USE OF AN AIRBORNE LASER DEPTH SOUNDING SYSTEM IN A COMPLEX SHALLOW-WATER ENVIRONMENT

R. W. Pope, B. A. Reed and Lt. Cdr. G. R. West, RN, Naval Oceanographic Office
W. J. Lillycrop, U.S. Army Engineer Waterways Experiment Station

Abstract

Between January and April 1996, the Naval Oceanographic Office contracted the U.S. Army Corps of Engineers' Scanning Hydrographic Operational Airborne LIDAR Survey (SHOALS) System to carry out a survey on the east coast of the Yucatan Peninsula, Mexico. The survey area consisted of approximately 1000 km^2 with a complex seabed of depths ranging from 0 - 40 meters.

Introduction

Since the mid-70's the Naval Oceanographic Office (NAVOCEANO) has been involved in a number of Airborne Laser Hydrography (ALH) initiatives, but following the end of the Hydrographic Airborne Laser Sounder (HALS) project in 1982, NAVOCEANO has largely followed developments in this field from afar. However, since several systems have now reached maturity and gone operational, it has become clear that ALH has proven its worth as a survey tool for hydrographic nautical charting surveys. Accordingly, a process to procure a system to be called the Laser Airborne Bathymetry Survey (LABS) system has been initiated and will result in delivery to NAVOCEANO in 1999. This procurement is intended to take advantage of existing off-the-shelf technology, rather than be a totally new system. The advantages of this approach are clear, but it was quickly realized that this could be maximized only if advantage could also be taken of existing operational experience. Since an ALH is already operated by another U.S. government department, a survey was proposed employing their system to gain operational experience in addition to satisfying NAVOCEANO survey requirements. The survey was conducted on the east coast of the Yucatan Peninsula, Mexico, extending from the shoreline adjacent to the city of Cancun to 12 miles offshore (Figure 1), between 18 January and 16 April 1996. During this time approximately 780 km^2 with a complex seabed of depths in the range of 0 - 40 meters were comprehensively surveyed at a cost of $1.5 million; this equates to less than $2000 per km^2.

Figure 1 Map of Survey Area

The SHOALS System

The SHOALS system, seen in Figure 2, is owned by the U.S. Army Corps of Engineers (USACE) and operated by John E. Chance & Associates (JECA). National Oceanic and Atmospheric Administration (NOAA) Aircraft Operations Center (AOC) provides all flight support including the Bell 212 helicopter, pilots, and maintenance. SHOALS is one of five operational light detection and ranging (LIDAR) survey systems, the other systems being the Laser Airborne Depth Sounder - LADS (Australia), Larsen 500 (Canada), and two HAWKEYE systems (Sweden). The SHOALS system operates on the principle that water depth may be calculated from the difference of time measurements of laser energy which is reflected by the sea surface, and energy which penetrates the water column before being reflected by the seabed. The maximum depth measurable by a system is heavily dependent on water turbidity and bottom reflectivity, but can vary considerably from just a few meters in very turbid water to several tens of meters in very clear water. SHOALS has a maximum operating depth of approximately 40 meters in optimum conditions.

Figure 2 SHOALS helicopter with external pod-mounted laser system

Selection of the Survey Area

The primary factors in selecting a survey area were timing, availability of the system, and NAVOCEANO survey requirements. Since the SHOALS system is heavily committed to Continental United States (CONUS) tasks for most of the year, the window of availability to NAVOCEANO was limited to the winter months, when water clarity in CONUS is less desirable for ALH system surveys. Given the fact that environmental drivers are the principal factors affecting the

performance of any ALH system, a location where the climatology indicated favorable water clarity during this window of opportunity had to be found. The second requirement, that of selecting an area close to CONUS, thus came into consideration in focusing on a region.
This requirement was a result of several concerns:

a. One of the primary purposes of the survey was to give a large number of NAVOCEANO personnel ALH system operating experience. It was therefore important to facilitate easy rotation of personnel from NAVOCEANO through the project in order to allow the maximum possible exposure of personnel to the LIDAR field operations.

b. Since the system was not originally intended to operate outside CONUS, there was not a proven spares and logistics plan to support it overseas. Easy air access to CONUS for spares and technical support was therefore desirable.

c. The cost of transporting the helicopter by air cargo to a remote location would be substantial and would significantly impinge on the funds available for survey operations.

For these reasons, it was clear that a survey area in the Central Americas or the Caribbean would be preferable. The next step was to examine climatologies in this region in order to establish a short list. The two main environmental considerations were incidence of strong winds, which could make line-keeping for the helicopter difficult, and turbidity, which is the limiting factor for water penetration by the laser. Information on the former was readily available from a variety of standard meteorological sources; turbidity data of the required resolution is much less readily available. Studies soon focused attention on a number of NAVOCEANO survey requirement sites on the Yucatan Peninsula. These sites were then further narrowed down to the Cancun area as the logical choice. Selection of this site had the benefit of long-standing good relations with the Mexican Navy’s Oceanographic Directorate through the Hydrographic Cooperative Program (HYCOOP); indeed, two Mexican Navy Officers were attached to the survey throughout its duration.

<u>System Mobilization</u>

Mobilizing for the Yucatan mission included preparing the helicopter and the SHOALS system. The NOAA AOC uses two Bell 212 helicopters to support SHOALS operations, switching aircraft after approximately 300 engine hours to perform maintenance. Prior to the Yucatan survey, the NOAA AOC helicopter was switched out so the mission could began with a newly serviced helicopter. An auxiliary fuel tank was added to extend the flight range of the aircraft to about 3.5 hours for transiting from Tampa, Florida, to Cancun, Mexico. Spares to sustain the expected 250 hours of survey flights were identified and packed for shipment.

The SHOALS system concluded its scheduled USACE surveys in early December 1995 and was demobilized from the aircraft and transported to Lafayette, Louisiana, for scheduled maintenance prior to deployment to Mexico. In late December, the SHOALS system, spares, maintenance equipment, and supplies were shipped with the helicopter spares and maintenance equipment to

Cancun. In January, the helicopter made the five-day transit from Tampa to Cancun by circumnavigating the Gulf of Mexico with two pilots and one mechanic onboard. The SHOALS operators flew commercial air to Cancun one week before the helicopter arrived. They set up the processing office and prepared to initiate the survey flights.

During the first week, the office was established with support and data processing equipment. Three SHOALS processing stations were set up with printers and plotters. Each of the three stations included a SUN Sparc workstation running the SHOALS depth extraction program and a Hewlett-Packard workstation running TerraModel, a commercial CAD software package used for mapping survey data. In addition to establishing the office, two tide gages were installed, one at Punta Cancun, located in the hotel zone and directly exposed to the Caribbean Sea. The other gage was located on west side of Isla Mujeras, approximately 20 kilometers offshore. A satellite-based, commercial Differential Global Positioning System (DGPS) service, Starfix, was provided by JECA and used throughout the survey. A repeater station for the satellite correctors was set up on the roof of the office building to enhance reception.

Once the helicopter arrived, the auxiliary fuel tank was removed, and the SHOALS system installed. This involved mounting the external pod and the internal equipment racks. The aircraft installation required approximately 1.5 days followed by one day of shakedown flights.

Survey Operations

Survey operations were split between the aircraft operations at the Cancun International Airport and the processing office located in rented office space in the business district of Cancun. Eighty days were spent onsite, excluding a one-week shutdown due to a mechanical failure of the laser system about halfway through the survey; Figure 3 shows the percentage time by survey activity. Of the total time spent, only 8 days (10%) were lost through bad weather, which was primarily sustained

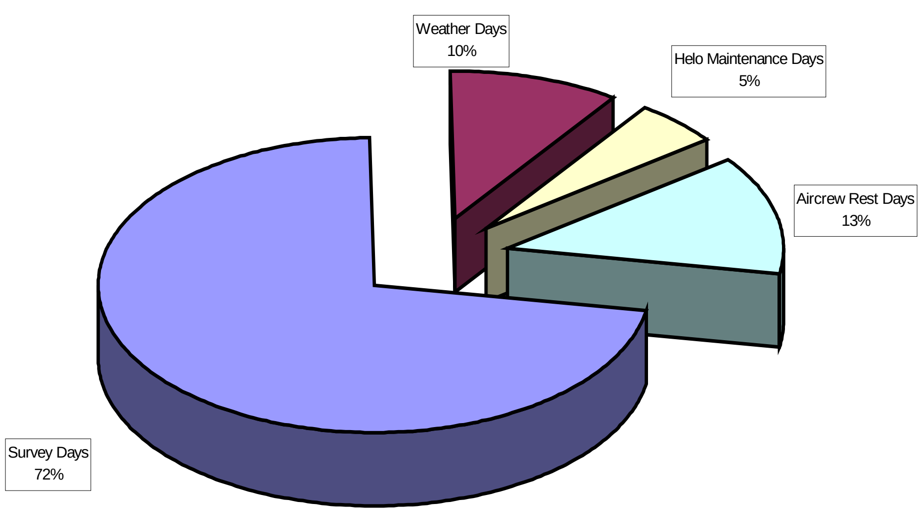

Figure 3 Survey Activity by Days (Total 80)

strong winds, while all other non-survey days were occupied with planned maintenance of the helicopter and air crew rest days. On each of the remaining 58 days (72.5%), three flights typically were flown, each lasting about two hours and covering approximately 9 km^2. These flights were usually flown "back-to-back" as early in the day as possible to take advantage of optimum wind and wave conditions before on-shore winds increased in the afternoon. Due to Mexican air-traffic control requirements, no flying was permitted between dusk and dawn. Table 1 shows the flight parameters used by the SHOALS aircraft during this survey.

Altitude	200 m
Speed	60 kts
Line Spacing	110 m
Sounding Density	4 m x 4 m

Table 1 Nominal Flight Parameters

Each flight was conducted with two pilots, one SHOALS operator, and one NAVOCEANO or Mexican Navy hydrographer. The average number and types of personnel deployed to Cancun at one time are shown in Table 2.

SHOALS	
Pilots	2
Helo Mechanic	1
SHOALS Operators	2
Data Processors	2
Project Manager	1
NAVO	
Senior NAVOCEANO Rep.	1
Observers/Processors	3
Mexican Navy	
Hydrographers	2

Table 2 Breakdown of average personnel onsite during survey operations.

Main development lines were flown on an east-west orientation in order to coincide with prevailing wind direction; this also enabled a logical progression of completed work from south to north across the whole width of the area. This resulted in a 15-nmi average survey line length requiring 15 minutes to complete at the nominal survey ground speed of 60 knots. While a north-south orientation would have better minimized time in turns, it would have resulted in more piecemeal survey progress (with consequent data management problems) as well as increased vulnerability to crosswinds, making line keeping difficult. The chosen line plan proved to be a reasonable compromise, as evidenced by the small number of days lost to weather and the achievement of the target survey area coverage. However, it did have the effect of increasing the amount of time spent on transit as the survey progressed toward the northern survey limit away from the airport.

Notwithstanding the above, Figure 4 shows that the main impediments to maximizing survey results from the total of 133 flights undertaken were the loss of DGPS signal (11%), line-keeping holidays (11%), and re-flys for outlier investigations (6%). The loss of DGPS, although individually short in duration, had a disproportionate affect on re-flies, as they were often widely dispersed and consequently involved much "dead" transit time between holidays. In the case of the line-keeping holidays, the cause was, in almost all cases, due to the lack of an autopilot in the SHOALS system. While these small holidays can either be ignored or easily filled in during the course of a typical small SHOALS engineering/volumetric survey, the more stringent requirements of a nautical charting survey resulted in a substantial amount flight of time spent ensuring the completeness of the data set.

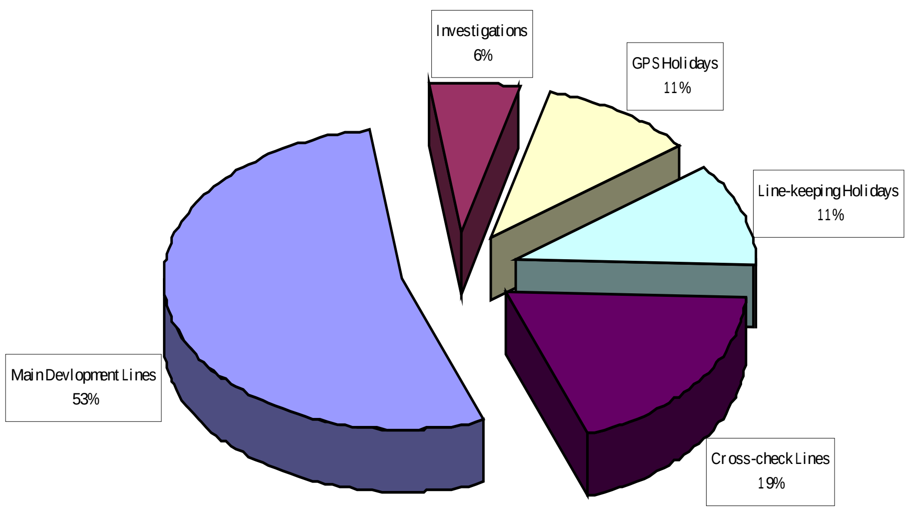

Figure 4 Breakdown of survey flights by activity

Data Processing

Immediately following each flight, the tapes with survey data and down-looking video were transported from the airport to the post processing facility located in an office in the business district of Cancun. The data tape was stripped and loaded into a data base, depths auto-extracted, and automatic outlier detection accomplished. Data review using an iterative processing approach, as depicted in Figure 5, was established jointly by NAVOCEANO and SHOALS personnel during the first week of operations.

The hydrographer has available several parameters for use to optimize the SHOALS processing algorithm to reflect the environmental conditions experienced during each survey mission. These Project Environmental Parameters (PEPS) are adjusted for each flight for the approximate wave height, water clarity, expected maximum depth, and bottom type. Another parameter allows the hydrographer to select a desired depth detection logic, depending on the purpose of the survey mission. Normal procedures for USACE surveying are to use the "strongest- pulse," or return, as the identified depth. For the hydrographic survey in Cancun, the "first-pulse" logic was used. This logic selects the first return energy to return as depth and was selected to ensure that potential navigation hazards were flagged to the hydrographer. Under most circumstances, first-pulse and strongest-return logic yield the same depth, except when a detected object is suspended above the sea bottom. Under such conditions, using the first-pulse logic ensured that possible hazards were detected at the expense of adding numerous anomalies to the data. Most detected anomalies were determined to be schools of fish; however, several sunken boats, isolated corals, and a submerged tourist submarine were located.

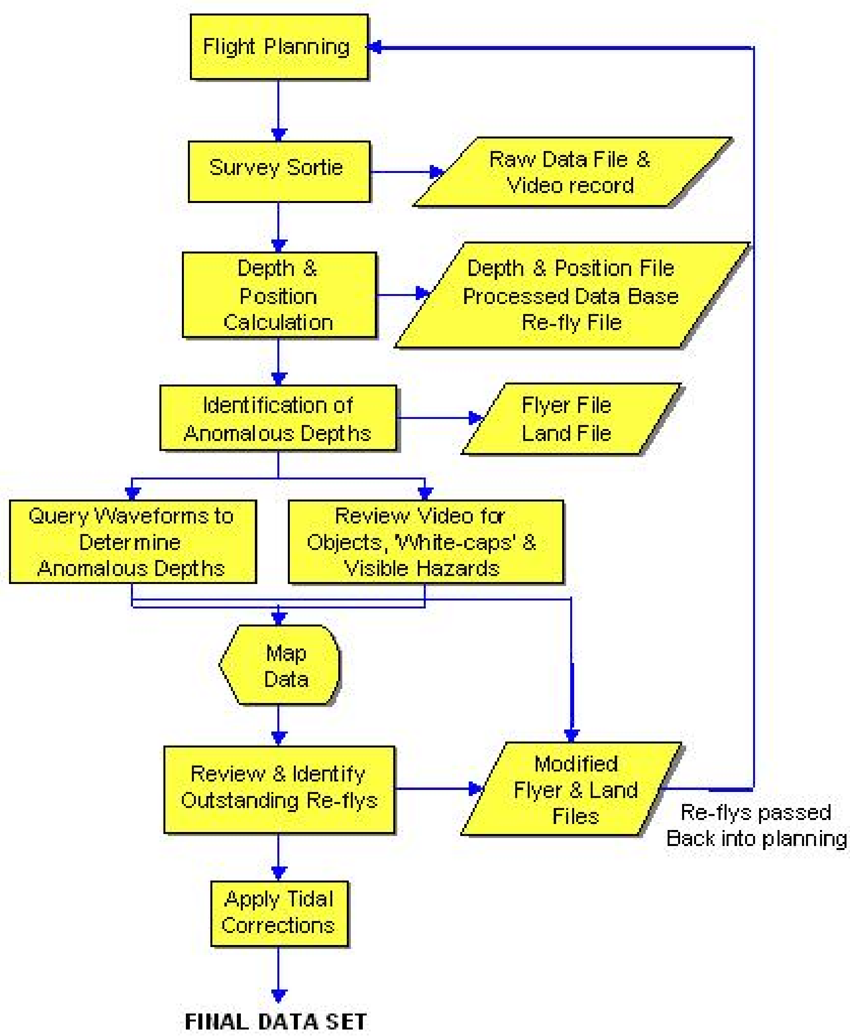

Figure 5 Flowchart of processing methodology.

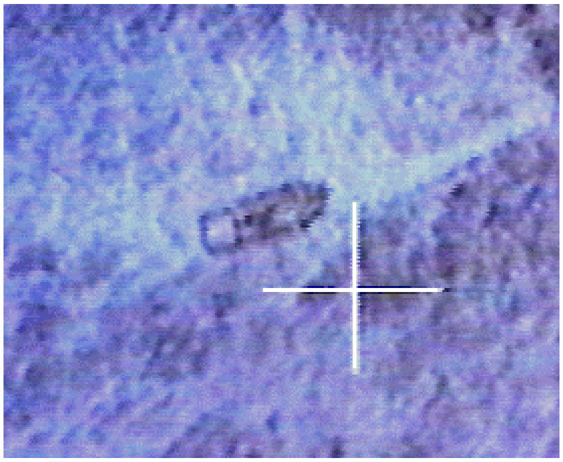

Figure 6 Video frame from survey showing a previously uncharted wreck.

Figure 7 Video frame from survey showing submarine *Atlantis* submerging on reef.

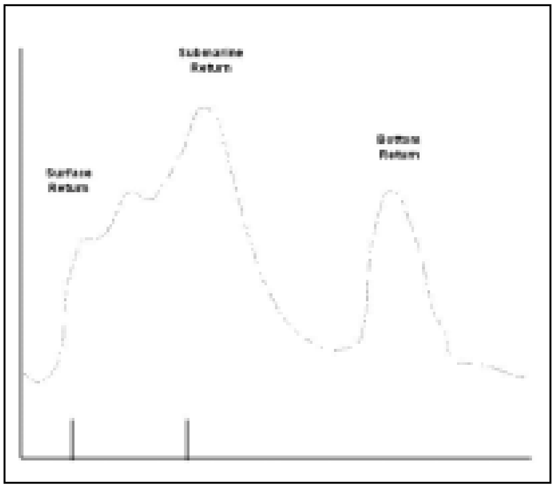

Figure 8 Waveform from encounter with submarine *Atlantis* showing 'suspended' return

All automatically detected outliers were manually validated by examining the waveforms, video, aircraft audio, and any overlapping data. Figure 6 shows a previously uncharted submerged wreck. Figure 7 is video frame from SHOALS camera showing the tourist submarine *Atlantis* submerging on a reef near Punta Cancun. Figure 8 is one of eight waveforms recorded from *Atlantis* encounter. Once processing, mapping, and data review were completed, field sheets were produced. Final products included smooth sheets and digital data recorded on CD-ROM and tape. Data processing for the survey was performed by JECA and NAVOCEANO personnel. The JECA SHOALS team was responsible for overseeing the entire processing effort and providing much of the expertise, considering the inexperience of NAVOCEANO personnel with the SHOALS processing system.

Water clarity throughout the survey region was normally good with the exception of a shallow semi-enclosed bay ten miles north of Punta Cancun. Laser performance in this area was greatly reduced due to an increase in biological activity. The green-colored water in the bay was very apparent from the aircraft and was obvious in a Landsat image of the survey area. Very few laser soundings were collected in this area.

Conclusions

The project proved to be a two-way learning experience, with NAVOCEANO personnel drawing heavily on the advice and experience of SHOALS surveyors and vice-versa. This was the first large area survey undertaken by SHOALS; indeed the area surveyed exceeded the total for all previous projects combined. Consequently it was necessary to develop survey management procedures for evaluation of possible navigation hazards. Since SHOALS is normally employed for the purpose of coastal engineering rather than hydrographic charting, NAVOCEANO hydrographers had a major role in developing quality-control practices and criteria for investigation of anomalous depths. Peculiarities of the SHOALS software often meant that much of this investigation involved time-consuming procedures for NAVOCEANO personnel, but it did teach many useful lessons that will be used to ensure that LABS will be better optimized for nautical charting. It also clearly illustrated the need for experienced hydrographers in the field.

NAVOCEANO learned several important lessons that relate to the philosophy of how any LIDAR system should be employed. Probably the most important of these issues is the extreme vulnerability of these systems to degraded water clarity; indeed it is clearly the single most important element in determining the ability of a LIDAR system to successfully measure water depth. All countries now operating LIDAR systems have invested considerable effort in characterizing the suitability and seasonality of their own waters for these surveys. This means that the optimization of survey conditions is critical, and NAVOCEANO, with its worldwide operations, will be challenged to develop its water clarity analysis capabilities to support future LABS operations

The experience of this survey has also reiterated the relationship between spot density and target detection. Although increased spot densities will eventually improve coverage in very shallow areas, the physics of LIDAR means that small objects ($<1\ m^3$) will usually be undetectable. For the foreseeable future, a LIDAR survey will not enjoy the same degree of confidence of hazard detection as a conventional sidescan search. However, recent studies which appear to have been borne out by the Yucatan experience have shown that in clear waters, there is a high confidence in detecting most obstructions of 2 meter cube size or larger likely to be of danger to a surface vessel. Therefore, LIDAR has an important role to play in surveying many areas of complex shallow seabeds where critical navigational channels are not an issue.

Lastly, despite not being a problem in Yucatan (due to the very small tidal range), the large areas covered and the speed of a LIDAR system present tidal problems considerably more complex than any previously experienced in conventional hydrographic surveying. The example of the Australian LADS system which could, in the space of only 15 minutes, be collecting data in positions separated by over 37 miles, illustrates the problem amply.

The Yucatan survey has been an important first step in establishing NAVOCEANO's LIDAR survey capability. Not only did the survey result in a completed hydrographic survey, but it was highly successful in providing LIDAR surveying experience to a group of people who will in the future play an important role in making LABS one of NAVOCEANO's core surveying capabilities.