Development and Deployment of a Precision Underwater Positioning System for *In Situ* Laser Raman Spectroscopy in the Deep Ocean

Sheri N. White*, William Kirkwood, Alana Sherman, Mark Brown,
Richard Henthorn, Karen Salamy, Peter Walz, Edward Peltzer, and Peter Brewer

Monterey Bay Aquarium Research Institute
7700 Sandholdt Road, Moss Landing, Ca. 95039

*Corresponding author
email: sheri@mbari.org
phone: 831-775-1903
fax: 831-775-1620

Development and Deployment of a Precision Underwater Positioning System for *In Situ* Laser Raman Spectroscopy in the Deep Ocean

Abstract

The field of laser Raman spectroscopy has been expanded to include operations taking place in the deep ocean. While this technique has proved to be successful for transparent targets, difficultly exists in positioning and controlling the laser spot with respect to opaque samples of interest. Scientists and engineers at the Monterey Bay Aquarium Research Institute (MBARI) have developed, tested, and successfully deployed a laser Raman spectrometer and a precision underwater positioner deployable by ROV to perform geochemical measurements in the deep ocean.

The Precision Underwater Positioner (PUP) is capable of translating the Deep Ocean Raman *In Situ* Spectrometer (DORISS) probe head with a precision of 0.1 mm over a range of 15 cm. This capability has allowed us to acquire quality Raman spectra of targets such as rocks, shells, and gas hydrates on the seafloor, including the ability to scan across a rock surface in sub-millimeter increments. The PUP will greatly enhance our ability to perform *in situ* Raman analysis on the seafloor.

1. Introduction

Exploration of the oceans has progressed from large-scale bulk measurements to smaller-scale measurements that illuminate the heterogeneity of the ocean environment. Early studies of the ocean floor using dredges dropped from surface ships to pull up seafloor material provided scientists with a general idea of the make-up of the ocean floor. As technology progressed, manned and unmanned submersibles have allowed scientists to actually view the ocean floor and observe the changes from sedimented abyssal plains to rocky mid-ocean ridges [e.g., *Ballard et al.*, 1975]. Today imaging systems such as high definition video provide the most detailed images to date of the ocean floor and its various biological communities.

The next step in the progression is the ability to make microscopic measurements on the seafloor. Instruments such as laser Raman spectrometers have the ability to perform these measurements, however they are limited by the ability of deep submergence vehicles to position them precisely [*Brewer et al.*, 2004]. This limitation has led us to develop a precision positioning system deployable by ROV for use with a deep-ocean laser Raman spectrometer. In this paper we will discuss MBARI's Deep Ocean Raman *In Situ* Spectrometer (DORISS) and the development of the Precision Underwater Positioner (PUP) for the acquisition of quality Raman spectra on the seafloor. It should be noted that although PUP was designed for use with DORISS, it is a stand-alone system that can be used with other sensors that have similar positioning requirements.

2. Background

Laser Raman spectroscopy is a type of vibrational spectroscopy in which a laser is used to excite a target and the inelastically backscattered light is measured [e.g., *Nakamoto*, 1997] . The peaks observed in the Raman spectrum are due to the vibrational modes of the target molecule; thus information about both chemical composition and structure is obtained. Laser Raman spectroscopy is rapid, non-destructive, and can be performed *in situ*, making it a power tool for performing geochemical analyses in the ocean. In addition, it can be used to analyze solid, liquid or gaseous targets.

MBARI has developed and successfully deployed a sea-going laser Raman spectrometer (DORISS – Deep Ocean Raman *In Situ* Spectrometer) [*Brewer et*

al., 2004]. DORISS is based on a laboratory model Kaiser HoloSpec f/1.8i spectrometer [*Owen et al.*, 1998] with a holographic transmissive grating and a 2048 x 512 CCD camera by Andor Technology. For deployment in the deep ocean (up to 4000 m depth) the components have been divided into three pressure housings. The housings containing the spectrometer, laser, and single-board computer are mounted in the ROV toolsled (Figure 1). The probe head is contained in a 35.5 cm long, 14 cm diameter titanium housing. It is connected to the laser and spectrometer via pressure-tolerant fiber optic cables. The probe head is carried on the front of the ROV and can be positioned at a target of interest using the ROV manipulator (Figure 2). DORISS has been deployed over a dozen times in Monterey Bay and the Gulf of California. It has been successfully used to perform gas dissolution experiments [*White et al.*, in press], to analyze gas hydrates, and to analyze natural gas venting from the seafloor [*White et al.*, 2003].

3. System Specification

3.1. Science Drivers

The DORISS instrument has a very small focal volume – the laser spot size is on the order of tens of microns, and the depth of focus is as small as ~0.15 mm in water (Figure 3). When analyzing transparent targets, the focal point is positioned inside the volume of the target. However, when analyzing an opaque target, the focal point must be positioned exactly at the surface of the material. This requires the ability to position the target with respect to the probe head with a precision of ~0.1 mm.

The two approaches to precision positioning are: 1) present the target to a stationary probe head, or 2) present the probe head to the stationary target. The key advantage of DORISS over other techniques is the ability to non-destructively analyze a specimen *in situ* without any sample preparation. In order to maintain the experimental flexibility that DORISS provides, positioning the probe head is favored. During initial deployments of the DORISS instrument, the probe head was positioned using the ROV manipulator. This method was successful for analyzing transparent pools of liquid CO_2 on the seafloor (Figure 2), and semitransparent samples of calcite. However, it was quite difficult to obtain spectra from opaque rock samples in this manner.

The Precision Underwater Positioner (PUP) was developed to provide the stability and precision positioning needed to collect quality Raman spectra of opaque targets on the seafloor (e.g., gas hydrates). Ideally, the PUP would be generic enough to support the DORISS probe head in various configurations, and would be able to serve the needs of other types of instrumentation that may require precision positioning (e.g., deep sea microscopy).

3.2. Functional Requirements

A set of functional requirements were developed to specify the features needed in a precision underwater positioner. These include general requirements on how the system will be used and specific performance requirements (Table 1). The performance requirements were based on the operational needs of the DORISS system (i.e., motion and stability requirements) and the operations and limitations of MBARI's two remotely operated vehicles – *ROV Tiburon* and *ROV Ventana* (i.e., physical size, electrical, and environmental requirements).

GENERAL REQUIREMENTS

1. Shall be capable of operating in stand-alone mode (in air or water) for in-lab use and testing
2. Shall be deployed on the seafloor by an ROV
   - 2.1. Shall be powered by the ROV
   - 2.2. Shall accommodate the DORISS stand-off distance of 5 m
3. Shall maintain stability over full range of motion
   - 3.1. Shall accommodate uneven ocean floor (e.g. slopes up to 30 degrees)
   - 3.2. Shall accommodate a variety of seafloor surfaces (e.g., rocks, sediment, mud)
4. Shall accommodate a sensor head in either the horizontal or vertical orientation
   - 4.1. May be capable of changing orientation during deployment
5. Shall be capable of positioning the laser beam normal to some optimal plane associated with the target
6. Shall have one external camera mounted to the sensor mount for positioning
   - 6.1. Shall have external lighting
   - 6.2. Shall have two crossing lasers for positioning reference to assist the pilots in placing the positioner in the appropriate location
7. Shall be controlled by a shipboard scientist
   - 7.1. Shall have a user interface software capable of control and display
   - 7.2. Shall have position feedback
   - 7.3. Shall have dual speed positioning
8. May accommodate other (non-DORISS) sensors

Table 1. Performance Requirements

Requirements	Specified Value
Motion requirements (for each dimension)	
Minimum position travel of the beam spot	15 cm
Maximum travel increment of the beam spot	0.1 mm
Maximum time to travel full range	1 minute
Relative accuracy	1 mm
Pan and tilt range (horizontal or vertical orientation)	+/- 45 degrees
Physical size requirements	
Maximum sensor weight (in air)	30 kg
Maximum sensor size allowed on mounting surface	60 x 20 x 20 cm
Maximum weight of complete system (in air)	100 kg
Maximum stowed size (W x H x D)	122 cm x 61 cm x 61 cm
Electrical requirements	
Input Power	240 VDC or 110 VAC
Environmental requirements	
Operating depth limit	4000 m
Operating temperature (ambient)	0-50 degrees C
Operating current (water velocity)	0-0.5 knots

3.3. Design Concept

Several concepts were considered to meet the requirements listed above, including a 3 degree of freedom (DOF) Cartesian system (i.e., X-Y-Z) and a 6 DOF Stewart platform (i.e., hexapod). The X-Y-Z and hexapod platforms did not provide adequate flexibility for DORISS operations, and could not easily meet the size and weight requirements. The concept selected was a 5 DOF system (Figure 4). The axes of motion are Z (up-and-down), R (in-and-out), and theta (rotation about the Z axis). A pan & tilt device at the sensor head provides the remaining 2 degrees of freedom. A tripod platform is used for stability with adjustable legs to accommodate various seafloor topologies. A small web camera, light, and lasers are mounted on the sensor head to aid in positioning.

Due to time and resource limitations, the phase I prototype consists of 3-DOF (Z, R, and theta), with rigid legs, and a camera, light and lasers. Additional axes and features will be added as time and resources permit.

4. System Build

A system block diagram for the DORISS/PUP system is shown in Figure 5. PUP consists of actuators, a camera, light, lasers, and electronics (e.g., servos, motion controllers, Ethernet hub and video server) in a single off-loadable unit. As noted above, the DORISS electronics and spectrometer housing are mounted in the ROV toolsled. An additional housing, the vehicle interface can (VIC), is also mounted in the toolsled and provides a single power and communications interface to the ROV for both DORISS and PUP. Note that DORISS and PUP can each be used individually on the ROV without the VIC housing. The ROV provides power (Tiburon: 240 VDC; Ventana: 110 VAC) and communications via the Ethernet protocol. The system is controlled by the ROV pilots and scientists in a control room aboard the support ship.

4.1. Mechanical

The mechanical components can be broken down into thee catagories: the actuators and ways, the frame, and the electronics housing. Other than the frame weldment and the DORISS probe head mount, most of the PUP mechanical components were purchased as commercially-off-the-shelf (COTS) technology.

The selected motors came from Exlar, a manufacturer of oil-cooled, high precision linear actuators. These oil-filled actuators were easily adaptable for high-pressure deep-sea applications. A small [size?] compensator on PUP provides approximately 6 to 10 psi of pressure over ambient, insuring any leakage will move external to the housing and no water will ingress into the system. A custom manifold was designed and manufactured at MBARI that integrated the three standard connector openings from the manufacturer. The manifold allowed for a single connector thereby reducing the overall cost for underwater connectors, increasing the reliability by limiting the number of wet connections, and minimizing the number of cables between the various moving stages of PUP.

Structural ways (pathways) are required to provide provide stability and to accommodate side-loading. Two sets of guide ways were constructed: the common trapezoidal cross section (dovetail) found in precision tooling applications (Figure 6); and a U-shaped cross-section design which allows for lightening holes and the use of more plastic for stabilizing portions of the design. Both sets were constructed in stainless steel for the sliding rail components and the stationary guides were constructed from Delrin™. After initial testing and some modifications from the initial design, the U-shaped ways were selected for the final deliverable. Each axis has a matched set of opposing ways to support the cantilevered system weight while delivering the low stiction performance required for smooth operation over final scale command inputs. The rotational axis uses a linear actuator to drive the motion of a rotational bearing [more info here] (Figure 6).

The supporting framework of PUP is a weldment constructed of 6061 aluminum heat treated to the T6 condition. The frame is lightweight while also providing the strength for positioning stability during operations. Three rigid legs are bolted on at mounting points on the corners of the frame. These legs can be replaced with adjustable legs on the next generation PUP. A polypropylene bridal fixed at the three corners of the frame serve as a lifting harness (Figure 7).

A Benthos glass sphere, commonly used for deep-sea applications, was selected for the pressure housing (Figure 8). The glass sphere was chosen primarily for cost and weight. The glass sphere is mounted in the frame using a standard Benthos polyethylene hardhat which provides an easy means for attachment while also giving the sphere protection form impact.

The total weight of the PUP system is 195 kg. in air (52 kg. in water). When used with DORISS, the probe head is mounted on PUP adding an additional 12 kg. in air (6 kg. in water). Lead weights were added to the rear leg such that PUP would hang trim from the lifting harness (the glass sphere does not sufficiently counter balance the extended probe head).

4.2. Electrical

All the electronics needed to power and control PUP's motors, lasers, camera, and light are housed in a glass sphere (Figure 8). Each actuator requires a stand-alone motion controller (DMC-2183, Galil Motion Control,

Inc.) and digital servo drive (DR100RE30A40NDC, Advanced Motion Controls). The actuators are equipped with a resolver, which was chosen over other position sensors because it was easy to integrate into the oil-filled environment. Consequently, the digital servo drives were selected primarily because they feature resolver-based commutation; they also provide an emulated encoder output. These encoder signals provide feedback for the motion controller's position servo loop. The actuators also are equipped with two Hall effect sensors that are triggered as the shaft passes through the home position and the forward limit. The motion controller monitors the status of these limit switches. During early sea trials we experienced a lot of false triggering of these limit switches, which would result in the motion controller essentially locking the motor. It was determined that noise of the 24V power lines to the switches was causing the false triggering. This was remedied by placing tantalum capacitors across the power lines.

In addition to motor drive electronics, the PUP sphere houses electronics for peripheral devices mounted on the probe head including: an underwater camera (DeepSea Power and Light, Multi Seacam 2050), a pair of 635nm crossing lasers (C-Map Systems Inc, SLD10), and a custom LED light. The video signal from the underwater camera is fed into a video server (AXIS 2400, Axis Communications). The video server and the motion controller are both TCP/IP compatible, so all communications to the PUP system are through the Ethernet protocol. Two relay boards are used to switch the power provided to the camera, lasers, and lights. Since both the lights and the lasers would affect the Raman spectra during collection, it is necessary for the user to be able to turn these components off during spectral acquisition. Additionally, the sphere houses two sensor boards (900-45T, Applied Geomechanics Inc.) which measure pressure, water, humidity, temperature, and tilt. The signals from these sensors feed into an analog I/O board (DB-20840, Galil Motion Control, Inc.) attached the motion controller. The values of these sensors are displayed on a GUI so the user can monitor environmental conditions. The tilt meter reading provides valuable information when working on uneven areas of the sea floor.

PUP is connected to the ROV by a single cable which provides power and communications. MBARI's two ROVs have different power availability: ROV Ventana provides 120 VAC, and ROV Tiburon provides 240 VDC. Most of the power needs were satisfied by off the shelf power supplies which were

compatible with both the AC and DC inputs. A commercial 12 VDC supply provides power to an Ethernet switch, and the relay boards. A 24 VDC supply provides power to the motion controller, video server, and Hall effect switches. A custom power supply, which accepts either 120 VAC or 240 VDC as input, was built to provide power to the motor drivers.

4.3. Software

In an effort to accelerate development and improve quality, the project team re-used a software design and code framework from the Environmental Sample Processor (ESP) [*Cline et al.*, 2001], a successful MBARI project with similar precision motion control requirements. The object-oriented framework software was developed and implemented in C++, using Microsoft's Visual Studio. Reusing the code from ESP allowed the PUP team to focus immediately on the particular motion control requirements of the PUP, saving significant development hours. Moreover, the ESP framework code had been tested and in use for a number of years, proving to be a capable and reliable foundation upon which to build the PUP software.

The framework includes a number of core object classes intended to work within a variety of motion control applications. The 3 axes of the PUP are represented with 3 Axis objects, each containing a Motor object. The main application dialog takes the actions from the user and translates them into the appropriate calls to member functions of the Axis and Motor objects. Adding axes to the system simply requires adding Axis/Motor object pairs to the application and useful controls to the PUP dialog along with the translation code.

The Axis and Motor classes are designed to work with a generic controller system, using generalized controller functions commands. Housed within the glass sphere, the Galil Motion Control unit handles all the low-level motor control logic. Galil provides software and a simple API and command language to move the motor in the desired direction and linear distance. The application developer integrated the specific Galil controller into the framework by deriving a new class from the generic controller class, overriding the generalized member functions, and providing a translation for the linear distance to motor controller units.

The PUP graphical user interface (GUI) was designed to offer a simple control interface to accommodate deployments with users unfamiliar with the system design and development. As a result, the interface is straightforward, intuitive, and easy to use (Figure 9). Top left section of the GUI shows the environmental conditions inside the sphere, tilt angles, and motor error states. The middle left section is devoted to motion control. Arrow buttons are used for incremental movement of the Theta, R, and Z axes with current position displayed above them. Below the increment arrows are controls that allow the user to change the incremental movement distance and the absolute motor speed. Direct positioning controls allow the user to enter the Z, R, and Theta axis positions and command PUP to move the actuators directly to that position. The bottom left section of the GUI contains buttons for turning devices on the PUP on and off: a pair of crossing lasers, the camera, an LED light, and DORISS. The middle portion of the dialog is used for storing and recalling positions of interest that the user may want to revisit or document. The right side of the dialog are controls for commanding the Galil controller directly using the Galil command language. The user types commands in the upper edit box while the response from the controller is written to the lower edit box. This feature is useful for troubleshooting and experimenting with unusual movements.

5. Testing

5.1. Sub-system testing

The actuators were tested to verify that PUP could provide the precision movement stipulated in the functional requirements (0.1 mm increments). The actuators were found to be capable of motion in increments smaller than 0.05 mm. A small amount of backlash (+/- 0.0127 mm) was measured when the direction of travel was changed (Figure 10).

A key concern during the development of the PUP was the rigidity of the actuators. The linear actuators were modified from the “as-built” mechanisms received from the vendor to provide a stiff assembly capable of carrying the weight of the probe head. Early prototype testing of the slide sub-assembly under various load conditions was performed to verify that the system could meet the load requirements and to characterize the flexure in the system. The load testing was conducted for 1 cm incremental extensions of the slide mechanism up to 15 cm. Loads were increased in 20 lb (9.1 kg) increments

from 25 to 85 lbs (11.3 kg and 38.5 kg, respectively). The data revealed that the system behaves repeatability and can be characterized mathematically (Figure 11). For a 25 lb (11.3 kg) load, the deflection is just within our precision requirement of 0.10 mm (see figure below). The DORISS probe head is 13 lbs (5.9 kg) in water.

5.2. System testing

Once PUP was fully assembled, tests were performed with the DORISS instrument to verify PUP ability to precisely position the DORISS probe head. This testing was performed using the DORISS immersion optic which has a focal depth of ~0.15 mm in water (Figure 3) and ~0.2 mm in air. We used PUP to focus DORISS on a polished silicon wafer (a strong Raman scatter with stringent positioning requirements) that was masked by a thin aluminum plate with a 1 mm diameter hole. The DORISS optic was focused onto the silicon wafer in air through the 1 mm hole. The initial position of the actuators was Z = 100 mm, R = 100 mm, and Theta = 30 degrees. After obtaining a spectrum, each actuator was moved to the home position and commanded back to the position at which the first spectrum was taken. The spectra acquired after moving the Z, and R axes matched the initial spectrum exactly, thus verifying the ability to return to a previous position with a high degree of accuracy. After moving the Theta axis, the spectrum was slightly weaker (~5%) than the initial spectrum (Figure 12A). Next, all three axes were moved throughout their ranges of motion repeatedly, then returned to the initial location. This time the silicon wafer could not be detected. After jogging the actuators slightly, the silicon spectrum was reacquired and maximized. The spectrum acquired at this location matched the initial spectrum exactly (Figure 12B). The new position was Z = 99.9 mm, R = 100.0, theta = 29.8 degrees. Thus, the repeatability of the actuators is approximately +/- 0.1 mm for the Z axis, within 1.0 mm for the R axis, and approximately +/- 0.2 degrees for the theta axis.

6. Field Results

PUP and DORISS have been deployed a number of times in the deep ocean for testing (Figure 7), and exploratory measurements. Field deployments in Monterey Bay to depths as great as 1022 m provided the opportunity to test all of the components of the PUP system, and to solve minor problems related to the effects of the cold, high-pressure deep sea environment. Additionally,

Raman spectra were acquired with the DORISS instrument which proved the necessity and effectiveness of PUP.

Samples of marble, granite and other rocks were carried to the seafloor for Raman analysis. With PUP, we were successfully able to collect spectra from these solid, opaque targets. Additionally, we were able to collect spectra along profiles of the samples in increments as fine as 0.1 mm. Examples of the spectra collected are shown in Figures 13 and 14. We also attempted to collect spectra from natural targets in the deep ocean. We located a patch of shells at the base of Invert Cliff at a depth of 1024 m in Monterey Bay. Using PUP we were able to focus in on a piece of shell and collect a Raman spectrum (Figure 15). In the Raman spectrum we observed the 1086 Δcm^{-1} peak of calcium carbonate. By looking at the weaker bands present in the lower wave number region we were able to determine that calcite and aragonite (polymorphs of $CaCO_3$) are both present. Although these two minerals have the same chemical composition, there structure is slightly different which results in distinct Raman peaks. Calcite exhibits peaks at ~282 and ~713 Δcm^{-1}, while aragonites bands are located at ~207 and ~706 Δcm^{-1}.

Some spectra of natural targets were obtained accidentally. While acquiring spectra from the granite sample in a 0.1 mm grid pattern, a snail climbed onto the sample and approached the laser beam. Because the immersion optic was ~ 1 mm from the granite sample, the snail could not get fully into the laser path. However in those spectra we were able to detect carotenoids which we believe to come from the snail shell [e.g., *Withnall et al.*, 2003] (Figure 16).

7. Conclusions

The Precision Underwater Positioner (PUP) greatly enhances the ability for DORISS to obtain *in situ* Raman spectra in the deep ocean. PUP provides the ability to move in sub-millimeter increments and to scan over the surface of a target in order to perform analyses on the scale of mineral grains. This capability is unique and will lead to new analyses that will further our understanding of various environments in the deep ocean. While PUP was developed for the DORISS system, it is capable of being used for any deep ocean sensor with similar positioning requirements. This technology will continue to impact the study of the ocean and the understanding of environments

such as natural gas vents, hydrothermal venting sites, geologic formations, hydrate studies, and microbial communities.

Acknowledgements

We thank the officers and crews of the R/V Point Lobos and R/V Western Flyer, and the ROV teams of Ventana and Tiburon, for their skill and support at sea; collaborator John Freeman of Washington University, St. Louis; and the technical support of John Ferreira, Jim Scholfield, Randy Pricket, Duane Thompson, Tom Marion, and Jose Rosal . Funding was provided by a grant to MBARI from the David and Lucile Packard Foundation.

References

Ballard, R., W.B. Bryan, J.R. Heirtzler, G. Keller, J.G. Moore, and T.H. van Andel, Manned submersible observation in the FAMOUS area: Mid-Atlantic Ridge, *Science*, *190* (4210), 103-108, 1975.

Brewer, P.G., G.E. Malby, J.D. Pasteris, S.N. White, E.T. Peltzer, B. Wopenka, J. Freeman, and M.O. Brown, Development of a laser Raman spectrometer for deep-ocean science, *Deep-Sea Res.*, *51*, DOI:10.1016/j.dsr.2003.11.005, 2004.

Cline, D., T.C. O'Reilly, T. Meese, B. Roman, and D.R. Edgington, The Environmental Sample Processor (ESP) software design: Software for detection and quantification of microorganisms, in *IEEE/MTS Oceans 2001*, pp. 287-294, IEEE Press, Honolulu, HI, 2001.

Nakamoto, K., *Infrared and Raman Spectra of Inorganic and Coordination Compounds: Part A*, 387 pp., John Wiley & Sons, Inc., New York, NY, 1997.

Owen, H., D.E. Battery, M.J. Pelletier, and J. Slater, New spectroscopic instrument based on volume holographic optical elements, *Proc. SPIE*, *2406*, 260-267, 1998.

White, S.N., P.G. Brewer, and E.T. Peltzer, Determination of gas bubble fractionation rates in the deep ocean by laser Raman spectroscopy, *Mar. Chem.*, in press.

White, S.N., P.G. Brewer, E.T. Peltzer, W.J. Kirkwood, J.D. Pasteris, and N. Nakayama, First expeditionary deployments of the Deep Ocean Raman In Situ Spectrometer, in *Fall AGU Meeting*, San Francisco, CA, 2003.

Withnall, R., B.Z. Chowdhry, J. Silver, H.G.M. Edwards, and L.F.C. de Olivera, Raman spectra of carotenoids in natural products, *Spectrochim. Acta A*, *59*, 2207-2212, 2003.

Figures

Figure 1. DORISS and PUP being deployed on the ROV Ventana. The DORISS electronics and spectrometer housings are mounted in a drawer in the back of the ROV toolsled. The DORISS probe head and the PUP are carried on the front porch and secured by the ROV manipulator.

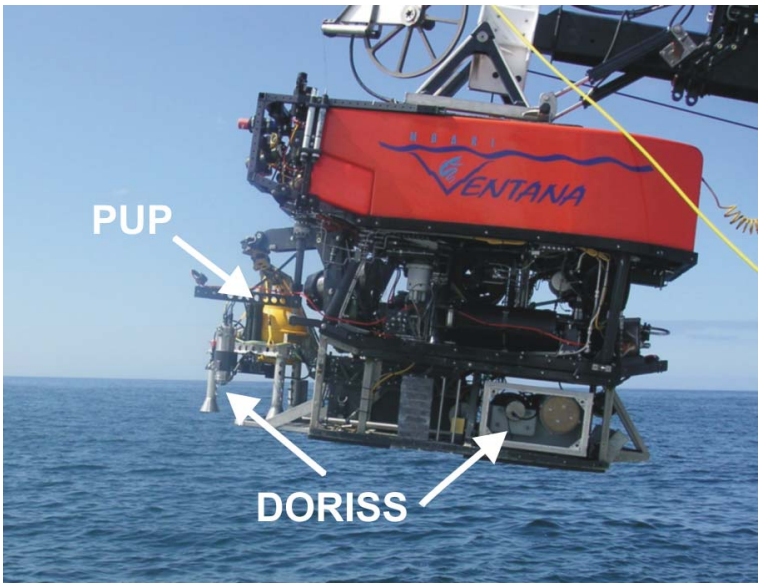

Figure 2. The DORISS probe head is positioned over a pool of liquid on the seafloor (3607 m depth) by the ROV manipulator. The fiber optic cables connecting the probe head to the DORISS electronics and spectrometer housings can be seen on the left.

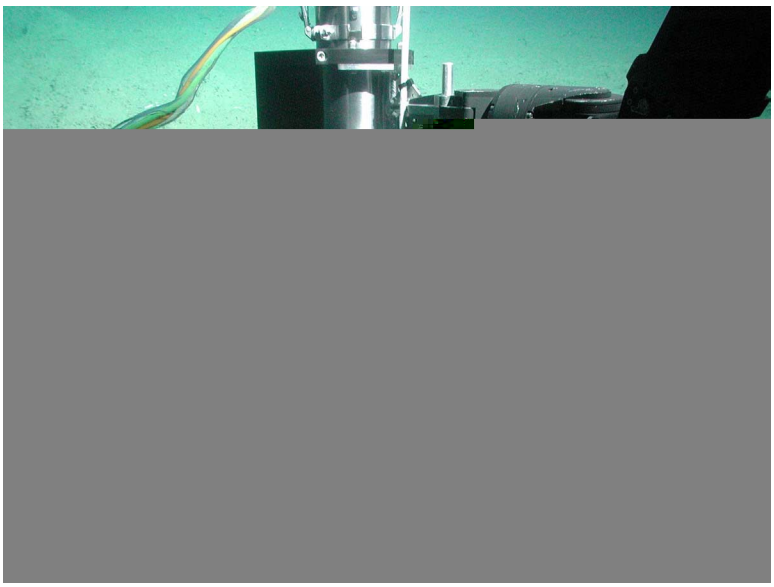

Figure 7. PUP sitting on the seafloor at 1022 m depth in Monterey Bay. The rope bridle is used for lifting PUP with the ROV manipulator. The R axis is fully extended, and the Z and Theta axes are fully retracted in this picture. The green laser spot from the DORISS probe head can be seen on the sediment.

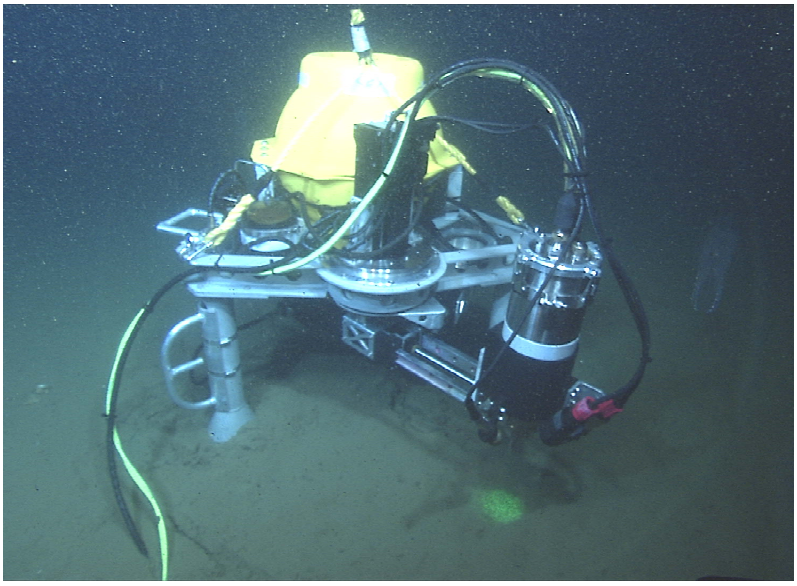

Figure 8. The PUP electronics are housed in a Benthos glass sphere. The electrical components include a power supply, motion controllers, servo amplifiers, a video server and an Ethernet hub. Six penetrations provide connection to the three actuators, the camera, the lights and lasers (single connector), and the ROV for power and communications.

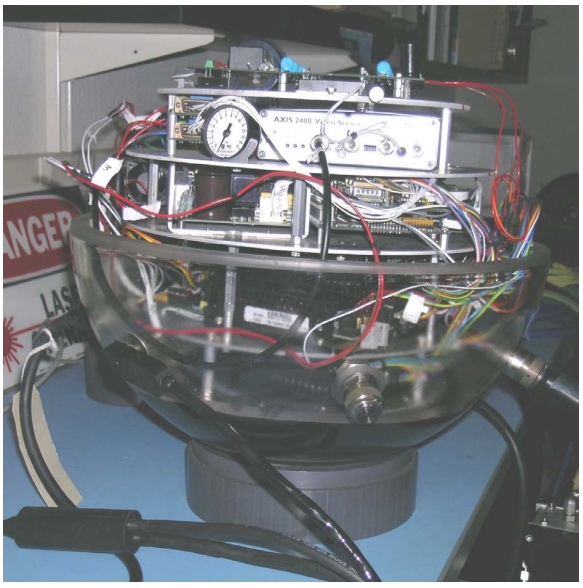

Figure 9. The PUP GUI allows the shipboard scientist to monitor conditions inside the electronics sphere, control PUP's motion, and control power to the lights, camera, lasers, and DORISS (left side). Position locations can be stored and recalled (center panel). The right side allows the user to input commands directly to the motor controllers.

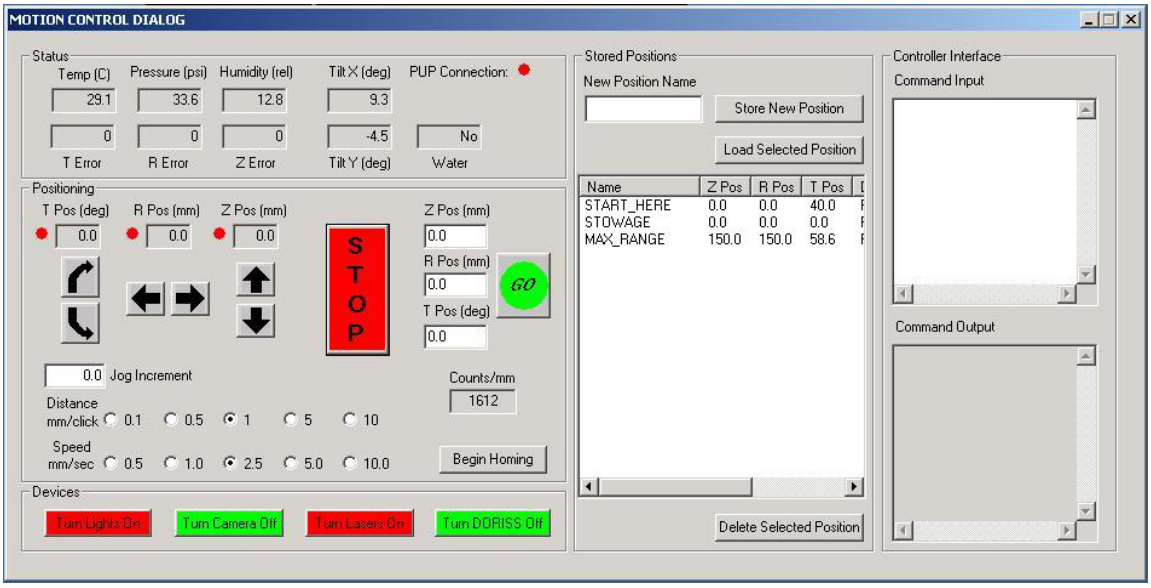

Figure 10. The PUP actuators are capable of moving in increments smaller than 0.05 mm. The actuators move in the precise increments commanded by the user. However, when the direction is changed, the system exhibits a small amount of backlash (+/- 0.0127 mm).

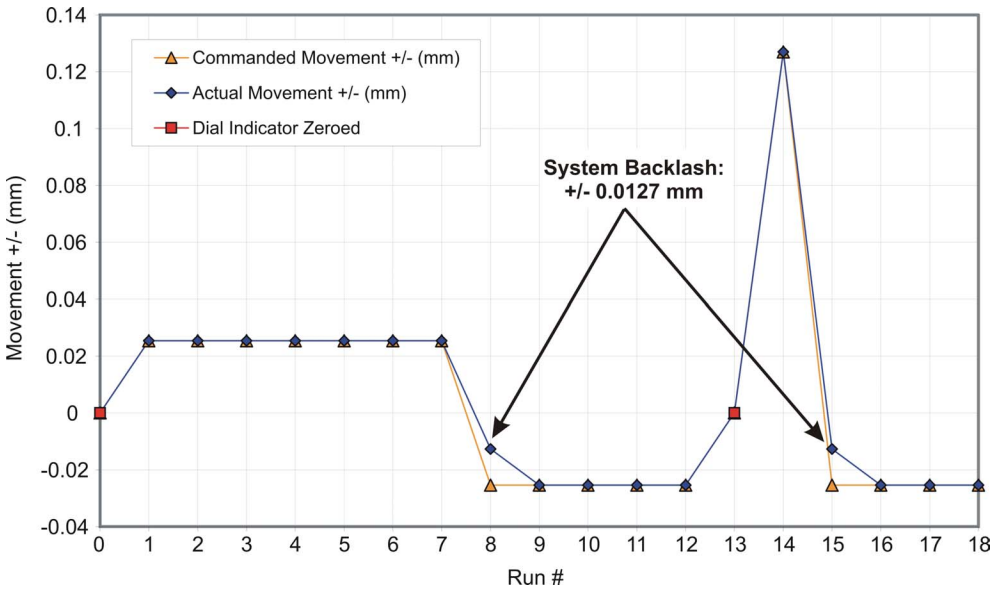

Figure 11. The actuator sub-assembly was tested under various load conditions to determine deflection. At full extension (15 cm) the deflection is ~0.1 for a 11.3 kg (25 lbs) load to ~0.25 mm for a 20.4 kg (45 lb.) load. The DORISS probe head is 13 lbs (5.9 kg) in water.

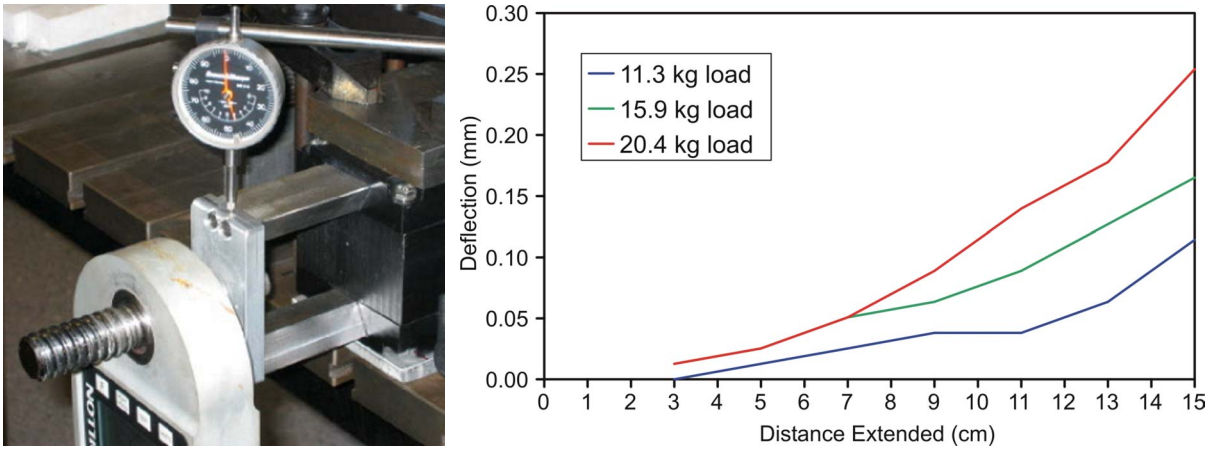

Figure 12. Raman spectra of a polished silicon obtained using DORISS and PUP. The red line I s the initial spectrum collected at position Z=100.0 mm, R=100.0 mm, Theta=30.0 deg. In plot A, the blue dashed-dotted line was collected after the Z axis was retracted then returned to the same position. The green dashed line was collected after both the Z and R axes were retracted then returned to the same position. The purple line was collected after all three axes (Z, R, and Theta) were retracted then returned to the same position. In plot B, the blue line was collected after all three axes had been moved back and forth throughout their full ranges of motion. The position during the collection of this spectrum was (Z=99.9 mm, R=100.0 mm, Theta=29.8 deg).

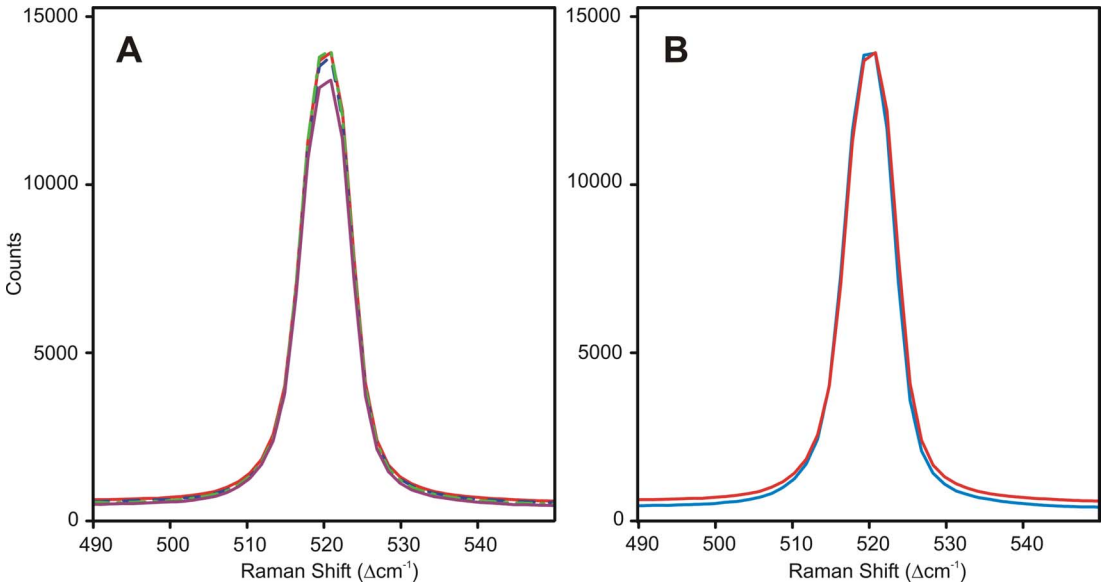

Figure 13. Spectrum of marble sample on the seafloor at 1022 m depth using PUP to position the focal spot. The immersion optic with a focal depth of 0.15 mm in water was used on the DORISS probe head. Marble is characterized by peaks at ~302, 725, 1098, and 1441 Δcm^{-1}. The ~1332 Δcm^{-1} band is from a diamond plate in the probe head to provide a calibration reference. The water stretching bands can be seen at longer wavenumbers. The peaks on the right of the spectrum are due to impurities in the sapphire pressure window of the immersion optic.

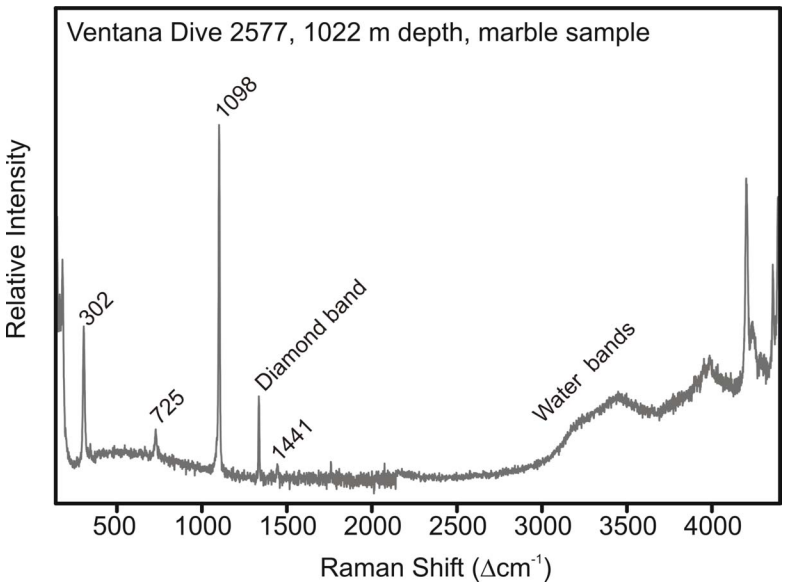

Figure 14. Spectra of a granite sample on the seafloor at 1022 m depth using PUP to position the DORISS focal spot. These spectra were collected in a grid pattern with 5 mm spacing. The primary mineral can be seen to be quartz with albite and some plagioclase. The peaks at 1332 Δcm^{-1} are from the diamond calibration reference.

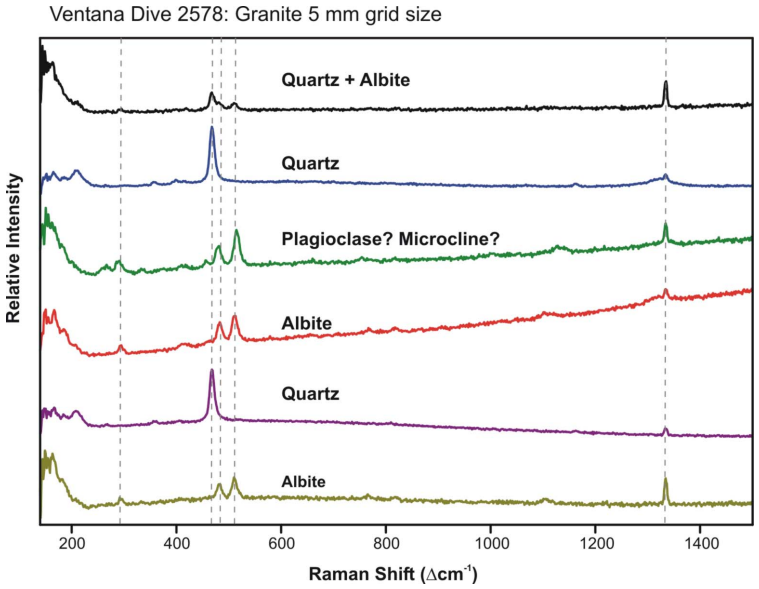

Figure 15. Spectrum of a shell fragment found on the seafloor at 1022 m depth. The DORISS probe head was positioned using PUP. From the Raman spectrum one can observe that calcite and aragonite (polymorphs of $CaCO_3$) are both present.

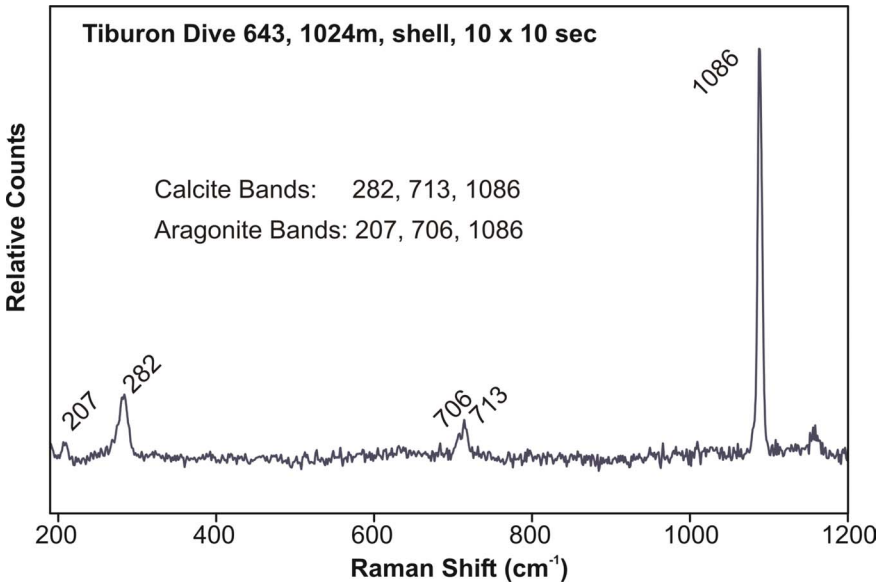
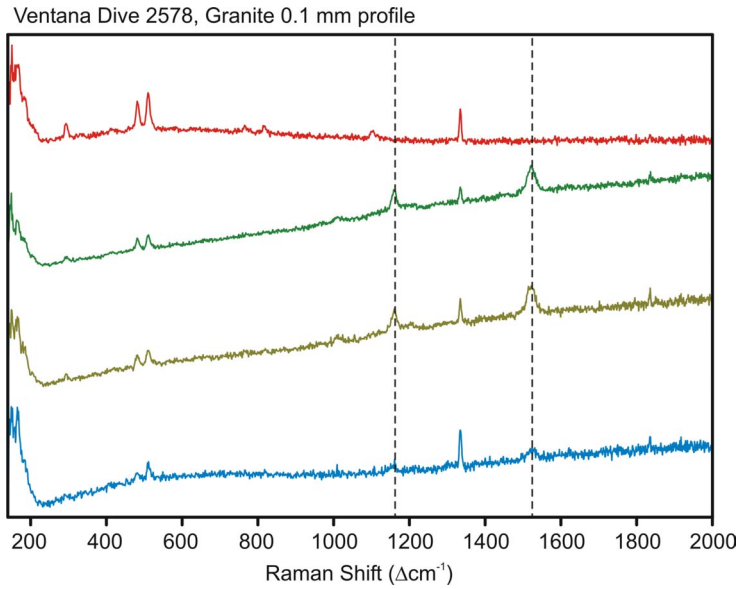
Figure 16. Spectra from a 0.1 mm profile of granite. Albite is present in all of the spectra. The bottom three spectra show peaks at ~1159 and 1524 Δcm^{-1} (dashed lines) which indicate carotenoids. The carotenoids appear to come from the shell of a snail that came close to the beam during our acquisitions.