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Workshop Proceedings

DEVELOPING TECHNOLOGIES FOR ENVIRONMENTAL MICRO-CHEMICAL SENSORS

Ann Arbor, Michigan
April 20-22, 2004

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

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An ACT 2004 Workshop Report

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

Developing Technologies for Environmental Micro-Chemical Sensors

Ann Arbor, Michigan
April 20-22, 2004

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

Hosted by ACT Partner, University of Michigan.

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: DEVELOPING TECHNOLOGIES FOR ENVIRONMENTAL MICRO-CHEMICAL SENSORS

EXECUTIVE SUMMARY

The Alliance for Coastal Technologies (ACT) convened a Workshop on, *Developing Technologies for Environmental Micro-Chemical Sensors* in Ann Arbor, MI on April 20-22, 2004. The primary objectives of this workshop were to: 1) increase the awareness of managers and industry representatives of the potential benefits and application of new enabling nanotechnologies under development; 2) discuss the current state of nanotechnology applications in environmental sensors; 3) define application priorities and performance requirements for environmental sensors used by coastal resource mangers; and 4) recommend strategies for promoting a more rapid advancement of these emerging nanotechnologies into commercially available products. To meet these objectives we brought together a mixture of leading research scientists, resource managers, and industry representative for a focused one and a half day workshop. The workshop featured three plenary talks followed by breakout sessions in which arranged groups of participants where charged to respond to a series of focused discussion questions.

The potential value of emerging nanotechnologies to reduce the cost, power requirements, and difficulty of use of in situ chemical sensors is generally accepted but their remains much uncertainty as to the timing and applications for which these advanced sensor packages will be available. Yet traditional sampling and lab-based analyses procedures are inadequate to monitor dynamic coastal environments where analyte distributions vary rapidly in response to a host of physical, biological, and anthropogenic drivers. To that end a common goal of both the research and management communities is to seek the development of advanced, miniaturized sensor packages that can be deployed for continuous in situ monitoring, and that poses the capability of self calibration, performance evaluation, and data integration. The following general recommendations were made for helping to advance future availability and application of micro-chemical sensors:

- Develop a white paper defining the status of sensor system development including the three facets of sensor technologies, systems technologies, and deployable field units. The paper should also help prioritize the development of a common set of sensor technologies that will support a broad range of applications and have strong commercial backing
- Develop a list of Agencies/Labs to bring together in a workshop aimed at developing funding opportunities targeted to 'selected' sensors

- Encourage academic institutions with strong environmental engineering programs to develop workshops or summer courses for training students in the development and use of field-based sensor systems

- Develop a web site that can build upon these workshop efforts by identifying funding opportunities and promoting research/industry partnerships

- Talk to lead managers at National Oceanographic Partnership Program to help direct new announcements of opportunity for sensor development

- Identify resource management issues where sensor development could provide needed data in a cost effective manner

- Establish and foster informed partnerships that are ready to jump on new opportunities by having identified priority applications and system requirements up front

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 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 www.act-us.info.

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.

GOALS FOR THE ENVIRONMENTAL MICRO-SENSOR WORKSHOP

The ACT workshop on environmental micro-sensors was convened on April 20-22, 2004 in Ann Arbor, MI to examine the state of emerging nanotechnologies and their application into designing a new generation of sensor and sensor platform technologies. The overall goal of the workshop was to foster the awareness and communication among leaders from industry, resource managers, and academic researches as to the needs and limitations for bringing new technologies into practice and to recommend strategies for increasing the rate at which new sensor packages become available.

Participants were given the following specific charges to address:

- Identify problems or limitations in current environmental monitoring programs due to inadequate instrument or sensor capabilities

- Define desired performance requirements of new sensor systems

- Review the current status of new micro-sensors and enabling nanotechnologies

- Define the perceived advantages of nanotechnology application in environmental sensors

- Identify the challenges that limit the development of commercially available sensors
- Recommend strategies for bringing new sensors "on-line".

ORGANIZATION OF THE ENVIRONMENTAL MICRO-SENSOR WORKSHOP

The workshop was sponsored by NOAA's Alliance for Coastal Technologies and hosted by the University of Michigan. The workshop was organized by Dr. Tom Johengen and facilitated by Dr. Steve Weisberg of the Southern California Coastal Water Research Project and Mr. Steve Ruberg of the NOAA Great Lakes Environmental Research Laboratory. The workshop was held over two and a half days on the campus of the University of Michigan and followed a prescribed format that ACT has developed for these technology workshops. The workshop opened with an evening dinner reception during which participants were introduced and two presentations given. The first presentation was delivered by ACT's Chief Scientist, Dr. Mario Tamburri, and described the structure and goals of the ACT program. The second presentation was given by Dr. Volpe from Lawrence Livermore National Laboratory and was designed to set the stage for the following two days of deliberations. On the morning of the second day participants were briefed on the format and objectives of the workshop by Dr. Johengen and then listened to two plenary talks given by Dr. Thomas Haddock of Ardesta Systems Inc. and Mr. Larry Langebrake of the Center for Ocean Technology (COT) at the University of South Florida. Following the presentations a series of breakout sessions were convened to stimulate discussion and address the charges of the workshop. For each breakout session, three groups of 10 participants each were formed and asked to respond to a set of specific questions. For the first round of discussions the three groups were organized by professional background (researchers, industry, and managers), and then for the second session the groups were mixed to contain an equal number of members from the three sector areas. After each breakout session all groups reconvened in plenary to report out the responses from each group and to allow for additional discussion. On the final day, the facilitators led a discussion among all participants to synthesize the main conclusions from prior discussions and to develop a set of specific recommendations for ways to advance the development of micro-chemical sensors that incorporate these emerging technologies and that better serve the needs of the environmental research and management community. Lastly, participants tried to identify some specific action items or functions that ACT should try to accomplish to promote these technology advancements.

STATEMENT OF THE PROBLEM

It is widely recognized that current sampling and analytical approaches are woefully inadequate for developing monitoring programs that can provide the requisite data for understanding, modeling, and managing our coastal and freshwater ecosystems. Most water quality parameters of interest vary tremendously in both space and time and cannot be easily characterized by infrequent, fixed-interval sampling or by sampling schedules dictated by available resources, such as required when using the standard research cruise approach. Chemical distributions can be affected by a variety of naturally occurring physical and biological processes, as well as from anthropogenic stressors often seen within the nearshore coastal environment. Most of the available instruments for in situ monitoring are often quite expensive, require fairly extensive engineering support, and have limited reliability for longer term deployments. To overcome these limitations will require the development of new and improved sensors that are cheaper, more reliable and easier to use. These new technologies should also have the capability of onboard data processing so that they can deliver data that is immediately useable and has undergone internal quality control checks.

Although most new applications may be years out, it is generally perceived that the incorporation of emerging nanotechnology systems into environmental sensors has the potential to radically alter the spatial and temporal scales over which we will be able to conduct water quality monitoring programs. It is also believed that ultimately these systems will be cheaper to build and significantly easier to operate due to their miniaturized size and weight, and integrated circuitry. What remains largely undefined is how quickly or broadly these technology advancements will actually make it into the commercial market place, and to what extent these technologies may be tailored to application in environmental sensors.

We recognize that we are using the term nanotechnology in a very broad manner and that this type of usage may tend to make its meaning become vague. We also recognize that the emerging technologies that are likely to be applied to environmental sensors may range from true nanotechnology, i.e. human-built structures at a scale of 100nm or less, up to the multiple cm scale and greater when considering systems that can be deployed within the natural environment. Our goal for this workshop was not to be constrained about size scales but to broadly evaluate emerging technologies occurring at the nano- and micro- size scales, often referred to as 'small tech' and that appear to hold significant promise for applications in environmental chemical sensors. The foundation of these technological advancements involves the utilization of new engineering capabilities such as wireless integrated microsystems (WIMS) and micro-electromechanical systems (MEMS). It is envisioned that sensor packages incorporating these technologies could be designed to measure a variety of physical and chemical parameters, interpret data, and provide communication over a bi-directional wireless link at scales of a few inches to a few miles.

Most of the research and development of these emerging small technologies is occurring at University research centers and small start-up companies focused on just one or two specific products. This process creates a real lack of awareness within the management community and general environmental research community as to the potential that exists for developing new sensors technologies that could directly serve their needs. Furthermore there is a lack of knowledge or appreciation as to the potential market value of developing in situ chemical sensors for the environmental community. Thus established environmental sensor companies appear hesitant to invest in the research and development necessary to incorporate these emerging nanotechnologies into new commercially available products. We organized this ACT technology workshop in the hopes of addressing some of these communication and awareness issues.

The Woods Hole, July 2003 workshop on, *The Next Generation of in situ Biological and Chemical Sensors in the Ocean*, stated that there is beginning to emerge among the scientific community a consensus on the issues related to sensor design and sensor platform technologies, which includes a vital role for developing nanotechnology systems. The findings from this current workshop would support that conclusion. The current workshop also brings the additional perspective of examining these issues from the standpoint of addressing the needs of the resource management community. This report describes the results and recommendation of the April 2004 ACT workshop on, *Developing Technologies for Environmental Micro-Chemical Sensors*.

PLENARY PRESENTATIONS

Three keynote presentations were delivered the workshop to help set the stage for the discussion breakout sessions. Dr. Volpe presented the talk, *Real-Time Ocean Chemistry in Dynamic Coastal Environments*, during which he described some real-world examples of the limitations associated with current monitoring strategies within the coastal ocean environment. Dr. Volpe described the effort and expense of conducting ship-based sampling cruises off of coastal California and how difficult it was to meaningfully sample within such a dynamic environment where chemical distributions were changing rapidly in response to a variety of physical and biological processes. The talk helped to highlight the need for bringing innovative in situ micro-chemical sensors to market and how that would greatly benefit the field of chemical oceanographic research.

On the second day of the workshop Tom Haddock gave a stimulating presentation entitled, *Developing the Bridge for Enabling Nanotechnologies and Micro-sensor Development to Commercial Products*. This presentation described a wide range of small technologies and products under development through a unique business plan operated by Ardesta Integrated Systems, Inc. Ardesta is a company focused on bringing 'small technology' products (MEMS, Microsystems and nanotechnology) to the global marketplace by investing talent and capital to create product-based Small Tech companies. They provide business and technical resources to support these companies, and develop the starting infrastructure to get the companies up and running. This approach serves as a striking contrast to the model of small start-up companies trying to develop new products through Small Business Innovative Research grants, or the model of existing sensor companies investing in the research and development to incorporate emrging nanotechnologies into a new line of products. Dr. Haddock described a wide range of small technologies and products under development within the family of companies supported by Ardesta. These products included optical MEMS gas detection sensors, active infra-red gas sensors on a single chip for assessing biological hazards, concentration and acquisition systems for airborne bio-organisms, bio-analysis systems for security and clinical use (flow cytometers, DNA analysis, blood-typing, etc.), distributed, self-configuring and self-healing RF peer-to-peer communication networks (that can serve as a reporting platform for small-tech sensors), lab-on-a-chip sensor technology for water, food, chemical and biological fluid applications (a single disposable chip comprising a self-calibrating, multi-analyte test panel including potentiometric polyurethane ionophore membranes, oxidation-reduction potential electrodes, resistive temperature devices (RTD), pH, stripping voltammetry, and others), optical waveguide systems written in glass monoliths by femtosecond lasers to produce building blocks for components for telecommunications, biomedical detection, liquid monitoring and industrial optical sensing (for example biodetectors, engine-oil monitors and vibration sensors for predictive maintenance), titanium dioxide nanoparticle Grätzel cells produced by an inexpensive and high-volume "cold sintering" process to give low-cost solar cells that can be deployed in large quantities to harvest solar energy. The presentation provided new insight into the breadth of products and applications under development that hope to utilize the benefits of emerging nanotechnology systems. The challenge for the environmental community appears to be how to broker or effectively capture these emerging technologies for sensor development where market incentives may not be as great as for other fields.

The third plenary talk was entitled, Development of Micro-Scale Sensors to Meet Future Demands for Coastal Monitoring, and was presented by Mr. Larry Langebrake. This presentation again reiterated the limitations of current marine sensors including expense, size, difficulty of use, and large power demands. The goal for future sensor development is to capture the potential of MEMS technologies to miniaturize coastal sensors using photolithographic techniques and thereby reducing both the cost and power consumption of sensors. One of the main goals of COT is to modularize MEMS based microsensers so that they can be deployed on underwater vehicles for continuous and real-time monitoring within the coastal marine environment. Mr. Langebrake described several products under development including a micro-CTD and an in-situ mass spectrometer. These products were just completing lab development and were being readied for field-deployment testing. These developments represent some of the first examples of bringing cutting edge nanotechnologies into real world application for oceanographic monitoring. The development of an in situ mass spectrometer represents a particularly important step forward as this analytical approach can be used for many different applications and has superior detection limit capabilities. The ability to apply these approaches in situ would address many of the spatial and temporal limitations of traditional water sampling and laboratory based analyses, and allow for measurement systems that could deal with dynamic biogeochemical ecosystems and rapidly varying analyte distributions.

SYNTHESIS OF DISCUSSION QUESTIONS

1. *Problems with current environmental monitoring approaches*

Current monitoring programs that rely on sample collection for later laboratory analyses are limited in their ability to collect samples associated with episodic or transient events.

Furthermore the cost of both collection effort and laboratory analyses greatly limits the extent of spatial and temporal sample coverage. These limitations may severely impact the value of any monitoring data collected in dynamic coastal environments. Environmental research and monitoring and public health monitoring systems could potentially benefit from sensors that provide continuous measurements in real-time, even if detection levels are somewhat higher than those achieved with laboratory-based analyses. In situ measurement systems can provide greater access to the environment during severe weather or marine conditions compared to conventional ship or personal sampling procedures.

2. *Requirements for micro-scale environmental sensors systems*

The potential range of measurement technology requirements expected from nanotechnology sensors extends from freshwater systems to deep ocean environments, and from collecting point measurements to continuous, broad spatial scale data acquisition. Measurement scenarios involving groundwater systems, ocean carbon cycling, sewage treatment systems, coastal and open ocean episodic events, river systems, point source tracking, and environmental research and monitoring will benefit from sensors that can make reliable *in-situ* measurements of nutrients, toxicants, and microbial parameters.

However, *in-situ* sensors must be able to operate for extended periods of time in a harsh environment without significant amounts of maintenance, or the high costs of making measurement just gets transferred to the upkeep of the instrument. Consequently sensor packages must be resistant to bio-fouling as well be capable of self-calibration to prevent performance drift over long deployments. Sensor and data acquisition complexity must allow setup and operation without specialized technical personnel.

This broad range of expectations could lead to a conflict in terms of promoting the development of new sensor packages. There will be trade-offs between increasing measurement capacity for the research community versus developing systems that provide ease of use and lower cost for managers. For example, the ability to detect a wide variety of chemical and biological parameters could provide valuable information to managers and support decisions for more detailed analyses even when these measurements are at minimal sensitivity or accuracy levels. However, other uses or parameter measurements may require extremely low detection levels in order to provide useful information. As an example, in some cases, measurement requirements for persistent organic contaminants must be made over the range of 0-1 parts-per-billion with a resolution of 1 part-per-trillion.

It was recognized that the end goal was not to simply make sensors that are orders of magnitude smaller, but to incorporate technologies that will make sensors cheaper to build, easier to operate, and provide enhanced capability through better system integration. A major expectation or requirement is that new sensors have the ability to process measurement signals and provide data in a directly useable format.

3. *Status of micro-scale environmental sensors and enabling technologies*

There are three distinct components to consider with regard to developmental status including; sensor technologies, systems technologies, and deployable field units. Each of these components may move independently in relation to risk/reward factors present for academia and industry in terms of research and development efforts. Micro-sensors that are constructed using integrated circuit manufacturing technologies are referred to as micro-electromechanical systems (MEMS). Sensors developed using integrated circuit manufacturing techniques have the potential to be lower cost and can provide immediate, even real-time, measurement results. MEMS currently in widespread use are capable of sensing acceleration, pressure, and some gases. Further research and development of MEMS based sensors will depend on a variety of enabling technologies including system power considerations, data telemetry and internal communications for what will be an *in situ* chemical analysis system. Micro-fluidic systems will depend upon the ability to incorporate pre-concentration, sorting, filtration, and lysing technologies for sample preparation. All systems deployed for long periods must be resistant to chemical and biological fouling and designed to operate in a marine environment.

Micro-sensors with application to the measurement of chemical parameters in water are currently at the demonstration level. Some promising examples of MEMS sensors include multi-parameter systems measuring conductivity, temperature, oxygen, and chemical compounds using ion-selective electrodes [Brown et.al. 2000], lab-on-a-chip micro-fluidic chemical detection systems [Bhansali, et.al. 2004], *in situ* spectrometers [Johnson and Coletti 2002], and Polymerase Chain Reaction used in micro-fluidic systems. Additional systems that are known to be under development and thought to be field testable within less than a year included a micro-scale CTD system for operational oceanographic measurements, micro-fluidic based bio-sensors, and an in-situ mass spectrometer.

In general, it was perceived among management and industry participants that the industry is still several years away from offering nanotechnology-based instruments that are generally accepted by the user community. It was suggested that most of the developments are still occurring within the research community and represent the 'state of the science' versus a new 'state of the art' useable technology. Where in some cases we may be at the threshold in terms of technology capability, the major delay likely will be waiting for the identification of a true market to drive the actual development and commercialization of these products.

4. *Perceived advantages of micro-scale environmental sensors*

During the past decade, researchers have become much more aware of the fact that most biological and chemical parameters of interest in coastal environments do not simply vary according to steady state processes. Instead, many marine biogeochemical cycles are driven by short-term and sporadic events. Such events include storms, periodic upwelling, fluvial plumes, and phytoplankton blooms that are difficult to observe with traditional coarse-resolution methods. These phenomena can best be observed by continuous in situ measurements over extended time periods. The further understanding of these non-steady state processes requires autonomous in situ instrumentation capable of long-term deployments. Although a variety of such instruments exist for measuring physical and optical characteristics (which are sometimes used to calculate biological properties), there is a distinct lack of such instruments for the direct monitoring of dissolved and particulate chemical concentrations. Such basic detection systems are needed to make direct observations of the chemical links between physical forcing and biological responses within the ocean, as well as to monitor the natural temporal variability of important biogeochemical tracers. These instruments have a wide area of applicability in oceanography; from monitoring estuaries, to open oceans, to pore waters, as well as other aquatic environments. [H.W. Jannasch, http://www.mbari.org/staff/jaha/objectives.htm].

It is largely perceived that once these technology developments have advanced to the stage of commercial practicality, and that sufficient market potential exists, that the total cost of acquiring the desired spatial and temporal scales of monitoring data with be significantly reduced. Another perceived benefit is the ability to use in situ sensors as detection alarms, which could trigger a required monitoring effort or health response effort. Once these new chemical sensors have reached full-approval as an accepted method for making water quality measurements they will be of tremendous value to EPA and the States for compliance monitoring in river reaches of conventional parameters such as nutrients, dissolved oxygen, suspend matter, and contaminants such as heavy metals. Lastly, the ability to use integrated circuit technology has the potential to lead to the development of smart sensors that can essentially self calibrate and self-assess their performance during long term deployments to assure that higher data quality standards can be maintained.

5. *Identified challenges for bringing new micro-sensors on-line*

The established sensor industry is intrigued about the potential that micro-sensor research and development has to offer but appears unconvinced of the ability of this technology to provide reliable measurements or the ability to develop a commercially viable market that would justify significant research and development investment. Industry perception is that dependable systems using micro-sensor technology is still several years off. In addition, calibration issues associated with sensors capable of providing measurements previously made in a highly controlled laboratory will present logistical problems. In certain applications, the use of advanced sensors will depend on regulatory compliance to meet quality assurance requirements. In addition, in situ sensors designed to be disposable must not be a hazard to marine life. In general very little is known about the potential hazards associated with the production and use of many nanotechnology products.

There is a definite lack of knowledge among most managers and users of current sensors about the advanced engineering technologies being pursued within University research centers and small start-up technology companies. More importantly, environmental researchers and managers are not being brought into this development processes in an effective manner that allows them to define the critical performance requirements and application priorities needed to improve fundamental understanding or to provide vital monitoring capabilities. Consequently new technologies are less likely to directly serve the needs of the environmental user.

Lastly, a significant challenge can arise from legal issues behind protecting intellectual property rights and establishing equitable terms of profit sharing as technologies transition from University or research centers to industry. Without this transfer there is little capability for developing actual field-deployable instruments.

6. *Strategies for Bringing New Sensors Online.*

Discussions on strategies for bringing sensors on-line mainly focused on the need to improve communication among developers and users, and the need to increase funding opportunities in order to promote more rapid research and development. It was felt that research investment must be supported through industry and academic partnerships, as well as, through the support of ongoing federal programs such as the Small Business Innovative Research program and through the establishment of federal initiatives for sensor development under programs such as the National Oceanographic Partnership program, or through the National Research Laboratories.

Participants also identified a definite need for continued education and communication of the needs and value for developing new micro-scale chemical sensors. Scientists and managers must begin to define the critical measurements required to serve their research and monitoring requirements. It was suggested that continued demonstration of these technologies to industry and management sectors is important and can help steer development into products that will serve the environmental community.

It was felt that the research community could help to focus these initiatives through the development of white papers that help prioritize a common set of sensor technologies with broad application potential and that help identify funding and investment opportunities. As military, homeland security, or medical applications may be advancing the application of technologies at a much greater rate we need to look for opportunities for technology transfer and market development into the realm of environmental sensors.

SPECIFIC WORKSHOP RECOMMENDATIONS

- Develop a white paper defining the status of sensor system development including the three facets of sensor technologies, systems technologies, and deployable field units. The paper should also help prioritize the development of a common set of sensor technologies that will support a broad range of applications and have strong commercial backing

- Develop a list of Agencies/Labs to bring together in a workshop aimed at developing funding opportunities targeted to 'selected' sensors

- Encourage academic institutions with strong environmental engineering programs to develop workshops or summer courses for training students in the development and use of field-based sensor systems

- Develop a web site that can build upon these workshop efforts by identifying funding opportunities and promoting research/industry partnerships
- Talk to lead managers at National Oceanographic Partnership Program to help direct new announcements of opportunity for sensor development
- Identify resource management issues where sensor development could provide needed data in a cost effective manner.
- Establish and foster informed partnerships that are ready to jump on new opportunities by having identified priority applications and system requirements

SPECIFIC RECOMMENDATIONS FOR ACT

- Develop a formal process that captures the needs and strategies identified in our workshops and take it to funding and research agencies
- Support the development of a white paper review by hosting organizing workshops
- Follow-up ACT workshop on this topic should be considered given the pace of technology advancement
- Develop a discussion board targeted at users of in situ environmental sensors
- Encourage submission of emerging sensor systems (pre-commercial) in the ACT demonstration program
- Fund a use/need assessment survey for environmental micro-sensors in hopes that it would generate the justification for a formal market survey to be conducted by Industry (should include volume/cost assessment, packaging/interfacing requirements, i.e., how you use it)

APPENDIX A. REFERENCES

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