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Scanning laser mapping of the coastal zone: the SHOALS system

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Abstract

The SHOALS system uses lidar technology to remotely measure bathymetry and topography in the coastal zone. During five years of survey operations, SHOALS has demonstrated airborne lidar bathymetry's benefits to the coastal community by providing a cost-effective tool for comprehensive assessment of coastal projects. This paper discusses the application of lidar technology for water-depth measurement, specifically outlining the SHOALS system and introducing a SHOALS survey from Saco River, ME. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: hydrographic survey; lidar; remote sensing; Saco River; SHOALS

1. Introduction

Airborne lidar (LIght Detection And Ranging) bathymetry was conceptualised in the mid-1960s, and successful development of first-generation systems in the US, Canada, and Australia followed in the 1970's (Cunningham, 1972; Abbott and Penny, 1975; Kim et al., 1975; O'Neil et al., 1978). Today there are three fully operational airborne lidar bathymetry systems in operation: SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey), LADS, and Hawk Eye (Setter and Willis, 1994; Steinvall et al., 1994; and Lillycrop et al., 1996). The SHOALS system, developed for the US Army Corps of Engineers (USACE), employs lidar technology to remotely collect accurate, high-density measurements of both bathymetry and topography in coastal regions. SHOALS has been in full operation since March 1994 and to date surveyed more than 230 projects totalling 5000 km^2. These surveys cover a variety of project types including coverage of maintained channels and harbours, coastal structures, and dredged material placement areas as well as adjacent beaches. SHOALS data collected for the US Navy and for the National Oceanic and Atmospheric Administration (NOAA) were used for creation of nautical charts. Other SHOALS surveys were for beach nourishment and erosion monitoring and for emergency response to hurricanes and ship groundings. In the following, we describe lidar bathymetry technology by presenting the SHOALS system and introducing the SHOALS survey at Saco River, ME.

2. Lidar technology

An airborne lidar bathymeter uses lidar technology to measure water depths. A laser transmitter/receiver mounted on an aircraft transmits a laser pulse which travels to the air–water interface where a portion of this energy reflects back to the receiver (Guenther et al., 1996). The remaining energy propa-

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gates through the water column and reflects off the sea bottom. The water depth comes directly from the time lapse between the surface return and bottom return, and each sounding is appropriately corrected for surface waves and water level fluctuations (Fig. 1). In practical application of this technology, laser energy is lost due to refraction, scattering, and absorption at the water surface, sea bottom, and as the pulse travels through the water column. The combination of these effects limits the strength of the bottom return and therefore limits the maximum detectable depth. Optical water clarity and bottom type are the two most limiting factors for depth detection. Typically, lidar bathymeters collect through depths equal to three times the site's Secchi (visible) depth.

3. The SHOALS system

The SHOALS system uses a scanning, pulsed, infrared (1064 nm) and blue-green (532 nm) laser transmitter with five receiver channels mounted on either a Bell 212 helicopter, a fixed-wing Twin Otter, or other equivalent aircraft of opportunity (Table 1, Fig. 2). Infrared and blue-green frequencies were selected to optimise air–water interface detection and water penetration, respectively. Typically, SHOALS operates at an altitude of 200 m and a speed of 60 m/s giving a survey swath width of 110 m and a horizontal spot density of 4 m. SHOALS survey rate is nominally 16 km^2/h thus is several orders-of-magnitude faster than conventional swath-fathometer survey rates. Two receiver channels

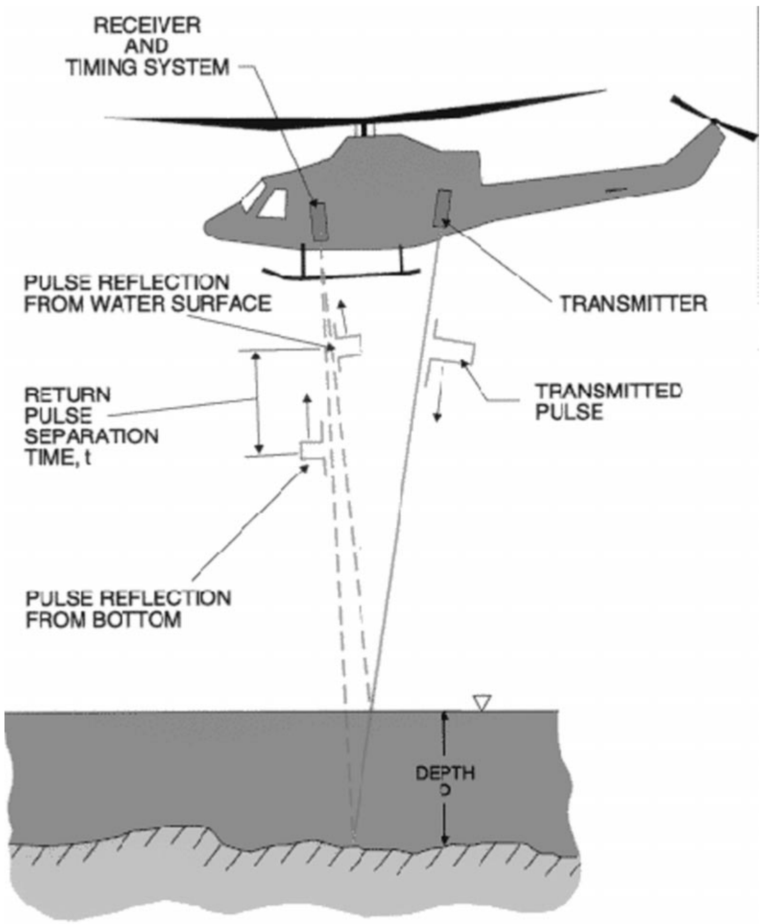

Fig. 1. Lidar operating principle.

Table 1
SHOALS sensor summary

Laser type	Nd:YAG infrared: 15 mJ at 1064 nm blue-green: 5 mJ at 532 nm
Laser pulse rate	400 Hz
Laser pulse width	6 ns (governed by eye-safety restrictions and surface return optimisation)
Scanner type	Flat mirror, dual-axis, programmable
Scan rate	Variable
Scan pattern	Variable (nominal arc ahead of aircraft 20° off nadir)
Laser receiver	20-cm catadioptric Cassegrain telescope with five-way splitter
4 avalanche photodiode detectors	1064 nm (2) 532 nm (1; shallow water and topography) 645 nm (1)
1 photomultiplier tube detector	532 nm (deep water)
Waveform digitisation rate	1 GHz

record energy vs. time (waveforms) for each reflected blue-green pulse and two record waveforms for each reflected infrared pulse. The fifth channel records a red Raman (645 nm) energy that results from excitation of the surface water molecules by the blue-green laser energy. SHOALS uses the two blue-green waveforms to determine the bottom interface where one is for shallower depths and the other for deeper depths to 60 m. To avoid problems associated with air-water interface detection, SHOALS uses any of two waveforms to determine this interface accurately. Prioritised by order of use these are the Raman then infrared channels. The second infrared channel is used in conjunction with the first to discriminate between land and water returns. In response to the USACE's need to map the upland beach, dunes, and above-water portion of coastal structures, SHOALS was modified in 1996 to include topographic capabilities. Unlike most topographic lidar systems, which use an infrared frequency, SHOALS uses its blue-green frequency to measure topographic elevations. All waveforms are recorded to Exabyte tape in raw form, and depths are extracted during post-flight processing.

SHOALS positioning comes either from differential GPS (DGPS) provided by Coast Guard beacons and OMNISTAR satellite system or from kinematic GPS provided by local stations. When SHOALS operates with DGPS, which provides horizontal aircraft position, horizontal and vertical accuracy are ± 3 m and ± 15 cm, respectively. When SHOALS operates with KGPS, which additionally provides vertical aircraft position, horizontal accuracy improves to ± 1 m. An inertial reference system mounted with the laser optics accounts for aircraft motion effects. In addition to lidar depth and elevation measurements, SHOALS' geo-referenced down-look video camera provides a visual record of the survey area. These records are frequently used to obtain approximate positions of coastal structures, navigation aids, and other objects of interest. Furthermore, the video record serves as an auxiliary

Fig. 2. The SHOALS system mounted on underside of a Bell 212 helicopter.

Table 2
SHOALS performance characteristics

Maximum depth	60 m
Vertical accuracy	±15 cm
Horizontal accuracy	
DGPS	±3 m
OTF KGPS	±1 m
Sounding density	4-m grid (variable)
Operating altitude	200 m (variable)
Scan Swath width	110 m (variable)
Operating speed	60 to 120 m/s

check for anomalous data discovered during post-flight processing.

Post-flight processing uses a depth-extraction algorithm developed by the NOAA National Ocean Service (NOS) (Thomas and Guenther, 1990; Lillycrop et al., 1993). The system software serves two functions: automated processing and manual processing. In automated processing, each sounding's five waveforms are analysed and a depth extracted. Automated processing also makes surface wave and water level corrections as needed. Manual processing allows the hydrographer to interrogate data sounding-by-sounding. When the automated processor flags a questionable sounding, the hydrographer accesses the waveform window display. Here, four recorded waveforms are visually displayed along with other

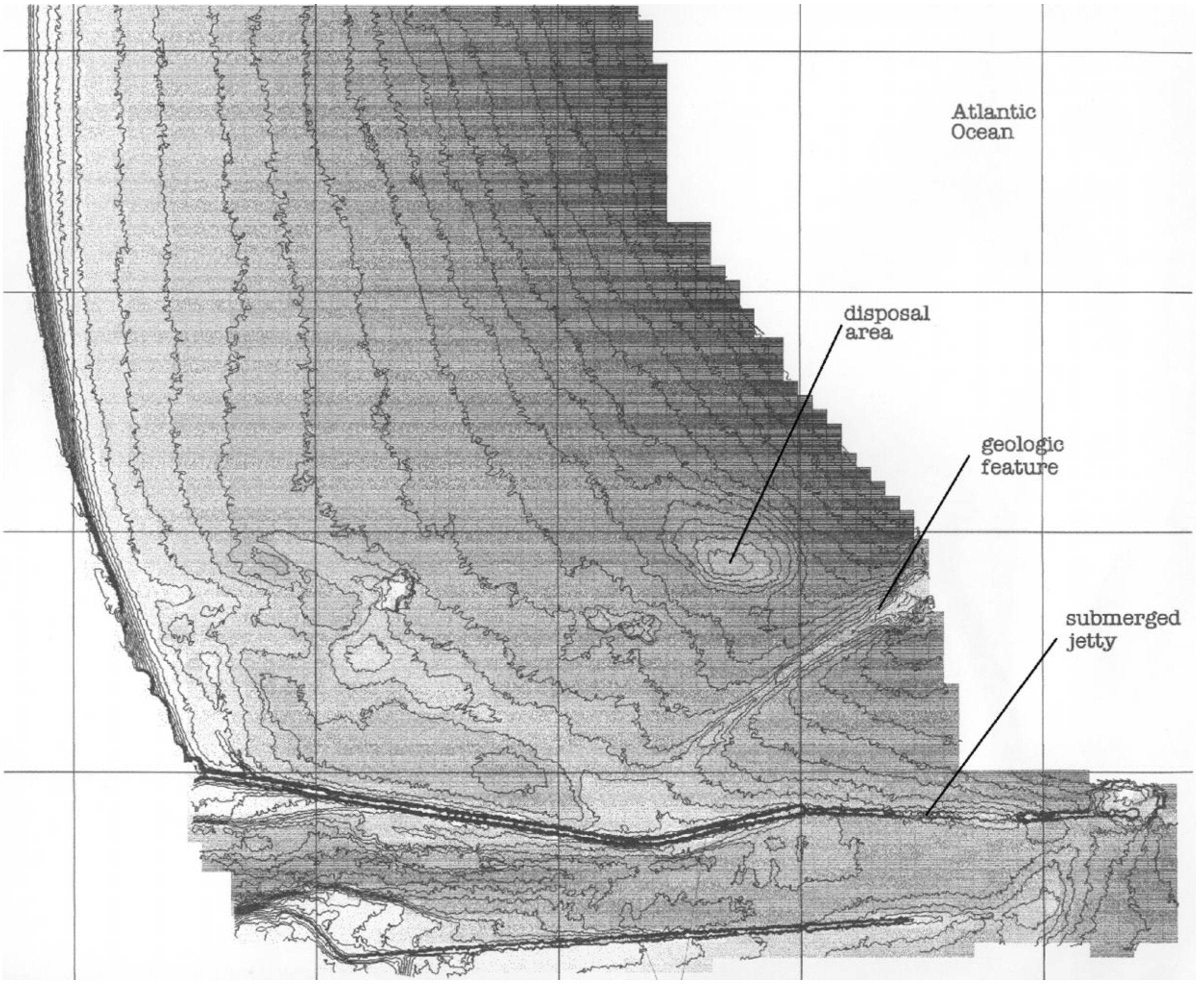

Fig. 3. Saco River, Maine, 1998; 0.5 m contours; 500 m grid; north is at top.

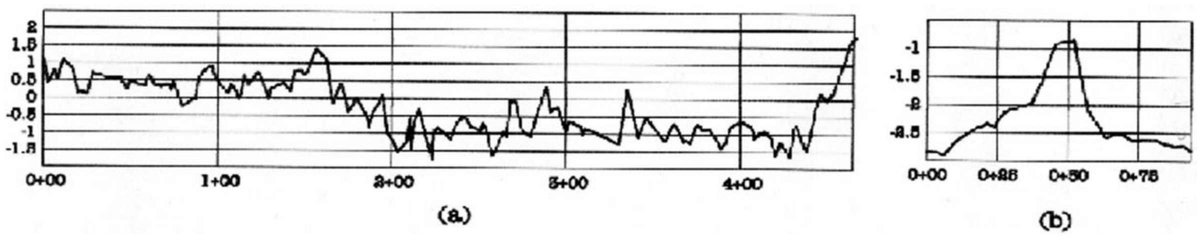

Fig. 4. Submerged jetty: (a) centerline and (b) cross-section; stations and elevations in m.

pertinent sounding information such as selected surface detection channel, selected bottom detection channel, aircraft altitude, and depth and position confidence. From this information, the hydrographer

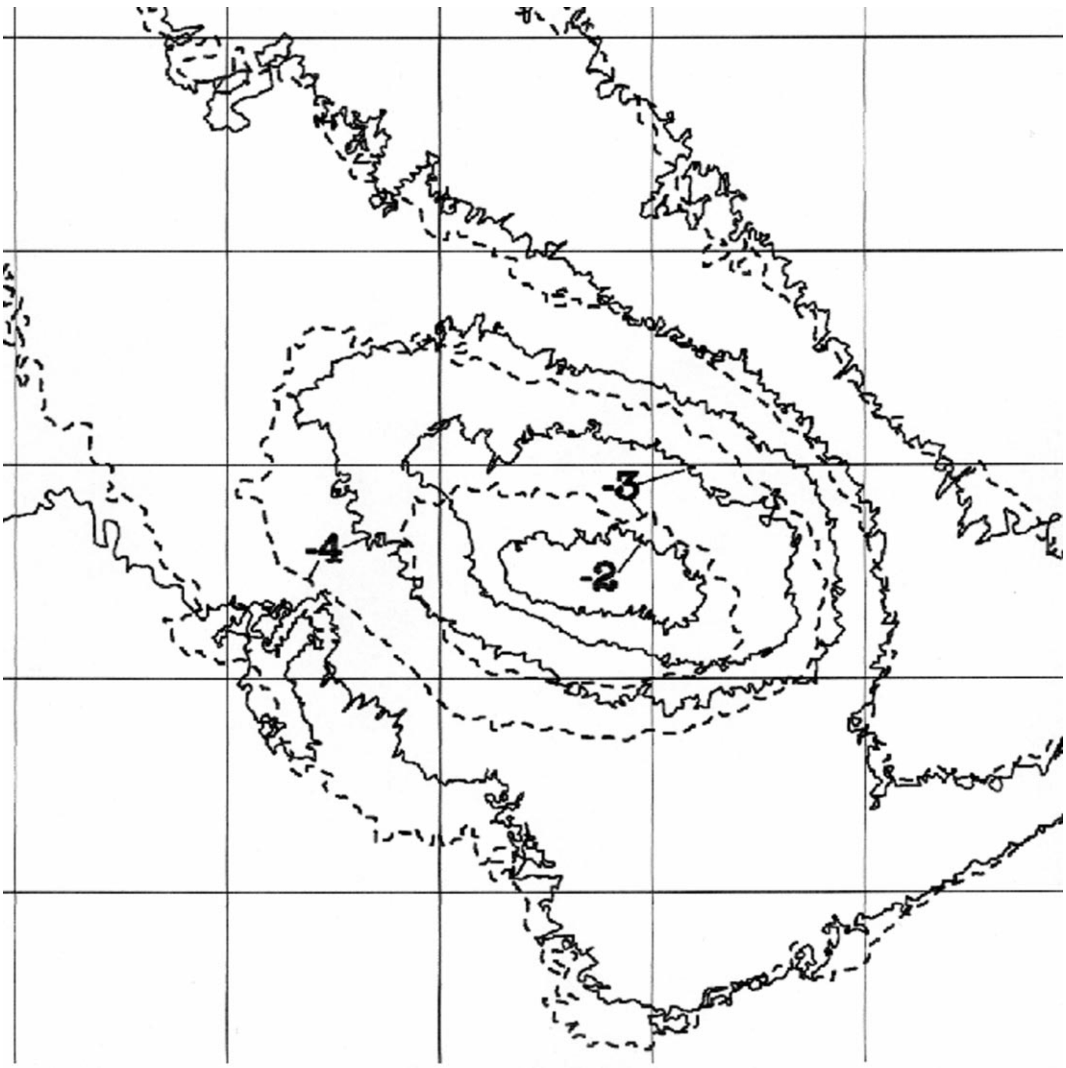

Fig. 5. Disposal area contours in 1997 (solid) and 1998 (dashed); 1 m contours; 100 m grid; north is at top.

makes an informed decision about that sounding's integrity. Once post-flight processing is complete, the data are written to an ASCII text file with latitude, longitude, and depth for each qualified sounding.

4. SHOALS performance

Data collected with SHOALS meets USACE Class 1 and International Hydrographic Organisation (IHO) Order 1 standards. Through independent testing, both the NOS and US Navy verified that SHOALS met IHO charting standards (Riley, 1995). Additionally, the USACE conducted extensive field tests to ensure that SHOALS met the USACE Class 1 survey standards, which are more restrictive than the IHO standards. Table 2 summarises SHOALS current performance characteristics.

5. Saco River, Maine

On two occasions, SHOALS surveyed the Saco River exit into the Atlantic Ocean along the US coast of Maine. Two parallel jetties to the north and south, a maintained channel between the jetties, a disposal area to the north, and several rock outcrops characterise the river mouth. The most recent SHOALS survey during June 1998 covered 4 km^2 and included nearly 500 000 soundings and elevations (Fig. 3). The contour map generated from the data quantifies the three-dimensional bathymetry in the navigation channel and maps the beach and near-shore to the north. Centrelines and cross-sections of the jetties created from the SHOALS data illustrate the current structure condition (Fig. 4). Comparisons between this survey and the previous SHOALS survey collected in May 1997 show that the disposal mound migrated inshore and to the south (Fig. 5).

6. Summary

Laser remote sensing to measure the coastal zone proves an integral tool for improving coastal engineering evaluation while maintaining cost-effectiveness. In addition to providing high-density data faster, remote collection of bathymetry and topography using a lidar system allows for data collection in very shallow or environmentally sensitive waters that are unreachable using conventional survey methods. Unlike conventional surveys, the SHOALS survey of Saco River is an instantaneous picture of the entire near-shore system that completely represents existing conditions and quantifies interaction of various features within the system. In summary, SHOALS capacity to map in detail shorelines, coastal structures, the near-shore, and upland topography provides the USACE with a tool for total project assessment. Furthermore, SHOALS ability to collect synoptic hydrographic and topographic data supports the USACE's regional sediment management initiative. The SHOALS program is based at the Joint Airborne Lidar Technical Center of Expertise (JALBTCX) in Mobile, AL. In addition to survey operations, research and development toward improving lidar bathymetry are conducted at the JALBTCX.

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