SEAFLOOR MAPPING AND IMAGING EFFORTS USING AUTONOMOUS UNDERWATER VEHICLES

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Abstract

The Monterey Bay Aquarium Research Institute (MBARI) has been developing and operating Autonomous Underwater Vehicles (AUVs) since 2000, focused on performing mapping and characterization of geophysical and biological features of unique interest, located within and outside the Monterey Bay of California. This research has led towards efforts targeted at both large- and small-scale observations, in the range of meter to sub-centimeter resolution. Technologies needed to address these diverse requirements include a combination of both acoustic and visual data collection, coupled with accurate navigation tools and methods. The system incorporates multibeam sonar technologies that provide high-detail results. Single camera observations are available and stereo vision components are also under development. The ability to validate observations with remotely operated vehicles (ROVs) also provides an excellent method with which to ground truth target identification in unique environments. This paper will present our near-term results in developing an integrated acoustic and visual mapping capability, including testing in relevant terrains using ROV deployments.

Introduction

The Monterey Bay Aquarium Research Institute (MBARI) is a research center whose mission is to advance the knowledge of our oceans through the development of new and improved technologies for oceanographic research. The development of Autonomous Underwater Vehicle (AUV) systems at MBARI has been ongoing since 2000, and has resulted in both large diameter (53-cm) and small diameter (30-cm) systems designed for a broad range of science goals and engineering objectives. MBARI AUVs are used to conduct research in mapping, chemistry, biology, geology, and artificial intelligence. Currently operating two vehicles, the Dorado AUV group regularly conducts operations within the Monterey Bay, and also participates in expeditions the world over. This document reports on the design and recent activities of an AUV outfitted for seafloor mapping with multibeam, side scan, and subbottom sonars. Also discussed will be the development of an imaging payload, using single and stereo camera arrangements. A general overview of the *Dorado* class AUV platform needed to achieve this goal will be discussed, as well as some of the key products produced in recent expeditions.

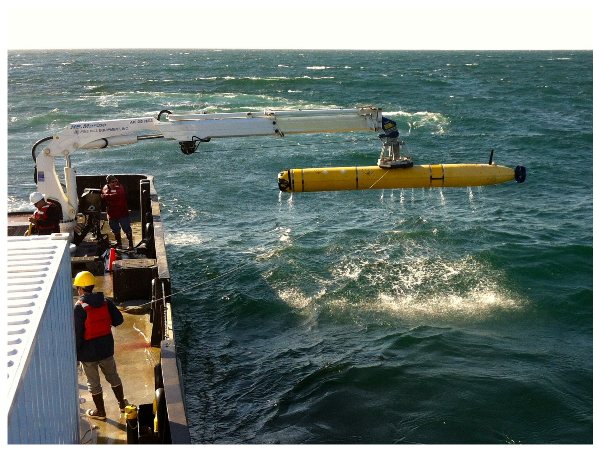

Figure 1: The *D. Allan B.* AUV during recovery at sea, using an overboard crane with an attached AUV capture head.

Background

Starting in 2000, MBARI engineers began design of an 0.53-m (21-in) diameter AUV class, called Dorado. A vehicle equipped to measure water properties began science operations in 2003. Simultaneously MBARI began development of a seafloor mapping vehicle which began regular survey operations in 2006.

The Mapping AUV, officially known as the D. Allan B., has now conducted 165 successful survey missions producing 1-m lateral resolution bathymetry, co-located sidescan, and chirp subbottom profiler data. The survey targets have been quite varied, including submarine canyons, seamounts, gas seeps, sub-surface hydrates, mid-ocean ridge spreading centers, deep-sea fan system, slumps, and shipwrecks. Although many operations have been in the Monterey Bay, particularly within Monterey Canyon, surveys have been conducted in the Gulf of California, along the continental margin from southern California to British Columbia, well offshore the Pacific Northwest along the Juan de Fuca Ridge, and in the western Pacific in the Lau Basin and offshore Taiwan. MBARI also maintains a number of Remotely Operate Vehicles (ROVs), which enables a unique science workflow. The MBARI mapping AUV is often sent in advance to create a meter-scale map, which is used to identify areas of scientific interest to be visited later in time by ROVs. This is an opportunity for increased ground truthing of sonar target identification, and is also a much more efficient method of conducting ocean exploration. The high level of detail that has been provided by this AUV class has led scientists to demand even higher detail maps and images.

Vehicle Configuration

Of the two fully functional Dorado class AUVs that MBARI operates, one is used solely in mapping and imaging configurations. This vehicle is named the *D. Allan B*, pictured in Figure 1. The vehicle is a torpedo shaped cylindrical hull, which measures 21 inches in diameter and averages 17 feet in length. Since this is a free flooding faired hydrodynamic shape, configuration for different operations is extremely flexible, limited primarily by instrument weight and size. All systems are rated to operate in up to 6,000 meters of seawater, and the deepest dive to date has been to 4000 meters. Along its length, the vehicle is comprised of modular sections which all have mission critical components. Figure 2 gives an overview of the typical mapping payload configuration. Three major sections exist: the nose, midbody, and tail.

The nose section holds 3 critical items. An Imagenex 881 scanning sonar used for obstacle avoidance. Also located here is a Seabird FastCat 49 CTD (conductivity, temperature, and pressure depth), whose data is used to calculate environmental acoustic sound speed for input to the acoustic multibeam system. Finally, the nose section carries two 17 inch diameter glass spheres, holding the battery payload of the vehicle. These two 5 kilowatt-hour lithium-ion battery assemblies provide the vehicle with enough power to conduct full survey operations for 17.5 hours at a speed of 1.5 meters per second.

The tail section holds the main electronics for communications and navigational sensors. The primary depth sensor, a Paroscientific Digiquartz, provides a highly accurate reading of the environmental pressure. The primary asset for navigation on the AUV is the inertial navigation system (INS) manufactured by Kearfott Corporation, referred to as the SeaDeViL. The SeaDeViL integrates the external pressure sensor, a position reported by an external GPS mounted in the vehicle antenna mast, its internal laser ring gyro, 3-axis accelerometers, and a 300kHz doppler velocity logger (DVL) using a Kalman filter to determine a highly accurate vehicle position. The Kearfott SeaDeViL, if properly aided, will experience drift less than 0.05% of distance traveled.

Other instruments in the tail help to provide control and communication. The vehicle is tracked by surface vessels using an ultra-short baseline (USBL) sonar system. In the AUV, there is a Sonardyne Wideband SubMini transponder the ship can interrogate to determine position. The same mast that houses the GPS antenna also contains antennae for an Iridium satellite link and for a wireless data radio link back to a nearby vessel when the vehicle is at the surface. The data radio link provides low bandwidth network access to the vehicle for mission programming and final system checks prior to mission start. This takes place after the vehicle has been deployed from the ship and is floating on the ocean surface. While underwater, a Benthos acoustic modem is integrated to provide the ability to send navigational fixes as well as a limited set of mission re-tasking commands. Mission aborts can be sent to this device or the tracking beacon, which energize a burn-wire attached to drop weight. The tail section also houses the center of propulsion and steering. The propeller and its surrounding duct can articulate as a pair and provide the vehicle's sole dynamic control surface. All of the above items communicate and log in the main vehicle controller (MVC) housed in another 17 inch glass sphere in the tail. This MVC is the central processing unit for mission execution and adaptive control.

The nose and tail sections of this vehicle comprise the mission critical components identified for all vehicle operations. The remaining mid-body section, aside from serving as the structural lift-point, houses the primary scientific sensor payload. Currently the *D. Allan B.* supports two arrangements; one for acoustic mapping and survey, and another for benthic digital imaging. The acoustic mapping suite is comprised of an EdgeTech FS-AU dual-frequency (120/410kHz) sidescan system and a 1 to 16kHz subbottom sonar chirp system. A Teledyne-Reson Seabat 7125 system provides highly accurate multibeam sonar records, which is the primary data collected during survey operations. The multibeam sonar can operate at 200kHz or 400kHz, for

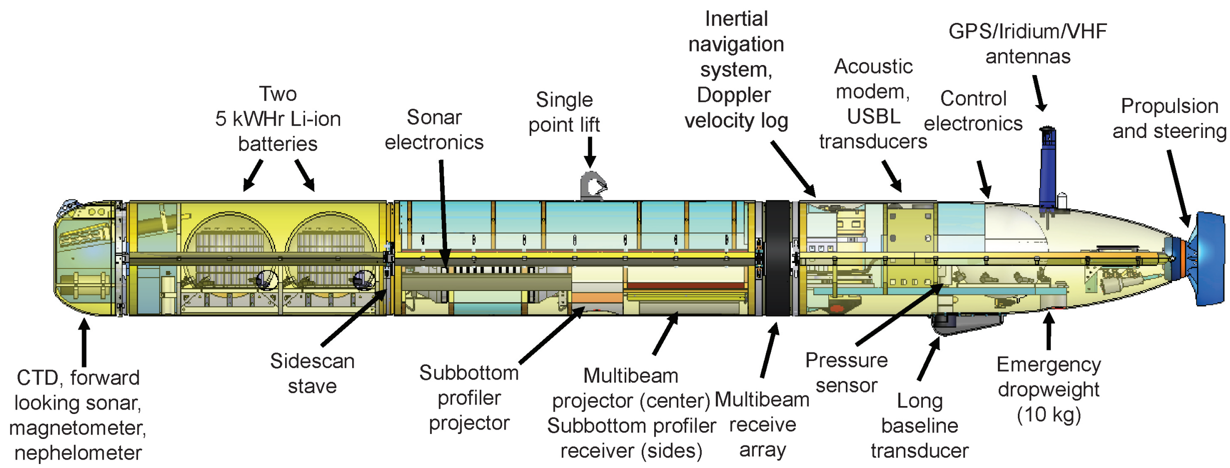

Figure 2: Design of the *D. Allan B.* Dorado class AUV used for seafloor mapping.

high or low altitude operations, respectively. Typically the D. Allan B. operates at a 50 m altitude, yielding 1-m lateral resolution multibeam bathymetry and chirp sidescan. Following data processing, the achieved vertical precision of the bathymetry is 0.1 m. The other sonar systems commonly provide context and aid in target identification. This mid-body has been highly productive for MBARI in collecting a wide range of survey information.

Developed more recently, the benthic imaging mid-body is a payload aimed at collecting along-track imagery from the Dorado platform. Currently this section holds a single digital camera, an off-the-shelf Nikon D3 with an 24mm wide-angle lens packaged with corrective optics design for a field of view of 74 degrees horizontal degrees. This camera can trigger a pair of Model 3831 Ocean Imaging Systems strobes with a combined light output power 200 Joules. Acquiring images at 0.5 hertz is a typical mode of operation, at a vehicle altitude of 3 to 5 meters. At 3 meter altitude the camera can image a patch of seafloor that is 4m wide by 2.1m long. Strobes are placed fore and aft of the camera for an optimal broad light field, and improved light to camera separation helps reduce backscatter as well. Also onboard are twin parallel lasers mounted inline with the camera's lens to provide image scale measurements.

High Resolution Results

All of these systems together present extremely high detail results in their data. Operations in recent years have produced excellent examples presented here, using the *D. Allan B.* AUV. The ability to visit some of these sites with an ROV further proved the effectiveness of this system to identify areas of interest for further scientific studies. All seafloor mapping data presented here were processed using MBSystem, an open source software package. [1]

Repeat Mapping of Axial Lava Flows

In 2011, as part of a multi-vessel expedition to the Pacific northwest, the *R/V Zephyr* was tasked with operations to study areas of interest in the Juan de Fuca Ridge spreading zone using the *D. Allan B.* AUV. Previous mapping in this area had taken place in 2006-2009. In July 2011, the remotely operated vehicle *Jason* detected a new flow had taken place, later dated to have occurred in April 2011. The *D. Allan B.* was tasked to re-map the areas from pre-eruption surveys.

These repeat bathymetric surveys of Axial Seamount produced data that allowed MBARI researchers to create 1 meter resolution maps, and compare these new maps against previous ones. Contrasting these data resulted in a map of the extent of new lava flows in the region. This map was used to identify features such as flow thickness, as well as lava eruption points. Some of these points were old fissures, tectonic fractures and collapse features. [2]

Discovery of New Vents in the Gulf of California

In March and April of 2012, MBARI performed AUV mapping operations in the Gulf of California [5]. Eleven missions were conducted along the volcanically active area known as the Alarcon Rise. This is an oceanic spreading segment 50km in length, and marks

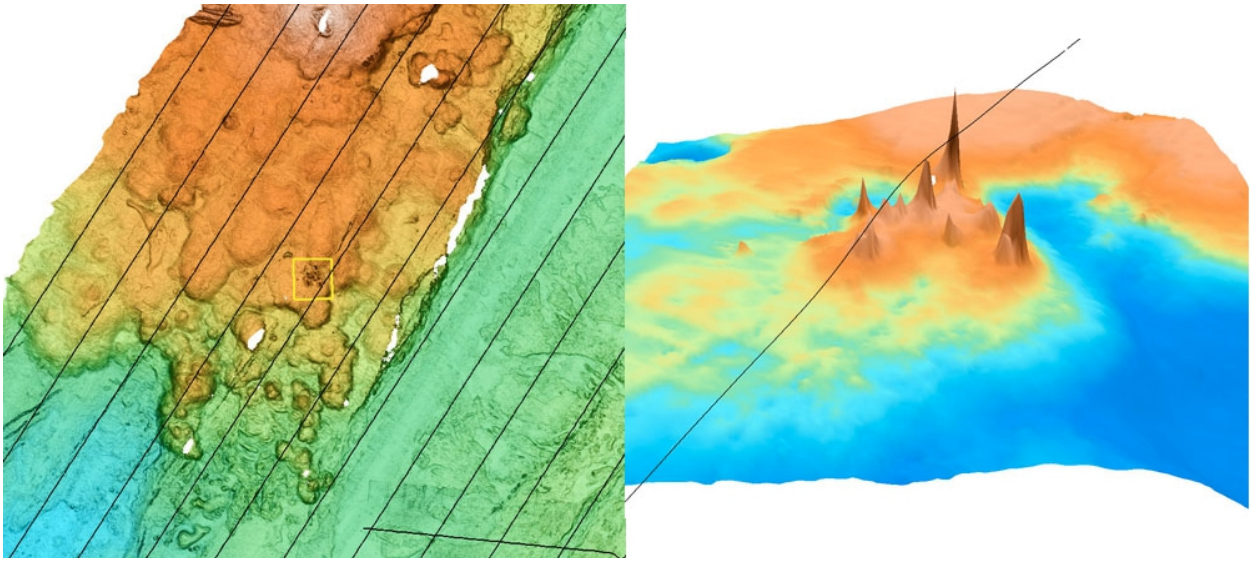

Figure 3: Multibeam AUV survey featuring the discovery of a new hydrothermal vent system on the Alarcon Rise. Left: Slope shaded 1-m resolution bathymetry with AUV tracklines at 150 m spacing. The area of interest is shown by the yellow box. Right: 3D view of the area of interest showing apparent hydrothermal vent chimneys later verified by an ROV dive.

the north end of the East Pacific Rise. These data were collected in order to support morphology studies looking at lava flows and other geological features. [3]

To demonstrate the high resolution capabilities of this system, one survey from this expedition is of particular interest. Figure 3 is a subset of one survey, and the black lines represent the vehicle track on this topography image. The image on the right is a zoom of the yellow box in the left view, approximately a 60m by 30m area. The sharp features here represent a single pass of the 200kHz multibeam sonar. Identified as a unique target, the *ROV Doc Ricketts* later visited the site which led to the discovery of a previously unknown set of active hydrothermal vents, complete with large chimneys as pictured in the data.

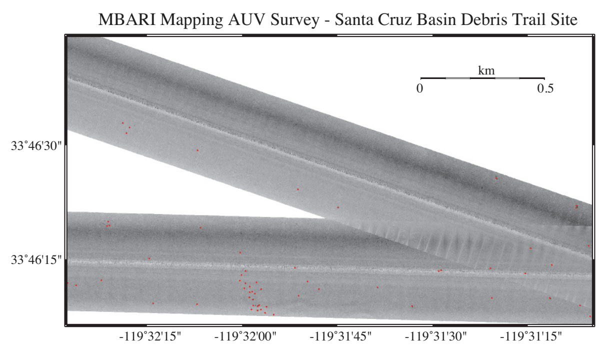

Figure 4: Low-Frequency sidescan (120kHz) identification of surface debris target in Santa Cruz Basin.

Seep Exploration in Southern California

In March 2012, the Dorado AUV in mapping configuration was used to conduct surveys of the Santa Monica and Santa Cruz basins. In the Santa Monica basin, missions were planned to extend surveys conducted by MBARI in conjunction with the USGS in this area during previous years. AUV survey data was used to characterize sites of interest such as geological fault locations, methane seeps and associated benthic biological communities. These extended surveys led to newly discovered methane venting sites. Identified as a common texture in the multibeam records, these vents are characterized in the multibeam by their carbonate formations. Figure 5 depicts an example of a carbonate mound and its distinctive texture as shown in the multibeam data.

Also on this expedition, the AUV team was directed to analyze data from the sidescan sonar to identify targets in a charted area designated as a former US Navy trash disposal site. This area was in the Santa Cruz Basin area, and Figure 4 is an example of some of the data from the 120kHz sidescan record. Debris targeted for ROV investigation is highlighted here as red dots. Later investigation by the ROV *Doc Ricketts* proved these to indeed be manmade waste deposits, which

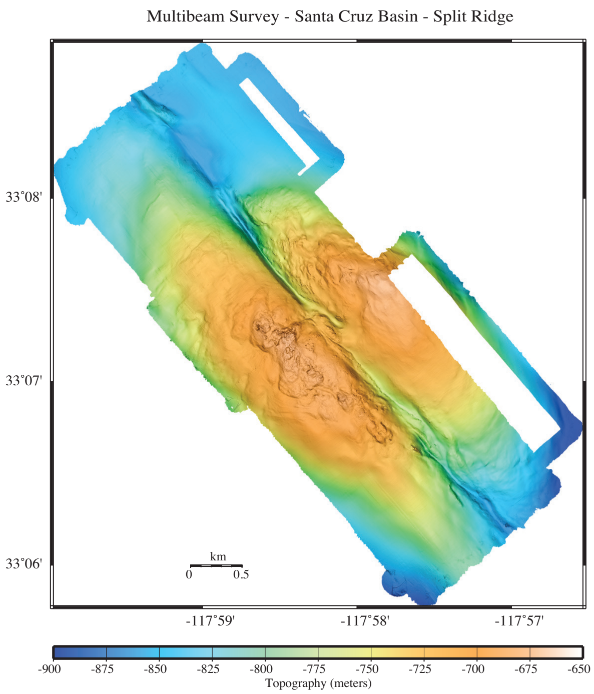

Figure 5: AUV multibeam bathymetry survey from a single mission. This area offshore southern California, called "Split Ridge", includes both the currently active San Diego Trough fault and authegenic carbonate outcrops associated with methane gas venting.

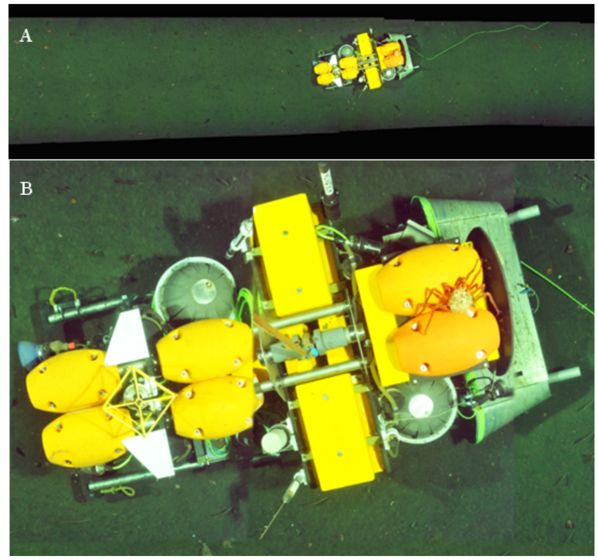

Figure 6: Benthic imaging mosaic (A) and single frame image (B) of the MBARI Benthic Rover taken from the *D. Allan B.* AUV.

ranged from 10cm to 2m sized objects.

Benthic Imaging

The benthic imaging payload discussed at the end of the *Vehicle Configuration* section has also produced interesting results. The primary science driver of this engineering development has been to study sub-meter benthic features for study of geological and biological communities. Figure 6 highlights one of the first successful benthic surveys in which a single run caught part of another MBARI vehicle, a bottom crawling benthic rover. These data were taken in December of 2009. One conclusion from these experiments was the knowledge that vehicle low-altitude control needed to be improved if rougher terrains were to be imaged. Following the bottom at 3 to 5 meters with a vehicle 5 meters in length has proven to be a significant control system challenge.

Future Efforts

In recent years, a group of engineers at MBARI have been developing the necessary components and techniques to begin merging benthic imaging and multibeam mapping into a survey system. This system targets development of data set with centimeter level resolution. One goal of such a system would be to help better understand fine-scale geomorphology and repeat surveys of areas in the Monterey Canyon will help determine subsea canyon dynamics. Also of interest to these studies are biological ecology studies of productive areas, and repeat surveys in these types of communities will shed light on population changes. Given the typical suite of oceanographic sensors also present on the *D. Allan B.* AUV, many conclusions may be possible from such detailed data.

To begin, techniques and testing have been conducted using remotely operated vehicles as a test bed. Developed as a specific new structural vehicle base, this arrangement can be attached and removed from the ROV *Doc Ricketts* easily. For this configuration, the key components are a new Reson SeaBat 7125 400kHz multibeam sonar, the Kearfott INS, the OIS Strobes from the benthic imaging payload, and a new pair of cameras for stereo imaging. The cameras are 2.8 megapixel Prosilica GX1920 model color machine vision cameras. Complete with corrective optics, these housings use a 5mm lens and 2/3" CMOS to yield a 95 degree field of view. At 2m altitude there is a 3.5m wide by 2.6m long image of the seafloor. Previous efforts have proven the success of subsea stereo imaging for fine scale detail. [4]

To test this system, sites of future interest have been identified in the Monterey Canyon. Data collected from

ROV will be compared against future data as this sensor configuration is integrated into a new AUV payload. Figures 7 and 8 illustrate these data. Notice the high level of texture in the lower left quadrant of the multibeam backscatter sonar image that corresponds to a dense clam community pictured in the mosaic. This type of result helps support the prediction that a synthesized set of sonar and stereo data will produce a higher quality result than seen from the independent sources. Another example of small area survey techniques which displays more vertical relief is presented in Figure 9. This figure highlights an 80m by 80m area containing sand waves. Notice how contours pictured here resolve features at a centimeter scale. This level of detail proves detection of small-scale geological change will be observable.

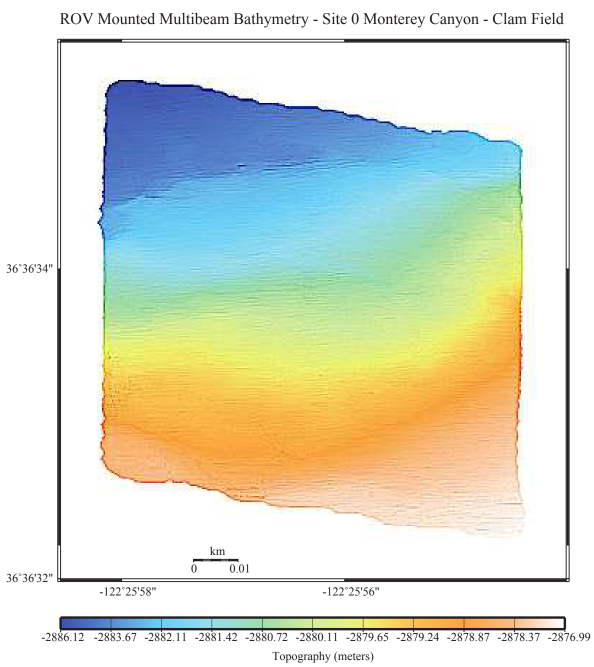

Figure 7: Multibeam bathymetry of a clam field collected using the ROV *Doc Ricketts* in the Monterey Bay. Surveys from 2-m altitude yield 5-cm lateral resolution bathymetry.

Conclusions

AUV technology has proven to be a reliable method of which to gather high-resolution survey data not obtainable from conventional shipboard systems. The *D. Allan B.* AUV itself has been very successful in detection of unique targets in varying ocean environments. This AUV now employs a mixture of multibeam, sidescan, subbottom, and imaging technologies to identify

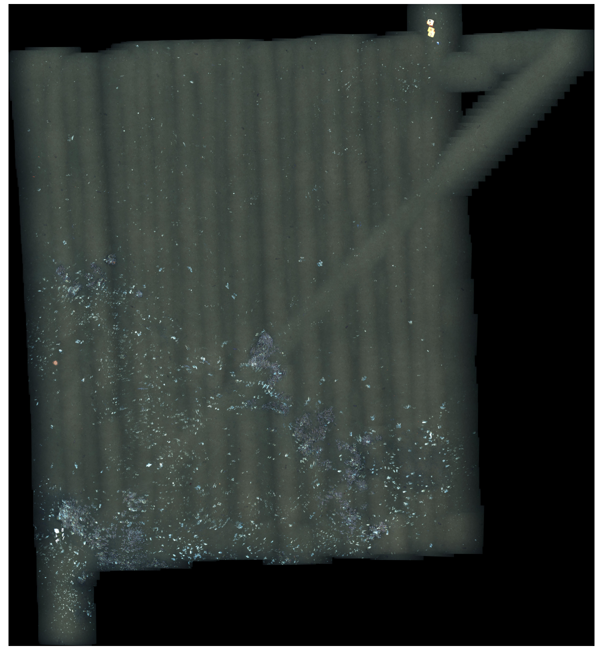

Figure 8: Image mosaic of a clam field gathered using the ROV *Doc Ricketts* in the Monterey Bay.

targets on a large scale. With imaging and even finer scale sonar observations the same AUV can now return to sites of interest and conduct small-scale surveys, effectively able to ground truth large scale observations. MBARI continues to be committed to carrying this technology forward and expanding the many capabilities available from AUVs.

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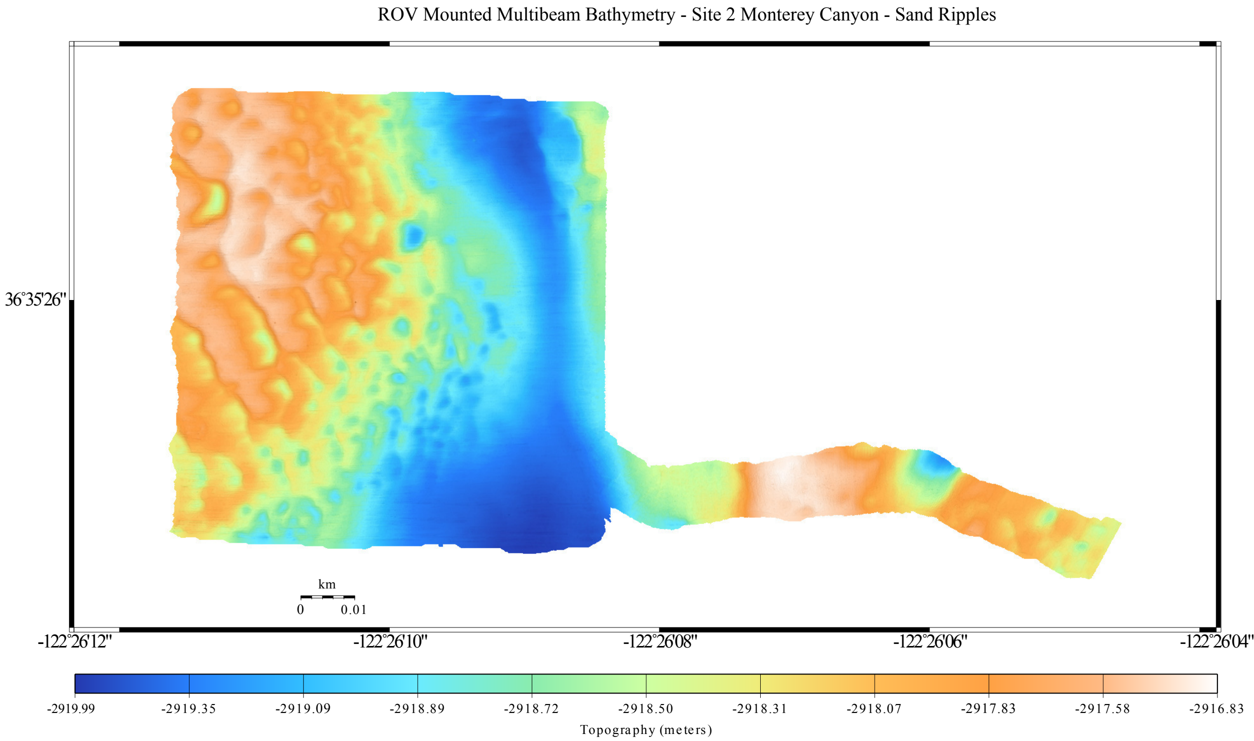

Figure 9: Multibeam bathymetry of large sand waves collected using the ROV Doc Ricketts in the Monterey Bay. Surveys from 2-m altitude yield 5-cm lateral resolution bathymetry; in this case very fine-scale features are revealed that may be depositional or erosional, and will be the subject of future ROV dives.

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