Advancements and Applications of the SHOALS Laser Bathymetry System

Mark W. Brooks, *John E. Chance & Associates, Lafayette, LA 70506*
Eddie Culpepper, *John E. Chance & Associates, Lafayette, LA 70506*
Gary C. Guenther, *NOAA National Ocean Service, Silver Spring, MD 20910*
Paul E. LaRocque, *Optech Inc., Toronto, Ontario, Canada M3J 2Z9*

BIOGRAPHY

Mark Brooks is Project Manager of the SHOALS program for John E. Chance & Assoc. and has been working with lidar bathymetry for four years. Before the SHOALS program began, Mr. Brooks worked with multi-beam echosounders. Mr. Brooks is a graduate of Purdue University with Bachelor of Science degrees in both Civil Engineering and Land Surveying.

ABSTRACT

SHOALS is an operational airborne lidar bathymeter owned by the U.S. Army Corps of Engineers and employed with the support of John E. Chance & Associates, the NOAA Aircraft Operations Center, the NOAA Coast Survey Development Laboratory, and its creator, Optech Incorporated. Hundreds of projects have been successfully surveyed over four field seasons.

The technology and techniques of airborne laser bathymetry are far from mature, and new understandings continue to be gained. The system was recently augmented, for example, with the capability to utilize kinematic GPS (KGPS) with on-the-fly (OTF) ambiguity resolution in order to permit the production of bottom elevations without concurrent tidal data. This also permits the system to be used more extensively over land, for beach profiling and topographic mapping, in addition to underwater bathymetry. The seamless integration of these capabilities permits continuous profiling through the land/water boundary. The ability to automatically detect possible hazards in the water has also been added. In our paper we will address the above capabilities and the associated algorithms and procedures. Future upgrades and modifications will also be discussed.

INTRODUCTION

The SHOALS system was originally designed to measure the depth of shallow water in coastal regions. As this capability was demonstrated around the U.S., other uses for this valuable tool were recognized. Typical applications include bathymetric and topographic surveys of federal navigation channels, shore protection projects, beaches and shorelines, jetties, breakwaters, coral reefs, ports, and harbors (Lillycrop et al., 1996; Cunningham et al., 1998). Since operations began in 1994, over 230 projects have been successfully surveyed for the U.S. Army Corps of Engineers (Irish et al., 1996; Irish and Lillycrop, 1997), and for other sponsors such as the U.S. Navy (Pope et al., 1997), the State of Florida, the U.S. Geological Survey, and the NOAA Office of Coast Survey (Riley, 1995).

Over the past few years, enhancements have been made which have allowed the SHOALS system to expand past its conventional shallow-water surveys. These improvements have included the ability to discern water depths of less than one meter, an automatic hazard detection program, and the ability to survey over land, with or without a relative water surface, using on-the-fly kinematic GPS.

BACKGROUND

The SHOALS system is an airborne lidar bathymeter (Guenther, 1985) currently mounted in a helicopter. A laser, a programmable scanner, an inertial navigation system, various receiver optics and electronics, and an operator's computer make up the hardware in the system. The laser repetition rate is 200 Hz and the laser power has been set to be eye safe at operational altitudes. The Litton LTN-90 inertial navigation system measures the movement of the platform and supplies attitude information to the SAAB programmable scanner to provide a straight swath and a regularly-based array of measurements, regardless of the movement of the aircraft. A total of five receivers are used in the SHOALS system, two green channels at 532 nm, two IR channels at 1064 nm and one red channel at the green excited, Raman wavelength of 645 nm.

One green receiver is used for shallow water returns and measures from the surface to about 13 meters of water depth. This same channel is used for land returns. The second "deep" channel measures from about 6 meters to 37 meters. One IR channel and the Raman channel are used as surface detectors only. The second IR channel is cross-polarized to detect land only returns in real-time.

A dedicated, VME-based computer handles all survey aspects of the airborne system. The computer controls pilot and operator display, data collection and recording and real time sounding and positioning. All airborne data are collected on 8-mm tapes. These tapes are then read on the ground by the post-flight Data Processing System (DPS).

The DPS is based on a SUN SPARC-10 workstation and utilizes an Informix database for easy access to data. Waveform data are stored in a file system on a per-flightline basis. After each flight is complete, the tapes are "stripped" and the data are input into the database. Automated processing is then conducted. Stripping and processing the data are completed at a 2:1 time ratio with respect to data collection. After automated processing has completed the operator manually scans the data to ensure that no anomalies exist. Portions of the data may be reprocessed to rid the data of environmental effects. Tidal information may be included in the data at any time.

The principal component of the DPS is the "waveform analyzer". This is the code that actually determines the resulting depth of water from each pulse. The waveform analyzer, which is executed only once for each laser pulse, contains four major sections: 1) estimation of necessary parameters, checking for saturated waveforms, surface tracking, and waveform normalization; 2) determination of surface return times; 3) detection of bottom return times; and 4) wave correction, estimation of depth (or land height), and bias correction (Guenther et al., 1996).

To properly determine the depth of water, the waveform analyzer must be able to locate the water surface for a sufficient number of pulses so that a mean water surface can be determined (Thomas and Guenther 1990). For the depth calculation, a bottom return must be found on a per-pulse basis. Each depth is initially referenced to the mean water level. The depth of each pulse is then reduced to a datum (such as mean lower low water) by applying a corrector for the concurrently measured external water level (tide).

SHORELINE DEPTHS

Performing beach surveys has been problematic for surveyors in the past. These surveys have generally taken at least two crews and many man-hours to conduct. While one of the crews perform beach profiles on land, the other runs hydro lines from a vessel as an extension of the profiles. Because the vessel cannot reach the water's edge, collecting data between the water's edge to the end of the hydro data has sometimes presented problems. Usually, a person would be required to enter the water to connect the beach profiles and the hydro data. In some environments, this could be dangerous and unhealthy.

The ability to determine the depth of these very shallow areas has recently been added to the SHOALS DPS. In water depths of less than one meter, this has been a difficult task because the surface and bottom returns merge together to form one return dominated by the stronger. In clear, shallow water the bottom return dominates the surface return in the Green APD channel and therefore allows the analyzer to select a shallow "shoreline depth".

The algorithms for topographic elevation and shoreline depth are generally the same and both use the shallow green channel's surface as the primary return. When a pulse is flagged as a land return, the waveform analyzer automatically defaults to the shallow green channel and uses its surface time for the land elevation calculation. The difference between the two algorithms is that the shoreline depth calculation is corrected for a speed of light change at the water surface, whose location is provided by the IR channel. The Raman channel is never used as the provider of the surface because the return time can be biased by bottom energy in very shallow water. Shoreline depths are only used after manual inspection of the data. Manual interpretation must be made on waveforms to be sure that 1) the water is actually shallow enough, and 2) the pulses have the correct shallow water characteristics. The water clarity at the time of survey must also be known. The shoreline depths could be erroneous if used in water that is unclear.

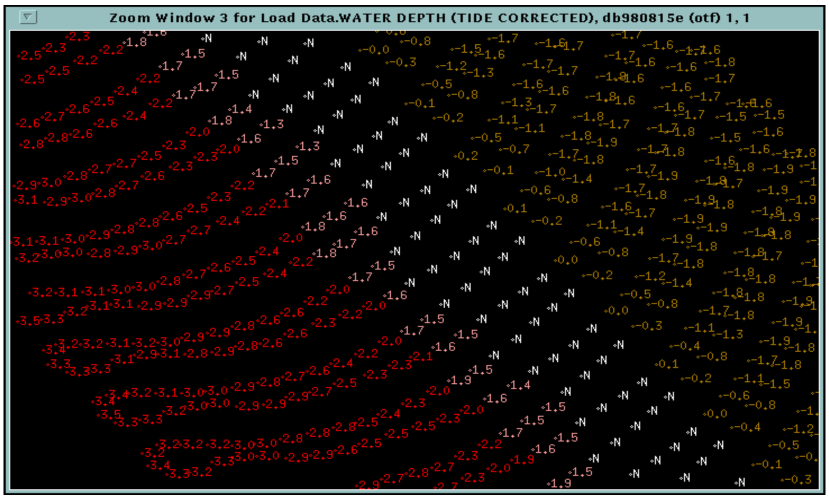

Figure 1 SHOALS Depths without the use of Shoreline Depths

Figure 2 SHOALS Depths with the use of Shoreline Depths

Figures 1 and 2 display a typical Zoom Window from the SHOALS DPS. The tide-corrected elevation of each pulse from a flightline is shown. (down is positive) In Figure 1 an "N" indicates that, because of shallow water, no depth could be determined without the use of the shoreline depth feature. Figure 2 displays the flightline after shoreline depths have been manually approved by the operator. The agreement of the data with the land returns and with the deeper depths is a good indication of the effectiveness of the shoreline depth algorithm.

KINEMATIC POSITIONING

Kinematic GPS (KGPS), using carrier phase techniques, can be used to provide highly precise vertical positions for aircraft with respect to the WGS-84 ellipsoid (Krabill and Martin, 1987). With the technique of on-the-fly (OTF) carrier phase ambiguity resolution, most cycle slips are automatically detected and repaired during processing (Remondi, 1991; Frodge et al., 1994). To ensure the highest possible reliability and accuracy, a procedure has been developed at John E. Chance & Associates, a member of the Fugro group of companies, which utilizes dual baselines to detect and prevent erroneous initializations (Lapucha and Barker, 1996). OTF KGPS is widely used to provide a vertical reference in airborne topographic systems (Reed et al., 1994; Gutelius et al., 1998; Manizade et al., 1996). Typical lidar applications range from powerline (Reed and Lynch, 1996) and vegetation (Blair et al., 1994) surveys to monitoring the level of the Greenland ice sheet (Krabill et al., 1995). OTF KGPS is also used for such things as monitoring sea levels with instrumented buoys (Rocken et al., 1990) and determining the attitude of cargo ships (Huff, 1997) for entry into channels where under-keel clearance is a prime concern.

In most coastal areas, the depth of water means little without a vertical reference. A tidal datum is usually used in these areas for charting and engineering purposes. This generally means that when surveys of the areas are performed the water level must be monitored. During conventional SHOALS surveys, the water level is measured by a survey technician or by a recording gauge. Problems arise when the survey area is very large and the tide changes considerably. Areas of restriction, such as an inlet, where an incoming or outgoing tide creates a build up of water during high flow, can cause tidal reductions to be erroneous.

SHOALS has added the use of OTF KPGS to assist in overcoming water level uncertainty and, additionally, to allow the system to collect elevations strictly over topographic areas without the necessity of a water surface. The use of KGPS allows the airborne platform to be positioned vertically, as well as horizontally, to very high accuracy. In conventional SHOALS surveys, the platform is referenced vertically by measuring the height of the airborne platform above the mean water surface. This is accomplished by using the slant range of each laser pulse to the water surface. When using OTF KGPS, the platform is positioned in three-dimensions so the water surface is not needed as a reference. Tide measurements to reference the water surface to a datum are also not required.

Because of the dynamic nature of the aircraft and the spinning blades around the airborne GPS antenna, the GPS receiver occasionally loses lock on satellites (mainly during aircraft turns). KGPS without OTF ambiguity resolution would be very difficult to use operationally. The ability to re-initialize while moving is critical when working in a dynamic and electronically noisy environment.

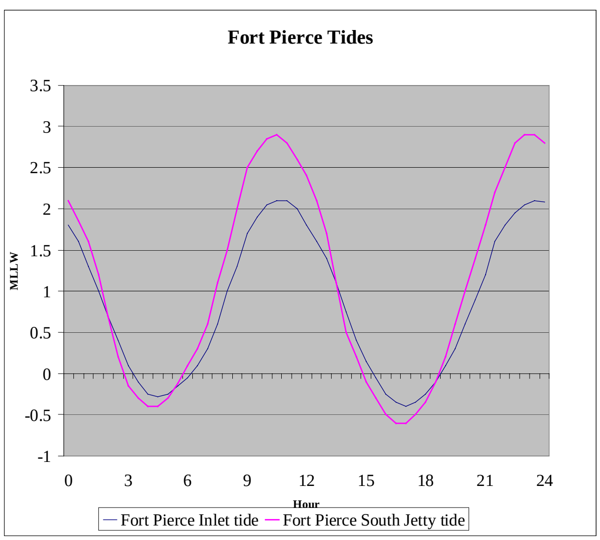

Figure 3 Tidal Plot

An example of how SHOALS, positioned with OTF KGPS relieves water level questions can be seen in Figure 3. The graph in Figure 3 shows the predicted tidal variation between two tidal reference stations at Fort Pierce Inlet, Florida. The two stations are approximately one mile apart. A difference in the peaks and in the tide phase can be noted. Typical surveys of the channel at the inlet generally use only the station in the back of the inlet because of the difficulty in using the South Jetty station. The graph indicates how data collected on the outside portion of the project are adversely affected if the inside measurements are used. Positioning the helicopter in three dimensions without referencing to the mean water level allows the SHOALS system to reduce error caused by inaccurate tide reductions.

HAZARD DETECTION

Airborne lidar bathymetry has become very useful to the world of nautical charting. The speed and efficiency of an airborne platform has allowed the amount of time used by data collection activities to be greatly reduced. One time consuming process, the identification of hazards, still remains.

Unlike most acoustic bathymeters that generally only record enough data to produce one return, airborne lidar bathymeters record the entire raw waveform data to determine bottom elevations in post-flight processing. The recorded waveform data can show more than one return in the water column. These intermediate returns may be a layer of dirty water, fish or more importantly, a hazard that protrudes from the sea floor. Coral heads and reef structures, large rocks, pilings, and sunken vessels are examples of possible hazards.

The automatic identification of hazards in the waveform data requires the analyzer to determine more than one valid return for a particular pulse. In the SHOALS processor, for a return to be considered valid, it must satisfy two requirements: 1) The return must have a sufficient risetime, and 2) the return must have a signal-to-noise ratio greater than a pre-determined minimum. The SHOALS DPS has the ability to automatically select the first, strongest or last return for any individual shot.

The three return modes all are very useful, and each has a specific function. When performing nautical charting surveys, first pulse mode is always used. This mode provides the highest probability that the operator will identify a hazard. Strongest pulse mode is typically used when the engineering surveys are being conducted. Last pulse mode is used when obstructions are not of concern and the survey area contains large schools of fish or large areas of dirty water. Generally, last pulse mode is only used during the manual reprocessing of data once the operator has determined that no harmful effects on the quality of data will be induced.

Locating hazards to navigation and finding the least depth on obstructions are the primary reasons behind nautical charting. Uncharted or incorrectly charted hazards can cause much damage to vessels. Because there are far too much data to view manually, special procedures have been designed to automatically find possible hazards. To ensure that no hazard is overlooked, a qualified operator must inspect each pulse flagged as a possible hazard. A decision must be made concerning the bottom return of each such pulse and a status indicator must be set.

The automatic hazard detector flags each pulse that contains two valid bottom returns. The operator must examine each return individually to determine if the pulse located an actual hazard. One of three actions must be taken regarding each pulse's status. First, the pulse may be "kept". In this case, the operator decides that the first pulse is the shallowest point of some object rising above the seafloor. If the first depth is not kept, it may be "swapped". Here, the operator may decide that the first return has come from a school of fish or some other floating object. If for some reason neither return is judged valid, the pulse may be "killed". Occurrences of this case are rare, but system noises, trees hanging over inlets, birds and dirty water have been identified as needs for this option.

Operators are trained on the analysis of waveforms so that correct interpretations can be made. Occasionally, however, because of the complexity of the return, the operator may not be able to reach a conclusion about the validity of a first return. In this case, the first return is "kept", and the area must be re-flown or investigated with a different survey system, such as side-scan sonar. Based on the results of the re-survey, the status of the pulse may be changed. This does occur when fish are very near the bottom or a thick layer of sediment rises above the seafloor.

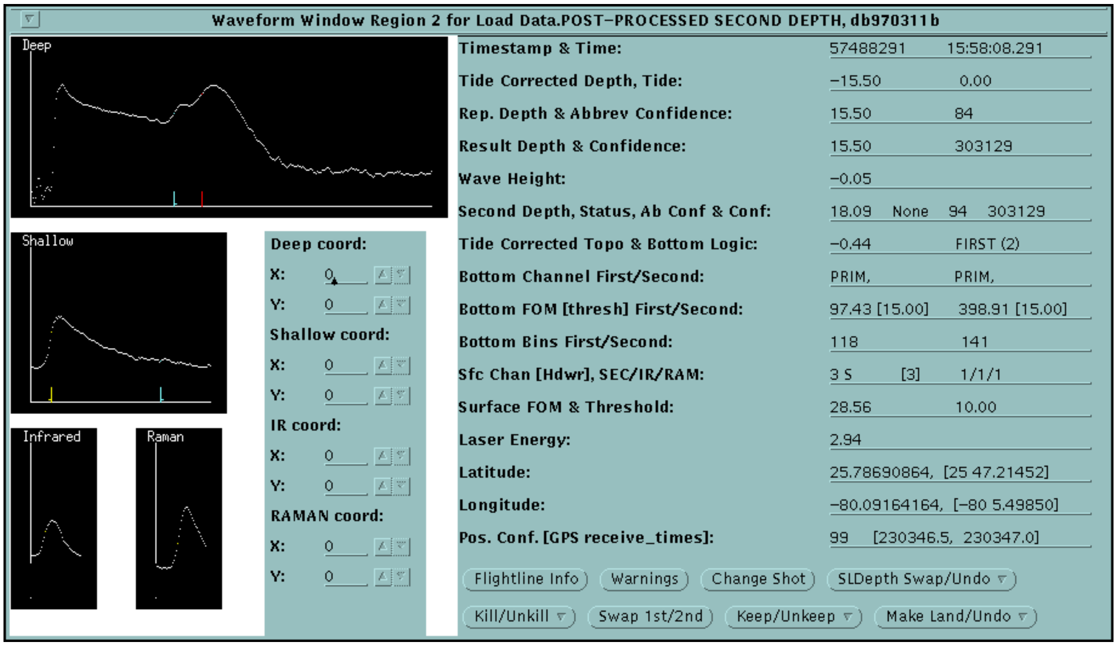

Figure 4 Waveform Window displaying a twin-return pulse

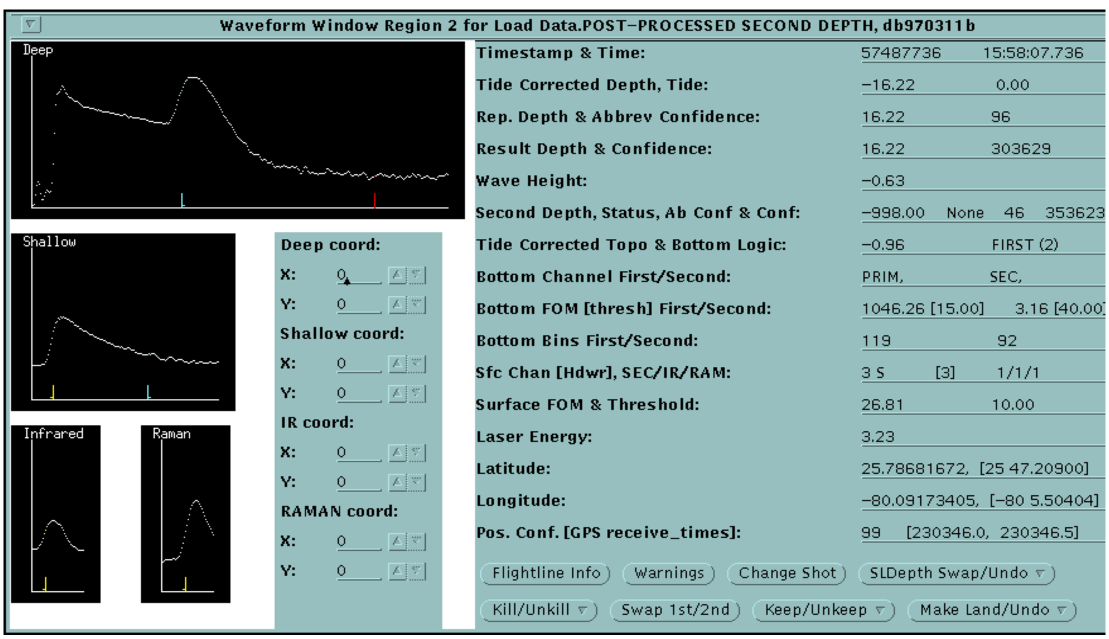

Figure 5 Waveform Window displaying a one-return pulse

Figures 4 and 5 show typical SHOALS waveform windows. Figure 4 is a pulse containing a double bottom return. In the window are the waveforms for the deep and shallow green channels and also the IR and Raman surface channels. The deep, green channel shows that a first return was found in 15.50 meters of water. The second and actual seafloor bottom return was found at 18.09 meters. The hazard detection program flagged this pulse. The word "None" on the sixth line on the right side of the window indicates that a decision has not been made concerning the status of the pulse. Figure 3b represents a more common pulse with only one bottom return. The "-998" on the sixth line represents no second depth was found.

If a hazard is so large that a significant fraction of the pulse does not hit the actual seafloor, the correct depth is reported, but the automatic hazard detector will not indicate its presence, per se. The problem is that occasional noise detections (false alarms) also fall into this category. For this case, an algorithm has been developed that locates pulses based on a change in elevation with respect to neighboring pulses and a change in the modeled bottom slope. This program must be run outside the SHOALS DPS, which at the current time has no digital terrain modeling capabilities, and in conjunction with an off-the-shelf terrain modeling package. If a pulse is identified as being outside the acceptable range of elevation change, that point is flagged. The point is then found in the DPS and a decision concerning the validity of the pulse is made. Obviously, this is not the most efficient method of locating and then analyzing suspect hazards. Methods for identifying hazards and false alarms with only one valid bottom return are currently being investigated for use in the DPS.

SHOALS UPGRADE

The SHOALS system is currently being upgraded for the purpose of more efficient data collection and processing activities. The upgrade includes replacing the current 200-Hz flashlamp-pumped Nd:YAG laser with a 400-Hz diode-pumped laser and the addition of a constant-temperature thermo-electric chiller. The upgrade will allow the platform to fly at twice the speed or twice the altitude without a loss of data density. The ability to fly faster permits the system to move to a fixed-wing aircraft. The benefits of flying on a fixed-wing aircraft are that the system can be utilized in more remote areas and more time can be spent on station.

The SHOALS DPS is also being upgraded. This upgrade includes faster tape drives used for data stripping, and a faster automated processor that does not use a database for information storage. The current system utilizes a database to store information for querying purposes. The database provides easy access to large volumes of information during testing and problem solving activities. During operational scenarios, however, the database is hardly needed, and the time used by the automated processor interfacing with the database is better spent during manual processing. Relieving the processor of the input/output time with the database reduces the automated time by nearly three times. The database capability becomes optional, as it will be retained for testing and quality control purposes.

CONCLUSIONS

A continuing effort is being made to improve airborne lidar bathymetry systems. Recent advancements to the SHOALS system permit the system to be used for a greater number of applications. The ability to collect data through the land-water interface is of great benefit. The use of OTF KGPS allows the system to collect hydrographic and topographic data without the need for a mean water surface and concurrent water level data as a reference for that surface. The automated hazard detector has helped increase the effectiveness of charting with a lidar bathymeter. Future advancements will increase the productivity and cost-effectiveness of the SHOALS system.

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