An Analysis of Long-Range Acoustic Propagation Fluctuations and Upper Ocean Sound Speed Variability

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LONG-TERM GOALS

The long-term goals of this research are to understand the predictability limits of long-range acoustic transmissions, and to delineate the important environmental factors contributing to predictability.

OBJECTIVES

The objectives of this work are both observational and theoretical. Several low-frequency long-range transmission data sets in which data was obtained on long vertical receiving arrays (VLA's) are being analyzed to quantify acoustic phase and intensity variability, as well as temporal and vertical coherence. One short range experiment (87 km) is being used to examine scattering over the first 2 upper turning points. In addition, analysis of oceanographic measurements of upper ocean processes will quantify acoustic scattering structures. Geometric (ray-based) and parabolic equation models are used to examine the underlying acoustic scattering physics.

APPROACH

From an observational standpoint the approach here has been to study the acoustic fluctuation properties of the SOFAR finale since this is the most energetic part of the arrival structure; this is particularly important when issues of temporal variability are addressed. The finale is characterized by a complex multi-path interference pattern (much like typical shallow water arrivals) while the early "wavefront" arrivals show weaker multi-pathing. In the analysis, a novel 2-D (time and depth) phase unwrapping procedure is used to provide both phase and intensity information over a series of acoustic transmissions. This analysis allows quantification of phase and intensity PDFs and in the analysis of coherence, allows a description of the theoretical form of the coherence function. Factorization of the 2-D (k_z, ω) phase spectrum may quantify the degree of factorization (k_z, ω) of the ocean internal wave spectrum. Analysis of one short range experiment (87 km) is allowing an examination of the fluctuations after the first two upper turning points.

Oceanographic observations I helped obtain during the North Pacific Acoustic Laboratory (NPAL) 98-99 field-year are being used to quantify upper ocean sound scattering structures. Moored thermistor, CTD, and ADCP data along with calibrated XBT and CTD transects are being used to quantify the space/time scales of sound speed variability in both mesoscale and internal wave frequency bands. A novel upper ocean acoustic scattering mechanism caused by near-inertial shear layers beneath the mixed layer is being examined.

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From a theoretical and modeling standpoint the initial approach was to examine ray propagation through Garrett-Munk internal wave fields to try and understand the breakdown of the path-integral formulation of acoustic scattering. Here I have worked closely with M. Brown (U. Miami), M. Wolfson (U. Washington), S. Tomsovic (Washington State), and G. Zaslavsky (New York University). Ray results have lead to new questions being addressed by parabolic equation numerical simulations.

WORK COMPLETED

Work has been completed in the analysis of 3 acoustic data sets utilizing broadband 75 Hz center frequency pulses; the Acoustic Engineering Test (AET; Range 3250 km, 6 days in November 1994), and the Acoustic Thermometry of Ocean Climate (ATOC) transmissions from Pioneer seamount to Hawaii (HVLA; Range 3500 km; 6 months in 1995) and to Kiritimati (KVLA; Range 5100 km; 6 months in 1995). Data reduction is underway for another set of broadband transmissions at both 28 and 84 Hz. Work has also been completed on the analysis of the oceanographic observations taken during the NPAL field year. Publications on these topics are in preparation [Colosi et al., 2003 and Colosi and Xu, 2003].

On the theoretical side a ray-based analysis of the experimental results from the AET has been completed [Brown et al., 2003, and Beron-Vera et al., 2003], and a kinematical analysis of the approach to saturation has been carried out [Colosi and Baggeroer 2003].
Parabolic equation results for the entropy of acoustical beams, and the approach to saturation have also been presented [Morozov and Colosi, 2003].

RESULTS

In the analysis of the AET, HVLA, and KVLA data we have quantified both temporal and depth variability of the acoustical fields in terms of: mean fields; variances of phase, intensity, and log-intensity; probability density functions (PDFs) of phase and intensity; covariance and spectra of phase and intensity; and coherence. Over 20-40 minute observation times, the measurements show surprisingly large mean fields which account for 20-80 percent of the overall energy. The fluctuations in phase and intensity show some aliasing at high frequencies (20-60 cph), but show nearly an a ω^{-2} form at low frequencies (2-10 cph). Vertical spectra of phase and intensity show nearly a pure k_z^{-2} behavior. Consistent with the picture of multipath interference the intensity PDF is very close to the exponential PDF of full saturation. The phase PDF shows some small deviations from Gaussian behavior which may have an oceanographic (non-Gaussian sound speed fluctuations) or acoustic (caustics) origin. Consistent with the large mean fields both depth and temporal coherences are large. The theoretical form of the coherence functions (both depth and time lagged) are shown to be a product of a phase and amplitude term, since phase and amplitude are shown to be uncorrelated. Amplitude de-correlation accounts for roughly 20 percent of the coherence loss, and because of the near Gaussian behavior of the phase, phase contributions can be expressed in terms of the (well know) exponential of the phase structure function. Two-dimensional spectra of phase are very nearly factorizable into a product of vertical wavenumber and frequency components. This analysis has been carried out for both large bandwidth (75 Hz +/- 30 Hz (3 dB)) and for narrow-bandwidth (75 Hz +/- 1 Hz) and the results are relatively insensitive to bandwidth. Further the calculated statistics are shown to be very insensitive to propagation ranges (3250-5100 km).

The analysis of the upper ocean sound speed structure is broken into two frequency bands where mesoscale/internal wave bands have frequencies below/above the local inertial frequency. The mesoscale band has rms sound speed variations of order 3 m/s rms in the upper ocean and 1 m/s rms at depth, whereas the internal wave band has rms variations of 1 m/s in the upper ocean and 0.3 m/s at depth. The mesoscale frequency spectrum has an ω^{-2} form with very little depth dependence. The internal wave frequency spectrum shows a GM-like continuum (i.e. ω^{-2} form) between the semidiurnal tide frequency and the buoyancy frequency, a strong semidiurnal tide line (plus second harmonic) and a gentle rise in energy near the buoyancy frequency. These spectral shapes are only a function of depth to the extent that the buoyancy frequency cut off changes with depth. The spectral levels (and the tide lines) do vary with season with most energy occurring in the winter and spring seasons. Seasonal sensitivity diminishes with depth. Two-dimensional spectra (k_z,ω) show near factorization across all frequencies. Vertical wavenumber spectra from both moored instruments and XBT surveys show a GM-like k_z^{-2} but the spectrum shows a cut off at 0.1-0.3 cpm. Horizontal wavenumber spectra from the XBT surveys show a non-GM behavior of $k_x^{-1.5}$. Statistics of the vertical shear of horizontal currents (du/dz, and dv/dz) show large values beneath the mixed layer; shear scatters sound the same way that sound speed gradients (dc/dz) do. While internal wave induced sound speed gradients dominate in the upper ocean, the shear effect is only less by a factor of 2-5. Sadly the acoustic data collected simultaneously with this oceanographic data were corrupted with bottom interactions so a direct comparison between observed acoustical and oceanographic conditions is not possible, however modeling studies can still be done.

Theoretically our ray work has clarified the mechanism by which the finale region of the arrival is separated from the wavefront region of the arrival; namely the combined effects of increasing wavefront time spread and diminishing deterministic wavefront time separation as one goes from high to low angle arrival energy, leads to an overlap of arrivals and the formation of the complex interference pattern which is the finale. Further it was shown that wavefront timespread is strongly controlled by the mean background sound speed profile, thus explaining the difference between finale/wavefront partitioning observed in tomography experiments in the N. Atlantic and N. Pacific. Finally our ray work combined with parabolic equation simulations has shown that a wavefront arrival is composed of many contributions (perhaps ray-like) which sample the ocean along a broad "ray-tube" which can deviate significantly (mostly in range not depth) from the unperturbed ray. This spatial non-locality, we believe, is the source of the breakdown of the path integral theory which expands about the deterministic ray.

Regarding the approach to saturation a kinematical model of broadband multi-path interference has been developed which elucidated the competing processes which may drive a system to saturation. In particular, it is shown that multi-path amplitude fluctuations compete against increasing multi-path number in the approach to saturation, and that bandwidth slows the saturation process by reducing the effective number of multi-paths (this mechanism is described by the time/bandwidth product). Thus conditions which favor a rapid approach to saturation do not favor large wavefront timespread.

IMPACT/APPLICATIONS

There are several implications of this work to the understanding of predictability and for the upcoming NPAL 2004 field year. A short list of the major issues/impacts are given below.

1)   The statistics of finale intensity suggests that the wavefield is very nearly saturated, yet the temporal stability over 20-40 minutes is quite good. We need longer transmission timeseries to investigate more of the "bandwidth" of acoustic field variability. Will the mean field persist over several hours of transmission? These longer measurements will be made in the NPAL04 experiment.

2)   Again, the finale statistics suggest a saturated wavefield but is the approach to saturation from above or below 1? Kinematically the approach from below or above 1 has strong implications for the multi-path statistics. In particular if the multi-path is dominated by chaotic rays, then the approach must be from above 1. Measurements as a function of range, as planned for the NPAL04 experiment will address this issue.

3)   The computed temporal coherences for the arrival finale are very close to those (very carefully) computed for the wavefront region (M. Dzieciuch, personal communication). If multi-pathing is weaker in the wavefront region how come the coherences are comparable?

4)   The oceanographic analysis we have done points out several differences between real ocean sound speed fluctuations and those modeled using the GM spectrum, and in particular the effect of shear may play an important role.

TRANSITIONS

RELATED PROJECTS

Effects of Sound on the Marine Environment (ESME; ONR N00014-00-1-0931), and ONR uncertainty initiative.

REFERENCES

See Publications below.

PUBLICATIONS

1) M.G. Brown, J.C. Colosi, S. Tomsovic, A.L. Virovlyansky, M. Wolfson, and G.M. Zaslavsky, "Ray dynamics in ocean acoustics", J. Acoust. Soc. Am. V113(5), pp2533-2547, 2003.

2) F.J. Beron-Vera, M.G. Brown, J.C. Colosi, S. Tomsovic, A.L. Virovlyansky, M. Wolfson, and G.M. Zaslavsky, "Ray dynamics in a long range acoustic propagation experiment", J. Acoust. Soc. Am. V114(3), pp1226-1242, 2003.

3) J.A. Colosi, and W. Munk, "Tales of the venerable Honolulu tide gauge", J. Phys. Oc., Accepted 2003

4) J. A. Colosi, and A. B. Baggeroer, "On the kinematics of broadband multipath scintillation and the approach to saturation", J. Acout. Soc. Am., submitted 2003.

5) A. Fredricks, J. A. Colosi, J.F. Lynch, and G. Gawarkeiwicz, "Analysis of multipath scintillations observed during the summer 1996 New England shelfbreak PRIMER study", J. Acout. Soc. Am., submitted 2003.

In Preparation:

1) J.A. Colosi, A. B. Baggeroer, and M.A. Dzieciuch, "Analysis of multipath acoustic field variability and coherence for basin-scale acoustic transmissions in the North Pacific Ocean", J. Acoust. Soc. Am, Special Issue on the North Pacific Acoustic Laboratory (NPAL) due Dec 2003.

2) J.A. Colosi, J. Xu, and The NPAL Group, "Observations of upper ocean sound speed variability in the North Pacific Ocean", J. Acoust. Soc. Am, Special Issue on the North Pacific Acoustic Laboratory (NPAL) due Dec 2003.

Conference Proceedings:

1) A. Morozov and J. Colosi, "Entropy of acoustical beams in a random ocean", IEEE Oceans Symposium, September 2003.

PATENTS

HONORS/AWARDS/PRIZES

A. B. Wood Medal for "significant contributions to the understanding of acoustic scattering by internal waves in long-range propagation".