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Mode Processing of LOAPEX Measurements

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LONG-TERM GOALS

Our long-term scientific goal is to understand the basic physics of low-frequency long-range sound propagation in the ocean and the effects of environmental variability on signal stability and coherence. We seek to understand the fundamental limits to signal processing imposed by ocean variability to enable advanced signal processing techniques, including matched field processing and other adaptive array processing methods.

OBJECTIVES

The objectives of this work are: 1) to further develop the theory of modal group time spreads in realistic deep ocean environments; 2) to test the predictions of the theory using measurements made during the recent LOAPEX experiment; 3) to develop improved robust signal processing algorithms whose purpose is to extract estimates of modal group time spreads using a deficient receiving array; and 4) to test the extent to which the intensities of scattered LOAPEX arrivals can be predicted using the most accurate environmental information available.

APPROACH

Our approach to addressing these objectives is centered on analysis of data recorded during the Long Range Ocean Acoustic Propagation Experiment (LOAPEX). Our work involves data analysis, testing and extending relevant theory as it relates to the LOAPEX measurements, and extensive propagation modeling. These topics are being investigated by I. Udovydchenkov as a WHOI postdoctoral fellow under the supervision of T. Duda in collaboration with NPAL investigators at RSMAS (especially M. Brown), APL/UW (especially J. Mercer, B. Howe and R. Andrew) and SIO (especially P. Worcester and M. Dzieciuch). The efforts are directed towards quantifying acoustic fluctuations observed in the data and providing a theoretical basis for understanding these observations. The theoretical work relies heavily on the modal description of the acoustic field and exploitation of links between asymptotic mode theory and ray theory, i.e., aspects of ray-mode duality. A theory of modal group time spreads (a modal group arrival is a contribution to a transient wave field corresponding to a fixed mode number) has been previously developed [1]. Relevant theoretical extensions are being developed with emphasis on improving our understanding of the connection between environmental variability and wave field structure and stability.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
Our long-term scientific goal is to understand the basic physics of low-frequency long-range sound propagation in the ocean and the effects of environmental variability on signal stability and coherence. We seek to understand the fundamental limits to signal processing imposed by ocean variability to enable advanced signal processing techniques, including matched field processing and other adaptive array processing methods.

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WORK COMPLETED

The first five items listed below are linked to analysis of the LOAPEX measurements. This work is currently being written up. The results have been separated into two papers. The first paper focuses on analysis of low mode numbers (which require special theoretical care as mentioned below in *3*.) This paper uses only data collected on an upper-ocean shallow vertical line array (SVLA). The second paper focuses on all mode numbers, where processing requires use of a combined shallow/deep VLA pseudo-array. That work has not yet been published, and in that sense is not yet complete, although most of the results that will be included in forthcoming publications have already been produced. Item six represents a new, and potentially very important, theoretical direction; some important preliminary results have been established.

1. Mode processing of LOAPEX measurements

The data processing method has been developed, tested and automated. Nominal transmission ranges were updated and the WGS 84 system for range computations was used. Mooring motion corrections were applied individually to each hydrophone. Linear interpolation in depth was used when necessary to fill gaps for mode processing. In addition a tidal interpolation in time was used to fill gaps when motion data was unavailable. The source motion has been accounted for. Linear interpolation in time was used to accurately estimate the position of the source at the exact time of a transmission. Clock corrections that included analog receiver delay, receiver processing delay and the receiver clock drift were taken into account too. Both motion and clock corrections were applied at transmission times, so the transmission time delay for each transmission was accounted for. All correctable phase errors were reduced to a quarter of a wavelength or less. Note, however, that errors associated with tidal interpolation are not known and SVLA/DVLA pseudo-array phase errors are not correctable. However, it is shown that the phase errors between the upper and lower part of the pseudo-array do not lead to catastrophic processing errors.

2. Reduction of environmental mismatch

It has been shown that some of the observed disagreement between measured and simulated mode processed LOAPEX wave fields can be reduced by performing simulations in a reconstructed sound speed profile. The reconstruction (inversion) algorithm uses as input the travel times of modal group arrivals obtained from the mode processed LOAPEX measurements; the theoretical framework for this procedure was originally described by Munk and Wunsch [2]. The inversion algorithm has been implemented and it has been demonstrated that use of the inverted profile results in better agreement between measured and simulated wave fields. It has been concluded that this environmental mismatch is largely attributed to a warm bias introduced into the sound speed profile estimated at the SVLA location from UCTD (underway conductivity-temperature-depth) measurements matched with climatological data in deep ocean. While the data available from deep CTD casts at the time of experiment is very limited, the inverted profile shows a very good agreement with the mean averaged profile constructed from deep CTD casts. This observation provides support to our assertion that tomographic inversion based on LOAPEX collected data is possible and yields good results. Figure 1 shows simulated and measured wave field intensities in the depth-time plane together with mode-processed results. That figure was constructed using the sound speed profile computed from UCTD measurements in the upper ocean matched with climatological data in deep ocean. Figure 2 shows four different sound speed profiles estimated for the LOAPEX experimental conditions and illustrates the result of the inversion. Figure 3 is similar to Fig. 1, but it was produced with the reconstructed sound speed profile. Better agreement between measured and simulated mode-processed wave fields is observed using the reconstructed profile. This work was presented at the 11th and 12th NPAL workshops and is currently being written up.

3. Low mode number scattering of acoustic energy

It is shown in [1] that the scattering-induced contribution to a modal group time spread grows in range as r^(3/2). However, the derived expression for the scattering-induced contributions is inaccurate for modes with low mode numbers. Low mode numbers require special care because, unlike high mode numbers, energy in the gravest mode can be scattered only into higher mode numbers. A theoretical framework for treatment of near-axial scattering was presented in [4] and [5]; those results have been incorporated into our theoretical framework and the resulting theoretical predictions have been evaluated numerically. Figure 4 shows theoretical estimations of variances of travel time distributions (which are proportional to scattering-induced time spreads) normalized by r^(3/2). It is shown that in a LOAPEX-like environment the scattering-induced contribution for lowest mode numbers is reduced by a factor of approximately 2 due to this correction. Figure 5 shows an example of simulated and measured wave filed intensities for the transmission range of approximately 500 km and off-axial acoustic source. With such a source acoustic energy in low mode numbers is not initially excited. In this figure we can see how energy is being scattered due to mode coupling into low mode numbers.

4. Mode processing using a deficient receiving pseudo-array

The mode processing associated with the estimation of modal group arrivals requires that the wave field be measured on a vertical array that is both long and dense. In the LOAPEX experiment vertical receiving arrays on two moorings were used to collect data. These moorings were separated by approximately 5 km. Because of the horizontal separation between the moorings there are phase differences between data recorded on the two vertical arrays. These phase errors are mode number dependent and cannot be corrected. However, for the purpose of estimating modal group time spreads in the LOAPEX experiment, we have shown that these errors are not so serious as to preclude mode processing when the two vertical arrays are combined to form a single pseudo-array. These errors lead to some smearing of energy in mode number, but they do not result in smearing of energy in time, because the pseudo-array processing conserves energy, and is both phase coherent and phase preserving. This work has been presented at the 12th NPAL workshop and is currently being written up.

5. Mode filtering

It has been discovered during analysis of the LOAPEX data that many commonly used mode filters, while being optimal in some sense may have other significant shortcomings. In particular, most of those filters violate the energy conservation condition. The energy conservation directly follows from the orthonormality of the acoustic normal modes. This observation becomes obvious if one notes that a statement analogous to Parceval's theorem which is usually applied in Fourier analysis holds for the generalized Fourier series with any basis functions that form a complete orthonornal set (and acoustic normal modes form such a set). Currently the importance of constraining mode filters to conserve energy is being investigated.

6. Resonant forward scattering

Traditional theoretical treatments of the forward scattering of sound treat scattering events as uncorrelated events. Recently, we (I Rypina, M Brown and myself) have explored a conceptually very different theoretical framework in which scattering is controlled by resonant scattering. Resonances are excited between background rays, which are periodic in range, and periodic structures in the sound speed perturbation. Because modes can be associated with interfering up- and down-going rays, the resonant scattering approach is also applicable to the description of mode coupling. For a narrowband (in horizontal wave number) perturbation only a small number of resonances are excited, while internal-wave-induced perturbations, which contain many length scales, excite many resonances. A general expression for resonance widths has been derived [3]. Exceptional deep ocean conditions are found in the vicinity of submarine ridges, which serve to generate internal tides that are both highly directional and have a narrow horizontal wave number spectrum. We expect the internal tides to be one of the dominant sources of ocean variability during 2009/2010 Philippine Sea experiment.

RESULTS

Considerable progress has been made on the development of a theory of acoustic scattering in long-range deep ocean propagation, especially the scattering of sound near the sound channel axis. Most of the LOAPEX data has been analyzed and generally good agreement between observations and theory has been observed. Also, we have significantly improved our understanding of the influence of the background sound speed structure on the resulting wave field fluctuations.

IMPACT/APPLICATIONS

The research described here has both scientific and operational applications. This work is contributing to an improved understanding and field verification of the basic physics of low-frequency long-range sound propagation in the ocean which is important in long-range tomographic systems, communication, and surveillance. Also, this knowledge contributes to an understanding of the limitations of advanced signal processing techniques, such as matched field processing.

TRANSITIONS

These results are being used to interpret the data collected during LOAPEX experiment. They also may be used for interpretation of previously collected data in the SLICE89, AET and SPICE04 experiments. We are unaware of transitions to system applications.

RELATED PROJECTS

The PI and collaborators listed above actively collaborate with many ONR-sponsored researchers who work on projects related to NPAL and participate in the NPAL workshops.

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PUBLICATIONS

[1] I. A. Udovydchenkov and M. G. Brown. Modal group time spreads in weakly range-dependent deep ocean environments. *J. Acoust. Soc. Am.*, 123:41-50, 2008. [published, refereed]

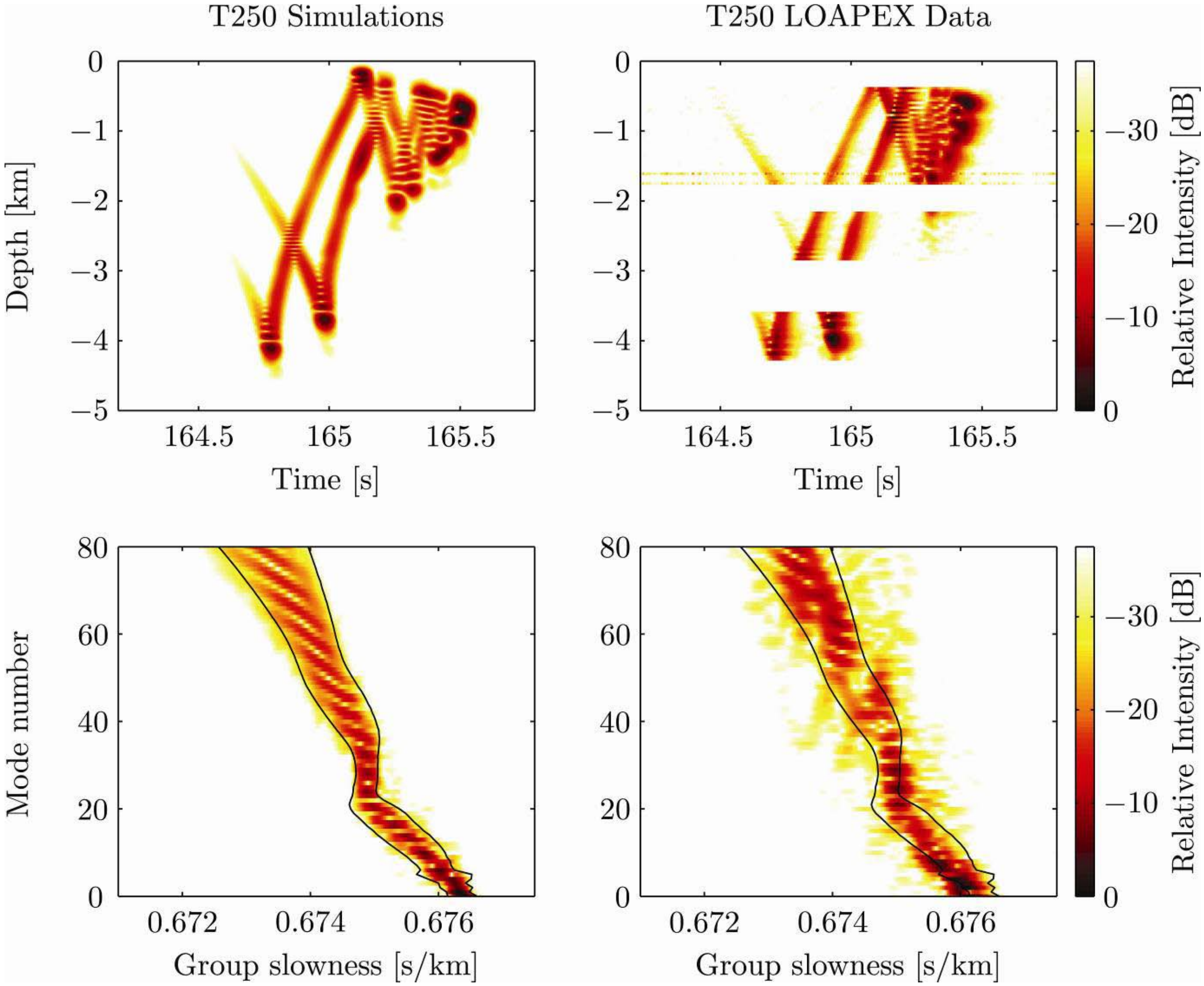

Figure 1. (upper panels) Simulated (left) and measured (right) LOAPEX wave fields in* (z,t) *at a range of approximately 250 km. The simulated wave field was constructed using an environment including an internal-wave-induced sound speed perturbation. (lower panels) The corresponding mode-processed wave fields in (m,S_g) where t = S_g r. Bounds on the predicted time spread are shown using solid lines. Note the mismatch between the mode processed data wave field and theoretical predictions.

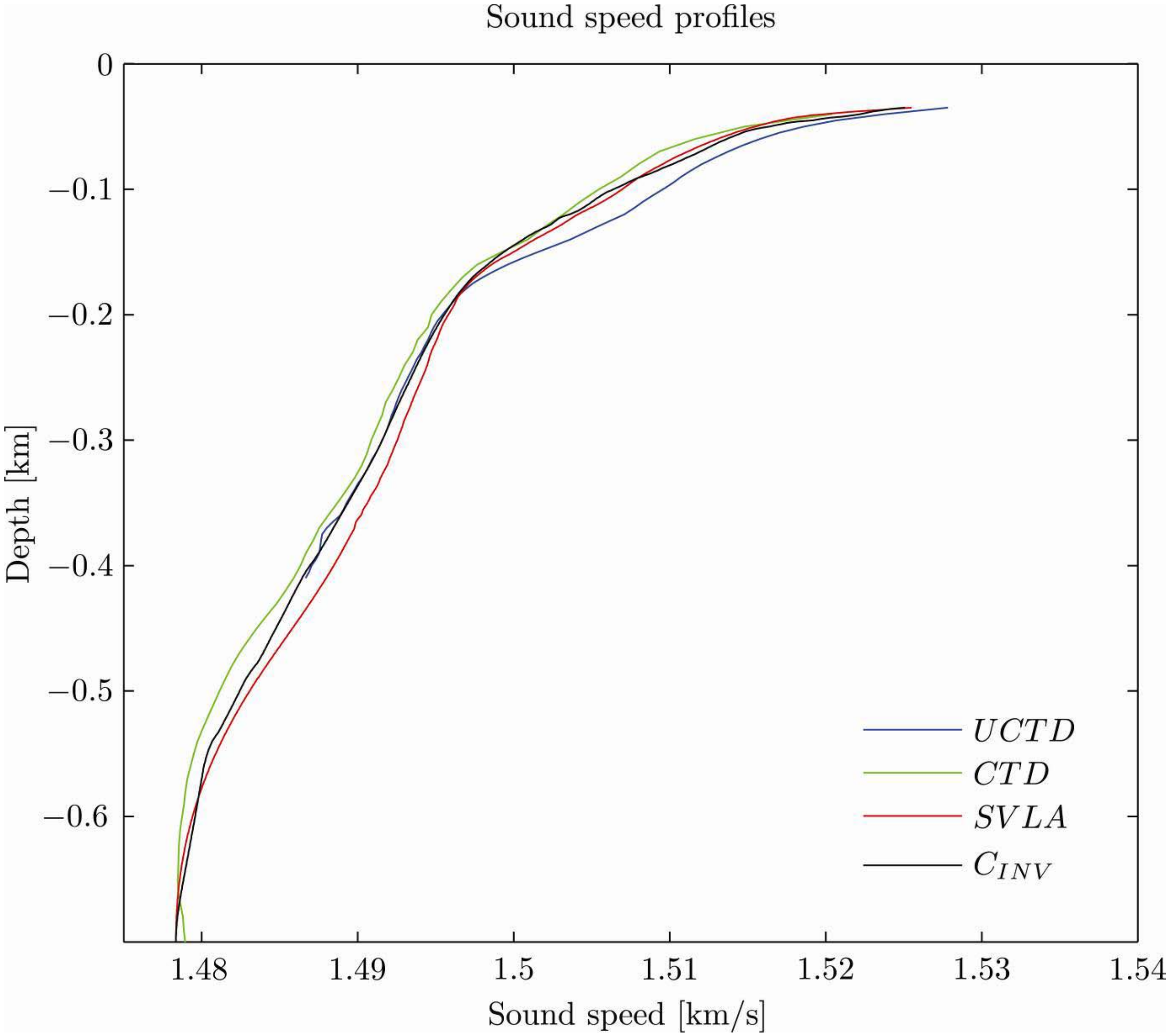

Figure 2. Four different sound speed profiles constructed for the LOAPEX experimental condition: (blue) range-averaged sound speed profile based on UCTD measurements; (green) range-averaged sound speed profile based on deep CTD casts; (red) estimated sound speed profile at the SVLA location based on UCTD data matched with climatological data in deep ocean; and (black) sound speed profile estimated from the LOAPEX data set. It is clear that the red SVLA profile has warm bias with respect to CTD-based profile (green). The inversion procedure eliminates most of that bias.

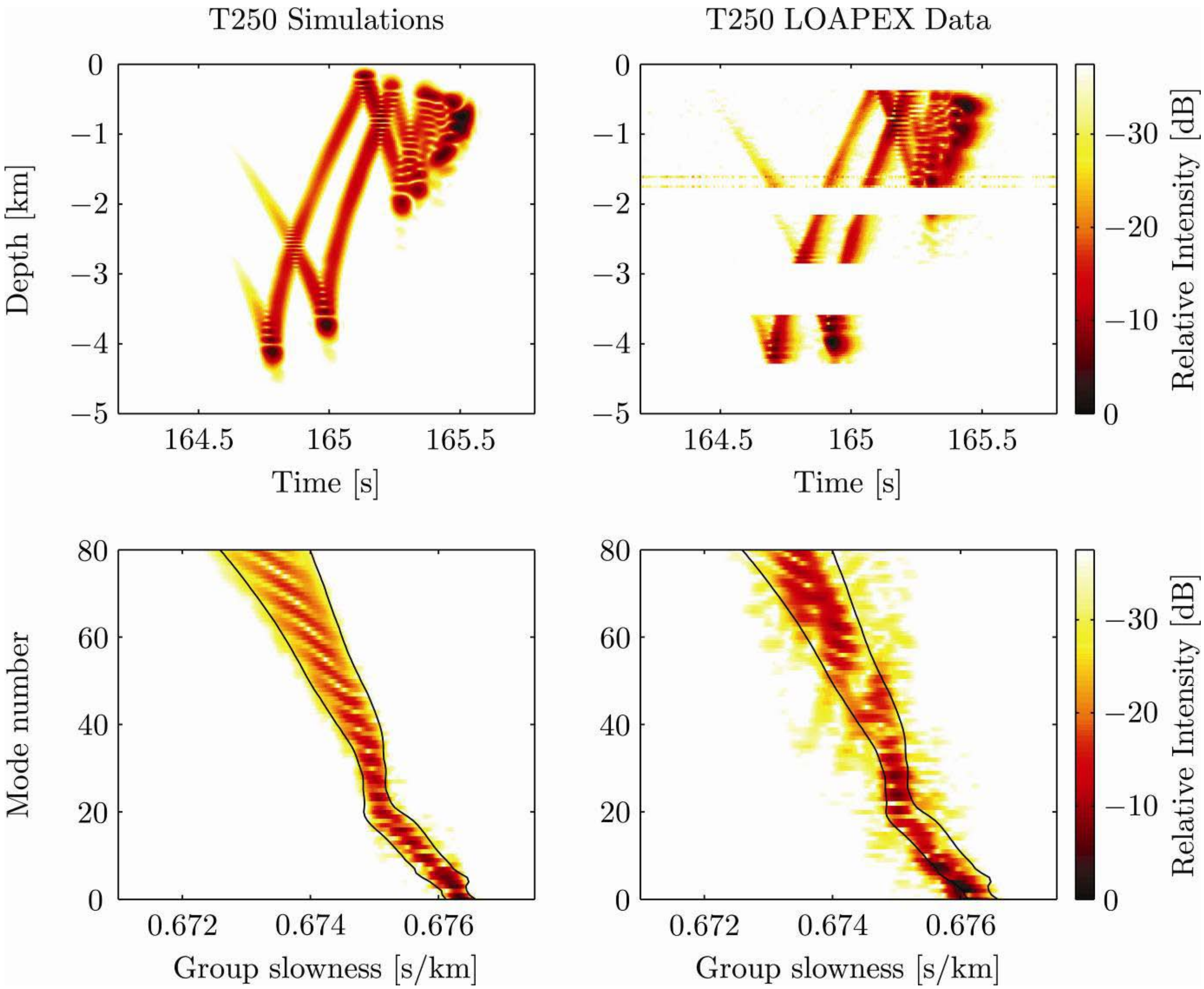

Figure 3. (upper panels) Simulated (left) and measured (right) LOAPEX wave fields in (z,t) at a range of approximately 250 km. The simulated wave field was constructed using a background environment reconstructed from measured modal group arrival times. An internal-wave-induced sound speed perturbation was superimposed on the background. (lower panels) The corresponding mode-processed wave fields in (m,S_g) where t = S_g r. Bounds on the predicted time spread are shown using solid lines. Note the improvement, relative to figure 1, between the mode processed data wave field and theoretical predictions.

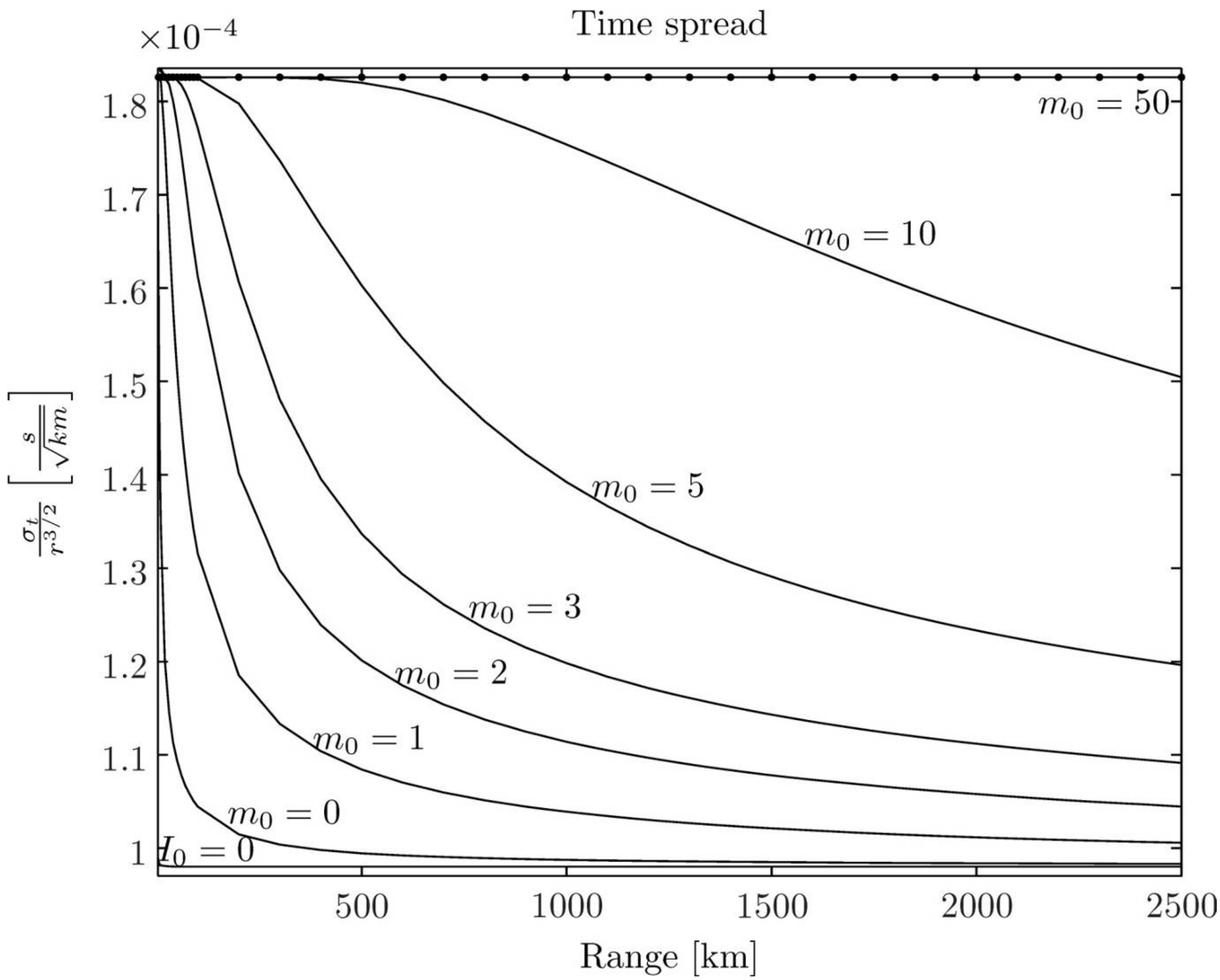

***Figure 4**. Theoretical estimates of variances of travel time distributions (which are proportional to scattering-induced modal group time spreads) normalized by r^(3/2). These estimates show how the range dependence of the scattering-induced contribution deviates from the r^(3/2)-law depending on the initial mode number. An asymptotic result for large m_0 is shown by dots.*

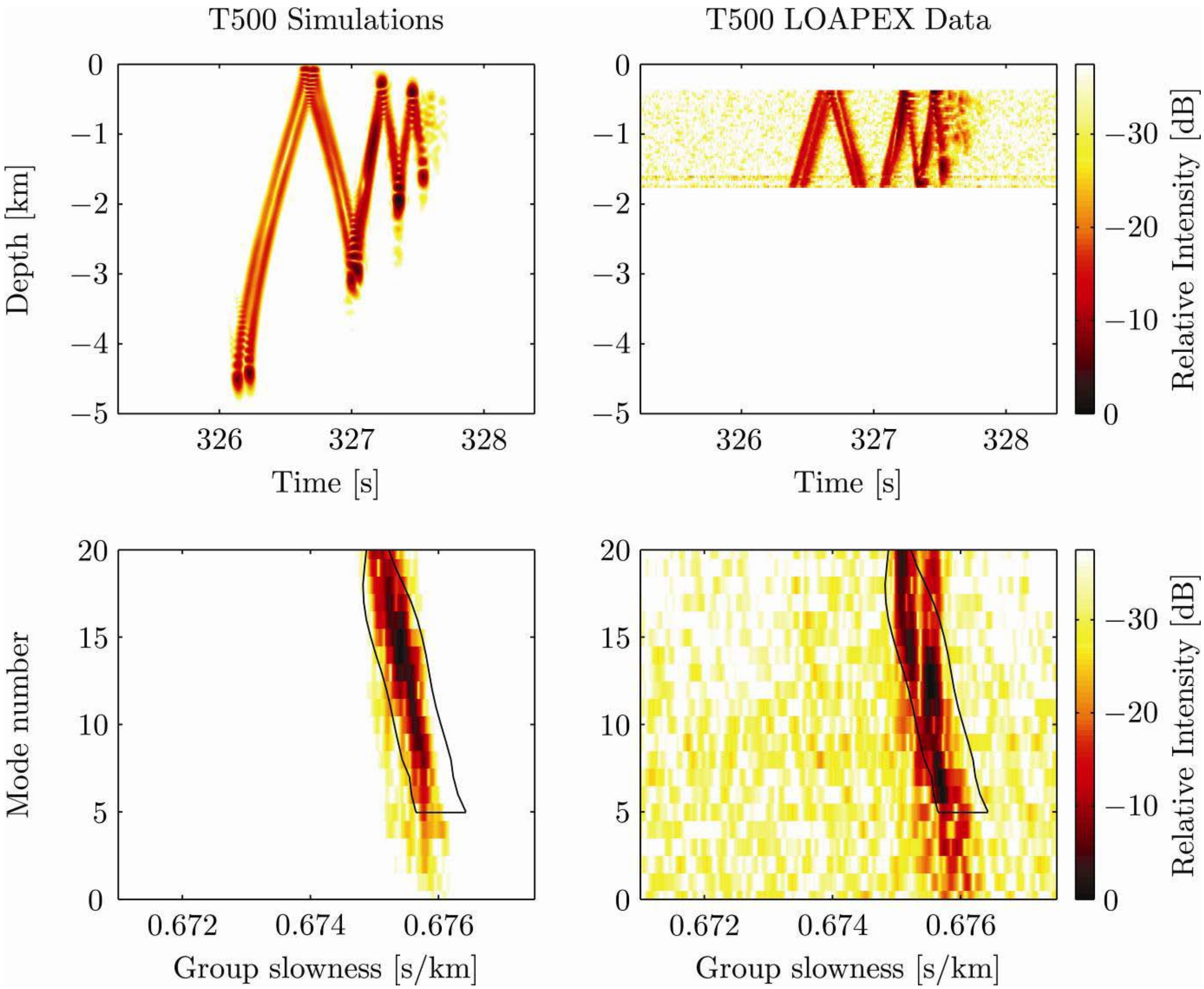

***Figure 5**. (upper panels) Simulated (left) and measured (right) LOAPEX wave fields in (z,t) at a range of approximately 500 km. (lower panels) The corresponding mode-processed wave fields in (m,S_g) where t = S_g r. Bounds on the predicted time spread are shown using solid lines. Only data collected by the SVLA is used.*