Deep-Water Ambient Noise Profiling; Marine Sediment Acoustics; and Doppler Geo-Acoustic Spectroscopy

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LONG-TERM GOALS

1) Deep-water ambient noise profiling Profile the spectral, temporal and spatial properties of broadband (3 Hz – 30 kHz) ambient noise from the sea surface to the bottom of the deepest ocean. Develop theoretical models of the second-order spatial statistics of the noise.

2) Marine sediment acoustics Develop a unified, physics-based model of sound wave and shear wave propagation in saturated, unconsolidated marine sediments. New focus is on very fine-grained sediments (silt and clay).

3) Doppler geo-spectroscopy Develop the use of a light aircraft as a sound source for performing inversions for the geo-acoustic parameters of the seabed in shallow water. New focus is on helicopter noise.

OBJECTIVES

1) The scientific objective of the deep-water ambient noise research is to measure the second-order spatial statistics of the ambient noise in the deepest oceans as a function of depth, from the sea surface to the seabed. Regions of interest include the Mariana Trench, notably the Challenger Deep (11 km), the Tonga Trench (9 km), and the Puerto Rico Trench (8 km). Environmental and system data will also be depth-profiled, including temperature, salinity, pressure and (directly measured) sound speed, along with all system motions (translational and rotational). Theoretical modeling of the spectral, spatial and temporal properties of the ambient noise will also be performed.

2) The sediment acoustics research is aimed at developing a unified theory of wave propagation in marine sediments in the form of the dispersion relations for the compressional and shear waves. Besides the frequency dependencies of the wave speeds and attenuations, these expressions will also return the dependence of the wave parameters on the mechanical properties of the sediment, namely porosity, density, grain size and overburden pressure. A new focus is on the inter-granular forces in silts and clays and their role in controlling wave speeds and attenuations.

3) The Doppler geo-acoustic spectroscopy technique, in which a fixed-wing aircraft is used as a sound source, is in support of the sediment acoustics research, providing a means of measuring the sound speed in the sediment at frequencies between 80 and 1000 Hz. The technique is being extended to include the sound from rotary-wing aircraft (helicopters).

APPROACH

1) Deep-water ambient noise profiling A deep-diving autonomous instrument platform known as Deep Sound has been designed and developed by my research group. Deep Sound consists of a Vitrovex glass sphere housing a microprocessor for system control, along with data acquisition and storage electronics. External to the sphere are several hydrophones (bandwidth 3 Hz – 30 kHz, calibrated to equivalent depths of 12 km), which may be arranged in various vertical and horizontal configurations, and an environmental sensor package [Conductivity-Temperature-Depth sensor (CTD) plus sound speed sensor (SVX)]. The system is untethered, descending under gravity and, after releasing a drop weight at a pre-assigned depth, returning to the surface under buoyancy. Throughout the descent and ascent, at a nominal 0.5 m/s, acoustic and environmental data are continuously recorded. Three beacons (a high intensity strobe, a radio antenna, and an Argos GPS) aid recovery of the system. Several fail-safe devices are onboard, intended to ensure that the weight is indeed dropped, thus allowing the system to return to the surface.

   In conjunction with the ambient noise experiments using Deep Sound, I am developing a series of analytical models for the spatial coherence and cross-correlation properties of ambient noise in the deep ocean. These models address the directionality and bandwidth of the noise as they affect the cross-correlation function. The models will help us interpret the two-point measurements of noise recovered from Deep Sound.

2) Marine sediment acoustics My theoretical approach involves the development of the compressional and shear wave dispersion relations, based on inter-granular interactions. In the latest version of the grain-shearing theory, the viscosity of the pore fluid is included in the analysis, which leads to low frequency (< 10 kHz) compressional wave behavior that is in accord with measurements made during the ONR-supported Sediment Acoustics Experiments 1999 (SAX 99) and 2004 (SAX 04). At higher frequencies, above 10 kHz, the effect of pore fluid viscosity is negligible and again the new theory fits the compressional wave data. Thus, the latest version of the theory fits all the available compressional wave and shear wave data from the SAX experiments, which involved medium sands. The theory is the basis for new research on very fine-grained sediments, which will incorporate the inter-granular bonding forces that are peculiar to these materials.

3) Doppler geo-acoustic spectroscopy A propeller driven, light aircraft flown at low level over the ocean acts as a sound source, which is used as the basis of an inversion technique for recovering the speed of sound in the seabed. The propeller sound from the aircraft consists of a series of harmonics, typically 80, 160, 240, ….. Hz. Some of this acoustic energy penetrates the sea surface and reflects off the seabed, acquiring information about the sediment in the process. From recordings made on hydrophones in the water column and/or buried in the seabed, an inversion is performed which returns the phase speed of the compressional wave in the sediment. Once the compressional speed is known, most of the remaining geo-acoustic parameters are estimated using the correlations provided by the grain-shearing theory. The technique is currently being extended to helicopters, which produce much lower frequencies than fixed-wing aircraft, perhaps

as low as 10 Hz. This should enable the wave properties of sediments to be determined rapidly and efficiently in a frequency regime that is otherwise difficult to access.

WORK COMPLETED

Three versions of Deep Sound, designated the Marks. I, II and III, have been designed and built. Each evolution of the system has progressively more instrumentation onboard. Deep Sound Mark I has been deployed a number of times to great depths, approximately 6 km in the Philippine Sea and 9 km in the Mariana Trench, and is now showing signs of wear. Spalling of the glass sphere around the internal equator has occurred, a result of the compression due to the extreme hydrostatic pressure encountered at depth. Mark I has now been retired from service and is no longer operational.

Deep Sound Mark II was deployed in the Mariana Trench in November 2009, where it successfully recorded ambient noise on vertically and horizontally aligned hydrophones from the surface to a depth of 9 km over the acoustic frequency band from 3 Hz to 30 kHz.

Deep Sound Mk. III is the most sophisticated of the three systems, capable of descending to a depth of 11 km. On board is a sound speed sensor (SVX), a sing-around instrument that records the speed of sound directly, for comparison with the computed values from the CTD. This allows us to test the validity of sound speed algorithms for the extreme pressures found at the bottom of ocean trenches.

An attempt was made to deploy Deep Sound Marks II and III in the Mariana Trench in July 2011, to depths of 9 km and 11 km, respectively. Working with a National Geographic group, a research vessel, the M/V Super Emerald, was chartered out of Saipan (at no cost to us) and used for the four-day deployment. Weather conditions were bad, with heavy seas and storms throughout the time at sea. The M/V Super Emerald was not well suited to the task, and at least one system (not one of ours) was lost. We should have been the last to deploy but decided against putting our systems in the water, given the extreme problems the other groups had experienced.

In early September 2012, Deep Sound Marks II & III were deployed in the Tonga Trench from the R/V Roger Revelle. The hydrophones on board each of the systems were fitted with newly designed flow shields, intended to suppress the effects of turbulent flow generated by the motion of Deep Sound through the water column. Both Deep Sound systems descended to a depth of 8.5 km, stayed on the bottom for extended periods (20 minutes for Mark II and 3 hours for Mark III), and then returned to the surface, all the while collecting broadband (3 Hz – 30 kHz) ambient noise data, along with environmental and system data.

An invited paper[1] on Deep Sound has been published in a special issue of the *Journal of the Marine Technology Society* commemorating the Golden Anniversary of the dive of the manned submersible *Trieste* to the bottom of the Challenger Deep. A theoretical paper[2] on the directionality of ambient noise and its effects on the two point (vertical and horizontal) cross-correlation function has been published in the *Journal of the Acoustical Society of America* (JASA). Another paper[3] has been published in JASA in which a theoretical model of a three–dimensional noise field is developed. The model represents noise from a storm, showing a strong peak in the horizontal combined with significant vertical directionality. This is relevant to some of the data that were collected in the Philippine Sea by Deep Sound Mark I as an intense storm passed more or less overhead. An analysis of the storm data is described in a recently published paper[4] in JASA. Wind-driven noise, also recorded during one of the deployments of Deep Sound Mark I in the Philippine Sea, is described in another paper[5] that recently appeared in JASA. A theoretical paper[6] has been published in JASA on band-limited noise, and the effects the filtering has on the cross-correlation function.

At great depth and at sufficiently high frequencies, the effect of attenuation on the directionality of wind driven ambient noise should be detectable. This operating regime is within the capabilities of Deep Sound. To help extract the effects of attenuation from the noise data, a theoretical model of wind-driven ambient noise in an attenuating ocean[7] has been developed and has been recently published in JASA.

RESULTS

The most recent deployments of Deep Sound Marks II & III were in the Tonga Trench, to a depth of 8.5 km, in September 2012. Both systems recorded ambient noise, environmental parameters and system data on the descent and for an extended period on the seabed. One of the findings concerns the sound speed profile computed from the CTD data, using various algorithms, versus the directly measured sound speed from the SVX. All the algorithms over-estimated the sound speed, relative to that from the SVX, the two best performers being Del Grosso and TEOS-10. Even these returned a sound speed residual of approximately 1 m/s in the deep sound channel. The origin of this discrepancy is currently under investigation, but there is evidence to suggest that it arises from hysteresis in the temperature sensor.

Deep Sound Mark III recorded ambient noise at a depth of 8.5 km on the bottom of the Tonga Trench for a period of about 3 hours. Three of the hydrophone pairs were vertically aligned and one pair was horizontally aligned. Examples of the spatial coherence functions that were obtained are shown in Fig. 1. As can be seen, the three vertical coherence functions, associated with the three different spacings of the hydrophone pairs, collapse onto the same curve when plotted against normalized frequency, indicating that the noise is spatially homogeneous, consisting of a random superposition of plane waves propagating in all directions. The black lines in Fig. 1, representing Cron and Sherman's theory[8] of ambient noise in a deep ocean, show zeros that are close to those in the data.

The theoretical analysis of the effects of attenuation in the ocean[7] shows that the directionality of very deep, high-frequency wind-driven ambient noise is modified to some extent by the attenuation. This modification is seen as a shift in the zeroes in both the horizontal and vertical coherence functions; the horizontal zeroes are shifted to higher frequencies and the vertical zeroes to lower frequencies. Although these effects are subtle, we are searching for them in the Deep Sound III data from the bottom of the Tonga Trench, which is just about in the operating regime where attenuation may be becoming significant.

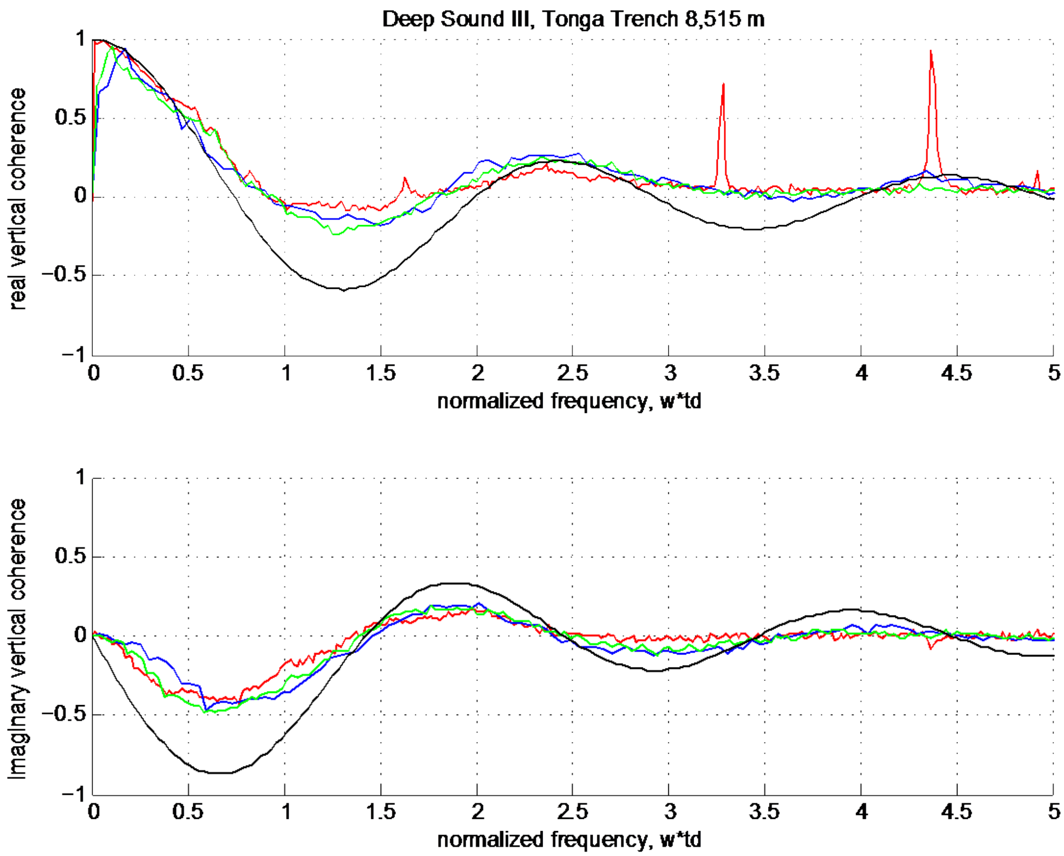

Fig. 1 Vertical coherence functions from Deep Sound III at a depth of 8,515 m in the Tonga Trench. The red, green and blue lines represent data from hydrophone pairs with different spacings and the smooth black lines are from Cron and Sherman's theory of wind-driven noise in a deep ocean.

IMPACT/APPLICATIONS

Deep Sound Mark III is modular, allowing the hydrophones in the current configuration to be replaced with any other type of sensor, for instance, dissolved oxygen, carbon dioxide or hydrocarbon sensors. Mark III can even profile the local current vector, since the on board inertial navigation system tracks translational (and rotational) motion due to advection from the current.

My theory of wave propagation in marine sediments[9] has a variety of applications, particularly in regard to acoustic inversions for the geo-acoustic parameters of the seabed. Charles Holland and Ross Chapman are independently using the theory to develop numerical inversion schemes for recovering the properties of the bottom.

Michael Porter is developing a suite of 3-D acoustic propagation models. He is using my analytical models[10, 11] of the penetrable wedge and the conical seamount, both developed many years ago, for comparison with his numerical results.

A conference was held recently on "Basic Science and the Future Warfighter" [ASD(R&E) Basic Science/Labs, Arlington, VA July 30-31 2012]. One of the prominent ideas discussed was the use of low-flying aircraft as sources of sound for underwater acoustics applications, including target detection and bottom characterization, as investigated theoretically and experimentally by my research group at SIO over recent years[12]. Our planned research on helicopter noise is also relevant in the same context.

TRANSITIONS

As previously reported.

RELATED PROJECTS

As previously reported.

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PUBLICATIONS

Journal Articles & Chapters in Books

1. M. J. Buckingham, "Theory of the directionality and spatial coherence of wind-driven ambient noise in a deep ocean with attenuation", *J. Acoust. Soc. Am.*, **134**, 950-958 (2013) [published, refereed]
2. D. R. Barclay and M. J. Buckingham, "Depth dependence of wind-driven, broadband ambient noise in the Philippine Sea", *J. Acoust. Soc. Am.*, **133**, 62-71 (2013) [published, refereed]
3. D. R. Barclay and M. J. Buckingham, "Depth dependence of the power spectral density and vertical directionality of rain noise in the Philippine Sea", *J. Acoust. Soc. Am.*, **133**, 2576-2585 (2013) [published, refereed]
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PATENTS

As previously reported.

HONORS/AWARDS/PRIZES

1. Member of the Executive Council, Acoustical Society of America, 2010 – 2013.
2. General Chair, Acoustical Society of America meeting, San Diego, California, Fall 2011.

3. Member of scientific committee, 1st International Conference on Underwater Acoustics, Corfu, Greece, 23 – 28 June 2013.