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Workshop Proceedings

SEABED SENSOR TECHNOLOGY

Savannah, Georgia

February 1-3, 2006

Funded by NOAA's Coastal Services Center through the Alliance for Coastal Technologies (ACT)

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An ACT 2006 Workshop Report

A Workshop of Developers, Deliverers, and Users of Technologies for Monitoring Coastal Environments:

Seabed Sensor Technology

Savannah, Georgia

February 1-3, 2006

Sponsored by the Alliance for Coastal Technologies (ACT) and NOAA's Center for Coastal Ocean Research in the National Ocean Service.

Hosted by the Skidaway Institute of Oceanography (SkIO), an ACT Partner organization.

ACT is committed to develop an active partnership of technology developers, deliverers, and users within regional, state, and federal environmental management communities to establish a testbed for demonstrating, evaluating, and verifying innovative technologies in monitoring sensors, platforms, and software for use in coastal habitats.

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ACT WORKSHOP: *SEABED SENSOR TECHNOLOGY*

EXECUTIVE SUMMARY

Future coastal management practices require that a holistic, ecosystem management approach be adopted. Coastal ecosystems, however, present a variety of specific and unique challenges relative to open ocean systems. In particular, interactions with the seabed significantly influence the coastal ecosystem. Observing technologies must be developed and employed to incorporate seafloor interactions, processes and habitat diversity into research and management activities.

An ACT Workshop on Seabed Sensor Technology was held February 1-3, 2006 in Savannah, Georgia, to summarize the current state of sensor technologies applicable to examining and monitoring the coastal seabed, including the near-bed benthic boundary layer and surface sediment layer. Workshop participants were specifically charged to identify current sensors in use, recommend improvements to these systems and to identify areas for future development and activities that would advance the use of sensor technology in the observation, monitoring and management of the coastal benthic environment.

WORKSHOP RECOMMENDATIONS

ACT should promote the development of commercially-available benthic sensor systems. The use of benthic sensor technologies for research and management would be accelerated if more off-the-shelf instruments and systems were available to potential users. Many of the needed improvements to expand usefulness and marketability are related to system integration. Specific areas that could be pursued are: 1) to offer integrated instrument packages where present sensor, data, power and telemetry systems are already integrated for easy use, 2) to advocate industrial standard protocols for output from sensors to facilitate easier integration, configuration flexibility and plug-and-play functionality, and 3) to promote consistency for how sensor specifications are reported to facilitate comparison of results and instrument capabilities.

ACT should assist in communicating measurement and operational requirements of coastal benthic researchers and managers to ensure that future developments result in systems capable of sampling at the frequencies required to resolve benthic processes and applications (e.g. faster sensors for eddy correlation flux estimates).

ACT should continue to promote research and development directed at mitigating biofouling. Biofouling remains a major obstacle for long-term sensor measurements. Although it was the focus of the previous ACT workshop, it is worth revisiting to discuss recent advances and to solicit input from other industries and communities (material science, nanotechnologies, surface chemistry, biomedical engineering, EPA). Furthermore, it must be recognized that minimizing biofouling requires a holistic approach, not just an analysis of the sensor tip. The entire instrument design must be evaluated to minimize growth on all surfaces.

ACT should promote the development of non-intrusive systems for studying benthic processes and conditions. Examples of potential systems include the further development of the eddy correlation method for estimating benthic fluxes and acoustic and optical methods for evaluating benthic habit.

ACT should promote the expanded incorporation of benthic sensor systems in research and management by providing training workshops on specific benthic sensor types. Most users are comfortable with water column instruments with which they are more familiar. ACT can promote the incorporation of benthic sensor technology into management strategies by familiarizing managers with their operations and interpretation.

ACT should continue to promote the development, commercialization and use of benthic sensor and observing technologies in coastal management and research through additional workshops. Potential topics for future workshops include: 1) standardization of techniques for defining/measuring sediment erodibility; 2) techniques for sea floor mapping; and 3) sensor and autonomous instrument measurements of nutrient concentrations in low nutrient regimes.

ALLIANCE FOR COASTAL TECHNOLOGIES

There is widespread agreement that an Integrated Ocean Observing System (IOOS) is required to meet a wide range of the Nation's marine product and information service needs. There also is consensus that the successful implementation of the IOOS will require parallel efforts in instrument development and validation and improvements to technology so that promising new technology will be available to make the transition from research/development to operational status when needed. Thus, the Alliance for Coastal Technologies (ACT) was established as a NOAA-funded partnership of research institutions, state and regional resource managers, and private sector companies interested in developing and applying sensor and sensor platform technologies for monitoring and studying coastal systems. ACT has been designed to serve as:

- An unbiased, third-party testbed for evaluating new and developing coastal sensor and sensor platform technologies,
- A comprehensive data and information clearinghouse on coastal technologies, and
- A forum for capacity building through a series of annual workshops and seminars on specific technologies or topics.

The ACT workshops are designed to aid resource managers, coastal scientists, and private sector companies by identifying and discussing the current status, standardization, potential advancements, and obstacles in the development and use of new sensors and sensor platforms for monitoring, studying, and predicting the state of coastal waters. The workshop goals are to both help build consensus on the steps needed to develop and adopt useful tools while also facilitating the critical communications between the various groups of technology developers, manufacturers, and users.

ACT Headquarters is located at the UMCES Chesapeake Biological Laboratory and is staffed by a Director, Chief Scientist, and several support personnel. There are currently seven ACT Partner Institutions around the country with sensor technology expertise, and that represent a broad range of environmental conditions for testing. The ACT Stakeholder Council is comprised of resource managers and industry representatives who ensure that ACT focuses on service-oriented activities. Finally, a larger body of Alliance Members has been created to provide advice to ACT and will be kept abreast of ACT activities.

ACT Workshop Reports are summaries of the discussions that take place between participants during the workshops. The reports also emphasize advantages and limitations of current technologies while making recommendations for both ACT and the broader community on the steps needed for technology advancement in the particular topic area. Workshop organizers draft the individual reports with input from workshop participants.

ACT is committed to exploring the application of new technologies for monitoring coastal ecosystem and studying environmental stressors that are increasingly prevalent worldwide. For more information, please visit http://www.act-us.info/.

GOALS FOR THE SEABED SENSOR WORKSHOP

The ACT Workshop on Seabed Sensor Technology was held 1 - 3 February 2006 in Savannah, Georgia to summarize the current state of sensor technologies applicable to examining and monitoring the coastal seabed, including the near-bed benthic boundary layer and surface sediment layer. Workshop participants were specifically charged to identify current sensors in use, recommend improvements to these systems and to identify areas for future development that would advance the use of sensor technology in the observation, monitoring and management of the coastal benthic environment.

Workshop breakout discussion groups were given the following general questions to initiate discussions.

1. What types of sensor systems presently exist and what parameters/conditions do they address?
2. How operational are the systems and where are improvements needed?
3. What types of new systems and deployments strategies are recommended?

Employing these questions to stimulate initial discussions, the final morning was devoted to identifying common recommendations that would advance development and use of sensors in benthic coastal environments.

ORGANIZATION OF THE WORKSHOP

The workshop was sponsored by ACT and hosted by the Skidaway Institute of Oceanography (SkIO), an ACT partner institution. The workshop was organized by Drs. Herb Windom and Rick Jahnke (SkIO) with R. Jahnke also serving as workshop facilitator. On the first evening, workshop participants convened for a reception and dinner during which Dr. Windom gave a presentation on the mission of the ACT Program. The workshop commenced the following day with a plenary session including an introduction lecture and discussion of the charge to the breakout discussion groups. Group composition was controlled to provide a reasonable balance amongst the researchers, managers and industry representatives.

INCORPORATION OF SEABED PROCESSES INTO COASTAL ECOSYSTEM AND MANAGEMENT MODELS

Future coastal management practices require that a holistic, ecosystem management approach be adopted. This strategy was recently highlighted in the U. S. Commission on Ocean Policy Report (2004). Coastal ecosystems, however, also present a variety of specific and unique challenges relative to open ocean systems. In particular, the sea floor significantly influences the coastal ecosystem. Past conceptual models of coastal ecosystem function have not given adequate attention to material fluxes and transformations across the sediment water interface.

Numerous examples exist of how the sea floor exerts considerable control on the overall functioning of coastal ecosystems. For example, at many locations, light penetrates to the sea floor and supports significant benthic primary production. On the continental shelf adjacent to the southeastern US, recent estimates suggest that benthic primary production is 58% of water column production. Adding this additional production to the water column production significantly increases the estimated total biological production of the shelf environment. Benthic production may play an important ecological role because it is most likely out of phase with water column production. That is, when water column production is high, benthic production is generally depressed because most of the available light will be intercepted and utilized in the water column. On the other hand, when water column production is low and suspended particle concentrations are also often low, benthic production is maximal because more light reaches the sea floor. Therefore, even at locations where benthic primary production contributes only a small amount to the total biological fixation of organic carbon, benthic production may play an important ecological role by supporting grazers during times of water column oligotrophy. Furthermore, because benthic fluxes of many solutes, such as phosphate and iron, are very sensitive to the redox state of surface sediments, the occurrence of even minor rates of benthic photosynthesis (and hence oxygen production), can influence nutrient inputs and cycling.

The sea floor may also play a major role in recycling organic materials. Again, on the Carolina Bight continental shelf, sea floor respiration is estimated to be 48% of the total of water column and benthic primary production. It is likely that this large respiration rate is supported, at least in part, by the direct filtration of organic materials from waters advecting through the sandy sediments that characterize most shelf environments. While unknown import of organic materials prevent a full mass balance estimate, this estimates emphasizes the importance of the sea floor in the overall metabolic balance of this coastal system. Furthermore, recent studies reveal that much of the organic nitrogen released during the degradation of organic materials in the sediments is denitrified. This loss of biologically available nitrogen is important both to the local biogeochemistry and to the global N cycle.

There are numerous other examples of important processes that link sea floor - water column interactions with the overall functioning of coastal ecosystems. These include sediment re-suspension, migration of organisms to and from the sediments, export in topographically-controlled offshore bottom currents and nutrient inputs due to groundwater inputs.

These interactions impart a different temporal variability of coastal ecosystems to external forces than their open ocean counterparts. Technologies for observing benthic interactions must be developed and implemented to incorporate these interactions into coastal ecosystem descriptions and models.

EXISTING BENTHIC SENSOR TECHNOLOGIES

The first two questions provided to the breakout discussion groups focused on identifying existing sensor technologies and their use. Previous workshops (i.e. COS, Jahnke et al. 2002; SCOTS, Glenn and Dickey, 2003; CORA, Jahnke et al. 2003; CBED, Reimers, et al. 2004) have discussed and highlighted existing sensor systems capable of monitoring coastal processes, many of which are also relevant to benthic studies. Here, however, we emphasize those sensors and sensor systems that focus specifically on characterizing the sea floor and quantifying the rates and variability of benthic solute and particulate transport processes. A non-exhaustive summary of sensors, organized by main measurement technique, with examples of use are provided in Table 1. In addition to the direct measurement, it is important to note that through combinations of sensor measurements, many additional processes can be estimated. For example, combining high frequency velocity measurements and solute concentration may yield flux estimates via eddy correlation analysis. The development of this technique is currently being examined for nitrate and oxygen.

It is clear from the list, that many aspects of seafloor dynamics and habitat can now be observed remotely and in many cases non-invasively. However, before these techniques can be routinely included in studies and monitoring efforts, workshop participants identified a variety of developmental challenges that must be met. These include:

Biofouling - Biofouling continues to limit deployment duration of most sensor types. While acoustic sensors are amongst the least sensitive, all sensors are affected. Impacts include the overall operations of the sensor system and sensor calibration.

Electrolysis - Long-term deployments also require that instrument frames, pressure cases, sensor surfaces, etc. not be subject to significant corrosion. While in many cases, this can be minimized by careful selection of materials, complete exclusion of dissimilar metals is difficult to achieve and in some cases can significantly increase cost which ultimately limits use.

Calibration - Maintaining sensor calibration is key to acquiring long-term, useful data records that are comparable between sensor locations and over time. Calibrations are sensor specific and generalized solutions can not be formulated. Nevertheless, extending the length of time specific sensors provide accurate measurements, in conjunction with minimizing biofouling impacts, is important to expanding sensor system use.

Miniaturization - Towed and autonomous sensor platforms offer greatly expanded capabilities for spatial coverage of sensor measurements. As large, bulky instrument packages cannot be accommodated on these vehicles, and in some cases would interfere with flow conditions and results, miniaturizing sensors and associated electronic components will facilitate the use of these systems.

Power - In addition to size, power requirements currently limit the types and number of sensors that are deployed on an instrument platform. Reducing power requirements will also facilitate the use of multiple sensor packages.

Telemetry - Telemetry of sensor data to end-users promotes the usefulness of environmental measurements in two fundamental ways. First, certain types of information are time-critical and their usefulness to decision makers decreases rapidly with increasing latency. Examples might be decisions about evacuation of coastal areas with the approach of a hurricane, closure of a beach based on trajectories of a harmful algal bloom or patch of stinging jellyfish or direction of containment for mitigating an oil spill. Second, ocean researchers can employ realtime information to directly sample and study marine phenomena for which there are not yet sensors available. For example, monitoring locations of fronts can help direct sampling of larvae that may be transported specifically along those fronts. Developing systems that would more readily integrate sensors and sensor systems with telemetry systems would facilitate their use.

CHALLENGES

This section focuses on the deliberations stimulated by question 3, "What types of new systems and deployment strategies are needed?" There are many challenges that future systems must meet. Participants agree that signals that are important to understanding and monitoring the functioning and condition of coastal ecosystems occur on a wide spectrum of space and time scales. Single deployment strategies in general can only focus on a part of this spectrum. Therefore, it is likely that a full monitoring of coastal systems to support holistic ecosystem management will require multiple deployment strategies. Additionally, many sedimentary sampling, measurement and modeling techniques are substrate dependent. However, most sampling methods have been developed for muddy sediments that are relatively easy to core with stratgraphically intact sediment and pore water samples and for which a rich history of reaction - transport models have been developed. The majority of continental shelves of the world, however, are geologically classified as relicit - often dominated by sands. Most sampling techniques and modeling frameworks do not work well in sands. Many of these regions have elevated permeability and significant whole-sale advective pore water transport may occur. Exchange processes of solutes and particles and biogeochemical reactions occur and respond to external forces fundamentally differently in this environment than their muddy counterparts. It is clear that multiple deployment and measurement strategies will be required to advance understanding of coastal ecosystems.

DEPLOYMENT STRATEGIES

It was quickly recognized by the participants that the optimal deployment strategy will vary with the targeted application or specific problem being addressed. There is a long history of expeditionary research and monitoring in coastal zones. Discussions of needed future deployment strategies focused primarily on establishing "long term" and "continuous" measurements, which cannot be obtained via ship-based expeditions.

In general, the need for continuous and long-term measurements is supported by the recognition of the major role, short-term, episodic events, such as storms, floods, blooms, or hypoxic events associated with temporary stratification, have on a coastal ecosystem. As each of these types of events is associated with its own characteristic occurrence frequency and duration, it is clear that the terms "continuous" and "long-term" are defined differently for each. The goal for benthic sensors is to provide measurements that resolve the basic forces and environmental responses to important events over a sufficiently long period that a representative sampling of these events can be observed. Given our current state of knowledge, time-series measurements covering at least one annual cycle and being capable of resolving sub-hour variations are critically needed.

Additionally, it was recognized that deployment strategies that facilitate the integration of individual approaches would be beneficial. This could include combining sensors that integrate space and/or time scales and that can support advances in modeling. It was recognized that individual events often can dominate specific aspects of coastal systems such as sediment transport. Therefore, one way to match observation resolution to that needed is to control sampling/measurement frequency through two-way communications or "smart" sensors. Thus, measurements may be maintained at a background, low rate during periods between events and then increased to obtain the resolution needed during an event.

Resolving spatial variability also presents significant challenges. Fixed sensor systems can only be deployed at relatively few locations. Autonomous and towed sampling systems have been successfully employed in the past. This includes benthic sampling where bottom sediments are continuously pumped on board ships and high-resolution samples recovered.

Other deployment issues discussed included design criteria and strategies to minimize alteration of the natural flow conditions. Because of the fundamental linkages between flow and bottom characteristics and exchange and because of the strong gradients in flow characteristics in the near-bottom boundary layer, this is a critical concern. Biofouling was also raised as a major limitation to long-term accurate observatory measurements. Design strategies need to minimize instrument surfaces on which organisms can attach and grow, as well as seek environmentally friendly techniques for keeping sensors clear.

While many of these issues apply to observatories of all categories, several issues were raised that are particularly important for benthic observatories.

How representative are sites of intensive measurements? Although spatial heterogeneity is an issue with water column observatories, unimpeded circulation of water past a fixed observatory location integrates processes occurring over broad spatial scales. On the sea floor, the problem of heterogeneity is exacerbated because the sea floor is basically fixed, except during sediment transport events and characteristic rates can vary significantly over small spatial scales. For example, irrigation of burrows by larger (and patchily distributed) infauna can contribute substantially to sediment water solute exchanges. The problem of local context of measurements highlights the need for integrated sensor systems. That is, accurate assessment of solute fluxes will require both accurate chemical sensors and an estimate of the spatial variability of seafloor exchange. Thus, the issue of how representative measurements made at a specific benthic site are to the region is critically important to using that information. Benthic observatories will most likely need to incorporate into their strategy mobile, survey platforms. These may be towed, such as the Continuous Sediment Sampler, or may be autonomous. Within a reasonable proximity of the observatory site, mobile platforms with an umbilical cable to provide power and communications, such as bottom crawlers or ROVs would also be very useful.

A second major issue to benthic observatories is the potential changes the observatory may have on the local environment. The widespread practice of creating artificial reefs on the coastal seafloor to enhance sport fisheries is an obvious, everyday example of the impacts of placing structures on the seabed. Such structures quickly attract different species and alter bottom currents in the immediate vicinity. Thus, benthic instruments placed directly on these deployment structures may not accurately reflect natural conditions. There is no easy solution to this issue. Each type of measurement may have different spatial scales at which it is affected by the presence of the structure. Potential solutions may require employing mobile platforms so that measurements can be made at some distance from the observatory. For certain small-scale measurements, it is possible that an open structure can be built with a vertically mobile instrument system to periodically make measurements at the sea floor and then move away from the boundary to permit natural, relatively un-impacted, current interactions.

NEW SYSTEMS

Participants also discussed and described potential new sensor systems that would be of use to researchers and coastal managers. General attributes identified include:

1. The system must minimize disturbance to the measurement environment. This includes disturbance to local flow and larger "island effects" discussed above.

2. Systems need to be less expensive than current, research-grade instruments. Cost is a critically important constraint limiting use amongst coastal managers.

3. Systems must be either fully integrated or modularly constructed to facilitate sensor, data management and telemetry system integration to permit use by a more general workforce.

In addition to these general criteria, several specific areas of development were identified. These include developing:

- methods for quantifying fauna on small scale without direct sampling/counting (e.g., acoustic scanning?)

- molecular techniques to serve as indicators for regulated components (e.g., specific indicators of contaminants)

- systems for in situ, high-resolution vertical measurements of sediment "textural" properties and changes with time (thresholds for resuspension; sediment compaction/dewatering following deposition).

- reasonably high data transmission without requiring cable that will expand the use of sensor systems.

Examples of integrated instrument packages that could be commercialized include:

1. AUV/towed "flying" vehicle chemical sensing package:

Existing: ADCP, side-scan, oxygen, CTD, fluorometer, backscatter
Commonly needed: Nutrient sensors, turbulence sensor, very high sampling of chemistry (one exciting application is mapping of turbulent benthic fluxes in space - i.e., drastic increase in spatial resolution).

2. A standard sensor interface and modular plug-and-play standards:

If an existing standard interface were adopted by many sensor manufacturers, then the logger/telemetry units could be separated from the sensors in terms of manufacturer, capacity, etc., and different sensor types, loggers, telemetry, etc., could be swapped in and out much more easily. Sensor systems could be maintained and upgraded much more easily.

3. Benthic particle imaging system (and settling column):

Combine a very high mega-pixel commercially available digital camera with a high quality collimated light source, settling column and a logging system (measures particle size distribution, settling velocity and thus infers density).

4. Sediment profile camera combined with a chemical sampling system:

Combine a high resolution prism interface camera with probes for oxygen, pH, fluorometry, and other biochemical sensors (documents sediment fabric, penetration, biological structures, sediment color, and sediment particle types -- all in an in-situ spatial context).

5. Integrated multifrequency Acoustic Backscatter (ABS) and Doppler technology:

Combine ABS and Doppler together in multi-frequencies and in a bistatic arrangement with multi-directional receivers so that particle properties and turbulence can be resolved in detail through lower water column (simultaneously measures temporally varying Reynolds stress profiles along with particle size spectra and concentration profiles - and resistant to calibration drift and biofouling!).

6. Integrating fast chemical sensors with eddy resolving velocity measurements:

The chemical and velocity sensors need to be commercialized together. The technology for the velocity is highly developed. Fast response chemical sensors need to be made available for with the velocimeters as a package. (This allows direct, non-intrusive measurement of vertical benthic fluxes just above the bed. Can water sampling be done fast enough to allow storage of physical samples for later lab analysis? This would greatly expand the types of fluxes that could be measured using the eddy flux technique.)

7. Time-series benthic sampler:

Commercially available lander which periodically samples bed in discrete places, perhaps with an arm which rotates around a circle or systematically moves over a small grid. Samples could be preserved for later lab analysis. In-situ chemical samples and bed imaging could be combined in time-series fashion with multiple small cores. Two key missing elements are available probes and highly accurate and reliable mechanical sampling systems.

8. Sled or crawler-based benthic sampling system:

A benthic plow which drags chemical sensors and benthic camera along the seabed, continually or periodically sampling across the sediment water interface to give spatially distributed samples.

In addition, a variety of unproven but promising approaches were also identified. These included an AUV benthic "hopper" where the AUV would be capable of moving to a new location and then contact the bottom and either take a sample (limited by buoyancy considerations) or make a sensor-based measurements.

RECOMMENDATIONS

Building on the discussions of the preceding day, the workshop participants developed a list of recommendations. These are:

The development of commercially-available, integrated benthic sensor systems should be promoted. The use of benthic sensor technologies for research and management would be accelerated if more off-the-shelf instruments and systems were available to potential users. Many of the needed improvements to expand usefulness and marketability are related to system integration. Specific areas that could be pursued are: 1) to offer integrated instrument packages where present sensor, data, power and telemetry systems are already integrated for easy use, 2) to advocate industrial standard protocols for output from sensors to facilitate easier integration, configuration flexibility and plug-and-play functionality, and 3) to promote consistency for how sensor specifications are reported to facilitate comparison of results and instrument capabilities.

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Continued research and development for mitigating biofouling is needed. Biofouling remains a major obstacle for long-term sensor measurements. Although it was the focus of the previous ACT workshop, it is worth revisiting to discuss recent advances and to solicit input from other industries and communities (material science, nanotechnologies, surface chemistry, biomedical engineering, EPA). Furthermore, it must be recognized that minimizing biofouling requires a holistic approach, not just an analysis of the sensor tip. The entire instrument design must be evaluated to minimize growth on all surfaces.

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TABLE 1. SUMMARY OF EXAMPLE BENTHIC SENSORS AND OBSERVING SYSTEMS

MEASUREMENT TECHNIQUE **application**	**COMMENTS**
ACOUSTIC SENSORS	
larger-scale bed mapping	*multi-beam/swath mapping; single beam; sub -bottom profiling; side-scan*
smaller-scale bed mapping	*high-frequency mobile side-scan (e.g., AUV); sector-scanning sonar ('rotating'); high -resolution chirp sonar (seabed profiling)*
acoustic scattering	*currents; particle fields, relative particle concentrations; turbulence, zooplankton signals*
acoustic Doppler	*profiler: small, high -frequency 5beam Doppler profilers* *point measurement: bistatic high res Doppler current meter*
near-bed water-column acoustic backscatter (multi -frequency ABS)	*combine ABS and Doppler, multi -frequency, bistatic multidirectional*
sonar (various scales)	*seabed classificaton/topography/bedforms*
in situ imaging	*bed features, biosurveys*
OPTICAL SENSORS	
optical backscatter/transmission	*turbidity; particle concentration; suspended mass*
optical imaging	*still camera imaging; video imaging including particle imaging velocimetry; hyperspectral imaging*
radiometers	*light, PAR, attenuation - integrated view of particle field*
fluorescence	*phytoplankton biomass index; chla, CDOM tracers*
spectrophotometric	*biogeochemistry: nutrients; absorption properties; particle size distribution*
laser applications; diffraction, Doppler velocimetry, altimetry incl. LIDAR, laser linescanning	*bathymetry; small-scale topography; particle size*
optical chemical sensors	*planar optodes: 2-D solute distributions at sed/water interface; oxygen, pH; fluorometry*
x-radiography	*portable digital xrays; CT systems*

TABLE 1. CONTINUED

ELECTRICAL SENSORS	
potentiometric	*pH*
thermistor	*temperature*
conductivity	*salinity*
resistivity	*bed porosity, tortuosity*
piezo-electric	*pressure; to estimate fluid flow*
hot film velocimeter	*shear*
voltametric	*redox-active chemical species*
WET CHEMICAL SENSORS	
nutrient autoanalysers	*targeted solutes (nutrients, selected metals)*
genetic sensors	*individual species*
mass spectrometer	*dissolved gases; volatile organics*
gamma detector	*U-containing deposits; waste sites*
MECHANICAL	
flux chamber instrument	*solute fluxes; groundwater seepage*
sled	*elements; organics in fine particles*
sediment trap	*particle fluxes, particle collections*

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