Geoacoustic Parameters of Marine Sediments: Theory and Experiment

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LONG-TERM GOALS

There are two long term goals, as follows. 1) Sediment Acoustics Develop a physics-based model to characterize the inter-relationships that exist between the geo-acoustic properties (*i.e.*, compressional-wave speed and attenuation, shear-wave speed and attenuation, frequency, density, porosity, grain size, grain shape and overburden pressure) of saturated, unconsolidated granular media such as marine sediments. 2) Deep Water Ambient Noise Profiling Depth-profile the spatial and temporal properties of ambient noise from the sea surface to the greatest depths of the ocean over a broad frequency band (10 Hz - 100 kHz).

OBJECTIVES

1) The scientific objectives of the sediment acoustics research may be conveniently divided into six categories. (a) Incorporate the effects of pore-fluid viscosity into my analytical theory of wave propagation in saturated granular materials. (b) Continue developing my recently introduced Doppler geo-spectroscopy measurement technique for estimating the geo-acoustic properties of marine sediments using a high-Doppler airborne sound source. (c) Develop analytical and numerical models of wave propagation in a 3-layer waveguide (atmosphere-ocean-sediment) from a moving airborne sound source. (d) Develop inversions, based on the 3-D numerical forward model, for extracting sediment parameters and sub-bottom structure from Doppler geo-spectroscopy data. (e) Identify the relationship between the geometrical properties of individual grains (*e.g.*, size and shape) and the physical properties (*e.g.*, porosity) of the bulk granular material. (f) Develop transient solutions of the wave equations of classical physics (Stokes' equation, van Wijngaarden's equation and the time-dependent diffusion equation).

2) The scientific objective of the deep-water ambient noise research is to characterize the ambient noise in the deep ocean as a function of depth, from the sea surface top the seabed, to depths as great as 11 km (the Challenger Deep in the Mariana Trench).

APPROACH

1) Sediments

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14. ABSTRACT

There are two long term goals, as follows. 1) Sediment Acoustics Develop a physics-based model to characterize the inter-relationships that exist between the geo-acoustic properties (i.e., compressional-wave speed and attenuation, shear-wave speed and attenuation, frequency, density, porosity, grain size, grain shape and overburden pressure) of saturated, unconsolidated granular media such as marine sedi-ments. 2) Deep Water Ambient Noise Profiling Depth-profile the spatial and temporal properties of ambient noise from the sea surface to the greatest depths of the ocean over a broad frequency band (10 Hz - 100 kHz).

15. SUBJECT TERMS

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a) Pore-fluid viscosity and the grain-shearing theory of sound waves and shear waves in sediments

In the original version of my grain-shearing (GS) theory of waves in saturated porous materials, effects due to the viscosity of the pore fluid were neglected. Such effects manifest themselves at lower frequencies, below 10 kHz, which is below the frequency band of many of the published measurements of wave properties of sediments. However, new, lower-frequency measurements from SAX99 show a sound speed (attenuation) that is somewhat lower (higher) than predicted by the GS theory. To accommodate these observations, the GS theory was extended by incorporating the viscosity of the microscopically thin layer of pore fluid separating contiguous grains. The generalized form is designated the VGS theory, where the first initial serves as a reminder that viscous effects are now included in the model. At higher frequencies, above 10 kHz, the VGS dispersion curves approach those of the GS theory asymptotically; and at lower frequencies, below 10 kHz, the VGS theory shows a very reasonable match to the SAX99 dispersion data. The VGS theory fits the available dispersion and attenuation data, from SAX99 and other experiments, over the frequency range 1 - 400 kHz.

b) Doppler geo-spectroscopy

This technique for measuring the low-frequency (80 Hz to 1 kHz) sound speed in marine sediments relies on a high-speed airborne sound source (a light aircraft) for ensonifying the ocean and sediment. Most of the received sound is in the form of engine and propeller harmonics, whose frequencies extend from about 80 Hz up to 1 kHz. As the source approaches toward (recedes from) the sensor station, the harmonics are Doppler up-shifted (down-shifted). Each harmonic excites normal modes in the water column, which are detected on our autonomous line array of 11 non-uniformly spaced hydrophones. A high-resolution spectrum of a single harmonic exhibits sharp peaks, representing the Doppler up- and down-shifted modal field. The magnitude of the modal shifts depends on the speed of the source and the properties of the sea bed. An inversion of the modal shifts returns the sound speed in the sediment; and the remaining geo-acoustic parameters are determined from their correlations with the sound speed, which are known from the VGS theory.

c) Theoretical models of sound from a moving source in a 3-layer waveguide

Two analyses of sound in a 3-layer waveguide (atmosphere, ocean and sediment) from a high-Doppler, horizontally moving, unaccelerated airborne source have been developed based on multiple integral transforms in conjunction with appropriate boundary conditions. The first is a 2-D model (horizontal line source perpendicular to the source track), which yields an exact analytical solution for the field in all three layers, including a new 3-layer dispersion relation that takes account of all the Doppler shifts introduced by the moving source. The second is a 3-D model (point source), whose solution is a double wavenumber integral that is evaluated numerically. Both field solutions exhibit interesting fore-aft asymmetries, which appear to be consistent with the geo-spectroscopy experimental observations.

d) Geoacoustic inversions for Doppler geo-spectroscopy

Based on a comparison of the predictions from the 3-D, double-wavenumber integral model and the data obtained from our Doppler geo-spectroscopy experiments, a “best match” is obtained, from which the sediment parameters are estimated. Essentially, a cost function is formed and minimized.

e) Grain shape and sediment porosity

Of all the physical properties, it could be argued that the porosity of a sediment is the most important in determining its wave properties. The porosity is related to the mean grain size, although not uniquely, suggesting that another parameter is involved, perhaps grain shape or roughness. By examining the shapes of individual grains under a microscope, the relationships between mean grain diameter, rms roughness and bulk-sediment porosity are being investigated.

f) Transient solutions of three wave equations
The solutions of the classical (dispersive) wave equations for harmonic waves have long been known but the solutions for pulse propagation are less well understood, with a number of misconceptions appearing in the literature. Three classical wave equations for acoustic propagation in a dispersive medium have been investigated: Stokes' equation for waves in a viscous fluid; van Wijngaarden's equation (VWE) for waves in a viscous, bubbly liquid; and the time-dependent diffusion equation (TDDE) for waves in the interstitial gas in a porous solid.

2) Deep-water ambient noise profiling

a) To obtain time series data on the ambient noise as a function of depth, a system known as Deep Sound has been developed. Deep Sound consists of a Vitrovex glass sphere, approximately 0.5 m in diameter, which houses data acquisition and storage electronics along with a control CPU (basically, a stripped down PC). Outside the sphere, a suite of hydrophones is arranged in vertical and horizontal configurations, allowing, in addition to the spectral level, the spatial coherence of the noise to be determined in the two orthogonal directions. Environmental sensors (CTD) are included in the package, and system orientation is monitored by three-axis accelerometers. Deep Sound descends under gravity to a pre-assigned depth, where a burn-wire releases a weight, allowing the system to return to the surface under buoyancy. The descent and ascent rates are approximately 0.5 m/s.

b) In support of the experimental work with Deep Sound, an analytical model of ambient noise in the deep ocean is being developed. The theoretical model is based on a bi-exponential sound speed profile, which resembles profiles found in the deep ocean inasmuch as it exhibits a sound speed minimum, and thus it acts as a waveguide in which sound is trapped and may propagate for long distances. One advantage of the model is that it allows the temporal and spatial properties of the noise to be examined in the vicinity of the conjugate depth.

WORK COMPLETED

1) Sediments

a) Pore-fluid viscosity and the grain-shearing theory of sound waves and shear waves in sediments
The VGS theory has been completed and its predictions compared favorably with the dispersion and attenuation data from SAX99. The new theory has been published in the September 2007 issue of *Journal of the Acoustical Society of America*.

b) Doppler geo-spectroscopy
During September 2005, as part of the ONR-sponsored MAKAI experiment, conducted off the west coast of Kauai, we performed Doppler geo-spectroscopy experiments using our Fly-By line array of 11 non-uniformly spaced hydrophones. A light aircraft (Maule MXT7-180 STOL) was used as the sound source. A further set of flying experiments was conducted at a deeper site, close to the R/V Kilo Moana, the research ship participating in MAKAI. Some data from our aircraft experiments may be downloaded from our web site and is freely available for anyone to use.

c) Theoretical models of sound from a moving source in a 3-layer waveguide
Both the 2-D and 3-D model are complete and have been published in the October 2006 issue of the *Journal of the Acoustical Society of America*.

d) Geoacoustic inversions for Doppler geo-spectroscopy
Refinements to the geo-acoustic inversion procedure have continued, including the development of an adaptive filtering technique for enhancing the modal peaks in the Doppler-shifted spectrum.

e) Grain shape and sediment porosity
Measurements of the 2-D outlines of hundreds of grains have been made with a computer-controlled digital microscope and the statistics of the outlines determined from a newly developed Matlab code. The outlines of grains from beaches, sea beds, river estuaries and sand dunes have been found to possess essentially the same normalized power spectrum, which takes the form of an inverse-power-law, varying as $n^{-10/3}$, where n is the number of the Fourier harmonic. An algorithm has been developed which produces grain shapes that are visually similar to actual grains and which have exactly the same statistical properties. This work was published in the *J. Geophy. Res.* in January 2009.

f) Transient solutions of three wave equations
The analysis of the transient solutions of Stokes' equation, the VWE and the TDDE are complete. The solutions of Stokes' equation have been published in *Physical Review E* in August 2005 and a paper on the VWE and TDDE was published in the *J. Acoust. Soc. Amer.* in October 2008.

2) Deep-water ambient noise profiling

Two versions of Deep Sound, designated Mk I and Mk. II, have been built and tested in the ocean. The Mk. I system has just two vertically aligned hydrophones, while Mk. II has four hydrophone channels, an improved suite of environmental sensors plus a number of other enhanced design features. We successfully deployed the Mk. I system in the Philippines Sea on three occasions in May 2009 to depths of 5,200 m, 5,500 m and 6,000 m. Each of these deep deployments lasted about six hours, and recovery of the system was facilitated by the three beacons on board (a high intensity strobe light, an RF antenna, and an argos GPS antenna).

RESULTS

1. Sediments

a) Pore-fluid viscosity and the grain-shearing theory of sound waves and shear waves sediments
The new theory is complete and has been published [JASA, v. 122(3) 1486-1501 (2007)].

b) Doppler geo-spectroscopy
Preliminary analysis of the MAKAI data indicates that the low-frequency (≈ 100 Hz) sediment sound speed is in the region of 1650 m/s, consistent with expectations for a water-saturated medium sand.

c) Theoretical models of sound from a moving source in a 3-layer waveguide
Complete solutions have been derived for the 2-D and 3-D fields in a Pekeris waveguide in the presence of source motion. As part of both the 2-D and 3-D analyses, a new dispersion relation has been derived, allowing the Doppler frequency shifts of the modes to be determined from straightforward algebraic expressions. The new models have been published. [JASA, **120**, 1825-1841 (2006)]

d) Geoacoustic inversions for Doppler geo-spectroscopy
Significantly improved spectral resolution of the Doppler-shifted modal peaks has been achieved using adaptive filtering.

e) Grain shape and sediment porosity

The new technique for synthesizing the 2-D shapes of sand grains is complete. The algorithm yields grain shapes that not only possess the same statistical properties but also visually resemble the measured outlines. We are now in a position to investigate the packing structure of irregularly shaped particles, which has a direct bearing on the porosity of marine sediments. This work has been published. [JGR, **114**, 1-12 (2009)].

f) Transient solutions of three wave equations

All three equations satisfy causality. Stokes' equation and the TDDE return physically realizable Green's functions, even though in the case of Stokes' equation the phase speed diverges to infinity at infinitely high frequencies. These infinitely fast Fourier components are infinitely attenuated and hence do not propagate through the medium. Van Wijngaarden's equation is non-physical in that it predicts instantaneous arrivals, associated with infinitely fast Fourier components that are not infinitely attenuated and which do, therefore, propagate through the medium. The analyses of the three dispersive wave equations have been published in two papers. [Phys. Rev E, **72**, 026610, 1-9 (2005); JASA, **124**(4), in press (2008)]

2) Deep-water ambient noise profiling

a) The three Philippines Sea deployments of Deep Sound were both engineering tests and data collection exercises. Based on the deployments, several design changes have been made, including the use of custom-made, open-pore foam boots on the hydrophones, which reduce significantly the effects of hydrodynamic fluctuations on the output of the sensors. Even without the boots, much of the Mk. I noise data from the Philippines Sea is usable, with preliminary analyses indicating that there is little change in the level and character of the noise as the transition is made through the conjugate depth.
b) The most difficult part of the analytical theory of ambient noise in deep water, namely the analysis of acoustic propagation in the bi-exponential profile, is complete and almost ready for publication. The propagation analysis has been incorporated into a theory of ambient noise, which itself is well on the way to completion and should be ready for publication within the next year.

IMPACT/APPLICATIONS

My theoretical and experimental work on the wave properties of marine sediments, and dispersive media in general, has gained a following in the ocean acoustics research community. At international conferences on acoustics, my theories are cited regularly, suggesting that the work is influencing other scientists in their research on wave propagation in granular materials.
Our work on Deep Sound, although relatively recent, has received considerable attention from the research community. The fact that the system can conduct acoustic surveys to depths well below the conjugate depth is of interest to the US Navy.

TRANSITIONS

Several research groups in the USA and elsewhere are using the results of my theoretical work in their own programs, including investigators at the Applied Physics Laboratory, University of Washington, the University of Hawaii, NRL Washington D.C., NRL Stennis and in UK government research laboratories. This includes my work on ambient noise, waves in sediments, acoustic propagation in shallow ocean channels, sound in multi-layer waveguides, and underwater sound fields from high-Doppler, airborne sources.

RELATED PROJECTS

U.S.A.

1. Dr. Michael Richardson, N.R.L., Stennis, and I are continuing to collaborate on the collection and interpretation of sediment data. I am also closely linked to Dr. Eric Thorsos and the group at APL, University of Washington in connection with sediments and other issues.

2. I have worked with Dr. Michael Porter of HLS Research and Dr. Martin Siderius of Oregon State University in helping to plan the ONR-supported MAKAI experiment (selection of sites, etc). I am also collaborating with Martin with research on sediments and deep-water ambient noise. Recently, I gave a seminar at HLS on my grain-shearing theory of wave propagation in granular materials.

3. Prof. Giorgio Gratta, Stanford, and I are continuing research on the underwater acoustic detection of extremely high energy neutrinos. Acoustic data for this project are being provided by the U.S. Navy's AUTEC range off Andros Island, Bahamas.

Canada

1. Prof. Ross Chapman, University of Victoria, B.C., and I are collaborating on a shallow water experiment aimed at determining low-frequency (80 Hz to 1 kHz) sound speed and attenuation in marine sediments. In particular, we shall try to use the head wave for extracting the required information. For this frequency band, Ross has a low-intensity air gun source and we use an airborne source of opportunity, two completely different ways of exciting the head wave, but which should yield compatible answers.

United Kingdom

1. Prof. Tim Leighton, Institute of Sound and Vibration Research, University of Southampton, and I are discussing several joint research projects on underwater acoustics. These will involve the inter-change of graduate students, post-docs and perhaps more senior staff between ISVR and SIO. In May 2006, under a UK initiative known as "SETsquared Collaborative US UK Research Programme", I met Prof. Phil Nelson, Vice Chancellor, University of Southampton, with a view to starting a joint research program between SIO and ISVR. It is not yet clear how this will develop, but under the SETsquared initiative, the UK has funds to supportive such collaborative efforts. (I hold a visiting Professor appointment at ISVR).

2. Dr. Nicholas Pace, University of Bath and I are discussing the possibility of using an airborne source for low-frequency measurements of sediment properties in the Mediterranean.

3. Nathan Price and Gareth Somerset, SEA Ltd. are developing a system for inverting ambient noise measured on a vertical line array to obtain sediment parameters. Their system uses the vertical coherence of ambient noise, as I proposed some years ago, combined with my recent theory of waves in sediments, to yield the majority of sediment properties.

4. Dr Alastair Cowley, DERA, Winfrith is continuing to collaborate with me on phased array techniques applied to acoustic daylight imaging. Several years ago, his team of engineers conducted tests in San Diego Bay using our ADONIS array head of 128 hydrophones with their

high-speed beamformer. This phased array system, without the spherical reflector that we used in our original acoustic daylight experiments, yielded recognizable images of targets at ranges of approximately 10 m solely from the acoustic illumination provided by the ambient noise in the ocean.

Netherlands

1. Prof. Dick Simons and his group at Delft University have been applying a signal processing technique that they have developed to the Doppler geo-spectroscopy data from our shallow water experiments north of La Jolla, California. They presented some of this work at the recent Acoustics '08 meeting in Paris, France. Our data sets containing aircraft acoustic signatures above and below the sea surface may be downloaded from our web site and are freely available for anyone to use.

PUBLICATIONS

Journal Articles & Chapters in Book

1. D. R. Barclay and M. J. Buckingham, "On the shapes of natural sand grains", *J. Geophys. Res*. **114**, B02209, doi:10, 1-12 (2009) [published, refereed]

2. S. D. Lynch, G. D'Spain and M. J. Buckingham, "Temporal variability of narrow-band tones in a very shallow coastal waveguide", *J. Acoust. Soc. Am.*, (2008) [submitted, refereed]

3. M. J. Buckingham, "On the transient solutions of three acoustic wave equations: van Wijngaarden's equation, Stokes' equation and the time-dependent diffusion equation", *J. Acoust. Soc. Am.*, (2008) **124**, 1909-1920 (2008) [published, refereed]

4. M. J. Buckingham, "On pore-fluid viscosity and the wave properties of saturated granular materials including marine sediments", *J. Acoust. Soc. Am.*, **122**, 1486-1501 (2007) [published, refereed]

5. M. J. Buckingham and E. M. Giddens, "Theory of sound propagation from a moving source in a three-layer Pekeris waveguide", *J. Acoust. Soc. Am.*, **120**, 1825-1841 (2006) [published, refereed]

6. M. J. Buckingham and E. M. Giddens, "On the acoustic field in a Pekeris waveguide with attenuation in the bottom half-space", *J. Acoust. Soc. Am.*, **119**, 123-142 (2006) [published, refereed]

7. M. J. Buckingham, "Causality, Stokes' wave equation and acoustic pulse propagation in a viscous fluid", *Phys. Rev. E.*, **72**, 026610(9) (2005) [published, refereed].

8. M. J. Buckingham, "Compressional and shear wave properties of marine sediments: comparisons between theory and data", *J. Acoust. Soc. Am.*, **117**, 137-152 (2005) [published, refereed].

9. M. J. Buckingham, "Acoustic remote sensing of the sea bed using propeller noise from a light aircraft," in *Sounds in the Sea: Introduction to Acoustical Oceanography*, edited by H. Medwin, (Cambridge University Press, Cambridge, 2005) pp. 581-597 [published, refereed].

10. P. D. Thorne and M. J. Buckingham, "Measurements of the form function and total scattering cross section for suspensions of sands," *J. Acoust. Soc. Am.*, **116**, 2976-2890 (2004) [published, refereed].

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12. M. J. Buckingham, "On the sound field from a moving source in a viscous medium," *J. Acoust. Soc. Am.*, **114**, 3112-3118 (2003) [published, refereed].

13. T. R. Hahn, T. K. Berger, and M. J. Buckingham, "Acoustic resonances in the bubble plume formed by a plunging water jet," *Proc. Roy. Soc. Lond.* A, **459**, 1751-1782 (2003) [published, refereed].

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15. M. J. Buckingham, E. M. Giddens, J. B. Pompa, F. Simonet and T. R. Hahn, "Sound from a light aircraft for underwater acoustics experiments?," *Acta Acust. united with Acust.*, **88** (5), 752-755 (2002) [published, refereed].

16. M. J. Buckingham and M. D. Richardson, "On tone-burst measurements of sound speed and attenuation in sandy marine sediments," *IEEE J. Ocean. Eng.*, **27** (3), 429-453 (2002) [published, refereed].

17. M. J. Buckingham and M. S. Garcés, "Airborne acoustics of explosive volcanic eruptions," *J. Comp. Acoust.*, **9** (3), 1215-1225 (2001) [keynote address, published, refereed].

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22. C. L. Epifanio, J. R. Potter, G. B. Deane, M. L. Readhead, and M. J. Buckingham, "Imaging in the ocean with ambient noise: the ORB experiments," *J. Acoust. Soc. Am.*, **106**, 3211-3225 (1999) [published, refereed].

23. M. J. Buckingham, “Theory of compressional and transverse wave propagation in consolidated porous media,” *J. Acoust. Soc. Am.*, **106**, 575-581 (1999) [published, refereed].

24. M. J. Buckingham, “On the phase speed and attenuation of an interface wave in an unconsolidated marine sediment,” *J. Acoust. Soc. Am.*, **106**, 1694-1703 (1999) [published, refereed].

25. M. J. Buckingham, “Acoustic daylight imaging in the ocean,” in *Handbook on Computer Vision and Applications*, vol. 1, Sensors and Imaging, B. Jähne, H. Haubecker, and P. Geibler, Eds. San Diego: Academic Press, 1999, pp. 415-424 [published, refereed].

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28. G. B. Deane, M. J. Buckingham, and C. T. Tindle, “Vertical coherence of ambient noise in shallow water overlying a fluid seabed,” *J. Acoust. Soc. Am.*, **102**, 3413-3424 (1997) [published, refereed].

29. N. M. Carbone, G. B. Deane, and M. J. Buckingham, “Estimating the compressional and shear wave speeds of a shallow-water seabed from the vertical coherence of ambient noise in the water column,” *J. Acoust. Soc. Am.*, **103**, 801-813 (1997) [published, refereed].

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31. M. J. Buckingham and N. M. Carbone, “Source depth and the spatial coherence of ambient noise in the ocean,” *J. Acoust. Soc. Am.*, **102**, 2637-2644 (1997) [published, refereed].

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Conferences, Workshops and Seminars

1. M. J. Buckingham, “Sound waves and shear waves in marine sediments”, Seminar, Seoul National University, Seoul, Korea, September 2009 [INVITED].

2. M. J. Buckingham, “Geo-acoustic Doppler spectroscopy: a novel technique for surveying the seabed”, Shallow Water Acoustics Conference (SWAC-09), Shanghai, China September 2009 [INVITED].

3. M. J. Buckingham, “Geo-acoustic Doppler spectroscopy: a novel technique for surveying the seabed”, Joint Assembly of IAMAS, IAPSO and IACS, Montreal, Canada (MOCA-09), July 2009 [INVITED].

4. D. R. Barclay and M. J. Buckingham, "Ambient noise profiling with 'Deep Sound'", ONR-sponsored conference on Underwater Acoustics Measurements: Technologies and Results, June 2009 (David Barclay received an Honorable Mention in the Best student Paper Olympiad) [INVITED].

5. M. J. Buckingham and D. R. Barclay, "Theoretical developments on sound wave and shear wave propagation in marine sediments", ONR-sponsored conference on Underwater Acoustics Measurements: Technologies and Results, June 2009 [INVITED].

6. M. J. Buckingham, "Sound waves and shear waves in marine sediments", Symposium on the Acoustics of Poro-Elastic Materials, Bradford, UK, 17-19 December 2008 [KEYNOTE ADDRESS].

7. M. J. Buckingham, "Sound waves and shear waves in marine sediments", seminar, California Institute of Technology, 30 October 2007 [INVITED].

8. M. J. Buckingham, "Wave propagation in sediments: strain hardening and the G-S dispersion relations", 8th International Conference on Theoretical and Computational Acoustics (ICTCA), FORTH, Heraklion, Crete, 2-5 July 2007.

9. M. J. Buckingham, "Inversions - a radical idea: information from ambient noise", Pacific Rim Underwater Acoustics Conference (PRUAC), Vancouver, Canada, pp. 1-2 [INVITED].

10. M. J. Buckingham, F. Simonet and D. R. Barclay, "Geo-acoustic inversion experiments in shallow water off Kauai using sound from a light aircraft", in *Underwater Acoustic Measurements: Technologies and Results*, edited by J. S. Papadakis and L. Bjørnø (FORTH, Heraklion 2007), pp. 125-131. [published, refereed]

11. M. J. Buckingham, E. M. Giddens and F. Simonet, "Inversion of the propeller harmonics from a light aircraft for the geoacoustic properties of marine sediments", in *Acoustic Sensing Techniques for the Shallow Water Environment: Inversion Methods and Experiments*, edited by A. Caiti, N. R. Chapman, J-P. Hermande and S. M. Jesus (Springer, Dordrecht, 2006) [INVITED] pp. 257-263. [published, refereed]

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14. M. J. Buckingham, "Sediment acoustics measurements using a light aircraft", SA04 Workshop, 22-23 March 2006.

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2. M. J. Buckingham and J. Edwards, “Suspension apparatus”, Patent Application No. 8127155, September 1981.
3. M. J. Buckingham, “Improvements in or relating to sonar systems (HARP), Patent Application No. 8200720, January 1982.
4. M. J. Buckingham, “Acoustic imaging in the ocean using ambient noise”, Patent Application No. 08/012894, Notice of Allowance issued in February 1994.
5. M. J. Buckingham, “Method and apparatus for measuring the speed and attenuation of sound”, 28 November 2003, UCSD Ref. No. SD2004-080-1 [provisional application].

HONORS/AWARDS/PRIZES

1. M. J. Buckingham, Royal Aerospace Establishment, Clerk Maxwell Premium, IERE, U.K., for research on the detection of gravitational radiation (1972).
2. M. J. Buckingham, Royal Aerospace Establishment, A. B. Wood Medal, Institute of Acoustics, U.K. (1982)
3. M. J. Buckingham, Commendation for Distinguished Contributions to Ocean Acoustics at the Naval Research Laboratory, Washington D. C., U.S.A. (1984)
4. M. J. Buckingham, Alan Berman Publication Award from the Naval Research Laboratory, Washington D. C., U.S.A. (1988).
5. M. J. Buckingham, Scripps Institution of Oceanography, Science Writing Award for Professionals in Acoustics from the Acoustical Society of America (December 1997), for the article on “Seeing underwater with background noise”, Scientific American, v. 274 (No. 2), 40-44 (1996).
6. M. J. Buckingham, Scripps Institution of Oceanography, Finalist, Discover Magazine Awards for Technological Innovation, June 1998 (Sight category) for pioneering acoustic daylight imaging.
7. M. J. Buckingham, Scripps Institution of Oceanography, Multiple entries in Marquis Who’s Who and Strathmore’s Who’s Who.
8. M. J. Buckingham,Scripps Institution of Oceanography, Technical Program Chair of the 134th Meeting of the Acoustical Society of America, San Diego, California, 1-5 December 1997.
9. M. J. Buckingham, Scripps Institution of Oceanography, Technical Program Chair of the 148th Meeting of the Acoustical Society of America, San Diego, California, 15-19 November 2004.

My graduate students have been awarded seven “best student paper” prizes for presentations at international acoustics conferences.

1. <u>Thomas Berger</u>, 1st Prize for “Low-frequency acoustic emissions of a plunging water jet. Part 1: experiment”, 136th Meeting of the Acoustical Society of America, 12-16 October 1998.
2. <u>Thomas Hahn</u>, 3rd Prize for “Low-frequency acoustic emissions of a plunging water jet. Part 2: theory”, 136th Meeting of the Acoustical Society of America, 12-16 October 1998.
3. <u>Eric Giddens</u>, 1st Prize for “Sound from a light aircraft for underwater acoustic applications”,144th Meeting of the Acoustical Society of America, Cancun, Mexico, 2-6 December 2002.

4. Eric Giddens, 1st Prize for “Geoacoustic inversions in shallow water using Doppler-shifted modes from a moving source” 148th Meeting of the Acoustical Society of America, San Diego, California, 15-19 November 2004.
5. David Barclay, 1st Prize for “The effect of grain shape on the porosity of marine sediments”, 154th meeting of the Acoustical Society of America, New Orleans, Louisiana, 27 November-1 December 2007.
6. David Barclay, 2nd Prize for “Doppler geo-spectroscopy in the Makai experiment”, 155th meeting of the Acoustical Society of America, Paris, France, 29 June-4 July 2008.
7. David Barclay, Honorable Mention in the Best Student Paper Olympiad for “Ambient noise profiling with ‘Deep Sound’”, Underwater Acoustics Measurements: Technologies and Results, ONR sponsored conference, Nafplion, Greece, June 2009.