MBARI Mapping AUV Operations in the Gulf of California 2015

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***Abstract*-The Monterey Bay Aquarium Research Institute (MBARI) has conducted high-resolution multibeam bathymetry, sidescan, and subbottom sonar surveys in the Gulf of California and offshore northern Baja California using an autonomous underwater vehicle (AUV) as part of a four-month, two-ship oceanographic expedition, Fig 4. The seafloor mapping AUV D. Allan B was operated from R/V Rachel Carson, achieving 21 successful surveys during February and March 2015, operating to a maximum depth of 3800m. The 1-meter lateral resolution bathymetry maps and subbottom profiles were used to guide subsequent ROV Doc Ricketts dives made from MBARI's R/V Western Flyer, which combined visual surveys, sampling, and in situ experimentation by several different science groups.**

The vehicle is a modularized Dorado Class 53 cm (21 inch) diameter, 6.4 meter (21 feet) length, 770 kg (1700 pounds) air weight. The interior of the AUV floods with water when launched; electronics are contained in either one-atmosphere hermetic housings or in pressure-compensated enclosures. The AUV is ballasted to be approximately 3.63 kg (8 pounds) positive in seawater. Flotation is accomplished with 6000 meter rated syntactic foam. The D. Allan B has three mapping sonar systems onboard: a Reson 7125 200 kHz multibeam sonar, an Edgtetech FS-AU Sonar Package which includes 110/410 kHz chirp sidescan and 1-6 kHz chirp subbottom profiler. The Mapping AUV has 10 kWhr of lithium-ion batteries achieving about 16 hours endurance at a speed of 1.5 meters per second, for a maximum range of about 85 km. The Mapping AUV is equipped with a Kearfott inertial navigation system (INS) with Doppler velocity log, a Paroscientific pressure sensor, and an ultrashort baseline (USBL) and acoustic modem for communications and navigation. It also has an Iridium Satellite Short Burst Data modem, a drop weight, radio direction finder, Homer Pro sonar beacon and visible strobe location aids for emergency relocation. Propulsion is accomplished with a duct-protected articulated propeller which provides 52 Newtons (12lbf) of thrust at 300 rpm as well as elevator and rudder functions. The turning diameter is less than 20 meters; climb/dive rate is between 30 and 60 meters per minute.

Launches and recoveries were made from the R/V Rachel Carson, a 41.1 m (135 ft) length, 10.4m (34 ft) beam former oil-field supply boat that operates with six crew and six science personnel, Fig. 1, Fig 3. It is outfitted with an AK25 sea crane for AUV launch and recovery, as well as a PM43 main crane for overboarding a remotely operated vehicle (ROV). Once the AUV is in the water, the mission is sent from a computer on the Rachel Carson to the AUV over a wireless Freewave Ethernet link. At the start of the mission, the AUV spirals down to the start-of-line while receiving USBL-based position updates from the support vessel over the acoustic modem. Once on bottom, the support vessel is free to perform other operations. A Bottom Pressure Recorder used to provide in situ tide data for bathymetry correction was deployed prior to most of the AUV missions, and recovered afterwards, using an AVTRAK beacon to burn an anchor release wire.

The seafloor mapping data were processed using the open source software package MB-System, developed at MBARI and the Lamont-Doherty Earth Observatory. Post-processing steps include interactive bathymetry editing and tide correction. Survey navigation is adjusted so that bathymetric features match in overlapping swaths, yielding navigation with relative precision equivalent to the 1-m bathymetric lateral resolution. Sidescan data are corrected for 3D grazing angles using the 1-m resolution bathymetry.

I. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) are programmed at the surface, then navigate through the water on their own, collecting data while underway. MBARI AUVs can measure physical characteristics of the water, such as temperature, salinity, and dissolved oxygen, detect chlorophyll from microscopic marine algae, and measure concentrations of small particles in the water, map the

Fig. 1. AUV Launch from RV Rachel Carson

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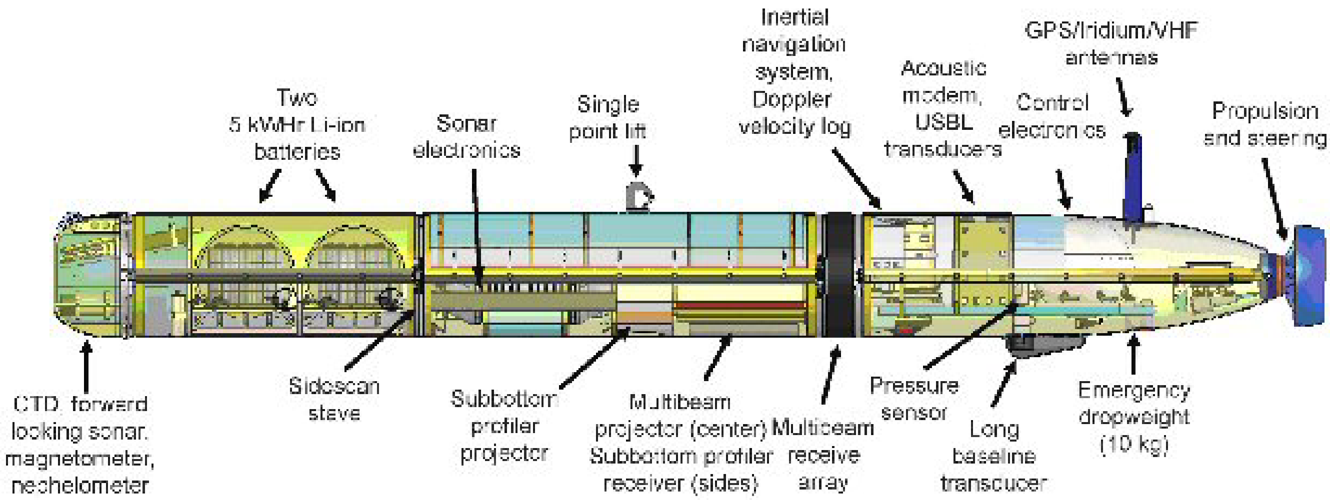

Fig. 2. Interior View of the D. Allan B Mapping Autonomous Underwater Vehicle

seafloor and collect images of the seafloor and the midwater.

A. *Mapping AUV Description*

The D. Allan B. Mapping AUV, Fig. 2., named after MBARI's late, long-time board member, D. Allan Bromley, is a Dorado class vehicle with a diameter of 53 centimeters (21 inches) and a length of 6.4 meters (21 feet). The vehicle's weight in air is 770 kilograms (1700 pounds); full of seawater it weighs 1018 kilograms (2240 pounds). It is typically ballasted to 3.63 kilograms (8 pounds) positive buoyancy prior to launch.

Main power is provided by two one-atmosphere Lithium Polymer battery stacks (manufactured by Eagle Picher Inc.) with a capacity of 308 Amp-Hours. A 24 VDC backup battery pack runs the Radio Direction Finder beacon, GPS receiver, Iridium transmitter and the strobe; it has enough capacity to operate for up to one week.

Propulsion and control is accomplished with a propeller enclosed in a ducted tailcone mounted on a gimbal; the AUV has no other control surfaces. Stepper motors with Acme leadscrews move the tailcone horizontally and vertically, and a brushless DC motor drives the propeller, providing 52 Newtons (12 lbf) of thrust at 300 revolutions per minute. The tailcone's electronics and motors are pressure-compensated with mineral oil.

The AUV has three sonar systems onboard. The Reson 7100 Multibeam generates data at 1 meter resolution when flying autonomously at 50 meters altitude. The Edgetech Sidescan sonar operates at 110 and 410 kHz, imaging the seafloor at approximately 10 cm resolution. The Edgetech Subbottom Profiler, operating at 1 to 6 kHz, can image features up to 50 meters below the seafloor with 20 cm resolution.

Ancillary instruments include the Seabird SBE-49 FastCat, a conductivity and temperature sensor, used for sound velocity calculations. The temperature sensor in the SBE-49 has indicated plumes of hot water from hydrothermal vents and chimneys. A pressure sensor, the Paroscientific UCB7000, provides precise depth information; it has a 7000 meter depth rating, and 0.005% full scale accuracy (35 cm) accuracy.

The Mapper's navigation system includes the Kearfott SeaDevil Inertial Navigation System (INS), a 24 centimeter ring laser gyroscope, an RDI 300 kHz Doppler Velocity Log (DVL), an Ashtech GPS receiver (which operates while the AUV is at the surface), and a Kalman filter which integrates data from the navigation instruments. The acoustic modem system transmits position fixes from the ship to the AUV during descents on dives deeper than 200 meters. Navigation position accuracy is 0.05% DT CEPR (Distance traveled, circular error probability). Heading accuracy is 0.1 degree. Roll and pitch accuracy is 0.025 degree.

Communications from the surface vessel to the AUV while on the surface is accomplished with a Freewave Ethernet link at 57.6 kilobits per second. Once the vehicle dives, communications is via a Benthos ATM-891 acoustic modem, running at 8 to 15 kHz bandwidth.

Fig. 3. Rachel Carson and BPR Recovery from Drone

Vehicle location aids include a visible strobe, a radio direction finder beacon, a PTT Argos satellite radio beacon, an Iridium satellite system transceiver, and a Homer Pro acoustic transceiver. A 10 kilogram (22 pound) dropweight can be released from either the onboard computer or via acoustic command.

B. Bottom Pressure Recorder

Prior to starting the Mapping AUV missions, the team deploys a bottom pressure recorder. The recorder is mounted on an elevator equipped with a sonar-detachable anchor. The data is retrieved after recovery, which allows tidal variations to be removed from the sonar mapping data during processing.

C. Mapping Mission Planning

MBARI AUV technicians plan missions by using the application MBgrdviz, which is part of the MB-System software suite. The operator defines a box on an electronic chart, and the software constructs a "lawnmower pattern," which fills the box with waypoints and a survey line of AUV tracks that will allow the sonar returns to slightly overlap.

II. TYPICAL MISSION

About an hour before launch, the AUV crew runs through the pre-launch checklist, performing physical checks, making sure all the systems are working and insuring there is enough disk storage space for the sonar data which will be collected. The sonars ping at 2 Hz, resulting in 200 Mbytes of data every 20 minutes.

When the Rachel Carson arrives at the launch point, the

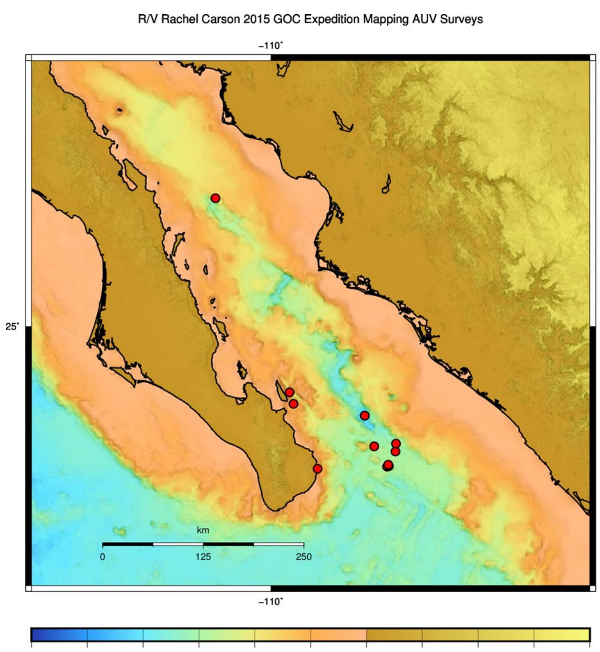

Fig. 4. Gulf of California AUV Mapping Sites

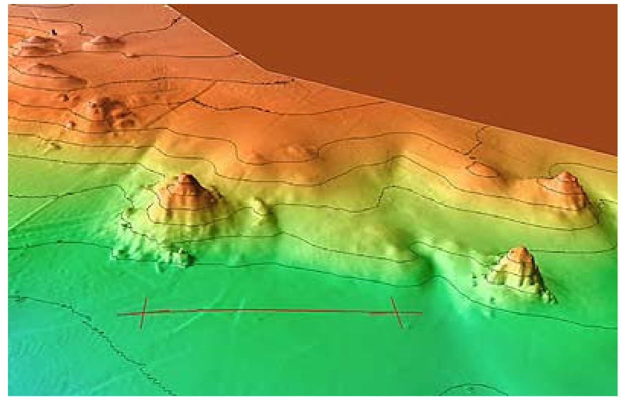

Fig. 5. AUV Bathymetry Map

AUV technician turns off the deck power supply and removes the tether; the onboard batteries then power the AUV. The AUV is unstrapped and the deck crew positions the sea crane over the AUV and latches the crane's hook into the lifting bail. The crane lifts and positions the AUV just above the surface of the water, and when a crew member pulls on the crane hook line, the AUV is released.

The mission is initiated by sending the mission script from the control laptop computer across the Freewave ethernet link to the AUV. The AUV goes through initialization of all instruments, gets GPS fixes, spins the propeller, turns into the correct direction, and dives to fifty meters. The AUV swims to the planned descent location and starts spiraling down.

During the descent, the acoustic modem sends position updates to the AUV. The ship's GPS position is combined with the AUV's known location relative to the Rachel Carson via USBL, and the modem sends the calculated position information to the AUV. Once the AUV is approximately 50 meters from the seafloor and bottom lock achieved, the mapping portion of the mission is initiated by acoustic command.

The mission typically lasts 16 hours, limited by battery capacity. During the mission, the AUV's progress is usually tracked with the USBL system, although it isn't strictly required to continuously monitor the AUV; other ship operations can be performed during an AUV mission.

At the end of the mission, or upon acoustic command to abort, the AUV powers up to the surface. If the batteries are depleted, the AUV floats up unpowered. The Rachel Carson stands off the predicted surfacing location to avoid collision.

III. RECOVERY

When the AUV reaches the surface, it transmits a radio direction finder signal and flashes a strobe. Every fifteen minutes, it transmits the AUV's current Lat/Lon position in a Short Data Burst transmission to the Iridium satellite network.

Fig. 6. Sulfide Flange Chimney

Upon arrival at the pick-up location, the engineer readies the crane, and the captain positions the Rachel Carson so that the AUV is located just off the port stern. A crew member with a fending pole prevents collision with the ship, and using a weighted line, another crew member guides the crane hook into the AUV's lifting bail. The crane lifts the AUV, the water drains out, and the AUV is brought back on board and secured into the deck cradle. Technicians rinse the nose CTD instrument with fresh water and install the deck tether. The ship's power supply then takes the load off the batteries. Data is download onto the control laptop and checked for navigation, control, and scientific data. If a re-launch is scheduled, a high current charge is started, which takes about 5 hours if the batteries are completely discharged. Data processing begins during the charge process.

IV. Data Processing

MB-System is an open-source software package consisting of programs which manipulate, process, list, or display swath sonar bathymetry, amplitude, and sidescan data. The raw sonar data is processed to generate maps of the seafloor bottom and sub-bottom. Tide variations are also removed from the data. Pixel size is 1 meter.

A. Bathymetry Editing

Mbedit and Mbeditviz are interactive bathymetry editors used to remove extraneous soundings or artifacts, such as caused by the USBL or the acoustic modem. The user flags suspect pings which are then excluded from further processing, but the raw data are retained.

B. Navigation Adjustment

Accurate navigation is necessary in seafloor mapping. Precise location of features on the seabed as well as placement of features in relation to each other in overlapping swaths are essential. Vertical offsets due to pressure sensor accuracy as well as tidal variations cause artifacting. Mbnavadjust allows the user to determine offsets required to match features.

C. Bathymetry Gridding

Mbgrid maps processed swath bathymetry data into a uniformly spaced grid, calculating location and size of each pixel with sonar geometry, altitude, and angular beam widths. Resolution greater than raw data is obtained by using a weighting value for each pixel that partially or fully lies within the beam footprint.

D. Sidescan Processing

This is performed after bathymetry editing and navigation adjustment. First the data is located on the seafloor using the AUV multibeam bathymetry, then corrected for amplitude variation with grazing angle using an average. The imagery is then mosaiced for look angle and swath position.

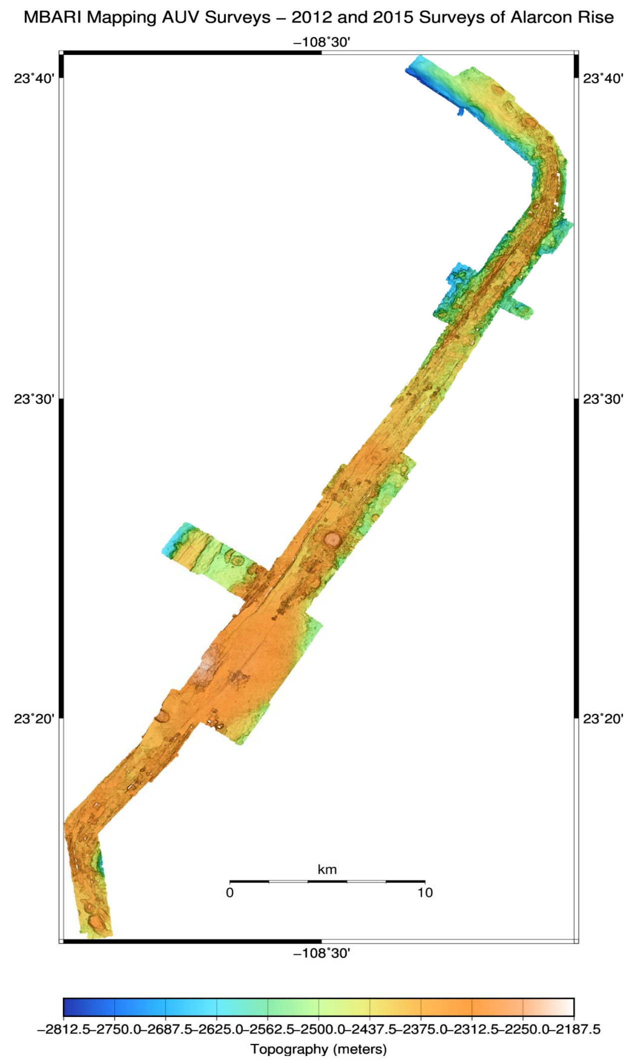

Fig. 7. High Resolution Map of the Alarcon Rise

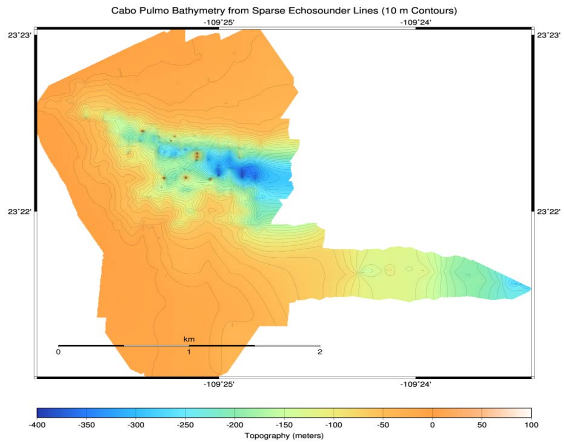

Fig. 8. Shipboard mounted sonar map of Los Frailes canyon.

E. *Subbottom Profiler Data*

Subbottom data is extracted to line files in the SEGY seismic data format, allowing profile sections to be plotted either within MB-System or with other software which works with seismic reflection data.

V. Results

Following the generation of high resolution maps from the AUV, the ROV Doc Ricketts on the Western Flyer examined areas of interest depicted in the maps.

Several surveys were completed on the Alarcon Rise to fill in areas which were not completely covered during the 2012 seafloor mapping expedition, Fig. 7.

Los Frailes canyon, south of Cabo Pulmo, had been previously mapped with shipboard sonar, which appeared to indicate several small seamounts in mid-channel, Fig. 8. But when the higher resolution AUV maps were generated, it was discovered that the apparent seamounts had been artifacts, Fig. 9.

Using bathymetry maps from the AUV, the deepest (3685 m) hydrothermal vents in the Gulf of California were located on thick sediment in the Pescadero Basin, which is 3800 m depth, Fig. 5. The vent field is at least 400 meters along a fault on the western edge of the basin. Three active chimneys were discovered, up to 12 meters (40 feet) tall, and dozens of low mounds, perhaps collapsed chimneys. Vent communities feature a mix of animals from seep and black smoker settings. This is only the second place in the world known to have carbonite chimneys, instead of sulfide-based chimneys; the other is in the Mid-Atlantic Ridge. Sulfide flange-like chimneys were discovered. The flanges trap hot vented water underneath, shimmering like a rippled mirror, with upside-down waterfalls of hot water rising around the edges, building the flange outward as minerals precipitate out, Fig 6.

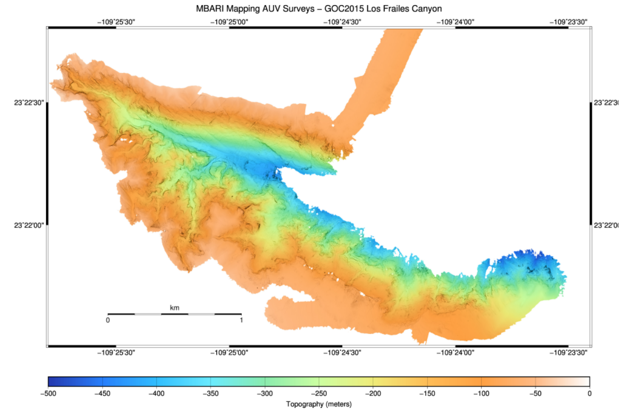

Fig. 9. High resolution map of Los Frailes canyon

Most underwater volcanic domes are composed of basalt, which being low in silica content forms smooth pillow-like formations, usually erupting at a temperature of 1100 to 1200 degrees C. To the south west of the Pescadero Basin, the eastern-most of the Alarcon Seamounts feature a volcanic dome composed of rough and corrugated rhyolite, a silica-rich mineral which is unusual to find in an underwater setting. Rhyolite erupts at 800 degrees C, and is associated on land with volcanoes which are explosive and hazardous. By carbon-dating microfossils in the sediment, the dome is thought to be 25,000 years old.

Surveys were also completed on the way back to Moss Landing, just south of the USA/Mexico boarder, Fig. 10.

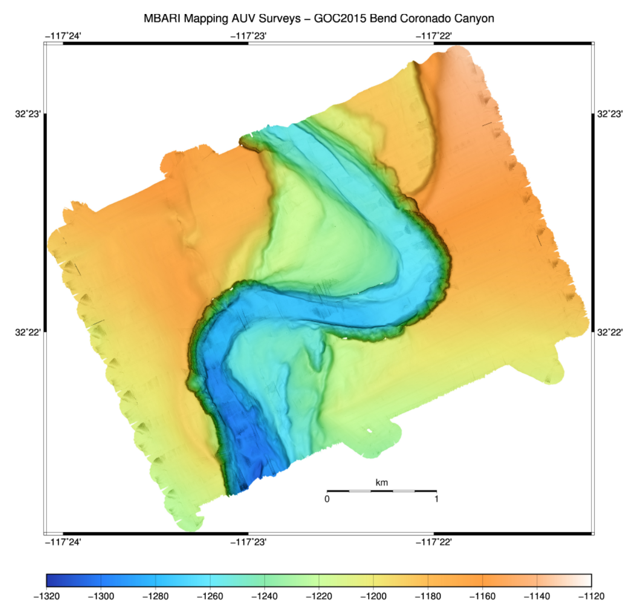

Fig. 10. Coronado Canyon near US/Mexico border

Fig. 11. AUV Fouled in fishing line

VI. Unusual Recoveries

On the morning of 20 February 2015 while performing the Cerralvo survey, the AUV crew noticed the AUV had been relatively stationary in the water column since about midnight. By examining the sonar data record, it appeared the AUV was somehow caught in the water column at about 900 meters depth, and doing a slow watch circle. In the area many fishing floats were visible; one of them was quite close to where the AUV was stuck. MBARI's flagship, the Western Flyer, was docked at Pichilingue, several hours away. On Sunday, 22 February, the Western Flyer arrived, and was able to free the AUV using a kitchen knife attached to one of its manipulators. A fishing line had been holding the AUV down, Fig. 11, fouled in the vehicle's antenna. Upon recovery of the AUV, it was determined that damage was minimal, quickly repaired with a length of electrical tape, Fig. 12. The decision was made to not redeploy in this area due to the large number of fishing floats. Subsequent missions ran perfectly.

On 14 March 2015, after a full day of AUV and small ROV operations at Los Frailes, just south of Cabo Pulmo, the Bottom Pressure Recorder (BPR) would not rise from the seabed after being given repeated release commands. The Rachel Carson now had a small ROV on board. The team attached a kitchen knife on a pole to the ROV, and by tracking the BPR's sonar beacon, the ROV was able to locate and free the BPR by cutting its anchor line. The instrument rose to the surface and was recovered in normal fashion. Upon examination of the release system, it was discovered that seawater had penetrated the burn wire assembly and corroded the metal contact button; the button had dissolved instead of the burn wire.

VII. Advantage of feature location with AUV vs ROV

MBARI Scientist Dr. Robert Vrijenhoek has noted, "In the 1990s, following the discovery of plumes of warm water over the Mid-Atlantic Ridge, researchers from four countries searched for seven years to find what eventually became known as the 'Rainbow vent field.' They were limited by inaccurate and imprecise bathymetric maps. This spring it took us only two days to do the same thing in the

Fig. 12. AUV Antenna damage

Pescadero Basin, using MBARI's high-precision seafloor-mapping AUV."

VIII. Future Efforts

The team is working to replace the drive electronics and stepping motors with higher efficiency brushless DC motors in the AUV's tailcone in order to realize energy savings which will allow longer missions.

Another project underway is the design and fabrication of battery arrays using modular Lithium Ion battery packs, which will facilitate individual replacement of a deteriorated battery cell, as well as permit safer transportation of the batteries, as the individual battery packs have been approved for transportation. Fifty five of the modular packs are housed in a 43.18cm (17 in) diameter Benthos sphere; two of the spheres will be installed in the AUV.

I2MAP is a project nearing completion which places a high-resolution video camera, external LED lights, a video recorder and control system in a modular AUV nose assembly. This will allow the AUV to do time series video transects which have traditionally been accomplished with the Rachel Carson and the ROV.

The IceBerg AUV will feature a side-looking multibeam sonar array which will map the circumference of icebergs in the Antarctic Ocean; it will include an upward-looking sonar to map the bottom of the icebergs. Many technical challenges include the procedure to follow when the AUV encounters a problem; while beneath ice simply burning a wire and dropping a weight is not an option for recovery.

Construction of a second Mapping AUV is underway.

Acknowledgement

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