Near-bottom Multibeam Surveys for Deep Sea Scientific Applications

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The US National Deep Submergence Facility (NDSF) provides near-bottom multibeam mapping capabilities from the autonomous underwater vehicle *Sentry* and the remotely operated vehicle *Jason*. These vehicles can be used to depths of 4500 and 6500m respectively. Both vehicles are equipped with Reson 7125 400khz multibeam sonars as well as compatible navigation equipment (inertial navigation systems, doppler velocity logs, and acoustic navigation systems). These vehicles have produced maps of rugged Mid-Ocean Ridge terrain in the Galapagos Rift, natural oil and gas seeps off the coast of Southern California, deep coral sites in the Gulf of Mexico, and sites for the Ocean Observing Initiative off the coast of Oregon. Multibeam surveys are conducted from heights between 20 and 80 meters, allowing the scientific user to select the tradeoff between resolution and coverage rate. In addition to conventional bathymetric mapping, the systems have used to image methane bubble plumes from natural seeps. This talk will provide summaries of these mapping efforts and describe the data processing pipeline used to produce maps shortly after each dive.

Introduction

The U.S. National Deep Submergence Facility (NDSF) is funded by the US National Science Foundation (NSF) to support deep ocean exploration and science. NDSF clients are primarily members of the U.S. academic community; however, NDSF also periodically supports research performed by governmental, international, and commercial agencies. In support of such research, NDSF offers three vehicles that can operate to 4500 meters or deeper: Human-occupied vehicle (HOV) *Alvin*, remotely operated vehicle (ROV) *Jason* (6500m), and autonomous underwater vehicle (AUV) *Sentry. Sentry* joined NDSF in 2010 after the loss of the *Autonomous Benthic Explorer* (ABE) AUV earlier in 2010 and after a year of use in the field.

AUV *Sentry* was the first NDSF vehicle to add in 2008 a Reson Seabat 7125 400 kHz, 512 beam sonar to its inventory. *Alvin* and *Jason* have since added the same model sonar. Designed as a mapping vehicle, *Sentry's* speed and stability make it the preferred platform for multibeam usage and it is proffered as such by the NDSF. Nevertheless, there are frequent opportunities in the schedules of *Alvin* and *Jason* to use a high quality multibeam sensor, sometimes for uses other than seabottom mapping [1]. Requests by the oceanographic community that *Alvin* and *Jason* carry an equally capable sonar were therefore heeded and funded by NSF. *Sentry* can also carry sensor systems provided by science, such as the TETHYS mass spectrometer [2], permitting simultaneous survey and sampling. Vehicle speed and battery duration allow *Sentry* to travel up to 85 kilometers in a dive, depending on the power needed for instrumentation. *Alvin* and *Jason* are configured primarily as sampling vehicles, with speed of one-quarter *Sentry's*, robotic arms, video cameras, sampling systems, and approximately 100 lbs of payload. As of this writing, the Seabat 7125 systems of *Sentry* and *Jason* have been used operationally. The development of *Alvin's* system is a work in progress, performed on dives of opportunity.

Reson Seabat 7125 systems carried by NDSF vehicles were used in the following 2009 and 2010 research cruises:

1. Lophelia2-2, AUV *Sentry*, June 17-July 1 2009, Gulf of Mexico, R/V Brooks McCall, *Sentry* dives 18 to 28.
2. Seeps2009, HOV *Alvin* and AUV *Sentry*, Sept 13-29, 2009, coastal southern California. R/V Atlantis, *Sentry* dives 29-37.
3. GRUVEE, HOV *Alvin* and AUV *Sentry*, March 15-April 14 2010, Galapagos Spreading Center, R/V Atlantis, Sentry dives 38-59.
4. OOI/Enlighten'10, ROV *Jason* and AUV *Sentry*, Juan de Fuca Plate, leg 1: July 26-August 9 2010, leg 2: August 10-24 2010, Sentry dives 66-70 (leg 1), Jason dives 513-515 (leg 2).

An effective use of the joint-mission scenario was successfully employed on three of the research cruises listed above. During these cruises AUV survey dives were conducted sequentially or simultaneously with sampling and observation operations using *Alvin* (Seeps2009, GRUVEE), *Jason* (Enlighten'10 leg 1), and a towed camera system[3] (GRUVEE, Enlighten'10). Science mission planners were able to make use of low-altitude, high-resolution maps resulting from the surveys by *Sentry* to optimize use of the other vehicle's observation and sampling strengths. In some cases during the Seeps2009 and GRUVEE cruises a bathymetric product was preliminarily processed and provided to *Alvin* passengers within two hours of Sentry's recovery. Upon the departure of *Sentry*, Jason performed multibeam surveys on the second leg Enlighten'10

Sensor configurations on NDSF Vehicles

Alvin and *Sentry* carry the AUV version of the Reson model Seabat 7125. Independent computers using remote access clients from Microsoft and Reson communicate with the Reson control computer (iCPU). *Jason* carries the ROV version of the Seabat 7125, with the iCPU housed in J*ason's* control van. For post-processing, raw multibeam files are transferred upon dive conclusion from the respective iCPUs to data processing stations aboard the ship.

To compensate for arrival time differences of a spherical pressure wave on the flat face of the Seabat 7125's receive array, accurate sound velocity values for the water volume in the vicinity of the array are necessary. *Jason* carries a Reson-branded sound velocity probe. *Alvin* and *Sentry* data collection systems have been modified to broadcast UDP datagrams of sound velocity that are calculated from conductivity-temperature measurements to the vehicle's computer network, which is monitored by the Seabat 7125 iCPU.

With their distinct designs and modes of operation, no NDSF vehicle has the same suite of navigation sensors. For each vehicle primary navigation is derived from a Doppler Velocity Log (DVL) system in combination with heading from a high performance inertial navigation system (INS). The INS also reports vehicle pitch and roll. DVL velocities are integrated to estimate dead reckoned position using software developed by the Dynamical Systems and Control Laboratory at Johns Hopkins University (JHU/DSCL) [4]. These estimates are augmented by georeferenced information from ultra short baseline (USBL) and/or long baseline (LBL) acoustic navigation systems. Because the navigation systems of *Alvin* and *Jason* are always under human control, correction of DVL drift by resetting to USBL or LBL position in the midst of the dive is routinely performed.

Alvin and *Jason* have historically carried DVL units that operate at 1200 kHz. These are capable of consistent bottom lock to an altitude of 25 meters. In order to take better advantage of the altitude range offered by the Seabat 7125 (up to 120 meters), *Alvin and Jason* have added lower frequency DVL systems to their inventories. The maximum altitude at which the 300 kHz RD Instruments Workhorse DVL maintains bottom lock is approximately 200 meters. The 600 kHz unit will maintain bottom lock to an altitude of approximately 110 meters. Shifting to these lower DVL operating frequencies brings them within the acoustic operating band of the Seabat 7125, and external synchronization is required to control cross-system interference. We provide this synchronization control using a triggering board developed for *Sentry.* Triggering rates for the DVL and Seabat 7125 on both *Sentry* and *Jason* are twice per second, and corresponding delays are determined experimentally.

Table 1: Doppler Velocity Log Navigation Sensor Suites for NDSF Vehicles

Vehicle/Sensor	DVL-1	DVL-2	INS
Alvin	RDI Workhorse Navigator 1200 kHz	RDI Workhorse Navigator 600 kHz	Ixsea Octans
Jason	RDI Workhorse Navigator 1200 kHz	RDI Workhorse Navigator 300 kHz	Ixsea Octans
Sentry	RDI Workhorse Navigator 300 kHz	n/a	Ixsea Phins

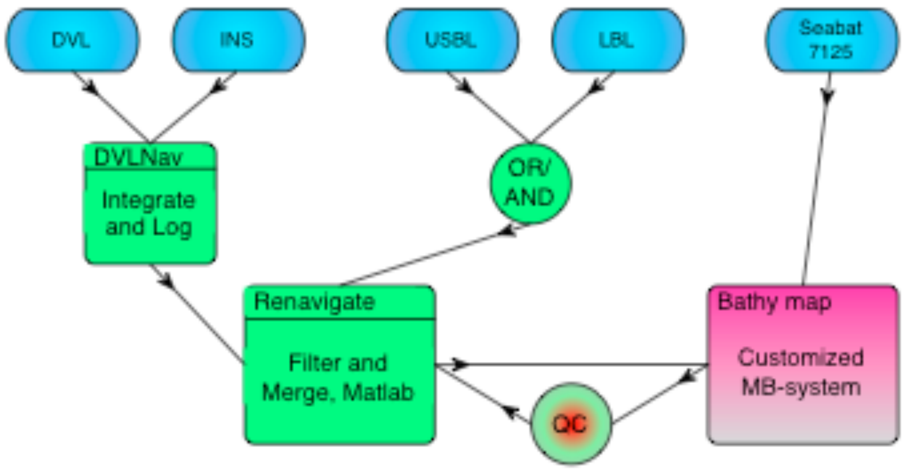
Long baseline positioning was recommended by NDSF for more than a decade for precise acoustic navigation and survey work. In 2009 a WHOI-developed LBL system, dubbed N456 [5], replaced the Benthos 455 system that had been used for many years. Also in 2009 we introduced into our operations Sonardyne Ranger USBL positioning systems for each vehicle, which can work along with or in place of LBL. In most circumstances, we now recommend use of USBL. Among the advantages offered by use of USBL is a potentially significant savings in setup time. LBL requires the deployment, positional survey, and recovery of a transponder net at each work site, using approximately two hours per transponder. In comparison, a Sonardyne-specified calibration procedure, which is expected to apply for the duration of a cruise, typically requires five hours. When results from this calibration have been applied to a Ranger USBL system, precision and accuracy are comparable to N456 LBL. We continue to use LBL when a preset transponder net exists at a work site. We have also used LBL to navigate *Sentry* when a dive plan calls for *Sentry* to perform its survey while *Alvin*, *Jason,* or towed camera operations take the ship out of USBL range. When operating in a limited area for multiple dives with *Sentry*, installation of an LBL net can be a good investment of time.

The transceiver portion of the USBL system for *Alvin*, which is permanently attached to R.V. *Atlantis*, is integrated with the ship and offers the most consistent performance. Transceiver motion is compensated through use of *Atlantis'* INS. Because *Jason* and *Sentry* deploy from vessels of opportunity, the transceiver portions of their USBL systems are mounted to side-rail systems that are extended when the vehicles are in the water, or we use the vessel's moon pool if available. In these configurations, an Ixsea Octans INS or Sonardyne Lodestar is mounted with the transceiver to compensate for ship and pole motion.

Post-processing

The essential purpose of our bathymetry post-processing is to produce a map that indicates that the raw data was collected properly. Additional goals are to produce a map that can inform follow-on cruise operations. We describe it as a preliminary product, one that our clients should expect to improve themselves for publication or for rigorous analysis. Because of our personnel constraints, we have made it a priority to develop a bathymetry map post-processing pipeline that requires minimal interaction with the data.

This pipeline includes two processing flows, both of which we are now working to automate. The first is renavigation of the real time track history, in which an improved estimate for the vehicle track is produced. The second is the treatment of the Seabat 7125 ping history, during which vehicle attitude and biases are compensated, beam anomalies are removed, and adjoining swaths are trimmed or merged as appropriate. We perform renavigation post-processing using software developed within the WHOI Deep Submergence Laboratory, or collegially with the JHU/DSCL. This renavigation software is predominantly written as Matlab scripts. For processing of the raw multibeam record we use a version of MB-system[6] that we have modified to better support our automated pipeline.



Several papers, e.g.[7][8], discuss the method of improving vehicle navigation through the combined use of high update rate (1-5 Hz) DVL dead reckoned position with lower rate (0.1-0.25 Hz) LBL position. Whitcomb, et al, [8] reports a factor of three improvement by the use of DVL with LBL versus the use of LBL alone. Our USBL and LBL systems exhibit very similar performance and we interchange the two readily, or combine them when both are employed.

Because we regard it as prudent to perform post-processing on the data derived directly from the sensor, we log real time position estimates from these systems individually and merge them post-dive. Two methods are currently implemented: a least-squares technique described in [9] that uses LBL/USBL to estimate DVL track alignment error; and, a complementary filter technique that applies low pass filtering to the LBL/USBL record and combines this with alignment corrected, high pass filtered DVL[8].

Post-processed navigation is merged with raw Seabat 7125 files (.s7k) as one of the first steps of an MB-system shell script. Subsequent steps include 1. application of a customized version of the *mbclean* utility to remove anomalies; 2.application of global corrections (e.g. roll bias; or a 180 degree rotation in the case of *Jason,* upon which the Seabat 7125 sonar heads are mounted facing aft); 3. gridding, plotting, and assessment of the resulting map; and 4. if necessary, adjustment of navigation, repeat.

Examples

Figures 1 through 4 depict two examples of gridded bathymetry product from the post-processing pipelines of *Sentry* and *Jason*, respectively. We wish to emphasize that these are the result of applying our automated pipelines. No interactive editing of pings was performed.

Figures 1 and 2 show the survey from *Sentry* dive #55, performed April 8-9, 2010 at the Galapagos Spreading Center, northwest of the islands. Survey time was 12.2 hours, during which *Sentry* traveled 44 kilometers at a nominal rate of 1 meter/s. Vehicle altitude was 80 meters, maintained by *Sentry's* bottom-following mode, and spacing between swaths was 200 meters.

Figures 3 and 4 show the survey from *Jason* dive #515, performed August 7, 2010 at the Juan de Fuca Plate at a feature called the “Pinnacle”. Vehicle altitude was 30 meters and vehicle average speed was 0.25 meters/sec. Spacing between swaths was 50 meters. We note that this Seabat 7125 unit recorded high quality profiles out to approximately 55 meters to each side of its center beam (total swath width 110m). Because this was the *Jason* unit’s first-ever bathymetry map, survey design was deliberately conservative and significant swath overlap was allowed.

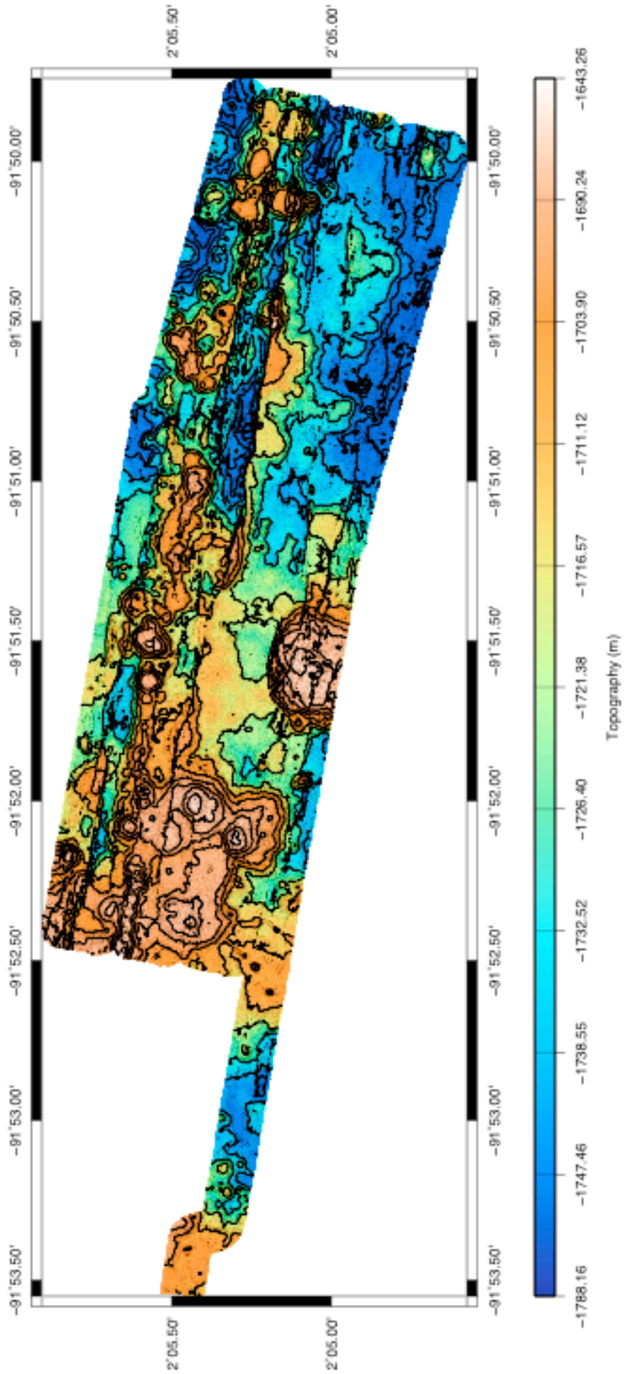


Figure 1: Bathymetry at the Galapagos Spreading Center, *Sentry* dive number 55. *Sentry* traveled 44 linear kilometers in 12 hours, altitude 80 meters, swath width 200 meters.

from sentry dive #55 at the Galapagos Spreading Center.

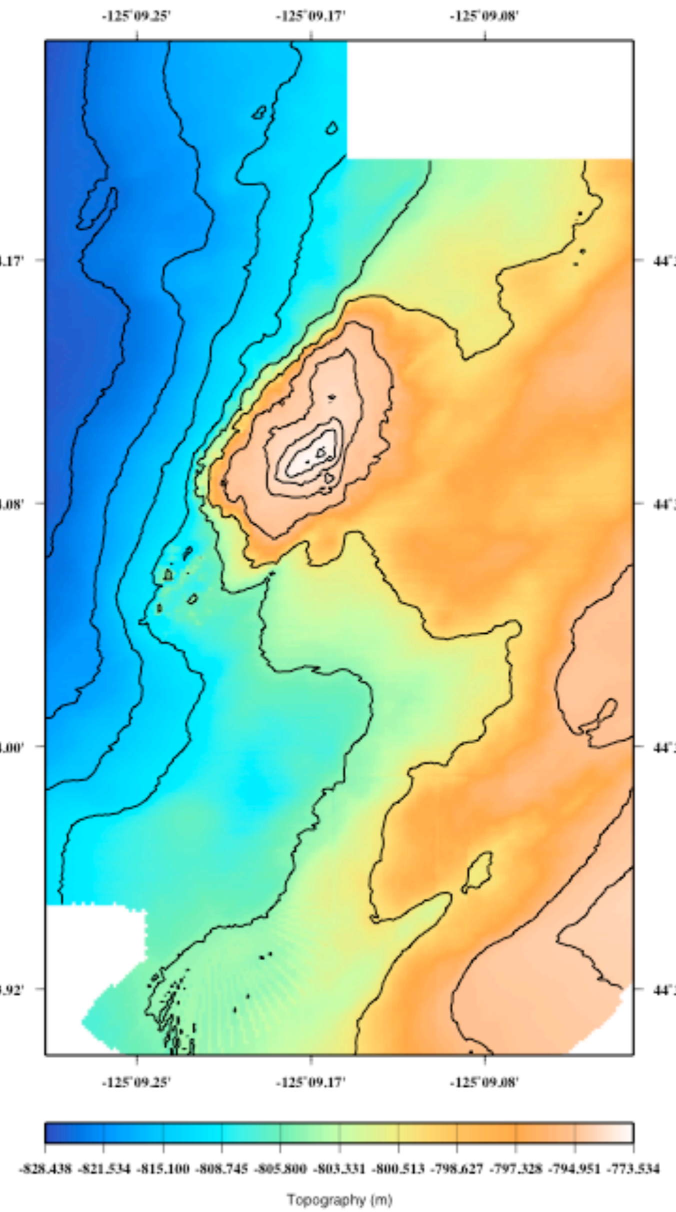


Figure 3: Bathymetry at Juan de Fuca Plate, "Pinnacle", ROV Jason dive #513.

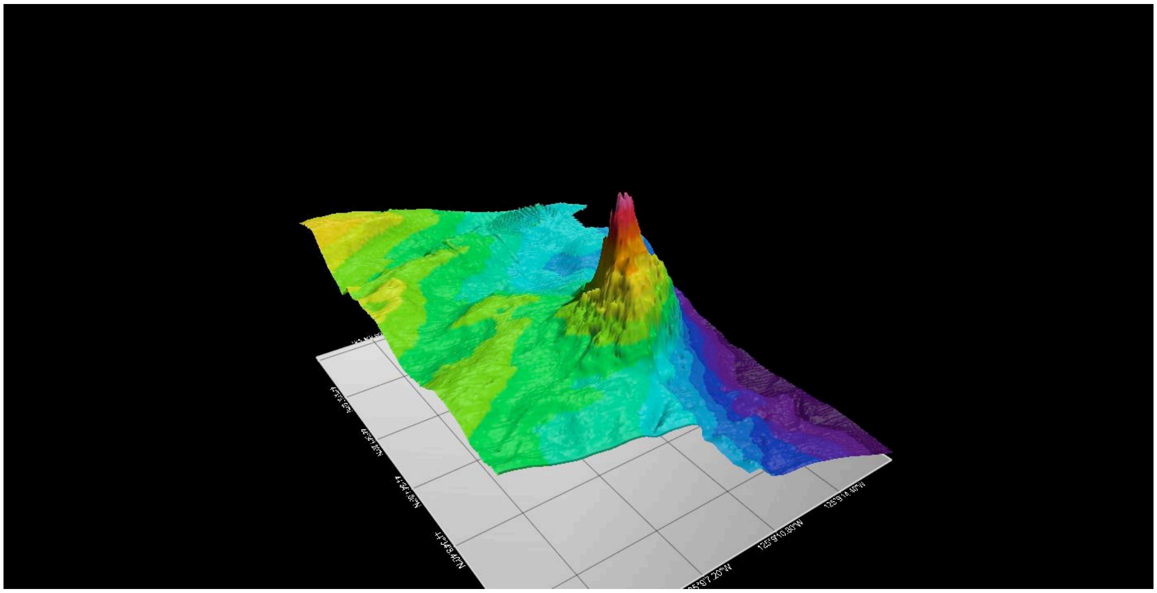


Figure 4: Three-dimensional depiction of feature "Pinnacle", Juan de Fuca Plate. Jason dive # 515, August 2010.

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