Bermuda Sensor System Testbed

First Accessible, Regularly Serviced, Deep-Ocean Mooring with Satellite & Ship-Shore Communications to Test Interdisciplinary Sensors—Hurricane Proven

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Interdisciplinary oceanographic programs to improve our understanding of the causes and effects of global change depend on new and emerging measurement technologies. Real-world testbeds are necessary for testing and verification of sensors and systems relevant to ocean processes as well as for developing methods of data interpretation.

The Bermuda Testbed Mooring (BTM) is one of the first deep-sea moorings available for testing long-term oceanographic sensors and systems. The BTM program, established in June of 1994, is funded by the National Science Foundation (NSF), the Office of Naval Research (ONR), the National Aeronautics and Space Administration, the Monterey...
### Acronyms

<table>
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<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>BATS</td>
<td>Bermuda Atlantic Time-Series Study</td>
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<td>BBSR</td>
<td>Bermuda Biological Station for Research</td>
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<td>BIOPS</td>
<td>Bio-optical system</td>
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<td>BTM</td>
<td>Bermuda Testbed Mooring</td>
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<td>JGOF5</td>
<td>Joint Global Ocean Flux Study</td>
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<td>LED</td>
<td>Light emitting diode</td>
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<td>MBARI</td>
<td>Monterey Bay Aquarium Research Institute</td>
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<tr>
<td>MIT</td>
<td>Massachusetts Institute of Technology</td>
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<tr>
<td>MITESS</td>
<td>Moored in-situ trace-element sampler system</td>
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<td>MORS</td>
<td>Moored optical system</td>
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<td>MVMS</td>
<td>Multi-variable moored systems</td>
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<tr>
<td>NSF</td>
<td>National Science Foundation</td>
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<td>ONR</td>
<td>Office of Naval Research</td>
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<tr>
<td>PAR</td>
<td>Photosynthetically available radiation</td>
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<tr>
<td>PARd</td>
<td>Photosynthetically available radiation cosine collectors</td>
</tr>
<tr>
<td>TPOD</td>
<td>Self-contained recording temperature sensors</td>
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<tr>
<td>UCSB</td>
<td>University of California Santa Barbara</td>
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Bay Aquarium Research Institute (MBARI), the Vitielen Foundation, and the Andrew Mellon Foundation. Serviced at approximately four-month intervals, the BTM allows investigators to regularly deploy instruments in order to evaluate sensor and system performance. Time-series data collected from the instruments are compared, calibrated, and interpreted in conjunction with comprehensive shipboard data sets obtained during monthly or biweekly cruises conducted as part of the Bermuda Atlantic Time-Series Study (BATS) program (an element of the Joint Global Ocean Flux Study (JGOF5)) and the 45-year-long Hydrostation S program, as well as other related mooring and remote sensing programs conducted out of the Bermuda Biological Station for Research (BBSR).

Located about 80 kilometers southeast of Bermuda (31°44'N, 64°10'W), the BTM site is within about five kilometers of the BATS sampling site. The site was chosen because: it is within a representative open-ocean gyre; it is in deep waters (about 4,600 meters), yet is easily accessible; it has a rich historical data base; and the JGOF5 BATS program presently collects in-situ and remotely sensed data at the site.

### Sensor Systems

A variety of ocean instrumentation has been deployed on the BTM. Of particular interest are newly developed sensors and systems which have been undergoing long-term testing and validation. These include:

- The multivariable moored systems (MVMS) developed over the past eight years by the UCSB group.
- The bio-optical systems, MORS and BIOPS, also developed by the UCSB group.
- The osmotically pumped nitrate analyzer, OsmoAnalyzer, developed by MBARI.
- The trace-element serial-sampler system (MITESS) developed at MIT.
- Inductive modem telemetry system developed at WHOI.

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beam transmissometer made by Sea Tech Inc. (Corvallis, Oregon) is used to determine the beam attenuation coefficient at 660 nanometers. In addition, stimulated chlorophyll fluorescence intensity is measured with a Sea Tech fluorometer. Other measurements include PAR and nadir upwelling radiance at 683 nanometer natural fluorescence (both sensors are made by Biospherical Instruments Inc. (San Diego)).

The BIOPS instruments include sensors to measure chlorophyll fluorescence and PAR in addition to a model AC-9 spectral absorption-attenuation meter from WET Labs Inc. (Philomath, Oregon). The AC-9 concurrently measures spectral attenuation coefficients and spectral absorption coefficients at nine wavelengths (412, 440, 488, 520, 560, 630, 650, 676, and 715 nanometers) using dual-path measurements.

Satellite and mooring data may both be used to estimate biomass and primary productivity. Satellite-based measurements have the advantage of providing broad spatial coverage of the very near surface ocean whereas moored instruments provide excellent temporal resolution as well as data at depth. Therefore we developed another system to provide needed in situ verification and interpretation of remotely sensed ocean color data. The MORS radiometers, deployed at depths of 15 and 35 meters, measure downwelling spectral irradiance and nadir upwelling spectral radiance (both made by Satlantic) at wavelengths of 412, 443, 490, 510, 555, and 665 nanometers which are compatible with those of the SeaWiFS satellite color imager. They also measure light levels at 683 nanometers for natural fluorescence measurements. In addition, the MORS system has scalar irradiance sensors with both spherical PAR and cosine collectors (PARd) (both sensors by LI-COR) plus tilt, temperature, and pressure sensors.

Analyses of nitrate concentrations are accomplished using OsmoAnalyzers. The analyzers utilize osmotic pumps which propel both sample and reagents through a miniature flow-injection-style manifold. This technology is used to eliminate almost all moving components and to minimize power requirements. Osmotic pumps are driven by molecular diffusion of water across a rigid, semipermeable

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### System Description

The mooring is supported by a 2.5-meter-diameter surface buoy fabricated of syntactic foam. Surface recording systems, controllers, and batteries are housed inside a watertight aluminum well in the center of the buoy. The buoy tower supports an Argos transmitter to provide buoy position and data transmission. An RF antenna for short-range data transmission, meteorological instruments, and a radiometer package. Buoy optical measurements include spectral downwelling irradiance at 412, 443, 490, 510, 555, 665, and 683 nanometers [instruments by Satlantic Inc. (Halifax, Nova Scotia, Canada)], and downwelling photosynthetically available radiation (PARd) [instruments by LI-COR Inc. (Lincoln, Nebraska)].

The MVMS uses instruments by EG&G IC Sensors (Miltonia, California) to sample temperature and currents along with optical properties. A

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membrane separating a saturated salt solution from freshwater.

The OsmoAnalyzer uses a cadmium catalytic surface to reduce nitrate to nitrite, which is determined colorimetrically by the formation of a bright azodye. The dye concentration is measured with a light emitting diode (LED)/photodiode photometer, and is calibrated with periodic nitrate standard injections every four days. The analyzer is controlled by a self-contained data logger, which is capable of telemetering the data up the mooring hourly via an inductive modem. The OsmoAnalyzer, which has proven successful in both coastal and open ocean environments, operates for about four months per deployment, taking readings at 5- to 10-minute intervals.

The mooring is configured with three OsmoAnalyzers, one at 200 meters to monitor the top of the nutrientcline and two at 80 meters to sample for nutrient injections into the mixed layer.

A new moored in-situ trace element serial sampler (MITESS) is deployed at 51 meters. MITESS records the temporal variability of trace metals in the upper ocean. Its goals and criteria for the mechanical and electronic design included:
- The sampler materials must be fundamentally trace-metal clean and easy to re-clean after deployment
- The sample bottles should be flushed well before sealing
- The mechanical operations must be simple

- The system must be deployable from standard moorings and withstand stresses of extended deployments (6-12 months) at any depth
- The system should be inexpensive and straightforward to fabricate

The MITESS system consists of a dozen independent sampling modules mounted on a tension rod. The sampling time for each sealed unit is programmed prior to deployment using infrared (IR) transmission through the polyethylene housing. Inter-unit communication and external event-driven triggering is also possible using these IR ports. Non-volatile memory records "opening" and "closing" times in the field.

Polyethylene sample bottles (500 milliliter capacity) are initially filled with dilute high-purity hydrochloric acid. The timer-controlled DC motor opens the screw-cap bottles by rotary motion allowing the low-density dilute acid to be replaced by dense seawater via passive density-driven flow. Laboratory tests show that fluid replacement occurs within a few minutes. In the field, the bottles are left open for 15 minutes, and the salinities of the resulting samples indicate complete fluid exchange.

**Communications**

To collect data from a number of subsurface instruments, an inductive telemetry system was developed. The method entails use of an inductive coupling via toroidal pick-ups on the standard mooring line—the electrical return is by the seawater. Inductive...
modem, interfaced to subsurface instruments, transfers data to the surface buoy at 1200 bits per second via the insulated mooring line. The data are stored and a subset transmitted via Argos. The stored data can also be off-loaded by wireless Ethernet telemetry when the Weatherbird II is within range (about two kilometers). The

Moored, in-situ, trace-element, serial-sampler system—MITESS. Note: “S.S.”= stainless steel; “UHMW”=ultra-high molecular weight.

short-range RF data are full bandwidth whereas the Argos data are limited to hourly averaged samples. Full bandwidth data are also stored internally on all systems and downloaded after each deployment. The system’s two-way communication capability allows changing of instrument parameters from shore (e.g., gain adjustments) and for carrying out event specific experiments.

The development of the telemetry aspect of this work is important in the long-term scheme of utilizing moored and drifting instrumentation arrays for remote sites as part of global ocean/climate observing networks.

Nature at Work

The third deployment of the BTM (April 6-August 24, 1995) was especially interesting. In July 1995 a subsurface eddy with the highest chlorophyll levels in several years passed through the mooring site. This event was observed in the MVMS and OsmoAnalyzer data as reflected in cool, nutrient (nitrate) rich waters with high concentrations of chlorophyll and increased turbidity.

A month after the passage of this eddy, the first of three hurricanes (Felix, Luis, and Marilyn) passed near Bermuda and the BTM. Hurricane Felix was an especially large hurricane with a diameter of 200-250 miles and storm-force winds extending out to 400-500 miles. Felix had its minimum barometric pressure and maximum
winds (143 knots) as it approached Bermuda on August 11, 1995. The eye of Felix passed about 40 miles from the BTM on August 15. Winds of over 85 knots were recorded on the buoy and the surface temperature decreased by about 4°C. Near surface inertial currents of about 1 meter/second were recorded as the mixed layer deepened rapidly. Considerable mixing was evident and water turbidity of the upper layer decreased as waters with lower biomass were entrained into the upper layer. The swaths of cool surface water resulting from Felix was about 120 miles wide.

Although few hurricanes have passed over heavily instrumented moorings in the past, Hurricane Lilly passed near the BTM in the fall of 1996, and Hurricanes Eduard and Hortense passed south of Cape Cod also in the fall of 1996, near an ONR Coastal Mixing and Optics mooring which included the UCSB BIOPS packages (see cover of Sea Technology: February: 1997).

Epilogue

The BTM program has demonstrated its utility for developing, testing, calibrating, and intercomparing interdisciplinary instruments. Creative ideas and emerging instrumentation will continue to be tested using the BTM.

Many of the sensors and systems developed and tested on the BTM are also suitable for deployment on other platforms such as drifters, AVUs, and offshore structures, all of which will likely be used in future Global Ocean Observing Systems.

Time series of lead concentration collected most recently with MITESS and from ships over the past 16 years have demonstrated that upper ocean lead concentrations near Bermuda have declined because of phasing out of leaded gasoline through 1990. The high degree of variability over time necessitates relatively frequent sampling (enabled by MITESS) in order to understand the origin of the variability.

The present observations are being used for biogeochemical models and will also be used for algorithm development for ground-truthing of satellite color sensors.

Finally, the BTM is available to the general oceanographic community. A summary of the various deployments, a guide to data reports and papers, recent data highlights, and information for potential BTM users may be found on the worldwide web site http://www.marsh.ucsb.edu/opl/opl.html and ancillary data from the BATS program can be found at http://www.bbsr.edu/8080/bats/bats.html.

Dr. Tommy D. Dickey received his doctorate from Princeton University in geophysical fluid dynamics. He has served as chairman of the technology committee of the U.S. JGOFS, U.S. GLOBEC, and International GLOBEC programs. He has taught oceanography to over 4,000 undergraduates. Graduate students and postdoctoral fellows in his group pursue diverse topics including coastal ocean pollution, ocean response to hurricanes, and time series of primary productivity in regions ranging from the equator to 60°N.

Daniel Free is the manager of Applied Engineering Laboratory at Woods Hole Oceanographic Institution. He holds a master’s degree in physical oceanography from Oregon State University. His research interests are in moon and mooning design, ocean data telemetry, and ocean instrumentation.

Dr. Ed Boyle has served on the NSF-MESH Global Change program and has instructed graduate students in marine geology and chemical oceanography for 20 years. His research group studies trace element chemical oceanography, quaternary paleoceanography, and polar ice cores. Boyle received his doctorate from the MIT and Woods Hole Oceanographic Institution Joint program.

Dr. Hans W. Jamasch’s current work focuses on developing in situ chemical detectors and samplers for studying the chemical variability in the ocean. He received his doctorate in chemical oceanography from the University of Washington in 1990.

Dr. Anthony Knap has authored 75 peer-reviewed publications in the fields of environmental and climate science and is presently chairman of the Group of Experts on Methods Standards and Inter-calibration (GEMS) jointly sponsored by the Intergovernmental Oceanographic Commission, the International Maritime Organization and the UN Environmental Program. Knap received his doctorate in chemical oceanography from the University of Southampton, United Kingdom in 1998.