Statistical Properties of the Acoustic Field in Inhomogeneous Oceanic Environments: Acoustic Uncertainty due to Horizontal Refraction

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LONG-TERM GOALS

To quantify the degree to which uncertainty in the knowledge of cross-range variation of environmental parameters and their variation in time (or purely statistical information on the variations) degrades the ability to detect, locate, and track targets acoustically.

OBJECTIVES

- To develop an efficient formalism of transferring uncertainty in the 4-D spatial-temporal fields of environmental parameters into uncertainties of observable acoustic quantities.

- To quantify the amount of environmental information necessary to achieve a specified accuracy of acoustic field modeling and to determine, for various nearshore hydrodynamic processes of interest, when 2-D (as opposed to 3-D and 4-D) environmental and propagation models are acceptable.

- To develop a numerical algorithm for predicting statistical moments of acoustic signals in underwater waveguides with horizontally-inhomogeneous and time-dependent parameters.

APPROACH

Our approach to modeling acoustic effects of cross-range environmental gradients, oceanic currents, and time-dependence of the sound speed and the problem geometry, is based on considering these effects as perturbations with respect to sound propagation in a range-dependent, motionless, stationary waveguide. The problem is solved analytically for the three leading terms of the perturbation series. Account of the second-order terms is crucial because it is these terms that are responsible for ray travel time and mode phase biases. The perturbation solution is used to determine statistical properties of various acoustic observable quantities in terms of respective statistical properties of environmental parameters. The task of relating statistical properties of the sound field to statistical properties of the environment is greatly facilitated by the fact that the perturbation theory gives variations in travel times and other acoustic quantities as integrals in the source/receiver vertical plane of certain functions of cross-range gradients and time derivatives of environmental parameters. Kernels of the integrals are determined by the acoustic field in an unperturbed, stationary, range-dependent environment and are independent of the currents, the cross-range environmental gradients and time derivatives.

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14. ABSTRACT
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15. SUBJECT TERMS

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The key individuals involved in this work are Dr. Oleg Godin (CIRES/Univ. of Colorado and NOAA/ETL) and Drs. Alexander Voronovich and Valery Zavorotny (NOAA/ETL).

WORK COMPLETED

A quasi-stationary approximation has been developed to efficiently model acoustic effects of the time-dependence of the environmental parameters, such as sound speed and ocean surface variations due to internal and surface gravity waves, occurring on various time scales. In the quasi-stationary approximation, determining acoustic travel time, phase, and frequency is reduced to calculation of certain quadratures along the trajectory the wave would take in the stationary medium. It has been shown that, unlike the commonly utilized frozen medium approximation, the quasi-stationary approximation allows one to accurately simulate effects of the ocean nonstationarity on acoustic travel times, nonreciprocity, and signal spectrum (Godin, 2002g, e, f).

New and improved techniques have been put forward to incorporate data on oceanic currents into acoustic propagation models based on a coupled-mode representation of the field (Godin, 2002b) and a wide-angle, energy-conserving, 3-D parabolic approximation (Godin, 2002d).

Using theoretical results of (Godin, 2002i), a numerical algorithm has been created to predict statistical moments of ray travel times in the ocean where 3-D random inhomogeneities are superimposed on a range-dependent deterministic background. The algorithm has been applied to simulate the effects of random horizontal refraction of sound caused by internal waves.

RESULTS

Deviation of wave trajectory from the source/receiver vertical plane leads to ray travel times and adiabatic normal mode phases being *less* than predicted by the uncoupled azimuth approximation which neglects cross-range environmental gradients. Internal waves appear to be the major source of the travel time bias in the deep ocean. Magnitude of the bias increases as the range squared, is maximum for rays with shallow upper turning points, and can exceed 10 ms at the range of 1Mm. Magnitude of the bias is proportional to path-averaged energy of the internal waves. Variance in the travel time bias is of the order of the bias itself. Figure 1 shows the bias for various ray arrivals as a function of grazing angle at the receiver for two acoustic tracks under conditions of 1987 Reciprocal Tomography Experiment (RTE87) (Dushaw *et al*., 1993) for source and receiver at 1000 m depth near the waveguide axis. Simulations assumed Garrett-Munk spectrum of the internal waves. The travel time corrections due to horizontal refraction are close to travel time discrepancies resulting from different equations of state of sea water discussed in (Dushaw *et al*., 1993). Hence, account of the horizontal refraction is necessary if long-range underwater sound propagation is to be used to verify the equations of state. For continuous waves, the travel time bias due to horizontal refraction translates into a change in the conditions of interference of individual arrivals. In the example considered, neglect of the horizontal refraction due to the internal waves results in O(1) relative phase errors and, consequently, significant transmission loss errors at frequencies as low as 50 Hz.

In shallow water, horizontal refraction can lead to comparable effects at much smaller ranges when there are strong cross-range environmental gradients along the acoustic track, such as a bottom slope or variation of sound speed in the horizontal plane due to an oceanographic front or an internal wave soliton. Unlike the deep water case, significance of the horizontal refraction proves to be very sensitive to azimuthal direction of sound propagation. For instance, consider sound propagation over 13.5 km track between sound source A2 and northern vertical line array (NVLA) during the 1995 Shallow-Water Acoustics in Random Medium (SWARM) experiment (Apel *et al.*, 1997). Internal tide generated at the shelf brake was a major source of environmental variability at the SWARM site, with up to 10 m vertical displacements in 80 m-deep ocean. The observed internal tide (Apel *et al.*, 1997) was similar to a train of internal wave solitons (Fig.2). Neglecting ocean bottom slope, ray travel time corrections due to horizontal refraction have been found to exceed 11 ms for source and receiver at 20 m depth when the internal tide propagates exactly perpendicular to the source/receiver vertical plane. A 3^o uncertainty in the azimuthal direction of the soliton propagation translates into up to 10 ms change in the correction, which amounts to O(1) change in relative phase of different ray arrivals and consequent significant change in the CW transmission loss at sound frequencies above 80 Hz. Horizontal refraction is also responsible for unusually rapid variation of signal spectrum and travel times of individual arrivals. When an internal wave soliton propagates perpendicularly or almost perpendicularly to the acoustic track, travel times of individual arrivals and travel time differences of arrivals with different grazing angles can change by up to 10 ms during a few minutes (Fig. 3). This is because the acoustic travel time and phase corrections due to horizontal refraction are proportional to path-averaged value of the square of the cross-range sound-speed gradient, and the gradient changes rapidly when a soliton with a sharp front propagates through the acoustic track.

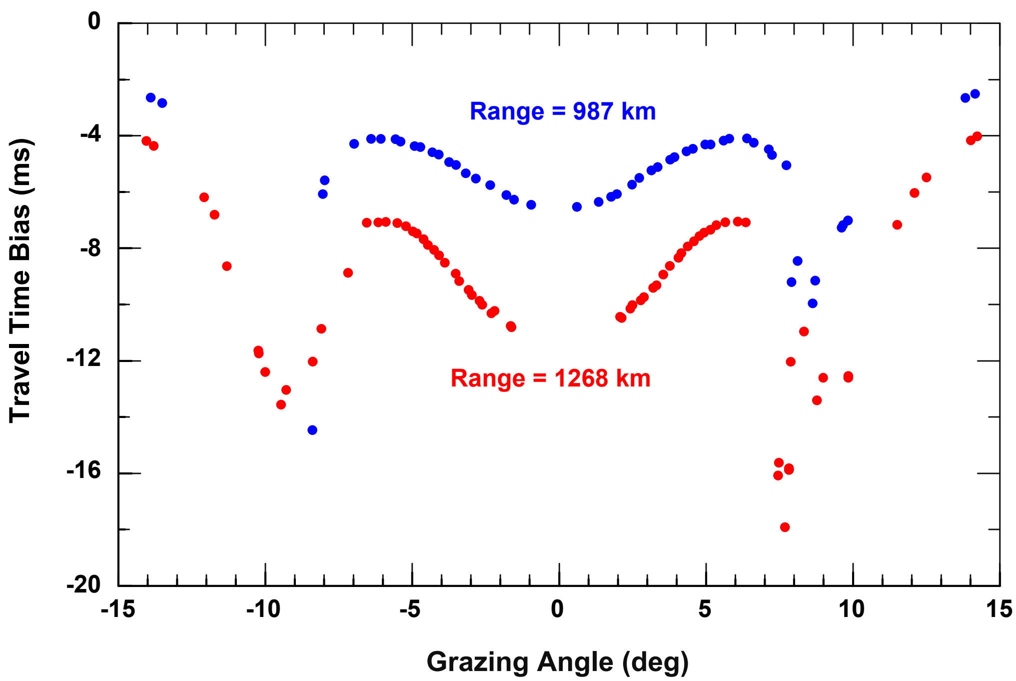

Figure 1. Ray travel time bias due to horizontal refraction for two acoustic tracks under conditions of RTE87 experiment.
[Graph: The bias is negative, its magnitude increases with range and varies from the minima of approximately 1 ms at grazing angles of ±15^o to maxima of 14 -18 ms around ±8^o grazing angles.]

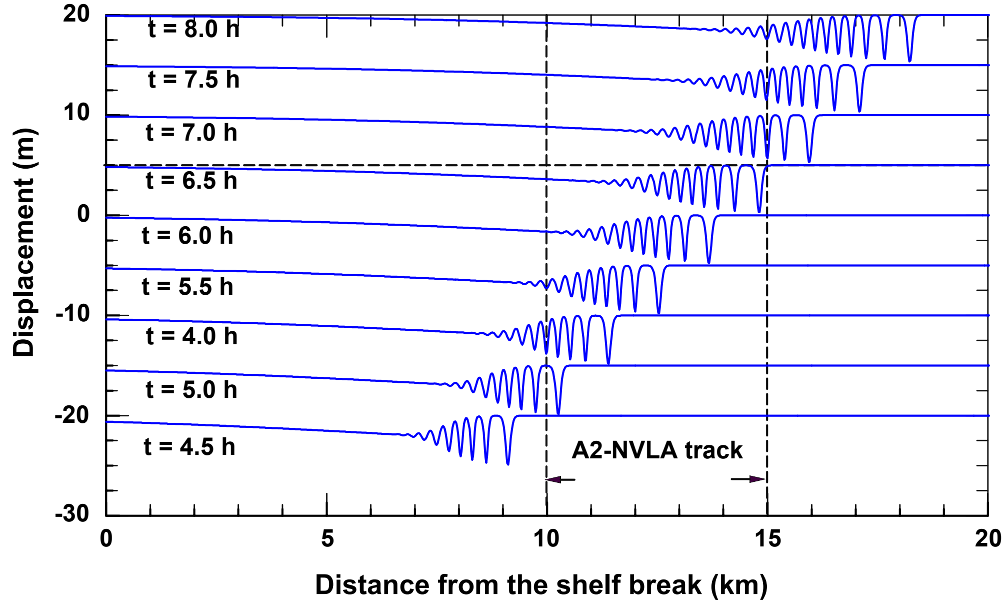

Figure 2. Evolution and propagation of internal wave solitons under conditions of the SWARM experiment. Simulated isopycnal displacement due to internal tide from a background depth of 20 m is shown as a function of geotime and distance from the shelf break. Consecutive graphs are shifted by 10 m in depth for clarity.

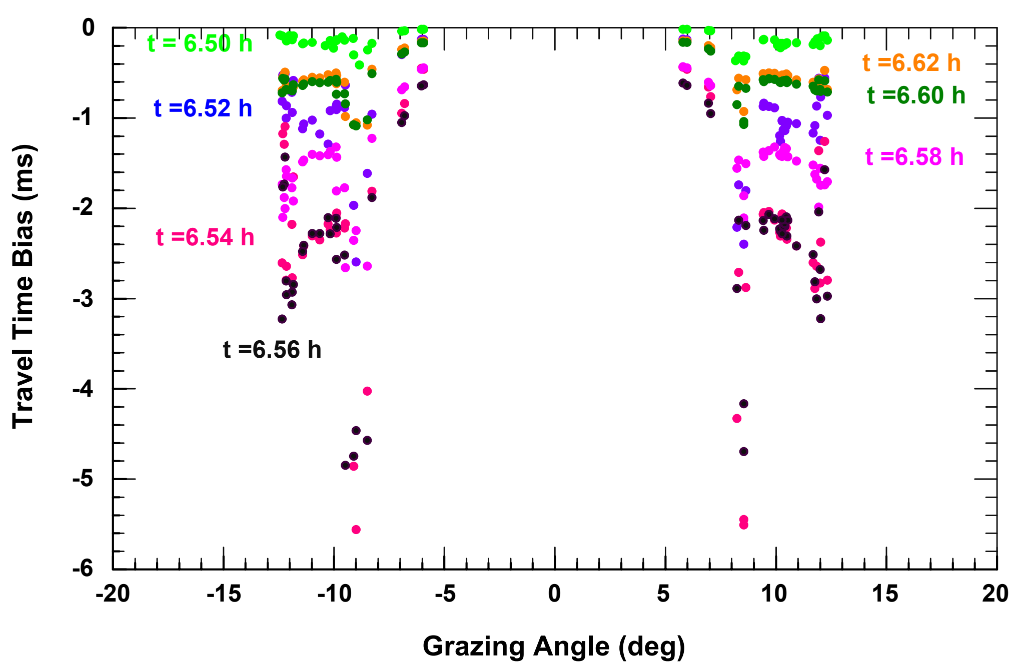

Figure 3. Ray travel time bias due to horizontal refraction caused by an internal tide in a coastal ocean. The bias is shown for source and receiver at 30 m depth 13.5 km apart, as a function of geotime and grazing angle at the receiver.
[Graph: The bias changes by an order of magnitude over 3.6 min.
Minimum value of the bias is –5.6 ms.]

IMPACT/APPLICATIONS

The most immediate impact of this work will be on the use of deterministic models of underwater sound propagation for making tactical decisions. Results of this work will quantify, in a statistical sense, reliability of predictions for various acoustic observables obtained assuming range-dependent ocean and disregarding horizontal refraction and effects due to ocean currents and time-dependence of the environmental parameters.

TRANSITIONS

None yet.

RELATED PROJECTS

None.

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