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Mobile receivers: releasing the mooring to 'see' where fish go

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Abstract Much has been learned from the large scale deployment of acoustic tags on aquatic species and associated networks of riverine and marine receivers. While effective in the linear environment of river systems, marine systems limit the ability to provide spatial information on fish movements and distributions due to a combination of costs, logistics, and lack of off-shore technology. At the same time, each year millions of dollars worth of tags are being released into the aquatic environment with extended battery/transmission life, yet detections are limited to coastal arrays. Here we explore new methods of tracking acoustically tagged species in the marine environment. A new miniaturized acoustic receiver, the Vemco Mobile Transceiver (VMT) can be carried by large marine organisms. In combination with satellite and archival tag technology, VMTs were deployed on northern elephant seals to monitor acoustic tags encountered during their migrations across the Northeast Pacific. Early results include acoustic detections of tagged great white sharks, salmon sharks, Chinook salmon, steelhead, lingcod, green sturgeon and other elephant seals. We also propose several alternative directions for future effort: 1) analyzing the growing number of passive acoustic survey recordings made from hydrophone arrays for acoustic tag detections, 2) working with acoustic technology providers to develop hull-mounted receiver systems for the thousands of ocean going vessels around the world and 3) integrating acoustic receiver technology

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into the thousands of moored and drifting oceanographic buoy arrays.

Keywords Acoustic tag · Mobile receiver · Elephant seal · Offshore tracking · Salmon

Introduction

Advancements in underwater acoustic tagging and tracking technologies during the late 20th century have resulted in the ability to place acoustic transmission tags on or in successively smaller fish and track these fish across successively larger spatial scales, providing new insights into life history and survival. As a result, the number of researchers using common technology has reached a threshold, where there has been cross contact between receiver networks and tagged organisms that were previously thought to be outside the spatial scale of a given organism's home range (Lindley et al. 2008; Jorgensen et al. 2009). This realization has led to a positive feedback in the research community and the development of large database sharing centers (post-coml.org, californiafishtracking.ucdavis.edu, hydra.sounddatamanagement.com) and coordinated research efforts that are yielding results at a rate that exceeds the original goals of individually funded projects. These efforts have been particularly successful in riverine and near shore marine environments, where organisms' movements are constrained by linear habitats, shallow bottoms, and coastlines, creating 'pinch point' opportunities where the transmission range of tags is on par with the economic and logistic ability to deploy a sufficient number of acoustic receivers to ensure high detection rates. As the results of this symposium (Electronic tagging studies of salmon migration) demonstrate, this field of research has gained sufficient momentum that it will continue to grow and reach its full potential in the near future.

What remains a daunting barrier, or perhaps frontier, is the ability to follow organisms into offshore habitats where their movements are no longer restricted spatially. There are visionary plans to establish large scale sea-floor arrays incorporating suites of receiver technologies for everything from acoustic tags to tectonics and temperature (NSF Ocean Observatories Initiative http://www.interactiveoceans.washington.edu/). Coupled with associated fleets of automated underwater vehicles, these arrays would increase the capacity to detect acoustically tagged organisms; however, this is both expensive and somewhat into the future (Prentice and McComas 2007). Ironically, barriers to offshore research may be less technological but rather simple economics. For example, the ship-time costs associated with chartering a vessel to deploy marine receivers, or to actively follow a tagged organism, can be tens of thousands of dollars per day, far more expensive than the actual receiver technology being used. Given the resources (both financial and carbon) required to accomplish offshore survey efforts, it is worth exploring existing platforms that could be multi-tasked to fulfill these new survey goals at reduced costs.

Our objectives are to simultaneously explore and propose potential solutions to these barriers, while at the same time stimulating other researchers to begin thinking "outside the box". Here we discuss several directions of research at various states of development ranging from implementation with preliminary results to the purely theoretical. A common theme is the idea of 'piggy backing' onto existing areas of research and marine platforms where data collection opportunities could be leveraged for minimal cost. First we will present preliminary results from a pilot study designed to integrate acoustic receiver technology into the archival and satellite-based instrumentation being used to study larger marine organisms, allowing these animals to collect data not only on their behavior and oceanographic environment but on the acoustically tagged organisms they encounter in their environment (Costa et al. 2009; Holland et al. 2009; Costa et al. 2010). Second, we propose exploratory analysis of the growing number of passive acoustic data sets that are sampling acoustic data at ultrasonic frequencies to record marine mammal vocalizations (Rankin et al. 2008; Holland et al. 2009) and may have recorded acoustic tags. Third, we will discuss the potential and challenges of attaching acoustic receivers to ships of opportunity, whose costs are already covered for other reasons. Finally, we will explore the idea of integrating acoustic receiver technology into unmanned buoy arrays already collecting oceanographic data.

Biological receiver arrays

In the past two decades, there has been a massive undertaking to increase our knowledge of distribution and movements of upper trophic level fishes and marine mammals through electronic tagging technology. Recognizing that the spatial scale of such studies could not be accomplished by any single team, large multi-institutional organizations have emerged with backing from both private foundations and governments in coordination with the Census of Marine Life (coml.org). This symposium focused on smaller fish species tagged with acoustic transmitters that are being tracked by a network of coastal or riverine arrays in coordinated efforts through organizations like POST (Pacific Ocean Shelf Tracking, www.postcoml.org), and the California Fish Tracking Consortium (californiafishtracking.ucdavis.edu). In contrast, organizations like TOPP (Tagging of Pacific Pelagics, www.topp.org) are working to tag large marine vertebrates (mammals, tuna, sharks, turtles) with larger, sophisticated archival tags that can be linked to the ARGOS satellite system to track their movements over large spatial scales (Costa 1993; Shaffer et al. 2006; Biuw et al. 2007; Costa et al. 2008; Bailey et al. 2009; Jorgensen et al. 2009; Bograd et al. 2010) along with oceanographic information about the animal's environment, over ranges that are beyond our ability to sample with ships or automated underwater vehicles (AUVs) and for a fraction of the cost (Boehlert et al. 2001). In the case of elephant seals (*Mirounga angustirostris*) and other pinniped species, the tagged animal typically returns to the tagging location for breeding or resting purposes, enabling the recovery of archival tags that record data at a higher resolution than what can currently be transmitted through satellite networks.

Elephant seals migrate throughout the northern half of the California Current Ecosystem and beyond through the Gulf of Alaska to the western edge of the Aleutian Islands (Le Boeuf et al. 2000). Acoustic tags have shown that fish such as Pacific salmon (*Oncorhynchus spp*.) have similar distributions and movements along the coastal edges of western North America (Welch et al. 2004; Melnychuk et al. 2010). While net-based surveys of the high seas and some archival tagging work have demonstrated that many species of fish spend a considerable portion of their life in the open ocean (Myers et al. 1996; Hayes et al. 2011), the tracking methods currently available to track fish as they migrate off the shelf into pelagic habitats are more limited.

In an effort to merge these research directions, we deployed archival acoustic receivers on elephant seals to create a roving array of sensors. Such an array would provide additional offshore data on the approximately 4,500 acoustically tagged fish that are being released into the ocean and Northeast Pacific rim rivers each year. Specifically, elephant seals were instrumented with geopositioning satellite tags and acoustic receiver tags (the Vemco Mobile Transceiver, VMT). In addition, the seals carried an archival tag that collected data on water column temperature, light levels and pressure/depth. This tag combination allowed us to recover the acoustic receiver tags and link any detection to a location along the seal's migratory path. The objective was to deploy VMTs on elephant seals, which make two migrations per year, from fall of 2009 through summer 2011, having approximately 10 to 13 VMTs deployed at any given time.

Methods

We used a prototype VMT re-engineered to withstand the pressures associated with elephant seal dive depths up to 1,000 m (Le Boeuf et al. 2000; Hayes et al. 2011). Prior to deployment on a migrating seal, we conducted two short term deployments on juvenile seals simply to evaluate the integrity of the instrument. In November 2009, two juvenile elephant seals, were captured at Año Nuevo State Park, California. Handling and instrumentation was done according to the methods of Kuhn et al. (2009). Animals were instrumented with a satellite tag glued to the pelage on the top of the head, and a VMT, TDR and VHF radio tag glued to the pelage of the mid-dorsal region (Fig. 1). The following day, the seals were then transported to Hopkins Marine Station (Stanford University, Monterey, CA) on the southern rim on Monterey Bay and released on the beach, where they entered the water and returned to the Año Nuevo colony (an established homing behavior in this species; Oliver et al. 1998). During February 2010 through and March of 2011, 19 adult female and 12 adult male seals were tagged at Año Nuevo with the complete instrument package described above.

Results

For the juvenile seal deployments, both VMTs operated within expected parameters during the time

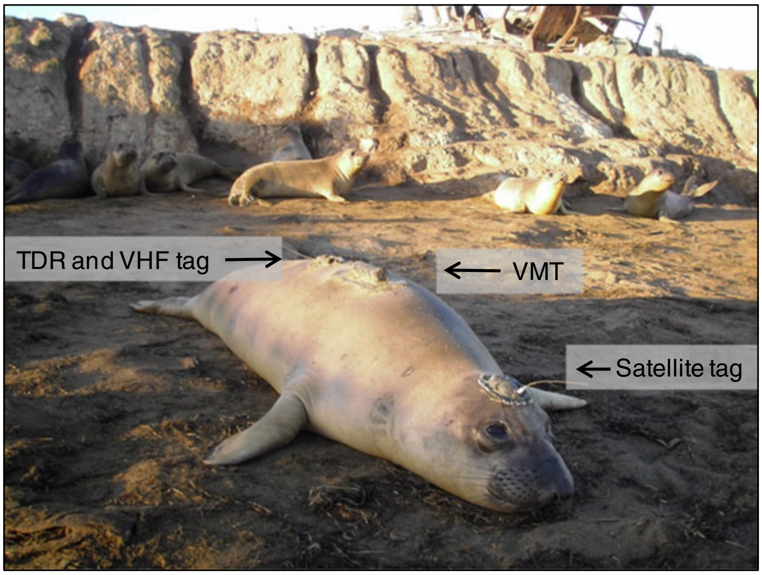

Fig. 1 Juvenile elephant seal carrying satellite tracking tag, VMT, TDR and VHF radio tags

at sea, and both seals dove to approximately 500 m depth during their return trip. An unexpected result was that the second seal swam within detection range of two acoustically tagged great white sharks (*Carcharodon carcharias*) that were part of another study (Jorgensen et al. 2009) (Fig. 2, Table 1).

Tagged adult seals departed the beach at Año Nuevo and migrated into the Northeast Pacific at four different times of year depending on sex of the animal (Table 1, Fig. 3.) Instruments were recovered from 16 of the females and 8 males (Table 1). Acoustic tag detections by VMT tags recovered from elephant seals were limited in number, but from an impressive diversity of species. In central California, two additional great white sharks were detected and a single salmon shark (*Lamna ditropis*) was detected by two different seals 6 months apart. Several other fish species were also detected. One juvenile Chinook salmon (*Oncorhynchus tshawytscha*) was detected by an adult female elephant seal on 30 April 2010 as she was transiting back across the central California continental shelf roughly 31 km offshore of the mouth of the Sacramento River at the Golden Gate Bridge (Fig. 2). The fish had been released into the Sacramento River near the city of Sacramento by the Army Corps of Engineers on 5 February 2010, transited downriver and was detected by an acoustic receiver passing the Golden Gate Bridge on 17 February 2010. An adult steelhead (*Oncorhynchus mykiss*) was also detected in Central California by a female elephant seal during her return migration on 13 May 2011. The fish had been tagged and released from Coleman National Fish Hatchery on the upper Sacramento River in March 2011. Finally, in April 2010, a VMT carried by an adult male elephant seal at the furthest extent of its migration (roughly 2,800 km from Año Nuevo), detected an acoustically tagged lingcod (*Ophiodon elongates*) in the Gulf of Alaska.

In addition, one of the seals detected another VMT-tagged seal during its return migration, approximately 3.25° (275 km) offshore, off the continental shelf just south of the Mendocino Ridge. This is one of the farthest-offshore acoustic detections ever recorded (Fig. 4). While only a single detection, it provides a tantalizing insight into the foraging behavior of elephant seals. Elephant seal satellite tracks are often seen ‘crossing’ each other, but typically the seals are not in the same region at the same point in time, and the resolution of the satellite geopositioning does not provide sufficient precision to establish proximity in these rare events (but is very effective at establishing the lack of it in most cases). Given the vast spatial scale, the limited number of seals tagged, and the lack of any patterns suggesting social interactions between seals at sea, this observation suggests that both seals were simultaneously attracted to a habitat feature, perhaps a prey patch associated with an upwelling front forming over the ridge. There was a second detection of one satellite tagged male by another male, however it could not be confirmed as there was only a single

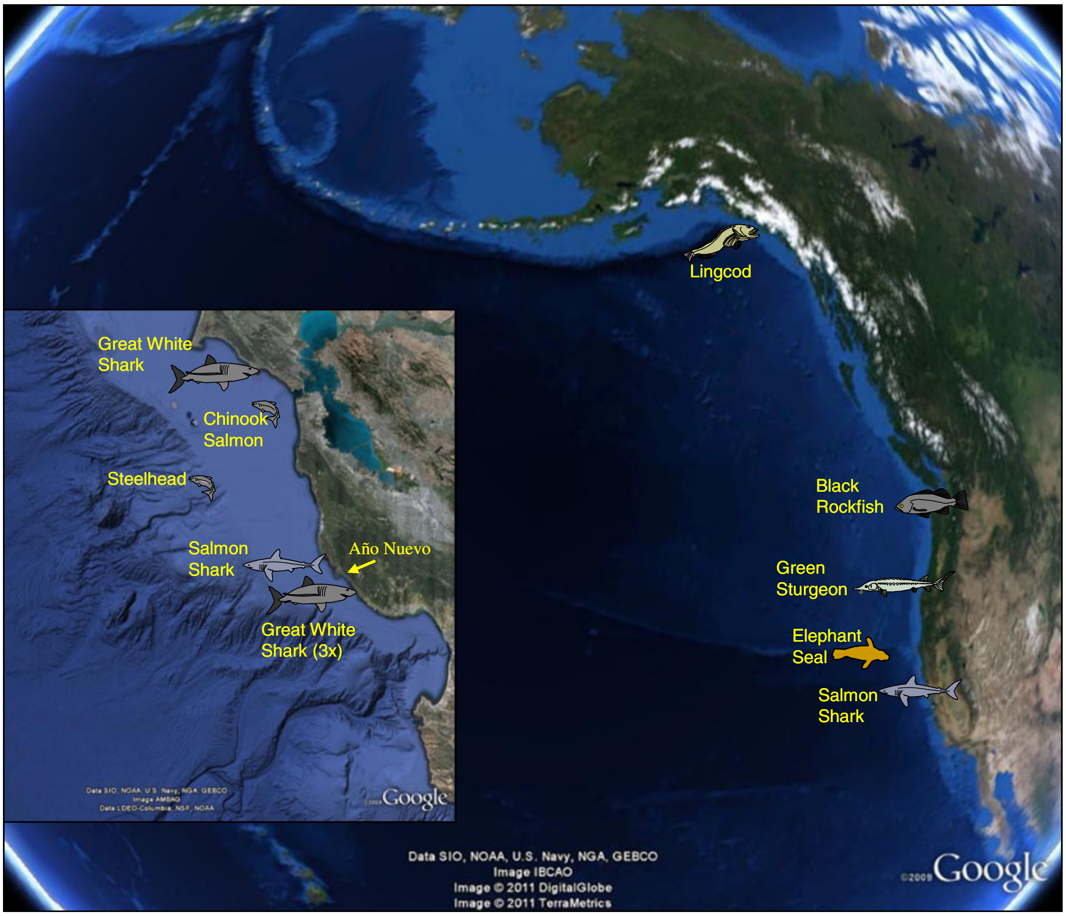

Fig. 2 Maps showing spatial distributions of species detected by roving acoustic receiver technology. Inset shows blow-up of Central California region where most detections occurred

Table 1 Summary data of VMT deployment effort and detections

Deployment time	Platform	Seal age class	Sex	# tags deployed	# tags recovered	Mean duration (days	Acoustic tag detections	Species detected
Nov-09	seal	juvenile	male	2	2	6	2	Great white shark (GWS)
Feb-10	seal	adult	female	9	8	81	3	GWS, elephant seal, Chinook salmon
Mar-10	seal	adult	male	4	2	~136	2	Lingcod, elephant seal*
Jun-10	seal	adult	female	5	3	238	0	
Aug-10	seal	adult	male	3	2	150	0	
Feb-11	seal	adult	female	5	5	85	2	GWS, steelhead, salmon shark
Mar-11	seal	adult	male	5	2	133	0	salmon shark
Jun-10	ship			1			1	black rockfish[a]
Jul-10	ship			2			1	GWS
Jul-11	ship			2			1	green sturgeon

[a] single detection only

Fig. 3 Satellite tracks of northern elephant seals migration paths (originating at Año Nuevo) for seals from which VMTs were successfully recovered during study. Males (n=8) in green, females (n=16) in white

detection, the satellite tags of both males had stopped transmitting at that point, so proximity could not be confirmed and the tags were not recovered from the second male to compare reciprocal detections.

Future directions of biological receivers

This pilot effort shows the potential for this combination of technologies. A total of seven confirmed species were detected. Due to the methodological focus of this paper, interpreting the biological significance for each species detected was avoided, with the data instead being provided to the team which tagged each organism. One significance of the data collected was that three of the species detected had 'gone off-line' and not been detected by the tagging team for some time, resulting in new insights on both movement range, and an update to the team that their animal's tag was still transmitting.

Despite the variety of species detected, the low rate of detections underscores how vast the oceans are and the probability of detections between tagged predators and prey is overall quite low. A variety of steps can be taken to increase the range and rate of tag detection in the open ocean for future efforts. The first is to increase the number of tags deployed both on seals and on fish. However, new results indicate that mortality of juvenile salmon during their downstream migration can be higher than thought (Muir et al. 2001; Welch et al. 2008; Rechisky et al. 2009; Michel 2010), suggesting fewer tags are surviving to reach the marine environment than previously expected. To compensate for this mortality, some researchers are beginning to tag and release fish in the lower river estuaries to increase the fraction of tagged fish that reach the marine environment (Michel Rub, Laurie Weitkamp Northwest Fisheries Science Center, Astoria Oregon, pers. comm.). A second solution

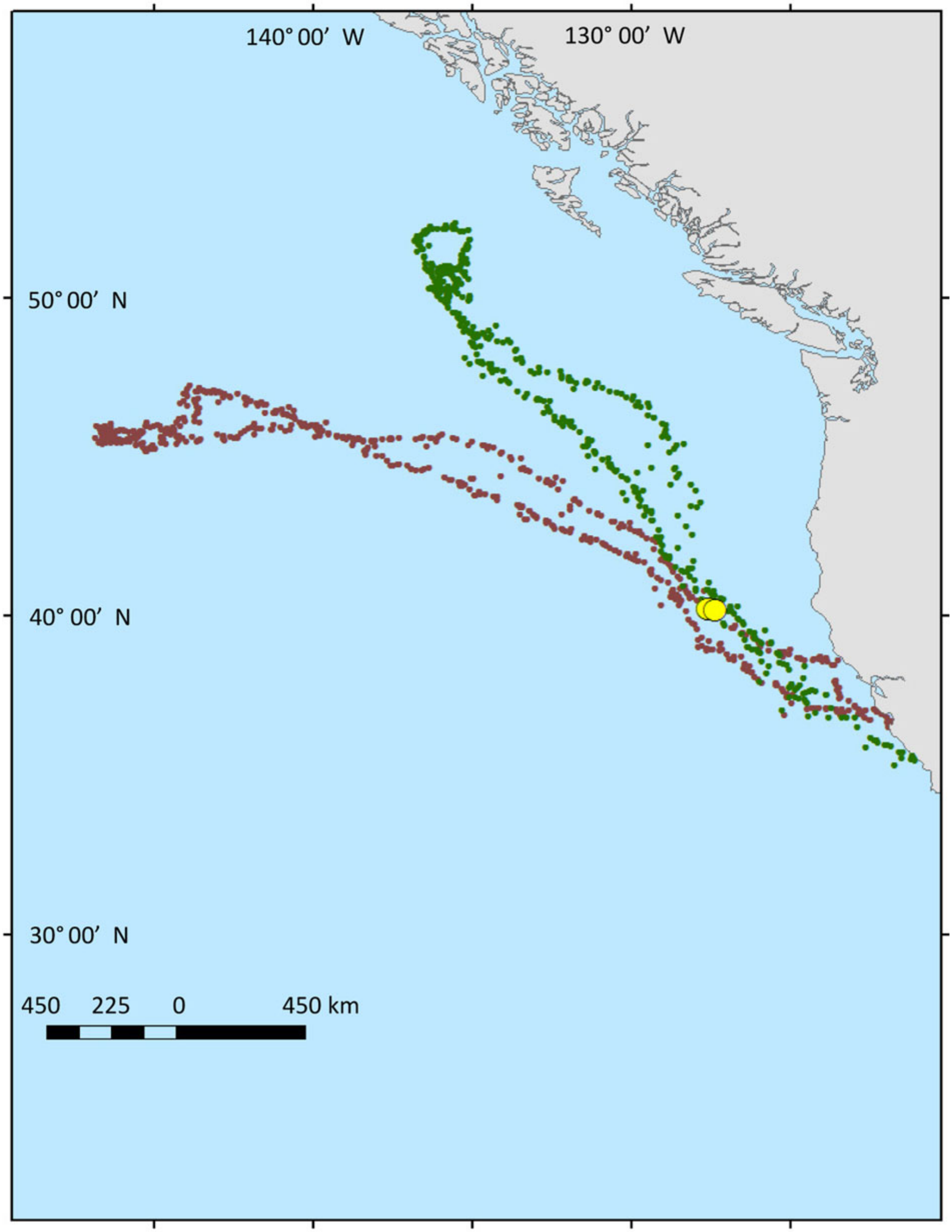

Fig. 4 Satellite tracks of two female northern elephant seals whose paths crossed. The VMT tag of one seal detected the other in close proximity, noted by yellow dots on the map

would be to increase detection ranges through a combination of increased power in fish tags and increased noise filtering on the VMT. Exact ranges were not determined for this study and are expected to be quite variable (roughly 100–1,000+ m) due to varying tag transmission volumes, flow noise over the transducer during seal swimming, and seal depth relative to the thermocline.

An additional problem comes from the risk of not recovering the archival data from the VMT due to any number of reasons including tag failure, animals not returning to the tagging location, or tag loss. This could be overcome with satellite-linked data uploads. Many sensor technologies have been incorporated into satellite tags, and the acoustic data are ideally suited for satellite transmission because the required data stream is quite small. In the case of our VMT pilot study, the elephant seal was chosen as the prototype testing species due to the high tag recovery rates associated with this species, even though they might not have the highest encounter rates with acoustically tagged species. If acoustic receiver technology were merged with satellite transmission technology, it would open a new suite of species with potentially greater encounter rates that could be tagged but were avoided for this pilot study because there was little hope of archival tag recovery [e.g. California sea lions (*Zalophus californianus*), harbor seals (*Phoca vitulina*), sub-adult male elephant seals, white sharks and salmon sharks (*Lamna ditropis*)].

The results of the project should not be evaluated by the full research costs of just the VMT work, as animals were being tagged for multiple projects that were all ‘piggy backed’ on each other for cost-sharing, and the animals carried many different instruments. While those study results are not yet available, past efforts have provided concurrent data sets on oceanography, animal behavior and physiology (Charrassin et al. 2008; Nicholls et al. 2008; Kuhn et al. 2009; Villegas-Amtmann and Costa 2010). In the future, additional sensors such as for conductivity and light (adjusted for measures of primary productivity) could be added in deployments (Simmons et al. 2007).

Ultrasonic data sets

There are a growing number of passive acoustic recording stations and mobile platforms in the marine environment, often deployed for the purposes of detecting marine mammal vocalizations (Mellinger et al. 2007; Rankin et al. 2008). Many of these recordings are sampled at a sufficiently high rate to detect ultrasonic pulses from acoustic tags (e.g. in the case of a 69 kHz tag, sampling rates greater than 138 kHz) It is theoretically possible to process audio recordings of tags using the tag manufacturers decoding algorithm and determine tag identification code, although one manufacturer has expressed concern that sampling rates may need to be much higher than this nyquist rate. The reasons for making these recordings range from basic to applied research to address a variety of questions, but an underlying purpose of many recordings is to determine animal presence/absence and seasonal distribution.

A feasibility test of this concept is currently underway. The NOAA Southwest Fisheries Science Center (SWFSC) conducted a marine mammal stock assessment survey of the Northern California Current in waters off California, Oregon and Washington from the coast to approximately 556 km offshore, during the second half of 2008. The survey used a 300 m hydrophone array including two hydrophone elements that were recorded continuously at a 480 kHz sampling rate. At this time, we are in the process of developing an automated detector using the software package ISHMAEL (Mellinger 2001) that will recognize 69 kHz pulses in the data, and screen the recordings for tag detections to be decoded. If successful, additional data sets can be explored for such detections. One benefit to such recordings is the underlying statistical design for data collection to assess marine mammal distributions could be applied to the distribution of acoustically tagged organisms.

Vessel receiver arrays

The use of large research ships for active tracking of acoustically tagged organisms in marine environment is too expensive due to operating costs of roughly $10–25 000 per day, far outweighing the cost of receiver technology. However, estimates of the number of vessels already at sea range from at least 40 000 (USCG 2010) to upwards of 70,000 vessels (Lloyd’s List Intelligence) providing near universal coverage between the Arctic and Antarctic Circles (Fig. 5a) at any given moment. Due to new technology and legislation, many of these vessels are tracked by combinations of VHF and satellite networks,

Fig. 5 **a** Example of worldwide ship distribution based on AIS data sources at 1,130 h December 21st, 2010. **b** Example of water temperature data provided by vessels in the AIS network. Images used by permission, copyright www.sailwx.info

generally referred to as Automatic Identification Systems (AIS). For a theoretical cost of less than one day's charter fee, a vessel could be instrumented with a hull-mounted receiver that would listen continuously (Klimley et al. 1998). As most ships are already transmitting position information on a regular basis, and many include environmental data (Fig. 5b), the equipment and logistics required for data upload to a centralized database are already in place. Such a network would obviously start small, primarily with research vessels, and likely expand to fishing fleets, then ultimately to other platforms of opportunity, as agreements are negotiated.

The primary challenges to using this technology would include low frequency noise sources from ship engines and flow noise on the hull and ultrasonic echosounders, necessitating significant noise filtering solutions. There are dual incentives for the tagging industry to work towards this goal. Aside from having a new technology to market, any noise-filtering solutions will likely be applicable to bottom-mounted receivers that are deployed in noisy aquatic environments where such noise sources as ship traffic, river flow and tidal surge all limit detection ranges of acoustic tags.

In the short term, until noise-reduction solutions can be addressed, there is a ship-based opportunity to collect additional acoustic tag data. Many oceanographic research institutions conduct surveys with regularly spaced stations where the ship stops (thereby reducing flow and engine noise) and deploys instrumentation on a cable to some depth in the water column, or alternatively tows equipment (i.e. nets) some distance behind the ship, providing additional listening opportunities if a low-cost receiver were simply attached to the instrument carousel. A pilot effort of this was conducted on the joint juvenile salmon ocean survey conducted by NOAA's Northwest and Southwest Fisheries Science Centers (NWFSC, SWFSC) in the Northern California Current between the northern Washington border and Pillar Point, California in 2010 and 2011, where VMT receivers were attached to the ships instrument cable for all vertical CTD and plankton net deployments, and a second VMT placed in a surface trawl net deployed 200 m behind the ship. Despite the limited deployment times of receivers (~7 h/day), there were several potential detections of fish during this effort, including a black rockfish (*Sebastes melanops*) originally tagged off Carmel California, and detected off northern Washington, a green sturgeon *(Acipenser medirostris)* detected off southern Oregon, and another great white shark detected inshore of the Farallon Islands, California (Fig. 2). The shark and rockfish detections were unconfirmed due to only a single detection on the receiver. Because of the potential for false positives in acoustic tracking, usually at least two detections are required for confirmation. This is a challenge with ship-based tracking, due to the transitory nature of vessels, potentially moving the receiver out of tag detection range after only on detection. In the case of the great white shark, the animal was confirmed to be in the vicinity by detections on ocean receivers operated by the SWFSC. The vertical deployments of VMTs below the ship were confounded by noise from scientific echo sounders attached to the ship's hull, creating many false-positive detections that were excluded based on further analysis of the data by the manufacturer.

Buoy receiver arrays

A large and growing number of oceanographic sampling buoys are deployed in the marine environment. Similar

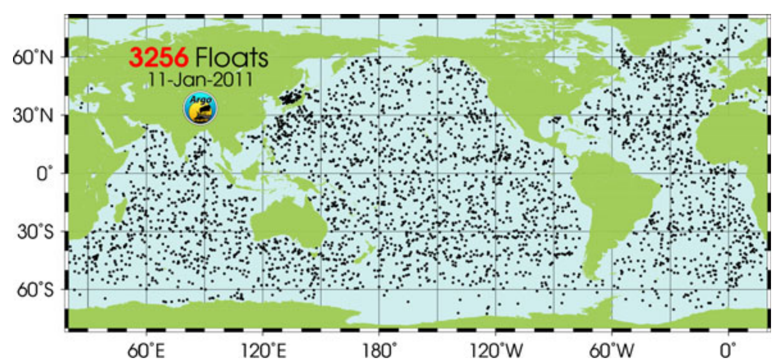

Fig. 6 The global distribution of Argo floats on 11 January 2011. Used with permission by the International Argo Project (www.argo.net) and the Argo Information Centre (http://argo.jcommops.org/)

to ships with AIS systems, these buoys typically have onboard VHF- or satellite-based transmitters to send data to a centralized database. Much of the engineering, maintenance and deployments costs for these systems are already financed. As many are designed for adding future instrumentation, the primary costs would be incorporating the acoustic receiver hardware and software. The tradeoff to consider when attaching acoustic monitors to ships versus buoys is noise versus power. Whereas ships typically have unlimited power, buoys, both moored and drifting; may be power-limited. In contrast, whereas hull-mounted receivers on ships still require engineering solutions to compensate for noise, buoys typically produce very little low-frequency noise and may only have sampling conflicts with onboard echo sounder technologies. In many coastal and offshore waters, NOAA and international collaborators have a growing network of moored weather and oceanographic buoys that could serve as platforms for acoustic receivers (1061 buoys- http://www.ndbc.noaa.gov) .

In the offshore environment, a currently untapped resource is the ARGO float network (http://www.argo.net/) with roughly 3,000 buoys drifting across the world's deep oceans (Fig. 6), maintained through international collaborations (Argo Project Office 2006). These buoys' primary sensors are designed to track global temperature, salinity and current patterns and spending 90% of its 8- to 10-day cycle at 1,000 m depth, and remaining time moving to and from the surface to conduct a water column profile and transfer data. The lack of time spent in the surface layer does decrease its value for detecting surface oriented organisms, however the array does still spend 5% of its time in the surface layer, and like the example above where VMTs are deployed on deep diving organisms, the ARGO buoys provide a unique opportunity to track organisms deep in the water column throughout the world's oceans, an almost uncharted research territory.

Conclusions

The coming decades will see rapid change in the way biological data are gathered in the open ocean. While much of this change will be due to technological innovation, a primary barrier to progress today is cost. By using creative solutions to take advantage of existing infrastructure, it may be possible to increase our distribution of acoustic receiver technology at a greater spatial scale with limited increases in both financial and carbon resources requirements.

Another challenge area that has seen rapid improvement in recent years but still has much room for potential growth is the spirit of collaboration between researchers. There is the need for centralized database infrastructure to hold the metadata for all the tagging efforts in an ocean basin to prevent the release of duplicated acoustic tag codes within a study area. Further collaboration will be required among the biological research community, oceanographic research community, and the public and private shipping industries to negotiate receiver installations and data transfer agreements. And while the cost savings associated with exploiting existing infrastructure are great, future projects will not be inexpensive, necessitating cost sharing among foundations, universities and governments.

While initial costs will be born by research projects associated with taxa that bear higher profiles because of charisma or commercial stock value, expanding infrastructure will enable the study of more obscure yet ecologically important species. The successful integration of archival and acoustic tracking methods to track marine organisms from primary consumers to climax predators will bridge trophic levels, allowing for increased understanding of our marine ecosystem. Given rapidly changing ocean conditions, the need for information on the responses of marine organisms is great. This can be met in part by implementation of an expanding array of mobile telemetry technologies.

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