ACOUSTICS IN OCEAN OBSERVING:

FROM ABYSSAL CABLED SYSTEMS TO GLIDERS

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Abstract:

The concept of integrated acoustics for ocean observing embraces passive acoustic monitoring, navigation and positioning, communications, and tomography using fixed and mobile platforms within the framework of unifying, data assimilating ocean and platform models. It has been maturing over the last two decades and longer. Selected results from the authors' past and present work illustrating the various components are presented. These include using a wave glider as a communications/navigation gateway and for passive monitoring, preliminary results of long range underwater glider precise positioning, and passive measurements at the ALOHA Cabled Observatory. Ongoing and new infrastructure developments will support these and many other continuing efforts. For example, the International Telecommunications Union is coordinating steps to have sensors included in commercial submarine cables; over the coming decades, normal cable replacement could yield a long-lived reliable observing network spanning the ocean basins.

Keywords: *ocean acoustic tomography, passive acoustic monitoring, acoustic communications, acoustic positioning, acoustic navigation, cabled ocean observatories, RAFOS-2*

1. INTRODUCTION

Over the last decades there have been significant advances in the technology of ocean observing, i.e., infrastructure and platforms, and the inclusion of acoustics therein ([1-4]). In many cases the acoustic components can be used for multiple purposes. Active sources can provide navigation, communication, and tomography signals. Receivers can listen for and make use of all of these signals, while at the same time monitoring for wind and rain or shipping and marine mammals, all part of "passive acoustic monitoring" (PAM). Here several examples the authors have been involved with are reviewed.

In section 2, a relatively new platform, the autonomous surface vehicle wave glider, is described and its use as a navigation and communications gateway and a PAM platform is described. In section 3, the similar use of the underwater autonomous glider platform, the Seaglider, is described, including recent results of precise long range underwater positioning. In Section 4, the ALOHA Cabled Observatory is presented as an example of a deep ocean system that presently supports PAM and is expected to add active components for the aforementioned applications. Lastly, we speculate on future directions.

2. WAVE GLIDERS

The wave glider (Liquid Robotics, Inc.) is a new autonomous surface platform introduced recently in 2008. Here we report on first tests of the platform with an acoustic modem (WHOI micro-modem) and a passive acoustic recording system (WHOI DMON). See [5] for more details.

Figure 1 shows the basic wave glider and how the acoustic transducers were mounted. The electronics for both were installed in the instrument bays of the float along with a HF radio unit for local communications. At the time there was no attempt to integrate these components with the wave glider to make use of, for instance, its Iridium satellite communications. Initial tests using the DMON system indicated that acoustic noise was significantly higher on the surface float than on the glider. This led to mounting the acoustic modem transducer (ITC 3013) on the glider as shown in the figure.

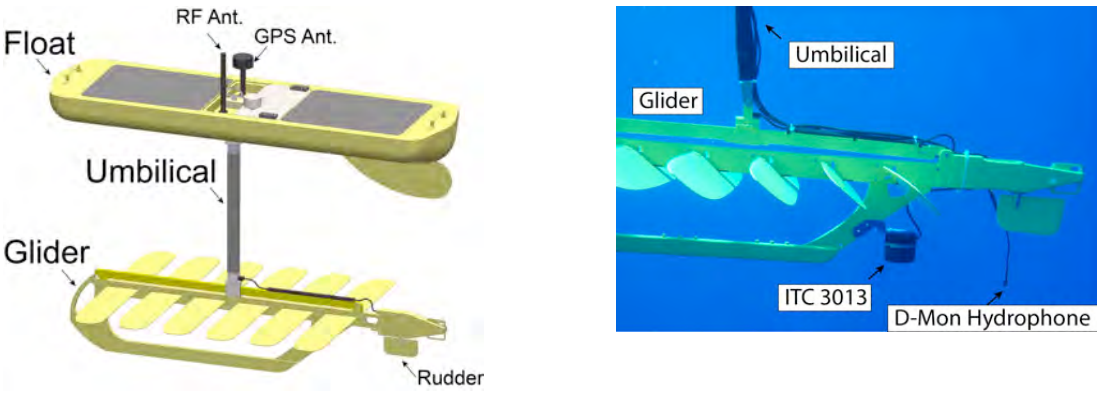


Fig.1: Wave glider components (from [5]).

To demonstrate the navigation capability, the wave glider was used to survey in a bottom transponder, Figure 2. The water depth was 235 m. The wave glider was commanded to run a pattern around the transponder with the micro-modem interrogating

the bottom transponder and measuring the round-trip travel time. The latter were exceptionally smooth as were the detailed GPS measurements (not shown), leading to a surveyed transponder position with 1.7 m rms horizontal errors, with only minimal data quality control (e.g., removal of the obvious outlier around 00:00 caused by another nearby acoustic transponder). In other missions, the communications function was confirmed. The wave glider modem was able to communicate with a modem at depths of 500 m and 2,500 m and at ranges in excess of 3 km, but the reliability and the input SNR varied with the local noise field around the surface receiver. Lastly, vocalizations of humpback whales were recorded (Figure 3). The latter results may be compared with those of Wiggins et al. [6].

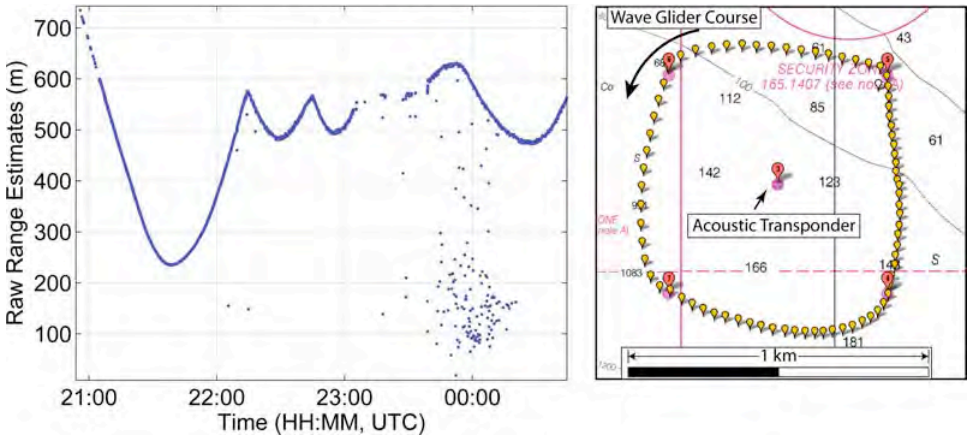


Fig.2: Wave glider navigation results from 10 March 2010 (from [5]).

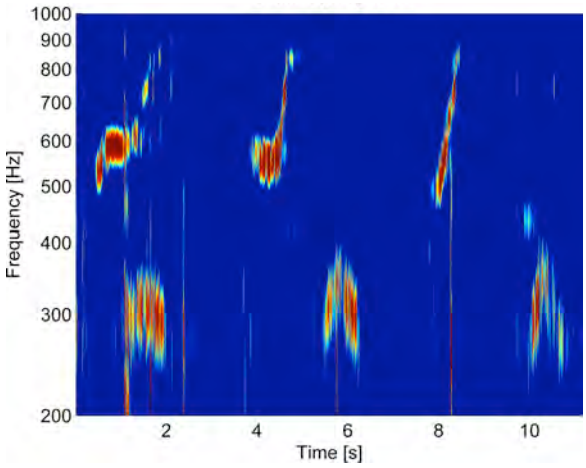


Fig.3: Wave glider passive acoustic listening results (from [5]).

The wave glider has proven to be a robust platform that is able to easily accommodate new instrumentation. For navigation and positioning subsea platforms, open ocean ranges up to 10 km (as normally obtained in practice) should be achievable with the wave glider as configured here. Some of the estimated positioning error is associated with the offset between the float GPS antenna and the acoustic transducer on the glider. Kraus has developed a dynamical model [7] as one step toward accounting for this constantly changing offset, and toward the use of the glider in seafloor geodesy application, for example. A major intrinsic limitation of the wave glider is its restriction to surface/near-surface applications. Acoustics can extend the reach as demonstrated above, though at some point significant direct access to increased depths, e.g., beneath the mixed layer, will

be needed, perhaps by a tether or winch system. LRI has recently introduced a somewhat larger wave glider version (~1/3 longer) that may facilitate this.

3. SEAGLIDERS

A RAFOS hydrophone and receiver system were first integrated in Seaglider and deployed in the 2004 LOAPEX experiment in the North Pacific. While setting at-the-time records for mission parameters (3000 km, 600 dives, 190 days), these gliders received signals from three RAFOS sources (260 Hz center frequency, 1.5 Hz bandwidth) off California at ranges up to 1900 km. This was the first demonstration of RAFOS capability on Seagliders, and has led to use in the Arctic under ice (Lee et al., [3])

During 2005-2006, a new acoustic receiver system (ARS) and a WHOI micro-modem were integrated into the Seaglider (Fig. 4) and deployed and tested. In the first deployment during July 2006 in the Philippine Sea (LWAD06), signals from acoustic sources near and far were received on the ARS. In MB06 in August in Monterey Bay, the micro-modem was used to command bottom-mounted instrumentation, demonstrating this communications gateway capability for the first time. The ARS system recorded the acoustic communications traffic as well as many marine mammal vocalizations, some shown in Fig. 5 and described in [8]. In September off Kauai, a Seaglider recorded 2-hour long ATOC signals (75 Hz center frequency, 37.5 Hz bandwidth) [9]. "IAP" processing (integrated autocorrelation phase, [10]) was used to estimated travel time and Doppler from the instantaneous broadband signals (Fig. 6 left). At a range of ~100 km, travel times agreed with ray predictions at the 100 ms level, and the Doppler agreed with the estimated glider velocity to roughly 5 cm/s (Fig. 6 right). For this very brief deployment and geometry, the Kauai mission demonstrated the ability to receive m-sequence coded signals, perform coherent processing (~5-10 min integration time, 14 dB gain), and to resolve and identify multipath ray arrivals on a moving glider; measured travel times and Doppler were in reasonable agreement with predictions/independent estimates.

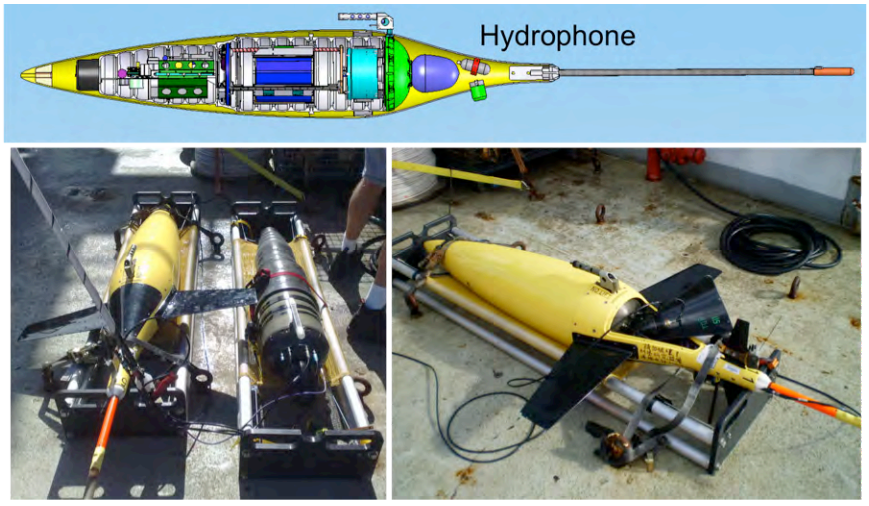


Fig.4: Seaglider components.

These preceding successes motivated continued effort to use ARS equipped Seagliders in a configuration with multiple sources to demonstrate high precision long-range positioning as well as to attempt the joint estimation problem of position and sound speed,

i.e., the RAFOS-2 and tomography framework described by Duda et al. [4]. For instance, if there are five sources and one glider receiving, two of the measured travel times/ranges are necessary to position the glider leaving three data that can contribute to the determination of the sound speed field, i.e., tomography. The division of information between position and sound speed is not self-evident in the data itself, rather that is left to the joint estimation/inversion procedure that incorporates additional constraints.

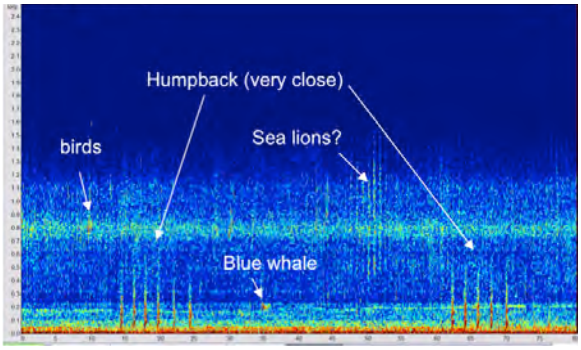


Fig.5: Seaglider MB06 passive acoustic monitoring results (0-2.5 kHz on vertical axis and 0-60 s on horizontal axis).

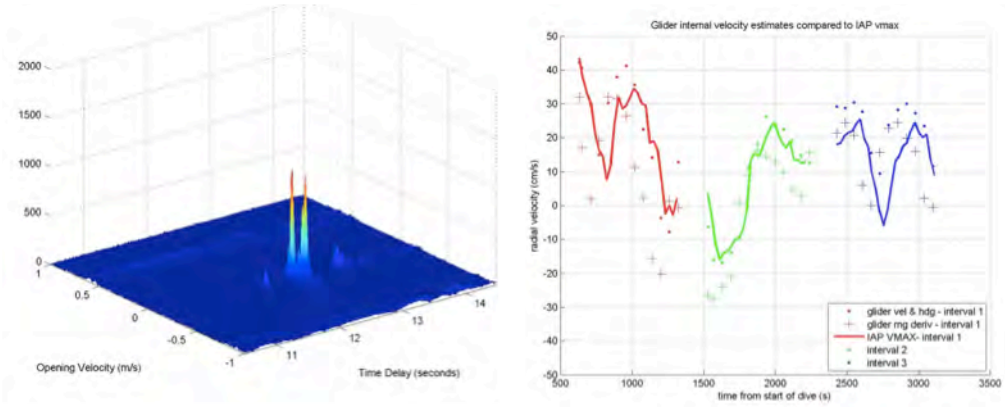


Fig.6: Kauai 2006 results: (left) Doppler-time surface showing multipath arrivals, and (right) glider Doppler velocity (solid) compared with glider-estimated velocity (points).

In November 2010, four ARS-equipped Seagliders were deployed in the Philippine Sea as part of the larger PhilSea10 experiment with six acoustic tomography transceiver moorings and a distributed vertical line array receiver (DVLA; Fig. 7; [11-13]). The glider acoustic data was replica-correlated to obtain arrival patterns for each transmission. For the preliminary positioning analysis reported in [13], the predicted eigenray arrival pattern for a particular reception was shifted in time to match the received arrival pattern. Time offsets were multiplied by 1500 m/s to obtain range offsets that were used to produce the intersecting circles shown in Fig. 8. The range offsets were used in a least-squares solution to obtain position offsets relative to the a priori glider position (based on GPS surface offsets and on its kinematic (dead reckoning) model that used heading, roll, pitch, and buoyancy). For the 270 cases that had five source receptions (one source had failed), the estimated position range offset was 914 m rms; a summary scatter plot is shown in Fig. 8. The estimated x and y position error is 106 m rms; other statistics indicate overall consistency. The results indicate that the glider is being advected significantly during a dive by water velocities that are “unobserved” by the time-space path-averaged velocity

inferred by the combination of glider kinematic velocity and GPS. Further accounting for non-simultaneous source transmit times (offset by 540 s) and a constant glider velocity offset during the reception period, and ultimately a joint estimation of glider state (position and velocity) and ocean water velocity and sound speed will tell us how well we can position a moving platform over these distances, and whether there is enough information left to improve the estimation of the sound speed field.

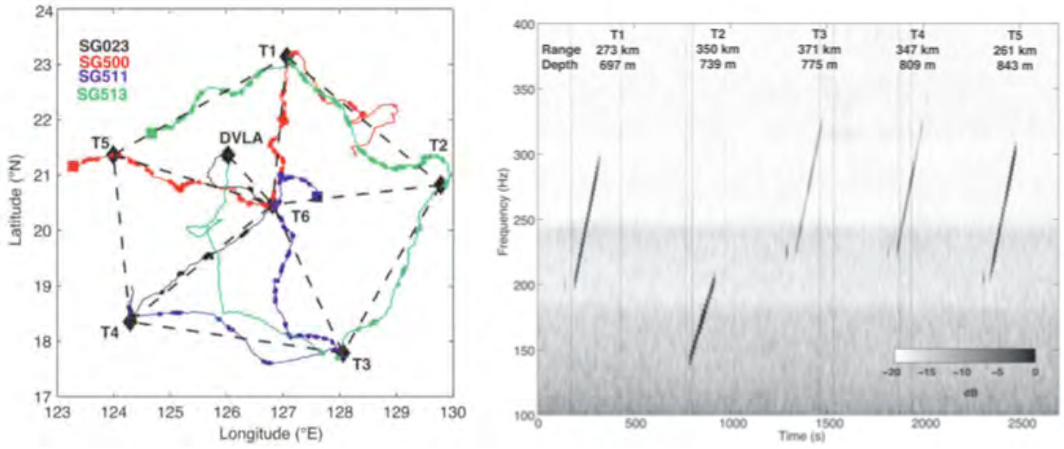


Fig.7: Seaglider PhilSea10 paths and spectrogram (from [13]).

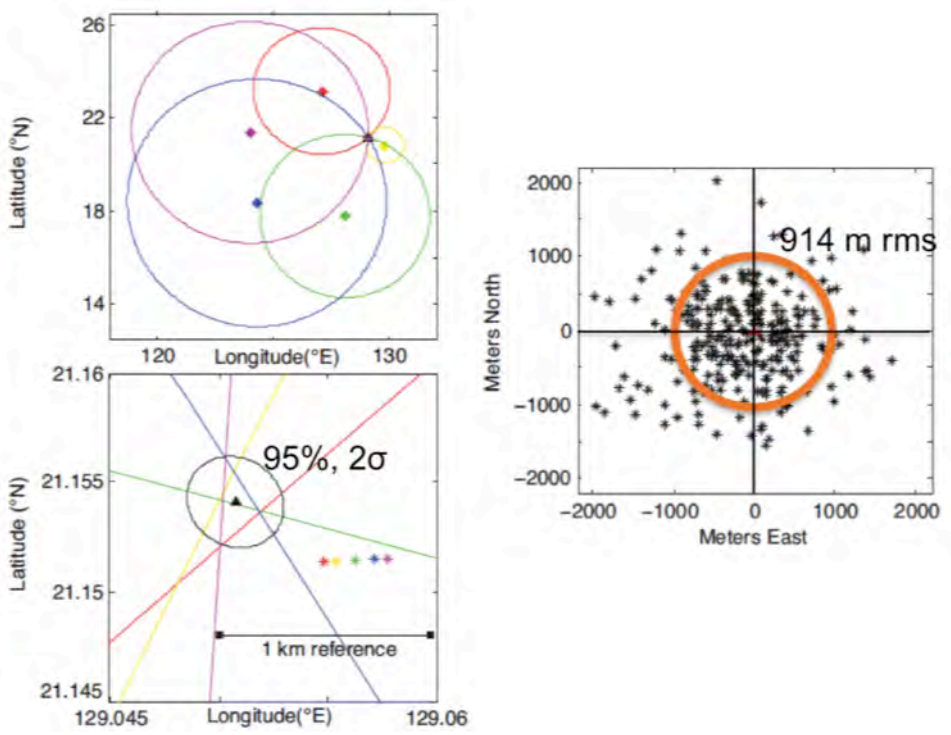


Fig.8: Seaglider PhilSea10 positioning circle and scatter plots (from [13]).

4. ALOHA CABLED OBSERVATORY (ACO)

The ACO is located at Station ALOHA 100 km north of the Hawaiian island of Oahu (Fig. 9). Station ALOHA is the site of the Hawaiian Ocean Timeseries (HOT) project that has conducted ship-based ocean sampling on a monthly basis since 1988 and the WHOTS meteorological/upper ocean mooring operating since 2007. The ACO was installed to

complement and supplement the monthly visits, ideally with full water column profiling capability that can provide near-continuous real time observations of water column variables that are amenable to robotic sampling. Also, during the various stages of science planning for the US NSF Ocean Observatories Initiative, Station ALOHA was identified as a "global mooring" site supporting an acoustic thermometry transceiver.

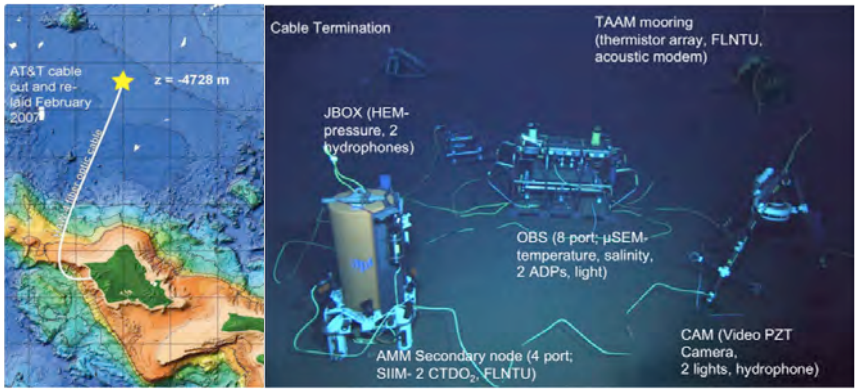


Fig 9: ACO location north of Oahu and bottom configuration as deployed June 2011.

The main node and instruments shown in the figure were installed in June 2011. A description of the system and the installation is given in [14]. While not all the instruments are presently working (several suspected cable ground faults, to be repaired in late 2013), the broadband hydrophone is providing excellent data. The latter (including data collected on an earlier proof module) has been used to study wind speed dependence as a function of frequency and surface gravity wave-wave interaction [15, 16] and marine mammal vocalizations [17,18]. One day and one minute of acoustic data is shown in Fig. 10, clearly showing vocalizations of four marine mammal species and the Lloyd's mirror pattern of a transiting ship. Fig. 11 shows data associated with a very heavy rain event.

Future plans for ACO include a 10 kHz WHOI acoustic micro-modem to enable navigation, communications, and tomography (depending on configuration) with remote platforms. A new camera system with another broadband hydrophone will also be installed; some directional capability will result when combined with the existing hydrophone. In the long-term, we are working to install a low frequency source to use in the same way as the modem, but for longer range, ideally cross-basin.

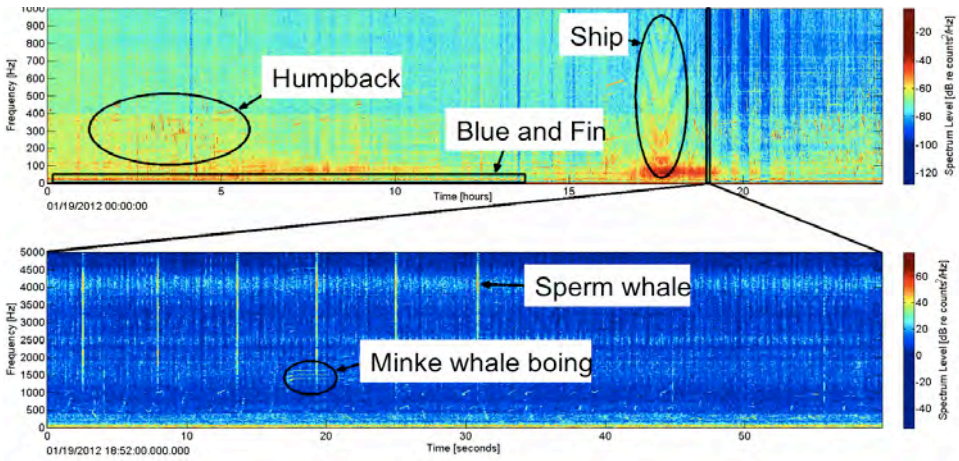


Fig. 10: One day and one minute of ACO acoustic data, February 2012.

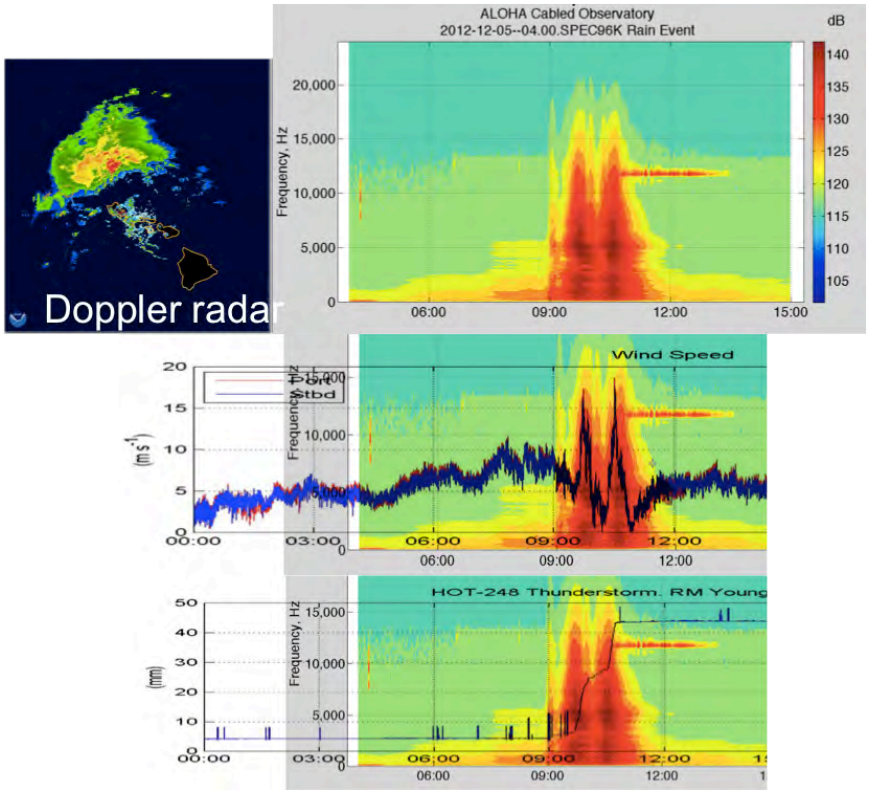


Fig.11: Data associated with a heavy rain event 14 April 2013 (spectrum, wind speed, cumulative rainfall).

5. CONCLUDING REMARKS

In addition to these several examples of essential acoustic elements of ocean observing from the authors' work, there are many other efforts contributing to the evolving acoustic component of the ocean observing network. The large number of related contributions to this UAC2013 conference reflects the forward progress.

Continuing technology development is required. Low-frequency, efficient, compact and light weight acoustic sources are still needed for fixed (e.g., moorings) and mobile platforms (e.g., AUVs). An ultra-low-power acoustic equivalent to GPS receivers is necessary to encourage the integration thereof onto Argo floats and other platforms; it should also include PAM capability. On the "software" side, better ways to process PAM data in situ to reduce volume is needed (e.g., as is done for rainfall rate). To best use the active positioning data, ocean model data assimilation methods need to be developed and improved to jointly estimate platform state (i.e., where the measurements are being made) along with the ocean state using the travel time data.

Lastly, the International Telecommunications Union (a United Nations agency composed of member states, industry and academia) is coordinating efforts to include sensors in "green repeaters" in commercial submarine telecommunications cable systems spanning the ocean basins (see http://www.itu.int/ITU-T/climatechange/task-force/sc/index.html and [19]). Candidate initial sensors are temperature, pressure, and acceleration. The next on the list would be an acoustic modem that could serve the integrated acoustics concept while providing inverted echosounder data for depth-

averaged temperature; eventually "nodes" may be possible a la ACO and other science cabled observatories.

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