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INTERNAL WAVE EFFECTS ON ACOUSTIC PROPAGATION

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Abstract: *Internal gravity wave induced acoustic fluctuations are reviewed. It is well known that internal waves cause temporal and spatial variability above and beyond that caused by mesoscale and larger ocean heterogeneity. Increasingly detailed work over many decades has shown that deep-ocean internal waves, which have often been parameterized using the Garrett-Munk spectrum as a guide, are responsible for rapid acoustic field variability at all propagation ranges. Numerous experiments have shown that various sections of wavefronts from impulsive sources have fluctuation qualities well-described by theory, simulation, or both. In contrast, fluctuations in shallow water experiments, although known to be consistent with those expected from internal waves via theoretical and simulation arguments, are incompletely described by theories for a number of reasons. These reasons include nonstationary, inhomogeneous or anisotropic wave environments, unknown geoacoustic properties, and rapidly changing background currents, all of which prevent detailed comparison of observation and prediction. At this time, many different shallow-water internal wave scenarios give rise to similar field fluctuations, within reasonable confidence intervals for the predictions. This may simplify order-of magnitude fluctuation prediction, while simultaneously making inversion and highly-detailed prediction problematic*

Keywords: *Acoustic propagation, acoustic fluctuation, internal gravity waves*

1. INTRODUCTION

The fields of ocean acoustic tomography (OAT) and wave propagation through random media (WPRM) collide head on. In this paper, progress in deep-water and shallow water acoustics research over the last 15 years will be reviewed, demonstrating how sound-speed fluctuations of short temporal and spatial scale (the subject of WPRM) influence the effectiveness of OAT in both deep-water and shallow-water environments. Sound in the range of 40 to 500 Hz is considered. In tomography, sound is transmitted for the purpose of remote mapping of large scale (mesoscale to basin scale) background conditions. To accomplish the inverse mapping, the propagated signals must have stable, recognizable, and identifiable features, and those features must exhibit slight variations that are related to the conditions at those scales [1]. However, random (or quasi-random) sound-speed anomalies caused by internal-wave displacements or intrusive fine structure, which have short time and space scales, cause rapid variations of signal properties superimposed over the slow variations that are used for the mapping [2,3]. The small-scale anomalies and the fluctuations they cause are well suited to statistical investigation, and their study fits into the more general field of WPRM. In the most-favorable case, the small-scale anomalies create unbiased fluctuations and arrivals are identifiable, so that averaging reduces the noise and enables inversion [2 (sections 5.3 and 5.8)]. In the least-favourable case, the fluctuations obliterate some or all of the arrival structure and identification is not possible [2 (section 4.4), 3, 4].

In any ocean acoustic application, not limited to tomography, a basic question is "What is the signal to noise ratio?" In the case of OAT, identifiable and trackable travel-time deviations comprise the signal, whereas unresolved travel-time fluctuations that interfere with arrival identification comprise the noise. As will be shown, the signal to noise ratios can be very different for basin-scale propagation, mesoscale-resolving propagation, and shallow-water propagation. In particular, in shallow-water and coastal areas, the signal-to-noise ratio may be large enough to allow tomography under limited conditions.

Here, we distill the relationship between the stable pulse structure (the signal) and the strong fluctuations (the noise) down to basics by examining coupled-mode propagation. We use 2-D propagation physics, and ignore additional noise effects from azimuthal coupling.

2. LONG-RANGE (DEEP WATER) PROPAGATION

In the deep-water situation, trackable travel-time deviations of impulsive multipath arrivals (the signal) are known from observational evidence to exist. They are understood and can be predicted in terms of either full-wave or ray-trace physics. For this situation, a considerable amount of work has been done on properties of internal-wave induced fluctuations (the noise). Internal-wave anomalies in these investigations are usually governed by the Garrett-Munk (GM) internal-wave spectrum [5]. Although the oceanic internal-wave spectrum is known to vary, the energy of the internal-wave field is generally between one-third and three times the GM energy level for a large percentage of the ocean, making the effects fairly steady. In addition, the oceanic depth-dependence of vertical displacements, the source of sound-speed anomalies, usually follows the linear buoyancy-frequency $N(z)$ scaling of GM, with the result that sound-speed anomalies are stronger near the surface than at deeper positions because $N(z)$ tends to be higher near the surface (except in the surface mixed layer).

The most frequently studied long-range deep-water case is the temperate ocean waveguide. This type of waveguide has a sound channel with a sound-speed minimum between roughly 600 and 1200 m and a surface sound-speed conjugate depth of between 2500 and 4500 m. Fully refracted or refracted/surface-reflected rays describe most of the acoustic energy in this type of waveguide at distances greater than a few double ray-loop lengths. In this waveguide, a pulse emitted from a source will repeatedly focus and triplicate, forming an accordion-shaped locus in the time front diagram [1]. The locus will have two similar legs, one each for sound emitted upward and downward of horizontal.

Initial studies using a single source and a small receiver (either one phone or a closely-spaced group) demonstrated that early arrivals consistent with high-angle rays having shallow upper turning points could be identified as having travelled along predicted ray paths, and were stable in time, allowing tomography [6,7]. Late arrivals consistent with low-angle rays having turning points closer to the sound-speed minimum were not stable. Experiments that followed which used long vertical line array receivers showed that the accordion time front described the mean early arrival structure, with superimposed small-scale time front variability [8,9]. The late arriving sound was not stable in time, with a complete breakdown of the accordion time front into a sound field appearing to be nearly random. The late-arriving sound also filled an increased depth range not consistent with low angle rays following geometrical optics ray paths through the background sound channel. As for the stable early arrivals, there was evidence that they were sometimes broken into micro-multipaths [4,10], as shown in Figure 1. The computational time front results shown in Figure 1 are consistent with micro-multipath effects in early trackable arrivals of RTE87 North Pacific experiment signals recorded at ranges greater than 1000 km from the sources [John Spiesberger, personal communication]. Because the accordion pattern for the temperate profile becomes more closely spaced at later times, when low-angle near-axial energy arrives, the same micro-multipath and travel-time fluctuation effect that would not prevent time-front identification and tomographic use of early arrivals can prevent time-front identification in late arrivals (i.e. the micro-multipath spread and the time fluctuations exceed the spacing of the arrivals).

A comprehensive and consistent method of explaining the observations was offered by Colosi and Flatté [11]. Using broadband parabolic equation simulations of 75-Hz sound propagating 1 to 3 km, both with and without internal-wave induced sound-speed anomalies, they showed that the strongly fluctuating portion of the arrival pattern in the with-wave case was consistent with multiple arrivals of each normal mode present in the signal. Without internal waves, the simulations yielded the expected adiabatic mode propagation result: a single arrival of each mode. Mode coupling behavior of this type has also been examined at lower frequencies and longer ranges [3].

Overall, rapidly fluctuating small-scale sound-speed anomalies in the ocean cause time-front variations that are functions of waveguide parameters. Generally speaking, many of the early arrivals (high-angle energy) are stable enough for tomographic uses, whereas late arrivals contain excess quasi-randomly appearing high-angle (high mode) energy and are not stable. The transition between the two regimes, and the fraction of arriving energy that is usable for tomography, varies with frequency and with propagation distance. Finally, recent studies of ray dynamics relate internal wave effects to the shearing in phase space of patterns associated with wave fronts [12], so that waveguide parameters may control how perturbations cause fluctuations, not simply the perturbations alone.

3. SHALLOW-WATER PROPAGATION

In the past decade there have been many studies of propagation through one of the most prominent features of the shallow-water continental shelf environment: Nonlinear internal waves. Studies of sound passing through individual waves [13] and groups of waves [14-19] have been made. A salient feature of these waves is their steepness, an aspect of their nonlinearity, which means that they create very strong horizontal gradients of sound speed. Strong gradients of this type cause coupled-more propagation. Figure 2 compares two pulses passing through shallow-water waveguides with and without two packets of internal waves

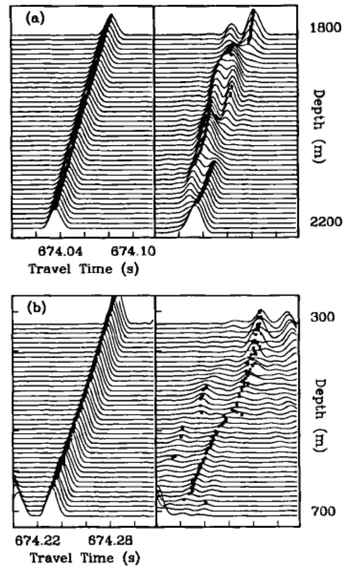

Fig. 1: Computer-simulated time fronts for propagation through sound channels with (right) and without (left) internal-wave induced sound speed anomalies. One section of the full double-accordion time front pattern is shown in each panel. (a) and (b) show two different arrival depth ranges. The source-receiver range is 1000 km, the sound-speed profile is taken from the SLICE89 experiment, and internal waves are governed by the Garrett-Munk spectrum. Figure reproduced from Ref. 4.

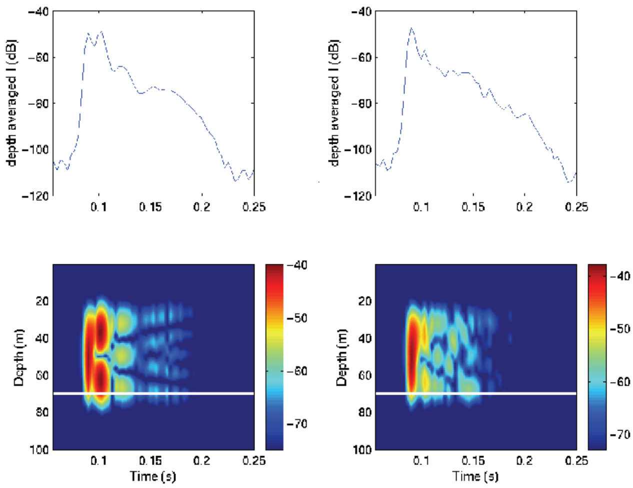

Fig. 2: Pulses with zero (left) and two (right) wave packets. Propagation is through the gently upslope environment of Ref 1, with a thermocline and no shelfbreak front. Pulses are hanning taper, 300-Hz bandwidth, 300-Hz centre frequency. The bottom shows sound intensity (transmission loss, in dB) as color vs. depth and time. The top shows depth-averaged (linear) intensity converted to dB. The RAM PE code was used.

between the source and the receiver. The propagation is 27 km upslope through the environment described in a recent paper [17]. The pulse in the environment without the two wave packets displays adiabatic mode propagation, with mode one arriving first, followed by modes two, three, four and five. In contrast, the pulse passing though the same environment with two three-wave packets at 1 and 14 km from the source shows a complicated depth-pattern of arriving energy resulting from mode coupling at each of the six internal waves.

The effect of wave packet motion on acoustic signals is easily described by the packet mode coupling expression $P^+ = \boldsymbol{C}\,P^-$. Here, P^- is the vector of complex mode amplitudes, on the source side of a wave or wave packet, normalized to eliminate cylindrical spreading, and P^+ is the vector of similarly normalized mode amplitudes on the receiver side. The matrix $\boldsymbol{C}$ describes the mode coupling of the wave or wave packet, and is independent of wave or packet position between the source and receiver. However, the modal composition of P^+ depends very strongly on the packet or wave position because the relative phases of P^- components are functions of that position [15]. Furthermore, the mode stripping process serves to make the received intensity at many kilometres distance beyond the mode coupler a strong function of the P^+ modal content, and thus also on the P^- phases and, in turn, coupler position. In the case of propagation through moving wave packets, these many factors work together so that sound fields fluctuate as packets move distances of order 100 m. Because the waves move at speeds near 1 m/s this means that acoustic correlation times are of order 100 s.

Nonlinear wave packets have been observed at many coastal locations, often with space-based sensors [20]. Most of these waves of the first baroclinic mode, with no zero crossing (in depth) of vertical velocity. The strong surface convergences that make them visible also indicate strong lateral internal gradients, the feature that causes acoustic mode coupling. Thus, coupled-mode propagation with rapid and strong intensity and phase fluctuations is expected to be ubiquitous. Although they have been conducted in only a few locations, detailed acoustical experiments support this. Data from the SWARM study of 1995, one of a series of experiments in the Mid-Atlantic Bight, collected over a fixed path of 32 km, show strong intensity fluctuations with correlation times of a few minutes [21] that are consistent with coupled mode propagation through moving waves [15,16,19]. The data also show multiple arrivals of each of the lowest four normal modes, Figure 3, inconsistent with the adiabatic mode prediction of a single arrival of each mode [21].

One aspect of fluctuations caused by shallow-water internal waves is that they have a saturation-like quality. The mode coupling causes complicated arrivals, as shown in Figures 2 and 3, regardless of whether a few waves, one packet, or many packets are in the acoustic path. Computational and field studies show this. This means that only a few waves, when combined with weak mode coupling or variable adiabatic propagation expected from ubiquitous small-amplitude linear internal waves, mask the pulse structure associated with the background waveguide.

4. COMPARISON OF THE DEEP- AND SHALLOW-WATER CASES

It has been shown that coupled-mode propagation provides a useful description of deep-water fluctuations. The effect masks the time front structure most effectively for near-axial arrivals, which are more closely spaced in their unperturbed form than other arrivals. Coupled-mode behaviour is also typical for shallow water propagation because of ubiquitous steep nonlinear internal waves. Thus, internal-wave induced fluctuations can be described and understood in similar terms for the two regimes.

However, there are important differences between the two cases in how the mode coupling masks the pulse structure associated with the waveguide (the structure which would exist with no internal waves). In the deep-water case, rays, which are phase-coherent sums of modes, organize into time fronts in the absence of internal waves, but the coherence is lost when internal waves cause large amounts of mode coupling. In the shallow case, rays do not form time fronts because there are not many propagating modes. Mode stripping caused by bottom interaction limits the number of modes. The mean structure thus has a dispersed modal quality (Figure 2 left). Despite this difference, mode coupling effectively destroys the organized pulse structure in shallow water, just as it does in deep water.

One difference in the cases is that mode-coupling acts on all portions of the shallow-water signal, whereas the later portion of deep-water pulse in the temperate waveguide tends to be more sensitive to the effect. This means that the signal-to noise ratio for tomography, as described earlier, may be low for all energy in shallow water. This is under investigation.

Many computational examples of shallow-water internal wave mode coupling have been examined, some published [15,17-19] and some not. Similar complicated pulse structures arise for wave packets of differing quantity, amplitude, horizontal scale length, and wave direction with respect to acoustic path. Steep bathymetry can also cause mode coupling

5. DISCUSSION

Thus far, it has been shown that coupled mode propagation describes internal wave-effects in both shallow and deep water. In deep water, the large number of waves encountered along long propagation paths, and the fact that propagation range is usually much longer than the internal-wave scale length, make the problem suitable for stochastic treatment. In shallow water, although the number of waved encountered may be fewer, the many modes included in the P^- and P^+ vectors also give the fluctuations a stochastic-like nature. In both cases, the effects of mode coupling mask stable pulse features that would otherwise be useful for tomography.

Although acoustic signals propagating over long ranges in the ocean exhibit these unstable qualities because of internal waves, they may also retain stable qualities. For example, a pulse propagating many kilometres on the continental shelf may have arrive at a hydrophone as a series of overlapping unresolved arrivals having a rapidly varying structure, but the leading edge of the pulse may be stable and slowly varying.

Tomography in deep water has already been proven possible in many locations, with a summary of oceanographic results appearing ten years ago [1], and with other results since. Tomography may also be successful in shallow water under certain constraints. For acoustic paths at angles of zero to sixty degrees from the propagation direction of internal waves, which our work suggests will exhibit mode coupling for waves of sufficient steepness, tomography may be possible at source-receiver ranges smaller than the projected distance between tidally synchronous packets. Such paths may be free of coupling much of the time. Reciprocal transmission velocity measurements may also be possible if the leading edges of pulses remain sharp despite the coupling, as seen in Figure 2. On the other hand, tomography becomes less useful at short range because in that situation it would yield data similar to that from a single moored vertical sensor array. For acoustic paths at angles of 80 to 90 degrees from the internal-wave propagation direction, where strong mode coupling may be avoidable, tomography may also be successful. However, horizontal refraction effects may occur in that situation, creating a different set of challenges with respect to tomography [22]. Finally, to be used for source localization or tracking, signals must be stable enough to pass reliably

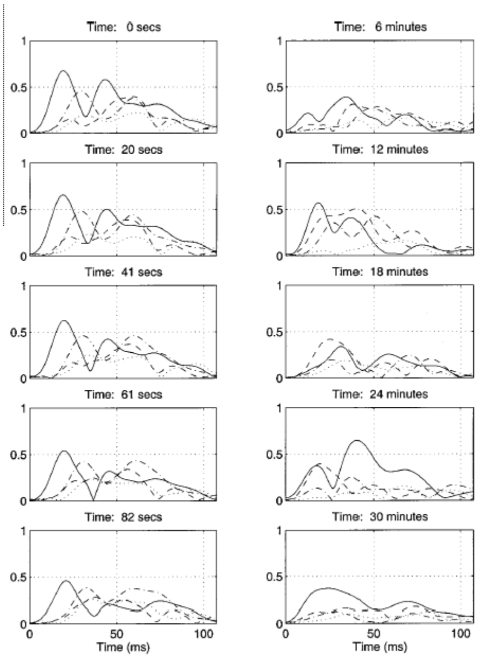

Fig. 3: 100-Hz bandwidth, 400-Hz centre frequency pulses measured with a vertical line array in the SWARM experiment and passed through a mode filter are shown. Amplitudes of modes one through four are shown for pulses recorded over an interval of 30 min. are shown (mode 1 solid, mode 2 dash, mode 3 dot-dash, mode 4 dotted). Multiple arrivals of each mode and an arrival pattern that changes over time can be seen. Figure reproduced from Ref. 21

through coherent processing systems such as array beamformers and Kalman filters. Unstable signal qualities such as variable fades and phase dislocations from internal-wave induced mode coupling may interfere with operations of systems of this type.

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