AN INTRODUCTION TO COASTAL ZONE MAPPING WITH AIRBORNE LIDAR: THE SHOALS SYSTEM

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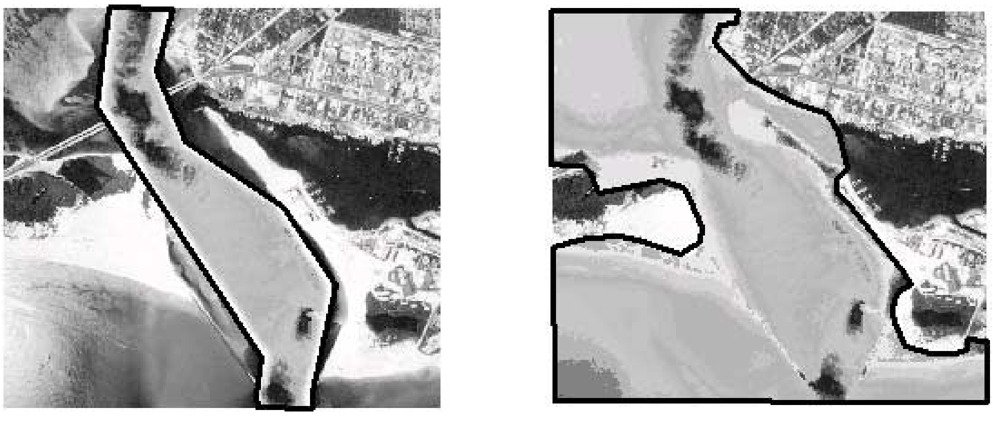
ABSTRACT

Recent advancements in lidar sensors now allow for near-synoptic, regional-scale mapping of the coastal zone. One such sensor is the US Army Corps of Engineers SHOALS system. SHOALS is unique in that it is the only lidar sensor, worldwide, that simultaneously collects bathymetry and adjacent topography. Because of SHOALS' rapid collection rate, data density, and system accuracy, it is now cost effective to quantify regional coastal geomorphology and to better engineer management solutions on a regional scale. This paper gives an overview of airborne lidar bathymetry technology and the SHOALS system and discusses the value of lidar mapping to the coastal management community by presenting recent regional SHOALS surveys in Hawaii, USA.

1.0 INTRODUCTION

With the advent of lidar mapping technology, near synoptic, regional-scale mapping of the coastal zone is now realizable. During the last decade, airborne lidar bathymetric and topographic sensors have become fully operational tools used by the terrain mapping community. Today, there are 6 bathymetric lidar sensors and more than 50 topographic lidar sensors in operation throughout the world. Airborne lidar is an ideal tool for monitoring the coastal zone on regional scales (Wozencraft and Irish, 2000). In contrast to conventional coastal mapping techniques, which include singlebeam and multibeam acoustic techniques combined with wading-depth profile techniques, airborne lidar bathymetry (ALB) and topography sensors rapidly (orders of magnitude faster) collect high-resolution soundings and/or elevations throughout an entire coastal region, or sub-region (Figure 1.1). Such comprehensive datasets allow coastal engineers, scientists, and managers to quantify terrain change and geomorphic feature interaction throughout the entire coastal system.



(a) (b)

Figure 1.1: Conventional USA project survey plan (a) versus airborne lidar survey plan (b).

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**

4. TITLE AND SUBTITLE **An Introduction to Coastal Zone Mapping With Airborne Lidar: The Shoals System**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Joint Airborne Lidar Bathymetry ,Technical Center of Expertise,109 St. Joseph Street,Mobile,AL,36602-3630**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Proceedings, 21 Corso di Aggiomamento in: Techniche per la Diffesa Dallinquinamento,, Cosenza, Italy

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

One such ALB sensor is the U.S. Army Corps of Engineers' (USACE) SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey) system (Irish *et al*., 2000). SHOALS is unique in that it is the only lidar sensor, worldwide, that simultaneously collects bathymetry and adjacent topography, thus allowing seamless survey coverage from the nearshore through the shoreline and onto the adjacent above-water terrain (Figure 1.2). Since 1994, when the system became fully operational, SHOALS has conducted over 300 survey missions. This year to date (January through September), SHOALS has mapped 5000 km^2 of coastal waters and adjacent topography comprising 300 million individual depth and elevation measurements. SHOALS data have been used to assist coastal managers, engineers, and researchers in developing sediment budgets, monitoring shorelines and predicting shoreline erosion, modeling hurricanes and storms, managing natural resources, managing navigation projects, developing regional management strategies, and creating nautical charts (Mohr *et al*., 1999; Pope *et al*., 1997; Watters and Wiggins, 1999; Weber, 2000; Irish and Lillycrop, 1997).

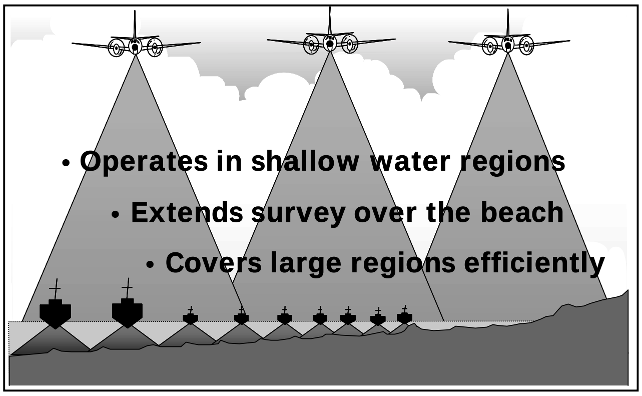


Figure 1.2: Advantage of SHOALS over multibeam acoustic surveys.

In 1999, SHOALS mapped the nearshore regions, from the shoreline to the 30-m depth contour, surrounding the islands of Maui, Kauai, Molokai, and Oahu in Hawaii, USA. The survey mission was to provide an accurate map base for numerical simulations used for hurricane evacuation management and to support coral reef monitoring initiatives. Such an extensive survey provides insight to both large- and small-scale bathymetric and shoreline irregularities critical to the success of these numerical simulations. Because of SHOALS rapid collection rate, data density, and system accuracy, it is now cost effective to monitor regional coastal processes and to better engineer management solutions on a regional scale. The following sections describe airborne lidar bathymetry technology and the SHOALS system. The value of lidar mapping to the coastal management community is demonstrated with survey examples from Hawaii, USA.

2.0 PRINCIPLES OF AIRBORNE LIDAR BATHYMETRY

An ALB sensor uses lidar technology to directly measure water depths (Guenther *et al*., 1996). A laser transmitter/receiver (transceiver) mounted on an aircraft transmits a laser pulse that travels to the air-water interface where a portion of this energy reflects back to the transceiver (surface return, Figure 2.1). The remaining energy propagates through the water column and reflects off the sea bottom (bottom return). The water depth comes directly from the time lapse between the surface return and the bottom return. In addition, each sounding is appropriately corrected for water level fluctuations using either vertical aircraft positioning from GPS or by referencing the lidar measurements of water surface location with water level gage measurements.

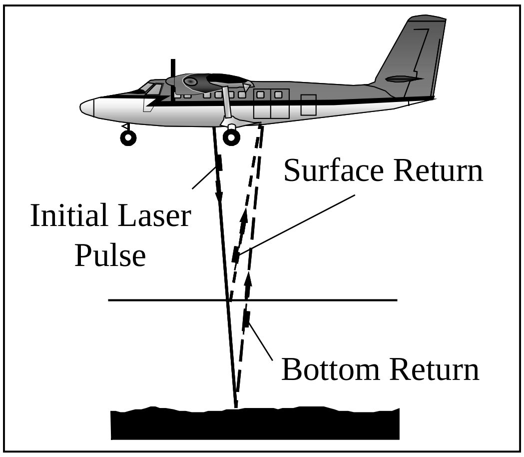


Figure 2.1: ALB operating principle.

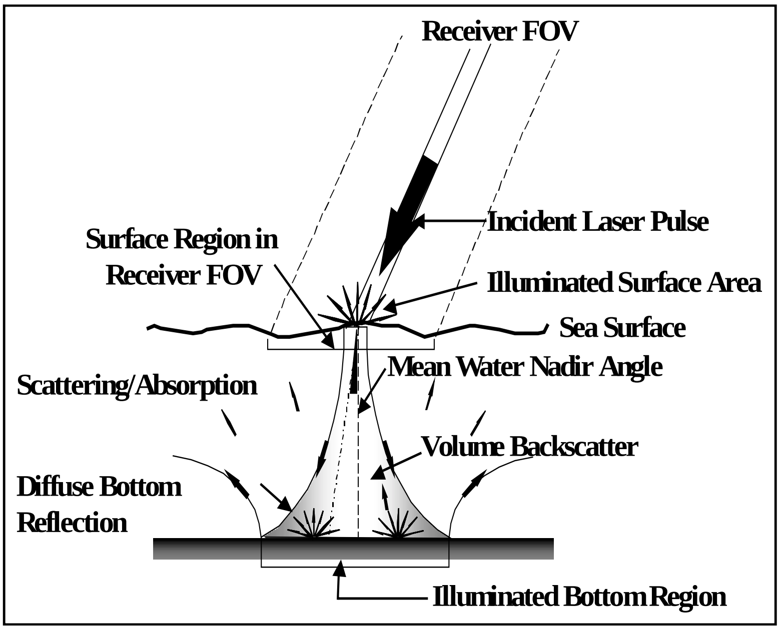


Figure 2.2: Water column and interface effects on system performance (FOV is field of view).

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 (Figure 2.2). The combination of these effects limits the strength of the bottom return and therefore limits the maximum detectable depth. Optical water clarity is the most limiting factor for ALB depth detection. Typically, an ALB sensor collects through depths equal to three times the Secchi (visible) depth. In optically clear water, ALB sensors have successfully measured to depths to 70 m (Sinclair, 1999).

3.0 THE SHOALS SYSTEM

The SHOALS ALB system operates from both fixed-wing and rotary-wing platforms (Figure 3.1a; Guenther *et al.*, 2000; Guenther *et al.*, 1996; Irish *et al.*, 2000; Irish and Lillycrop, 1999). Inside the aircraft are the laser transmitter and receiver (transceiver), operator interface consoles, and pilot guidance system (Figure 3.1). The SHOALS system's laser transceiver emits two energy frequencies: a blue-green frequency (532 nm) and an infrared frequency (1064). In addition, the transceiver records laser energy return time series (waveforms) with four receivers. One receiver records the infrared energy reflected from the water surface (surface return) and two collect the blue-green energy reflected from the sea bottom (bottom return, Figure 2.1). A fourth receiver records Raman energy, at 645 nm, which results from excitation of water molecules at the sea surface by the blue-green laser energy. The Raman waveform and the infrared waveform provide direct ranging of the sea surface, while the two blue-green waveforms directly range the sea bottom from 0 m to 10 m and from 10 m to 60 m. The infrared waveform is also used to distinguish dry land from water. Additionally, one blue-green waveform is used to directly range topographic elevations.

The SHOALS laser pulses at a rate of 400 Hz, providing 400 individual range measurements per second. An optical scanner mounted with the transceiver positions each laser pulse to provide uniform sounding and elevation spacing on the earth's surface (Figure 3.2). For coastal monitoring surveys, SHOALS typically collects data from an altitude of 400 m, resulting in a scanner swath width of 220 m. Along with an aircraft speed of 60 m/s, this results in an individual sounding or elevation measurement every 8 m and a survey speed of 25 km^2 per hour. Table 3.1 gives SHOALS operation and performance characteristics.

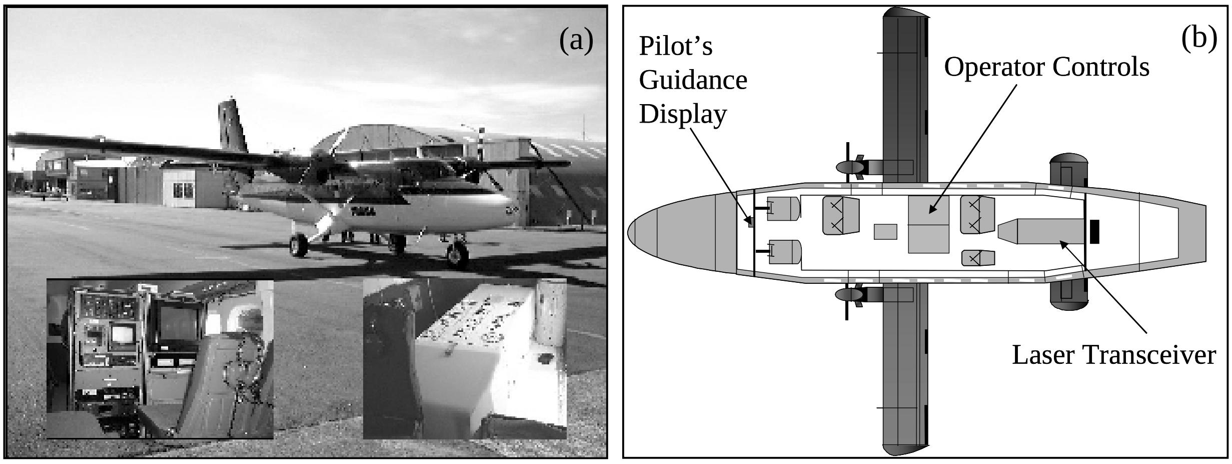


Figure 3.1: (a) SHOALS system mounted on a Twin Otter and
(b) layout of SHOALS system inside Twin Otter.

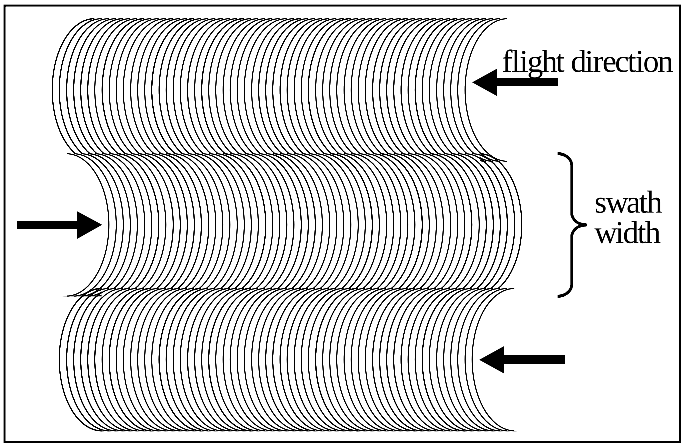


Figure 3.2: SHOALS scan and flight patterns.

Table 3.1: SHOALS operation and performance characteristics.

Maximum Depth	to 60 m
Vertical accuracy	±15 cm
Horizontal	
DGPS	±3 m
KGPS	±1 m
Sounding density	8-m grid (variable)
Operating altitude	400 m (variable)
Scan swath width	220 m (variable)
Operating speed	50 to 70 m/s

SHOALS receives its positioning from GPS (Global Positioning System) in either differential (DGPS) or kinematic (KGPS) mode. With DGPS, horizontal positioning of the aircraft is accurately known and directly translates to a known horizontal sounding/elevation position. Accurate vertical positioning for each measurement is then obtained by correlating the lidar surface return with independent water level measurements. In contrast, KGPS provides both horizontal and vertical aircraft positioning accurately, thus the full three-dimensional positioning for each measurement is independent of supporting water level measurements. SHOALS vertical positioning accuracy is ±15 cm and horizontal positioning accuracy is ±3 m and ±1 m with DGPS and KGPS, respectively (Irish *et al*., 2000; Pope, 1997; Riley, 1995).

The SHOALS system also collects a directly downward-looking, geo-referenced video concurrently with the lidar measurements. In addition to offering a visual record of the survey area, the video is frequently used to position coastal features such as navigation aids, piers, and other objects of interest.

4.0 COASTAL MANAGEMENT WITH LIDAR DATA – HAWAIIAN ISLANDS, USA

Between February and April 1999, the SHOALS system was deployed to the Hawaiian Islands, USA to conduct bathymetric and topographic surveys in support of the State of Hawaii and USACE Hurricane Evacuation Study (HES) and the US Geological Survey (USGS) coral reef mapping and monitoring initiatives (Wozencraft *et al.*, 2000). During the 2-month deployment, SHOALS conducted 60 survey flights totaling 215 operational hours and resulting in more than 25 million soundings and elevations. The surveyed coastlines are shown in Figure 4.1.

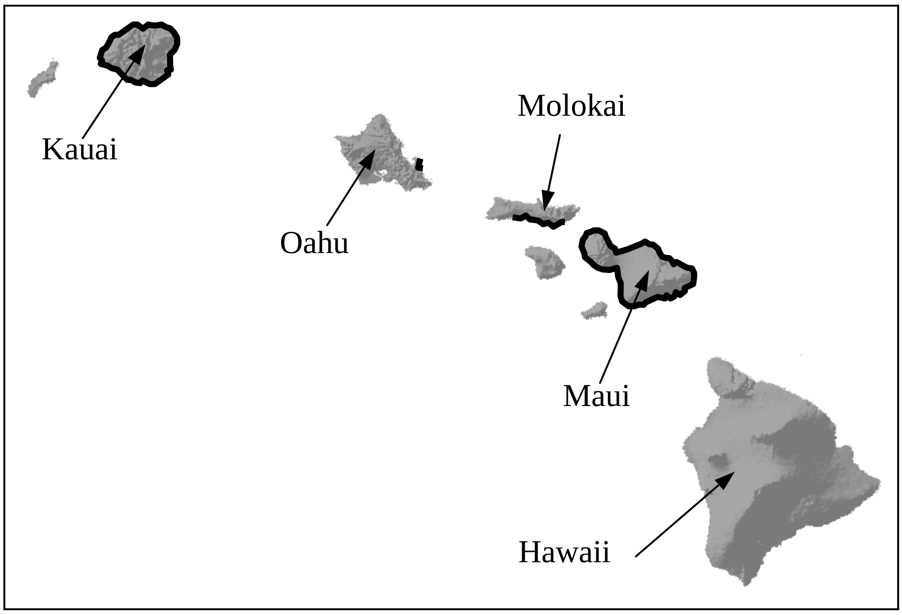


Figure 4.1: Hawaiian Islands, USA, coastlines surveyed with SHOALS (shown in black) in 1999.

4.1 Hydrodynamic Studies

SHOALS mapped the entire Maui and Kauai coastlines, 200-km and 150-km respectively, specifically to generate a detailed digital terrain model (DTM). The SHOALS data, collected with an 8-m horizontal spot density, extended from the upland terrain through the 30-m depth contour. Because of the highly complex nearshore and upland topography characteristic of the Hawaiian Islands, an accurate DTM is essential for successful model predictions. Along the Maui coastline are numerous natural headlands and coves (Figure 4.2). In addition, areas of rock outcropping and coral reef systems are prevalent in the nearshore. These irregular features impact the spatial variation in hydrodynamic properties like wave refraction and setup and sediment transport. Along with the SHOALS data collected in Kauai, the USACE, State of Hawaii, and Sea Engineering, Inc. are presently using the SHOALS data collected in Maui to generate baseline regional-scale DTMs for numerical model simulations of hurricane flood inundation to support the HES (personal communications, April 2000).

4.2 Natural Resource Monitoring

In 1993, the USGS began using airborne remote sensing to map and study the coral reefs of Molokai, Hawaii. The USGS is using both digital aerial photography from 1993 and 2000 and SHOALS bathymetry from 1999 to map and track changes of coral reef features like short-term seasonal and long-term changes in elevation and elevation features (Chavez *et al.*, 2000). Figure 4.3 shows SHOALS bathymetry collected in Molokai. These data extend from the shoreline through the shallow waters of the nearshore to depths greater than 7 m.

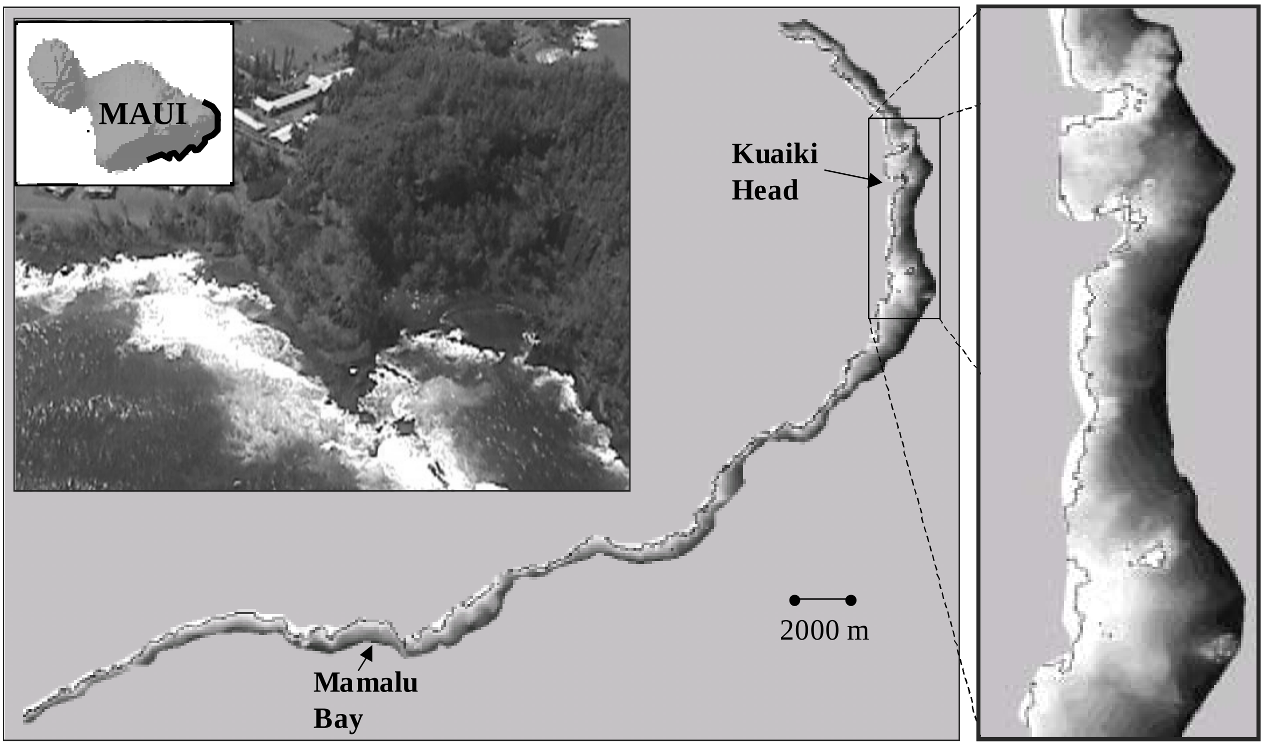


Figure 4.2: SHOALS data at Maui, Hawaii (1999). Shoreline is black line. Depth contours are every 3 m. North is to top.

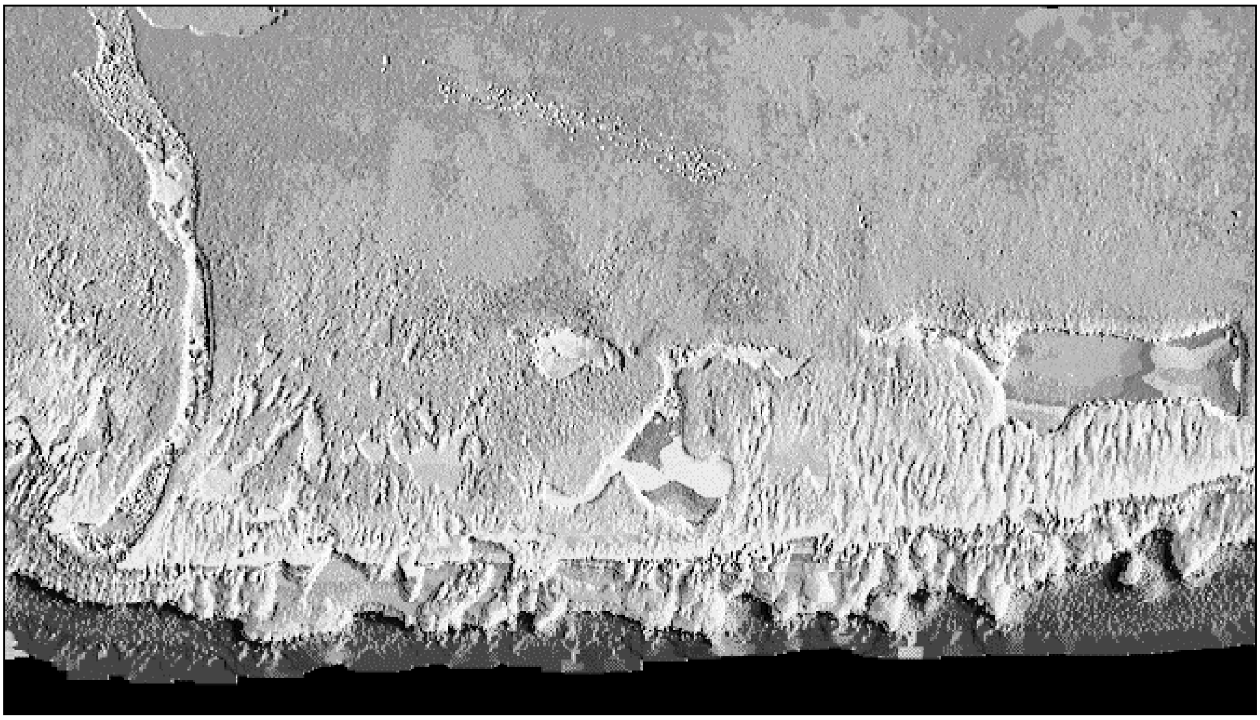


Figure 4.3: Image of SHOALS data at Molokai, Hawaii created by USGS (Wozencraft *et al.*, 2000). Shoreline is to top, offshore to bottom, and shallow to deep depths correspond with lighter to darker shading, respectively.

5.0 SUMMARY

The SHOALS system has three obvious advantages over conventional survey methods (Figure 1.2). Firstly, operation from an airborne platform allows data collection over large areas at rates that are several orders of magnitude faster than singlebeam and multibeam fathometer techniques and wading-depth profile techniques. Along with SHOALS high resolution, the speed with which data are collected provides the coastal user with a detailed, near-synoptic quantification of the coastal zone.

Another advantage of ALB technology is its ability to safely and efficiently measure depths in very shallow areas. Because ship-based sensors cannot safely navigate in depths shallower than 2 meters, swath-fathometer technology cannot be used to measure these shallow depths. Typically, shallow-water depth measurements are collected using time-consuming and costly wading-depth profile techniques. For coastal monitoring missions, detailed terrain models within the 0-to-2 m zone are critical for understanding coastal sediment processes in an area.

Thirdly, SHOALS ability to simultaneously collect water depths and topographic elevations results in complete mapping of the beach and nearshore. Continuous data collection through the land/water interface allows for accurate shoreline positioning. Seamless terrain models from the nearshore through the adjacent upland area are important for coastal management and engineering design.

SHOALS' capacity to map in detail shorelines, the nearshore, upland topography, coastal structures, and natural features provides the coastal community with a tool for total project assessment on both small (a few square kilometers) and regional (100's square kilometers) scales. The SHOALS program is based at the US Army and US Navy Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) in Mobile, AL. In addition to survey operations, research and development toward improving airborne hydrography are conducted at the JALBTCX.

ACKNOWLEDGMENTS

The projects, analysis, and resulting data described herein, unless otherwise noted, were obtained from work funded by or performed at the U.S. Army Corps of Engineers Joint Airborne Lidar Bathymetry Technical Center of Expertise. Permission was granted by the Chief of Engineers to publish this work.

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