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Measurement and Analysis of Sound Speed Dispersion During SAX04

FY05 Annual Report for Office of Naval Research Award N000140310883

John C. Osler
Paul C. Hines

Prepared for:
US Office of Naval Research
875 N Randolph Street, Suite 1425, Code 321OA
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Defence R&D Canada – Atlantic

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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 are being achieved by pursuing complementary approaches to making the sound speed dispersion measurements, including: angle of refraction; acoustic impedance; reflection loss; and time of flight techniques. Work completed in FY05 includes: participation in the SAX04 field experiment in the Gulf of Mexico; development and testing of data processing algorithms; presentation and publication of initial results at international conferences; a preliminary examination of measurement sensitivity and error analysis; application of array element localization software to refine position estimates for all sources and receivers in the water column; and refinements to the numerical model for the acoustic propagation from a point source in water into marine sediments near the critical angle, including the effects of homogeneous and inhomogeneous plane waves.

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 sont 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 techniques du temps de vol, etc. Les travaux complétés au cours de l'exercice 2005 comprennent ce qui suit : participation à l'expérience en conditions réelles SAX04 dans le Golfe du Mexique; développement et mise à l'essai d'algorithmes de traitement de données; présentation et publication des résultats initiaux à des conférences internationales; examen préliminaire de la sensibilité des mesures et analyse des erreurs; application d'un logiciel de localisation d'éléments de réseau afin de préciser les estimations de position pour toutes les sources et récepteurs dans la colonne d'eau; et améliorations du modèle numérique pour la propagation acoustique à l'intérieur de sédiments marins près de l'angle critique à partir d'un point source dans l'eau, y compris les effets d'ondes planes homogènes et inhomogènes.

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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 are being achieved by pursuing complementary approaches to making the sound speed dispersion measurements, including: angle of refraction; acoustic impedance; reflection loss; and time of flight techniques.

Results

Work completed in FY05 includes: participation in the SAX04 field experiment in the Gulf of Mexico; development and testing of data processing algorithms; post sea-trial calibration of sources and receivers, presentation and publication of initial results at international conferences; a preliminary examination of measurement sensitivity and error analysis; application of array element localization software to refine position estimates for all sources and receivers in the water column; and refinements to the numerical model for the acoustic propagation from a point source in water into marine sediments near the critical angle, including the effects of homogeneous and inhomogeneous plane waves. The numerical model is being used to establish experimental geometries where Snell's Law is directly applicable or when corrections to angle of arrival estimates must be applied. The analysis of acoustic arrivals transmitted from three orthogonal directions is being used to determine the absolute position and orientation of the buried vector sensor receivers. Preliminary sound speed measurement results indicate that sound speed dispersion is being observed and that the results in SAX04 differ from those in SAX99, as the frequency band with the most rapid increase in sound speed is at a higher frequency in SAX04.

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

FY06 activities will include: further data and error analysis; model and data comparisons; participation in a SAX04 workshop in March, 2006; and the preparation of a journal manuscript to document the experimental findings.

Osler, J.C., Hines, P.C., 2005, Measurement and Analysis of Sound Speed Dispersion During SAX04, DRDC Atlantic ECR 2005-248, 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 compressionnelle 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 sont 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, techniques du temps de vol, etc.

Résultats

Les travaux complétés au cours de l'exercice 2005 comprennent ce qui suit : participation à l'expérience en conditions réelles SAX04 dans le Golfe du Mexique; développement et mise à l'essai d'algorithmes de traitement de données; présentation et publication des résultats initiaux à des conférences internationales; examen préliminaire de la sensibilité des mesures et analyse des erreurs; application d'un logiciel de localisation d'éléments de réseau afin de préciser les estimations de position pour toutes les sources et récepteurs dans la colonne d'eau; et améliorations du modèle numérique pour la propagation acoustique à l'intérieur de sédiments marins près de l'angle critique à partir d'un point source dans l'eau, y compris les effets d'ondes planes homogènes et inhomogènes. Le modèle numérique est utilisé pour établir des géométries expérimentales lorsque la loi de Snell est directement applicable ou lorsque des corrections des estimations de l'angle d'arrivée doivent être appliquées. L'analyse des signaux acoustiques d'arrivée, émis dans trois directions orthogonales, est utilisée pour déterminer la position et l'orientation absolues des récepteurs/capteurs vectoriels enfouis. Les résultats préliminaires de mesures de la vitesse du son indiquent que la dispersion de la vitesse du son est observée et que les résultats de SAX04 diffèrent de ceux de SAX99, car la bande de fréquences où la vitesse du son augmente le plus rapidement est plus élevée dans le cas de SAX04.

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 l'exercice 2006 comprendront d'autres analyses de données et d'erreurs; des comparaisons de modèles et de données; la participation à un atelier SAX04 en mars 2006; et la préparation d'un manuscrit-journal pour documenter les conclusions expérimentales.

Osler, J.C., Hines, P.C., 2005, Measurement and Analysis of Sound Speed Dispersion During SAX04, DRDC Atlantic ECR 2005-248, Defence R&D Canada – Atlantic.

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 are being achieved by pursuing complementary approaches to making the sound speed dispersion measurements (Osler *et al*., 2005a). The experimental equipment that has been developed (Fig. 1) permitted data to be collected to pursue five different approaches to measure the sound speed dispersion. These approaches are: a) measuring the angle of refraction of an acoustic pulse into the seabed that was transmitted from a projector at known source positions in the water column, and solving for sediment sound speed using Snell's Law (Osler *et al*., 2005b); b) similar to the first approach, but using ship radiated noise below 1 kHz as the acoustic source (Lyons *et al*., 2005); c) measuring the energy lost when acoustic pulses undergo a specular reflection from the seabed at different grazing angles, and then looking for a frequency dependent critical angle; d) measuring the time-of-flight between sources and receivers buried in the seabed at fixed separations, repeating the measurement at different frequencies (Hines *et al*., 2005a and 2005b); and e) measuring acoustic impedance at vertical incidence as a function of frequency.

WORK COMPLETED

1) *Participation in SAX04 experiment*: The equipment developed to measure sound speed dispersion during SAX04 was shipped to NSWC Panama City to be loaded onto the *R/V Seward Johnson*. All of the equipment was packed into a 20 foot long sea container that also served as a portable laboratory onboard the research vessel. DRDC Atlantic personnel made three trips to Florida: a) from 20 to 24 September, 2004 to unload the container, re-configure it as a portable laboratory, and assemble equipment such as the sensor burial jig on the dock; b) from 10 to 15 October, 2004 to bury vector sensor receivers and acoustic sources into the seabed; c) from 24 October, 2004 to 5 November, 2004 to conduct experiments and then pack equipment for shipping back to DRDC Atlantic. The cruise report of DRDC participation in SAX04 contains a daily summary of activities and measurements (Osler, 2005). Technical details regarding the experimental techniques, equipment developed or procured, and deployment techniques are described in Osler *et al*., 2005a.

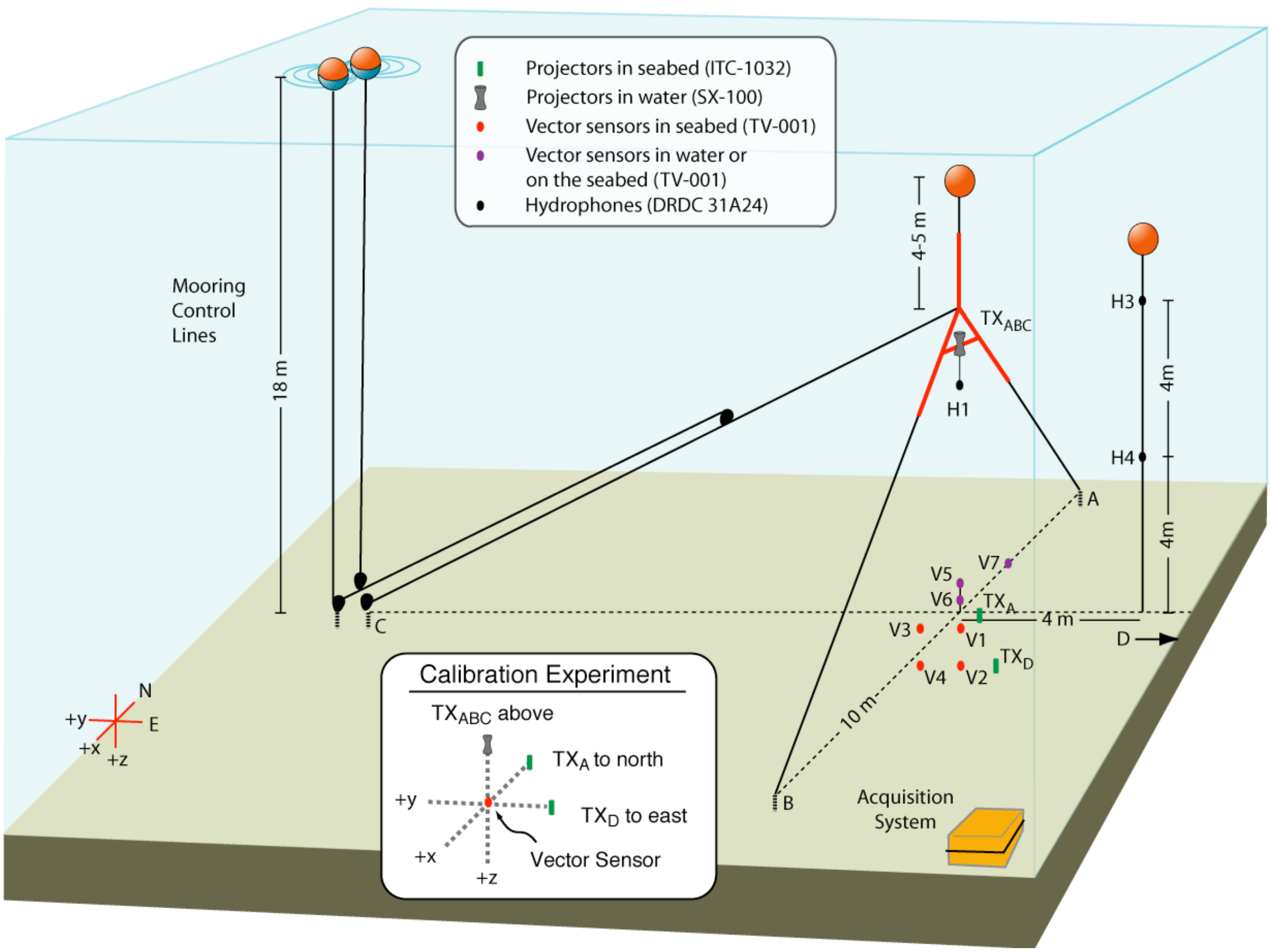

Figure 1: The experimental geometry to measure sound speed dispersion. Acoustic arrivals are received by sensors buried in the seabed and moored in the water column. There are acoustic sources buried in the seabed and in three point moorings (one of two is shown) that can adjust the angle of incidence.

2) *Numerical simulations:* A Mathematica notebook has been developed at DRDC Atlantic to support analysis and interpretation of the SAX04 data (Chapman *et al*., 2005). It calculates the acoustic field in a (fluid) seabed from a point source in the water (Fig. 2). A CW source is assumed, and the calculations are performed by numerically computing the Weyl-Sommerfeld integral, adapted from electro-magnetics to acoustics by Brekhovskikh. All components of the field are included, including homogeneous and inhomogeneous plane waves. The geometric ray path between source and receiver is computed for reference purposes, but there is no "geometric acoustics" approximation applied. Effects often attributed to a distinct "lateral wave" are included as a matter of course. Both the pressure and the particle velocity (time and space derivatives of the acoustic potential, respectively) are calculated allowing direct comparison to be made with measurements using the Wilcoxon vector sensors. One can individually compute the received sound level (pressure), the particle displacements, and the energy flux (product of pressure and velocity), and the impedance (ratio of pressure and velocity).

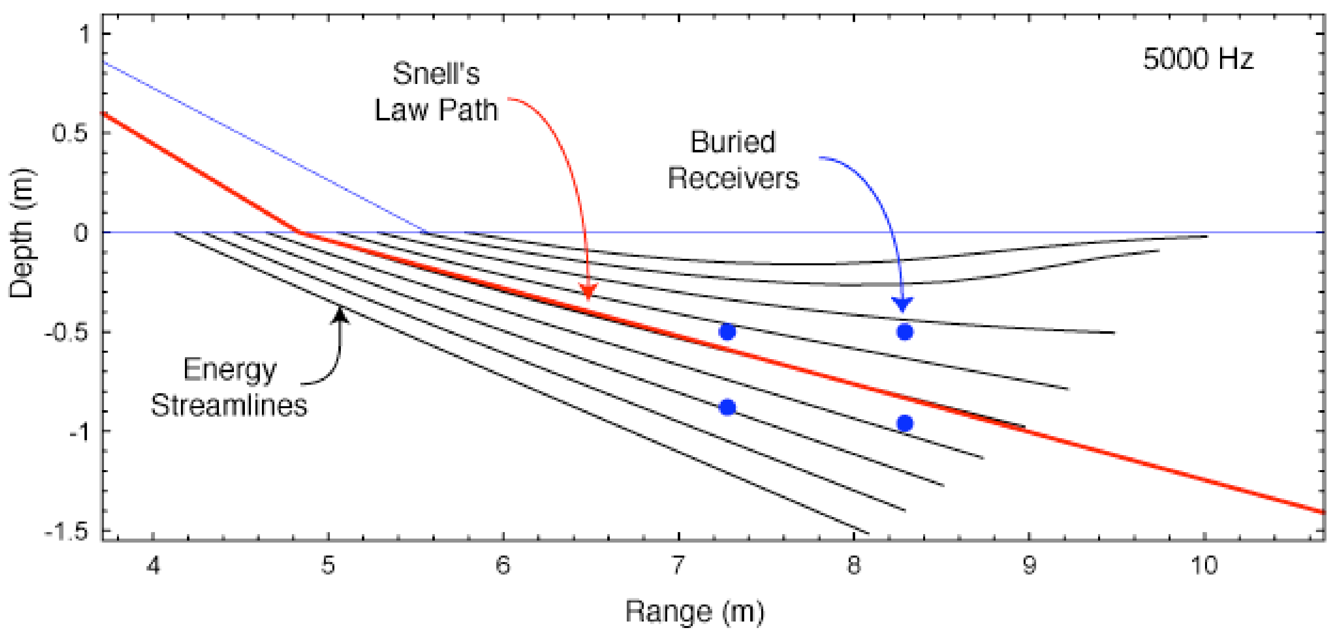

Figure 2: Energy flux streamlines into the seabed (black lines) for an acoustic arrival at 5 kHz just above the critical grazing angle (blue line). One application of this simulation is to determine the sensor positions (blue dots), frequencies and grazing angles at which Snell's Law (red ray path) is valid and when it is not because of the influence of inhomogeneous waves.

3) *Source and receiver locations*: An accurate determination of source and receiver locations is critical to the application of the experimental techniques. For the sources and receivers in the water column, this has been determined using a regularized inversion of travel time information (Dosso *et al*., 2004). For the buried receivers, their orientation is being determined by measuring the arrival angle of acoustic pulses arriving at the sensors from three orthogonal directions (inset in Fig. 1) using two sources buried in the seabed and one overhead in the water column (Osler *et al*., 2005c). The horizontal position of the buried receivers is fixed by the burial jig. The deployment technique can allow a vertical offset of the receivers from their intended burial depths. This is being investigated using the consistency between time-of-flight data from three orthogonal directions (Hines *et al*., 2005b) and time differences between the direct arrivals and reflections from sediment-water interface.

4) *Post sea-trial calibrations*: Following SAX04, the seven Wilcoxon TV-001 vector sensors were re-calibrated to confirm that their frequency response had not changed due to deployment and handling during the sea-trial. In addition, beam pattern calibrations were made at 0.8 and 1.2 kHz, two frequencies at which measurements were made, but pre-trial calibrations were not conducted. Transmitting voltage response curves were also obtained for the ITC-1032 transducers that served as the buried sources during SAX04.

5) *Data analysis:* Two approaches to analyze the time-of-flight data have been developed. The first uses a frequency domain correlation between received arrivals and a replica pulse (the source monitor or another data channel). The second measures the time-of-flight between the onset time of the acoustic projector (monitored via transducer current and voltage) and the onset time of an acoustic pulse received on one or more of the buried receivers. This has been applied to different travel time paths between the buried sources and buried receivers (Hines *et al*., 2005a) as well as between the source in the water column and the buried receivers (Hines *et al*., 2005b). For the determination of angle of arrival using the vector sensors, two analysis techniques have been developed (Osler *et al*., 2005c). The first determines the tilt angle of the semi-major axis of the elliptical particle motion that one observes if two of the acceleration components are plotted against each other. The second technique determines the arrival angle by computing the acoustic intensity (pressure times acceleration) for two vector sensor components (assuming a 2-D geometry initially). These algorithms have been tested with synthetic data, including noise, to determine the signal to noise ratio required to obtain the angular resolution that is necessary for the sound speed dispersion measurements. They have been used to conduct a preliminary analysis of the SAX04 data set.

6) *Sensitivty and error analysis*: Different potential sources of error are being identified and quantified. Thus far, this has included determining the position and orientation of the buried vector sensors using the transmissions from the sources situated in three orthogonal directions (Hines *et al*., 2005b, Osler *et al*., 2005c). For the time-of-flight measurements, the data analysis techniques have been applied to acoustic arrivals transmitted from the source in the water to receivers in the water to quantify the error in estimating the speed of sound. This analysis indicates that the sound speed dispersion observed in the seabed is far greater than the uncertainty in the data processing technique (Hines *et al.*, 2005b). For the angle of arrival measurements, a theoretical sensitivity study has been conducted. Assuming conditions under which Snell's Law is valid, the uncertainty in the angular resolution is being converted to an uncertainty in sound speed for the different experimental geometries that were used for the SAX04 measurements (Osler, 2005).

RESULTS

Preliminary results obtained using the Snell's Law and time-of-flight techniques indicate that sound speed dispersion is being observed (most recent results in Hines *et al.*, 2005b). The results in SAX04 differ from those in SAX99 as the frequency band with the most rapid increase in sound speed is at a higher frequency (Fig. 3). Three possible explanations are offered and will be evaluated as results and supporting environmental information from other researchers become available. The explanations are: a) the sediment composition is different due to the effects of Hurricane Ivan; b) the sediment composition is different because the SAX04 location is closer to the coast line than SAX99; or c) the relative sound speed measurements in SAX99 from 1 to 10 kHz (open diamonds in Fig. 3) should have been combined with the absolute measurements above 10 kHz using a different reference value for the sediment to water sound speed ratio. Collaboration between DRDC Atlantic and Dr. Tony Lyons at the Applied Research Laboratory at The Pennsylvania State University (ARL/PSU) is ongoing. The ARL/PSU results obtained by using ship radiated noise below 1 kHz and the Kramers-Kronig relations between attenuation and sound speed are consistent with the intial results being obtained by DRDC Atlantic (Lyons *et al*., 2005).

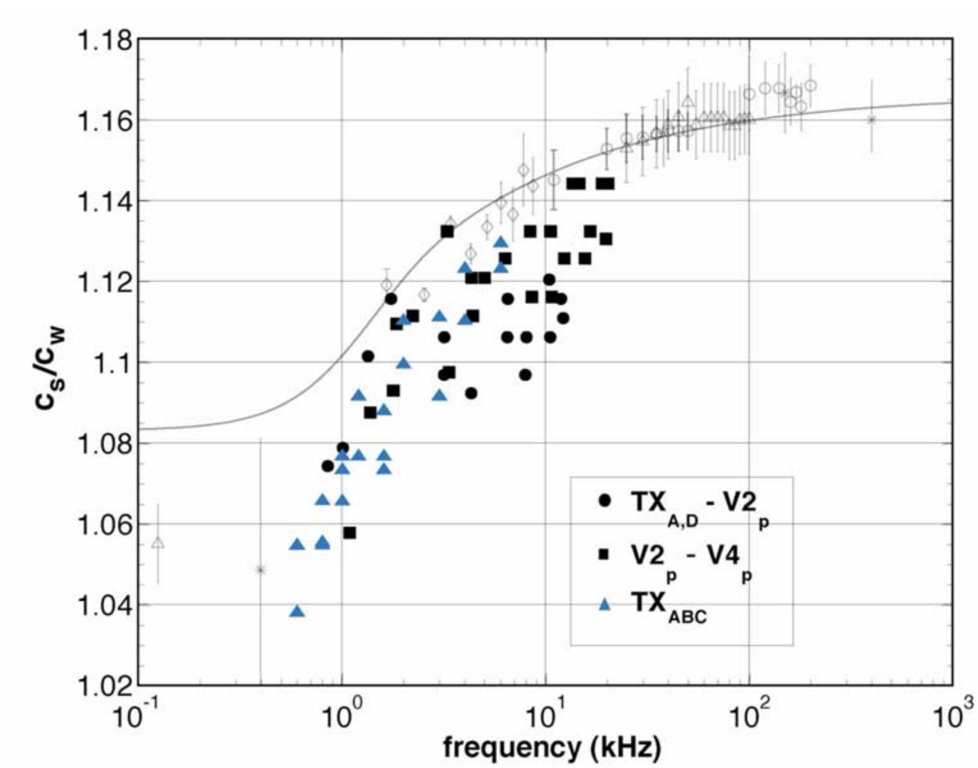

Figure 3: A comparison of sound speed measurement during SAX04 (solid symbols) using the time-of-flight technique (Hines et al., 2005b), including vertical and horizontal propagation paths between sources and receivers, with the results from SAX99 (hollow symbols) (Williams et al., 2002).

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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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 are being achieved by pursuing complementary approaches to making the sound speed dispersion measurements, including: angle of refraction; acoustic impedance; reflection loss; and time of flight techniques. Work completed in FY05 includes: participation in the SAX04 field experiment in the Gulf of Mexico; development and testing of data processing algorithms; presentation and publication of initial results at international conferences; a preliminary examination of measurement sensitivity and error analysis; application of array element localization software to refine position estimates for all sources and receivers in the water column; and refinements to the numerical model for the acoustic propagation from a point source in water into marine sediments near the critical angle, including the effects of homogeneous and inhomogeneous plane waves.

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