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ACOUSTIC TAGGING AND THE INTEGRATED OCEAN OBSERVING SYSTEM: REPORT FROM THE WORKSHOP HELD 14-15 NOVEMBER 2006 IN SANTA CRUZ, CALIFORNIA

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Summary

We convened experts in acoustic telemetry at a workshop to discuss how this rapidly evolving technology might be incorporated into the emerging Integrated Ocean Observing System (IOOS). Workshop participants from the fields of fisheries, marine ecology, and oceanography agreed that inclusion of acoustic tagging and tracking technology would offer substantial benefits to ocean observing by adding a much needed biological component to IOOS. Workshop participants also made recommendations on how several challenges of an expanded acoustic network may be addressed, including how a cooperative system might be operated, how data could be analyzed, and ways the technology might be extended to yield even greater benefits.

Background

NOAA and other federal agencies are developing the Integrated Ocean Observing System (IOOS, Fig. 1) to support ecosystem-based marine resource management. The goals of IOOS include enabling the sustained use of ocean and coastal resources and increasing the effectiveness of coastal ecosystem protection and restoration. Meteorological and physical oceanographic portions of IOOS are relatively well-developed, while biological components are not. Currently, observations of marine animals rely on ship-based surveys, but relying solely on ship-based observations will result in severe undersampling of the biological components of ocean ecosystems. What is urgently needed are ways to gather data on animals at temporal and spatial scales achieved by satellites, moorings and shore-based radars.

Electronic tagging of marine animals can generate high-resolution biological data, like the physical data coming from moorings and satellites. Archival and global positioning system (GPS) tagging of large pelagic species illustrate the potential of electronic tagging (e.g., Lutcavage et al., 1999; Boustany et al., 2002; Stokesbury et al., 2004; Block et al., 2005). Acoustic tagging has similar potential for the many species not well-suited to satellite pop-off, GPS or archival tags, such as those with coastal or demersal habits, small size, or low recapture rate (Comeau et al., 2002).

Acoustic tags report the identity (and possibly other data, such as depth) of tagged animals by emiting a coded pulse of ultrasonic sound, which is detected and decoded by data-logging hydrophones when animals come in range. Under good conditions the range may reach up to 1 km. Tags and hydrophones are relatively small (Fig. 2) and cheap, approximately $300 per tag and $1000 per hydrophone. The hydrophones operate continuously, providing complete coverage in time. Spatial coverage depends on the quantity and location of hydrophone deployments. Over the past three years, the Pacific Ocean Shelf Tracking (POST) program, part of the Census of Marine Life, has maintained arrays of hydrophones on the continental shelf around Vancouver Island, and has extended coverage to southeast Alaska and northern Oregon. This year, the Canadian Foundation for Innovation has awarded over $30M U.S. to the Ocean Tracking Network (OTN) project, which

Figure 1: *Conceptual model of an integrated ocean observing system. The system incorporates sensors carried by satellites, aircraft, ships, moored and drifting buoys, and sea-bed platforms. Data is telemetered from collection platforms to ground stations by satellite communications. From www.ocean.us.*

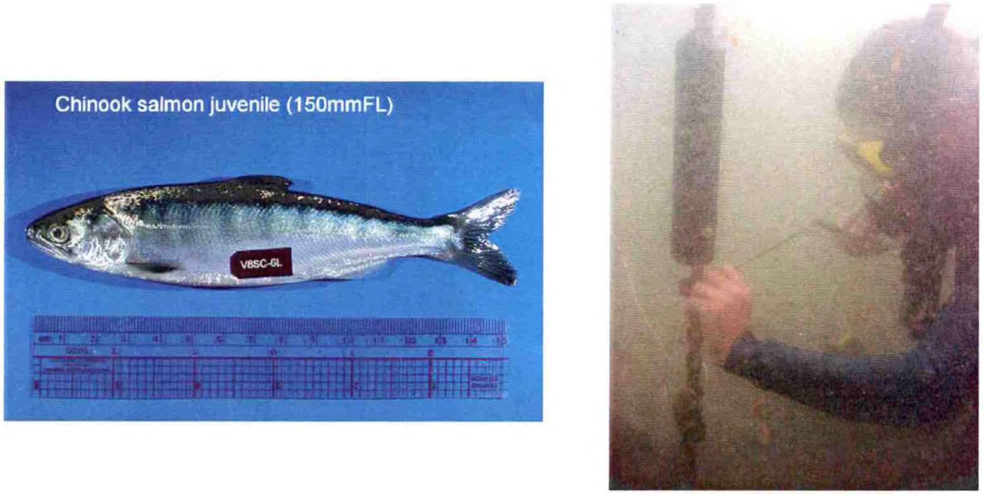


Figure 2: *Acoustic tags and receivers. Left: Size of an acoustic tag relative to a juvenile Chinook salmon. Right: Diver installing an acoustic monitor.*

will deploy POST-style hydrophone arrays in select sites around the world and develop next-generation acoustic tags and receivers.

Several challenges must be met before acoustic tagging can be effectively incorporated into IOOS, including clarifying the kinds of questions acoustic tagging can address, resolving issues of data sharing and data ownership, and developing systems for data management and methods for analyzing tagging data. Here we report the findings of a workshop held in November 2006, where workshop participants identified the types of research questions and species that would benefit from a large-scale, coordinated acoustic tagging and tracking component for IOOS and made preliminary recommendations on the design of such a component for IOOS. Workshop participants also made recommendations on methods of data analysis and how such a program could best be managed so that it will meet the needs of all participants, including academic, government and NGO scientists and institutions. Workshop participants are listed in Table 1.

Utility of acoustic tagging

It was clear from presentations at the workshop that acoustic tagging is currently used to obtain information in a number of research areas important to marine resource scientists and managers. From identification of migration and residency patterns, hotspots, critical habitats, and stage-specific demographics (survival and migration rates)to monitoring effectiveness of habitat restoration and effects of marine protected areas (MPA), acoustic tagging has provided very valuable insights on marine animal movement patterns, demographics, habitat utilization, and species interactions. Fig. 3 shows some results of recent acoustic tagging projects.

Observing migration patterns is a straightforward application. For example, acoustic tags have been used to document the movement of sharks among outlying islands of the Galapagos archipelago (Fig. 3A), the movement of bull trout from freshwater through marine waters of Puget Sound (Fig. 3B), and the movement of green sturgeon among various habitats on the west coast of North America (Fig. 3D). Acoustic tags are also readily applied to problems of estimating demographic rates such as survival of salmon smolts as they migrate down river and through the coastal ocean (Fig. 3C). Other applications presented at the workshop examined movement in and out of MPAs.

The efficacy of the studies presented at the workshop could be greatly enhanced if there was a well-designed, semi-permanent deployment of hydrophones throughout relevant ecosystems. Currently, receivers are deployed by investigators for the purposes of their individual study, and data is shared on an ad-hoc basis through informal networks of researchers. The limits of such a system are already becoming apparent, and will only become more so as the number of tagged animals and investigators using the technology increases. These limits include loss of information when tag detections are not communicated among researchers, possible use of duplicate tag codes, and limited spatial and temporal coverage of receiver arrays. Future developments in tag technology (discussed below) will only increase the need for better coordination among researchers.

Suggested designs

What can be learned from acoustic tagging depends on how acoustic receivers are deployed in space and time. Workshop participants suggested improving receiver array coverage by combining long-term cross-shelf lines, with shorter-term grid-based arrays deployed around marine protected areas, islands and seamounts, and other biotic "hot-spots", depending the research question. Once the grid-based array had served its purpose it could be moved to another suitable location as required. Such a system would facilitate studies ranging from the fine scale movements of rockfish or lobsters, through the large-scale movements of salmon and sturgeon, to the basin-scale movements of white sharks or tunas. An expanded coast-wide array of receivers would benefit from the IOOS framework through opportunistic deployment of receivers on coastal and deep-sea moorings (Fig. 4). Incorporating this type of biological monitoring into IOOS would allow the behavioral and demographic data generated by tagging studies to be interpreted in the light of the relevant oceanographic and environmental data.

Data management

Workshop participants identified data management as a critical challenge facing a large-scale tagging program. Current-generation, commercially-available hydrophones log their

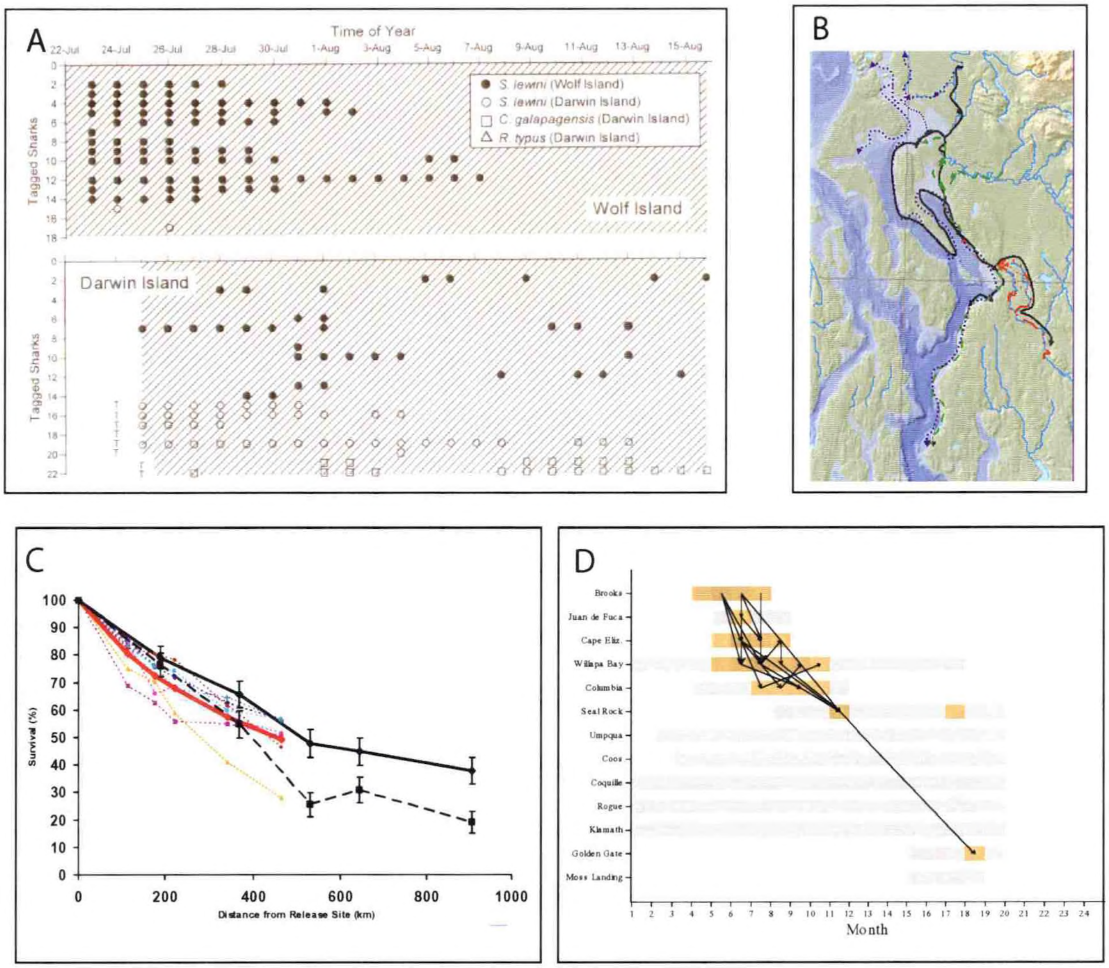
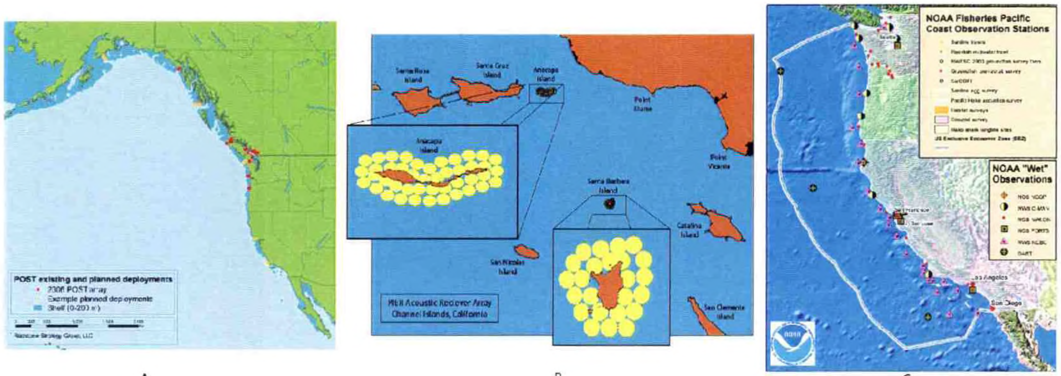


Figure 3: *Examples of recent applications. A: Movement of individual sharks of three species between two islands of the Galapagos. Data from A. P. Klimley. B: Movement of a bull trout from the Skagit River to the Snohomish River through marine waters (bull trout not previously known to use marine waters). Data from F. Goetz. C: Survival of salmon released in the Columbia River as they migrate down the river and through the coastal ocean. Colored lines are results for various PIT tag release groups, black lines are results for acoustic tag release groups. Data from D. Welch. D: Movement of green sturgeon tagged in Willapa Bay, WA in 2003 among various habitats in 2004-05. Arrows indicate movement of individual fish; yellow bars indicate presence of green sturgeon; gray bars indicate periods of receiver deployment. Data from S. Lindley.*



A B C

Figure 4: *Components of a large-scale acoustic tracking system. A: lines of receivers acting like a picket fence along migration routes (from POST project). B: Arrays of receivers concentrated around specific points of interest such as islands and marine protected areas (from J. Lindholm). C: Existing NOAA surveys and moorings (from B. Southall).*

data to internal memory, and must be downloaded manually either with an acoustic modem or by recovering the instrument. The information recorded by the hydrophones is only useful in the context of accurate and complete data and metadata on tagged fish and hydrophone deployments. It is therefore critical that all data and metadata be maintained in a relational database, and that appropriate data handling protocols be in place to manage the flow of from original sources to the database and on to end users. Data management is a major component of IOOS plans, and the IOOS framework is well-suited to turning raw detection data into useful information (Fig. 5). In the future, data flow tasks may be made easier by systems capable of relaying data acoustically to hard-wired nodes that can then uplink through satellites, cell systems, or land lines to automated data transfer systems.

A significant outstanding issue in the acoustic telemetry community is data ownership. Useful data are produced when tags are detected by receivers, each of which might be part of a different program. Objectively, the tagger and the receiver operator each have some claim to the data. Data from government-owned and operated monitoring systems (e.g., data from NOAA's National Data Buoy Center buoys[1] or the Argo system[2]) are typically available to any interested party in near-real time. Under this kind of model, scientists would need to make their tagging data available before they could receive detection data from the system. The POST project is pursuing such an approach, except data would be available only to officially sanctioned participants for some period of time before it becomes publicly available. The Tagging of Pacific Pelagics (TOPP) program has taken a different approach: summarized tag data are published on the web in near-real time, but researchers wishing to use TOPP data must obtain permission from the TOPP principal

[1]http://www.ndbc.noaa.gov/
[2]http://www.argo.ucsd.edu/

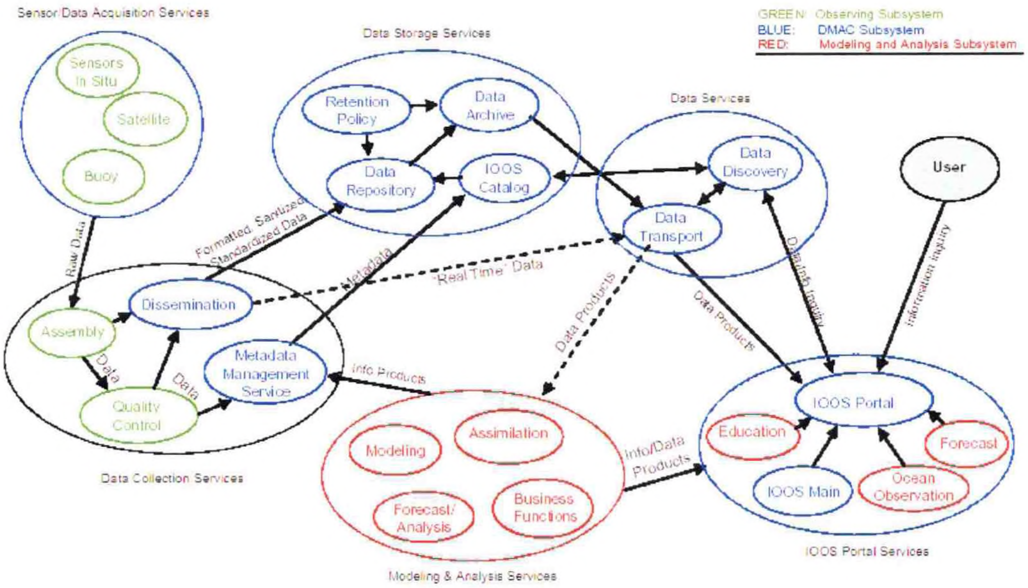


Figure 5: *Conceptual model of data flow in IOOS, from observing systems (e.g., acoustic receivers) to end users. From Lockheed Martin (2006) RFQ #123298.*

investigator. Many, but not all, workshop participants seemed comfortable with immediate release of and free access to data. Further discussion is needed to find a way to meet the needs of resource managers for timely data access and thorough analysis, and the need for scientists to accrue appropriate recognition (coauthorship on papers, acknowledgments, etc.) for their efforts.

Data analysis

Effective use of acoustic tagging data will require advances in data analysis and presentation. Satellite tags can provide high resolution tracks for one or a few animals over a relatively short time period that can be plotted over maps of sea surface temperature, and this simple visual presentation can be revealing (for example, tagging of sea turtles has shown that they forage along the chlorophyll transition zone of the subtropical north Pacific (Polovina et al., 2000)). The data arising from acoustic tagging programs is fundamentally different: movements must be inferred from sporadic detections at disparate sites. The long life and low cost of acoustic tags makes it feasible to tag enough animals such that useful patterns at the population level might be detected. Also, active tags in the vicinity of receivers are not always detected, due to interference among tags or the presence of sound scattering, absorbing or deflecting objects such as thermoclines, kelp nematocysts, or seabed irregularities. These aspects of acoustic tagging data require a statistical approach to analysis. One attractive approach is to use mark-recapture models to infer survival and

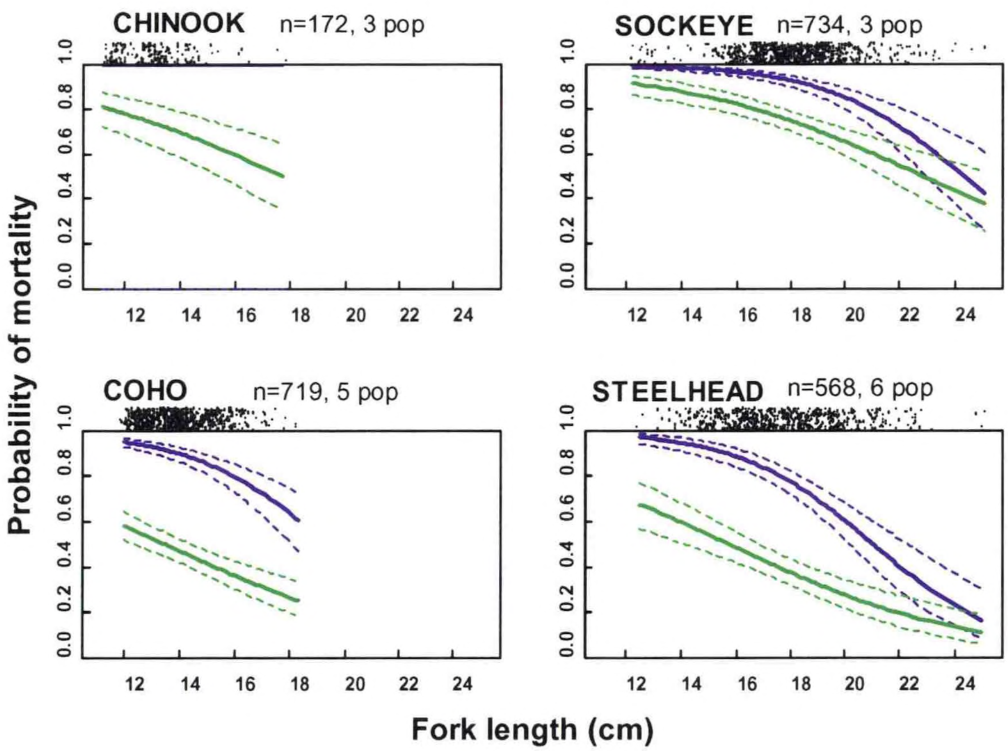


Figure 6: *Size-specific survival rates of four species of Pacific salmonids in 2004 (purple lines) and 2005 (green lines). Data from M. Melnychuk, C. Walters and D. Welch.*

migration rates from the acoustic detection data (Kendall and Nichols, 2002; Pine et al., 2003). For example, size-specific survival rates can be estimated for different species of Pacific salmonids released in different years (Fig. 6). However, the more complex mark-recapture models capable of capturing stage-specific (i.e., age, size, sex, stock or origin) migration and survival are data-intensive, requiring large release groups to produce parameter estimates with useful precision. Another approach is to use state-space models of animal behavior to make inferences on behavior from observations of animal movement (James et al., 2005; Jonsen et al., 2005).

Emerging technologies and integration

Workshop participants anticipate that hybrid tags will soon be available that combine geolocation, environmental, and physiological data logging with acoustic transmitters. For example, TOPP researchers have been collecting temperature-depth profiles from sea lions using satellite tags (Fig. 7). Hybrid tags will download archived data to underwater receivers via acoustic modems. This would produce greatly enriched data sets and make acoustic technology attractive for application to oceanic species, because such tags would

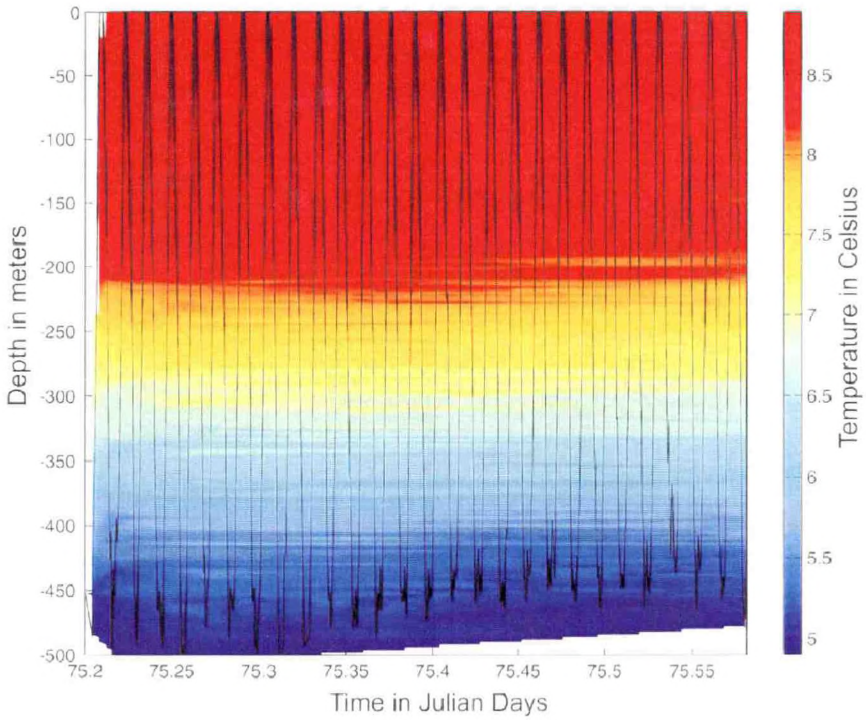


Figure 7: *Dive profiles (line) and thermal structure from a time-temperature-depth recorder on a northern elephant seal from a series of dives over a period of 9.6 h on 16 Mar 1998. The seal was located at 42.58°N, 144.63°W. From Boehlert et al. (2001).*

be implanted internally (greatly reducing tag shedding), but not require recapture of the animal.

Further on, we anticipate development of "business card" tags that could communicate with other tags, and report the tags that they have detected when they eventually pass within range of a receiver (Fig. 8). Ultimately, one can imagine an undersea data network, where the data is transported in part by the animals themselves.

Passive acoustics systems are also being investigated for inclusion into IOOS. Currently, these systems are envisioned as recording the activities of soniferous animals, but in concept, they could record acoustic tag transmissions which could then be decoded in software.

Recommendations

Acoustic tags, coupled with a comprehensive system of data-logging hydrophones, would provide extremely valuable information on nektonic organisms and substantially increase the utility of IOOS for ecosystem-based management of living marine resources. NOAA and DFO, with guidance from the broader scientific community, should begin planning to

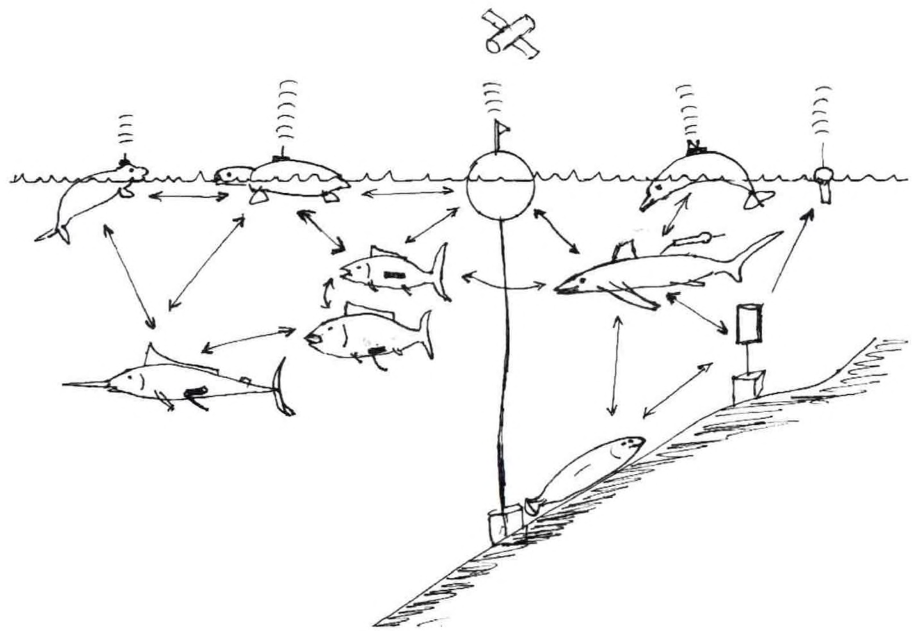


Figure 8: *Conceptual diagram of a data network formed by animals carrying tags capable of exchanging storing data. Credit: K. Holland.*

incorporate existing and emerging acoustic and hybrid technologies into IOOS.

Acknowledgments

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Table 1: *Attendees of the workshop.*

Person	Affiliation
Arnold Ammann	NOAA SWFSC
Barry Berejikian	NOAA NWFSC
Barbara Block	Stanford U.
John Carlson	NOAA SEFSC
Cedar Chittenden	U British Columbia
Chris Chrisman	Redstone Consulting
Ken Cooke	DFO Canada
Mike Domeier	Pfleger Institute of Environmental Research
Fred Goetz	US Army Corps of Engineers
Churchill Grimes	NOAA SWFSC
Michelle Heupel	Mote Marine Laboratory
Heather Holden	Pacific Ocean Shelf Tracking program (POST)
Kim Holland	U Hawaii
Michael Parsley	USGS
Steve Katz	NOAA NWFSC
Elise Kelly	UC Santa Barbara
Heather Kerkering	Monterey Bay Aquarium Research Institute
Denise King	Amirix Corp
Pete Klimley	UC Davis
Steve Lindley	NOAA SWFSC
James Lindlholm	CSU Monterey Bay
Christopher Lowe	CSU Long Beach
Bruce MacFarlane	NOAA SWFSC
Scott McKinley	U British Columbia
Mike Melnychuck	U British Columbia
Roy Mendelssohn	NOAA SWFSC
Mark Monaco	NOAA NOS
Mary Moser	NOAA NWFSC
Chris Neville	DFO Canada
John Payne	Pacific Ocean Shelf Tracking program
Brandon Southall	NOAA
Rick Starr	CA Sea Grant and Moss Landing Marine Laboratory
Mike Stokesbury	Dalhousie U., OTN
Steve Teo	UC Davis
Jonathan Thar	Vancouver Aquarium, POST
John Ferguson	NOAA NWFSC
Michael Webster	Moore Foundation
David Welch	Kintama Research
Lisa Wooninck	NOAA SWFSC