Studying seafloor bedforms using autonomous stationary imaging and profiling sonars.

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***Abstract*— The Sediment Transport Group at the U.S. Geological Survey, Woods Hole Coastal and Marine Science Center uses downward looking sonars deployed on seafloor tripods to assess and measure the formation and migration of bedforms. The sonars have been used in three resolution-testing experiments, and deployed autonomously to observe changes in the seafloor for up to two months in seven field experiments since 2002. The sonar data are recorded concurrently with measurements of waves and currents to: a) relate bedform geometry to sediment and flow characteristics; b) assess hydrodynamic drag caused by bedforms; and c) estimate bedform sediment transport rates, all with the goal of evaluating and improving numerical models of these processes. Our hardware, data processing methods, and test and validation procedures, have evolved since 2001. We now a fairly standard set of sonar configurations that provide us with the data to look for correlations between flow conditions and bedform morphology. Plans for the future are to sample more rapidly and improve the precision of our tripod orientation measurements.**

Keywords—sonar, sea floor bedforms, sediment transport

I. Introduction

Mapping bedforms and monitoring them as they change is an important component of U.S. Geological Survey (USGS), Coastal and Marine Geology Program sediment-transport research studies. Seafloor bedforms are four-dimensional features: their size, shape, and orientation changes with time under the influence of waves and currents. Bedforms contribute hydrodynamic drag to the overlying flow that in turn shapes the bedforms. Thus, bedforms are an important influence on the flow and provide clues as to the currents and sediment dynamics that built them. Seafloor sonars mounted 0.5 - 1.5 meters (m) above the bottom on stationary tripod platforms allow us to resolve bedforms with horizontal dimensions ranging from a few centimeters to about 10 m at intervals as short as minutes. These small bedforms typically adapt to new flow conditions more rapidly (minutes to hours) than larger features (which may take hours to years), so the ability to sample repeatedly over short time intervals is important. Sensors that measure waves and currents are mounted on the same platform, so the bedforms and the processes that shape them can be quantified together for up to several months per deployment.

Sonars on seafloor tripods are controlled by autonomous logger/controllers, and power is supplied by battery, so the sampling scheme must be planned to achieve adequate temporal resolution to capture events while conserving power. Autonomous sonar deployments are especially challenging because the configuration must be correct when entered – there is no cabled real-time connection, so tweaking settings to improve image clarity or aim a different direction is not possible. Testing in controlled environments is critical to understanding how the sonars operate, the size features that can be resolved, the optimum settings for deployment, and how the data must be treated to ensure correct interpretation.

The objective of this paper is to document how we use seafloor sonars to observe and measure fine-scale morphologic change on the seafloor, and the calibration process employed for validation.

II. Goals

Our goal in deploying instrumented tripods with sonars is to correlate flow conditions (waves, currents, and turbulent mixing) to the shape and behavior of bedforms. To accurately quantify the scales, orientation, and movement of the bedforms, the capabilities of the sonars must be evaluated and understood. The interaction between bedforms and the overlying flow is not well characterized in numerical models of coastal dynamics, and we hope to use the sonar results to enhance the models and improve predictive capability.

III. History

The Sediment Transport Group at the U.S. Geological Survey, Woods Hole Coastal and Marine Science Center (WHCMSC) has used stationary, seafloor-mounted sonars to describe and quantify bedforms as part of sediment-transport research since 2002. Figure 1 shows a timeline of sonar and logger use in experiments and major tests.

Our methods have evolved with technology and as we have learned from deployments and test experience. Initially an Imagenex (www.imagenex.com) 881 tilt-adjusted imaging (fan) sonar was deployed to document bedform evolution. The data provided wavelength and orientation, but did not allow any determination of height. We added an Imagenex 881a profiling (pencil) sonar in 2006 to scan features along a line

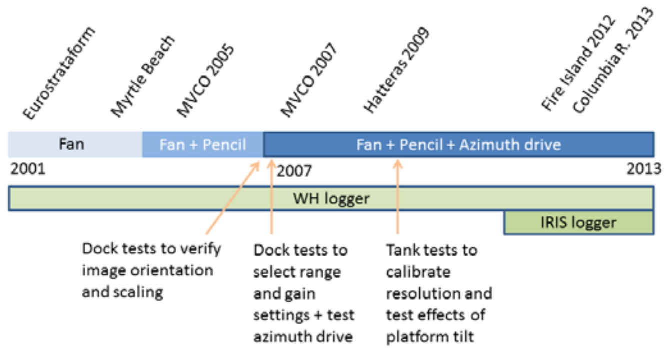


Figure 1: The experiments and tests using sonars, and the progressive changes in sonars and loggers used at USGS Woods Hole Coastal and Marine Science Center.

that overlapped the fan image. These data provided some information about bedform heights, but the heights had to be extrapolated to apply to other parts of the image. In 2007, we added a stepping motor (azimuth drive) to rotate the profiling head, which provides elevation data over a small (~2- to 5-m radius) area. In 2012 we purchased a high frequency model 881a imaging (fan) sonar to complement the measurements of the other sonars.

Autonomous sonar deployments require a logger/controller to direct data acquisition and storage. Our original logger/controller (the WH logger) was custom-built in 2000 by Jim Irish and Robin Singer of Woods Hole Oceanographic Institution (WHOI) when no commercial models were available. It controls and logs data from the fan and pencil heads sequentially with configurable sample timing. We were able to modify in-house the software to add capability as needed until the firmware compiler was no longer supported. Recently we purchased two IRIS (Image Recorder for Imagenex Sonar) loggers from ASL Environmental Sciences (www.aslenv.com) to replace the original WH logger. The IRIS provides a graphical user interface (GUI) to configure Imagenex 881A model sonars and the azimuth drive. One IRIS operates one sonar, so two IRIS loggers are required to replace the WH logger. The IRIS is relatively low power, has user-configurable sampling with limited rapid-sampling capability, provides a duration estimator tool, has expandable storage, and has a watchdog timer to restart sampling while deployed if necessary.

Our sonars are typically deployed on tripods placed on the seafloor with other sensors that measure near-bottom currents, turbidity, and surface waves. By combining this information with the sonar data, we are able to animate the evolution of bedforms with flow data to identify correlations of seafloor changes with currents and waves. Figure 2, a snapshot from an animation of data from water depth of 10 m off Myrtle Beach, South Carolina, shows the fan sonar data rendered in Cartesian (x-y) coordinates and rotated so that the top of the image corresponds to North (true) at the site. Overlaid are a current vector (red), indicating the direction of water flow at that time, and a vector (enlarged 5x) indicating the crest orientation and wavelength of the predominant bedforms in the image (aqua). The values corresponding to the vectors are also listed at the top right of the frame. A time-series plot of wave heights during the six-week deployment is shown at the bottom of the plot, with a red dot indicating when these data were measured.

IV. Data Format and Processing

Development of software to process the sonar data has occurred concurrently with the expanding use of sonars. Our sonar parsing, processing, and display software is written in Matlab™.

The processing of both types of sonar occurs in the following steps: offload raw files from the logger, convert data files from raw binary formats to standardized formats, apply trigonometry to rotate data into x-y coordinates, analyze data and combine results from both sonars, and incorporate with current and wave measurements.

The sonar raw data consists of header information followed by a series of acoustic amplitudes as a function of time and associated directional information. The time axis can be converted to distance using the speed of sound in water for the relevant temperature, salinity, and depth. The locations of the acoustic returns can then be positioned relative to the sonar head using the sweep angle (fan beam) or the sweep angle and azimuth angle (dual-axis pencil beam). To relate these amplitudes at distances and bearings from the sonar to real-world coordinates, the location and orientation of the sonar heads must be known. We accomplish this by measuring the position of the sonar head relative to other instruments on the platform that have compasses and tilt sensors (for example, acoustic Doppler current profilers or acoustic Doppler

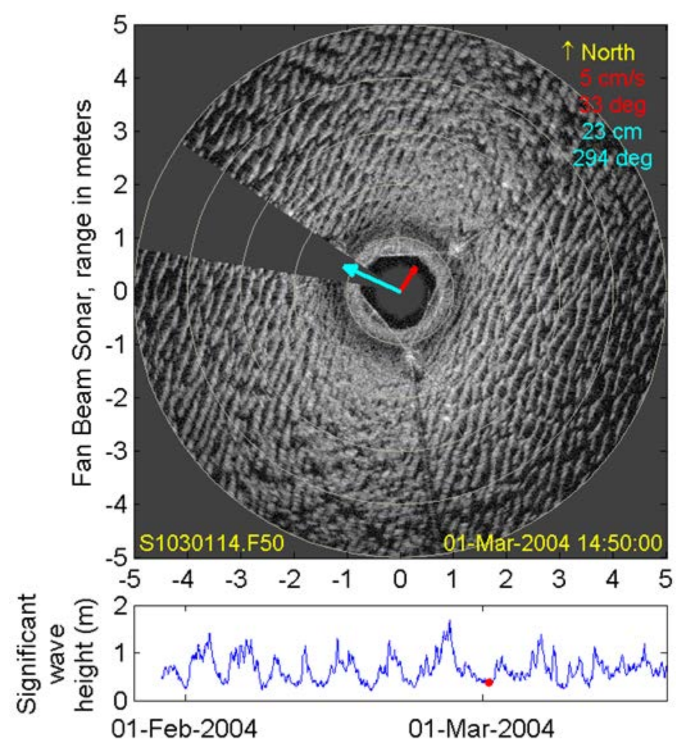


Figure 2. Fan sonar image with current direction and speed (red) and feature wavelength and direction (aqua, enlarged 5x) vectors overlaid. The bottom frame shows the wave climate during the experiment; the red dot indicates the time of the image.

velocimeters). We then translate the reported orientation of these instruments to the sonar head to determine the in-situ orientation of the sonar.

The two types of loggers store raw data differently. The WH logger saves data in a unique format, and the IRIS loggers output Imagenex “81a” format files. For fan data, both loggers can instruct the sonar to make multiple sweeps as part of a “sample” at each time interval. The WH logger stores all sweeps of a sample in a single file and the IRIS logger stores each sweep in a separate file. Similarly, all 60 rotational positions of a typical dual-axis profiling sample are stored in one file by the WH logger, but 60 individual files are written by the IRIS logger. These differences require for each logger a separate program to read raw files and organize the data prior to storing for use with post-processing routines.

We began to store our sonar data in netCDF (network Common Data Format)[2] in 2008. We use this portable, binary, self-describing format for all of our oceanographic data because it allows us to combine metadata with the data and publish it in a compact format accessible with open-source software. Unprocessed sonar data in our netCDF files are arranged as three-dimensional arrays, with dimensions of acquisition time, ping number, and range bin. The azimuthal head angle and profile range are saved in separate one-dimensional arrays. Metadata, including the deployment location, water depth, and operational settings for the sonar are saved as attributes that apply to the entire file. One file contains all the data for a single deployment of a fan or pencil sonar. The dual-axis profiling sonar generates more data (typically equal to 60 pencil images for each of 4 - 12 samples each day), so these data are stored in multiple files, each containing 1 day of data. These raw-data files are subsequently processed to generate images, profiles, or topographic maps of the bottom, depending on the type of sonar.

A. Fan (Imaging)

We typically configure the fan sonar to acquire 512 data points at azimuthal angle intervals of 0.3 degrees over 348 degrees. The location of sonar returns are, therefore, expressed in polar coordinates consisting of slant range (cm) and azimuth (relative to the sonar head orientation). The slant range can be converted to horizontal distance from the nadir point below the sonar head by using the elevation of the sonar head and assuming a flat bottom. The azimuth can be adjusted to true compass heading using information about the sonar orientation (discussed below). We map these polar coordinates to x-y coordinates by bin-averaging the amplitude of returns within selected x, y bins, typically with bin sizes of 0.02 to 0.05 cm. The optimal bin size varies with the azimuthal angle interval and the range. Larger bin sizes produce coarser images, and finer bin sizes tend to be noisy because they contain fewer returns, especially at longer ranges.

B. Pencil/Azimuth (Profiling)

We typically configure the downward-looking pencil sonar to acquire 512 data points at 0.3 degree intervals over 132 degrees, and each pencil scan is rotated 3 degrees for 60 steps. The primary advantage of the profiling sonar is that it allows the actual bottom height to be computed from the travel time. The raw data include an azimuth angle (or heading), a vertical angle, and return amplitudes as a function of travel time (which can be converted to slant range using the sound velocity). Firmware in the instrument provides an estimate of the strongest return along this range, which is called the “profile range”. The algorithm for choosing the profile range does not always provide the best estimate of distance to the bottom. Sometimes it is affected by objects along the sound path (sediment, fish), sometimes a bright acoustic reflection from a nearby target influences the returned value, and sometimes the bottom does not stand out clearly from background noise. We have developed methods based on the raw scan data that use information not available during data acquisition to make more robust estimates of the bottom location. For example, we can use information from previous or adjacent scans to restrict the range of bottom locations, or filter noisy data to help identify the actual bottom return.

Once we have determined the slant range, we can use that distance and the two angles to identify the x, y, z coordinates of a point representing the bottom return (or other strong reflector). After these geometry calculations are performed on scans from all of the different azimuthal and vertical angles, we have a point cloud of sonar returns. It is often easy to view this point cloud from various directions to visualize the bottom and tripod components, but extracting the bottom topography from the cloud often requires iterative calculations to remove points not associated with the bottom (tripod and water-column reflectors) and to combine the remaining points into a small-scale topographic map. We have written algorithms in Matlab™ that achieve this by a) fitting a surface to a subset of points in a range likely to contain the bottom, b) differencing points from this surface and excluding those too far from the surface, and repeating this sequence two or three times. We can also exclude points in regions we know contain tripod artifacts (feet, other instruments), allowing us to see past them.

V. Testing and Validation

We conducted several tests to address specific sonar-use questions. The first in-water test was conducted in 2007 with two objectives 1) determine if our software converts the raw data into a radial image correctly and 2) assess the resolution of the (new) profiling sonar. We deployed known targets around the tripod to confirm the image orientation and we placed a sandbox directly under the profiling head. Divers formed patterns with various wavelengths and heights in the sandbox that were captured by both sonars. The results allowed us to modify our image processing software to display the image correctly, and proved the profiling sonar accurately detected 5-40 cm wavelengths and heights as small as 5 cm. Longer wavelengths are within the detection limits, but did not fit in the sandbox.

The second test also had two components: 1) find the optimal configuration for use at our potential deployment heights (the sonar head was tested at intervals between 0.75 and 2 m above a sandy seafloor, corresponding to practical mounting elevations on our tripods), and 2) capture data with the new azimuth drive for developing processing software. The Imagenex real-time viewing and logging interface was used to interact with the profiling head, allowing us to observe the effects of installation height and gain on the returned images in real time. The optimal elevation for the profiling sonar on our tripods is about 1 meter above the seafloor. At this height, using range of 3 m, a gain of 20 dB, and a sweep span of 132 degrees, the data has strong returns without clipping. Clipping occurs when the returned amplitude saturates the analog – digital converter, causing it to return the maximum value, masking variations in the actual return. We used these settings for all subsequent deployments until the 2013 experiment in the Columbia River, where we mounted the profiling sonar higher (1.7 m) and increased the range to 5 m.

The geometry calculations used to locate the position of a sonar return require measurement of the angular orientation of the sonar head (called pitch, roll, and heading by analogy to a ship orientation). Accurately determining this orientation is difficult because the sonar has no precise reference marks, and our methods for attaching the sonars to the tripod are based on laser sighting alignment that may not ensure repeatable positioning. Even if the sonar is precisely oriented on the tripod, the tilt of the tripod as it sits on the seafloor can also affect the interpretation of the sonar data. Other parts of the tripods often appear in the images and can provide convenient checks on our geometry calculations, so we developed methods for precisely mapping the location of tripod components (feet, legs, cross-bars) and prominent sensors. In addition to uncertainties in the sonar head position, we also found that the angles indicating the scan direction of the fan beam sonar were offset and depended on the direction of the scan. It was apparent that the sonars required calibration tests to ensure the precise location of ground validation features.

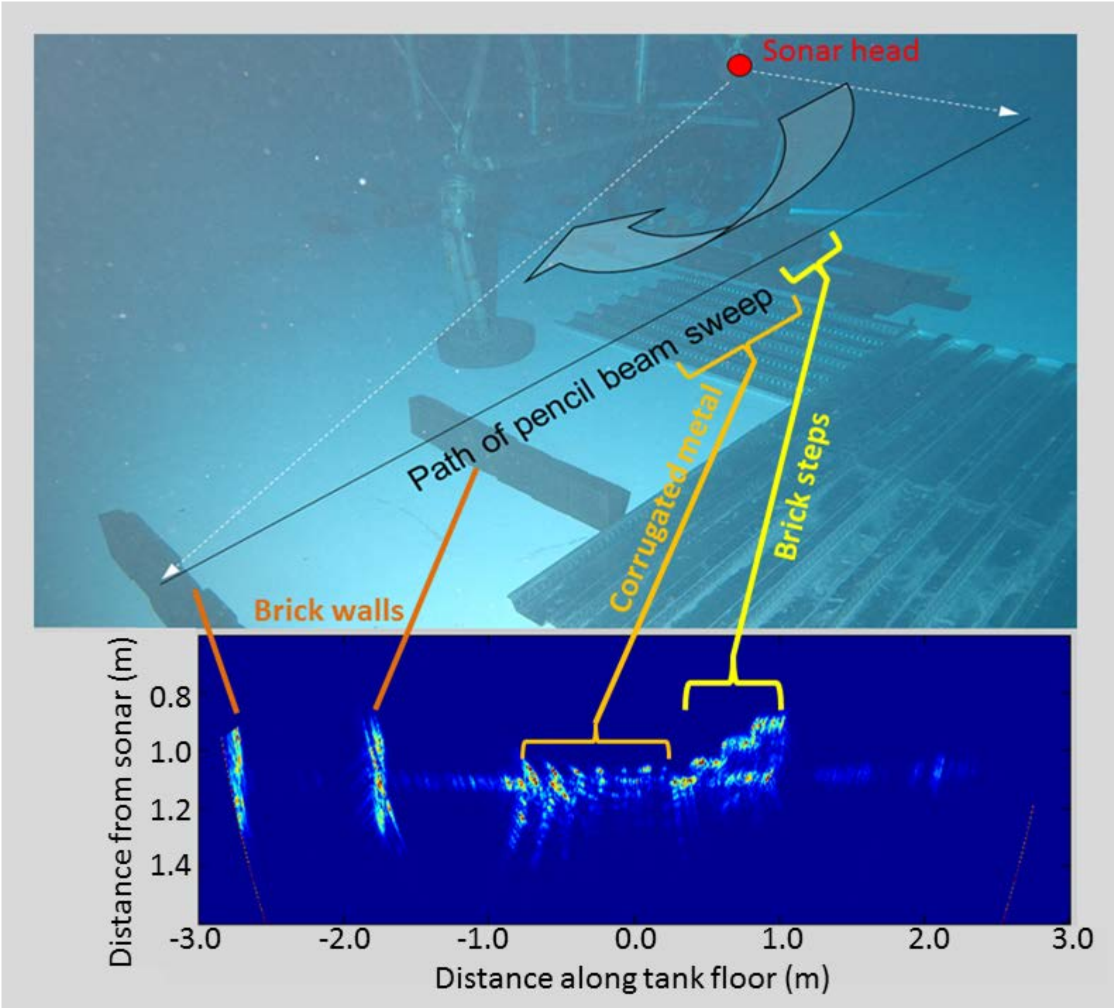
The third test focused on collecting a dataset where targets of various scales could be scanned and the tripod tilted by lifting one or more legs a known amount. The Ocean Engineering Department at the University of New Hampshire (UNH) has an outstanding facility with a tank large enough to submerge the tripod and operate the sonar at full range without reflections from the tank walls. This test [1] allowed us to measure the angular offsets and confirm that our geometry calculations were correct.

Our process for measuring and mapping the locations of instruments and other tripod components in relation to the sonars was refined during the UNH test. To start, the floor beneath the tripod is covered with paper or plastic sheeting on which measurements are recorded. We establish an arbitrary and convenient coordinate system, often aligned with the reported azimuth of the acoustic Doppler profiler. The origin and x- and y- axes on the plane of the floor are drawn with the aid of a line laser, T-squares, and straight edges. A laser plumb bob is used determine the nadir location of instruments or tripod features on the x, y plane of the floor, and tape measurements are used to determine elevations. The orientation of tilted sensors can be measured with electronic leveling devices or by mapping the projection of the instrument axis onto the floor with a laser pointer and comparing it with the nadir point. Once the x, y, z location of instruments and tripod features is mapped in a consistent coordinate system and the orientation of sonars and instruments with compass and tilt sensors is known, we plot these in three dimensions to confirm our measurements. Once the relative locations are established, we use the geometric principles of solid-body rotation and translation to relocate everything based on the external compass and tilt sensors.

Figure 3 shows the direction of the pencil sonar scan with the targets that should be detected, with the associated profiling sonar data corrected for a -2.4 degree sensor tilt. Colored lines connect the targets in the image with their representations in the sonar map.

The distances and heights of all targets were measured by divers, so we were able to evaluate the precision of our position estimation algorithms. The tilt-corrected image was used to obtain estimates of the precision and accuracy of the measurements. The map shows the tank bottom to be 1.1 m below the sonar, matching our measurements. The bricks piled at the right side of the scan were good reflectors. They were stacked in a ramp of 1 brick (20 cm by 6 cm) offset each layer, and the shape was detected accurately, but the edges were not well defined. Regardless of how the edge is determined, there is 2 cm of high-signal return for this target. The corrugated metal sheet in the center has peaks 5 cm high by 5 cm wide separated by 10 cm troughs. The shape and reflectivity of this target lead to larger than expected returns when the target peaks were hit obliquely. Each of the 7 peaks on the corrugated sheet is discernible, but the processed image suggests that they get progressively taller, further from the head, when they are actually of uniform height. The misleading 2 cm increase in height should be considered within the noise level. Finally, the stacks of bricks separated by 1 m horizontal distance on the left were detected successfully, though the second was barely within the range. This confirms that the sonar can actually detect targets at the horizontal distance we expect, accurate to within 5 cm.

Another factor highlighted in these tests was that where the features align with the direction of the fan sonar ping, resolution is poor, so with a consistent wave field, there will be 2 sectors of the image opposite each other that should not be used in computations. In figure 3, the corrugated metal sheet aligned perpendicular to the direction of the pencil sweep was poorly resolved in the fan images because the ridges and troughs are along the fan sweep direction.



VI. CONFIGURATION

Our deployment settings were obtained from the second test, and have remained the same once the settings that provide optimum data quality were found. The fan, pencil and azimuth rotation settings are shown in table 1.

fan						
height (m)	gain (dB)	LOGF (dB)	Absorption (dB/m)	Range (m)	pulse length (ms)	Freq (kHz)
0.65	16	20	0.06	5	10	675

pencil							rotations	
height (m)	gain (dB)	LOGF (dB)	Absorption (dB/m)	Range (m)	pulse length (ms)	Freq (kHz)	deg/ step	steps
1.1	20	10	0.6	3	10	900	3	60

Table 1- Settings used for fan sonar deployments shown (top) and settings for pencil/Azimuth deployments (bottom).

Although they operate at different frequencies, we do not try to sample the two sonars simultaneously to avoid potential interference. The original logger does this automatically, and the IRIS loggers have to be configured so the start time and duration of multiple sonars will not overlap.

VII. SYNTHESIS

We use several validation methods to ensure that the sonar images are correctly oriented. The first involves checking the orientation of a blank sector in the image, which allows us to identify the origin of the azimuthal coordinate. A second check is that identifiable features on the tripod appear in the correct locations, as determined by our pre-deployment measurements. Sometimes we attach an extra pipe on one leg of the tripod as a target for this purpose. Next, we evaluate whether the ripple orientation is reasonable in the context of any available measurements of wave and currents, diver observations, and large-scale regional surveys. Finally, we overlay onto the fan sonar images the profiles or small-scale topography determined from the profiling sonar, as both a check for internal geometric consistency, and as a product for interpretation. Examples of two images made during a month-long deployment on a boundary between fine sand (west) and coarse sand (east) at 12 m depth approximately two km south of Martha's Vineyard in fall 2007 are shown in Fig. 4. The earlier image shows uniform short wavelength ripples oriented northeast to southwest, and two days later, the seafloor has changed markedly, with much larger bedforms in coarse sand on the right part of the image. The bathymetric map for this period shows several large ridges

(~50 cm spacing, 6 – 8 cm high) that do not show up well in the fan images because they are almost parallel to the radial imaging direction.

VIII. Future Directions

We plan to continue to deploy autonomously operated sonars in our research programs. Several of the enhancements we hope to implement to improve the quality of our data are discussed in this section.

We would like to sample more often than is currently possible in autonomous deployments. Ideally we would like to acquire a complete map at half-hourly intervals over a typical deployment lasting three months. This will require a) faster scans, b) more power, and c) more memory for data storage. One solution for power and data storage is a cabled observatory, where power and internet are provided from land. Where cables are not available, lower-power operation or greater battery capacity is needed. Both types of logger are powered by similar capacity (100Ahr nominal) alkaline batteries. Lithium batteries could be used to provide more power, but are more difficult to ship and not as safe. The IRIS loggers have expandable memory, which we plan to use.

We plan to fabricate registration tabs for mechanical alignment, and jigs to hold measurement tools that should improve our ability to precisely orient the heads and increase pre-deployment tripod mapping accuracy. We would like to improve the precision of in-situ orientation data and plan to experiment with a micro-electromechanical system (MEMS) inertial measurement unit (IMU) for this purpose.

IX. Summary

Our standard practice is to deploy a fan sonar to image a 10-m diameter circle and a pencil sonar rotated by an azimuth drive to measure bathymetry on an overlapping 3-4 m diameter region. The fan sonar provides images from which the length and orientation of bedforms can be determined, and the pencil sonar provides a three-dimensional map of bedform topography over a smaller region. As we prepare the systems for deployment, we measure the location and relative orientation of instruments with internal compass and tilt sensors (for example, acoustic Doppler profilers) so that we can use their in situ measurements to determine the orientation of the sonars and, ultimately, reconstruct the location of the sonar returns in map coordinates.

We have been successful in characterizing the seafloor evolution in seven research programs, and capturing a wide range of conditions in which sediment may be moved by the local currents and waves. We use the synthesized sonar data to enhance ocean models describing sediment transport in the. coastal environment

X. Acknowledgment

We wish to thank Jim Irish and Robin Singer of the Woods Hole Oceanographic Institution for making our original logger. Marinna Martini from our group supported all the interim

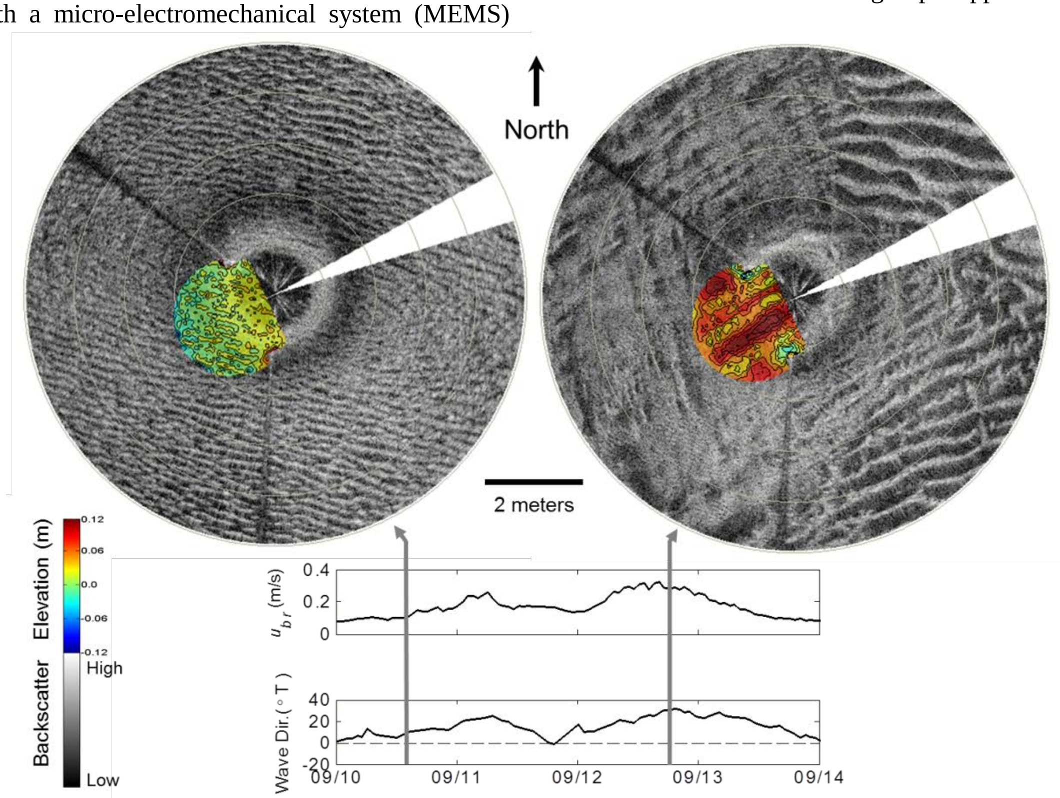


Figure 4. Composite images of fan sonar backscatter (grayscale images) and azimuth sonar topography (inset colored contour maps) made about two day apart in 12-m water depth about 2 km south of Martha's Vineyard, MA. Wave conditions (orbital velocity and wave direction) are shown in the time-series plot.

firmware modifications. Doug Wilson at Imagenex was very patient in providing support for the Imagenex sonars. Murray Clarke from ASL environmental provided insightful support for using the IRIS logger. The UNH Ocean Engineering department was very accommodating in letting us use the tank and supporting us in accomplishing our testing goals.

XI. References

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