Geoacoustic Parameters of Marine Sediments: Theory and Experiment

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LONG-TERM GOALS

The long term objective is to characterize fully 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. This will be based on at-sea experiments and the development of new, physics-based theories of wave propagation in saturated granular media.

OBJECTIVES

The scientific objectives of the sediment research may be conveniently divided into seven categories.

(1) Develop my recently introduced Doppler geo-spectroscopy measurement technique for estimating the geo-acoustic properties of marine sediments using a high-Doppler airborne sound source.

(2) Continue refining my analytical theory of wave propagation in saturated granular materials.

(3) Develop an analytical theory of wave propagation in a 2-layer (Pekeris) waveguide with an attenuating bottom.

(4) Develop analytical and numerical models of wave propagation in a 3-layer waveguide (atmosphere-ocean-sediment) from a moving airborne source.

(5) Develop inversions, based on the numerical forward model, for extracting sediment parameters and sub-bottom structure from Doppler geo-spectroscopy data.

(6) Develop a (causal) theory of pulse propagation in a viscous fluid.

(7) 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.

We are also beginning an investigation of the visual and acoustic properties of ship-wakes. The aim is to relate the strong spatial variability of the void fraction in the bubbly wake to its acoustic properties.

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On a more abstruse level, I am working with Prof. Giorgio Gratta, Stanford, in an attempt to detect extremely high energy neutrinos from their acoustic signature in the ocean, using the US Navy's AUTEC array of hydrophones off Andros Island, Bahamas.

APPROACH

Sediments

1) 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 or propeller harmonics extending 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). Normal modes are excited in the water column and are detected on our autonomous line array of 11 non-uniformly spaced hydrophones. A high-resolution spectrum of a 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 shifted modal frequencies, an inversion returns the sound speed in the sediment; and the remaining geo-acoustic parameters are determined from their known correlations with the sound speed. Two of my graduate students, Eric Giddens (who now has his Ph.D.) and Melania Guerra, 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. My current graduate student, David Barclay, participated in the MAKAI experiment.

2) Grain-shearing theory of the wave properties of sediments

My grain-shearing theory of the wave properties of saturated granular materials such as marine sediments is becoming fairly widely recognized as an alternative to the Biot theory in which the loss mechanism is viscosity of the pore fluid. The grain-shearing theory is derived from the linearized Navier-Stokes equations and is based on the physics of micro-sliding at grain-to-grain contacts. The theory is analytical, yielding simple algebraic expressions for the compressional and shear wave speeds and attenuations as functions frequency as well as the physical properties (porosity, density and mean grain size) of the sediment. Essentially, the theory predicts compressional and shear attenuations that increase linearly with frequency and corresponding wave speeds that show weak dispersion, varying approximately logarithmically with frequency.

3) Theory of acoustic propagation in a Pekeris waveguide with bottom attenuation

Based on multiple integral transforms, a solution of the Pekeris problem is obtained for the case when attenuation in the bottom is significant. An efficient analytical technique for obtaining the complex eigenvalues from the dispersion relationship is introduced, based on the familiar Newton-Raphson iterative algorithm. The EJP branch-line integral is investigated using various asymptotic approximations.

4) 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 are being developed based on multiple integral transforms in conjunction with the 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 and also 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.

5) 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. This work was performed mainly by my (then) graduate student, Eric Giddens.

6) Causal theory of pulse propagation in a viscous fluid

In 1845, Stokes published a classic paper in which he developed an equation for wave propagation in a viscous fluid. Since then, solutions of Stokes' equation for harmonic waves have been well documented. With regard to pulse propagation, however, Stokes' equation has been (incorrectly) called into question on several occasions over recent years because, it is said, it predicts non-causal arrivals. Such claims are based on approximate, time-domain solutions to Stokes' equation. To investigate the properties of broadband pulses predicted by Stokes' equation, I performed an analysis of the Green's function, using multiple integral transforms. The result shows that Stokes' equation is perfectly well behaved, predicting pulse arrivals that are causal in the strict sense of having no arrivals prior to activation of the source, nor any instantaneous arrivals. The failure to satisfy causality in previous authors' analyses of Stokes' equation stems from poor quality approximations to pulse solutions, not from any intrinsic defect in the equation itself.

7) 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. This work is being performed by my graduate student, David Barclay.

Ship wakes

Aerial photography, with a 35mm Canon 5D camera, is being used to obtain high-resolution (12.8 Megapixel), high-dynamic-range (16-bit) digital images of the visible wake produced by various types of maritime vessel. In such images, the detailed geometrical shape of the bubbly wake can easily be observed, as can the patchy structure of the bubble concentration along the length of the wake. As the wake evolves, it is clear from the images that it diverges slightly. Assuming that turbulent diffusion is responsible for the divergence, it may be possible to obtain the diffusion coefficient from the geometry recorded in the photographs. Moreover, the images show that the wake has a characteristic light greenish color, which may yield information on bubble size, amongst other things, depending on the mechanism that is responsible for the coloration.

WORK COMPLETED

Sediments

1) Doppler Spectroscopy field experiments

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), rented from a local tour-flight company at Lihue airport, was used as the sound source. Multiple low-level flights were made over the sensor station, yielding a variety of interesting data sets. A further set of flying experiments was conducted at a deeper site, close to the 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 remarkably calm, in consequence of which the noise was of such low intensity as to be almost undetectable.

2) Grain-shearing theory of the wave properties of sediments

Recently, the dependence of the wave properties on various physical parameters (*e.g.*, shear speed versus porosity), as predicted from the grain-shearing theory, were compared in detail with extensive data sets on compressional and shear waves culled from the literature. With no adjustable parameters available, excellent agreement was found on essentially all counts, as reported in the *Journal of the Acoustical Society of America*.

3) Theory of acoustic propagation in a Pekeris waveguide with bottom attenuation

This work is complete and has been published in the *Journal of the Acoustical Society of America*.

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

These models are complete and are to be published in the October 2006 issue of the *Journal of the Acoustical Society of America*.

5) Geoacoustic inversions for Doppler Spectroscopy

An early version of the geoacoustic inversion technique is complete and has been described fully in Eric Giddens' Ph.D thesis. Refinements to the inversion procedure are still under development.

6) Causal theory of pulse propagation in a viscous fluid

The analysis is complete and has been published in *Physical Review E*.

7) Grain shape and sediment porosity

This work which is progressing, based on micrographs of various types of grains from collected different locations worldwide.

Ship wakes

To date, two flights have been made for airborne photography of ship wakes. Several hundred high-quality digital images of the wakes from half a dozen vessels have been acquired.

RESULTS

Sediments

1) Doppler Spectroscopy field experiments

Several data sets collected at the fine-sand experiment site north of Scripps pier have been inverted, each of which yields a full compliment of sediment parameters. For instance, at a frequency of 80 Hz, the values returned for the geoacoustic parameters are: sound speed ≈ 1634 m/s; sound attenuation ≈ 0.0095 dB/m (= 0.12 dB/m/kHz); sound speed ratio ≈ 1.0769; shear speed ≈ 94 m/s; shear attenuation ≈ 3.1 dB/m (= 39 dB/m/kHz); density ≈ 2019 kg/m^3; porosity ≈ 0.4123; and mean grain diameter ≈ 83.4 μm. On comparison with measurements made at higher frequencies by other researchers in similar sediments, these results are consistent with a weakly dispersive sound speed and a sound attenuation that varies linearly with frequency. The Doppler geo-spectroscopy data obtained in the MAKAI experiment are still being analyzed but preliminary results are also consistent with weak dispersion and attenuation that varies linearly with frequency. Both data sets will be included in a paper that is in preparation.

2) Grain-shearing theory of the wave properties of sediments

The grain-shearing theory predicts relationships between wave and physical properties of marine sediments that match experimental measurements on all types of granular materials, ranging from the finest clays to the coarsest sands. This agreement goes well beyond the frequency dependence of the dispersion expressions, covering, for example, shear speed as a function of depth in the sediment, sound speed as a function of porosity, and all other combinations of wave and physical properties. One important fact that emerges from the theory is that the sound speed and attenuation in the coarser sands, as found, for example, at the SAX04 site, are highly sensitive to the porosity. [JASA, **117**, 137-152, (2005)]

3) Theory of acoustic propagation in a Pekeris waveguide with bottom attenuation

A new type of proper normal mode is identified, designated a “dissipation” mode, that arises solely from the presence of attenuation in the bottom. Dissipation modes are exact solutions of the wave equation which also satisfy the radiation condition at great depth in the basement. In the absence of bottom loss, the only proper modes in the problem are the conventional trapped modes, but as the attenuation in the bottom rises, the total number of proper modes supported by the channel increases approximately linearly with the bottom loss. [JASA, **119**, 123-142 (2006)]

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

As part of both the 2-D and 3-D analyses, new dispersion relations have been derived. From these dispersion relations, the frequency shifts of the modes, due to the motion of the source, may be determined. The full 2-D and 3-D theories are to be published shortly. [JASA, **October 2006**]

5) Geoacoustic inversions for Doppler Spectroscopy

This inversion procedure yields results such as those cited in sub-section 1) above.

6) Causal theory of pulse propagation in a viscous fluid

The solutions of Stokes' equation for pulse propagation in a viscous fluid have been shown to satisfy causality in a very strict sense: there are no arrivals before the source is activated at $t = 0$, nor are there any instantaneous arrivals. For the first time, it is shown that everywhere in the viscous fluid at $t = 0$, the pulse is perfectly smooth in the sense of being *maximally flat*, that is, at $t = 0$ the pulse and all its time derivatives are identically zero. [Phys. Rev. E, **72**, 026610(9) (2005)]

7) Grain shape and sediment porosity

Preliminary results on a sample of sand from Candidasa Beach, Bali, indicate that the rms roughness of the grains scales with the mean grain diameter.

Ship wakes

As an example, Fig. 1 shows the wake from a powerful new *Dolphin* Class harbor tug, Morgan Foss, operating out of Longbeach, CA. The photograph was taken on 8 March 2006 from a Cessna 172, altitude 300m, using a Canon 5D camera with an image-stabilized 28-135mm zoom lens and a circularly polarizing filter to enhance the contrast between the bubbly wake and the bubble-free sea surface. The vessel in the photograph is powered by two diesel engines, each developing 2365hp at 1800rpm and driving a 4-blade propeller of diameter 2.3m. In this image, the Kelvin wake stands out clearly, showing the classic 19.5˚ and 35˚ angles. The bubbly wake, formed by propeller cavitation, is almost parallel sided, with fairly regular scalloping along the edges, the "wavelength" of which, presumably, is related to shaft rpm, vessel speed and number of propeller blades. Inside the wake, the void fraction is highly variable with obvious dark regions where the bubble concentration is relatively low. It would seem plausible that similar factors (rpm, etc.) govern the spatial distribution of this patchiness in the bubble concentration.

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.

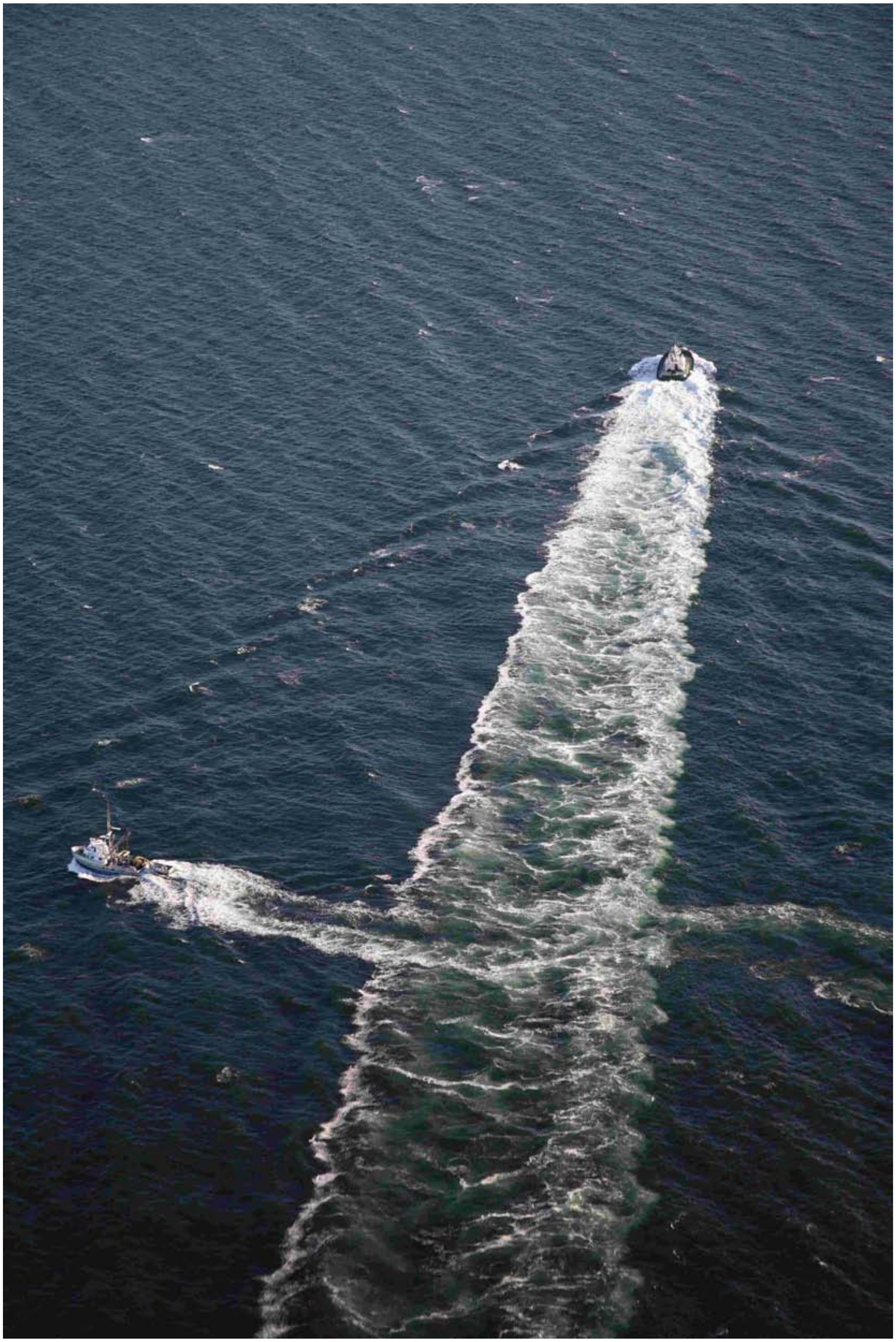

Fig. 1. Wake from the Dolphin Class harbor tug, Morgan Foss,
off Longbeach, CA, 8 March 2006.
(The original of this photograph is a 12.8 Megapixel, 16-bit, RAW image.)

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.

4. Prof. H. K. Cheng, University of Southern California, and I are collaborating on research to investigate sonic booms underwater. He is developing a theory of the shear wave excited in the sediment by a sonic boom, using my theory of waves in sediments as a central element of his analysis.

5. I am in close contact with Dr. Van Holliday, BAe Systems, mainly concerning the complicated bubble structure and the color observed in ship wakes.

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.

PUBLICATIONS

Journals & Chapters in Books

1. 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.*, (2006) [in press, refereed]

2. 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]

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

4. 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].

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1. M. J. Buckingham, S. Simonet and D. Barclay, “Doppler spectroscopy and ambient noise inversions in the Makai experiment”, Eight European Conference on Underwater Acoustics, Carvoeiro, Portugal, 12-15 June 2006.

2. M. J. Buckingham, “Sediment acoustics measurements using a light aircraft”, SA04 Workshop, 22-23 March 2006.

3. M. J. Buckingham, “Inversions for sediment geoacoustic parameters using a high-Doppler airborne sound source”, ONR SW Progress Review, MBARI, 14-16 March 2005.

4. M. J. Buckingham, “Inversions for the geoacoustic properties of marine sediments using a high-Doppler, airborne sound source”, Seventh International Conference on Theoretical and Computational Acoustics, Hangzhou, Zhejiang, China, 19-23 September 2005 [KEYNOTE].

5. M. J. Buckingham and E. M. Giddens, “Low frequency sound speed measured using a light aircraft as an acoustic source”, International Conference on Boundary Influences in High Frequency, Shallow Water Acoustics, University of Bath, U.K., 5-9 September 2005 [INVITED].

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21. M. J. Buckingham and T. K. Berger, "Low frequency sound from a bubble plume", Proc. 17th Int. Conf. on Acoustics, Rome, Italy, 2-7 September 2001, A. Alippi (ed.), **1**, 2-3 [CLOSING KEYNOTE ADDRESS, published, refereed].

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PATENTS

1. D. N. Riches and M. J. Buckingham, “Improvements in or relating to tilt sensors”, Patent No. 3504/78, January 1978.

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 Chair of the 148th Meeting of the Acoustical Society of America, San Diego, California, 15-19 November 2004.

My graduate students have been awarded four prizes by the Acoustical Society of America:

1. Thomas Berger, First Prize for Best Student Paper, 136th Meeting of the Acoustical Society of America, 12-16 October 1998: “Low-frequency acoustic emissions of a plunging water jet. Part 1: experiment”.

2. Thomas Hahn, Third Prize for Best Student Paper, 136th Meeting of the Acoustical Society of America, 12-16 October 1998: “Low-frequency acoustic emissions of a plunging water jet. Part 2: theory”.

3. Eric Giddens, First Prize for Best Student Paper, awarded by the Underwater Acoustics and Engineering Acoustics Technical Committees at the 144th Meeting of the Acoustical Society of America, Cancun, Mexico, 2-6 December 2002: “Sound from a light aircraft for underwater acoustic applications”.

4. Eric Giddens, First Prize for Best Student Paper, awarded by the Acoustical Oceanography Technical Committee at the 148th Meeting of the Acoustical Society of America, San Diego, California, 15-19 November 2004: “Geoacoustic inversions in shallow water using Doppler-shifted modes from a moving source”.