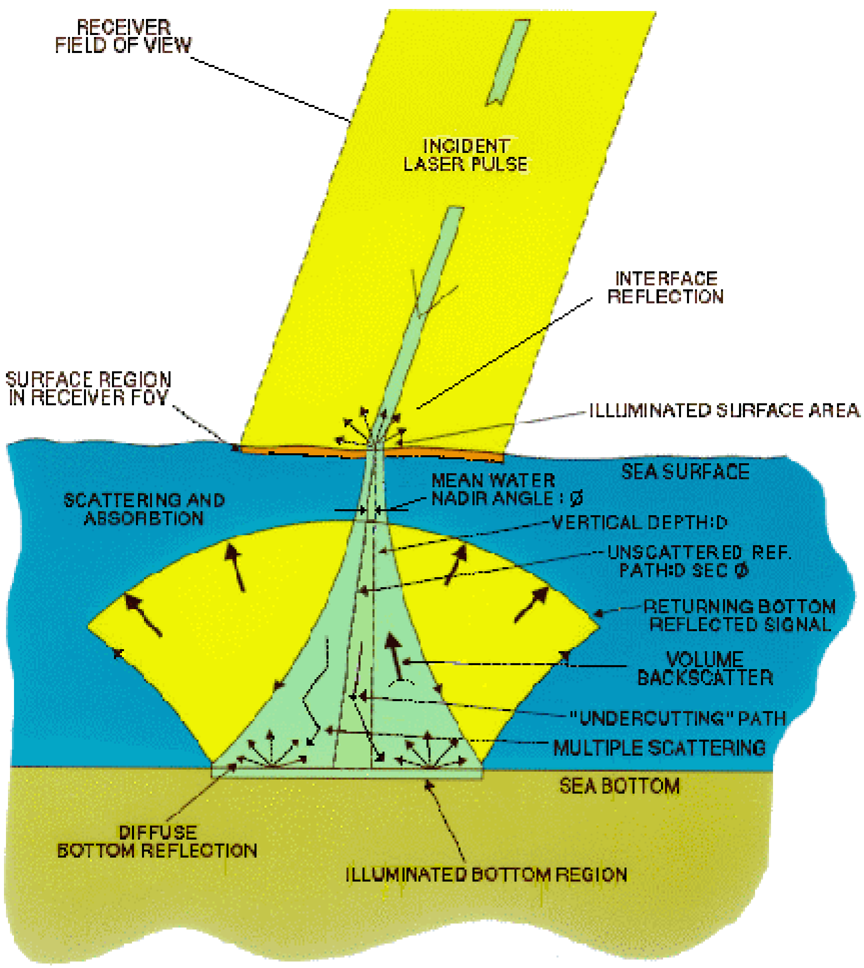

Figure 4: Schematic diagram of the effects of scattering on the green lidar beam.

The detection probabilities for small objects (or "targets") such as rocks and coral heads sitting on the bottom, with heights above the bottom in the 1.0 - 1.5 meter range, are much higher at a 20-degree nadir angle than they are at or near nadir (81). This is because, for the near-nadir case, all rays to off-axis targets are longer than on axis. This tends to cause the target returns to merge with the generally much stronger bottom returns, making the target undetectable. A constant nadir angle will result in a constant target detection probability across the swath.

Waveform recording

Although approximate depths can be calculated in real time, it is considered necessary to record all received waveforms for each pulse in order to permit accurate depths to be calculated in post-flight data processing. In the past, sufficient computer capability to process all received waveforms in real time may not have been available, and hardware pulse timing circuits such as constant fraction discriminators are known to be less accurate than needed because of factors such as sensitivity to pulse shapes and signal baselines. The primary reason for saving all data, however, is that it may need to be examined manually and reprocessed to yield best results. It would not be wise or cost effective to save only the results of a possibly erroneous real-time depth calculation and to throw the valuable waveforms away. Reasons for reprocessing might involve environmental factors such as fish schools, turbidity layers, or bottom hazards. Occasionally, it may be necessary to adjust processing parameters to handle new or unusual circumstances. Although it would be more operationally efficient for the aircraft to return finished depths, that scenario is not presently practical. The ability to detect rocks and other relatively small bottom hazards requires a waveform digitiser with excellent resolution in both time and amplitude. The recommended configuration is a unit with 1-ns time bins digitised to 1024 levels. Devices with these specifications are not easy to find.

Scanner

The scanner may be a gyro-stabilized rotating mirror or a mirror servoed under computer control in two axes to produce the desired scan pattern. The programmable scanner provides significantly greater flexibility. It is important to actively compensate the scan for aircraft roll and pitch, as measured with an appropriate attitude sensor, so that the edges of the swath remain straight regardless of changes in aircraft attitude. This minimizes the need for overlap between swaths and reduces the likelihood of data gaps ("holidays") in the coverage between swaths. The scanner is one of the most important components of the system. It must be extremely stable and reliable. Because scanner movement is rapid, and precise knowledge of the scanner angles and the resulting beam nadir angle is crucial to system depth measurement and position accuracies, the scanner angles should be measured as near as possible to the instant of laser firing. Triggering the laser firing times directly from the scanner when the angles are measured is a recommended method to minimize associated computer latency problems.

Vertical reference

The traditional approach is to perform bathymetry with respect to the extant mean water level. This is accomplished by applying a sophisticated wave-correction algorithm (99, 100) to the surface return measurements. With the application of absolute water levels measured concurrently at nearby water level (tide) gages, depths measured with respect to the mean water level are reduced to appropriate project tidal datums for charting and mapping.

Kinematic GPS (KGPS), using carrier phase techniques, can be used to provide highly precise (subdecimeter accuracy) horizontal and vertical positions for aircraft with respect to the WGS-84 ellipsoid (101). With the technique of on-the-fly (OTF) carrier-phase ambiguity resolution, most cycle slips are automatically detected and repaired during processing (102). To ensure the highest possible reliability and accuracy, a procedure that utilizes multiple baselines to detect and prevent erroneous initialisations should be used (103). KGPS/OTF provides the ability to use an ellipsoidal vertical reference independent of the water surface and thus to conduct unlimited topographic surveys over land in addition to bathymetric surveys over water. This greatly improves the efficiency of surveying both sides of the land/water boundary in areas of irregular coastline geometry. Importantly, this approach permits the production of sea bottom and topographic elevations without the need for concurrently measured water-level data.

Vertical accelerometer

The water surface may have long-period waves (swell) whose wavelengths of several hundreds of meters need to be properly sampled for the wave-correction process which occurs in post-flight data processing. For adequate accuracy, this requires that a span of at least several wavelengths be measured. The across-track swath is not wide enough for this purpose, and the modeling of the wave field is best done along the aircraft track. Because the spectrum of typical vertical aircraft motion overlaps that of the sampled swell (99), the vertical motion of the aircraft must be measured independently so that it can be removed from the wave height calculations. One method of providing the required data is to doubly integrate the output of a vertical accelerometer. This permits 10 to 20-second averaging times, and provides the needed low frequencies in the surface model for detecting and removing long-period swell. It may be noted that this modeling is not necessary if KGPS is used to provide an ellipsoidal vertical reference instead of the mean water level.

AC-coupled electronics

Sun glint, the bright reflection of the sun from the water surface, is a noise source in ALB. Sun glint, which varies with wind speed and sight angle, can affect the ability to fly in certain directions relative to the sun and can require that flight operations avoid mid-day when the sun is high in the sky (64). For the very short time durations of interest for lidar pulses, the solar background level is effectively a constant. In a system with dc-coupled electronics, sun glint would represent a variable loss of dynamic range for the digitiser, because the resulting level shifts could force stronger lidar return signals into saturation. This is highly undesirable. System electronics should thus be ac-coupled. In this case, the sun glint provides only an increase in the shot noise associated with the lidar signals, and operations can be successfully conducted even in the presence of moderate glint. Again, as noted above, while nighttime operation would be preferable from the point of view of physics, flying at low altitude over water at night is not operationally desirable.

Operator interface

For efficient data collection, the operator should be presented with access to the following displays: digital shorelines and survey area boundaries, aircraft track lines, all available parameter values, a subset of real-time waveforms, error messages and warnings, and a selection of real-time depths displayed either geographically or in "waterfall" format. For ease of use, all receiver options should be computer controlled through a graphical user interface.

Other

Waveform distortions and unknown delays must be avoided. The laser and optics must be suited to the difficult aircraft environment of shock, vibration, and large temperature variations and must be absolutely stable. All system parameters should be stored on the data tape to become part of the mission record. Lidar altitudes should be presented to the pilots for precise control of the aircraft. A down-looking video camera, annotated with flight parameters, can provide an invaluable record for later use by data processors.

SHOALS

SHOALS is an operational airborne lidar bathymeter (4, 67) owned by the U.S. Army Corps of Engineers (USACE) and employed in cooperation with the U.S. Navy out of the Joint Airborne Lidar Bathymetry Technical Center of Expertise (Mobile, Alabama). It was built and is maintained by Optech Incorporated (Toronto, Ontario, Canada). Operations are conducted by John E. Chance & Associates (Lafayette, Louisiana), a member of the Fugro group of companies, and Kenn Borek Air Ltd. (Calgary, Alberta, Canada), Figure 5. SHOALS is operated to meet both USACE “Class 1” and International Hydrographic Organization “Order 1” hydrographic accuracy standards for most applications. It has topographic and KGPS capabilities, as well, and operates seamlessly across the land/water boundary.

Seven successful field seasons have been conducted, and over 300 projects have been surveyed, for a variety of sponsors, around all continental U.S. coastlines (including the Great Lakes), in Hawaii, and in a number of other countries. Operational missions have been flown for general-purpose hydrography (104), monitoring of shoaling in navigation channels (105), coastal engineering studies of sediment transport (106, 107), monitoring seasonal change (108), and rapid-response storm damage assessment after Hurricane Opal (109). Comprehensive surveys of the coastlines of the Hawaiian Islands of Maui and Kauai were conducted in order to improve storm wave run-up prediction models that are used by FEMA to plan evacuation routes for hurricanes (110). Surveys have been completed economically and safely in disparate areas. These include a large, relatively shallow, mostly flat area in the Bahamas with an occasionally complex bottom topography of intersecting sand waves and "blue holes" (82), and a deeper, rocky area in New Zealand that is rife with pinnacles which pose a danger to surface vessels (10). Recent notable survey locations include Portugal (111), Puerto Rico, Florida, Lake Tahoe (Nevada, California), and the Hawaiian islands of Oahu and Hawaii.

Figure 5: SHOALS lidar bathymeter in Kenn Borek Twin Otter over Hawaii.

SHOALS hardware was designed and built according to the considerations discussed above. The system is compact and has been operated from a Bell 212 helicopter as well as in a Twin Otter fixed-wing aircraft. The laser is a Cutting Edge Optronics diode-pumped Nd:YAG with an IR output of 5 mJ at 1064 nm and simultaneous, collinear, frequency-doubled green output of 5 mJ at 532 nm. The pulse-repetition rate is 400 pps, and the green pulse width is about 7 ns. The Saab Instruments programmable scanner (53) is a mirror servoed under computer control in two axes to produce the desired scan pattern and to compensate for aircraft roll and pitch, as measured with a Litton LTN-90 inertial navigation system. In order to maintain a nearly constant nadir angle of twenty degrees, the scan pattern selected for operational surveying is a segment of a circular arc aimed ahead of the aircraft.

The dynamic range problem is handled by this selection of the nadir angle, by employing logarithmic amplifiers, and by the use of two green channels -- one high gain, with a grid-gated PMT, and one lower gain, using an avalanche photodiode. The high-gain channel is gated on only after the pulse has passed through the air/water interface. There is no after-pulsing, and no problem with saturated waveforms. Vertical acceleration measured by the LTN-90 provides information for the wave-correction algorithm so that it can handle extremely long-wavelength swell. The electronics are ac-coupled to preserve digitiser range. Surface detections are made in both IR and Raman channels linked with cascade logic. Green surface returns are never used in depth calculations due to the inherent ambiguity of their origin. Channel bandwidths are consistent with the laser pulse risetime.

The digitiser is an Analytek 1-GHz unit with 1-ns time bins and 10-bits of amplitude resolution. All four channels are digitised simultaneously, over appropriate time spans. Data are recorded on 10-GB 8-mm Exabyte Eliant tape cartridges. The system includes a built-in optical simulator, using light-emitting diodes, for exercising system functionalities. A real-time depth algorithm, which is a primitive subset of the post-flight waveform processing algorithm, supplies approximate depths to the airborne operator for quality control.

SHOALS SOFTWARE

The major software components are the Automated element, the Manual element, and the Visualization and Editing tool. Software design features and algorithms are equally important with hardware for performance and accuracy; a detailed description of the SHOALS post-flight data processing software is, however, beyond the scope of this document. A brief summary is presented here in several categories to emphasize important features and characteristics.

Automated algorithms

The following list highlights some of the major functions performed by the post-flight waveform processor and depth determination algorithms.

1) Timing latencies in scanner angles, attitude, and altitude data are deskewed. Low-rate sensor data are interpolated for each pulse.

2) A tracking algorithm is applied to surface times. Wild points are rejected in order to protect the integrity of the following wave-correction process.

3) Surface and bottom returns are discriminated. It has been demonstrated that algorithms containing heuristic rules (112) can provide excellent recognition of the desired returns along with rejection of noise, system artefacts, and some false targets in the environment (93). In order to avoid timing errors associated with waveform distortions, high-pass and low-pass filters are not used. The detection criteria are based on signal-to-noise ratio. All detected surface and bottom returns are subject to stringent tests for minimum signal-to-noise ratio and waveform quality. Waveforms not meeting these criteria are not used in the production of depths.

4) Recorded waveforms, which are logarithmically compressed, are linearised, and precise pulse arrival times are estimated. Studies have shown that the most accurate and precise pulse-location algorithm is a half-peak-height amplitude threshold applied to the linear waveform (91).

5) Timing correctors are utilized for hardware and environmental time delays. Hard-target timing constants from ground calibrations are applied. This includes delay versus amplitude tables that are required for each channel because transit times through logarithmic amplifiers are slightly longer for weaker signals. The predicted biases associated with the measured water Raman-scattering surface times (2, 94) are added.

6) Several types of automated channel priority logic are available for selection of the optimal surface channel for each pulse.

7) The mean water level is calculated. This acts as the primary depth reference and permits the removal of wave heights from the measured water-column depths (99, 113). This routine doubly integrates the vertical acceleration data to permit long-period surface waves, with wavelengths greater than the swath width, to be properly handled. The algorithm has different modes of operation depending on the quality of the surface data; it has been designed to be impervious to vertical acceleration sensor biases. Using this approach, depths can be calculated even for pulses that do not have a valid surface return (at a modest cost in accuracy as long as the wave heights are not too large). For this reason, very comprehensive tests are applied to all surface data, and any questionable pulses are rejected. The wave corrector will provide a better answer from no surface return than from an erroneous surface return.

8) The value of the speed of light in water is based on the expected salinity in the geographic area. The depths are determined in a manner consistent with the quality of available surface data and the

goals of the survey. Two possible bottom returns per waveform are saved in order to permit valid depths to be calculated in the presence of fish and other biota in the water column. For bottom returns, first-pulse, strongest-pulse, and last-pulse modes of depth calculation are available for automated processing. Regardless of the logic used to produce the primary depth for each pulse, depths from both detections, if available, are presented for possible manual inspection. Automated depth selections may be manually swapped to an alternative if desired. When KGPS/OTF is used as the primary vertical reference, bottom elevations are calculated with respect to the ellipsoid (11).

9) A predicted corrector for propagation-induced bias is applied as a function of depth and nadir angle (2, 80, 113). Small biases are also applied for overall system calibration and to handle the fact that the fields of view are different in the two green channels.

10) Topographic heights are calculated for pulses on land.

11) So-called "shoreline depths" (114) are calculated for the problematic 0-1 meter depth range. These may be invoked manually by the operator if desired.

12) A large number of internal consistency checks are conducted during processing. If waveform characteristics or a number of other factors are not exactly as expected, one or more "warnings" will be issued for that pulse. Some warnings are serious enough to require that a depth not be reported for that pulse. The philosophy is that reporting no depth is better than reporting a bad depth. These warnings are tabulated and may be presented to the operator during manual processing.

13) For each pulse, an overall level of "confidence" in the result is provided as a key parameter. This confidence factor is based on a quantitative estimate of the depth-measurement accuracy for that pulse, and it contains inputs from a number of possible error sources. This value is much more meaningful than one based, for example, simply on signal return energy.

14) A large number of internal parameters are calculated and stored to provide insight, if needed, into the workings of the algorithm for each pulse. These were heavily used when the system was first built, and are now accessed only rarely for diagnostic purposes.

15) Processing is conducted in a flexible framework that provides interactive data displays and adaptability through efficient operator involvement.

Displays

Calculated depths for multiple flight lines are colour-coded in a geographical display. The colour bands are manually adjustable. The user may view selected regions in a magnified "zoom window". In the zoom window, each depth is reported numerically, and each sounding can be clicked with a mouse to bring up a "waveform window", as seen in Fig.6. This display contains plots of all four waveforms for that pulse plus a wealth of numerical information for use by the operator. Numerous other analytical features are available which are beyond the scope of this article.

Tools

A large number of internal and value-added parameters in a variety of categories such as "inputs", "outputs", "hardware", "results", and "diagnostics", to name just a few, are available to the user. Access to these parameters for analysis, correlation, and plotting is provided through the use of optional relational database and spreadsheet programs. Flexible operator interaction is provided to handle special cases through the use of a set of software control parameters. Quality control is augmented by redundancy in a number of areas such as overlapping depth ranges in the two green bottom channels, frequently redundant surface times in the two surface channels, and overlapping scan edges between flight-line swaths. A spatial data editing and three-dimensional visualization program is used as a final check for wild depths in geographic context. According to the laws of statistics, assuming a normal distribution, one pulse in every hundred is beyond the three-sigma level. If a relatively short 13-km flight line contains over 100,000 pulses, then that flight line will contain 1000 pulses whose depths are outside the three-sigma bound. Some of the larger of such statistically inevitable errors may need to be removed manually.

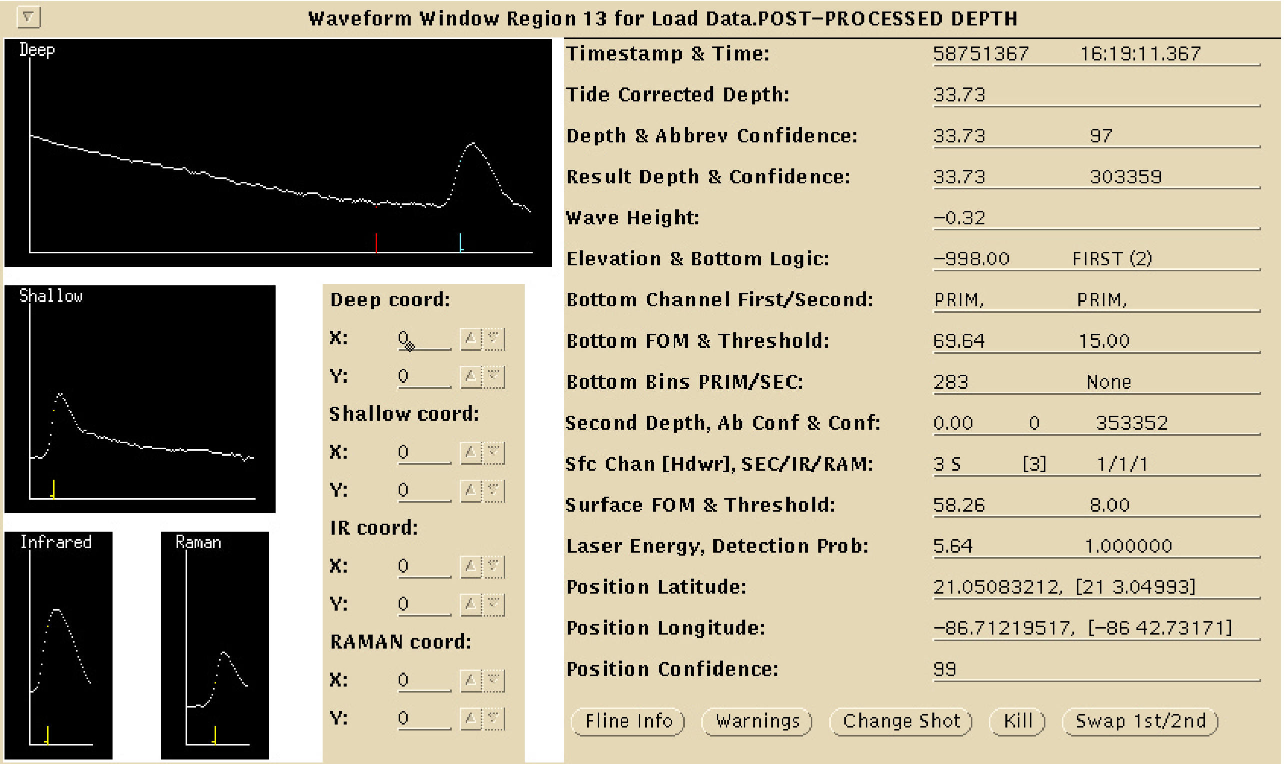

Figure 6: The SHOALS waveform window is available for each laser pulse; it contains waveforms from all four receiver channels and the values of key parameters.

Procedures

1) Timing calibration is maintained by occasionally firing the system on the ground at a fixed "hard target" whose distance is carefully measured. Constants thus derived are used in the software. These tests are conducted whenever major hardware changes are made and when problems are suspected. These calibration values have traditionally been very stable.

2) Periodic angle calibrations are carried out using a highly successful program that inverts the measured slant ranges to the surface to compute the requisite system orientation angles to extremely high accuracy. In order to provide the highest sensitivity in this routine, calibration flights are made with the scanner in a special raster pattern whose nadir angle varies over the range from 4-27 degrees. The use of a programmable scanner makes this possible. Results are confirmed by examining the character of a plot of estimated wave height versus scanner azimuth for survey data. Angle calibration errors would show up as nonlinearities or tilts in this plot. Calibration passes are made whenever the optical system is disturbed, as when laser heads are switched.

3) Because hydrographic and topographic intercomparison results with independent systems have been very satisfactory, such intercomparisons need not be conducted on a frequent basis. They are performed occasionally for quality control, after major hardware changes, and sometimes for new customers.

4) All flight lines are flown to overlap adjacent lines. Repeatability of results throughout every survey area is constantly reviewed by operators for quality control.

5) Difficult or questionable data segments can be reprocessed within limited geographic boundaries. False depths due to environmental effects such as schools of fish or turbidity layers can be selected by the operator and replaced with the underlying true bottom depths.

6) Data processing procedures can be adjusted for best efficiency and to meet customer needs. Especially rigorous hazard detection techniques are used for charting data.

7) Depths in the 0-1 meter range can be examined for validity and selected by the operators.

8) Processed KGPS data, if acquired, is substituted for use as the vertical reference and for the aircraft position.

9) All raw data are permanently recorded and saved. All processed depths, not just a subset of "decimated" depths, are saved for later review during chart verification and production.

RESULTS

The SHOALS hardware and software design features permit the production of bathymetric and hydrographic surveys in water, topographic surveys on land, and seamless operation across the land/water boundary. Performance is excellent in all respects. With its use of collinear green and infrared scanning beams, and two independent surface channels at red (green-excited Raman) and infrared wavelengths, SHOALS provides highly accurate and reliable (and often redundant) surface location at its 20-degree nadir angle. This is true across the entire swath under virtually all environmental conditions. The Raman channel fights through spray and sea smoke to detect the true surface. Through its use of vertical acceleration data, SHOALS handles long-period swell; the maximum detectable water wavelength is not affected by wind, surface conditions, or swath width. Operations are successful even under conditions of moderate sun glint. Afterpulses and waveform saturation have never been a problem. A high-resolution digitiser permits the discrimination of small bottom features.

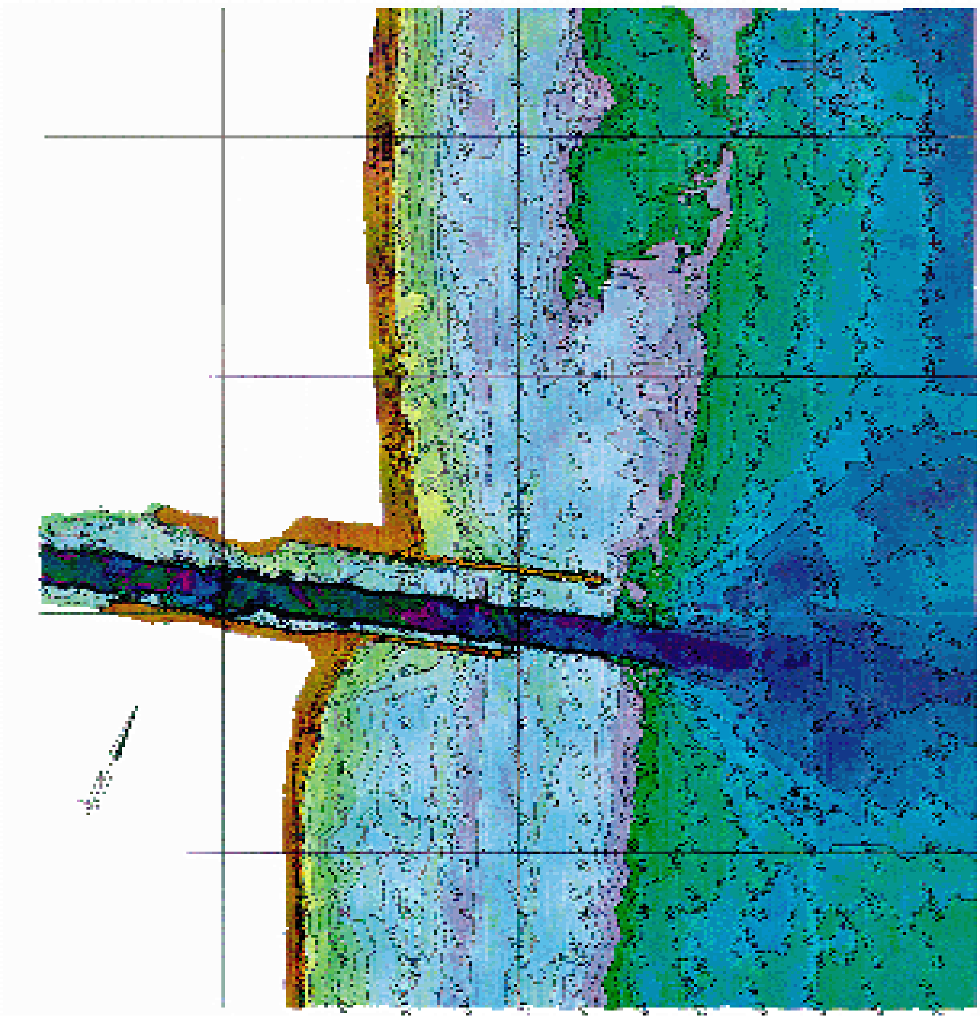

Figure 7: Colour-coded contours of the Jetties and navigation channel at Fort Pierce, Florida

First field trials of the system (66) revealed very accurate performance, and only a few small adjustments were required. Subsequently, excellent depth intercomparison results were obtained in shallow water against data from the USACE "coastal research amphibious buggy" (CRAB) mobile reference platform (115) at Duck, NC, and in deeper water with an operational National Ocean Service sonar survey (116) in Tampa Bay (Florida). The standard deviations of the depth differences ranged between 13 cm and 20 cm. Topographic accuracy was confirmed over an optical test facility at the Stennis Space Center (Mississippi). Accuracy is maintained operationally, as noted above, by regular checks of system timing and angle calibrations.

Depth measurement biases attributed to underwater light propagation characteristics have been quantitatively predicted by Monte Carlo simulation (80). The successful intercomparisons denote that these predictors, when used as bias correctors, produce accurate depths free of dependencies on depth, nadir angle, or water optical properties. This indicates that the propagation-induced bias model developed ten years prior to the fielding of the system and the associated correctors derived therefrom are correct.

There is a danger in the popular conception that, when lidar results are compared with those from older techniques, the latter are correct. This is not necessarily the case. Indeed, laser surveys have identified (or "brought to light") errors in associated sonar surveys.

Figures 7 and 8 provide small examples of typical SHOALS survey products. The depths are colour coded; land is represented as brown. If desired, the land topography can also be coloured. Figure 7 illustrates the navigation channel between jetties at Fort Pierce, Florida. Figure 8 presents an interesting volcanic bottom feature adjacent to a sharp, rocky peninsula at Kaneohe Bay, Oahu, Hawaii.

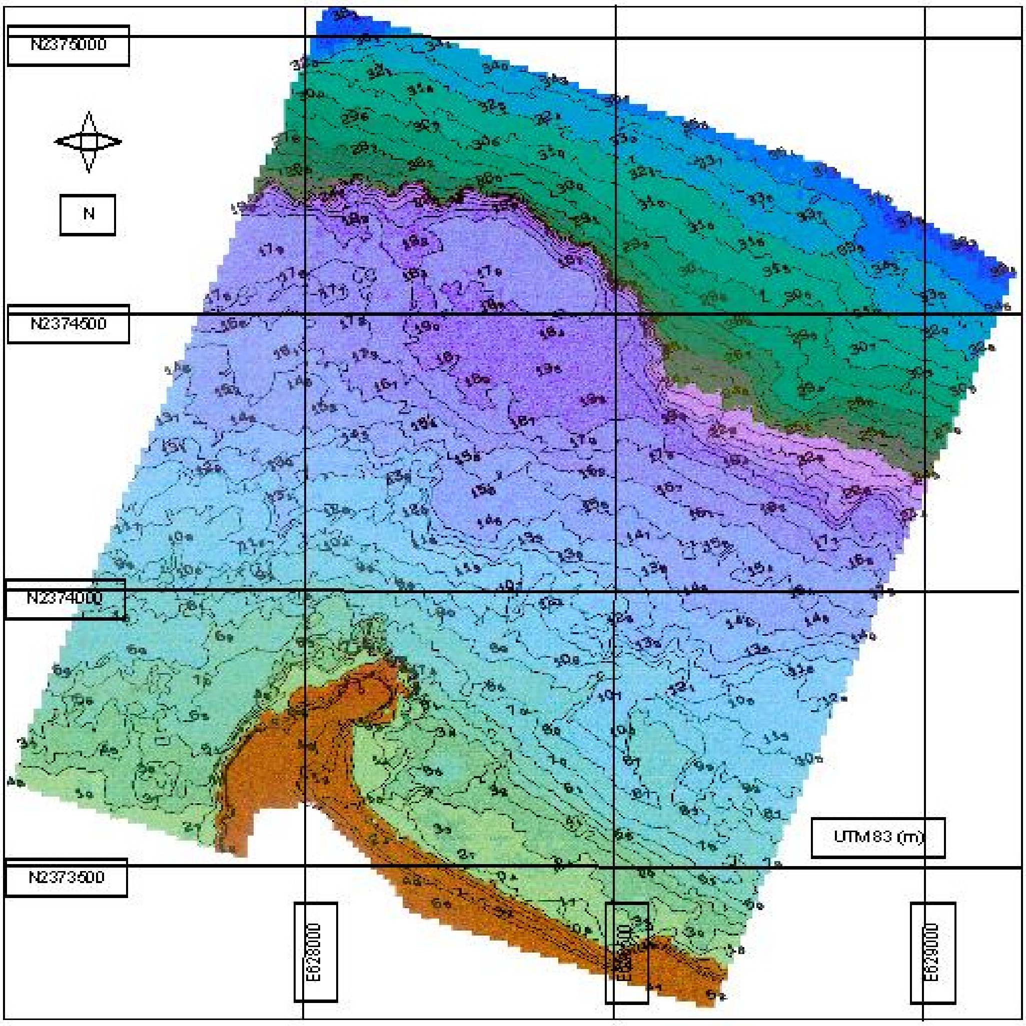

Figure 8: Colour-coded contours at Kaneohe Bay on the north shore of Oahu, Hawaii.

CONCLUSIONS

Airborne lidar bathymetry can be an accurate, capable, and cost-effective technique that offers a number of important products and services in coastal waters. ALB can survey safely in areas where sonar cannot, including on land, but it is not a substitute for sonar. ALB surveys are limited by water clarity. ALB cannot be expected to detect one-hundred percent of bottom hazards with size on the order of a one-meter cube. Regions where ALB and sonar overlap should be thought of as areas of cooperation rather than of competition.

It is relatively easy today to build a lidar system that can detect the sea bottom. It continues to be very difficult to build an accurate lidar bathymeter. Accuracy is attained by thoughtful design of hardware capability and software algorithms and by establishing procedures for limited manual interaction with the data. A number of critical hardware design strategies, software algorithms and tools, and operational procedures have been described.

The versatile SHOALS airborne lidar system has the proven ability to conduct rapid, accurate, and cost-effective surveys of large offshore areas, navigation channels, coastal structures, beaches, and shorelines. The design philosophy and judgements have been affirmed by outstanding performance and great success in the field. SHOALS' sophisticated surface detection strategies in both hardware and software have proven to be highly effective and demonstrate excellent accuracy with high reliability. Surface-return probabilities are extremely high across the entire swath under all environmental conditions.

All of the hardware and software strategies recognized for maximizing both the accuracy and the operational envelope of an ALB system were incorporated into the design and construction of the SHOALS system. The hardware and software designs were predicated on producing the best possible precision and accuracy of recorded and processed data by minimizing sensitivity to uncontrollable environmental effects while not introducing any uncorrectable errors. All design decisions were resolved in favor of accuracy as the primary driving factor, not cost or simplicity. The post-flight data processing software seeks to maximize detection probability while minimizing false alarms. It corrects for several unavoidable but predictable biases from the environment as well as removing effects inherent to the hardware configuration. Its automated component provides efficiency, while the manual components provide flexible operator interaction to handle differing survey requirements and special environmental circumstances. The result is a flexible system which has achieved nearly the limiting accuracy dictated by uncontrollable and unknowable environmental parameters.

SHOALS, depth measurement accuracy is maintained by periodic calibration of system timing and angles, by the constant monitoring of key quality control parameters, and by occasional intercomparisons with sonar data. SHOALS' calibration has been repeatedly proven to be extremely stable. Depth-measurement accuracy has been confirmed to be excellent and consistent. Based on seven years of successful operational experience with SHOALS, it has been demonstrated that the design decisions regarding surface detection strategy, scanner pattern, dynamic range compression, wave correction procedures, post-flight data processing algorithms, and system calibration techniques are valid. This system design is still considered to be optimal for current technology. All major design features have been demonstrated to be both necessary and sufficient for accurate performance and efficient operation over the entire operational envelope. No design changes have been required, although several new features have been added. It will be hard to improve the design for the next-generation system. A number of the required hardware components are still state-of-the-art and not readily available "off the shelf". Over the years, it has not become easier to build an accurate, capable, reliable, and cost-effective lidar bathymetry system.

ACKNOWLEDGEMENTS

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