Geoacoustic Parameters of Marine Sediments: Theory and Experiment

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LONG-TERM GOALS

There are two long term goals, as follows. 1) Sediments 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) Acoustics of ship wakes Relate the bubble structure to the acoustic properties of ship wakes.

OBJECTIVES

1) The scientific objectives of the sediment 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 objective of the ship-wake research is to relate the strong spatial variability of the void fraction to the acoustic properties of the bubbly wake.

APPROACH

1) Sediments

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. In an effort to fill the low-frequency gap, one component of the ONR-supported SAX99 experiment, conducted in the northern Gulf of Mexico, off Fort Walton Beach, was

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14. ABSTRACT
There are two long term goals, as follows. 1) Sediments 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) Acoustics of ship wakes Relate the bubble structure to the acoustic properties of ship wakes.

15. SUBJECT TERMS

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aimed at extending the frequency range of sound speed and attenuation data to the band below 10 kHz. The new, lower-frequency measurements returned 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 has been 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 approximate frequency range 1 - 400 kHz.

b) Doppler geo-spectroscopy

This recently introduced 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 (known as the "FlyBy array"). 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. From a precision measurement of the mode amplitudes and the shifted modal frequencies, an inversion 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. Three of my graduate students, Eric Giddens (who now has his Ph.D.), Melania Guerra and David Barclay, have been directly involved in our Doppler geo-spectroscopy research, along with my engineer, Fernando Simonet. One of my earlier graduate students, Dr. Thomas Hahn, who now holds a faculty position at the University of Miami, assisted us during our participation in SAX04. David Barclay and Fernando Simonet participated in the Doppler geo-spectroscopy component of the MAKAI experiment, conducted off the western tip of Kauai. Eric Giddens and David Barclay have both won "best student paper" awards from the Acoustical Society of America for their presentations on Doppler Geo-spectroscopy.

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, with careful analysis of the resultant computer-generated images, 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. Since these classical wave equations are closely related to the equations of the VGS theory, it is important to verify the properties of their transient solutions. 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. The technique for solving the equations involves multiple integral transforms, followed by the appropriate inverse transforms, yielding the Green's function in each case.

2) Ship wakes

Aerial photography using a 35mm Canon 5D camera returns high-resolution (12.8 Megapixel), high-dynamic-range (16-bit) digital images of the bubbly wake produced by various types of maritime vessel. In such images, the detailed geometrical shape of the bubbly wake can be observed, as can the pronounced patchy structure of the bubble concentration along the length of the wake. By extracting the spatial statistics of the void fraction distribution from the images, a numerical model of the "acoustic" wake is being constructed, which will be incorporated into 3-D numerical acoustic propagation/scattering models.

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 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. The array was deployed either horizontally on the seabed, aligned parallel with the depth contours, or vertically in the water column. A light aircraft (Maule MXT7-180 STOL) was used as the sound source. Multiple low-level flights were made over the sensor station, yielding a variety of good quality data sets. 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. At this location the Fly-By array was deployed vertically. Along with the Doppler shifted acoustic signature of the

aircraft, the Fly-By array recorded ambient noise at both sites, although most of the time the weather was calm, as a result of which the noise intensity was almost undetectably low. 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 a high-resolution, adaptive filtering technique for enhancing the modal peaks in the Doppler-shifted spectrum.

e) Grain shape and sediment porosity

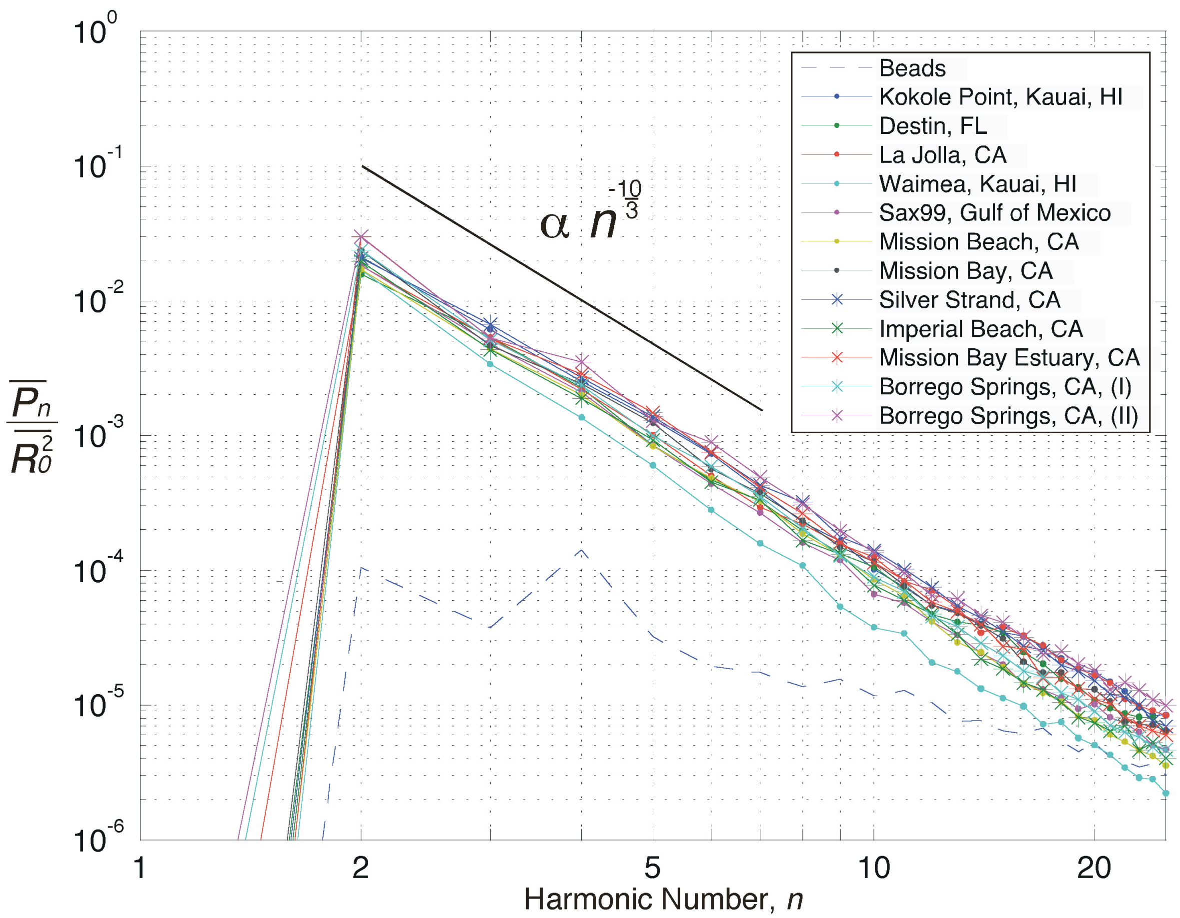

Fig. 1. Power spectra of sand grains from a dozen locations, normalized to the mean square radius. All the sand-grain spectra have collapsed onto essentially the same curve with a uniform negative slope, indicating an inverse-power-law dependence on the harmonic number.

Over the past year, rapid progress has been made on characterizing the shapes of natural sand grains.

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. We have found that the outlines of grains from beaches, sea beds, river estuaries and sand dunes gathered from various locations around the world all 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 (see Fig. 1). Based on this observation, 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 has been accepted for publication in the *Journal of Geophysical Research*.

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* and a paper on the VWE and TDDE has been accepted for publication by the *Journal of the Acoustical Society of America*.

2) Ship wakes

Aerial photographs of ship wakes have been taken routinely during flights for other purposes. Our collection of wake photographs is continually growing, including some showing the detailed bubble structure in a wake.

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)]. It returns dispersion curves that match those measured in SAX99 and elsewhere over the frequency band from 1 to 400 kHz.

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. As illustrated in Fig. 2, 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 random packing of irregularly shaped particles such as sand grains. The packing structure has a direct bearing on the porosity of marine sediments, which in turn is a factor governing wave propagation in such materials. This work has been accepted for publication. [JGR, accepted (2008)].

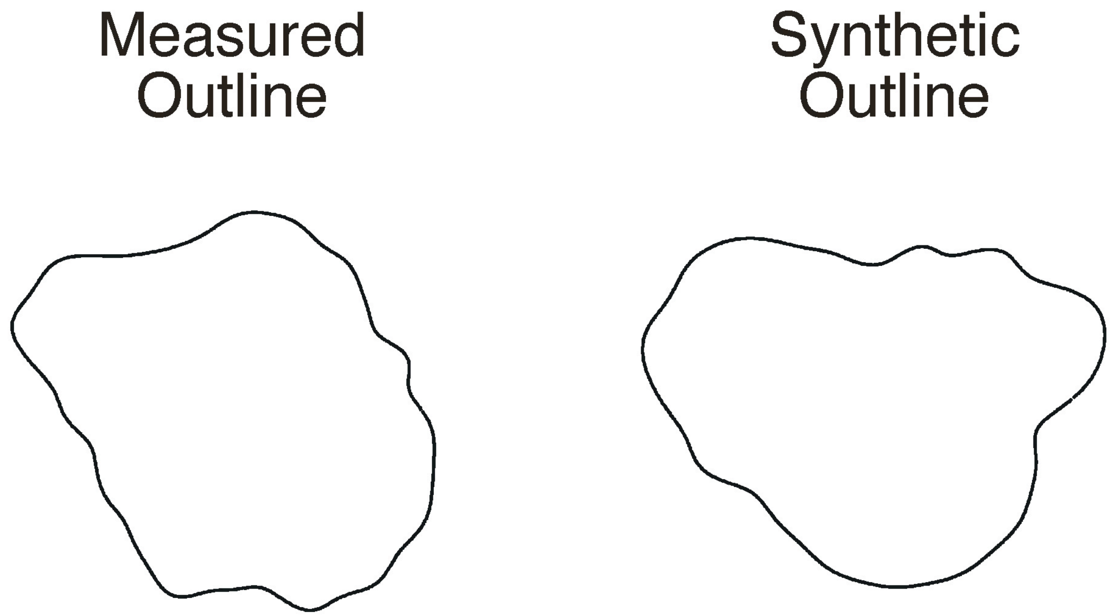

Fig. 2. 2-D outlines of sand grains. On the left the outline of an actual grain, as recovered from our optical imaging system; and on the right, a synthetic outline, computed using the new algorithm based on a random-pulse-train stochastic process.

f) Transient solutions of three wave equations

All three equations satisfy causality, that is, no arrivals are predicted prior to the onset of the source. Stokes' equation and the TDDE return physically realizable Green's functions, with no instantaneous arrivals, even though in the case of Stokes' the phase speed diverges to infinity at infinitely high frequencies. It turns out that these infinitely fast Fourier components are infinitely attenuated and hence do not propagate through the medium. Van Wijngaarden's equation, on the other hand, is non-physical in that it does predict 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) Ship wakes

Our collection of high-resolution, aerial photographs of wakes created by a variety of vessels is continually growing.

IMPACT/APPLICATIONS

My theoretical and experimental work on the wave and physical properties of marine sediments, and dispersive media in general, is broadly based and has gained a following in the ocean acoustics research community. At ASA meetings and international conferences on acoustics, my theories are cited regularly, suggesting that the work is influencing other scientists in their approach to the

complicated issues associated with wave propagation in granular materials.

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 been working with Drs. Michael Porter and Martin Siderius, HLS Research, in helping to plan the MAKAI experiment (selection of sites, etc). I am also helping HLS with research on sediments and 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.* (2008) [accepted, 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) [in press, 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].

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14. M. J. Buckingham, E. M. Giddens, F. Simonet and T. R. Hahn, "Propeller noise from a light aircraft for low-frequency measurements of the speed of sound in a marine sediment," *J. Comp. Acoust.*, **10** (4), 445-464 (2002) [published, refereed].

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].

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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].

32. M. J. Buckingham, “Theory of acoustic attenuation, dispersion, and pulse propagation in unconsolidated granular materials including marine sediments,” *J. Acoust. Soc. Am.*, **102**, 2579-2596 (1997) [published, refereed].

Conferences, Workshops and Seminars

1. 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].

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

3. 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.

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

5. 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]

6. 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]

7. M. J. Buckingham, F. Simonet and D. Barclay, “Doppler spectroscopy and ambient noise inversions in the Makai experiment”, in the *Proceedings of the 8th European Conference on Underwater Acoustics*, edited by S. M. Jesus and O. C. Rodriguez, (Carvoeiro, Portugal, 12-15 June 2006) pp. 687-693. [published, refereed]

8. M. B. Porter, B. Abraham, M. Badiey, M. J. Buckingham, T. Folegot, P. Hursky, S. M. Jesus, K. Kim, B. Kraft, V. McDonald, C. de Moustier, J. Preisig, S. Roy, M. Siderius, H. C. Song, and W. Yang, “The Makai experiment: high-frequency acoustics”, in the *Proceedings of the 8th European Conference on Underwater Acoustics*, edited by S. M. Jesus and O. C. Rodriguez, (Carvoeiro, Portugal, 12-15 June 2006) pp. 9-18 [PLENARY ADDRESS]. [published, refereed].

9. 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 six “best student paper” prizes by the Acoustical Society of America.

1. Thomas Berger, 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. Thomas Hahn, 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. Eric Giddens, 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.