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Workshop Proceedings

STATE OF TECHNOLOGY FOR IN SITU MEASURES OF SALINITY USING CONDUCTIVITY-TEMPERATURE SENSORS

Savannah, Georgia
December 3-5, 2007

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

An ACT Workshop Report

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

State of Technology for In Situ Measures of Salinity Using Conductivity-Temperature Sensors

Savannah, Georgia
December 3-5, 2007

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, Skidaway Institute of Oceanography.

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.

Table of Contents

Executive Summary

This Alliance for Coastal Technologies (ACT) workshop was convened to assess the availability and state of development of conductivity-temperature sensors that can meet the needs of coastal monitoring and management communities. Based on the discussion, there are presently a number of commercial sensor options available, with a wide range of package configurations suitable for deployment in a range of coastal environments. However, some of the central questions posed in the workshop planning documents were left somewhat unresolved. The workshop description emphasized coastal management requirements and, in particular, whether less expensive, easily deployed, lower-resolution instruments might serve many management needs. While several participants expressed interest in this class of conductivity-temperature sensors, based on input from the manufacturers, it is not clear that simply relaxing the present level of resolution of existing instruments will result in instruments of significantly lower unit cost. Conductivity-temperature sensors are available near or under the $1,000 unit cost that was operationally defined at the workshop as a breakpoint for what might be considered to be a "low cost" sensor. For the manufacturers, a key consideration before undertaking the effort to develop lower cost sensors is whether there will be a significant market. In terms of defining "low cost," it was also emphasized that the "life cycle costs" for a given instrument must be considered (e.g., including personnel costs for deployment and maintenance). An adequate market survey to demonstrate likely applications and a viable market for lower cost sensors is needed. Another topic for the workshop was the introduction to the proposed ACT verification for conductivity-temperature sensors. Following a summary of the process as envisioned by ACT, initial feedback was solicited. Protocol development will be pursued further in a workshop involving ACT personnel and conductivity-temperature sensor manufacturers.

Alliance for Coastal Technologies

The Alliance for Coastal Technologies is a NOAA-funded partnership of research institutions, resource managers, and private sector companies dedicated to fostering the development and adoption of effective and reliable sensors and platforms. ACT is committed to providing the information required to select the most appropriate tools for studying and monitoring coastal environments. Program priorities include transitioning emerging technologies to operational use rapidly and effectively; maintaining a dialogue among technology users, developers, and providers; identifying technology needs and novel technologies; documenting technology performance and potential; and providing the Integrated Ocean Observing System (IOOS) with information required for the deployment of reliable and cost-effective networks.

To accomplish these goals, ACT provides these services to the community:

- Third-party testbed for quantitatively evaluating the performance of new and existing coastal technologies in the laboratory and under diverse environmental conditions.

– Capacity building through technology-specific workshops that review the current state of instrumentation, build consensus on future directions, and enhance communications between users and developers.
– Information clearinghouse through a searchable online database of environmental technologies and community discussion boards.

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's goal is to help build consensus on the steps needed to develop and adopt useful tools, while facilitating critical communication among the various groups of technology developers, manufacturers, and users.

ACT is organized to ensure geographic and sector involvement:

- Headquarters is located at the UMCES Chesapeake Biological Laboratory, Solomons, MD.

- Board of Directors includes Partner Institutions, a Stakeholders Council, and NOAA/CSC representatives to establish ACT foci and program vision.

- There are currently eight ACT Partner Institutions around the country with coastal technology expertise 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.

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.

Charge Questions For The Workshop

The charge questions to be addressed in Day 1 of the workshop were summarized by Herb Windom (ACT Southeast Region Partner, Skidaway Institute of Oceanography) in introducing the workshop.

- What are key science and management questions to be addressed in environments with dynamic salinity regimes using conductivity-temperature sensors? How can improved resolution of temporal and spatial trends in salinity aid in understanding key processes?
- For the science and management questions identified:

  What are the sensitivity range, precision, and response time requirements for the sensors?

What are other requirements for the sensors/sensor packages (e.g., physical size, deployment conditions, length of deployments, unit costs, etc.)?

How well do existing technologies meet or approach these requirements?

On Day 2 of the workshop, the final session included discussion of the process leading to the conductivity sensor evaluation by ACT, which is scheduled for the spring of 2008. This was intended as an introduction for a focused protocol development and training workshop to be held prior to the field deployment of C-T sensors in the ACT Verification tests.

Organization Of The Workshop

The workshop was sponsored by ACT and hosted by the Skidaway Institute of Oceanography (SkIO), one of the ACT partner institutions. Workshop sessions were lead by Herb Windom (SkIO), Peter Swarzenski (United States Geologic Survey, Santa Cruz, CA), and Kevin McClurg (YSI, Inc.). On the evening prior to the workshop, participants met for a welcoming reception and introductory dinner in Savannah. Over the following day and a half (4-5 December, 2007), the workshop was conducted in the meeting facilities of the Courtyard Marriot Hotel near the historic district of Savannah, with dinner provided on the campus of SkIO on Tuesday evening.

Background -- Salinity As A Priority Variable For Ocean And Coastal Monitoring

A recent issue of Oceanography magazine was devoted to the subject of ocean salinity (March 2008, Volume 21, No. 1). This set of articles highlight the importance of salinity as a core variable in physical oceanography and climate science (Schmidt, 2008). With the establishment of the international network of nearly three thousand Argo floats, the salinity and temperature of the upper ocean (<1000 m) will be monitored with a new level of resolution in space and time (Riser et al. 2008; and see http://www-argo.ucsd.edu). The Aquarius satellite instrument, targeted for launch in 2010, will provide global coverage of ocean surface salinity from space with repeat coverage at approximately 7 day intervals (Lagerloef et al., 2008; see http://aquarius.nasa.gov/). The satellite package will include microwave radiometers measuring emission in wavebands sensitive to salinity and radar to correct for sea surface roughness. These data will be combined with sea surface temperature measurements from other satellite systems to estimate sea surface salinity (targeting global RMS error of about 0.2 psu).

An area of focus for the ongoing and planned time series measurements of upper ocean salinity aims at detecting trends in the ocean component of the global hydrological cycle and observing how these trends vary between ocean provinces. Through comparison to earlier surveys (e.g., those conducted under the WOCE and GEOSECS programs), it will be possible to document salinity changes that have occurred over decadal time scales. Along with an improved understanding of the role of the ocean in the global hydrologic cycle, the expanding database for salinity distributions and trends in the upper ocean will also contribute to further advances in coupled ocean-atmosphere models, including prediction of El Nino–Southern Oscillation (ENSO) cycles.

In the coastal ocean and estuaries, characterizing the variability in salinity over a range of time and space scales is fundamental to understanding many physical, chemical, biological, and geological processes. In planning documents for the Integrated Ocean Observing System (IOOS), salinity has been identified among the highest priority variables to be measured by both the open ocean and coastal ocean components of the national observing network. In one of the early IOOS planning efforts conducted under the auspices of Ocean.US, a diverse group of workshop participants prioritized some 50 variables in terms of information needs required to address the seven major societal goals of IOOS. The resulting "Airlie House Report" ranked salinity as the top measurement priority overall for the "national backbone" of IOOS (workshop report available at *http://www.ocean.us/Ocean_US_Workshops*; see Table 2 and Appendix VII).

Due to the importance of relatively small-scale variability of salinity in both time and space in many near-shore and estuarine environments, distributed arrays of salinity sensors will likely be needed for many research and management applications, supplemented with sensors on mobile platforms (vessels, autonomous vehicles, drifters). Given the breadth of coastal/estuarine research and management applications for salinity monitoring and variety of possible deployment platforms, the need for a range of sensor configurations is obvious. The present ACT workshop was intended to highlight conductivity-temperature sensor requirements for coastal applications and discuss priorities and possible options for further conductivity-temperature sensor development, by bringing together participants from industry, management, and academia.

Review Of Prior Workshop Recommendations

Given the long-standing interest in salinity measurements in the coastal zone, it is not surprising that prior workshops have addressed the requirements for salinity measurements for coastal science and management applications and what is needed in terms of sensor performance to meet these requirements. In the initial discussion at the present ACT workshop, Norge Larson (SeaBird Inc.) brought to the attention of the participants the report of an earlier workshop held in September, 1998 (in Hampton, Virginia), which addressed national needs for salinity measurements. Based on the workshop, a review of requirements and the available technologies for measuring salinity was reported in the Marine Technology Society Journal (Woody et al., 2000). For the most part, the background information and recommendations from the 1998 workshop remain relevant today. Some highlights from the MTS Journal article are summarized here.

Tracking heat exchange and the input and advection of freshwater and associated materials are fundamental reasons for measuring temperature and salinity in coastal waters. The hydrographic structure and circulation of estuaries is strongly influenced by where and when freshwater input occurs. As a conservative tracer of the estuarine/coastal mixing process, salinity provides a reference against a wide range of chemical properties (organic and inorganic constituents, stable isotope and radioisotope composition, etc.), which are compared to evaluate sources, transport, and transformations of materials within the estuarine and coastal zones. The annual range in salinity for a given location plays a major role in determining biological community structure within estuarine and coastal zones. Many important resource management issues in estuaries and coastal areas are closely associated with the vertical and horizontal distributions of salinity, including the development of stratified conditions that can contribute to hypoxia events in many coastal and estuarine locations.

As summarized by Woody et al. (2000) in a brief history of salinity measurements, the determination of salinity has moved from methods based on chemical titrations to methods based on measurement of conductivity, with the present "Practical Salinity Scale" being based on the conductivity of a seawater reference standard. It was noted that the constant ratio of ionic composition assumed for open ocean conductivity measurements does not strictly hold in coastal waters. However, at intermediate salinities, it was felt that somewhat lower precision in salinity based on conductivity measurements compared to open ocean work is generally acceptable, given the wide dynamic range for salinity in most mesohaline settings.

In the present ACT workshop, the basic performance specifications for commercial sensors that are presently available were summarized based on the input from the manufacturers represented at the workshop (below). It appears that the basic technologies described in the Woody et al. (2000) report remain those employed for the present commercial conductivity-temperature sensors, although there have been changes in vendors and in the available configurations of the sensors (e.g., as part of a range of multi-sensor packages). Similarly, the desired levels of accuracy, precision, and need for robust anti-fouling strategies (which translates to capabilities for extended deployments) defined by Woody et al. (2002) generally apply today, although in the present ACT workshop, a broader definition of requirements was discussed.

Targets For Resolution In Measured Salinity – What Is Required For Various Applications?

A topic that elicited substantial discussion at the present ACT workshop was whether the requirement for salinity resolution at the 0.1 psu level could be relaxed for some monitoring/management applications in the coastal and estuarine zones and if this meant that sensors could be made available for a lower cost. This is to say, might there be a significant market for lower-cost conductivity/salinity sensors with even lower resolution (e.g., at the 0.5-1 psu level), provided these sensors were robust enough for monitoring activities? Based on the discussion at the workshop, there were two basic views regarding this question.

Arguing on the side of the broader community's need for resolution at the 0.1 psu level and better, some saw this as what was needed to serve the range of requirements envisioned for the national and regional components of IOOS. Notably, it was felt that the needs of management and science can often be considered to merge in terms of modeling requirements. Based on discussions with modelers from the Pacific Northwest, it was felt that resolution at the 0.1 – 0.2 psu level or better was required to adequately prescribe salinity for model estimates of shelf geostrophic circulation. This is similar to the desired "near-term goal" for accuracy defined by Woody et al. (2000) and is consistent with the performance targets for the majority of commercial conductivity sensors available today.

On the other hand, others expressed the view that, while physical oceanographic modelers may drive one set of measurement requirements, he saw a need for fairly extensive monitoring networks of conductivity-temperature sensors for many coastal/estuarine management applications. In such cases, budget limitations often control the extent of monitoring activities that can be undertaken by management groups. Thus, cheaper sensors may mean more units can be deployed. In some cases, it was felt that some precision/accuracy could be sacrificed if this meant that relatively low-cost, easily deployed C-T sensors could be made readily available to the management community and more widely deployed than more expensive sensors.

The Expanding Range Of Conductivity-Temperature Sensor Applications – The Example Of Submarine Groundwater Discharge

The 1996 workshop on salinity measurement needs reported in Woody et al. (2000) focused on water column sensors, along with a brief discussion of salinity estimates based on airborne remote sensing. However, another area of growing management and research interest in the coastal zone,where conductivity-temperature sensors are employed, is monitoring submarine groundwater discharge (SGD). An ACT workshop held in 2005 considered sensor technology related to groundwater-surface water interactions, considering sensor needs, the existing technologies, and areas for future development (ACT, 2005). In introducing the present ACT workshop, the groundwater topic was revisited as an example of an area of developing applications, which includes a number of conductivity-related measurements and where further development of application-specific configurations for conductivity sensors may be valuable.

Understanding the impact of freshwater removal from aquifers has long been recognized as a critical management issue in many coastal areas, particularly where salt water intrusion into coastal aquifers has become a serious issue. There has been growing interest in recent years in monitoring groundwater input to the coastal zone to assess its impact on the biology and biogeochemistry of these systems. This is an area where both research and management needs require improved resolution of measurements in space and time. Peter Swarzenski of the USGS Laboratory in Santa Cruz, California provided an update on the topic, providing examples from a number of coastal settings.

Generally, submarine groundwater discharge has been a lesser known, and in many areas, an underappreciated route for material exchange. It is clear, however, that groundwater discharge can be a significant source of input of freshwater and associated materials in many coastal settings. The controlling forces vary between different coastal systems and include geologic controls (e.g., permeable versus impermeable formations) and climate-related variability in recharge. Relevant spatial scales for submarine groundwater discharge also vary considerably, from large regional aquifer systems, such as the Floridan Aquifer in the SE United States to localized impacts on scales of 10 cm or less associated with groundwater seepage (e.g., nutrients for benthic algae; trace metal precipitation; impacts of groundwater-borne pollutants). Swarzenski provided several examples of measurement approaches for discharge estimates, including electromagnetic seepage meters used by the USGS and resistivity measurements in cables, either towed ("streaming" mode) or stationary cables deployed in an area of interest. Geochemical tracers, notably radon, radium, and thorium isotopes, are also used to provide a more synoptic look at rates of groundwater discharge over a range of time scales (depending on the isotope half-life). (Available technologies for making *in situ* measurements of various geochemical tracers were summarized in the 2005 ACT workshop).

In summary, conductivity-temperature sensors are among a suite of measurement systems employed to evaluate submarine groundwater discharge rates in the coastal zone. On the practical side, given the range of instruments used, Swarzenski noted that an issue in these studies can be the consistent calibration across different sensors and getting them all working at the same time. Flexibility in sensor configuration and integration with other sensors are also needed for applications monitoring submarine groundwater discharge.

Science / Management Questions

The initial breakout sessions addressed the central charge questions for the workshop:

> What are key science and management questions to be addressed in environments with dynamic salinity regimes using conductivity-temperature sensors?
>
> How can improved resolution of temporal and spatial trends in salinity aid in understanding key processes?

In the initial discussion, a number of broad areas were identified where important science and management questions were related to salinity measurement. These are summarized below, recognizing that there is significant overlap in some areas and that the specific questions of importance vary on regional to local scales.

- *The water cycle* -- As noted above, one of the major questions related to climate variability is how this affects the global hydrologic cycle. In coastal and estuarine areas, salinity regimes can be influenced by a range of factors, including local rainfall, variability in surface water and groundwater inputs, and, in some areas, coastal circulation and water mass characteristics of coastal currents.
- *Physical characterization of the coastal/estuarine environment and coastal/estuarine circulation* -- Perhaps the most "traditional" applications of salinity measurements are in terms of characterizing water masses and their movements. Determination of salinity is fundamental to the basic dynamical description of coastal waters, with variability in the input of buoyancy (freshwater) at the coast often playing a dominant role in coastal/estuarine water mass structure and circulation.
- *Habitat Characterization* -- Salinity generally defines "where you are" in estuaries and coastal areas, in terms of many basic biogeochemical processes (e.g., influencing chemical speciation, particle flocculation, etc.) and is a major environmental factor affecting the distribution of biota and coastal/estuarine community structure. On the mariculture side, the range of salinity for a given location is critical to cost-effective operation of bivalve nursery and grow-out operations. The addition of salt to circulating culture water, required when salinities drop below about 15 psu, can represent a major expense for operators.

- *Coastal Living Marine Resources* -- On the resource management side, many significant diseases and parasites that can impact shellfish populations and some significant harmful algal bloom species are associated with specific salinity regimes. Examples include Dermo and MSX parasitic infections of oysters and parasitic dinoflagellate infections of blue crabs, which are more virulent in higher salinity regimes in estuaries. Thus, in drought years, the shellfish populations in a larger proportion of the total estuarine area are at risk. The salinity structure in estuaries and coastal zones is also often a major factor in the development of seasonal and event-related development of hypoxia.
- *Water Resource Management* -- The impact of upstream removal of freshwater for agriculture and municipal water systems is a major concern for coastal managers in many areas. A notable example is the ongoing legal battle in the SE U.S. between the states of Georgia, Alabama, and Florida and the U.S. Army Corps of Engineers over water rights and regulation of discharge from SE reservoirs to rivers that flow into the NE Gulf of Mexico. Concern over the estuarine/coastal impacts of upstream water use and management of flow through impoundments has been further raised as the result of the recent extended drought in the SE U.S. Restricted freshwater input to productive coastal systems, such as Apalachicola Bay, Florida, has raised concerns about impacts on the overall system function and on commercially important species, such as oysters and bay scallop. Saltwater intrusion into coastal aquifers is also a major issue in a number of coastal areas, with potentially significant economic impacts for coastal communities.
- *Salinity as a geophysical/geochemical water mass tracer* -- In assessing the behavior of materials transported through systems where waters of two or more sources (i.e., end members) having significantly different salinities (e.g., sea water, river discharge, groundwater, hypersaline discharges) are mixed, salinity is often used as a conservative component of the system. Advection-diffusion equations can then be established to determine if a material is removed or enriched as the end members are mixed.
- *Public Health: Tracking pollutants and toxic algae* -- The water mass tracer aspect of salinity also extends to freshwater-borne pollutants and potential pathogens, such as enteric bacteria and viruses and some toxic HAB species. For example, occurrences of blooms of toxic *Pfiesteria* have been most commonly observed in estuaries with broad mesohaline zones. Salinity provides critical ancillary information for tracking various pollutants through estuarine/coastal systems, such as non-point source inputs and for assessing the impacts of major input events associated with tropical systems when huge volumes of contaminated water are input into coastal systems on short time scales. Notable examples in the SE U.S. include the impacts of Hurricane Katrina (late August, 2005) on the Gulf Coast, when the discharge included flood waters from the city of New Orleans; and Hurricane Floyd (September, 1999), when flood waters impacting the coastal zone included waste released from massive hog farms in North Carolina. In estuarine systems with restricted exchange and relatively long residence times (as in North Carolina), such events can have ecological impacts over extended periods (Paerl et al., 2008).

The Need For Sustained Time Series Measurements

A general theme linking a number of these topics and climate variability is the need for climate-quality, long-term records for salinity, including both spatial and temporal components. Adequate time-space coverage was seen as often lacking in present monitoring programs (e.g., the National Coastal Assessment). Yet such records will be critical to detecting and evaluating the impacts of climate-related changes on coastal/estuarine systems. In addition to shifts in the hydrologic cycle, sea level rise would likely have a significant impact on the salinity structure of estuaries. One example is the concern that sea level rise will compress the mesohaline habitat of the Chesapeake Bay (what has been referred to as "estuarine squeeze") and dramatically change the biological composition of the bay.

Conductivity-Temperature Sensor Characteristics

The 1998 salinity workshop, reported in Woody et al. (2000), provided a starting point for the discussion of the basic requirements for salinity measurements. Summary statements from that report defined the basic desired characteristics for *in situ* salinity sensors for coastal waters that experience relatively high variance in salinity as:

> *Accuracy and stability* – A short-term goal of 0.1 psu accuracy and stability for a minimum of 6 months was stated, with a long-term goal of improvements in accuracy to 0.01 psu for values of 0.1-42 psu.
>
> *Capability for sustained deployment* – In addition to the stability of the sensor, the need for robust anti-fouling technology was seen as a priority for meeting the goal of 6-month deployment, with a long-term goal of 1-year.
>
> *Nationally coordinated monitoring of coastal salinity* – It was seen that coordination could provide better information on technical issues, comparative information on various sensors, improvements in sensor calibration across regions and nationally, a testbed framework, and the development of a data management/archiving system for salinity.

With regard to the last point, it is interesting to note that the participants in the Airlie House workshop (Ocean.US, 2002) saw the status of the available salinity monitoring at that time as being in a "pre-operational" status, as opposed to the "operational" status for measurements of basic marine meteorological variables and SST from the NDBC buoys and SST from satellites. This appears to remain the case today. While in recent years, upgrades of selected NDBC buoys has included installation of near-surface salinity sensors, at present, a nationally coordinated coastal ocean observing program (including coastal salinity measurements) has not been implemented.

The general factors for assessing the suitability of conductivity-temperature sensors for various applications were considered to be:

- Range
- Precision
- Response time
- Stability / Length of Deployment
- Spatial / Temporal coverage needed
- Cost of the sensors

However, the development of a matrix of Science/Management topics versus desired conductivity-temperature sensor characteristics was not cleanly resolved in the workshop discussion. For most matrix elements, what was needed or desired in terms of the sensor characteristics generally became a question of more specific sub-topics; that is, "it depends" on the specific location and application. It was felt that over-generalizing the requirements was an issue, with the matrix of requirements seen as varying with specific salinity regimes. In particular, requirements for coastal management (generally "inshore") can also vary considerably from those of more traditional oceanographic and climate research applications (often more "offshore").

Recognizing these constraints, the following tables summarize target (desired) capabilities for salinity sensors to address science and management questions. They are defined according to the environment and general package types utilized.

TABLE 1. General requirements for resolution and duration of deployments for salinity sensors.

Environment & deployment packages	**Vertical resolution**	**Horizontal Resolution**	**Deployment Durations needed**	**Targeted Service Interval**
Ocean --profiling --buoys --shipboard (along-track) --Argo floats	~ cm-scale for many PO applications; ~ meter-scale for more general applications	Generally km-scale or greater for most applications; to 10's of meters for surface mapping	Profiling CTD's are on-station time (min to hrs); sustained measurements require deployments of months and longer	Months between servicing is needed; desired to extend this to 6-months to more than a year; note: Argo floats are not serviced
Coastal -- *profiling* -- *buoys* -- *pier* -- *mobile platforms*	Similar requirements: Range of cm – m depending on applications	Desired at 10's to 100's of meters in areas of strong fronts, etc.	Again sustained deployments of months desired	Months
Estuaries/Rivers	Sub-meter	Meters to 100's of meters	Months	Months
Ground Water	~cm-scales in many coastal settings; to ~meter-scales for monitoring	Meters to 100's of meters	Months	Months

Table 2. Desired Range, Resolution, and Sampling Rates for conductivity-temperature sensors.

Environment	Range (psu or µS/cm)	Resolution (psu or µS/cm)	Sampling Rates
Ocean	10-45 psu	0.001 psu for high resolution PO applications	10 Hz for fast profiling applications; 1 Hz for slower profiling and along-track; min – hrs for fixed *in situ* packages
Coastal	0 – 45 psu	0.01-0.1 psu	From fast (1-10 Hz) for profiling, to 10-sec to minutes for fixed packages in zones of strong horizontal and vertical gradients
Ports	0 – 45 psu	0.1 psu	Minutes
Rivers/Estuaries	0 – 45 psu	0.1 psu	Minutes
Groundwater	Source: 0-500 µS/cm Aquifer: 0-10,000 µS/cm	1 µS/cm	minutes
Lakes	0 – 500 µS/cm	1 µS/cm	minutes

It is important to note qualifications in terms of the general requirements listed for conductivity/salinity measurement needs. Again, it was recognized that there is often a clear distinction between science and management requirements, with the physical oceanography (PO) requirements typically driving the need for fine vertical and horizontal resolution and, consequently, fast sampling rates. Also, participants felt it was important to acknowledge that user capabilities for making the measurements will vary widely. Achieving the objectives for the higher-end physical oceanography applications requires the appropriate instrumentation, very careful attention to calibration, and data processing capabilities. These are often not available to resource managers and routine monitoring programs.

Given the range of applications discussed and something of a lack of consensus on sensor requirements in the morning session, it was decided to remain as one group for the afternoon discussion. This focused initially on a summary of the available commercial systems and configurations.

Available Technologies For Salinity

A number of approaches for measuring salinity have been explored, including conductivity sensors, optical (refractive index based) systems (e.g., a new fiber optic-based system was reported to be under development), time-domain refractometry (TDR), measurement of microwave emission (the basis for remote sensing applications), and acoustic approaches (explored, at least in principle, from inverting the speed of sound). The present ACT workshop focused on the conductivity sensor technologies that are broadly available in commercial packages. The most fundamental technological differences among the present commercial systems for measuring salinity are whether these are based on inductive or conductive sensors, and whether the sensors are measuring in an “internal” or “external” configuration.

Compared to many classes of environmental sensors, the present market for conductivity sensors for environmental applications is fairly diverse in terms of manufacturers and sensor package configurations. The industry participants in this workshop provided a broad base of experience in terms of commercial C-T sensors, and a summary of the present commercial offerings was attempted. The following is based on input from the industry representatives present. It is intended to provide an indication of the breadth of sensor configurations available, basic performance characteristics, and price ranges, and is not intended to represent a comprehensive survey of all available products. Further information is available at the company websites and on the ACT Searchable Technology Database (*www.act-us.info/tech_db.php*).

- **AADI** (formerly Aanderaa; *www.aadi.no/Aanderaa/Products/Sensors/*) – The conductivity sensor design uses two inductive coils (primary/secondary) with an internal ceramic tube measurement. A cell constant determined during calibration provides external field compensation. The conductivity measurement is temperature and pressure independent, with a temperature sensor used to compute salinity. These are designed for AADI current meters but are also available as OEM self-contained units with analog, R2-232/422 output. All calibration coefficients (salinity, speed of sound, etc.) are applied “inside” the package, with accuracy of 0.018 mS/cm for conductivity. The cells can be cleaned with a toothbrush and anti-fouling paint can be applied.
- **ALEC Electronics Co. LTD** (*www.alec-electronics.co.jp*) -- Markets both inductive and electrode systems. Available systems target applications in the coastal ocean to ocean depths of 1,000 m. These use a large-bore inductive cell (no pump), measuring the external field. Systems with a range of sampling rates are available: 10 Hz for standard profiling units; 1 Hz for moored units; 100 Hz for specialized micro-structure profilers. Costs range from \$2,700 to \$15,000 for standard mooring and profiling units to \$60,000-\$70,000 for the microstructure unit. A separate product line targets mooring applications in fresh and salt water, using seven-cell electrode design and a wiper system for anti-fouling (7 cm diameter for unit). Deployments of 2-3 months are targeted, with resolution of 0.05 psu for seawater (0.01 psu with special calibration) and 10 µS/cm resolution in freshwater (provided by the same sensor). Unit costs ~\$6,000.
- **Campbell Scientific, Inc.** (*www.campbellsci.com*) – A three-ring electrode sensor is used for packages intended for groundwater and monitoring salt water intrusion, as well as for surface freshwater. A durable epoxy housing can tolerate exposure in sediments. Range is 10 µS/cm – 7 mS/cm standard (extended range is available) with accuracy at 0.25% of readings. Includes an integral thermistor. The unit has multiplex capability and is available with output directed to a Campbell Scientific logger.
- **FSI** (**Falmouth Scientific Inc.;** *www.falmouth.com/*) – Supplies a range of inductive cells, including OEM units to complete profiling packages. Present models include: a) an older model using a ceramic single toroid external field sensor; b) a newer model (rugged design) that uses ceramic tubes for an internal field measurement with resolution to 0.005 psu and shows good long-term stability. The primary application areas targeted are coastal and ocean profiling. Passive anti-biofouling is provided by copper components. C-T systems

are provided with aged thermistors and employs a simplified calibration process. Costs range from $300-2,500 for OEM sensors to $4,500-15,000 for multi-parameter systems.

- **In-Situ Inc.,** (*www.in-situ.com/*) -- Offers units for groundwater and surface water measurements. For wells, 1-inch diameter C-T units and 2-inch multi-sensor units are available, using a four-electrode (non-glass platinium) sensor. These are capable of a wide operating range with accuracy of 0.5% of the reading. These units are designed for extended deployments, sampling at a maximum rate of hourly, with recalibration at 6-month intervals. The sensors are telemetry and SCADA ready (can be interfaced to third-party telemetry and data acquisition systems). Sensor cost for conductivity only for a groundwater configuration is ~ $1,500 to ~$2,100 for a multi-sensor probe.
- **RBR LTD,** (*www.rbr-global.com/products/*) – Products include an inductive sensor for marine applications (0-70 mS/cm) and a three-electrode sensor for freshwater (0-2 mS/cm), with durable Delrin housings. The sensors have linear calibration characteristics, and a two-point calibration is used. Initial accuracy for the inductive cell is 3µS/cm with 20µS/cm stability at one-year. A CT unit (~$3,000) includes 8 Mbytes memory and battery pack and is designed for 1 year deployment for a 10 minute sampling interval. Packages can also be configured as an "open platform" to accommodate other sensors (6 input model $10,000-15,000). RBR also offers a new dual-cell (sample/reference) bench-top salinometer that can provide verification of performance of field instruments.
- **SeaBird Electronics Inc.,** (*www.seabird.com*) – A variety of systems are available with applications from lakes to higher salinity marginal seas. All use a three-electrode glass cell for salinity ranges of 0-45 psu (conductivity of 0-9 S/m). Accuracy is 0.002 psu with stability of 0.005 psu/year or better in the laboratory and 0.02 psu for 6 months *in situ*. Sensors are factory calibrated, with post-processing/adjustment possible with "field calibration." Sampling rates range from many times per second to once per hour. The cells are ducted or use a pump for moving sample water through the conductivity cell. Internal field measurement allows for integral anti-biofouling (tbt-impregnated plugs) on inlet and outlet of cells used for moored deployments. Costs range from $3,000 for CT only, stripped down models to ~ $20,000 for multi-parameter water quality measurement systems.
- **YSI Inc**., (*www.ysi.com/ysi/Products*)-- Product line includes instruments for freshwater, coastal, marine, and groundwater applications, with self-contained and hand-held instruments in 1.7-inch and 3.6-inch diameter housings. Conductivity measurements use a four-electrode system with auto-ranging (0-100µS/cm, 0-1,000 µS/cm, 0-10,000 µS/cm, 0-100,000 µS/cm) accuracy of 0.5% of reading and resolution of 0.01% of reading, and a thermistor for temperature readings. Costs for hand-held units start at about $700 and for full multi-parameter systems range from $10,000-15,000. Anti-biofouling can include copper additions and anti-fouling paint on bodies and an integral wiper on larger systems.

In addition to the commercial vendor sensors, a surface water monitoring package developed by The International Seakeepers Society for along-track measurements of salinity and other water properties was described. This modular package is installed on voluntary observing vessels and includes an anti-fouling system and proprietary technologies for sensor interface ("Ferrybox Sensor Interface Standard", FSIS) that are being offered on a fee-free basis.

Follow-Up Discussion

In discussion of the current commercially available conductivity-temperature sensors, several (somewhat inter-related) points were raised.

> It was noted that, in practice, the performance of instrument systems is important. That is, it is not the functioning of the conductivity-temperature sensors alone, but how the entire package performs that determines the quality of the salinity measurements obtained.
>
> Maintenance requirements are typically the key cost driver for monitoring programs. Whether a given sensor is capable of extended operation in the field often centers around the related topics of the effectiveness of anti-fouling, required servicing intervals, and ease of field maintenance.
>
> True costs of a given sensor package must consider "life-cycle" costs. Stability of the sensor is an example of a key consideration in this area. For example, costs associated with servicing and recalibration can quickly balance low initial unit costs if sensor stability in the field is poor. This is an area where information from experienced users can be quite valuable to those considering sensor purchases for a given application.
>
> Building and marketing a cheaper conductivity sensor is not simply a matter of relaxing requirements for resolution. As opposed to the a/d resolution in the electronic components, more typically the unit cost is associated with the mechanical package; what it takes in terms of engineering, fabrication, and hardware costs. Also, it is typically not simply the sensor that is needed but a package that includes power, data logging, and/or communications options. It was pointed out that there are presently conductivity-temperature sensors available for less than $1,000.
>
> Present options for measurements of pore water salinity appear to be probe-type measurements. While there are probes suited for monitoring in wells, there are not presently commercial options for direct long-term monitoring of pore water salinity (as might be useful for assessing possible roles of drought-associated die-back of coastal salt marsh grasses).

The Upcoming ACT Evaluation Of Conductivity Sensors

Tom Johengen (U. Michigan; ACT Chief Scientist) provided a summary of the planned ACT evaluation of conductivity-temperature sensors. This would involve both laboratory and extended field measurements. As background, Johengen summarized the basic approach and philosophy employed by ACT in prior sensor "verifications" and "demonstrations" and explained the difference between these. For the field evaluation, manufacturer input and feedback during the protocol development process is solicited; it is important to ensure that a particular sensor is deployed in the manner intended. The field trials would include diverse coastal environments, with salinity regimes from freshwater to estuaries and higher salinity coastal environments (a range of about 0-37 psu). Laboratory tests will include a salinity dilution series. It is recognized that potential issues related to deployment of multiple sensor package deployments will need to be discussed with the manufacturers (e.g., proximity effects for external field sensors). The scales of variability to be resolved at the deployment sites will also need to be considered.

In the discussion that followed Johengen's presentation, several questions were raised concerning the evaluations. The primary questions/concerns expressed regarding the field protocols concerned are as follows: assessing drift of sensors over time; ensuring appropriate warm-up times and sampling cycles to ensure that inter-comparable results are obtained; whether gradients in salinity would be sampled; and would there be "within-deployment" inspections and servicing at intervals appropriate for a given deployment environment. Other topics raised included whether there would be an independent measurement of temperature and whether measurements would be obtained against a standard reference. It was expressed that the actual values of conductivity and temperature for a given sensor should be reported (i.e., not simply the derived salinity value). These questions would be considered further in the protocol development workshop. It was emphasized that input from users was also desired.

Wrap-Up To The Workshop

To conclude the workshop, broad comments/recommendations were solicited and participants were asked to provide insight on what the potential roles for ACT could be. It was noted that ACT has been working under the constraint of a year-to-year funding and, thus, has been somewhat constrained in terms of the scope of what could be developed to date. Although not resolved in detail, possible areas for ACT involvement could be in terms of tracking developments in conductivity-temperature sensor technologies and developing mechanisms to better provide relevant information on the available options to users. The upcoming ACT evaluation of conductivity-temperature sensors may provide one avenue for further information dissemination.

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