Near-Axial Interference Effects for Long-Range Sound Transmissions through Ocean Internal Waves

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LONG-TERM GOALS

The long-term goal of this effort is to provide an improved way of interpreting the experimentally observed time-of-arrival patterns in long-range, low frequency near-axial sound propagation in a deep ocean.

OBJECTIVES

A series of long-range, low frequency ocean acoustic propagation experiments conducted since the mid 1980's attest to the complex nature of near-axial propagation in a ducted waveguide. All these experiments are consistent in their description of the time-of-arrival pattern of the received signal for near-axial propagation at long ranges; see, e.g. Ref. (1). This time-of-arrival pattern consists of early, resolvable, geometrical-like intensity peaks, followed by an axial crescendo of unresolved energy. The early intensity peaks can be identified with acoustic energy that propagates along ray paths calculated for ocean models that are reasonable representations of the ocean conditions along the propagation paths. The axial crescendo consists of a jagged buildup of acoustic energy with time to a relatively high peak followed by a rapid decay of the signal. Data from the Long-range Ocean Acoustic Propagation EXperiment (LOAPEX) was used to study this crescendo. In particular, LOAPEX transmissions with a source depth of 800 m from Station T1000 and Station "Kauai" were exploited.

APPROACH

The most efficient method to study the late arrivals is the simulation of low mode propagation. The LOAPEX Shallow Vertical Line Array (SVLA) was designed to resolve the lowest ten modes, those associated with the most energetic part of the signal. The intensity of late arriving energy generated by the source deployed to 800 m depth at Station Kauai and received at the depth of 525 m by hydrophone 6 of the SVLA is of the form shown in Fig. 1. In this case the resolution width of a signal corresponding to the lowest mode (a full width at half maximum of the lowest mode) is 33.4 ms. The goal of the present research is to compare the effects of internal waves, mode coupling, and change in

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14. ABSTRACT
The long-term goal of this effort is to provide an improved way of interpreting the experimentally observed time-of-arrival patterns in long-range, low frequency near-axial sound propagation in a deep ocean.

15. SUBJECT TERMS

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bandwidth of a radiated signal on the received intensity of the low modes when the source was deployed to 800 m depth at Station Kauai.

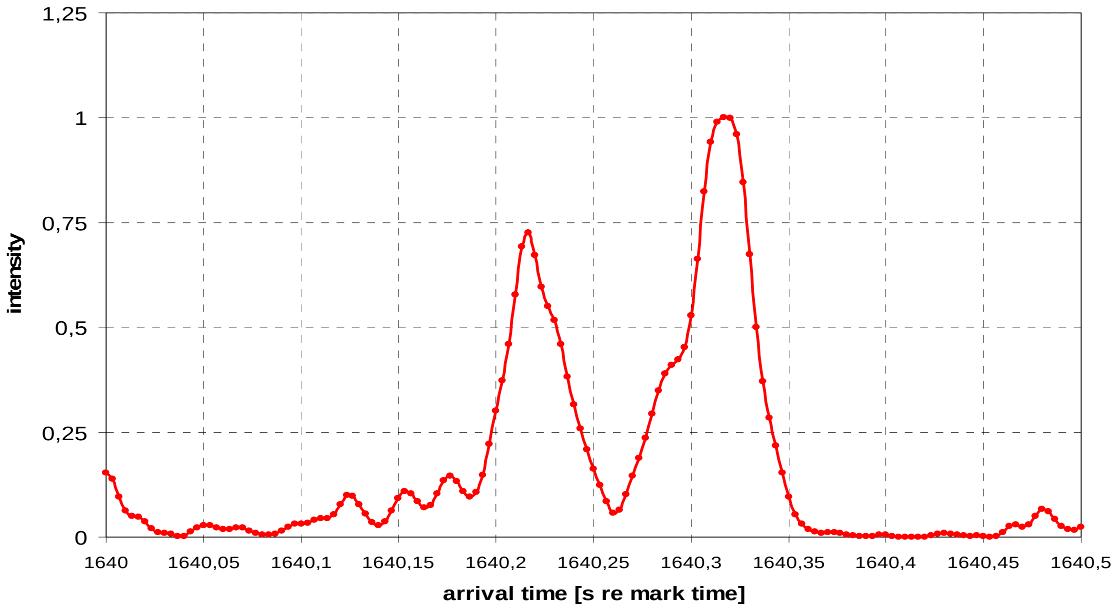

Figure 1. Intensity of the late arriving energy received at the depth of 525 m by the SVLA for the source deployed to 800 m depth at Station Kauai

Usually, if somebody wants to study a particular mode (or a group of modes) in an ocean having a strong internal wave field, one uses the parabolic equation modeling method at a fixed frequency, calculates a complete set of modes with a small step in range and resolves the sound field into this set of modes extracting the desired mode (or a group of modes). In pulse propagation modeling, these simulations must be carried out with a small step in frequency as well, that results in a huge body of simulations. But this method of modeling does not permit, for example, the comparison of effects due to coupling between neighboring modes and all other modes, etc. We used another way for simulating the late arriving energy when the coupling system for first modes has been solved.

WORK COMPLETED

For LOAPEX, not more than 5 of the lowest modes are resolvable in the time domain. To take into account the coupling between modes, the 15 first modes were calculated. For the Kauai – VLA propagation path, two sets of conductivity, temperature, and depth (CTD) data were used: data measured at Kauai and at Station T50. At the VLA the same sound-speed data were used as present at 50 km from the array. Measured sound-speed data were approximated by a 14th degree polynomial from the ocean's surface down to –1500 m and by a 35th degree polynomial from the bottom up to –1500 m. The propagation range was taken equal to 2432 km. To get a smooth two-dimensional sound-speed field, each coefficient of these polynomials was assumed to be a linear function of range. It was shown that along the propagation path the depth of the sound-channel axis monotonically decreases from 696.894 m to 625.348 m; on the other hand, the axial sound speed is almost constant.

To take into account the effect of the environmental variability caused by ocean internal waves, the buoyancy frequency profile from the LOAPEX CTD Station T50 was used. The maximal value of the buoyancy frequency is about 12 cph. It is reached at a depth close to 50 m. Using measured data, a smooth approximation was obtained. The description of the internal-wave-induced sound-speed fluctuations was based on the formula proposed in Ref. (2). As in that paper, we used 512 values of the horizontal wave number with the maximal mode number equal to 50.

At the first step, we calculated modes in the adiabatic approximation without taking into account the mode coupling. Figure 2 shows the dependence of the 1st eigenvalue on range at a frequency of 75 Hz in the unperturbed ocean and for one realization of the internal wave field. In Fig. 3 one can see the dependence on frequency of the first 5 eigenvalues at Kauai in the unperturbed ocean and in the ocean perturbed by the internal wave field in the frequency interval [56.25, 93.75] Hz.

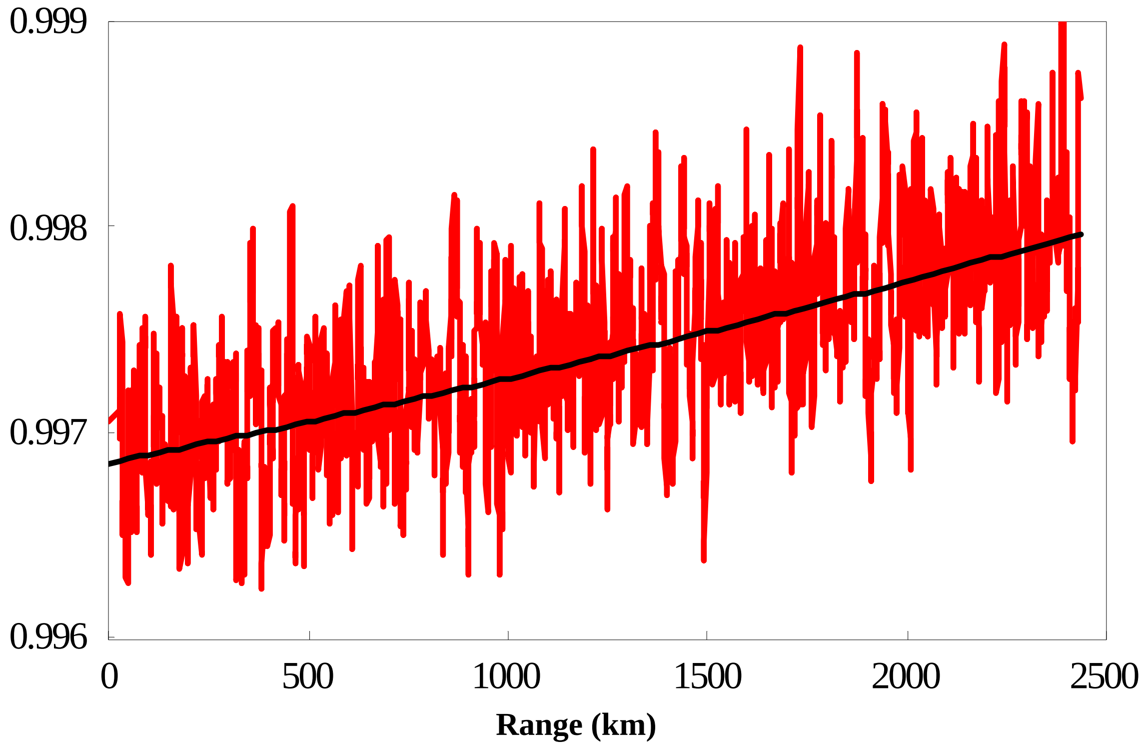

Figure 2. Dependence of the 1st eigenvalue on range at the frequency of 75 Hz in the unperturbed ocean (black line) and for one realization of internal wave field

Comparing the results of simulation for the unperturbed ocean and for the medium model taking into account the effect of environmental variability caused by the ocean internal wave field, we see that the internal waves strongly affect the first eigenvalues and modal functions both as functions of range and functions of frequency.

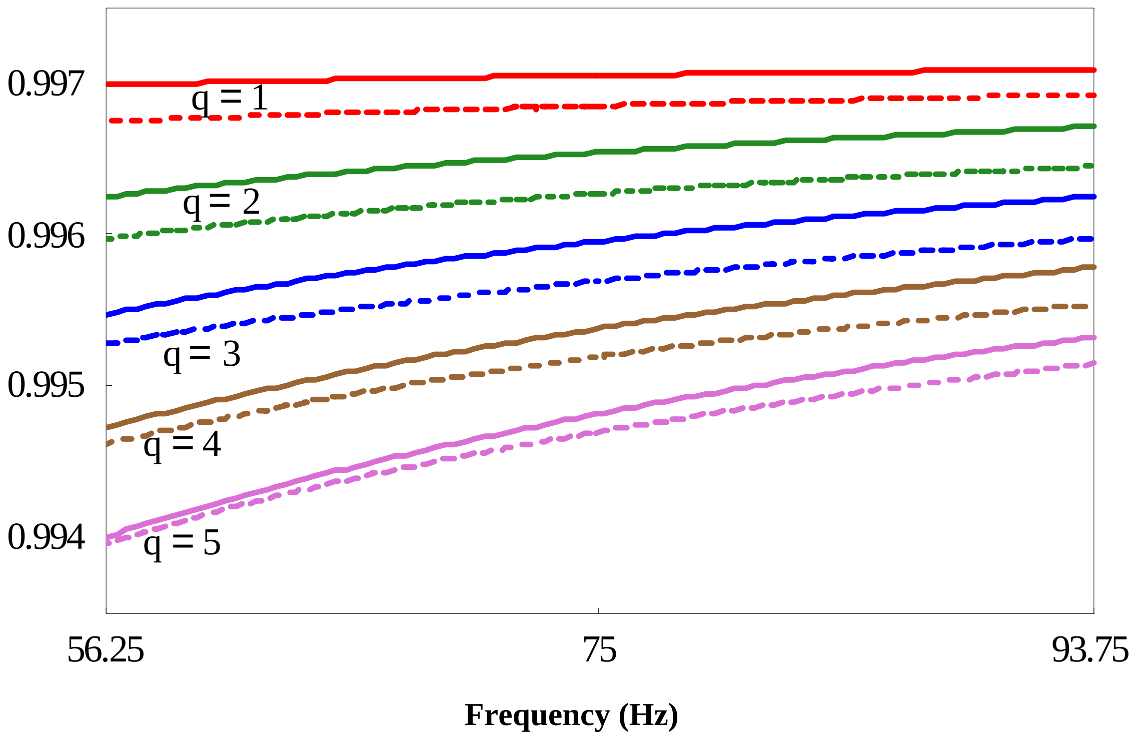

Figure 3. Dependence on frequency of the first 5 eigenvalues at Kauai in the unperturbed ocean (dashed lines) and for one realization of the internal wave field

Then the intensity of a part of the acoustic field generated by the five lowest modes in the time domain was simulated. A single transmitted M-sequence from LOAPEX is well approximated (after pulse compression) by a pulsed sinusoid modulated by Gaussian envelope with a center frequency of 75 Hz and bandwidth 37.5-Hz. The spectral width of this Gaussian pulse is 141.5 s^{-1}. The intensity of a part of the acoustic field generated by the five lowest modes for such a pulse is shown by a blue dashed line in Fig. 4. The depth of the source is 800 m and the depth of the receiver is 525 m corresponding to the depth of hydrophone 6.

The resulting graph was compared with the graph of the measured intensity of late arriving energy registered by hydrophone 6 of the SVLA; see Fig. (1). The comparison shows three main disagreements.

First of all, in the experiment the peak of intensity of the lowest mode arrives about 3 s earlier in comparison with the results of simulations. This is due to the path length difference between the two sections (SVLA and DVLA) of the vertical line array. They were approximately 5 km apart.

The second important disagreement is the resolution width of a pulse corresponding to the lowest mode. The results of simulation give 89.46 ms for the resolution width. In the experiment, at hydrophone 6 this value was 33.4 ms. A graph of the intensity of the late arriving energy received by hydrophone 6 from the 800 m source depth at Station T1000 gives a resolution width equal to 31.1 ms. So, in the experiment at large propagation ranges, the resolution width of a pulse corresponding to the lowest mode is almost independent of range.

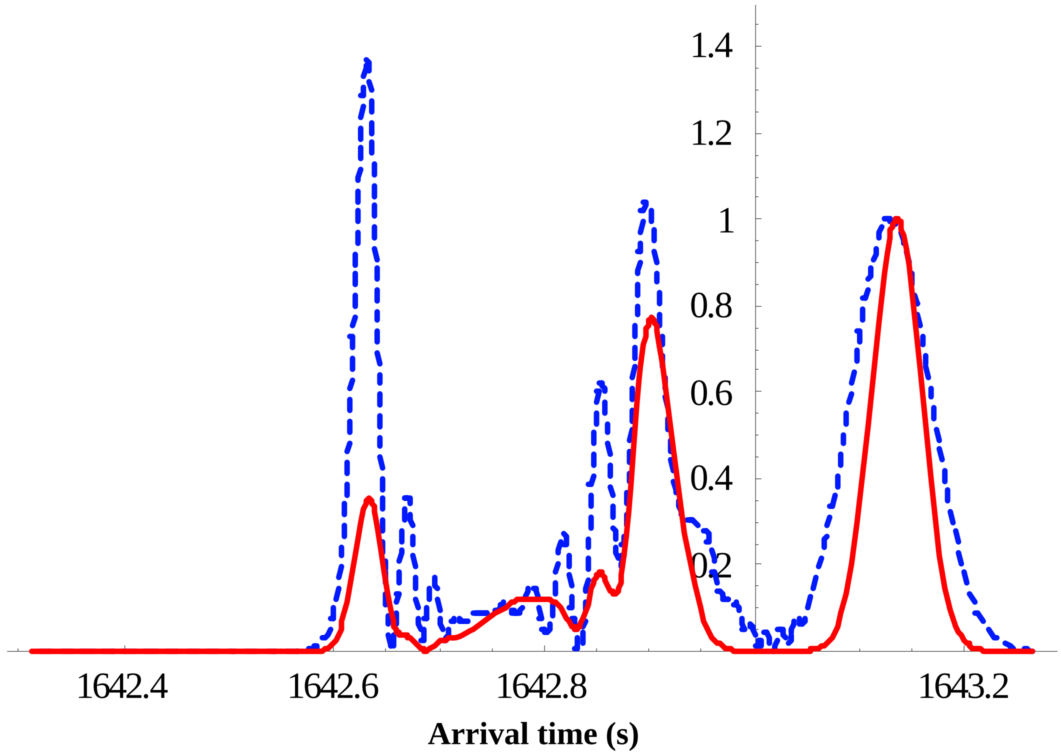

Figure 4. Intensity of a part of the acoustic field generated by the five lowest modes in the adiabatic approximation at the spectral width of 141.5 s^{-1} ***(blue dashed line) and at the spectral width equal to 75.7*** s^{-1} ***(red line)***

Let us assume that the pulse resolution width is equal to 31.1 ms close to Station Kauai as well. In the case of the Gaussian pulse, neglecting the pulse dispersion, we find that a resolution width equal to 31.1 ms corresponds to a spectral width equal to 75.7 s^{-1}. This value is nearly twice as small as the spectral width 141.5 s^{-1} that we used to describe a pulse modeling one M-sequence. In Fig. 4 one can see graphs of the intensity of a part of the acoustic field generated by the first five modes in the adiabatic approximation at a spectral width of 141.5 s^{-1} (blue dashed line) and at a spectral width equal to 75.7 s^{-1} (red line). In the second case the resolution width of a pulse corresponding to the lowest mode is 55.85 ms which is much better than the initially obtained result.

Comparing the graph of intensity obtained at a spectral width equal to 75.7 s^{-1} with the graph of the late arriving energy shown in Fig. 1, we see that the third disagreement is still present. In the experiment the difference in arrival times of the peaks of intensity of the two last arrivals is 100 – 110 ms; in our simulations we get a value equal to 234 ms. Let us show that even for the simplest case, when only the coupling between neighboring modes is taken into account, this difference between arrival times of the peaks of intensity of the two last arrivals significantly diminishes. Figure 5 shows the intensity of a part of the acoustic field generated by the five lowest modes when the coupling between neighboring modes is taken into account at the spectral width of a pulse equal to 75.7 s^{-1}. The source is simulated at the depth of 800 m at Station Kauai and the receiver at 525 m depth corresponding to the depth of hydrophone 6.

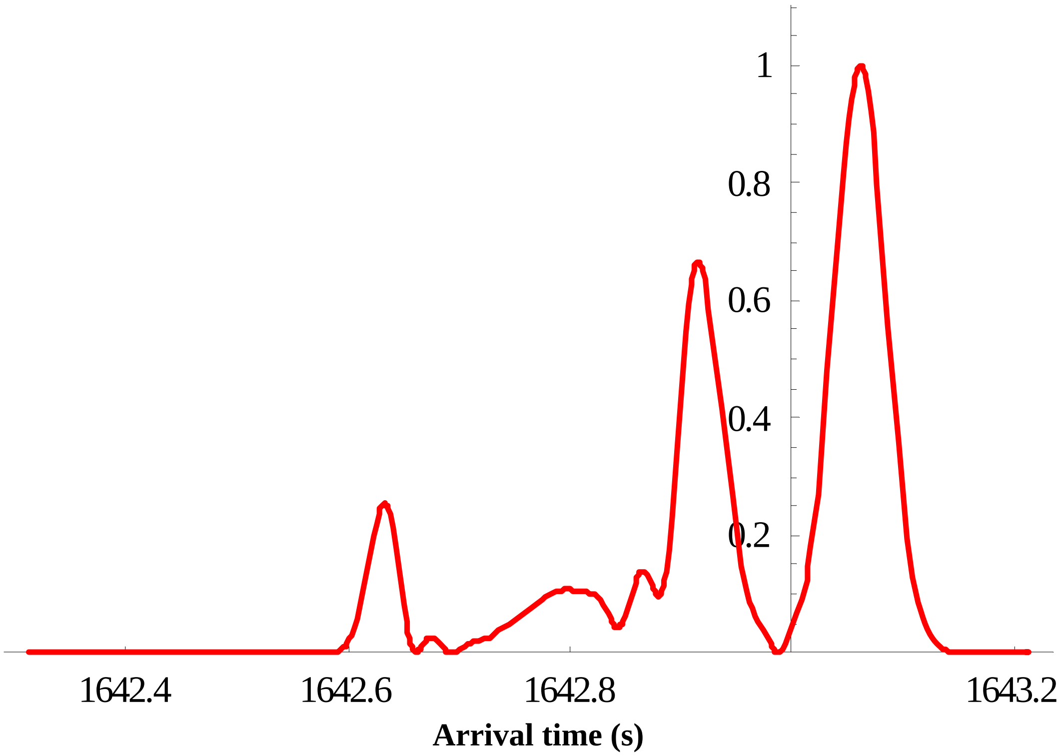

Figure 5. Intensity of a part of the acoustic field generated by the five lowest modes when the coupling between neighboring modes is taken into account. The spectral width of a pulse is 75.7 s^{-1}

The results of simulations show that the correction to the arrival time of the lowest mode is -73.84 ms. Corrections to the arrival times of the next two modes are +14.53 ms and +10.58 ms, respectively. The arrival times of modes 4 and 5 change insignificantly, if at all. So, by taking into account the coupling between neighboring modes, we find that the difference in arrival times of the peaks of intensity of two last arrivals diminishes being equal to 145.45 ms. The resolution width of a signal corresponding to the lowest mode is equal to 55.98 ms. Thus, this value changes insignificantly.

RESULTS

Using the range-dependent ocean model based on the LOAPEX CTD data and taking into account the effect of environmental variability caused by the ocean internal waves, we concluded that the internal wave field observed along the propagation path Kauai -VLA strongly effects the first eigenvalues and modal functions both as functions of range and functions of frequency.

It was learned that for the radiated signal simulation it is necessary to use the smaller value of the spectral width than the value of 141.5 s^{-1} corresponding to a pulse model of one M-sequence.

It was concluded that taking account of the coupling between the neighboring modes results in a significant reduction in the difference in arrival times of the peaks of intensity of the two last arrivals.

These results were included in the talk “Comparison the Effects of Internal Waves, Mode Coupling, and Change in Bandwidth of a Radiated Signal on Low Modes Energy Propagation” by N. Grigorieva,

G. Fridman, J. Mercer, R. Andrew, B. Howe, M. Wolfson, and J. Colosi given at the 11th North Pacific Acoustic Laboratory (NPAL) Workshop that was held at La Casa del Zorro, CA on 15 – 17 May, 2008.

IMPACT/APPLICATIONS

The primary application of this work is the improved interpretation of time-of-arrival patterns observed in long-range acoustic propagation experiments.

RELATED PROJECTS

This work falls within the contex of the ONR Ocean Acoustic Program (Code 321OA) S&T Trust, Long-Range Propagation and complements other Code 321OA theoretical works.

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