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14. ABSTRACT
This grant was a "Graduate Traineeship Award" in Ocean Acoustics for the support of Curtis F. Osterhoudt. The purpose of his research was to improve the understanding of the way that acoustic evanescent waves interact with targets buried in sediments in situations encountered in underwater acoustics. A method was developed and tested for the stable laboratory production of acoustic evanescent waves in water based on the reflection of a beam of sound at an interface between the water and an adjacent liquid. Responses of targets illuminated by this evanescent wavefield were measured and the major features were modeled. The emphasis was on backscattering from cylindrical targets having strong resonances. The research is discussed in detail in Osterhoudt's Ph. D. Thesis completed at Washington State University in April 2007. The title of the thesis is: "Evanescent acoustic waves: production and scattering by resonant targets."

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Evanescent Acoustic Wave Scattering by Targets and Diffraction by Ripples

"Graduate Traineeship Award" in Ocean Acoustics

August 2007

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Table of Contents

I. Summary

This grant was a "Graduate Traineeship Award" in Ocean Acoustics for the support of Curtis F. Osterhoudt. The purpose of his research was to improve the understanding of the way that acoustic evanescent waves interact with targets buried in sediments in situations encountered in underwater acoustics. A method was developed and tested for the stable laboratory production of acoustic evanescent waves in water based on the reflection of a beam of sound at an interface between the water and an adjacent liquid. The evanescent wavefield was measured and it was modeled using the wave-number integration code OASES. Responses of targets illuminated by this evanescent wavefield were measured and the major features were modeled. The emphasis was on backscattering from cylindrical targets having strong resonances. Some of the most important observations are: (1) the strong dependence of the backscattering on the cylinder location relative to the interface (that is, the effective burial depth of the cylinder), and (2) the strong dependence of the backscattering on the orientation of the cylinder. Unlike the research originally proposed for this Traineeship, simulations of the complications caused by ripples in a sediment interface were not explored. This was a consequence of the significant demands of the experiments undertaken.

II. Introduction

This grant (N00014-03-1-0262) primarily provided salary support at Washington State University (WSU) for a graduate Research Assistant, Curtis F. Osterhoudt, to facilitate research on the topic indicated by the grant title. After funds from this grant ($119,260) were depleted, to facilitate the completion of his Ph.D. thesis, Osterhoudt drew support from ONR grants N00014-03-1-0585 "Scattering of Evanescent Acoustic Waves by Regular and Irregular Objects" [1] and a follow-on grant (N00014-06-1-0045). The nature and size of the project was such that during much of research, assistance was needed from other students and research staff. Those persons were supported by grant N00014-03-1-0585 (which covered most of the facilities costs), or grant N00014-06-1-0045. Osterhoudt completed his Ph.D. thesis in April 2007, at which time he departed for his current employment at Los Alamos National Laboratory. He may be reached at: **cfo@lanl.gov** or at the address shown in the Distribution List. Copies of Osterhoudt's Ph.D. thesis may be requested from Professor Philip L. Marston by email: **marston@wsu.edu**. According to WSU regulations, Marston is listed as the Principal Investigator for this grant and Osterhoudt as the Co- Principal Investigator.

Two members of Osterhoudt's Ph.D. thesis committee were especially helpful in their comments on his thesis: Dr. Steven G. Kargl (Applied Physics Lab., Univ. of Washington, Seattle) and Prof. John B. Schneider (Washington State Univ.).

The scope and accomplishments of the thesis are summarized in the abstract given in Sec. III. This is followed by some technical discussion and references (Sections IV-VI) and a list of references that includes some of the External Communications supported in part by this grant. Additional information is available in archived reports [1], [2].

Background: The effective speed of sound in sediments typically exceeds the speed of sound in the water column above and this has some important consequences. For example the typical speed of sound in the water and in the sediment are $c_w = 1536$ and $c_b = 1770$ m/s, respectively. The corresponding critical grazing angle α_c is arccos(1536/1770) = 29.8° (which corresponds to a critical angle of incidence relative to the normal of $\theta_c = 90 - \alpha_c = 60.2°$). Neglecting the attenuation of sound in the sediment and in the water column gives the well-known prediction that: (1) plane waves incident with grazing angles $\alpha < \alpha_c$ are totally reflected and (2) for such waves the acoustic amplitude decays exponentially with increasing depth in the sediment. The associated exponentially decaying wavefield in the high-speed medium (the sediment) is commonly referred to as an evanescent wave or an "inhomogeneous" wave. While real sediments can have significant attenuation and often have non-smooth surfaces, there is considerable evidence for the existence of an evanescent nature of the transmitted sound and of the associated complications of using sound with *post-critical incidence* (grazing angles with $\alpha < \alpha_c$) for the detection of buried objects. (The following comment on terminology may be helpful: while in *optics* the angle of incidence θ relative to the normal is often used to specify the incident direction, in *underwater acoustics* most recent authors use the grazing angle so that the idealized total-reflection region is associated with "subcritical" incidence. To avoid confusion, the term "post-critical" incidence is used here.) There is evidence that diffraction by *ripples* on the sea floor frequently alters the post-critical reflection and transmission of sound. It has been reported, however, that even with moderate ripples, conditions below about 6 kHz can be found *at sea* where the dominant transmitted wave is an evanescent wave. Furthermore, it is expected, the ripple effect is lessened when the seafloor is viewed in a direction generally parallel to the ripples. It is frequently desirable to view the bottom acoustically from the greatest possible distance which means that the grazing angle is small and post-critical conditions apply. For this reason it is highly desirable to gain an improved understanding of the description of the scattering of sound by evanescent waves for both man-made and natural objects. **Figure 1** illustrates an example of the situation. The complications introduced by evanescence on the acoustic detection and classification of buried objects is the topic of research in this project.

III. Information on the Thesis
Student: Curtis F. Osterhoudt,
Ph. D. Thesis Title: Evanescent acoustic waves: production and scattering by resonant targets
Listed Date by Washington State University: May 2007
Length: 283 pages
Abstract: Small targets with acoustic resonances which may be excited by incident acoustic plane-waves are shown to possess high-Q modes ("organ-pipe" modes) which may be suitable for ocean-based calibration and ranging purposes. The modes are modeled using a double point-source model; this, along with acoustic reciprocity and inversion symmetry, is shown to adequately model the backscattering form functions of the modes at low frequencies. The backscattering form-functions are extended to apply to any bistatic acoustic experiment using the targets when the target response is dominated by the modes in question.

An interface between two fluids which each approximate an unbounded half-space has been produced in the laboratory. The fluids have different sound speeds. When sound is incident on this interface at beyond the critical angle from within the first fluid, the second fluid is made to evince a region dominated by evanescent acoustic energy. Such a system is shown to be a possible laboratory-based proxy for a flat sediment bottom in the ocean, or sloped (unrippled) bottom in littoral environments.

The evanescent sound field is characterized and shown to have complicated features despite the simplicity of its production. Notable among these features is the presence of dips in the soundfield amplitude, or "quasi-nulls". These are proposed to be extremely important when considering the return from ocean-based experiments. The soundfield features are also shown to be accurately predicted and characterized by wavenumber-integration software.

The targets which exhibit organ-pipe modes in the free-field are shown to also be excited by the evanescent waves, and may be used as soundfield probes when the target returns are well characterized. Alternately, if the soundfield is well-known, the target parameters may be extracted from back- or bistatic-scattering experiments in evanescent fields. It is shown that the spatial decay rate as measured by a probe directly in the evanescent field is half that as measured by backscattering experiments on horizontal and vertical cylinders driven at the fundamental mode, and it is demonstrated that this is explained by the principle of acoustic reciprocity.

IV. Laboratory Method for Generating Acoustic Evanescent Waves

At the time this grant started in 2003 there was no widely recognized standard approach for the laboratory generation of acoustic evanescent waves. Consequently various approaches were examined during the first grant year. While testing various combinations of liquids, a research faculty member having a background in chemical engineering (Dr. David B. Thiessen, supported by grant N00014-03-1-0585) discovered a suitable liquid mixture having the required sound-speed, density, and safety properties. Osterhoudt subsequently measured the detailed physical and acoustical properties of the system and scaled-up the system and characterized the evanescent waves [1]-[6]. This environmentally-friendly liquid mixture, when placed in contact with water, has the desirable acoustic contrast to facilitate the production of acoustic evanescent waves in water. The mixture does not mix with water. It is denser than water and has a 885 m/s sound speed. The low velocity liquid is in a 70 gallon tank surrounded by water in a 3000 gallon tank, **Figure 2**. The low velocity liquid is a mixture of HFE-7500 manufactured by 3M Corporation with 5 cS kinematic viscosity PDMS silicone oil. This system is used to generate wavefields having significant evanescent components by illuminating the interface with a beam having post-critical incidence. The source transducer is placed in the dense liquid mixture, which simulates the ocean water column. The water in the tank above the mixture simulates the ocean bottom. The typical operating frequency used is 60 kHz in a tone-burst mode of operation. The evanescent wavefield decays upward in the water since the simulated water column (the oil) is denser than (and is trapped below) the simulated sediment (the water). This is a convenient arrangement since it allows hydrophones and target positions to be easily scanned within the simulated bottom. This system of liquids is more suitable for long-term indoor use than the vegetable-oil/glycerin system used in related studies by a group at a Naval facility. The disadvantage of our system is the high cost of the liquids used in the mixture. In 2005 the price of the ingredients in the HFE-oil mixture was such that the cost of the mixture was approximately $175 per gallon. In most experiments it was necessary to use coherent background subtraction in which a background signal is recorded in the absence of a target and that signal is subtracted from the record when the target is present to infer the scattering.

Installing the appartus shown in **Figure 2** required significant modification of one of the existing water tanks. The manpower requirements for that task and for the installation and alignment of experiments is one of the reasons that at times multiple students were involved. Positioning systems were procured (or in some cases modified from an existing system) to facilitate target movement and adjustment of target orientation. In addition, a positioning system was installed to move the hydrophone.

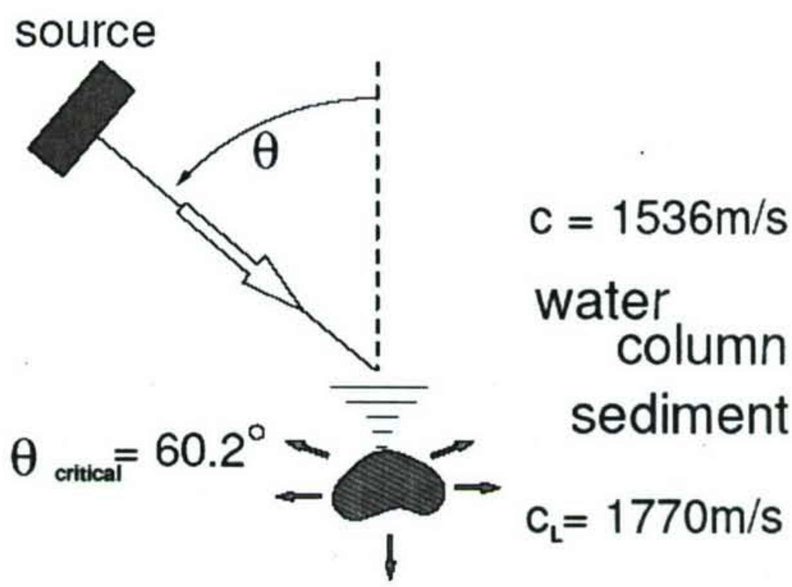

Figure 1. Generic problem associated with detecting objects buried in sediments with a sound source at grazing incidence. When the angle of incidence θ is larger than the critical angle $\theta_{critical}$ for some conditions the transmitted acoustic wavefield decays exponentially with depth in the sediment even when absorption by the sediment is weak. Furthermore the exponential decay rate increases the larger the value of $(\theta - \theta_{critical})$. The acoustic wave associated with this exponential decay is an evanescent wave.

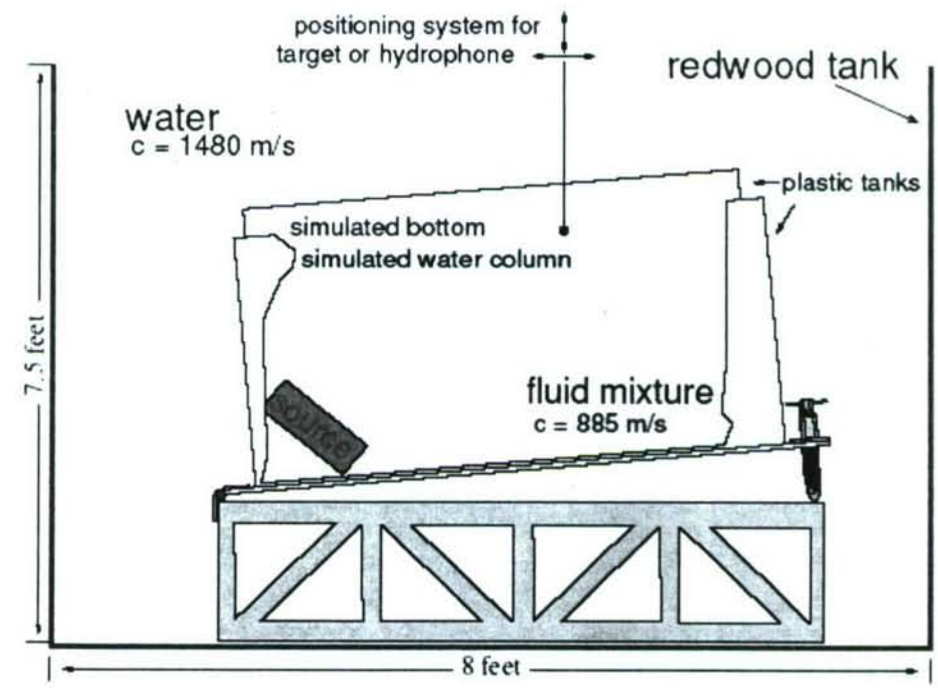

Figure 2. Main features of the apparatus for studying the acoustical scattering.

V. Target Selection for Studying Resonances Excited by Evanescent Waves

To assist in potential applications related to objects buried in sediments, it was decided to examine the scattering by objects having sharp or "high-Q" modes. The emphasis was on cylindrical objects. We mostly studied high-Q modes of water-filled hollow metal cylinders. These modes are related to ones previously examined by Hackman [7] for solid cylinders. These modes were studied by Osterhoudt and Marston [8] for water-filled cylinders excited by ordinary propagating waves. In our model for the scattering of sound by cylinders illuminated by ordinary waves, the high-Q of this "organ pipe mode" of the water filled cylinder is the result of the reflection coefficient being close to unity for sound waves in the liquid within the cylinder ([6], [9]).

In our experiments the cylinder is illuminated by evanescent waves generated using the apparatus shown in **Figure 2**. The backscattering to the source transducer is recorded as a function of the distance of the cylinder-end from the oil-water interface. For many of the experiments the cylinder's axis was perpendicular to the interface. The emphasis was on the high-Q modes of small water-filled hollow stainless steel cylinders. **Figure 3** shows an example of a time record for backscattering by a cylinder placed close to the interface. The figure shows the build up of the response of the mode followed by the exponential decay of the cylinder oscillations. The cylinder is driven by a 64 kHz tone burst. This signature is only present when the frequency of the tone burst is close to a resonance frequency of the target.

VI. Position Dependence of the Backscattering with a High-Q Resonance

One of the objectives of this research was to understand how the scattered signal varies with the effective target depth and orientation for the case of evanescent wave illumination. The interested reader is referred to the Thesis [6], published abstracts [10]-[12] and archived reports [1]-[2] for a discussion of the results.

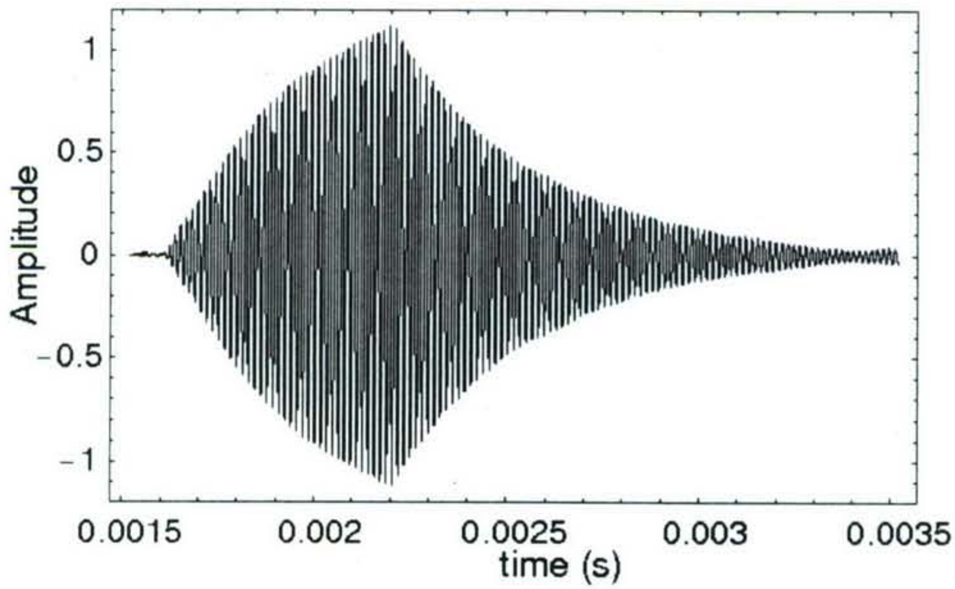

Figure 3. The signal scattered from the target back to the source when a horizontal water filled cylindrical shell is driven by a 64 kHz evanescent wave. Here, the target's lowest organ-pipe mode is strongly excited, and a ring-up is followed by a gradual decay.

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