GPS/TDR Satellite Tracking of Sperm Whales with 3-axis Accelerometers

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LONG-TERM GOALS

Create a satellite-monitored radio tag improving upon the recoverable GPS/TDR tag will include 3-axis accelerometer to better document the detailed dive behaviors and foraging ecology of large whales over scales of weeks to months for critically evaluating future noise response experiments. In the long-range planning process, the tag will hopefully also carry an acoustic recording device to measure signal strength at the animal and evaluate cumulative exposure issues.

We have made excellent progress this year in using JIP funds for analyses of the data acquired from tag deployments on sperm whales during 2011. We are also exploring options to fund the acoustic dosimeter sensor.

OBJECTIVES

The GPS/TDR tag (initially funded by JIP, MMS, and ONR) will be further developed to provide an accurate depiction of underwater dive behavior to especially examine sperm whale foraging behavior. Parts of the data will be sent as Argos messages summarizing selected aspects of whale behavior so future experiments can be monitored directly and more detailed data will be downloaded from recovered tags to evaluate complex foraging behaviors. The addition of an acoustic dosimeter remains an un-funded, but long-term goal that would help interpret TDR/3-D whale responses during future controlled-exposure experiments (CEE) or behavioral response (BRS) studies.

APPROACH

During this FY-11 and FY-12, Wildlife Computers fitted 3-axis accelerometers to replacement GPS/TDR tags (from a JIP/ONR-funded 2008 field effort), which were applied to 11 Gulf of Mexico sperm whales.

WORK COMPLETED

Review: Wildlife Computers incorporated a 3-axis accelerometer into the GPS/TDR tag (also known as PATF or Mk-10 tag). We began developing this tag in 2007 with deployments on sperm whales in the Gulf of California, when the corrodible wire holding the tag to the attachment sheath sheared causing a premature release of the tag. In 2008, WC modified the design to a heavier wire and OSU provided three large studs in the attachment sheath that penetrated into three voids in the tag float to prevent the tag from rotating and shearing the wire. However, in 2008 the manufacturer did not draw a vacuum on the casting matrix and small bubbles in the casting collapsed under the pressure of sperm whale dives, thus shorting out the electronics. Eleven tags were deployed in FY12 on sperm whales in the GoM (with ship logistics paid by the NRDA follow-up studies to the Deepwater Horizon/BP oil spill). This research was conducted in the same area as the Sperm Whale Seismic Study (SWSS) in the upper Gulf of Mexico (Jochens *et al*., 2008), which resulted in understanding the genetic relationships and movements of satellite-tagged sperm whales (Ortega *et al*., 2011) and where surveys by NOAA estimated the population of many cetacean species (Mullin and Fulling, 2004). Some results from the 2011 tags have already been reported to JIP focusing on the comparison of Argos and GPS locations, as well as the behavioral summaries sent as Argos messages. Further analysis of these data regarding home range and core area assessments have come a long way since early tagging efforts (Mate *et al*., 1997) and have been undertaken in a recent Natural Resource Damage Assessment report (Mate *et al*., 2012) using techniques developed by Bailey *et al*. (2010), Manly *et al*. (2002), and McDonald *et al*. (2006) to incorporate the use of environmental variables. The results of JIP-funded analyses conducted this year on the GPS/TDR tags focus on the 3-axis (3-D) accelerometer data that follow below.

RESULTS

Eleven GPS/TDR tags equipped with 3-axis accelerometers (Figure 1) were deployed on sperm whales during July 2011 (Table 1). These tags lasted an average of 26.1 days, during which they traveled a total distance of at least 14,846 km (Figure 2). A software error by the manufacturer failed to release the tags at their pre-programmed release times by only applying current to the corrodible attachment wire for a limited number of hours instead of letting it run until the mission was completed. As a result 10 of the 11 tags came off of the whales still in their attachment sleeves and sank to the sea floor where they will remain because of the intact wires. One tag stayed on a whale for 50 days, beyond the 42-day release date, when the wire-burn was initiated. After it came off, it drifted for 9 days during bad weather that prevented recovery until it was out in the central Gulf. The recovered tag provided a down-load of 3-axis data which is the basis for the new analyses reported here on lunges. These data are the first long-term record of foraging effort for any whale species in the world. It is regrettable that we did not recover all of the tags so we could address some of the social coordination issues that were the basis of our deployment strategy of tagging several whales in each foraging group.

Figure 1. Floatable and recoverable, the GPS/TDR tag fits into a stainless steel sleeve that has attachments similar to well tested location-only tags successful on sperm whales since 2001 (Mate *et al*. 2007). A small white Delrin fixture (left side-bottom of the dark gray float) is held to the tag by a wire, designed to corrode away with the application of electric current. A screw attaches the Delrin fixture (and thus the tag) to the attachment sleeve.

Table 1. Argos location data for the 11 Mk-10 tags applied to Gulf of Mexico sperm whales.

ptt	Tag Type	Double Tag #	Sex	Date Deployed	Most Recent	# Msgs	# Days Tx	# Locs Rec'd	# Locs Used	Dist.(km)
00833	MK-10	00845	U	20-Jul-11	15-Aug-11	825	25.3	214	109	1,486
00838	MK-10		F	17-Jul-11	7-Aug-11	449	20.5	173	83	1,089
00840	MK-10	05826	F	10-Jul-11	23-Jul-11	110	12.8	68	37	520
04173	MK-10	00823	F	17-Jul-11	5-Sep-11	1762	49.6	708	175	2,728
04177	MK-10	00832	U	11-Jul-11	15-Aug-11	788	34.8	285	142	1,220
05640	MK-10		U	11-Jul-11	29-Jul-11	260	17.9	123	56	623
05644	MK-10	05910	F	23-Jul-11	22-Aug-11	995	29.9	269	114	1,679
05654	MK-10		F	17-Jul-11	21-Aug-11	1027	34.2	253	107	1,894
05685	MK-10	05921	F	20-Jul-11	18-Aug-11	804	28.4	227	110	1,700
05701	MK-10	05655	F	23-Jul-11	17-Aug-11	800	24.4	219	94	1,343
05838	MK-10	05803	F	23-Jul-11	2-Aug-11	491	9.6	109	58	564
				MK-10	Subtotal	8,311	26.1	2,648	1,085	14,846

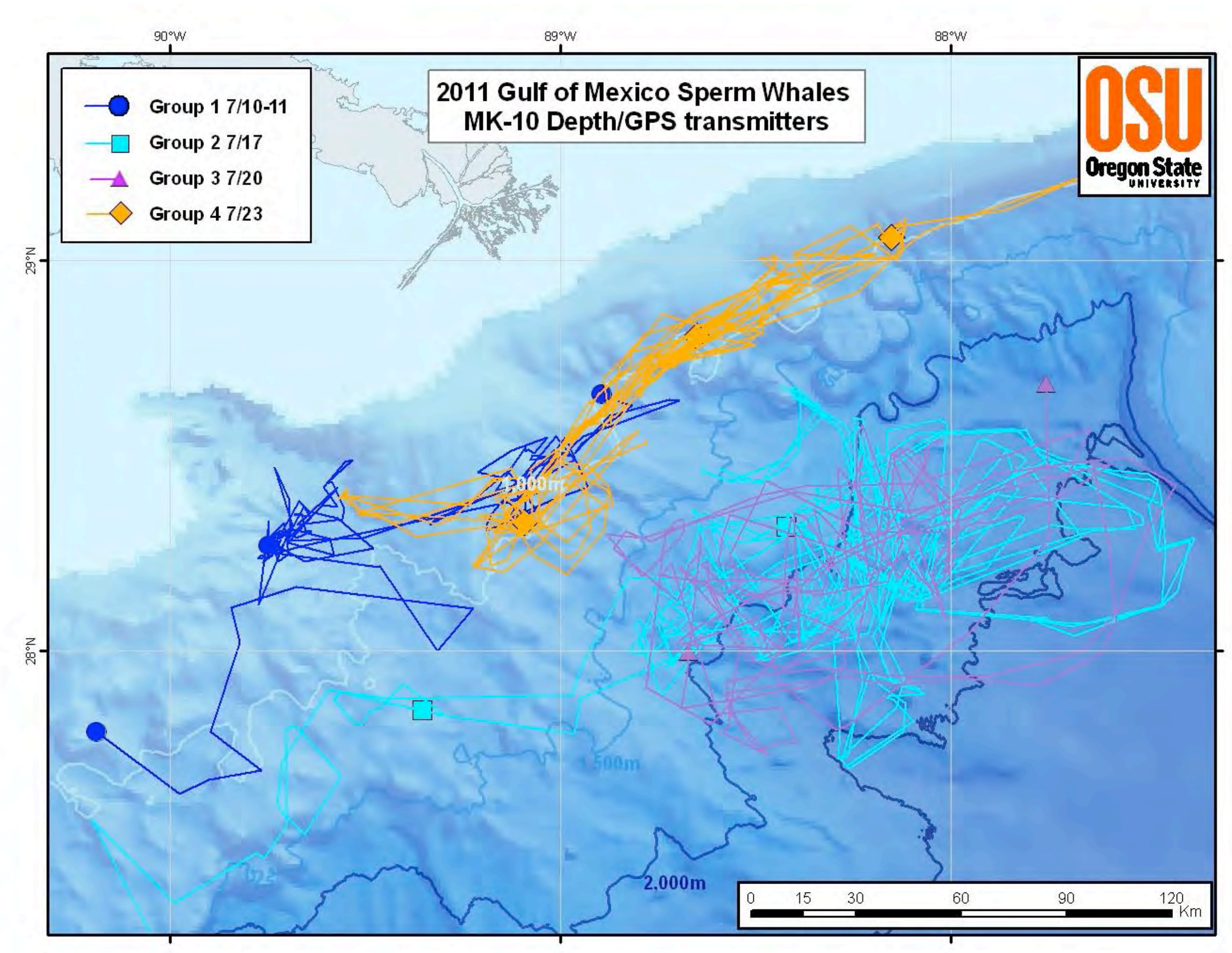

Figure 2. The tracks of 11 WC Mk-10 PATF (GPS/TDR) Argos tags with 3-axis accelerometers applied to sperm whales in the Gulf of Mexico in August 2011.

Summaries of dives and 1.5 to 5 GPS-quality locations/day were received from all MK-10 tags via Argos. MK-10 behavior messages received through Argos summarized 74% of all dives by reporting the dive duration, maximum dive depth, shape of dive, and subsequent surface duration of dives > 10 min duration and > 10 m depth. Histograms summarizing time spent in various depth ranges, maximum dive depths and dive durations were also received via Argos and included data from ~ 60% of the tag durations (previously reported to JIP).

Despite the failure of the release software, one MK-10 tag was recovered and contained a continuous 42 day record of: 1) 1 s temporal resolution depth data, which recorded 744 dives > 350 m depth, 2) a 1 s resolution 3-axis accelerometer data record from which body orientation of the whale could be derived, and 3) 855 GPS-quality locations. Median dive duration was 40.6 minutes and the average depth of the bottom phase of dives was 588 m.

Rate of change in body orientation was calculated and used to identify instances of high rates of change (acceleration), which were assumed to be foraging attempts. Our high pitch and roll criteria for a “lunge” event agreed well with the lunge events accompanying “creaks” recorded by shorter-term D-tags applied to sperm whales in the same region (Miller *et al*., 2004). A median of 14 lunge events occurred during dives >10 min and > 350 m deep. Lunges occurred almost exclusively during the bottom phase of dives (not descents or ascents, Figure 3 and 4) and occurred most frequently between 12:00 – 24:00 CST (local time). It is not presently possible to determine which lunges are successful in acquiring prey.

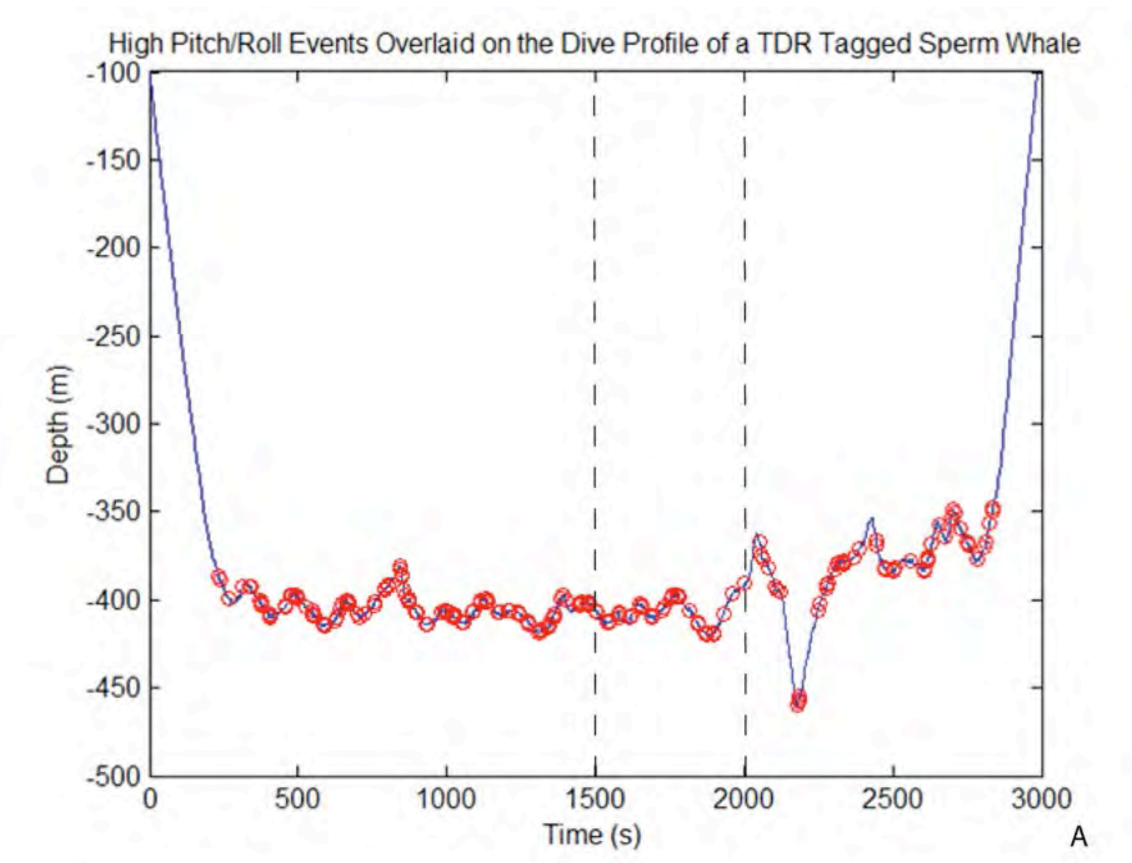

Figure 3. The occurrence of lunge events (red circles) during the course of a typical 50-minute sperm whale dive are limited to the bottom phase of the dive.

The number of lunge events per dive dramatically increased during the last 2.5 weeks of the data record, but was still highly variable, suggesting the whale encountered an area of higher average prey density (Figure 5).

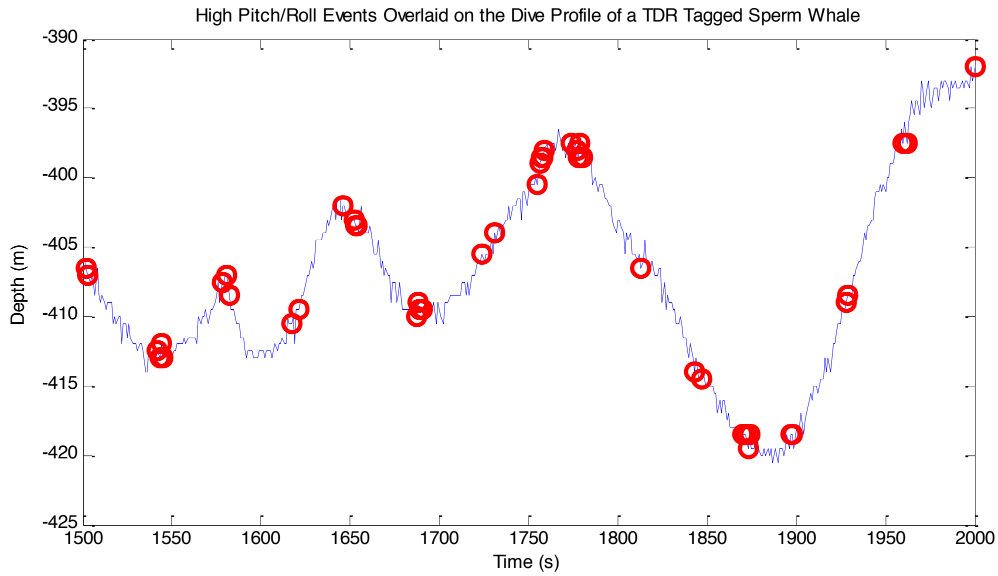

Figure 4. A dive profile for a Mk-10 (satellite GPS/TDR) tagged sperm whale in the Gulf of Mexico, showing a higher resolution plot of a part of the dive in Figure 3 (x-axis scale corresponds to between the dotted lines of Figure 3). The blue line is the recorded depth of the whale at 1-second intervals accurate to 2 m showing quite a bit of detail. Red circles are lunge events calculated from the 3-axis accelerometer data being simultaneously recorded.

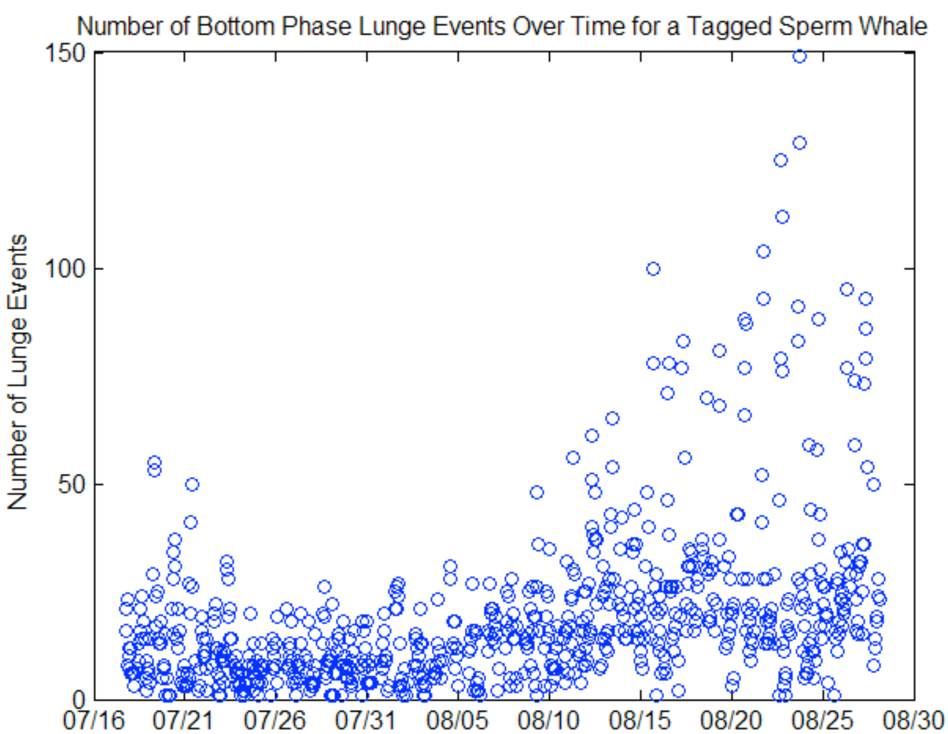

Figure 5. The number of lunge events per dive over the 42-day track.

During the 42-day dive record lunge events occurred at various depths (Figure 6), suggesting that the depth of squid concentrations is different depending upon the place, time and perhaps species of squids encountered. Although there are many species of squids known to this region, there is no accurate information about which species are preferred by sperm whales. EK-60 back-scatter data were recorded during the 2011 deployments of tags and are currently under analysis for the NRDA tagging study. In an ideal experimental protocol, such data would be collected in the immediate proximity of GPS/TDR-tagged whales to better evaluate the back-scatter characteristics of sperm whale regional prey species (squids).

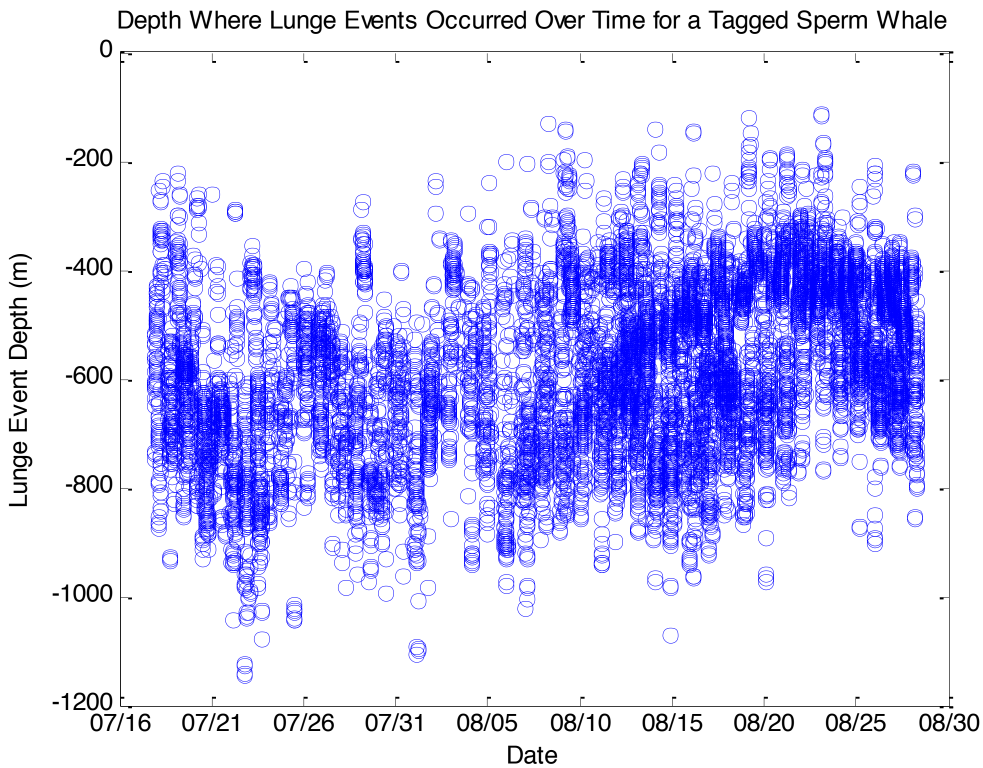

Figure 6. Plot of the depth where each lunge event occurred over 42 days.

Dives with many lunge events (likely high prey density) were close to other dives in the same region where fewer lunge events occurred, despite similar dive depths and durations (Figures 7 - 8). Highly variable lunge rates and travel distances (between or during dives) are evident in sequential dives, despite dives being of similar duration and depth. These data suggest very patchy prey distribution is the main reason sperm whales travel over such large areas (Figure 9). The spatial variability in lunge events across the whale's track suggests that sperm whale prey have a very patchy distribution. On a dedicated future cruise with GPS/TDR tags, EK-60 echo-sounder data co-located with dive behavior from the MK-10 tags could provide important information on prey detection, foraging, and thus habitat selection.

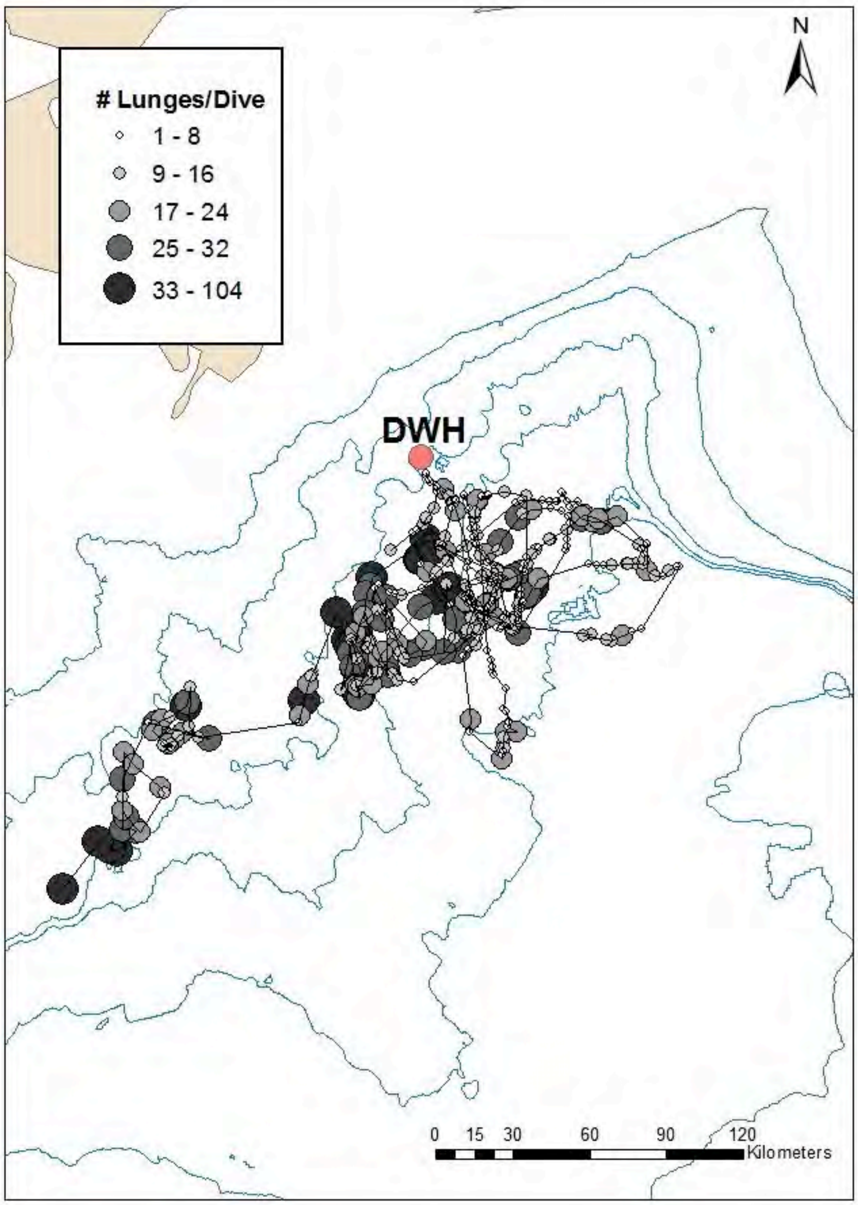

Figure 7. A map of GPS locations recorded by a satellite-monitored GPS/TDR tag attached to a sperm whale for 42 days during 2, 728 km of travel in the Gulf of Mexico. The size and shading of the circles relates to the number of lunge events that occurred during the bottom phase of each dive > 350 m at that position. Darker colors and larger circles equate to more lunge events/dive.

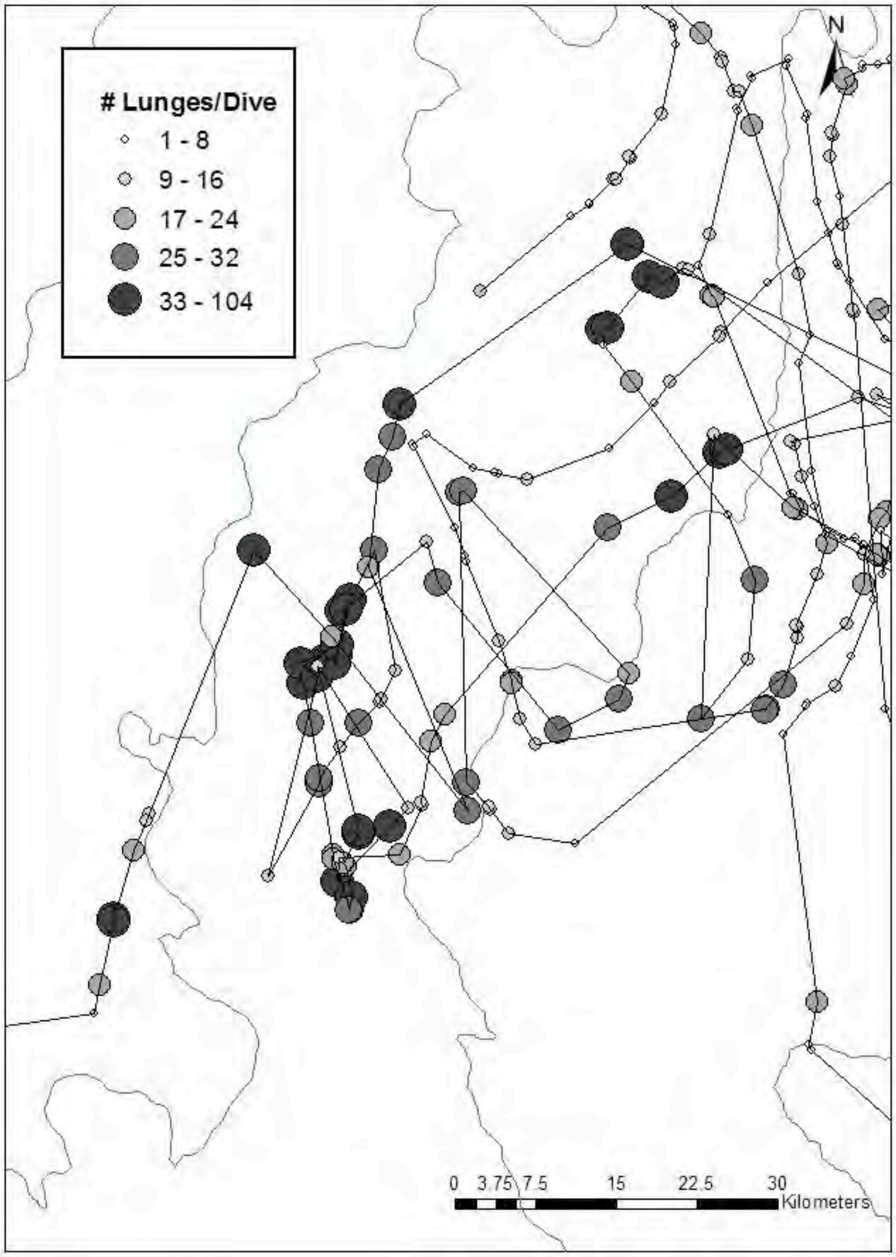

Figure 8. The number of lunges/dive (lunge rate) is shown for a GPS/TDR-tagged sperm whale during a portion of its 42-day track in the Gulf of Mexico. This image is not the full track (see Figure 7), but demonstrates in smaller scale the chronological and spatial variability of lunge rates. Trace along any line to see a sequence of how the whale changes location and how variable its lunge effort is from one location to the next.

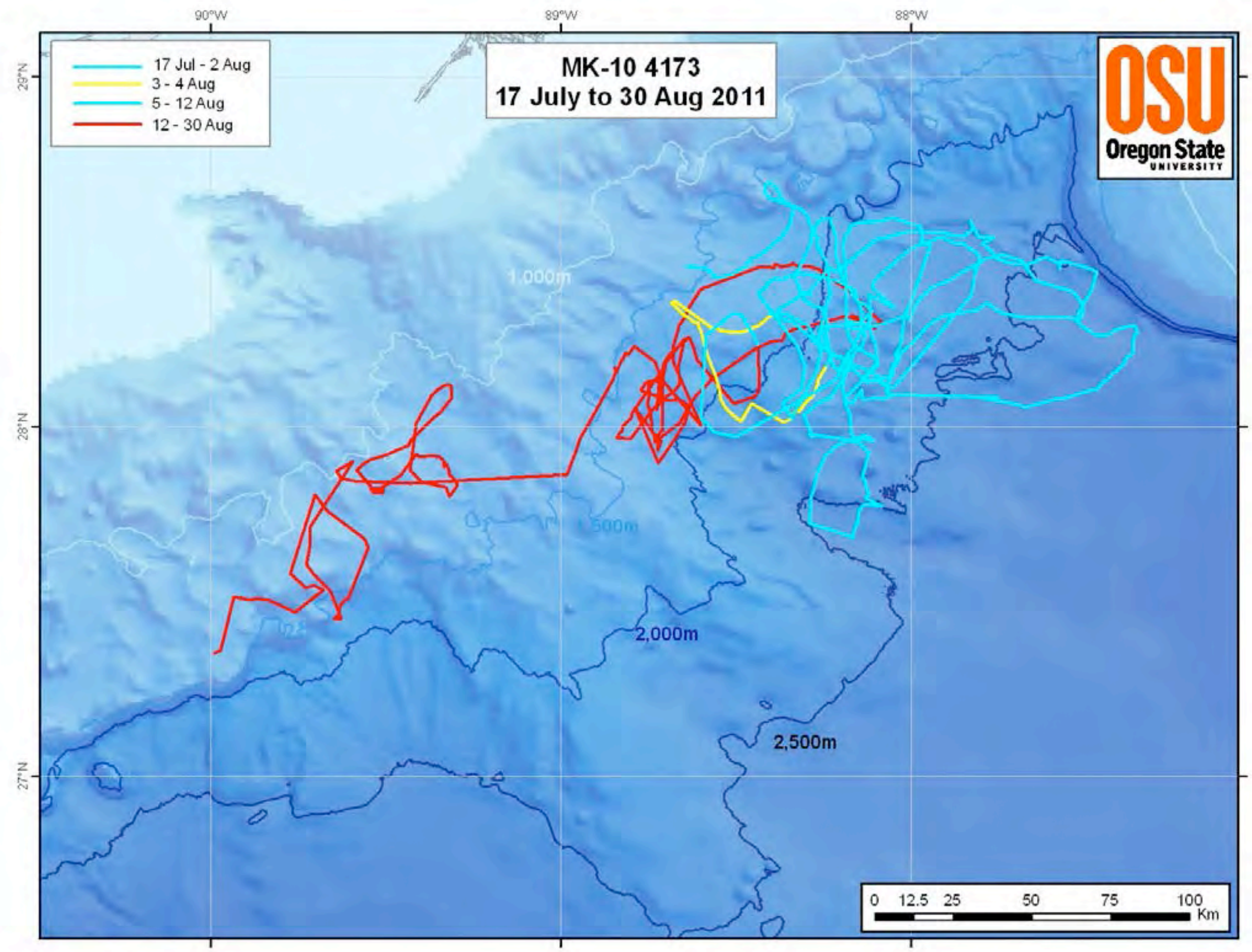

Figure 9. A color-coded track of MK-10 tagged sperm whale 4173 highlights 2 days when median bottom phase dive duration was short (yellow) and the last 2.5 weeks of the track when the lunge events per dive were higher on average (red).

This unprecedented record is an example of how this technology will enormously change our understanding of underwater behavior and especially foraging effort. In the past, it has been extremely difficult to study these topics for large whales because they cannot be captured for instrumentation or tag recovery like smaller species (birds, fish, and pinnipeds). This new technology allows scientists to visualize underwater behavior over longer periods than ever before.

IMPACT/APPLICATIONS

The GPS/TDR tags produced high quality, detailed data on sperm whale diving behavior that were accurately summarized and transmitted as Argos messages. The level of detail recorded and ability to transmit summary information makes this technology ideal for conducting behavioral response studies for sperm whales (or controlled exposure experiments) and would likely be adaptable to other large whales, including baleen whales that lunge (but not those that cruise with their mouths constantly agape). With the development of a simultaneous acoustic monitoring to measure exposures to noise (seismic or sonar) this tag will be a powerful tool to test whales for reactions, possible habituation, and subsequent recovery from disturbances. The long-lasting attachments of GPS/TDR tags and their ability to report values via satellite during such experiments makes them ideally suited to developing both good baseline control values and repeated exposures to better document thresholds, responses, and recovery patterns.

TRANSITIONS

Despite release problems, this proof-of-concept demonstration for GPS/TDR tags to monitor foraging effort of sperm whales was impressive and will result in a high-profile publication. We are continuing to work with WC to evolve the tag further, which will include the incorporation of Fastloc-3 technology (a 90% savings in energy consumption over the original Fastloc GPS version) and magnetometers to provide accurate compass bearings so a depiction of the whales' underwater movements can be obtained. The addition of magnetometers is important, so that "maps" of individual whales foraging underwater (termed "worms") can be accurately be depicted to determine where whales are navigating during their dives (between surfacings). The worms can then be co-registered (merged) in 3-D space and time to evaluate social foraging strategies, such as the "foraging volume" if sperm whales are coordinating their foraging efforts on a bait ball of squid. This anaylsis would be useful to better understand how possible impacts to individuals may in fact impact a larger group and also how groups may adapt their foraging strategies to accommodate disturbances (such as changing the group's direction). There should be great interest in a new tool like this that can provide better understanding regarding the impacts of sound sources (sonar, seismic, ship noise, explosions, etc.). The prototype tags will be available for our testing in the late winter, so evaluations can be fed back into production units by the 2013 summer field season. We do not as yet have a source of funding for the next application, but hope that the Gulf of Mexico may develop into an appropriate possibility as a part of perhaps longer-term montoring efforts.

In conjunction with the Mk-10 tag, we anticipate the develop of an acoustic dosimeter, although we have not yet found a funding source. This sensor would be extremely useful in conjunction with the underwater behavioral (dive) data to determine what levels of sounds may affect "normal" behavior and how much ambient noise whales encounter during their "normal" movements around active oil and gas development areas and near shipping routes.

Besides the oil & gas industries, there will likely be other industries and agencies interested in developing this type of information (BOEM, shipping interests, and NOAA).

RELATED PROJECTS, WORK PLAN and FUTURE PROPOSED PROJECTS

I would be interested in JIP (or individual member's) projects for field applications of this technology anywhere in the world. If other funding sources do not materialize, I will approach BP and the NRDA trustees to use the next-generation Mk-10 tags in 2013 to continue studies of sperm whales in the GoM. That data will allow the calculation of the area-volume worked by a group of socially affiliated whales. This will also allow us to evaluate how consistent the roles are in groups of foraging sperm whales, the way humpbacks seem to have regular roles during coordinated bubble-net feeding, to answer the question of whether all members of the group share equally in the foraging process and have the same relative response to variable prey densities (proportional increases or decreases in their foraging lunge rates as they move through regions with patchy prey density).

Under ONR funding, we will be laboratory testing the new 3-axis magnetometer sensors, Fastloc-3 GPS receiver system, and modifications to the tag release process in late winter. These changes will allow accurate portrayal of underwater tracks/activities, add capabilities with the existing power supply (or increase tag life) and reduce the chances of tag release failures. We are working this design to make tags re-usable three times, some of which may be for testing purposes, before they would go back to WC for manufacturer's refurbishment. The resulting 3-axis accelerometer and magnetometer data will help determine how sperm whales coordinate their foraging movements and allow us to animate their underwater tracks. For the magnetometer data to provide useful information, tags need to be solidly attached to the whale. Tethered approaches do not work due to resultant ambiguities in tag orientation.

We would like to carry through on ideas from the Houston JIP meeting to develop an acoustic dosimeter. We have the conceptual design in place. The steps would be: 1) a proof-of-concept demonstration that we can mask flow noise by placing the hydrophone-sensor in the implanted portion of the tag attachment mechanism (done by implanting it in a dead beach-cast animal towed behind a boat); 2) sufficient miniaturization of a stand-alone recorder to fit inside the attachment sleeve (this will be tethered to the GPS/TDR tag so it can be brought to the surface by the GPS/TDR tag) without risking complications to the existing tag (by physical integration, merging power supplies or shared micro-processor functions); and 3) software development to merge acoustic files with the accelerometer- magnetometer files. We are happy to develop projects ideas with JIP or members anywhere. We used Argos tags for DWH within 28 days of first discussions, but 3-axis tags reguire more advance planning.

ACKNOWLEDGEMENTS

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