Acoustic Seagliders in PhilSea10: Preliminary results

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***Abstract*— In November 2010, four acoustic Seagliders were deployed in the Northern Philippine Sea in the vicinity of an acoustic tomography array as part of the PhilSea10 project with the goal of characterizing this oceanographically complex and highly dynamic region. The gliders were flown between the moored transceivers of the pentagonal tomography array with a radius of approximately 330 km until their recovery in April 2011. During this mission they collected oceanographic and acoustic data in the upper 1000 m of the water column. Temperature, salinity, and pressure data collected by the Seagliders provide a time-evolving characterization of the sound-speed environment in the variable upper ocean between the transceivers. The gliders were also equipped with an integrated Acoustic Recorder System (ARS). The ARS was scheduled to record transmissions from the moored acoustic tomography sources, measuring the arrival structure between the various moorings in order to near-continuously map the arrival pattern as a function of range and depth. Spectrograms show the arriving linear frequency modulated signals from the sources, as well as other ocean sounds. With travel times determined from this data, we will determine whether, given the joint nature of the combined positioning/tomography problem, it is possible to use Seagliders equipped with an acoustic receiver as mobile nodes in the tomography array, thereby enhancing the resolution of the tomography system.**

Keywords-acoustic tomography; ocean gliders; mobile receivers; acoustical oceanography

I. INTRODUCTION

In a tomography system, the number of data increases as the *product* of the number of sources and receivers. Many inexpensive and opportunistic moving receivers provide a way to significantly increase the resolution and accuracy of ocean acoustic tomography systems. This is in direct analogy with GPS tomography of the ionosphere and atmosphere, with a few dozen "source" satellites and thousands of receivers on the ground and on other satellites [1,2,3].

Many papers have been written about drifting float receivers [4,5,6], moving ship tomography [7], and integrated acoustics for ocean observatories [8]. Experiments imaging a volume have been performed: the Moving Ship Tomography experiment in 1991 (MST91, [9,10]) demonstrated a "medical" CT scan of the ocean, with instruments reasonably well navigated.

Time, positioning, and coherence are important aspects of the problem. Accurate and precise time is a sine qua non not only for tomography systems, but many acoustics systems. In this case, gliders are synchronized with GPS time when they surface. A low power temperature-compensated crystal oscillator can keep millisecond accuracy over eight-hour dive durations.

Accurate underwater positioning – with a desired precision of between 1 m and 100 m depending on the application – is the primary challenge with using floats or gliders as tomography receivers. They are often hours, days, or longer from an accurate surface GPS or bottom fix. In principle, if a moving receiver hears N sources, it can use 2 travel times to determine its position, leaving $N - 2$ travel times to provide information about the ocean. If there is independent knowledge of the receiver position, for example by using an independent navigation system, then more of the degrees of freedom in the travel time data can be used to estimate the ocean parameters rather than the navigation parameters. This method was used to analyze the MST91 data where the accuracy of the receiver position that was used in the data assimilation was about 30 m (the GPS C/A code accuracy of the time). The Seagliders obtain GPS fixes when on the surface every 4 –8 hours, ± 2 –5 m, and navigate subsurface by dead reckoning using a 3-d fluxgate attitude and heading sensor.

Developing the capability of using hydrophone-equipped mobile platforms of opportunity listening to a number of dedicated or opportunistic sources can vastly increase the amount of tomographic data available to constrain and reduce uncertainty in ocean model nowcasts and predictions. For example, at any instant of time, 6 fixed moored transceivers and 1 vertical receiving array (as in the PhilSea10 described below) give 21 paths or nominal data; adding 4 gliders as we have done gives $(6 - 2) \times 4 = 16$ additional paths/data (two path data used for navigation), nearly doubling the number of data with associated improved spatial resolution. Thus over time, the resolution can be further improved. But we know the ocean will change over this time period and thus time dependent data assimilation/modeling is ultimately necessary.

As one of the first steps in the development of this capability we describe here the use of acoustic Seagliders as mobile receiving platforms in the ONR-sponsored PhilSea10 experiment.

The PhilSea10 science objectives are to (i) understand the impacts of fronts, eddies, and internal tides on acoustic propagation in this highly variable region, (ii) determine whether acoustic methods, together with satellite, glider and

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other measurements and coupled with ocean modeling, can yield estimates of the time-evolving ocean state useful for making improved acoustic predictions and for understanding the local ocean dynamics, (iii) improve our understanding of the basic physics of scattering by small-scale oceanographic variability due to internal waves and spice, and (iv) characterize the ambient noise field, particularly its variation over the year and its depth dependence.

In this experiment, collaborators at the Scripps Institution of Oceanography deployed six transceiver moorings and one water-column spanning distributed vertical line array (DVLA; Figure 1). Other collaborators deployed acoustic sources from ships and towed receivers.

The source transmissions were recorded by acoustic receivers on four University of Hawaii-deployed underwater Seagliders (Figure 2) to study deep-water propagation, to determine the accuracy of long-range underwater positioning, to augment the tomographic measurements with both acoustic data and profiles of temperature and salinity, and to collect ambient sound data.

In the balance of the paper, we describe the acoustic Seaglider and its acoustic receiver system (Section II) and the PhilSea10 experiment (Section III). This is followed by a description of the temperature and salinity data (Section IV) and the acoustic data (Section V). Concluding remarks are in Section VI. .

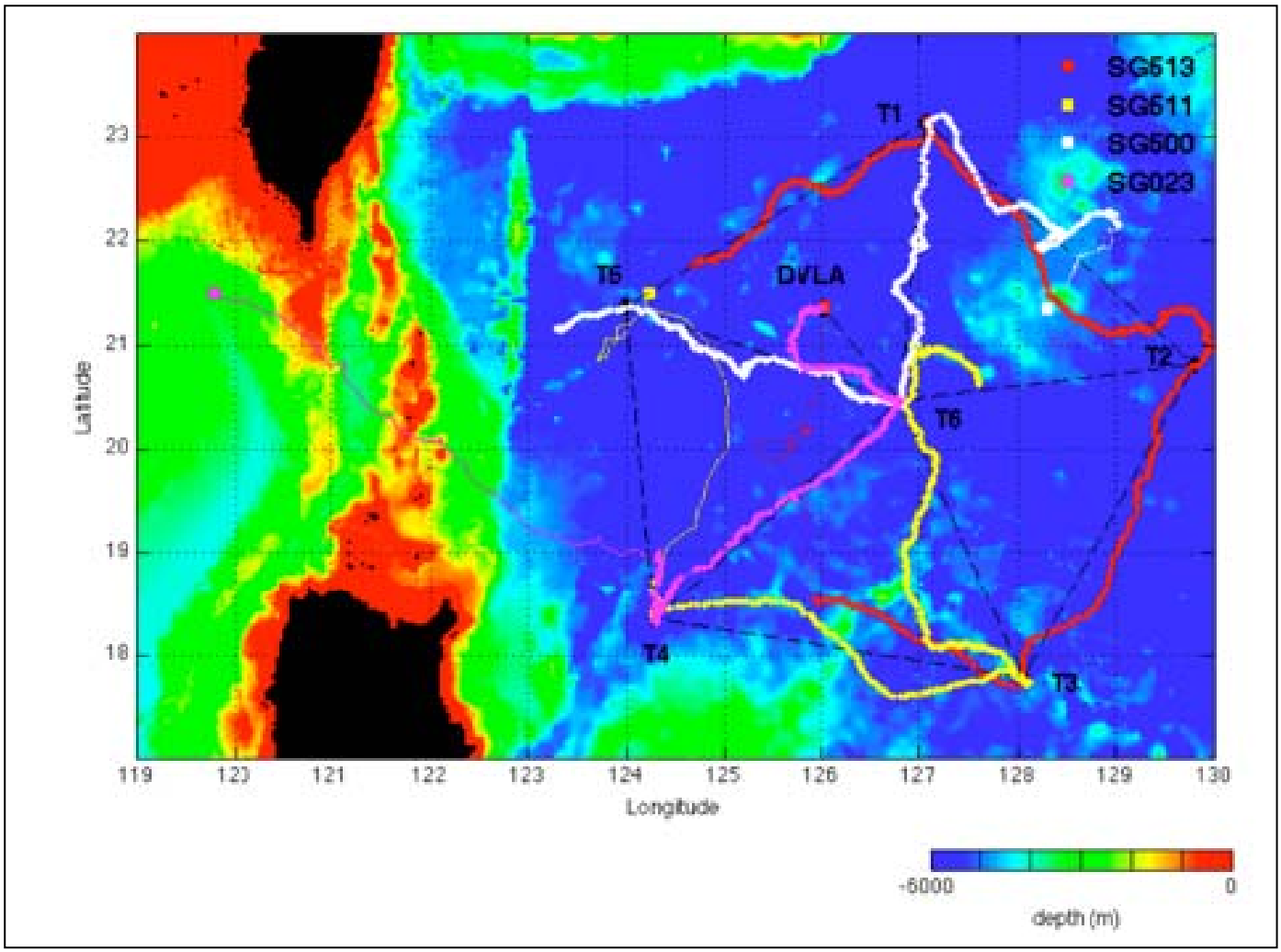


Figure 1. Acoustic Seaglider tracks in the Philippine Sea overlaid on Smith-Sandwell bathymetry. Heavy dots indicate surface positions of gliders while collecting data. Light dots for SG500 and SG513 indicate the glider is diving but not collecting data. Light solid lines for SG023 and SG511 indicate surface-drift paths. Squares indicate recovery positions.

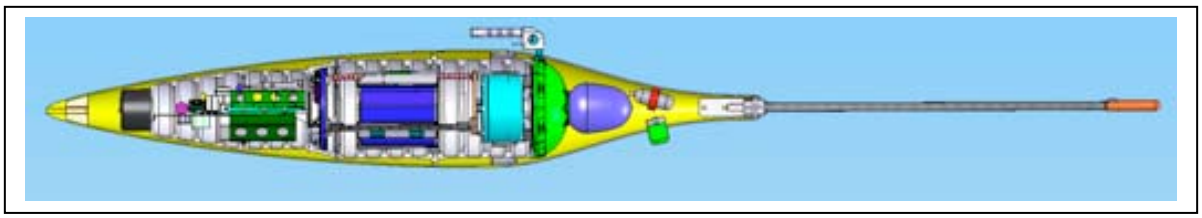


Figure 2. Acoustic Seaglider with the hydrophone in the tail cone, top right.

II. ACOUSTIC SEAGLIDERS

A. Background

The Seaglider (Figure 2), engineered at the University of Washington (UW) and now produced commercially by iRobot is a small (2.8 m) autonomous underwater vehicle designed to dive from the ocean surface to a programmed depth while measuring a standard suite of oceanographic parameters [11]. Seagliders are low power, comparatively quiet, and capable of multiple dives to 1,000 m over distances of tens to thousands of kilometers. The glider is propelled by buoyancy force (a pump moves oil between internal and external rubber bladders, changing the volume and thus the density), while shifting the battery pack fore and aft and side-to-side controls vehicle direction. Wings provide hydrodynamic lift to propel the vehicle forward as it sinks or rises, at speeds up to 0.7 knots. Global Positioning System (GPS) and Iridium units provide navigation and communication capability whenever the units surface.

In 2006, an Acoustic Receiver System (ARS) was designed and integrated into Seagliders at the Applied Physics laboratory, University of Washington with the effort led by the first author. During August 2006, marine animals (whales, sea lions, birds) were recorded during operations in Monterey Bay [12]. During September 2006 off Kauai, an acoustic Seaglider recorded signals from the ATOC/NPAL 75 Hz acoustic source. The results indicate that the signals can be processed coherently over ~5 –10 minutes, similar to fixed systems, and the Doppler shift can be accurately measured and accounted for. These results are not unexpected; in MST91, the receiving array was freely drifting at 10-30 cm/s (i.e., typical glider speeds), and Doppler velocities corresponded very well with ship ADCP measurements [10].

B. The Acoustic Receiving System

The Acoustic Recording System (ARS) is designed to be an extremely low power acoustic recorder for the Seaglider. The ARS uses a combination of very low power circuits, power cycling hardware, highly stable real-time clock, and sophisticated software to create a versatile acoustic recorder for a broad range of applications.

The recorder is built around several commercial off-the-shelf components:

- CF2 Processor Module (Persistor Instruments, Inc, Section 1.6)
- Big Idea Hard Drive Interface (Persistor Instruments, Inc)
- 60 Gb 2.5” Hard Drive (Hitachi)
- 8 GB Compact Flash Drive (Sansdisk)
- Ultra-Stable Real Time Clock (Seascan)

Most of these components are mounted to a custom designed printed circuit board that provides the various power, A/D converter, analog signal conditioning and digital interfaces (Figure 3). The CF2 microprocessor module provides a number of electrical interfaces to the Big Idea, Compact Flash, and other general use interfaces such as RS-232 serial, SPI, and general purpose digital I/O.S.

The ARS uses a High-Tech HTI-92-WB hydrophone to receive the underwater sound. The hydrophone signal is fed to two analog channels of signal conditioning; each channel supports hardware-configurable gain, low-pass (4-pole) and high-pass (1-pole) filters. The system has a noise level floor of 34 dB re 1 μPa/$(Hz)^{1/2}$. Signals from both channels can be acquired during operation but are not simultaneously sampled. A single 16-bit converter is used along with an analog multiplexer. Each conversion takes 10 μS (100 kHz sample rate) and the ARS software determines the sample-to-sample rate. A maximum sample rate is 64k samples per second. This maximum rate can be applied to either a single channel or divided between the two channels. Since an analog multiplexer is used the data collected between the two channels is not phased synchronized. Data is digitized and streamed to a compact flash disk for temporary storage. A power-cycled hard disk is used to periodically transfer data from the flash disk for permanent storage on the much larger hard drive media. This scheme minimizes the amount of power used by the system but maintains large storage capability.

The ultra-stable Real Time Clock (RTC) provides a low power, highly accurate time base that can be used for triggering recording events and time stamping data. The RTC draws ~1 mW, has a short-term jitter of 122 microseconds and a long-term stability of 5×10^{-8} equivalent to about 1 ms per 8 hour dive.

Communication with the ARS is performed using two RS-232 serial ports. The serial port dedicated to communicating with the main processor on the Seaglider is referred to as the Host Serial Port. This serial port is used during glider operation to receive glider state information messages and to pass data from the ARS to the glider controller for Iridium data transfer. Another serial port referred to as the Operator Serial Port is used to communicate with a user for ARS setup, test, and manual operation. These ports are used in different ways depending on the mode of the ARS software.

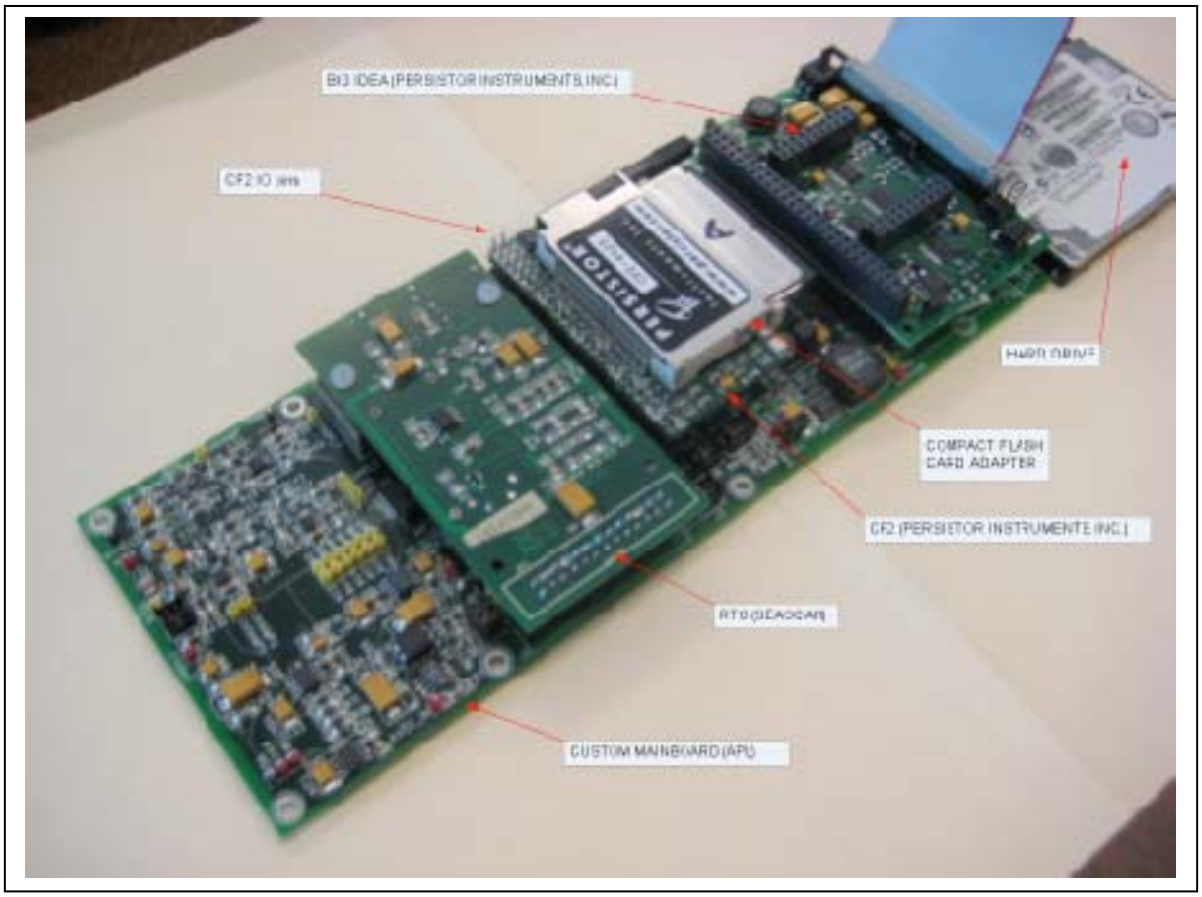


Figure 3. Acoustic Recording System (ARS) components and boards.

III. PHILSEA10 EXPERIMENT

A. Overview

The 2010–2011 PhilSea10 experiment combines measurements of acoustic propagation and ambient noise with the use of an ocean acoustic tomography array to help characterize the oceanographically complex and highly dynamic Philippine Sea. The tomographic array consisted of six acoustic transceivers that both transmit and record low-frequency (~200 – 300 Hz) acoustic signals. It had a radius of approximately 330 km, spanning much of the northern Philippine Sea. The tomographic measurements, when combined with satellite and other in situ measurements and with ocean models, will help characterize the structure of the rapidly varying oceanographic environment in the northern Philippine Sea, providing an eddy resolving, 4-D sound-speed field for use in making acoustic predictions. A seventh mooring with a distributed vertical line array (DVLA) receiver with 150 elements provided additional acoustic data. The moorings were deployed in April 2010 and recovered one year later.

B. Seagliders

Four Seagliders (SG023, SG500, SG511, and SG513) were deployed from the *R/V Roger Revelle* in November 2010. The tracks of gliders from the time of deployment to recovery are indicated in Figure 1.

On 11 January, SG023 completed its last successful dive. Pitch errors sent the glider into recovery mode and it was not sent diving again for fear of losing the vehicle. The glider drifted at the surface until a fishing boat recovered it on 26 January 2011, after crossing the Kuroshio. SG511 completed its last successful dive on 16 February 2011. The glider entered recovery mode when the 10-Volt battery, which controls the ARS, dipped below its cutoff value of 8.0. The glider drifted at the surface until the R/V Roger Revelle recovered it on 5 March 2011. The remaining gliders, SG500 and SG513 were recovered as planned during the tomography mooring recovery cruise on the *Revelle*.

IV. TEMPERATURE AND SALINITY DATA

Conductivity and temperature sensors on the glider were configured to take measurements every 10 seconds above 200 m, every 20 seconds from 200 to 300 m, and every 40 seconds below 300 m. Although SG500 and SG513 did not execute emergency recoveries, the 10-volt battery readings also indicated a drop, which is what caused SG511 to execute an emergency recovery. To conserve 10 V battery life, the ARS and conductivity-temperature sensors were deactivated prematurely because iridium communication and GPS positioning also relies on the 10 V battery. Therefore, although

SG500 and SG513 dove continuously throughout the deployment, the later dives did not collect acoustic or conductivity/temperature data (indicated as tracks with small dots, Figure 1, and Table 1). The cause of the excessive ARS power draw is still under investigation.

TABLE I. GLIDER DIVE STATISTICS

Glider	Total Dives	CT Dives	ARS Dives	ARS 4 kHz	ARS 64 kHz
SG023	237	226	21	45	
SG500	503	416	296	403	
SG511	392	391	215	391	
SG513	576	438	227	391	6

Cross sections of temperature and salinity data from the gliders are shown in Figure 4. Data shown are unfiltered and unedited. Outliers in salinity measurements on some gliders are likely due to stalling. The four rows in the figure correspond to the four gliders in numerical order. The abscissas are year day 2009. Figure 5 shows the same temperature data but in a time-independent 3-D visualization.

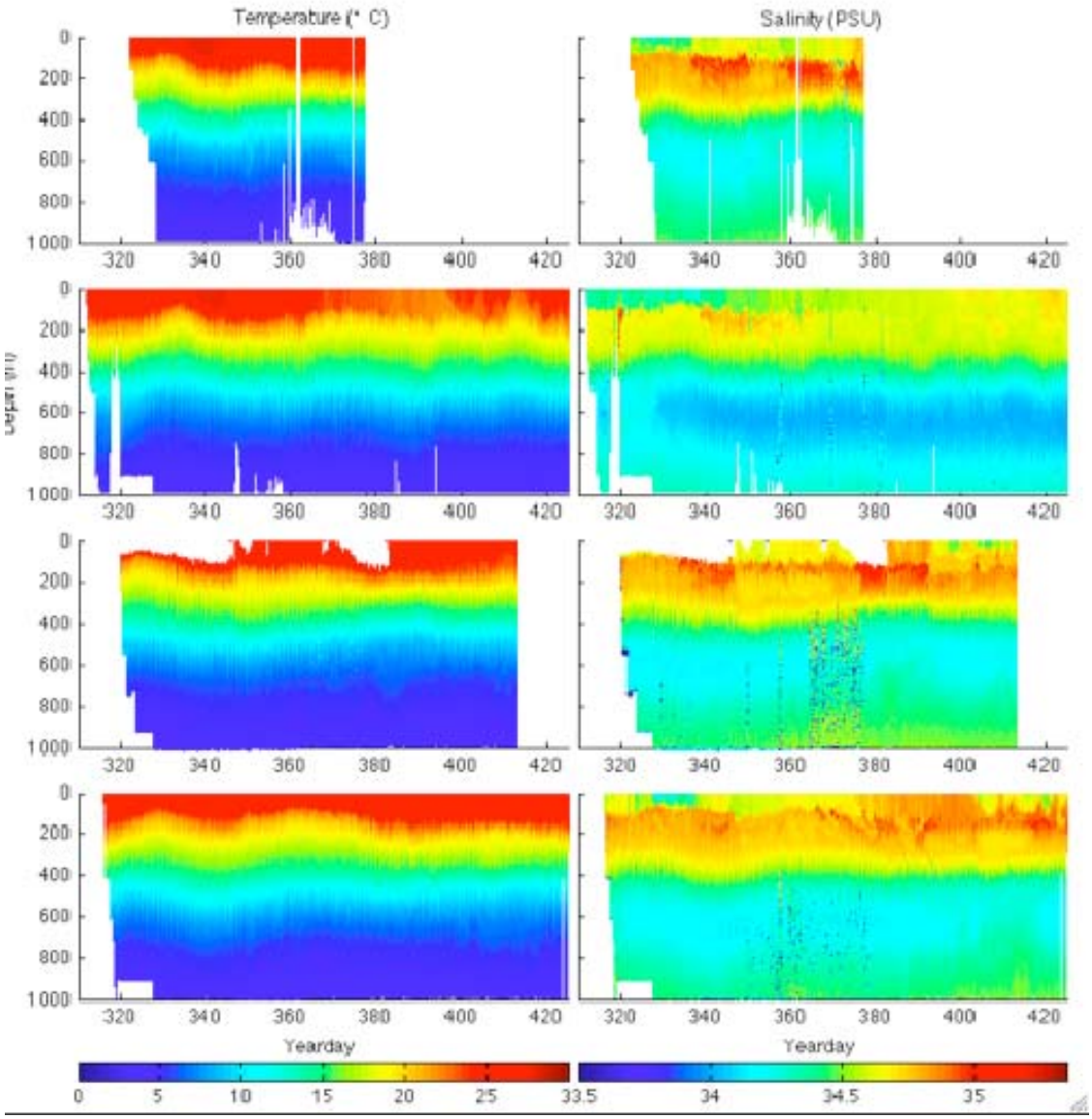


Figure 4. Temperature and salinity sections for SG023, SG500, SG511, and SG513 (from top to bottom).

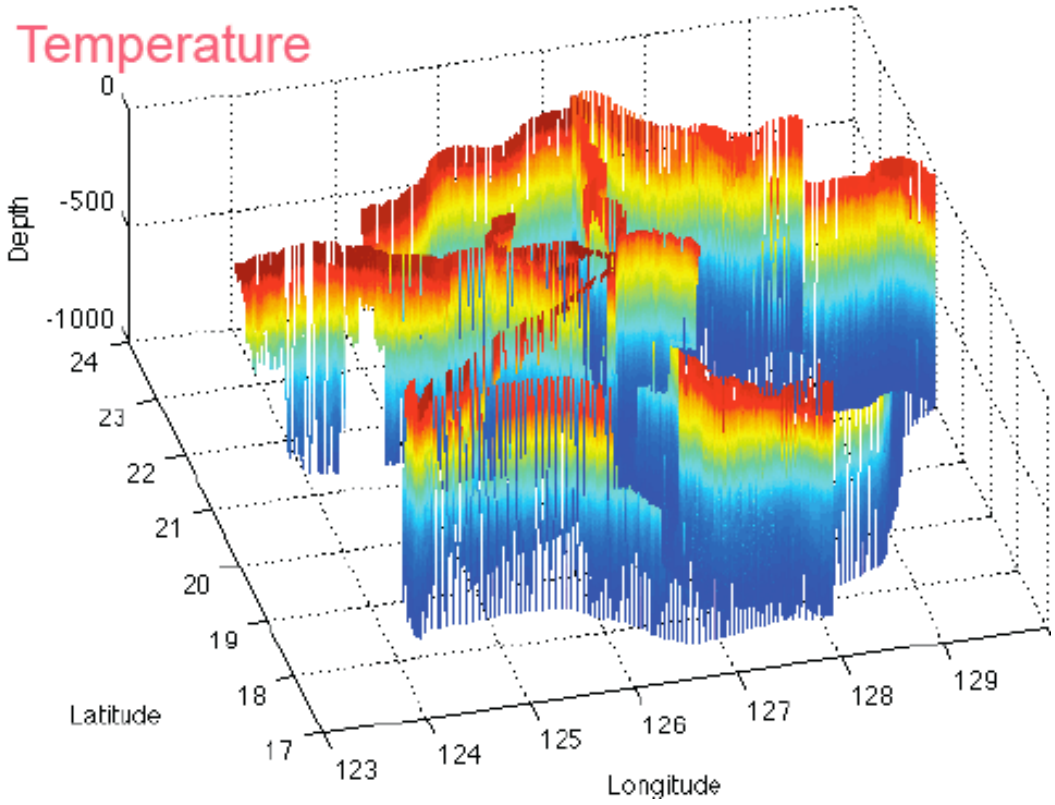


Figure 5. Temperature from the four Seagliders plotted in 3D assuming time independence.

V. Acoustic Data

The gliders diving to 1000 m sampled the upper half of the sound channel, Figure 6. Here, the SG023 glider path between T4 and T6 is plotted versus range and depth overlaid on transmission loss estimates. The latter are calculated using an the CRAM parabolic equation propagation code (K. Heaney, personal communication), and an average sound speed profile based on the World Ocean Atlas. The dive cycle distance of the Seagliders ~3-5 km, effectively samples the ocean on scales appropriate to the ray cycle distance of ~50 km.

For diagnostic purposes, ambient noise power spectra for the first 16 seconds of the first data file of a dive were calculated and transmitted in near-real time back to shore via Iridium. Several representative spectra for glider SG500 are shown in Figure 7. In general, the shape and level follows typical ambient noise curves, with an occasional outlier.

Figures 8 and 9 show various acoustic receptions.

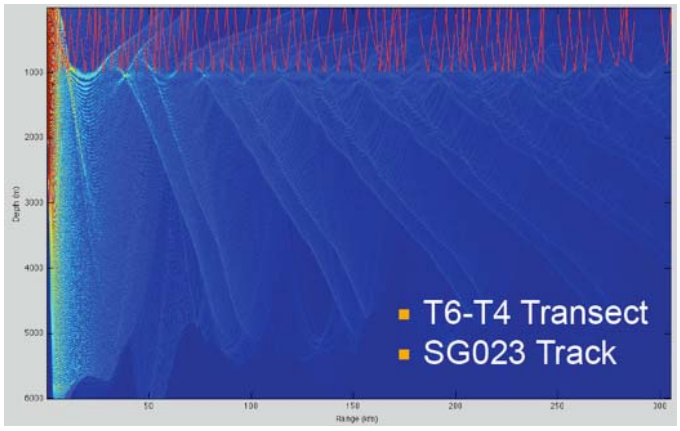


Figure 6. Glider trajectory overlaid on transmission loss.

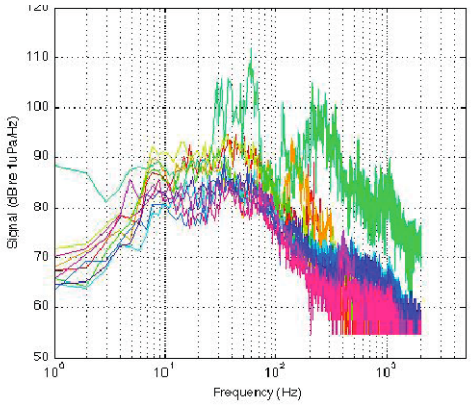


Figure 7. Power spectral density estimates, SG500

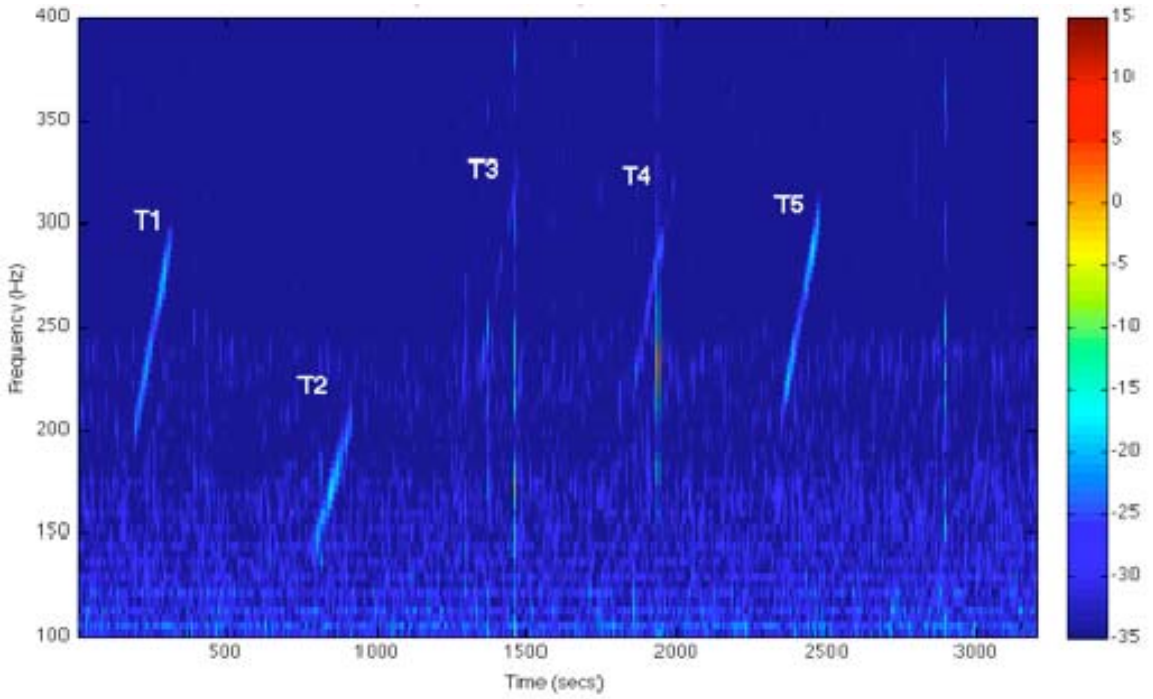


Figure 8. Spectrogram from SG023 Dive 90 recorded on 1 December 2010 at approximately 20.76°N/126.41°E showing receptions from moored acoustic sources T1-T5.

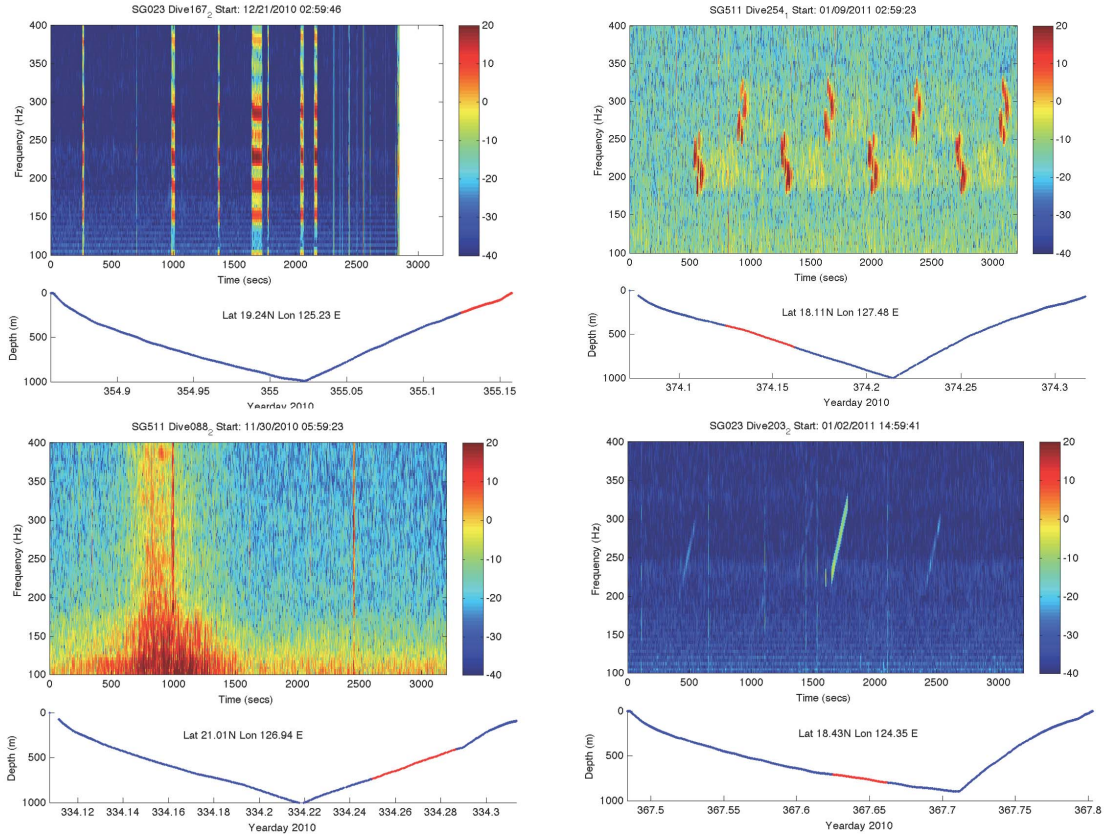


Figure 9. Spectrograms and dive profiles for various signals (see text)

A typical spectrogram showing the received tomography signals are shown in Figure 8. The spectrogram covers an approximately 1-hour window and the signals from the five moored transmitters are clearly visible (T6 transmitter failed), as are the slightly different frequency bands for each source.

Figure 9 shows four spectrograms that are examples of other signals. Included are the dive trajectories that show when and over what depth range the acoustic reception took place (red line). The top left panel shows glider noise (buoyancy engine pump and roll and pitch motors) as it approaches the surface. The top right panel shows SURTASS LFA signals. The bottom left panel shows some unidentified noise source. Finally on the lower right is a spectrogram showing the signal from a nearby source, including the short precursor source calibration signal.

VI. Concluding Remarks

Data analysis is in progress that will lead to positioning and tomography solutions. This will include Doppler processing, cross correlation/matched filter processing, and arrival pattern analysis such as peak picking and ray identification. The latter with the glider precise time will be used to generate absolute arrival times for the various rays as a function of time and glider position. As a first step, these absolute travel times will be used to estimate position of the glider that will then be compared with the best estimate of glider position underwater using the model of Eriksen [11]. Lastly, the joint tomography and position estimation problem will be tackled.

While the overall acoustic Seaglider mission in PhilSea10 was successful, the experience shows there is room for improvement. The inconsistencies in the glider power budget that led to near losses of vehicles require further investigation. The pitch motor in SG023 failed leading to aborting its mission. The compass in SG500 failed near the end of the mission (see track between T1 and T2 in Figure 1). In general the gliders proved difficult to trim and for symmetric, energy efficient profiles, partially responsible for the generally lower than expected speeds over ground and water.

The acoustic Seagliders in PhilSea10 further demonstrated their capability to record ambient sound and signals, e.g., SURTASS LFA. With the precise timing they are general-purpose mobile receivers that can be used for tomography. Given a more ideal realization of the experiment, four gliders flying at 20 km/day can collectively circumnavigate the experimental area in 22 days nearly doubling the number of acoustic data thereby improving the resolution with 700 additional paths in that time and reducing resolved length scales from ~130 km to ~100 km (~ (experimental area / N paths)$^{1/2}$).

As ocean observing systems are developed over the next decades, the integrating and N^2 advantages of acoustic measurements should be borne in mind. Both fixed and mobile platforms will be necessary.

Acknowledgment

We thank the many people who helped make the acoustic Seaglider portion of PhilSea10 a success. Dr. Peter Worcester deployed the acoustic sources. The captain and crew of the R/V *Roger Revelle* provided their expert assistance throughout all the operations. Co-chief scientist Dr. Barry Ma helped during deployment, and Chief scientist Dr. Peter Worcester helped during recovery. Dr. Chen-Fen Huang helped organize the first glider recovery using a local fishing vessel under command of Capt. Chao. The second glider was recovered by the R/V *Revelle*, Dr. Hans Graber chief scientist. The gliders were prepared by SOEST Ocean Gliders facility technician Jennie Mowatt. She worked with engineers from APL-UW (Russ Light, Pete Sabin, and Tim Wen and Geoff Shilling) integrating the ARS into the gliders. Fritz Stahr, director of the UW Seaglider Fabrication Center provided valuable advice and assistance.

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