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Measurement and Analysis of Sound Speed Dispersion During SAX04

FY04 Annual Report for Office of Naval Research Award N000140310883

John C. Osler

Paul C. Hines

Prepared for:
Office of Naval Research
800 N. Quincy Street, Code 321OA
Arlington, Virginia 22217-5660, USA

Defence R&D Canada – Atlantic

External Client Report
DRDC Atlantic ECR 2004-208
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Abstract

This project is developing equipment and techniques to measure sound speed dispersion in the 1 to 10 kHz frequency band during the Office of Naval Research SAX04 experiment. Historically, it has been difficult to make these measurements below 10 kHz. As a result, there is a paucity of experimental results with large uncertainties. Measurements in this frequency band are critical as this is where the most pronounced sound speed dispersion is expected and the predictions of various sediment acoustic models differ significantly. The objectives of this project will be achieved by pursuing complementary approaches to making the sound speed dispersion measurements, including: angle of refraction; acoustic impedance; reflection loss; and time of flight. Work completed in FY04 includes: numerical simulations; analysis of the APEX99 NATO data set; implementation of array element localization software; equipment design, procurement, and assembly; calibrations; field testing; and staging for SAX04.

Résumé

Les présents travaux ont pour but de développer des équipements et des techniques de mesure de la dispersion de la vitesse du son dans la bande de fréquences de 1 à 10 kHz pour l’expérience SAX04 de l’Office of Naval Research. Il a toujours été difficile de prendre des mesures à des fréquences inférieures à 10 kHz. C’est pourquoi il y a un manque de résultats expérimentaux et de grandes incertitudes. Les mesures dans cette bande de fréquences sont très importantes puisqu’on prévoit y observer les dispersions de la vitesse du son les plus marquées, et que les prévisions des différents modèles acoustiques des sédiments présentent des différences significatives. Les objectifs du projet seront atteints par la recherche d’approches complémentaires de mesure de la dispersion de la vitesse du son : angle de réfraction, impédance acoustique, perte par réflexion et temps de vol, etc. Les travaux complétés en 2004 comprennent ce qui suit : des simulations numériques; l’analyse d’un ensemble de données de l’APEX99 de l’OTAN; la mise en oeuvre d’un logiciel de localisation d’éléments de réseau; la conception, l’acquisition et l’assemblage d’équipement; des activités d’étalonnage; des essais sur le terrain; et la préparation de SAX04.

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Executive summary

Introduction

Results from a previous ONR funded experiment, SAX99, suggested that the speed of sound travelling through marine sediments might depend on the frequency of ensonification when the seabed is principally composed of sand. This dispersion behaviour contradicts a long-standing assumption that the compressional sound speed is independent of frequency. This project is developing equipment and techniques to measure sound speed dispersion in the 1 to 10 kHz frequency band during the Office of Naval Research SAX04 experiment. Historically, it has been difficult to make these measurements below 10 kHz. As a result, there is a paucity of experimental results with large uncertainties. Measurements in this frequency band are critical as this is where the most pronounced sound speed dispersion is expected and the predictions of various sediment acoustic models differ significantly. The objectives of this project will be achieved by pursuing complementary approaches to making the sound speed dispersion measurements, including: angle of refraction; acoustic impedance; reflection loss; and time of flight.

Results

Work completed in FY04 includes: numerical simulations; analysis of the APEX99 NATO data set; implementation of array element localization software; equipment design, procurement, and assembly; calibrations; field testing; and staging for SAX04. The numerical simulations have established that the proposed experimental concepts should be able to measure sediment sound speed dispersion. The analysis of APEX99 data from SACLANTCEN indicates that the angular resolution of the pair of accelerometers used in that study is suitable for their intended application, penetration studies, but not sufficient for dispersion studies. The TV-001 sensors to be used in the SAX04 studies have a better angular resolution and also overcome several limitations encountered in APEX99. The field tests have established that the equipment: sources, receivers, acquisition system, cabling, and burial jig are all working and provided valuable experience.

Significance

A frequency dependence in sediment sound speed has implications for the operation of naval sonars and systems that predict sonar performance. For example, geological sampling techniques that have been used extensively to provide “ground truth” measurements of sediment sound speed are done at much higher frequencies than those of interest for anti-submarine operations. A further example is the use of a mine hunting sonar to detect buried mines–it must operate above the critical grazing angle with the swath width and area coverage rates depending on the water/sediment sound speed ratio. With regards to the project in which DRDC Atlantic is directly involved, the measurements of sound speed dispersion will provide a fundamental metric that is used to evaluate competing theories that seek to explain the physics of how sound propagates in marine sediments.

Future plans

FY05 activities will include participation in the SAX04 field experiment, data analysis, and presentation of two invited papers at conferences in July and September 2005.

Osler, J.C., Hines, P.C., 2004, Measurement and Analysis of Sound Speed Dispersion During SAX04, DRDC Atlantic ECR 2004-208, Defence R&D Canada – Atlantic.

Sommaire

Introduction

Les résultats d'une expérience antérieure financée par l'ONR, SAX99, laissaient entendre que la vitesse du son dans les sédiments marins pourrait dépendre de la fréquence d'insonification lorsque le fond marin est principalement composé de sable. Cette dispersion vient contredire une hypothèse établie de longue date qui soutient que la vitesse du son compressionelle est indépendante de la fréquence. Les présents travaux ont pour but de développer des équipements et des techniques de mesure de la dispersion de la vitesse du son dans la bande de fréquences de 1 à 10 kHz pour l'expérience SAX04 de l'Office of Naval Research. Il a toujours été difficile de prendre des mesures à des fréquences inférieures à 10 kHz. C'est pourquoi il y a un manque de résultats expérimentaux, et de grandes incertitudes. Les mesures dans cette bande de fréquences sont très importantes puisqu'on prévoit y observer les dispersions de la vitesse du son les plus marquées, et que les prévisions des différents modèles acoustiques des sédiments présentent des différences significatives. Les objectifs du projet seront atteints par la recherche d'approches complémentaires de mesure de la dispersion de la vitesse du son : angle de réfraction, impédance acoustique, perte par réflexion, le temps de vol, etc.

Résultats

Les travaux complétés en 2004 comprennent ce qui suit : des simulations numériques; l'analyse d'un ensemble de données de l'APEX99 de l'OTAN; la mise en oeuvre d'un logiciel de localisation d'élément de réseau; la conception, l'acquisition et l'assemblage d'équipement, des activités d'étalonnage; des essais sur le terrain; et la préparation de SAX04. Les simulations numériques ont permis d'établir que les concepts expérimentaux proposés devraient permettre de mesurer la dispersion de la vitesse du son dans les sédiments. L'analyse des données de l'APEX99 du SACLANTCEN indique que la résolution angulaire de la paire d'accéléromètres utilisée pour l'étude convient à l'utilisation prévue, soit des études de pénétration, mais ne convient pas aux études de dispersion. Les capteurs TV-001 qui servent aux études SAX04 présentent une meilleure résolution angulaire et permettent de surmonter les nombreuses limites liées à l'APEX99. Les essais sur le terrain ont démontré que tout l'équipement (sources, récepteurs, système d'acquisition, câblage et matériel d'enfouissement) fonctionnait correctement et qu'il permettait d'effectuer une expérience valable.

Portée

Que la vitesse du son dans les sédiments soit dépendante de la fréquence a des répercussions sur le fonctionnement des sonars de la marine et des systèmes qui prédisent le rendement des sonars. Par exemple, les techniques d'échantillonnage géologique, qui ont été abondamment utilisées afin d'obtenir des mesures de la vitesse du son dans les sédiments basées sur la réalité de terrain, sont effectuées à des

fréquences beaucoup plus élevées que celles d'intérêt pour les opérations anti-sous-marines. Un autre exemple est l'utilisation d'un sonar de chasse aux mines pour détecter les mines enfouies; il doit fonctionner au-dessus de l'angle d'incidence critique avec la largeur de balayage et les taux de couverture de zone selon les rapports de vitesse du son dans l'eau et les sédiments. Quant aux travaux auxquels RDDC Atlantique est directement associé, les mesures de la dispersion de la vitesse du son offriront une méthode de mesure fondamentale qui sera utilisée pour évaluer des théories contradictoires qui cherchent à donner une explication physique à la propagation du son dans les sédiments marins.

Recherches futures

Les activités de 2005 comprendront la participation à l'expérience de terrain SAX04, l'analyse de données et la présentation de deux communications sollicitées pour des conférences en juillet et en septembre 2005.

Osler, J.C., Hines, P.C., 2004, Measurement and Analysis of Sound Speed Dispersion During SAX04, DRDC Atlantic ECR 2004-208, Defence R&D Canada – Atlantic.

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Measurement and Analysis of Sound Speed Dispersion During SAX04

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LONG-TERM GOALS

Results from a previous ONR funded experiment, SAX99, suggested that the speed of sound travelling through marine sediments might depend on the frequency of ensonification when the seabed is principally composed of sand (Williams *et al*., 2002). This dispersion behaviour contradicts a long-standing assumption, based on earlier compilations of experimental evidence (*eg.* Hamilton, 1980), that the compressional sound speed is independent of frequency. Sound speed dispersion measurements provide a fundamental metric for evaluating competing theories, some new and some revived (as summarized in Williams *et al*., 2002), that seek to explain the physics of how sound propagates in marine sediments as they predict different sound speed dispersion relationships.

OBJECTIVES

This project is developing equipment and techniques to measure sound speed dispersion in the 1 to 10 kHz frequency band. Historically, it has been difficult to make these measurements below 10 kHz. As a result, there is a paucity of experimental results with large uncertainties. Measurements in this frequency band are critical as this is where the most pronounced sound speed dispersion is expected and the various model predictions differ significantly.

APPROACH

The objectives of this project will be achieved by pursuing complementary approaches to making the sound speed dispersion measurements The experimental equipment that has been developed will permit four different approaches to measure the sound speed dispersion.

1) *Angle of refraction*: Short pulses, approximately 5 ms in duration, will be used to ensonify the seabed. The incident angle of the sound will be changed and the angle of refraction into the seabed will be measured using buried directional receivers (three axis acceleration and pressure sensors). The angle of refraction is a function of sound speed ratio and measurements will be made at discrete frequencies using two acoustic sources. The first is fixed to the seabed in a mooring that allows the grazing angle to be adjusted and keeps the end-fire beam pointing at the receivers. The second is omnidirectional and fixed below a small catamaran that is translated horizontally above the buried receivers (Fig. 1).

2) *Acoustic impedance*: Long pulses, approximately 500 to 1000 ms, will be used to create a steady state acoustic field. The field incident upon, reflected from, and transmitted into the seabed will be measured using three axis acceleration and pressure receivers in the water column and buried in the seabed. The amplitude and phase of the acoustic impedance of the seabed, pressure divided by

velocity, will depend on physical properties of the seabed, including sound speed. The acoustic source in this case will be moored directly above the receivers.

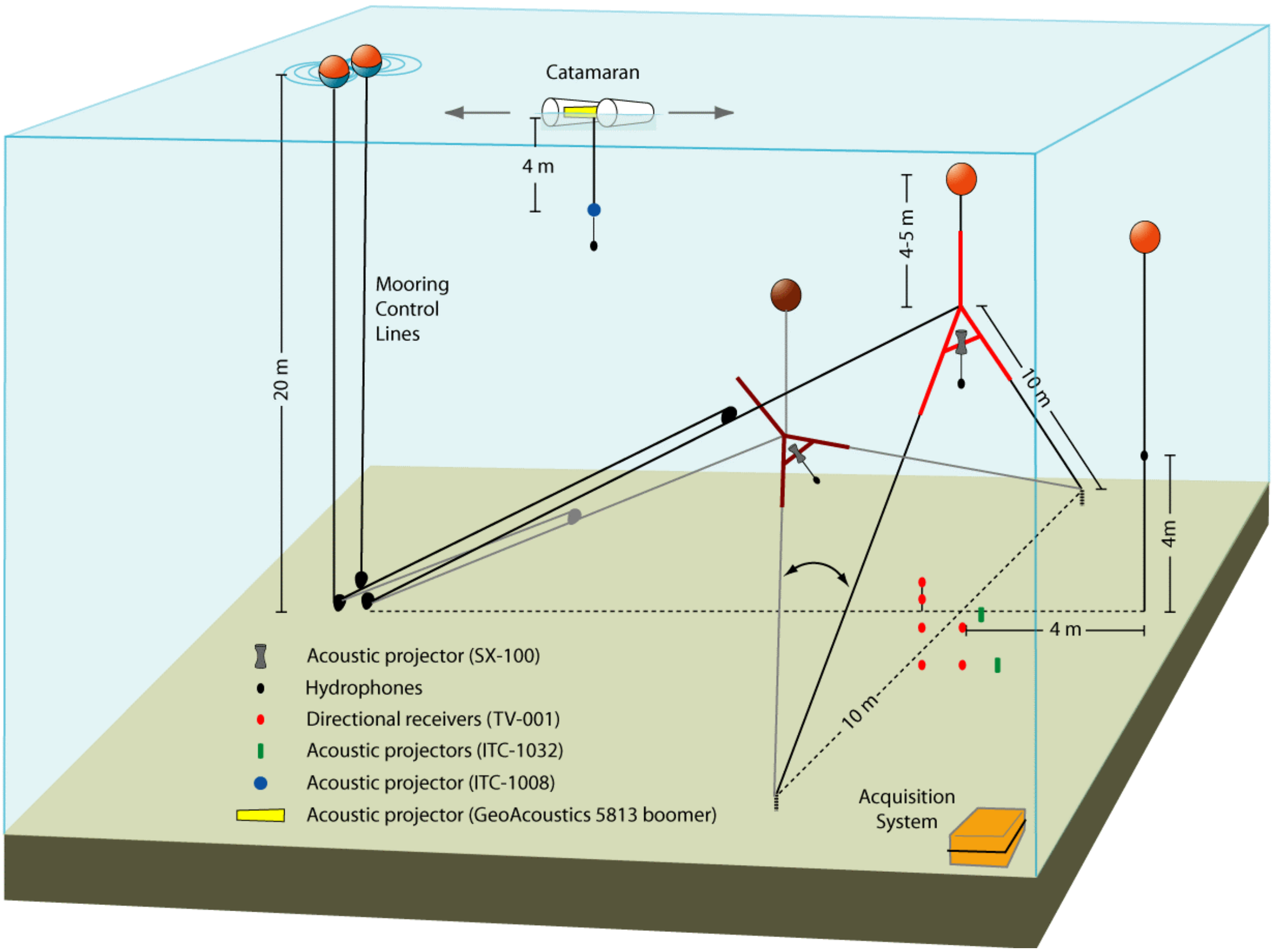

Figure 1: The experimental geometry to measure sound speed dispersion. Acoustic arrivals are received by sensors buried in the seabed and moored in the water column. There are acoustic sources buried in the seabed, mounted on a catamaran, and in three point moorings (one of two is shown) that can adjust the angle of incidence (grey lines at shallower angle).

3) *Reflection loss*: Short pulses, approximately 5 ms in duration, will be used to ensonify the seabed. The incident angle of the sound will be changed and the amplitude and phase of a specular reflection measured on a receiver in the water column. The reflection loss measurements will define a critical angle that depends on the speed of sound in the seabed and the measurement repeated at discrete frequencies.

4) *Time of flight*: Short pulses, approximately 1-2 ms in duration, will be transmitted from two projectors buried in the seabed and from two projectors moored in the water column. Absolute time of flight between sources and receivers and relative time of flight between pairs of receivers will be used to measure sound speed at different frequencies. The separation between the buried sources and receivers and their depth of burial will be carefully controlled using a jig that has been designed to insert them into the seabed (Fig. 3). In addition to the direct measurements using individual source and

receiver combinations, sound speed estimates may be made at different frequencies using all source and receiver paths and a regularized inversion for array element localization (Dosso *et al*., 2004) adapted to invert for sediment sound speed rather than, or in addition to, source and receiver locations.

WORK COMPLETED

1) *Numerical simulations*: The angle of refraction approach was simulated using OASP (Schmidt,1999) for fluid and porous seabed parameterizations. The former being independent of frequency, that is, with no dispersion. This established that changes in angle of refraction should be discernable with appropriate directional receivers. It was also used to investigate the angle bias and particle motion that may be introduced by reflections from deeper layers and from interaction between the evanescent and refracted arrivals. The acoustic impedance technique was also simulated using OASES and established that there should be discernable differences in the amplitude and phase of the impedance that depend on the physical properties of the seabed, including sound speed. The results were presented at the SAX04 workshops.

2) *Analysis of APEX99 data*: During their employment at the SACLANT Undersea Research Centre, Dr. Osler (DRDC Atlantic) and Dr. Lyons (ARL Penn State) collected particle motion data using an orthogonal pair of uni-axial accelerometers, buried at 50 cm depth in a sand seabed. This data has been analyzed to determine the suitability of directional receivers for acoustic penetration and sound speed dispersion studies (Fig. 2).

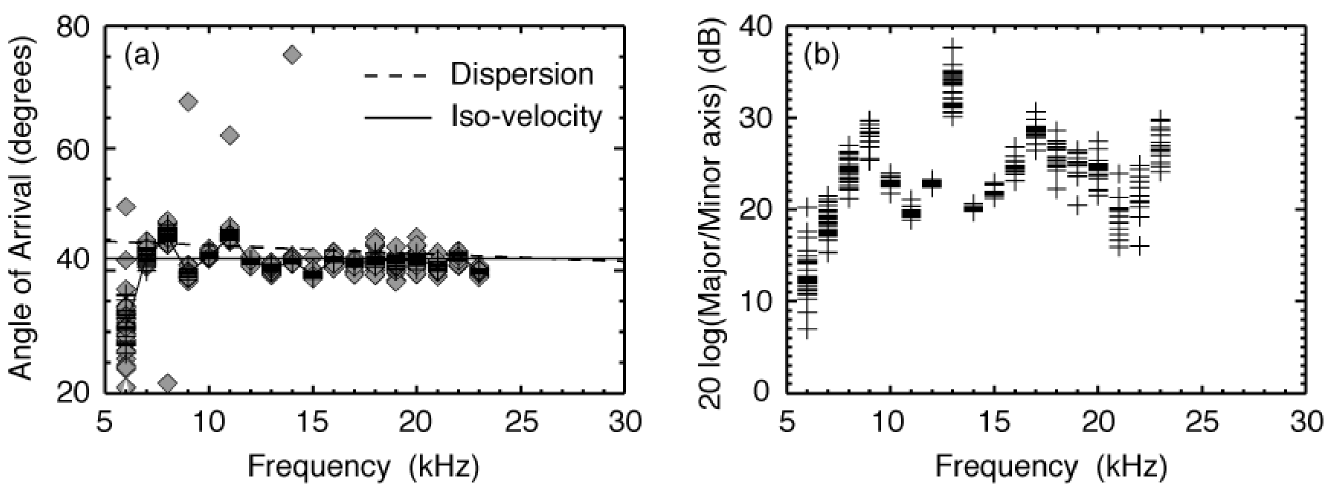

Figure 2: Left, angle of arrival, in the seabed, of APEX99 acoustic pulses incident upon the seabed at 49º (Osler and Lyons, in press). The lines are the anticipated angle of arrival for a non-dispersive sand (solid), and for a linear sound speed dispersion from 5-30 kHz for sound speed ratios from 1.09 to 1.15 (dashed). Poor performance at 6 kHz is due to low signal-to-noise. The variability from 8-11 kHz is related to the in situ calibration. Right, ratio of major and minor axes of the particle motion acceleration ellipses as a function of frequency.

3) *Array element localization*: Source code to conduct a regularized inversion of travel time information to determine source and receiver locations has been obtained from Dr. Stan Dosso (University of Victoria) and Dr. Nicole Collison (DRDC Atlantic). Using the two moored sources in the water column and the two buried sources (Fig. 1), it should be possible to determine the absolute location and orientation of all of the receivers and the uncertainty in their positions. This code has been

implemented at DRDC Atlantic and is being adapted for the SAX04 application. The possibility of using this inversion algorithm to obtain seabed sound speeds at different frequencies is being investigated.

4) *Equipment design, procurement, and assembly*: Considerable effort has been required to prepare the equipment necessary to make the measurements depicted in Figure 1. This includes designing some components, preparing technical specifications for items to be procured, assembly, and testing. This has been done in collaboration with Dr. Tony Lyons (ARL Penn State) who received a Defense University Research Instrumentation Program award to purchase instrumentation for this experiment.

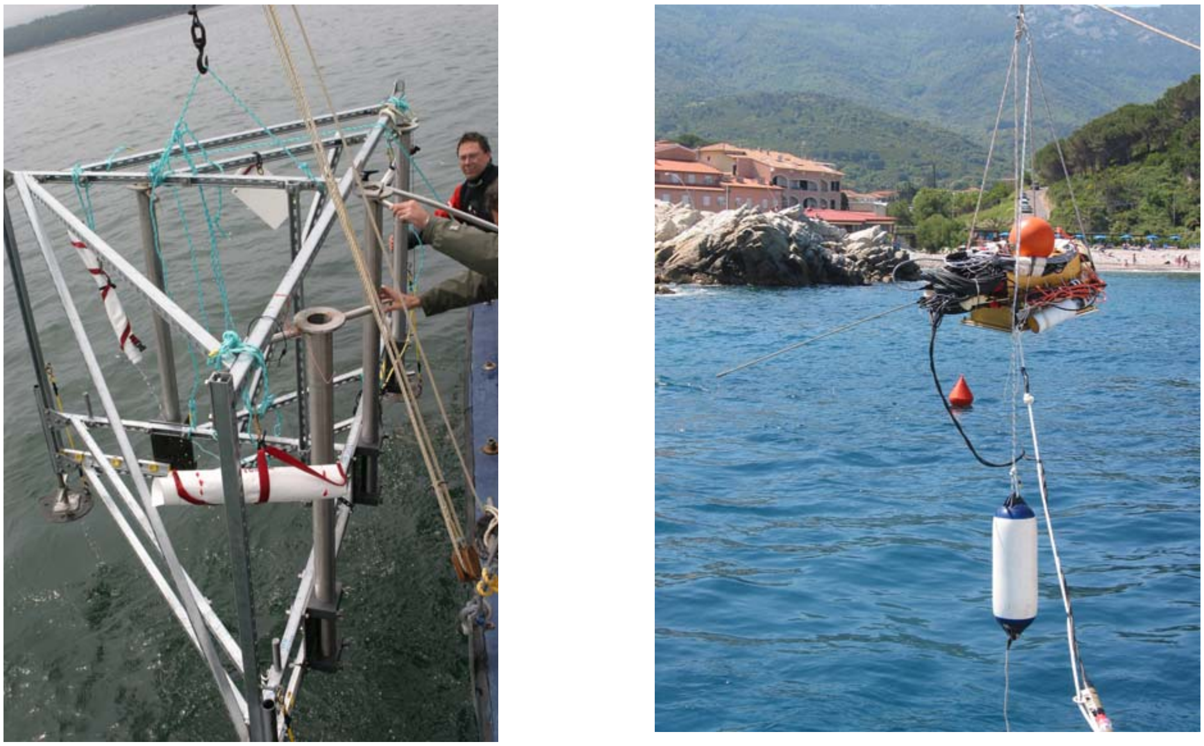

Figure 3: Left, photograph of the burial jig being deployed during a sea-trial in July 2004. It is used to insert four receivers and two projectors into the seabed with a fixed geometry. Right, photograph of the pressure vessel being deployed during a sea-trial in June 2004. It has two isolated internal compartments, one that serves as a junction box for all sensor, power, and communications cables and a second that houses the acquisition system and electronics.

5) *Calibrations*: The sources and receivers to be used in the SAX04 experiment have been calibrated at the DRDC Atlantic calibration barge in Bedford Basin, Nova Scotia. This includes beam patterns and transmitting voltage response curves for four SX-100 projectors, angular sensitivity (X, Y, Z, and pressure components) of 7 Wilcoxon TV-001 receivers, and 5 DRDC built hydrophones. A complete set of calibrations has been conducted at 0.6, 1, 1.6, 2, 3, 4, 6, 8, 10, and 12 kHz.

6) *Field Testing*: Two field tests have been conducted. The first used a single TV-001 receiver buried 75 cm deep in sand, an SX-100 projector, as well as the acquisition system, power and ethernet communications cables. It was conducted in June 2004 in a collaborative experiment with Dr. Lyons (ARL Penn State) and Dr. Eric Pouliquen (NATO Undersea Research Centre). The instrumentation

was cabled to shore at Marciana Marina, Elba Island, Italy (Fig. 3). The second test involved the jig that will bury four TV-001 receivers and two ITC-1032 sources with known depths and horizontal separations. It was conducted in local waters near Halifax, Nova Scotia, in July 2004 (Fig. 3).

7) *Staging for SAX04*: A modified 20-foot container has been prepared for SAX04. It will serve as a shipping container to send equipment to and from NSWC Panama City and as a laboratory when mounted on the deck of the *R/V Seward Johnson* during the SAX04 experiments.

RESULTS

The numerical simulations have established that the proposed experimental concepts should be able to measure sediment sound speed dispersion. They also revealed that numerical modelling will likely form an integral part of the analysis, especially at lower frequencies (< 2 KHz) where the influence of reflections from deeper layers and interaction with the evanescent field will be more pronounced. The analysis of APEX99 data from SACLANTCEN indicates that the angular resolution of the pair of accelerometers used in that study is suitable for their intended application, penetration studies, but not sufficient for dispersion studies. The TV-001 sensors to be used in the SAX04 studies have a better angular resolution and also overcome several limitations encountered in APEX99 (co-located acceleration components and pressure measurements).

The field tests have established that the equipment: sources, receivers, acquisition system, cabling, and burial jig are all working and provided valuable experience. Based on the ambient noise conditions encountered at Elba, there should be sufficent signal to noise (30 to 40 dB), to make sound speed measurements from 1 to 10 kHz. Measurements below 1 kHz may not be as robust.

IMPACT/APPLICATIONS

A frequency dependence in sediment sound speed has implications for the operation of naval sonars and systems that predict sonar performance. For example, geological sampling techniques that have been used extensively to provide “ground truth” measurements of sediment sound speed are done at much higher frequencies than those of interest for anti-submarine operations. A further example is the use of a mine hunting sonar to detect buried mines–it must operate above the critical grazing angle with the swath width and area coverage rates depending on the water/sediment sound speed ratio. With regards to the project in which DRDC Atlantic is directly involved, the measurements of sound speed dispersion will provide a fundamental metric that is used to evaluate competing theories that seek to explain the physics of how sound propagates in marine sediments.

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Osler J. C. and Lyons A. P., Using buried directional receivers in high-frequency seafloor studies. In *Proc. of the High Frequency Acoustics Conference 2004, La Jolla, California* (in press, refeered)

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