Spatial Statistics of Deep-Water Ambient Noise; Dispersion Relations for Sound Waves and Shear Waves

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LONG-TERM GOALS

1) Deep-water ambient noise Profile the spectral, temporal and spatial properties of broadband (3 Hz – 30 kHz) ambient noise from the sea surface to the seabed in the deep ocean trenches. Develop theoretical models of the second-order spatial statistics of the noise. New focus is on the deepest trench in the ocean at 11,000 m, the Challenger Deep in the Mariana Trench.
2) Dispersion relations for sound waves and shear waves Develop a unified, physics-based model of sound wave and shear wave propagation in saturated, unconsolidated marine sediments. New focus is on: 1) the dispersion associated with a frequency power law attenuation; 2) wave propagation in very fine-grained sediments (silt and clay).

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 deep ocean trenches 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). New objectives include profiling dissolved oxygen, carbon dioxide, hydrocarbons and pH from the surface to the bottom of the deepest trenches. A further objective is to develop theoretical models of the spectral, spatial and temporal properties of the ambient noise.
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 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. The theory has already been developed for sands and the new objective is to extend it to include the inter-particle cohesive forces in silts and clays and the role they play in controlling wave speeds and attenuations. On a

quantum mechanical level, these forces are the result of molecular and electrostatic interactions, and include van der Waals forces, whilst on a larger scale capillarity and excess charges are instrumental in affecting the cohesion of the particles. A new focus is on the dispersion relations associated with an attenuation obeying a frequency power law, since this type of attenuation is directly relevant to the propagation of waves, particularly shear waves, in marine sands, silts and clays.

APPROACH

1) Deep-water ambient noise Three deep-diving, autonomous instrument platforms, known as Deep Sound I, II, & III, have been designed and built by my research group. The Deep Sound instrument platform consists of a Vitrovex glass sphere pressure housing, containing microprocessors for system control, along with data acquisition and data storage electronics. External to the sphere are several High Tech, Inc. (HTI) hydrophones (bandwidth 3 Hz – 30 kHz, calibrated at SIO 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 satellite navigation system) aid recovery of Deep Sound. Several fail-safe devices ensure that the weight is indeed dropped, thus allowing the system, with the data onboard, to return to the surface.

   In support of the ambient noise experiments using the Deep Sound systems, a series of theoretical models for the spatial coherence and cross-correlation properties of ambient noise in the deep ocean is being developed. These models address the vertical and horizontal directionality of the noise and their relationships to the coherence function and the cross-correlation function. The models will help in interpreting the two-point measurements of noise recovered from the Deep Sound systems.

2) Marine sediment acoustics The theoretical approach, which has come to be known as the grain-shearing (GS) theory, is based on the idea that the dispersion and attenuation of compressional and shear waves in unconsolidated porous media, such as marine sediments, are governed by inter-granular interactions. The two-phase unconsolidated granular material is treated as a continuum in which, during the passage of a wave, internal stresses are present, associated with micro-roughness in the form of asperities on the surfaces of contact of the grains. Compressional and shear waves are represented by (time domain) wave equations, derived from the Navier-Stokes equation, taking account of the stresses that are present at the inter-granular contacts. These wave equations contain convolutions of partial-differential terms representing dissipation and dispersion associated with the mechanism of strain-hardening. As the grains slide against one another during the passage of a wave, the strain-hardening interaction becomes progressively stiffer until eventually the motion ceases. Although, on a microscopic level, this is a non-linear mechanism, the associated wave equations are linear. The compressional and shear dispersion relations that derive from the GS wave equations take the form of closed form algebraic expressions. The GS theory is the basis for two new lines of research: 1) wave propagation in very

fine-grained sediments (silts and clays), in which inter-granular cohesion is governed by a number of forces, including capillarity and forces associated with quantum mechanical interactions (van der Waals forces); 2) dispersion in materials exhibiting an attenuation obeying a frequency power law.

WORK COMPLETED

Three versions of Deep Sound, designated Marks I, II and III, have been designed and built. Each evolution of the system has progressively more instrumentation onboard. Deep Sound Mark I, which has been deployed a number of times to great depths in the Philippine Sea and the Mariana Trench, is showing signs of pressure-cycling fatigue. It 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 measures the speed of sound directly, thus providing a check on the sound speed computed from CTD data. This allows us to test the validity of the sound speed algorithms under the extreme pressures found at the bottom of the ocean trenches.

An attempt was made to deploy Deep Sound 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. However, severe weather in the form of Typhoon Mufia prohibited the deployment of any of the Deep Sound systems. Moreover, 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 that 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 four 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 of the Deep Sound systems descended to a depth of 8.5 km, stayed on the bottom for extended periods (20 minutes for DS II and 3 hours for DS III), and then successfully returned to the surface, all the while collecting broadband (3 Hz – 30 kHz) ambient noise data, along with environmental and system data. As far as we know, these are the deepest measurements of broadband ambient noise that have ever been made.

During December 2014, Deep Sound II & III were deployed in the Challenger Deep, Mariana Trench. The experiment was carried out from the R/V Falkor, a very-well appointed research vessel operated by the Schmidt Research Institute. To participate in the cruise to the Challenger Deep, we submitted a research proposal to SRI, which was successful. For the Challenger Deep deployments, DS II was programmed to descend to 9 km and DS III to the bottom at a depth of 11 km. DS II returned successfully but DS III never re-surfaced and was lost for reasons unknown.

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 Mk. 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 that 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 recently been published in JASA.

An analysis of the Deep Sound Mk. III ambient noise data from the bottom of the Tonga Trench has been performed and reported in a paper that has been published[8] in JASA.

Turning to wave propagation in porous materials, an analysis of shear wave propagation in sandy sediments has been performed in which the shear attenuation predicted by the GS theory is compared with all the available data sets in the literature on shear attenuation as a function of frequency. A paper on this analysis has been published[9] in JASA. Most recently, an analysis of dispersion associated with an attenuation obeying a frequency power law has been developed and submitted for publication[10] in JASA.

RESULTS

DS II was deployed about 20 minutes after DS III on 17 December 2014, when both systems were programmed to descend into the Challenger Deep, to 9 km and 11 km, respectively. At a depth of 8.2 km, DS II recorded the sound of an implosion in the form of a shock wave followed by a sequence of bubble pulses (see Fig. 1). No bottom-bounce signal was recorded by DS II but surface-reflection and surface-bottom reflections were clearly present in the record. The implosion was also captured on a near-surface hydrophone deployed from the R/V Falkor, and again, no bottom-bounce signal was present in the time series of the event. Several glass-sphere systems belonging to another research group from SIO were already resident on the seabed at the time that DS II and DS III were descending. One of these bottom-dwelling systems failed to return to the surface, as did DS III. The fate of DS III is not clear. It seems that it did not implode, since if it had, being in mid-water column, a bottom-reflection should have been present in the DS II recording of the implosive event. But no such bottom-bounce signal was detected. It is conceivable that one of the systems already on the bottom imploded, after which DS III continued its descent, only to become stuck in the ooze at the bottom of the Challenger Deep. How this could have happened, however, is not clear, since several failsafe devices were onboard to prevent just such an occurrence. We shall probably never know for certain what happened to DS III.

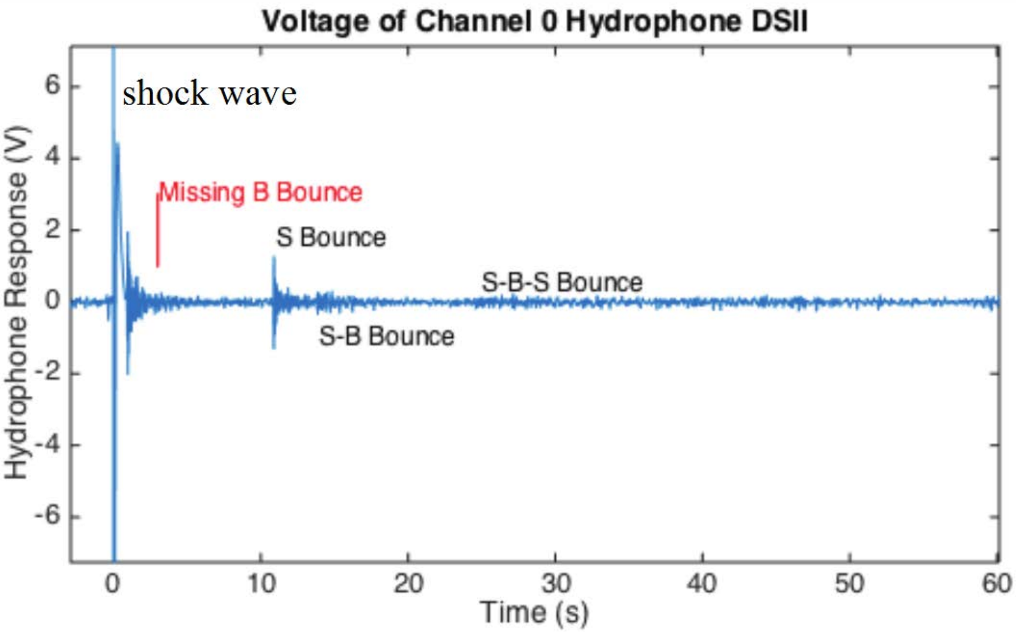

Fig. 1 DS II recording of an implosion in the Challenger Deep.

With regard to sediments, all the data sets available in the open literature on the frequency dependence of shear wave attenuation have been carefully examined and compared with the predictions of the grain-shearing theory. The data, which relate to sands and glass beads, saturated and dry, were all from laboratory experiments, since no *in situ* broadband shear-wave data were available at the time. (Since then, Megan Ballard and colleagues have reported broadband shear wave measurements in sediments in Currituck Sound[11].) In all cases, the theory accurately matches the frequency-dependent data[9].

In connection with sediments, a theory of phase speed dispersion in materials exhibiting an attenuation obeying a frequency power law has been developed[10]. An earlier dispersion formula, developed by Horton[12] and subsequently refined by Szabo[13], exhibits non-physical characteristics, which provided the motivation for the new development. The new dispersion formula, which is directly relevant to shear-wave propagation in sediments, has been derived in three different ways. 1) From the causal requirement that the inverse Fourier transform of the complex wavenumber of a propagating wave must be zero for all negative times; 2) from the strain-hardening wave equation; 3) from the simplest version of the Kramers-Krönig dispersion relations, which are sometimes known as the Plemelj formulas. The new formulation, which differs significantly from the Horton/Szabo version, is well behaved in that it does not predict any unphysical behavior. Moreover, it leads to the conclusion that certain values of the frequency exponent, including all the integers, are inadmissible. Physically, this occurs because, with these inadmissible values, it is not possible for the frequency components of the real and imaginary parts of the complex wavenumber to combine in such a way as to ensure that the inverse Fourier transform of the wavenumber is zero for all negative times.

IMPACT/APPLICATIONS

Deep Sound is a modular instrument platform, allowing the hydrophones in the current configuration to be replaced with any other type of sensor, for instance, dissolved oxygen, carbon dioxide, pH or hydrocarbon sensors. Deep Sound is capable of depth-profiling the deep ocean trenches, recovering oceanographic and acoustic data that has previously not been available. Deep Sound can even profile the local current vector, since the onboard inertial navigation system (INS) tracks translational and rotational motion due to advection from the current.

My grain-shearing (GS) theory of wave propagation in marine sediments[14] 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 GS theory to develop numerical inversion schemes for recovering the properties of the bottom. Megan Ballard has compared the predictions of the GS theory with her measurements of sound waves and shear waves in sandy sediments in Currituck Sound and found compelling agreement[11]. The GS theory and the new dispersion formula associated with an attenuation scaling as a frequency power law should also play central roles in future research projects aimed at understanding wave propagation in very fine-grained sediments, that is, silts and clays.

Michael Porter of Heat, Light & Sound Research, Inc. is developing a suite of 3-D acoustic propagation models. He is using my analytical models[15, 16] of the penetrable wedge and the conical seamount, both developed some years ago, to help validate 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[17]. We are planning a research project on helicopter noise, which 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, “Wave speed dispersion associated with an attenuation obeying a frequency power law”, *J. Acoust. Soc. Am.* **in review** (2015) [in review, refereed].
2. S. E. Freeman, M. J. Buckingham, L. A. Freeman, M. O Lammers and G. L. D’Spain, “Cross correlation triangulation and curved-wavefront focusing using a horizontal bi-linear hydrophone

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PATENTS

As previously reported.

HONORS/AWARDS/PRIZES

1. Member of the Scientific Committee, Underwater Acoustics Conferences, usually held in Greece.
2. Invited Lecturer, ASA School, 167th Meeting of the Acoustical Society of America, Providence, Rhode Island, 3 & 4 May 2014.
3. Member of the Advisory Committee, 11th International Conference on Theoretical and Computational Acoustics (ICTCA), College Station, Texas 10 – 14 March 2014.
4. Keynote lecturer, "Sound propagation in unconsolidated marine sediments" 11th International Conference on Theoretical and Computational Acoustics, College Station, Texas, 11 March 2014.
5. My graduate student, Simon Freeman, won Outstanding Student Paper Award for "Array-based hydroacoustic characterization of P, S, and T-phases in the Philippine Sea", Ocean Sciences section, American Geophysical Union Fall meeting, 9-13 December 2013.
6. My graduate student, Simon Freeman, successfully defended his Ph.D. thesis, 26 November 2013.
7. Chair, Session 4aNSb – Future of Acoustics, ICA/ASA Montreal, 6 June 2013.
8. Member of the Executive Council, Acoustical Society of America, 2010 – 2013.
9. Chair, External Affairs committee, Acoustical Society of America, 2012-2013.
10. General Chair, 162nd Meeting of the Acoustical Society of America, San Diego, California, Fall 2011.