SENSOR NETWORKS

The Design and Implementation of Aquatic and Marine Sensor Networks

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Initial Questions

- What are the most promising recent developments in aquatic and marine sensor networks?
- What critical components of the aquatic and marine environments are not adequately sensed with current technologies?
- What R&D activities are necessary for the environmental sciences community to capitalize on the capabilities of aquatic and marine sensor networks?

The Marine and Aquatic Breakout Group discussed these questions in some detail, as outlined below. The first portion of the breakout session was devoted to identifying what makes the marine and aquatic environment unique. Generally, it was agreed that the aquatic environment and especially the marine environment is a highly challenging place to work. Problems not encountered elsewhere to the same degree include fouling, a corrosive environment, high pressures, expensive access, and inclement weather. At the same time, the marine environment comprises more than 70% of the Earth's surface and is integral to some of our most critical environmental problems.

What are the most promising recent developments in aquatic and marine sensor networks?
A variety of new observational systems are being deployed in the oceans and nearshore environment, including:

- LEO-15: off the New Jersey coast
- ARGO: global, upper-ocean temperature sampling
- GoMOOS: Gulf of Maine Ocean Observing System

Planned projects include:

- MOOS: Monterey Bay Ocean Observing System
- DOES: Dynamics of Earth and Ocean Systems, including NEPTUNE and global moorings
- SURANet: Southwestern US coastal network

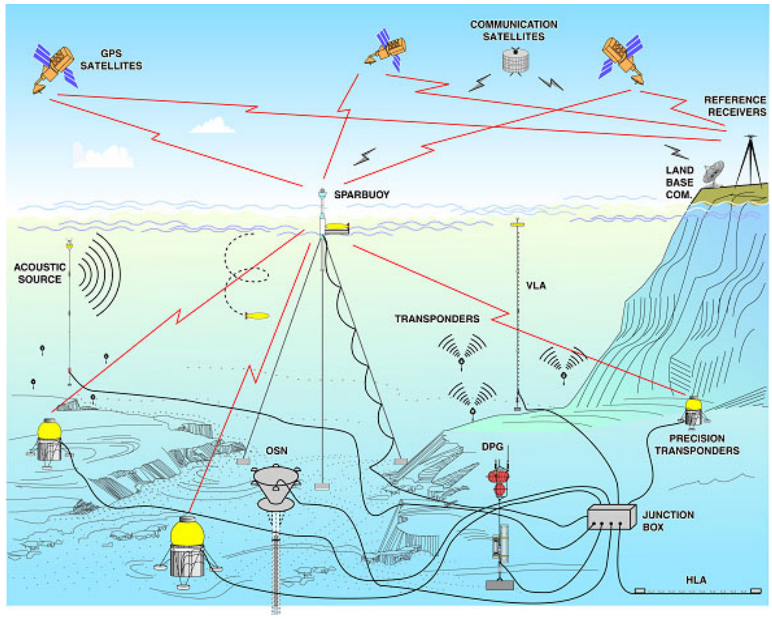
The development of these marine and coastal observatories has been made possible by a number of technological developments including the miniaturization of electronics and sensors, the rapid development by industry of remotely operated vehicles (ROV), reliable underwater connectors for both electrical and optical connections, continuous advances in underwater housings, and new approaches to communications.

What critical components of the aquatic and marine environments are not adequately sensed with current technologies?

Communications is a critical issue for aquatic and especially marine observations. While commercial systems in some cases provide excellent options for nearshore and inland use (e.g. cell phone coverage and wireless networks), marine observations do not enjoy the same commercial drivers that make terrestrial communications possible. Examples of communications systems presently used in the marine environment include Service ARGOS (France), Iridium (Private/DoD), GlobalStar, and Inmarsat. The longevity of System ARGOS cannot be assumed, the original Iridium provider went bankrupt, and funds are not yet available to maintain the satellite constellation over the long term. GlobaStar is really useful only near land and Inmarsat requires a directional antenna and is quite expensive.

The major issues for marine telecommunications include: longevity; bandwidth; directional antennae, which require tracking and stabilization; "store and forward" systems; latency; and duplex communications.

Agencies are generally more excited about the initiation of new measurements than maintenance over the long-term. For marine and aquatic observations, the infrastructure necessarily includes maintenance of ships and ROVs, as well as the sustained funding of qualified personnel. Critical long-term observations, necessary to answer important questions from climate change to species management, cannot be made without both a major, up-front investment and sustained maintenance.



"As part of its ongoing activities in both the coastal and open oceans, NSF's Division of Ocean Sciences has been working with the academic community to develop an Ocean Observatories Initiative. The effort would provide basic infrastructure for a new way of gaining access to the oceans, by starting to build a network of ocean observatories that would facilitate the collection of long time-series data streams needed to understand the dynamics of biological, chemical, geological and physical processes. Just as NSF supports the academic research vessel fleet for the spatial exploration of our oceans, the system of observatories provided for by the Ocean Observatories Initiative would facilitate the 'temporal' exploration of our oceans."

Testimony of Dr. Rita R. Colwell
Director, National Science Foundation
Before the House Committees on Resources and Science
Hearing on Ocean Exploration and Ocean Observations
July 12, 2001

What R&D activities are necessary for the environmental sciences community to capitalize on the capabilities of aquatic and marine sensor networks?

Further R&D is required in three major areas: *database management, communications, and networking and instrumentation*. Because useful environmental measurements can only be pursued through a consistent, systems-level approach, a balanced R&D program in each of these areas is of equal priority.

Database management is an interesting challenge, largely because with appropriate communications most data can be made available in near-real-time, with a latency of only seconds. In the past, database management in the environmental sciences has had the luxury of time, but this is no longer true. New real-time approaches to data and metadata must be taken, including the ability of instruments to develop as much metadata *in situ* as possible. Significantly, near-real-time data are likely to be of poorer quality than data corrected with the benefit of review and analysis. For example, time is difficult to quantify due to a variety of problems including drift and the loss of reliable references such as GPS for undersea systems. Thus, data corrected after the fact will almost certainly have greater timing accuracy. In this case, what should be done with the original data collected and presumably archived and even analyzed? Reference models of Earth systems may be also be necessary for data comparisons that will reveal when sensors were or are no longer behaving reliably. While it was generally agreed that data collected should be open and immediately available to any interested party, it will be an interesting sociological challenge to develop a broad consensus and practice in this matter. The exponentially increasing rate of access to real-time data, however, demands open data in order to avoid complexity and delays through the imposition of excessive rules on access.

The Breakout Group agreed that all instruments should be designed as IP-addressable devices, individually identifiable in a network. Data compression is seen as important, but the standards are likely to vary from measurement to measurement, and the issue of loss versus lossless compression must be considered in communicating data from a sensor through the network. For example, it would be undesirable for the communications system to induce compression losses in a data stream. Many felt that the ability of the sensor to do on-board computing was important to reduce the amount of information that has to be transmitted. This issue is likely to require the greatest R&D attention.

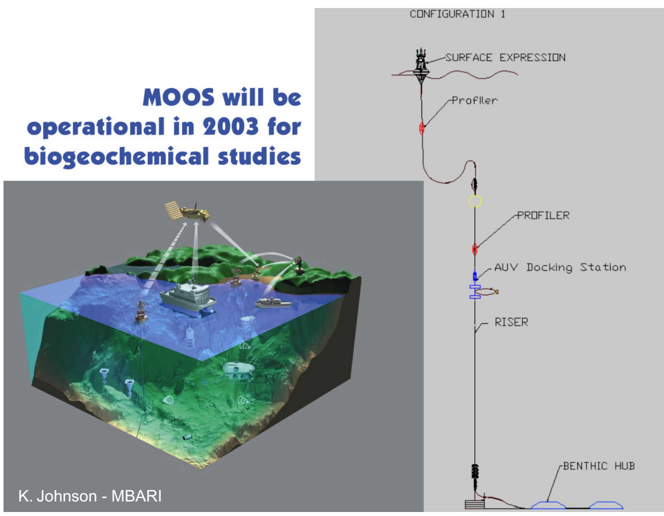
Data formats have traditionally been a matter of contention within scientific communities, and proprietary formats without open specification are particularly onerous. We briefly discussed platform-independent software such as the SDSC Storage Resource Broker [SRB], which provides the following services: federated access to data sets; protocol transparency to diverse and distributed storage systems; location transparency to distributed data sets; and access transparency to remote users.

Heterogeneity in data management systems becomes less important in this context, and there is no longer a need for the data themselves to be centralized into a single, community storage system. Responsibility for data and quality control can thus remain as near to (or far from) the organization responsible for collecting the data as desired. This provides a great degree of flexibility in choosing the degree of decentralization in a data network.

The Breakout Group also discussed communications issues between sensors that are independent of users; that is, how might a sensor network automatically adapt to changes and observations? An example could be the capability of increasing the sampling rate upon the occurrence of an observation. Such a network would undergo an autonomous self-organization that would almost certainly be nonlinear. Network simulation software would be very important in such designs and would help answer the question of *what must be measured at what scales?* Due to weather, networks might have to autonomously adapt to the loss of some component(s) of the primary communications system. Quality of Service (QoS) is an important consideration. For example, how can network and inter-sensor communications be used to ensure delivery of data to priority users? These are important basic research issues that must be answered as the complexity of the observing systems increases.

Instrumentation is a particularly challenging research and development issue. The problems associated with the availability of chemical and biological instrumentation were discussed. Generally, sensors in remote locations must be as power-efficient as possible. Instruments become fouled and must be cleaned. Can this be done remotely, and how can we know when an instrument requires attention? Calibration and drift is a problem for nearly every measurement in the environment. How can drift be detected and corrected? How do these procedures interface with the metadata of the measurement? How can physical data be managed, for example, samples? How can remote vehicles be managed, including mission and navigation and maintaining an overall system clock?

There are fundamental sampling issues that require great attention in network design. For example, can there be a compromise between global, coarse, synoptic measurements and detailed measurements at small scales? More generally, how can observation systems be designed to most effectively promote discovery and exploration of the oceans?



The MBARI ocean observing system (MOOS) program includes both mooring-based and cabled-based observatory systems. The mooring observatory system (illustrated here) will provide capabilities to instrument upper water column and benthic locations of scientific interest in various geographical sites. Advanced capabilities will include satellite based bi-directional communications, event detection and response, as well as integration and operation with other advanced platforms including AUV's and vertical profilers.

While all the above issues are of critical importance, environmental observations in the marine and aquatic environment must also deal with a number of significant legal and political issues, including the Law of the Sea, the definition of EEZ's, copyright, data access, international cooperation, and the movement of pollutants and marine life (including exotics) across international boundaries. It is difficult to quantify these challenges in simple terms of information vs. political costs, but practical observational systems must deal with all of these issues.

Recommendations

Initiate a study of marine science data communications requirements.

The marine environment is heterogeneous and vast in both surface area and volume. It requires significantly different approaches to communications for inshore, nearshore, and offshore settings, as well as for surface versus submarine environments. A comprehensive study of the communications architecture for a marine science data network is required to bridge these domains and to enable interoperation between the different and demanding requirements of these dissimilar environments. For example, commercial interests can play an important role for the inshore and nearshore settings, but can provide little help in the distant offshore and submarine environments.

Provide funding for modernization of shipboard data systems.

New technologies have made it possible to achieve significant improvements in the data management of existing shipboard measurement systems, and this will have major and near-term benefits for the entire scientific research community. Such efforts should be the beginning of a long-term effort to develop standards for instrumentation (shipboard and observatory) to facilitate the development of self-describing, autonomous sensors that can report their measurements to a data acquisition system (e.g., network) with minimal operator intervention and are capable of interoperating with other sensors and data systems in terms of adaptive routing, metadata-based services (such as reporting the existence and status of any given sensor), operating status, location, and similar housekeeping functions, including reprogramming. Emphasis should be placed on developing networked sensors with individual IP addresses and Internet operability.

Initiate competition for new ocean-spanning communications systems technologies.

Better communication services are required to support higher data rates from any new classes of sensors. It can be tempting to jump to the conclusion that this relates solely to satellite, wireless, and fiber-optical cable communications, but other platforms can be envisioned such as long-dwelling UAVs (Underwater Autonomous Vehicles), commercial aircraft, and volunteer ships equipped with transponders or other as yet unimagined backbone network platforms.

This communications infrastructure is the key limiter of network development, since expendable and recoverable sensors in the marine and aquatic environments have a high probability of failure due to the harshness of the environment. The ability to obtain data from "pop-up" platforms such as UAVs, gliders, surface drifters, or communications/data pods released from submerged sensor platforms, requires reliable, inexpensive, and global communications.

SENSOR NETWORKS

The Design and Implementation of Terrestrial Sensor Networks

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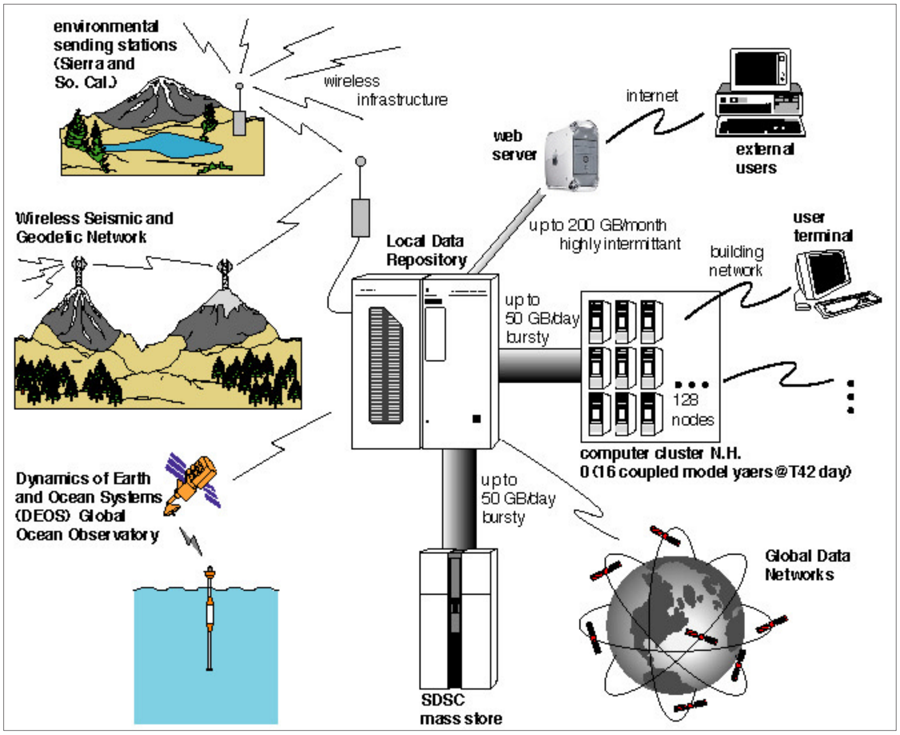
Initial Questions

- What are the most promising recent developments in terrestrial sensor networks?
- What critical components of the terrestrial environment are not adequately sensed with current technologies?
- What R&D activities are necessary for the environmental sciences community to capitalize on the capabilities of terrestrial sensor networks?

In this session, two different approaches, one question-based and the other architecture-based, led to essentially similar descriptions of a terrestrial sensor network. The first approach generated a design that was driven by scientific hypotheses, questions, or models, focusing on the distribution and kinds of sensors and the network needed to connect these sensors. The second approach began by assuming the need for internetworking of information at the broadest level, and constructed sensor networks that facilitated internetworking. Both approaches converged on a network design that emphasized domain-relevant flexibility at the interfaces between sensors and the environment and between the localized sensor network and other networks, while assuming more standardized approaches in aggregating, processing, managing, and archiving information.

What drives the architecture of sensor networks?
Most field biologists begin the design of a sensor network by defining the scientific question that will dictate the attributes of data to be collected. Such attributes include cost; the kinds of processes or organisms to be sampled (e.g. whether mobile or stationary); whether data collection needs to be continuous or event driven; the spatial and temporal scaling needed to include the relevant interval and extent; whether the data stream needs to be real time; requirements for data reliability, redundancy, and format; whether physical samples must be collected; the need for QA/QC measures and recalibration; and other factors. Once these factors are determined, communication among sensors and

local processing issues is addressed with the help of sensor and communications experts. Issues of power and efficiency become important in this part of the network design.



This is a schematic outline of the ITR Project ROADNet (Real-time Observatories, Applications, and Data management Network). ROADNet will enhance our capacity to monitor and respond to changes in our environment by developing both the wireless networks and the integrated, seamless, and transparent information management system that will deliver seismic, oceanographic, hydrological, ecological, and physical data to a variety of end users in real-time.

The ROADNet multidisciplinary science and technology team is building upon currently deployed autonomous field sensor systems, including sensors that monitor fire and seismic hazards, changing levels of environmental pollutants, water availability and quality, weather, ocean conditions, soil properties, and the distribution and movement of wildlife. ROADNet scientists are also developing the software tools to make this data available in real-time to a variety of end-users, including researchers, policymakers, natural resource managers, educators and students. The project is funded by the NSF and ONR with matching funds from the UCSD California Institute for Telecommunications and Information Technology [Cal-(IT)2], Scripps and IGPP. Much of the land-based network has already been installed by the SDSC/IGPP HPWREN (High Performance Wireless Research and Education Network) funded by the NSF. For more information see http://roadnet.ucsd.edu/.

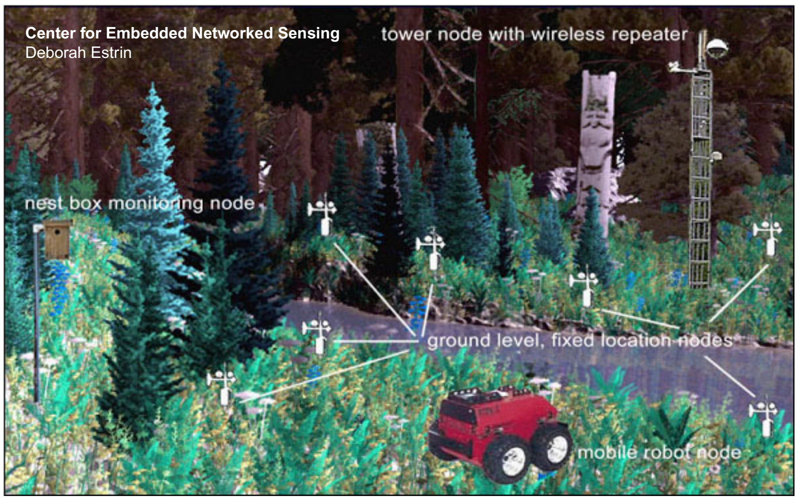
In developing a sensor network, information specialists first concern themselves with derived processing of information collected by sensors, aggregation of data, management of information, and archiving of value-added databases. The types of sensors may not be central to planning information management systems, but attributes of the data generated are. The need to adhere to standardized protocols for the description, storage, and accessibility of data are important in determining the information process components of a sensor network.

Networking specialists then focus on the distribution of processed data among higher-level nodes of a network. Key issues for this group include internetworking, interconnection, and interoperability. The development of interoperability faces challenges stemming from the nature of the data (from simple repeated measurements such as temperature to full motion video distributed across the same platform), and from the range of communication networks involved. An architecture that facilitates network communication must have a variety of communications options built into the system.

General Characteristics of a Terrestrial Sensor Network

The design of terrestrial sensor networks must accommodate investigation of a wide variety of scientific questions, while establishing generic protocols for information sharing among different sensors, networks, and users. Thus, sensor networks need to incorporate *flexibility* into the design of sensor grids along with *standardization* in the architecture of information exchange. The balance between flexibility and standardization is an important focus for future investigations.

Sensor networks should be of a recursive design, with components for data collection repeated for communication and storage. The basic unit of the sensor network requires a physical layer that interacts with the environment to be measured, recursive storage and node processing, communication among components, and the capacity to change sampling parameters through a sensor query language. Networks of these basic units need to incorporate derived processing (detection, identification, and extraction), aggregation mechanisms, information management and archiving capacities, and internetworking. Thus, there is both a logical and a physical change in structure between the *in situ* network and the derived information products to be managed and distributed. The number of iterations of the basic design element that will occur before higher level processing components need to be added may be idiosyncratic to the system and questions under consideration. The capability of re-tasking needs to be built into sensor networks so that new questions or new users can easily be accommodated. Sufficient flexibility in information management needs to be present to allow for the needs of both primary and secondary users of the data. This will include the ability for unanticipated users to overlay data from other disciplines.



Field Experiments at the James Reserve - A Model System

Sensing Infrastructure
Environmental sensors in different habitats.
Multimedia sensors in natural habitats and artificial cavities (nest boxes).
Physiological sensors on trees and shrubs.
Primary nodes for higher level data processing and communications on towers.
Mobile platform for high resolution sensors and tele-robotic operation.

Monitoring ecosystem processes
Imaging, ecophysiology, and environmental sensors
Study vegetation response to climatic trends and diseases.

Species Monitoring
Visual identification, tracking, and population measurement of birds and other vertebrates
Acoustical sensing of birds for identification, spatial position, population estimation.

Realizing the Potential of Terrestrial Sensor Networks

The development of terrestrial sensor networks as envisioned in this workshop will result in a paradigm shift for field biologists. Most ecological research is presently limited by the labor available to collect observations and measurements by hand. The advent of sensor networks with hundreds or thousands of nodes in which initial and derived processing will be accomplished automatically will increase the resolution of ecological data by orders of magnitude. This flood of data will create the need for greatly increased computational power, high-speed connections, sophisticated 4-D visualization techniques, mass archival of data, and data management, navigation, and access tools.

To prepare ourselves for this paradigm shift, ecologists need to begin to evaluate new and developing technologies, create and populate training programs at the undergraduate and graduate level, develop collaborations with sensor manufacturers and national laboratories to create the required new technologies, and participate in joint efforts with experts in sensor technology, communications, information management, and networking to design and implement prototype sensor networks. In the short-term, our most important goal is to initiate the development of such prototype networks, which will serve as test beds for new technologies and training grounds for future generations of scientists.

These prototype networks should focus on implementing the most promising recent developments in sensor networks, identifying needs for the development of new sensors to measure poorly understood processes, and focusing attention on future research and development needs. Specifically, prototype networks should address the elements below.

Promising Recent Developments in Terrestrial Sensor Networks

- IR sensing
- Mass-produced miniaturized sensors, processing and communication
- Satellite communication
- Radar/LIDAR/hyperspectral remote sensing
- GPS
- Ultrawide band radar (ground)

Recommendations

Sensor development needed for events that are not adequately measured.

- Stochastic events
- Sub-surface sensing
- Location: non-GPS (subsurface, sub-canopy etc)
- Sampling of metabolic processes
- Sampling of individual or group stress or "health"
- Species and individual identification on a large scale, including genetic structure
- Emergent ecosystem attributes
- Change
- Ability to instrument and process large areas

R&D activities needed for terrestrial sensor networks.

- Power/energy requirements: demand and supply to support scalable deployments
- Research on sensor design, including reusable or biodegradable design
- Processing architecture
- Mass production of available sensors
- Miniaturization of sensors
- Development of a sensor query and analysis language
- Statistical, modeling, and visualization tools
- Automated image interpretation

SENSOR NETWORKS

Emergent Sensor Technologies

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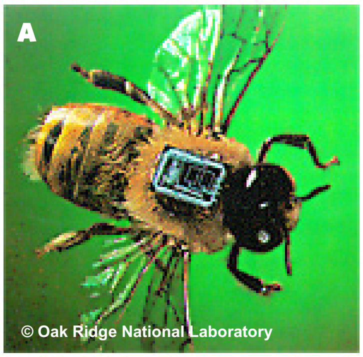
Initial Questions

- What are the most promising recent developments in sensor technologies?
- What critical components of the environment are not adequately sensed with current technologies?
- What R&D activities are necessary for the environmental sciences community to capitalize on the capabilities of sensor technologies?

Emerging Technologies

As sensors become smaller, smarter, and more specialized, the capability for deployment and use of new sensor technology suggests novel approaches to environmental research and data collection [Delin, 2001]. Although these trends are more likely to be driven by research in other fields, e.g. space research [Krabach, 2000], they show great promise for application in field environmental research. Three emerging technological trends are particularly promising: miniaturization, wireless communication, and "smart" sensors.

The trend toward the miniaturization of sensor systems will have a significant effect on how the environment is studied and monitored. "Systems on a chip" technology, for example, may replace chemistry and biology laboratories with portable hand-size instruments used for rapid and sophisticated chemical or biological agent (e.g. DNA, protein) detection and quantification *in situ* [Ho, 2001]. Another example is monitoring standard environmental parameters such as the weather. Despite the development of observation networks for a variety of environmental variables (e.g. weather/climate, solar radiation, rainfall chemistry), coverage is still sparse. For example, the continental United States is represented by fewer than 3,000 permanent meteorological observation sites, a density of less than one station per 10,000 km^2. Sensor miniaturization will enable much denser observation networks. Densities as high as several hundred instruments per km^2 are foreseeable in intensively studies sites. Coverage extent will also be enhanced by sensor miniaturization, since smaller sensors can be deployed in places where current generation sensors will not go. Instrumentation within canopies, underground, and even upon/within individual organisms from bats to earthworms, can be achieved via micro-sensor packages. Micro-sensors can readily be deployed within sensor clusters (i.e. packages of multiple sensors making coordinated observations) and within sensor webs [Nagel, *in press;* Delin, 2001]. These sensor webs may ultimately be reduced to very small size, e.g. "smart dust" [Pister, 1999], while retaining equivalent function to larger sensor clusters. Current research in meteorological and environmental instrumentation is already progressing toward this goal [Nagel, 2000; Delin, 2001]. Cost of miniature sensors could be a limiting factor of their use by environmental scientists. Although mass production of micro-sensors using modern manufacturing processes should drive down production costs, sensor housing continues to be a significant expense. If cost reductions can be achieved along with instrument size reduction, miniaturization will improve existing data collection methods as well as suggesting novel instrument siting opportunities.



Images:
(A) A computer chip powered by a solar cell is attached to a bee.
(B) The whale tag is a pod which includes microsensors and a radio transmitter. The tag is approximately the size of a TV remote control and weighs approximately 1 pound. These tags are being used to study the effects of noise pollution on whale behavior and physiology.
(C) A lightweight radio transmitter equipt with micro-sensors is used to record positional and physiological data of a Daubenton's bat, Myotis daubentonii.

An Ecological In Situ Sensor Resource: a compilation of information on in situ sensors, sensor arrays, and sensor manufacturers.
Sensors are an essential part of scientific inquiry, yet no central sensor resource is currently available to address the sensor needs of the ecological community. Many environmental sensor projects are known only in small scientific circles, and information regarding sensors and their manufacturers are not typically oriented towards the scientific community. To meet this need, a web site, targeted toward the terrestrial and aquatic ecology communities, has been created through a collaborative effort between the Long-Term Ecological Research (LTER) Network Office and the San Diego Supercomputer Center (SDSC). The website includes links to state-of-the-art sensor technologies, sensor manufacturers, and large-scale ecological projects and networks involved in the use of in situ sensors. ***For more information, visit http://www.lternet.edu/technology/sensors/index.html***

Miniaturization also benefits remote sensing. Digital camera and computational technology have enabled creation of small, low power, relatively low-cost multi- and hyperspectral sensor systems which could be deployed on modest aircraft with minimal modification [Price, 2001]. This type of remote sensing system could put powerful airborne imaging technology under the direct control of research groups. This would be an improvement over the current model, where sensor systems are either operated by government agencies or for-profit private ventures.

Along with miniaturization, wireless communications technology holds great promise for environmental sensing [Nagel, *in press*]. Often, the communication infrastructure needed to support instruments in the field (particularly at remote sites) is a significant limiting factor in field research. Remote operation of sensors requires emplacement of wiring, which is prone to failure in harsh environments, or use of *in situ* data logging equipment requiring periodic visits for maintenance and data retrieval. Wireless technology, coupled with the Internet, could replace these cumbersome systems with instruments capable of relaying data to a centralized collection site, and perhaps even directly to the researcher's computer. Wireless communication would also enable bi-directional communication with a sensor web [Delin, 2001], allowing "on-the-fly" sensor programming or retasking. Such programming capability would enhance the adaptability and flexibility of sensor networks. For the dense networks of micro-sensors described above, wireless communication systems are a necessity. Without them, solving control and data retrieval problems would not be feasible. Provision of power continues to be a significant issue for wireless data transfer networks.

As data storage and manipulation technology becomes more compact and powerful, smart sensors will become increasingly common. Smart sensors have the capability for on-board processing of data, hence some data analysis tasks currently carried out offline may become part of the data processing stream. This capability will greatly enhance the effectiveness of data-rich sensor clusters and webs, where the sheer number of sensors multiplies data compression and information extraction tasks [Delin, 2001; Nagel, *in press*]. Smart sensors will have the ability to selectively collect data, i.e. they will be able to discriminate noteworthy events or situations and sense them, while remaining inactive when no meaningful data collection opportunity exists. Smart instruments will also enable automated collection of data based on artificial intelligence or pattern recognition techniques. For example, video or audio sensors capable of distinguishing characteristic shapes and sounds of particular organisms could then selectively collect data about those organisms.

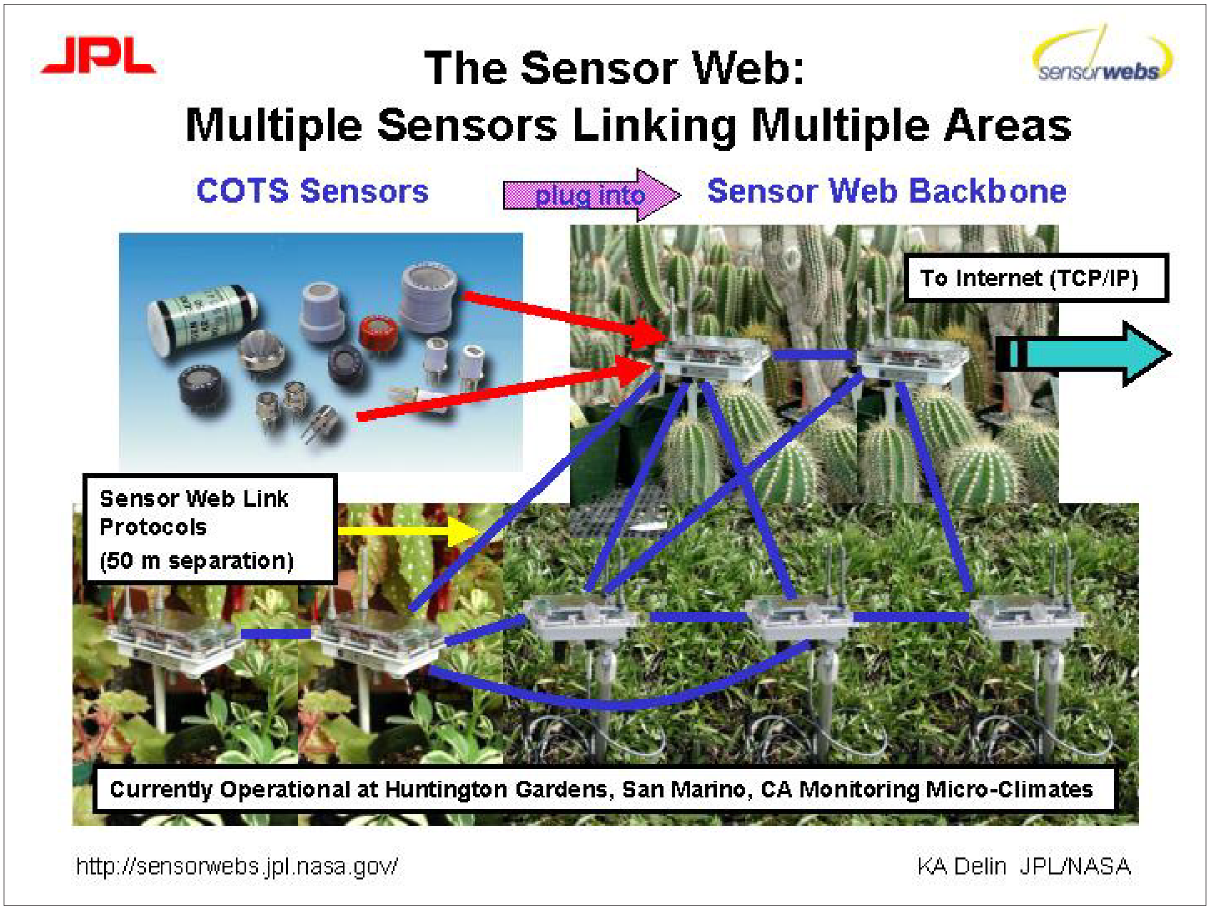
Extension to Unmeasured Variables

Current sensors respond to physical or chemical aspects of the environment. For example, meteorological sensors respond to temperature, humidity, solar radiation flux, and other energy fluxes. While these detectors are quite effective, they are limited to only a few environmental variables. In contrast, humans and other living organisms gather information about their environment through a variety of senses, each utilizing a biological detector evolved to respond to a particular biophysical or biochemical stimulus. Enhanced sensors, capable of emulating biological senses, are opening new windows for observation of the environment. Electronic "noses" and "tongues" now allow ecologists or biologists to directly detect in real time chemicals in the environment that could previously be detected only through lengthy, expensive, and difficult laboratory analysis [Staples, 2000]. Coupled with the miniaturized, wireless sensor technology described above, electronic "noses," "tongues," "ears," and "eyes" could be deployed in sensor webs alongside more conventional instruments, resulting in more robust and adaptable means to observe the natural environment. This technology may be particularly useful below ground, where the opaque nature of this environment makes sensing exceptionally difficult. Small instruments capable of operating outside the range of conventional sensors would greatly benefit the below ground environmental sciences and provide critically needed information.

New sensors to detect and measure properties not accessible to current sensors will utilize smart sensor technology. Thus, electronic eyes and ears will consist not just of audio or video detectors but also analytical components capable of detecting and identifying patterns of sound or vision. Similarly, electronic noses and tongues will be capable of detecting patterns and quantifying hundreds of organic and inorganic chemicals in the environment. This is important in identifying the source and significance of compounds and chemical cues within an ecosystem. These innovations will permit biological sensing at the organism or biota level, instead of the coarser physical/chemical sensing currently in use. Sensory emulation instruments (e.g. gas chromatographs) are available, but their size and cost still limits practical field use. Although faster and cheaper miniaturized portable electronic noses (using micro GC capillaries) are also available, lack of a large market keeps their costs higher than most scientists and federal agencies can afford. Hence, miniaturization holds great promise in adapting these technologies for practical use.

R&D Issues for Next-Generation Sensors

Development of the next generation of sensors should focus on two priority areas: (1) adaptation of existing sensors for field use, and (2) development



of innovative new sensors. Adaptation of existing sensors offers opportunities for extending current measurement technologies. Miniaturized temperature, humidity, and fluid flow sensors intended for application in laboratory or biomedical applications are already available. With suitable repackaging, these sensors could be used to create the small sensor clusters described above. Bi-directional wireless communication technology (necessary for effective exploitation of new sensor technology) is relatively less developed, but continues to improve [Cook, 2000]. Power requirements are a significant limitation, but the power consumption of these sensors continues to improve [Nagel, *in press*]. The environmental research community in general could greatly benefit from the establishment of a research program emphasizing innovative techniques for useful modifications of current technology and disseminating this information to field scientists.

Longer term R&D initiatives should emphasize development of new sensors including all the features (miniaturization, smart design, wireless communication, sense emulation) described in the previous sections. Standardization of sensors, sensor platform, and software interface between sensors and users is also critically needed. A practical limitation in the development of these sensors is the relatively small size and fragmented nature of the environmental sensor market. While much development research is carried out in universities, government labs, and other non-commercial settings, promising technologies are then transferred to the private sector for manufacturing and marketing. In order to be cost-effective, a sufficiently large market must exist to justify development expenditure by the private sector. In general, field environmental science is too small and specialized a market to attract large-scale private investment, so promising technologies are often not developed beyond the prototype stage, or are made in such low quantities that high cost limits their deployment. A possible solution to this problem lies in the convergence/similarity between sensor needs for field environmental science and the technological needs of larger-market activities such as biomedical applications, defense, and national security. As medical and defense/security applications make increasing use of miniature sensors and exotic detectors such as electronic noses and tongues, an opportunity exists for environmental scientists to "ride the market." A challenge for the environmental research community will be to work with manufacturers to identify small, feasible modifications to sensors intended for other applications that will allow them to be marketed to the environmental research community as well, resulting in larger markets with little capital investment. Standardization of sensors and sensor platforms may also help bring down the cost of sensors through mass production of interchangeable components, and will increase the availability of sensors and custom-designed sensor arrays. This path allows the same sensor systems to be used by ecologists, federal agencies (e.g., EPA, USGS, NOAA, DoE), and environmental monitoring and restoration companies, widening the environmental sensor market and allowing broader deployment by environmental scientists.