Two Years of Operating the SHOALS Airborne Hydrographic Survey System

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Abstract

The Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) system h~ completed over 50 project surveys for the US Army Corps of Engineers, National Ocean Service, and Navy. This amounts to over 1,500 km2 surveyed and 200 million soundings. Projects have ranged from ports and harbors to beach nourishment and shoreline condition surveys to nautical charting data collection. Through two years of operation and over 50 projects, much has been learned about the technology and system. System improvements have included faster data processing times and survey product turn-around, to new processing techniques to extract above-water elevations along beaches and navigation structures. SHOALS full bottom coverage has produced dramatic information and insight into many Corps' project conditions. This paper presents the SHOALS system, and summarizes several interesting project surveys.

Introduction

The Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) system has been in operation for over two years. The system has proven itself very versatile and capable of producing fast, accurate, and cost effective hydrographic surveys. The transition from developmental to operational has been an exciting journey, with many accomplishments. The system and technology have much to offer the hydrographic suryey community, if the tool is used properly. This paper describes the SHOALS system and describes four projects that illustrate airborne lidar capabilities.

Shoals System and Operation

The SHOALS system is based on light detection and ranging (lidar) technology and principles described by Guenther 1985. SHOALS consists of an airborne data collection system and a ground-based, mobile data processing center.

Airborne System. The SHOALS airborne system conducts all the hydrographic data collection and-is composed of three subsystems: 1) acquisition, control and display (ACDS), 2) transceiver (TRS), and 3) positioning and auxiliary sensors (APASS).

The ACDS is the primary subsystem through which all data are collected and recorded, system integrity and self-checks conducted, and operator monitoring of key real-time system and survey information. All airborne data are recorded on Exabyte TM 8 mm dual tape drives at a rate of approximately 300 Kbytes per second, which is the only link between the airborne data collection system and the data processing system. The tape also provides the ability to load survey flight information for each survey mission into the airborne system prior to each flight.

The hydrographer's interface with the system is through the ACDS. Real-time information is provided so that the operator can accomplish two tasks, first as the surveyor to ensure that the planned mission is successfully implemented and completed and accurate data collected and second, as the lidar system operator to monitor system status during the mission to ensure that the system operates within expected parameters, The ACDS also provides survey navigation information to the pilot, such as the required altitude, speed, and position along a selected survey line, necessary to conduct the planned mission and produce the desired sounding density, The second airborne subsystem is the transceiver, which is mounted in a pod beneath the helicopter. The main component is the laser, a Nd:YAG laser that operates at 200 Hz. There are five receiver channels, three for detecting the water surface and two for detecting the sea bottom. Included in the pod is a gyrostabilized scanner, which directs each laser pulse to a predetermined location on the sea surface. An inertial reference system, also mounted in the pod, provides aircraft attitude information allowing the scanner to compensate for aircraft motion and measure accelerations necessary to accurately resolve the sea surface location during post-flight data processing. The width of the scan is nominally equal to half the altitude of the helicopter. At a speed of 30 m/s (60 knots) and altitude of 200 m, this yields a uniform sounding spacing of approximately 4 m x 4 m at the sea surface.

Aircraft positioning and auxiliary sensors (APASS) consists of differential GPS and a video camera bore sighted in the pod to record an image of the area being scanned by the laser. Differential GPS is used for horizontal positioning of the aircraft and the differential correction is available through three sources; although only one is typically required during a survey mission. The original and least-used source for differential correction is from a stationary receiver positioned over a known geodetic location and linked to the airborne receiver via a radio link. This approach is seldom used because it requires setting up and monitoring a stationary receiver in the vicinity of each survey project. The other two methods do not require any pre-survey deployment of equipment and personnel or the need to monitor and protect them from theft during the survey flight. One is the US Coast Guard (USCG) differential beacon network that has been constructed around the coast of the United States. The service is accessed by radio receiver and is operated by the USCG 24 hours per day. The last source and the most used is the John E. Chance and Associates ST ARFIXTM system. Differential corrections are based on a wide area network and corrections are down linked through a satellite antenna mounted on the tail of the helicopter. All three sources produce 2 - 3 m horizontal accuracy.

Data Processing System. Data processing performs four functions; 1) down load data from the airborne tape and prepare it for processing, 2) automated data processing to produce a depth and position for each laser shot, 3) data evaluation using specially developed tools and software, and 4) final product generation. Following airborne data collection, the data are transferred from the helicopter to the data processing system via the 8 mm magnetic tape.

The first function down loads the raw airborne data and places them in an InformixTM database. The second function utilizes a state-of-the-art algorithm to calculate a depth from each raw lidar return. The algorithm was developed by the National Oceanic and Atmospheric Administration National Ocean Services (NOAA/NOS) (Guenther and Thomas 1981; Guenther and Thomas 1983). The third function allows the hydrographer to evaluate depths and ancillary data using several tools specially designed for SHOALS data; from review of the entire survey area to evaluating an individual sounding. The fourth and final function in the data processing system and in conducting a SHOALS survey, is to produce the final products.

Products have varied as much as the missions themselves. Most of what has been produced can be divided into two categories: 1) display of depth data, which includes two- and three-dimensional plots of data; and 2) analysis/engineering using depth data, which requires calculations and use of the data beyond just collection and display. The most often produced products are two-dimensional plots of depth contours or sounding numbers, with land masses located on the plot and any other pertinent information like navigation channel location or navigation aids. The most often produced analyses is calculation of a shoal volume in a channel or beach nourishment volume based on a specified design template. All products are typically produced in the mobile trailer.

Because the helicopter moves rapidly from project to project, so too must the data processing facility. Following each flight, the data must be stripped and checked to ensure that the mission has been successfully completed before moving to the next project. A truck with a 15 m trailer provides the mobility for the data processing facility. The trailer has been modified with a generator for electricity and air conditioning system to keep computers and personnel functioning. Cellular phone and fax provide a complete mobile office facility where all data processing and final products can be produced. The trailer also provides ample space for spare parts for the helicopter and SHOALS system. Table I summarizes SHOALS capability.

Table 1

SHOALS Performance	
Maximum depth	40m
Minimum depth	>1 m
Vertical accuracy	± 15 cm
Horizontal accuracy	± 3 m
Sounding density	4 m x 4 m (nominal)
Survey speed	30 m/s (nominal)
Data processing	>1:1

Operation of the SHOALS System. SHOALS is government owned and contractor operated. This approach was selected for two reasons: 1) to achieve the development program's long term goal of facilitating private sector interest in the technology required involving the private sector from the beginning and 2) to maximize operational flexibility necessary to implement a national (and international) annual survey program. SHOALS requires a national survey plan to produce enough work for the system to operate approximately 11 months per year.

The Corps provides overall management of the system including operation, maintenance, and system evolution required to pursue the program's long-term goals. John E. Chance and Associates (JECA), of Lafayette, LA, was selected to operate and maintain SHOALS for a 5-year contract period. JECA was chosen because of their established reputation in hydrographic surveying, extensive experience in satellite positioning systems, and they employed the necessary personnel to operate and maintain the state-of-the-art SHOALS system. In addition to technical accomplishments, JECA is a member of Fugro, an international geophysical company conducting world-wide operations. The SHOALS system is flown on a Bell 212 helicopter provided by the NOAA Aircraft Operations Center (AOC), MacDill Air Force Base, FL. They became involved mid-way through the development and provided all the engineering design and fabrication necessary to mount SHOALS in the helicopter. Today, NOAA/AOC provides all flight support including aircraft, pilots, maintenance, and design changes when necessary. The depth extraction algorithm that produces accurate water depths from each laser return was developed by the NOAA/NOS and they continue to improve and enhance it. Optech Inc., the manufacturer of SHOALS, remain involved in operations by providing some maintenance and repair and continued system evolution.

Daily operations involve a crew of nine; two pilots, an aircraft mechanic, two airborne hydrographers, two data processors, the truck driver/tide gage reader, and the SHOALS project manager from JECA. Figure 1 shows the survey system and mobile facility. Prior to deployment a regional plan is developed that identifies projects to survey and then it is executed based on conditions experienced during the mission period. The SHOALS project manager typically inspects the survey project to determine whether to conduct a flight. If the water appears sufficiently clear, the aircraft is deployed and the survey conducted. If conditions do not warrant attempting a survey that day, the project manager must then decide whether to attempt another project in the region or wait until the next day to fly the current project. Decisions are made daily and quickly implemented. A mobile system and well planned survey mission is the key to operating SHOALS and producing economical surveys.

Figure 1 The SHOALS System

If weather and water clarity conditions permit, three flights are flown daily, each lasting about 2 - 2.5 hours. The flight originates from an airport close to the project and typically in the US an airport can be located within 15 minutes of a survey project. This allows about two hours on station, surveying. The percent of time the system is on station surveying verses total mission flight time depends on the type of project. Small tidal inlet surveys covering only a few square kilometers can require more time changing survey lines and repositioning the aircraft between lines than actually spent surveying (although the SHOALS pilots require only 30 -60 seconds to reposition the aircraft). Conversely, beach surveys tens of kilometers in length result in high survey efficiency with only a few survey line changes per survey flight. Typically, 500k -750k soundings are collected each flight.

Between each flight and while the helicopter: is being refueled, the hydrographers carry the data and video tapes to the data processing facility, usually located at the airport. During the next flight the data tape will be stripped and depths processed. Usually, by the end of a survey day the data have been stripped from the data tape and reviewed for completeness. In the afternoon following the three flights, the airborne operators plan the next day's missions and create survey flight plan tapes.

Completed Project.

The SHOALS system was designed specifically for surveying US Army Corps of Engineer navigation channels to locate Shoal areas that require dredging, and to accurately quantify their volumes. The Corps operates and maintains hundreds of navigation projects throughout the United States-and prior to development, it was estimated that an airborne lidar system should be able to survey approximately 25 percent of these navigation projects, based on water clarity conditions. Since development, SHOALS has proven itself capable of surveying other project types, such as beach nourishment and shoreline condition surveys, emergency storm response, and nautical charting. With new system and data processing enhancements, SHOALS has extended its survey capabilities and mission scenarios. This section summarizes surveys to date and describes four projects that help to illustrate the SHOALS system's current capabilities.

Summary of Projects

The SHOALS system was accepted from its developer, Optech Inc., in March 1994. Immediately following, the system was deployed to Florida Bay to conduct a pilot study for the National Oceanic and Atmospheric Administration National Ocean Service (Parson et. al. in press). The purpose of the survey was to collect shallow water bathymetry (1-2 m depths) in Florida Bay for use in a numerical circulation model. The survey produced very high resolution depth data over the area of interest, successfully demonstrating an application of the system it was not specifically designed for. From this point on in the system's first two years, it was clear that many other survey uses would be found for the SHOALS system.

Table 2 summarizes surveys, conducted as of July 1996, ~y project type and cumulative area. They include surveys on five water bodies, the Atlantic, Pacific, Great Lakes, Gulf of Mexico, and Caribbean Sea, producing over 200 million soundings covering over 1,500 km^2, an area about the size of the state of Rhode Island.

Table 2

Project Type	**Area (km^2)**
Navigation Channels	345
Beach and Shoreline	290
Emergency Response	58
Nautical Charting	845
Other[1]	65

[1] including scientific research, sensor evaluations, and target detection

Project Examples

Navigation Channels. The first Corps project surveyed by SHOALS was a navigation channel at New Pass, in Sarasota, surveyed during field tests in February 1994. Results of the survey were stunning, yielding very detailed information about the navigation channel as well as information about the sedimentation mechanisms at the pass. Over 250,000 soundings were collected in approximately 1 hour over 4 km^2.

Figure 2 shows New Pass and figure 3 shows a three dimensional view of the survey data, from the perspective of looking from the Gulf of Mexico back towards the pass. This survey presents two important capabilities of SHOALS. First, the very high-density data (3 m x 3 m density) provides complete bottom coverage of the 4 km^2 area. yielding a detailed view of the puss' condition. Note that along the seaward edge of the ebb shoal, abrupt changes in the contours are visible. These were caused by a dustpan dredge that removed sand from the shoal for placement (beach renourishment) on the adjacent shoreline.

The second feature of interest is that much of the surveyed area has a depth of two meters or less. The ebb shoal north of the navigation channel is less than two meters deep, yet SHOALS was able to survey this area as densely (3 m x 3 m) as the deeper regions. Unlike acoustic multibeam systems, SHOALS survey width is not dependent on water depth. This feature of airborne lidar systems produces detailed measurement of shallow shoal features, necessary to accurately determine sediment movement in and around navigation channels. Irish and Lillycrop, in press, present a sediment budget for the pass and channel based on this first survey and two additional SHOALS surveys completed during the nine months following this first survey.

Beach and Shoreline. The purpose of the St. Joseph survey was to conduct beach and shoreline monitoring. St. Joseph is located along the southern shore of Lake Michigan and nas been-:r-Corps of Engineers beach nourishment project since 1976. In 1903 two jetties were constructed to stabilize the St Joseph River entrance into the lake. These jetties have intelTUpted the natural southerly longshore sediment transport of approximately 84,000 m3 per year and as a consequence, the downdrift beach has experienced erosion and the lake bed has suffered from down cutting (Parson and Smith, 1995).

Figure 2 New Pass, Florida

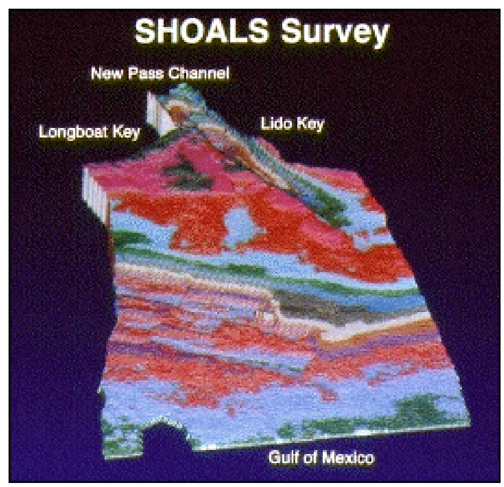

Figure 3 New Pass Survey

The eroding shoreline of St. Joseph consists of high bluffs, while the nearshore is characterized with a thin layer of unconsolidated sand and gravel overlying consolidated clay. Approximately 3 km south of the jetties a rubble revetment was constructed to protect the upland roadway and railroad. Since 1976, dredged material from maintenance dredging of the St. Joseph Harbor has been placed annually south of the entrance to act as a feeder beach, replenishing 6 km of shoreline to the south. By 1992, over 1.1 million m^3 sand had been placed along 850 m of shoreline.

In August 1995, SHOALS completed a high density survey of nearly 5 km^2 including the St. Joseph River entrance and adjacent shoreline, producing over a half million soundings. The survey took just over one hour to complete. The project has historically been surveyed with conventional techniques, including shore-normal profiles -that indicted shore-parallel depth contours throughout the project area. The SHOALS survey revealed the nearshore bathymetry is much more complete, figure 4. This difference in survey results translates into significant differences in engineering calculations and nearshore monitoring evaluations. Using the conventional beach profile surveys to estimate a design beach nourishment volume verses the SHOALS survey, a volume difference of 2.7 million m^3, which is substantial when a cubic meter of sand costs approximately $US 8.

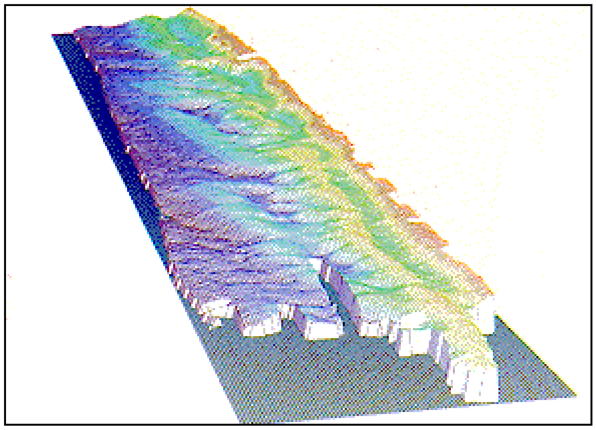

Figure 4 St Joseph Nearshore Bathymetry

Emergency Response. Hurricane Opal, a Category III storm, struck the panhandle of Florida on October 4, 1995. The minimum barometric pressure was 916 mb and the maximum recorded wind speed was 67 m/s, which created a 4.45 m storm surge. East Pass is also located on the panhandle, near where the hurricane's eye made landfall. The Pass is a Corps of Engineers navigation project that includes a channel dredged to a depth of 3.7 m and two jetties that stabilize the Pass and channel. When the storm struck, SHOALS was operating in Massachusetts, approximately 2,400 km northeast of East Pass. On the Sunday following the storm, SHOALS flew to the East Pass area, arriving on Monday. The first post-storm survey was of East Pass, which took approximately 1 hour to collect 300,000 soundings over a 2.5 km^2 area. The airborne system landed at 1700, and by 2300 that evening the lidar data were processed, mapped, and needed channel dredging volumes calculated. At the request of the Mobile District, the SHOALS data were also analyzed to evaluate the condition of the west jetty. Over 7,000 depth/elevation measurements struck the jetty as the system conducted the navigation channel survey. These superfluous data provided detailed information on the structure's condition. Through new data processing techniques, it is possible to extract from the SHOALS returns an above-water elevation when the water surface is located adjacent to the area of interest. This capability resulted in being able to accurately assess the condition of the jetty with data collected to assess the condition of the navigation channel.

Nautical Charting. This project was conducted off the northeast coast of the Yucatan Peninsula, and staged from Cancun, Mexico. The purpose of the survey mission was to produce accurate water depths and positions to upgrade existing published nautical charts and develop new charts to ensure safe navigation. The area included 800 km^2, which required 56 survey days and 329 flight hours to produce 120 million soundings. This survey was quite different from all previous SHOALS missions because it was conducted out of the United States, included an area equal in size to the cumulative total of all other surveys to date, and was primarily to locate navigation hazards and measure shoal depths in addition to the general bathymetry. Sounding density and the ability to resolve small objects in the lidar return signals became critical factors in implementation of the survey because of the numerous coral reefs in the area. It was important to locate any small features to ensure safe navigation.

To successfully conduct this mission, standard SHOALS data processing and depth extraction techniques were modified to extract shoal depths utilizing a system feature that locates depth based on first pulse logic, rather than strongest signal to noise ratio. This logic ensures that the tops of features or objects suspended off the sea bottom are identified as the shoal depth and then it is up to the hydrographer to determine if the object is a solid bottom feature or a transient school of fish. This determination was accomplished by reviewing the video tape and adjacent soundings. When no positive determination was possible, the area was resurveyed for verification.

Future efforts

SHOALS has exceeded its initial expectations regarding accuracy, products, cost of operation, and potential role in the Corps of Engineer's survey mission. However, new missions and challenges will continue to drive the system's evolution. Several of these are described below.

Kinematic Positioning. Key to any complete beach and nearshore survey is acquiring both the hydrographic and topographic data. Prior to SHOALS, this was accomplished with beach surveys out to a wading depth, where the survey launch would then extend the survey to the required water depth. Data density was the same along the topographic and bathymetric sections of each profile. However, profiles are typically spaced along the beach at 75 - 300 m intervals. SHOALS produces high-density data over the entire project, both in the on/offshore direction as well as the alongshore direction. Conventional topographic beach/wading depth surveys do not produce the same level of information to match with this high-density bathymetric data. Therefore, to improve beach and nearshore surveys, SHOALS is adding kinematic positioning of the helicopter in order to survey the topographic portion of the beach. This feature has application to offshore surveying as well by providing a depth elevation independent of tide measurements. By accurate vertical positioning of the helicopter with kinematic GPS, depth measurements can be determined based on the GPS ellipsoid.

Airborne Lidar Bathymetry Technical Center of Expertise. SHOALS has completed its development and is now a fully operational hydrographic survey system. The Corps will operate the SHOALS system and continue the development program's long term objective, the commercialization of airborne lidar bathymetry, through the establishment of an Airborne Lidar Bathymetry Technical Center of Expertise. The Center will continue to carry out the goals of the Program and evolution of the system and technology, with the objective of solidifying a broad customer base over the next 4-5 years. The Program will culminate with the transfer of the Corps's airborne lidar bathymetry system, SHOALS, either to a private enterprise or to a government/private cooperative venture. Following that transfer, the Center would continue to provide functions such as survey program -development and management and value-added product development and application.

The Center will be a joint operation between the US Army Engineer Waterways Experiment Station and the US Army Engineer District, Mobile, and located in Mobile, Alabama. The Center will concentrate on three primary activities: 1) conducting a national and international hydrographic survey program, operating the SHOALS system on projects similar to those described in the previous section; 2) developing new markets and applications, including non-government customers, both national and international, and 3) identifying and operating complementary sensors, such as multi- and hyperspectral passive imagers to identify and classify sea bottorn type. This concept was discussed by Lillycrop and Estep, 1995. Through sensor fusion, complementary data sets can be combined to produce more accurate and extensive information than either sensor could alone.

Summary

Lidar technology and the SHOALS system are new, exciting, and complex additions to the operational hydrographic survey community. The first two years of operating the SHOALS system has been very challenging and rewarding. The system has yielded surveys that surpassed expectations, producing hydrographic survey products for a range of project types. Surveys have included navigation channels, beach and nearshore evaluations, emergency post-storm damage assessments, and nautical charting. Based on these early results, SHOALS has the potential to evolve well beyond original expectations and extend its survey capabilities. Additions such as kinematic GPS, will aid the evolution of the system and survey missions. Finally, with a permanent operational Center, the Corps is ensuring that airborne lidar surveying will become a standard approach to hydrographic surveying.

Acknowledgements

The success and results of the SHOALS Program are due directly to its Team of dedicated professionals too numerous to name individually. Development of the SHOALS Program was sponsored by Headquarters, US Army Corps of Engineers, Operations, Construction, and Readiness Division and the Department of Industry, Science, and Technology, Canada. Operation of the SHOALS system has included Headquarters, US Army Corps of Engineers, Operations, Construction, and Readiness Division, many Corps Districts, NOAA National Ocean Service, US Navy and the Directorate of Naval Oceanography, Mexico. Permission to publish was granted by the Chief of Engineers.

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