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

Michael J. Buckingham
Marine Physical Laboratory, Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive, La Jolla, CA 92093-0238
phone: (858) 534-7977 fax: (858) 534-7641 email: mbuckingham@ucsd.edu

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http://extreme.ucsd.edu

LONG-TERM GOALS

1) Deep-water ambient noise profiling Profile the spectral, temporal and spatial properties of ambient noise from the surface to the bottom of the deepest ocean trenches over a broad frequency range (3 Hz – 40 kHz). 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. 3) Doppler geo-spectroscopy Develop the use of a light aircraft as a sound source in an inversion technique for returning the geo-acoustic parameters of the seabed in shallow water.

OBJECTIVES

1) The scientific objective of the deep-water ambient noise research is to measure the ambient noise in the deep ocean as a function of depth, from the sea surface to the seabed, in the deepest ocean trenches. These include the Challenger Deep in the Mariana Trench, Pacific Ocean, at a depth of almost 11 km, and the Puerto Rico Trench in the Atlantic at 8 km. Of particular interest is the behavior of the noise at and below the critical depth. Environmental and system data will also be depth-profiled, including temperature, salinity, pressure and sound speed, along with all system motions (yaw, pitch, roll and horizontal/vertical translations). 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 two sets of dispersion relations, one for compressional and the other for 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 geo-acoustic properties of the sediment, including porosity, density, grain size and overburden pressure.

3) The Doppler geo-acoustic spectroscopy technique 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.

APPROACH

1) Deep-water ambient noise profiling A deep-diving Autonomous Instrument Platform (AIP) 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 – 40 kHz, calibrated under high hydrostatic pressure to equivalent depths of 7 km), which may be arranged in various vertical and horizontal configurations, and an environmental sensor package (CTD plus sound velocimeter). The system is autonomous (untethered), descending under gravity at a rate of 0.6 m/s, and, after releasing a weight at a pre-assigned depth, returning to the surface under buoyancy at the same rate of 0.6 m/s. Throughout the descent and ascent, acoustic and environmental data are continuously recorded. Three beacons (high intensity strobe, radio antenna, and Argos GPS) aid recovery of the system. Numerous 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 experimental work 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 Experiment 1999 (SAX 99). 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 99 experiments and elsewhere.

3) Doppler geo-acoustic spectroscopy A 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 extracting the recovering the speed of sound in the seabed. The 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, picking up 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, the remaining geo-acoustic parameters are estimated using the correlations provided by the grain-shearing theory.

WORK COMPLETED

Three versions of Deep Sound, designated the Mk. I, Mk. II and Mk. III, have been designed and built and are complete. The Mk. 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 as a result of the compression due to the extreme hydrostatic pressure encountered at depth. Mk. I has now been retired and is no longer operational.

Deep Sound Mk. II has been deployed in the Mariana Trench, 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 40 kHz. Mk. II is still operational, having survived the deep descent intact with no obvious sign of spalling.

Deep Sound Mk. III is the most sophisticated of the three systems, capable of descending to a depth of 11 km, with all instrumentation outside the sphere specially designed to withstand the pressure at such depths. The Vitrovex glass sphere is slightly smaller than those in the previous versions, and it includes an inertial navigation system returning pitch, roll and yaw, as well as the three orthogonal translational motions. Also on board is a sound velocimeter which records sound speed 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 Mk. 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 appalling, with heavy seas and storms throughout the time at sea. The M/V Super Emerald was not well suited to the task, and unfortunately 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. Deep Sound Mk. II and III are now safely back in the laboratory and ready for another attempt at going to the bottom of the deepest ocean trench.

An invited paper[1] on the 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 submitted to 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 Mk. I, as an intense storm passed more or less overhead. This deployment of Mk. I, including an analysis of the storm data, is described in a paper[4] that is currently under review at JASA. A fourth paper[5] is in preparation for JASA on band-limiting noise, and the effects the filtering has on the cross-correlation function.

RESULTS

Deep Sound Mk. I and II were both deployed to a depth of 9 km in the Mariana Trench in November 2009, where they continuously recorded ambient noise data, along with environmental information, on the descent and the ascent. The spectral level of the noise was found to increase slightly with increasing depth, even through the critical depth, by an amount that depends on frequency. During an earlier deployment of Mk. I, in the Philippine Sea in May 2009, the sound of several rainstorms was captured by the system, and is clearly visible in the spectrograms. An analysis of the noise shows that the rain noise is very directional, with a strong lobe near the downward vertical[4]. An inversion was performed from which the storm was tracked across the sea surface, and some verification of the results was provided by ground truth measurements of rainfall rates made on board the research ship supporting the deployment.

My theoretical treatment of cross-correlation in spatially homogeneous, anisotropic ambient noise fields identifies the conditions necessary for extraction of the Green's function from directional noise[2], on the assumption that the noise spectrum is white. Several examples of anisotropy are considered in the analysis, including Cron and Sherman's deep-water, downward-traveling ambient noise field. In that particular case, because of the surface reflection, the Green's function depends on the depth of the transducers, whereas the cross-correlation function is independent of absolute position in the water column. It is, therefore, impossible to recover the Green's function from the noise, because the surface-reflected component will always be absent from the cross-correlation function. It is possible, however, to recover the sound speed in the medium from the noise, since the cross-correlation function exhibits sharp features at correlation delay times numerically equal to the travel time between the sensors.

In a related analysis, the effect on the cross-correlation function of band-limiting the ambient noise is investigated theoretically[5]. Horizontal and vertical alignments of the hydrophones are considered in the context of isotropic noise and also deep-water noise, as represented by the Cron and Sherman model. The focus of the analysis is sensor separations that are very much greater than the longest wavelength (associated with the lowest frequency) in the pass-band. It turns out that, if the filter has a low-frequency roll-off scaling as frequency to the power of $2n$, this acts as a differentiator of order $2n$ on the cross-correlation function. In general, cross-correlation functions of filtered ambient noise do not exhibit delta functions that could be identified with the Green's function, but they do possess sharp features that allow the travel time between the sensors to be determined. From the travel time, it is possible to recover the sound speed in the medium. The mechanism that gives rise to these sharp features in the cross-correlation function is, however, quite different from that responsible for the appearance of delta functions in the cross-correlation function of isotropic white noise.
In order to interpret the directional features of the storm noise recorded by Deep Sound Mk. I during the Philippine Sea deployment, a theoretical model of a three-dimensional noise field showing strong horizontal and vertical directionality has been developed[3]. The horizontal component of the noise is represented by a von Mises distribution, taken from directional statistics, whilst the vertical component, associated with wave-breaking, is consistent with a set of dipoles distributed randomly across the sea surface. A windowing function locates the storm center in range from the sensor station. The total noise field is treated as separable, given by the product of the horizontal and vertical components. Expressions for the spatial coherence and cross-correlation of the noise at two horizontally aligned hydrophones are derived. Through a couple of parameters, the intensity and angular position of the storm can be adjusted, allowing the spatial statistics of the noise for various geometrical configurations to be easily investigated.

IMPACT/APPLICATIONS

Deep Sound Mk. III is designed for making ambient noise measurements to a depth of 11 km in the ocean. The system is modular so, although the sensors in the current configuration are hydrophones, one or more of them could be replaced with any other type of sensor, for instance, oxygen, carbon dioxide or hydrocarbon sensors. Thus, Mk. III has the capability of profiling various entities, besides ambient noise, from the sea surface to any depth down to 11 km in the ocean. Mk. III can even profile the local current vector, since its on board inertial navigation system allows it track motion due to advection from the current.

TRANSITIONS

As previously reported.

RELATED PROJECTS

Charles Holland is using my three-parameter representation[6] of the Biot theory as an integral component of an inversion scheme for recovering sediment properties from acoustic reflections off the seabed. He is also interested in using my theory of wave propagation in marine sediments[7] as the basis of an inversion scheme for recovering the geo-acoustic parameters of the seabed.

Alessandro Ghiotto, L-3 Nautronix, Freemantle, Australia is interested in the deep ambient noise measurements from Deep Sound, in particular, the level and vertical directionality of the noise as a function of depth.

We are in contact with the Richard Branson's Virgin Oceanic team, who are planning a manned descent to the bottom of the Challenger Deep sometime in the near future (as yet, unspecified). They have invited us to visit Cheyenne, their catamaran parent vessel moored at Newport Beach, CA, with a view to setting up a collaboration with them. In particular, they are interested in having Deep Sound descend with the manned submersible in the Mariana Trench and subsequently in the Puerto Rico Trench. Deep Sound would monitor and record any sound from the vehicle, to be used later if needed for the diagnosis of any problems that may arise.

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