

Fluctuations, Coherence and Predictability of Long Range Shallow Water Propagation: Analysis and Modeling of SWO6 Acoustic Data

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LONG TERM GOALS

Understanding fluctuations and coherence in space and time for broadband signals transmitted over long ranges in shallow oceans is the primary goal. A secondary goal is the development of improved acoustic sources and pulse compression signal processing technology that will have practical application to Navy systems.

OBJECTIVES

Shallow ocean acoustic environments are complicated having variable bottom and sub-bottom bathymetry and acoustic properties and often intense internal waves that cause variability of the sound speed field. The emphasis here is on internal wave effects with the objective of determining the predictability of properties of acoustic signals with propagation models using observation of the internal waves as input.

APPROACH

The approach is the classic "fixed system" experiment, whereby broadband signals are transmitted between a moored sources and receivers so that the only source of variability is from oceanography of the water column in between. Experiments of this type have been the workhorse of basic research in sound transmission for then past 40 plus years. The most recent experiments SWO6 is by far the most thorough. Long continuous time series reveal temporal variability and minimize the randomizing effects of the stable (time invariant) bottom. Simultaneously detailed measurements of internal waves are accomplished with dozens of oceanographic mooring and with radar remote systems. Unique to this effort is the Miami Sound Machine (MSM) a multi frequency broadband autonomous source that can transmit for weeks under battery power. The MSM transmitted broadband signals ($q=4$) at each of five center frequencies with octave separation, (100,200,400,800 and 1600 Hz).

WORK COMPLETED

Data from SWO6 MSM transmissions to three of the SHRU receivers and the SHARK HLA and VLA receivers and environmental array data are being analyzed and compared. Included in the analysis are

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comparisons with very similar data sets from two experiments off the coast of south Florida; 1) the Florida Straits Propagations Experiments (FSPE) using the MSM and 2) towed source experiments using very long receiver HLA's of the Acoustic Observatory (AO). All three experiments had nearly identical signal processing employing m-sequence transmission and pulse compression. The analysis allows the unique separation and identification of arrivals with normal modes as computed with propagation models. As a result, spatial and temporal coherence and fluctuation can be compared for individual modes of propagation as well as the combined multipath.

RESULTS

Comparisons of temporal and spatial coherency calculations for a variety of widely varying internal wave fields, frequencies of transmissions and geometric parameters of the propagation channel reveal a consistent set of results that suggest that irregularities of the bottom and not properties of the internal wave fields may ultimately limit coherence in both space and time. The effect is frequency dependant with coherence properties of lower frequencies signals determined more by the internal waves and higher frequencies determined more by bottom properties.

A consistent observation is that spatial and temporal coherence depends on mode number. Lower order modes are always more coherent than higher order mode for all environmental conditions, intensity of the internal wave fields and frequencies of transmission but only slightly so for the lowest frequencies.

The discussion that follows considers SBRB modes that are ubiquitous in shallow water. Typically only a few modes (4 to 10) are received for most propagation channels. The very high order modes interact with the bottom at steep angles above the critical angle and are stripped away. For purpose of discussion figures have been extracted the listed publications which contain details of the analysis.

The pulse arrival pattern for the 100 Hz. transmissions as received with a vertical array during SW06 is shown in Fig. 1. Data are to the left and a PE model prediction to

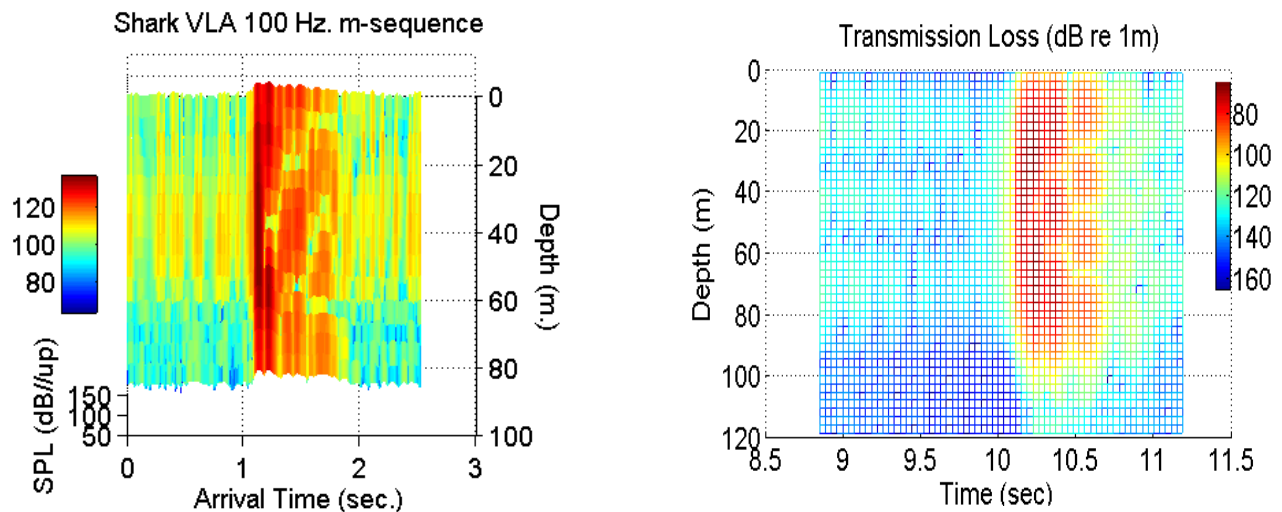


Figure 1 Observed vertical mode structure (left) and PE Model prediction (right)

the right. The modal structure is clearly apparent. Modes 1 through 4 are observed in both the data and model prediction. The environmental conditions are quiescent, that is, during a period of no detectable IW activity. Observations of the temporal fluctuations and coherence show that the only cause of signal variation is the barotropic tides and once the tides are backed out the pulse response remains unchanged in amplitude and phase for periods of three to four hours for all mode arrivals.

The bottom must appear flat and reflective to the 100 Hz wavelength. When internal waves are present, as observed during the passage of a solitary wave through the propagation path, the modal structure persists, but the fluctuations are much faster and the decorrelation time for individual pulses arrivals is less than 2 or 3 minutes. These data establish a ground truth of nearly perfect coherence in space and time for all mode arrivals.

Data for higher frequencies 200 Hz and above paint a different picture. The time histories of received channel pulses responses during periods of low internal wave activity at the SW06 site are compared for the 100, 200 and 800 Hz pulses in Figure 2. The 100 Hz signal shows distinct arrivals that persist for two hours and beyond as discussed. The 200 Hz pulses are not as distinct and sometimes smear together. Lower order modes are always more coherent in time than higher order mode. This is not strictly a temporal effect but also a spatial one.

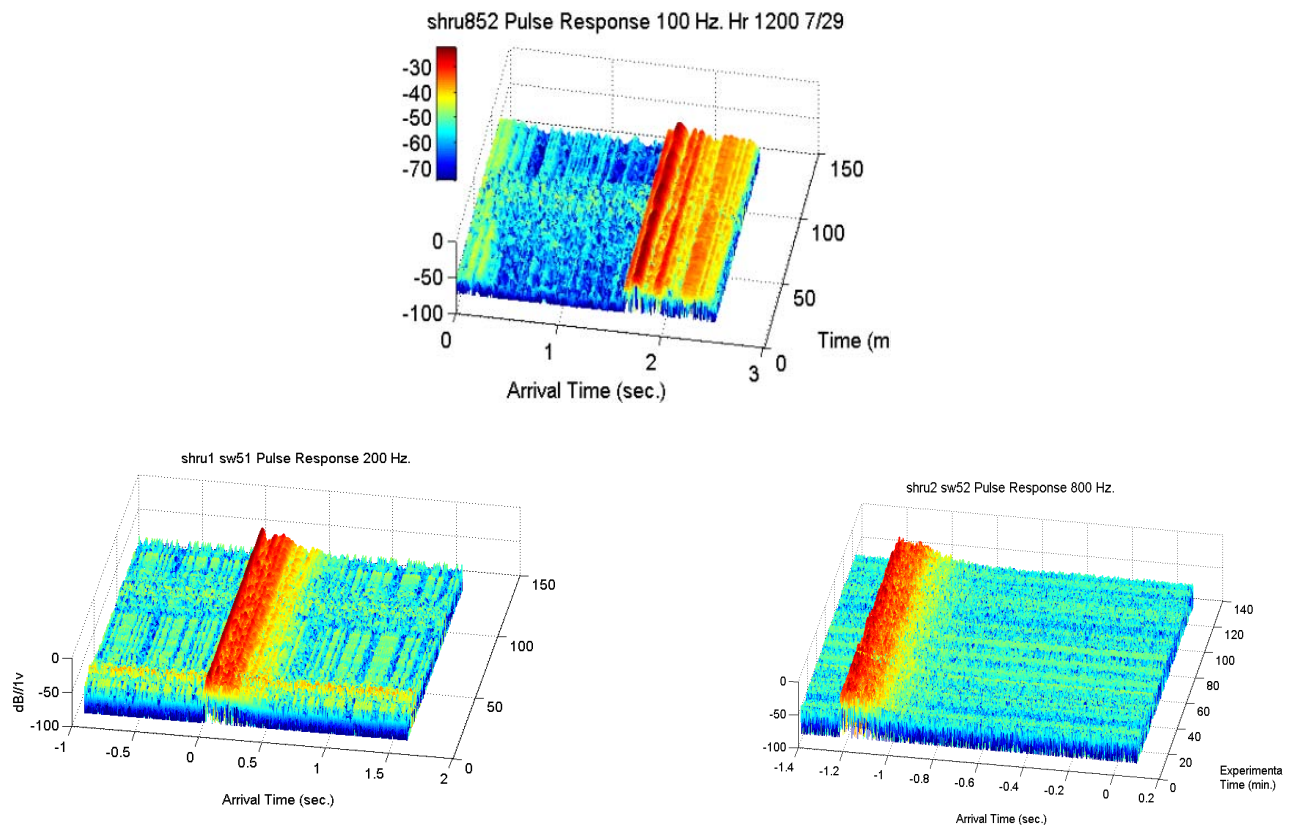
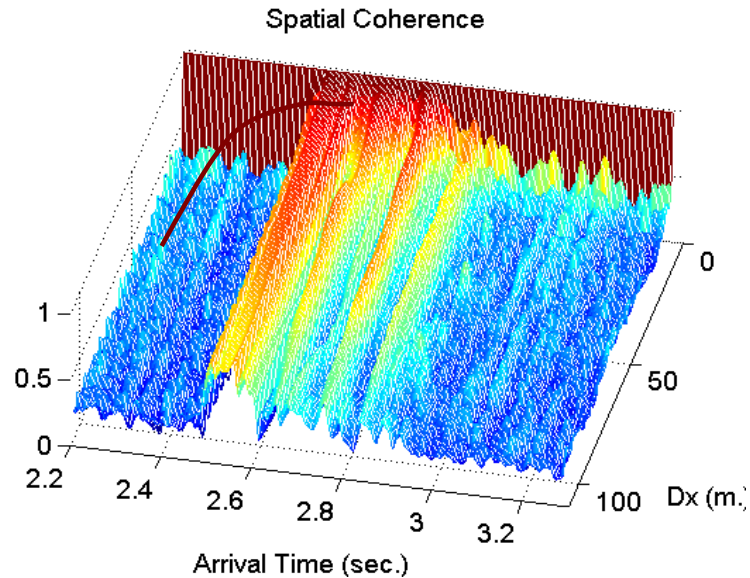


Figure 2 Comparison of channel pulse response time histories for three frequencies transmitted over the same range. Top 100 Hz, Left 200 Hz and Right 800 Hz

Figure 3 shows the spatial coherence calculated for a 250 Hz. transmission in the Florida straits. Each arrival in time is associated with a mode or propagation. This characteristic of decreasing coherence (length/time) with mode number is always observed for all data analyzed. In fact, correlation plots all look the same for time or space calculations!

For higher frequencies distinct arrivals are not always observed. The 800 Hz channel pulse response of Fig. 2 has no distinct arrivals at all even during the quiet internal wave periods. The arrival pattern is smeared in both time and space completely without distinct arrivals.



**Figure 3. Normalized co-variance across propagating wave front for pulse arrivals
250 Hz. Florida Straits**

The exact frequency where arrivals begin to smear depends on geometric parameters of the channel. Fig. 4 shows 800 Hz data collected using the same source but at a different site - the Florida Straits. A PE model using flat bottom properties predicts a number of surface/bottom coupled modes that produced identifiable pulse arrivals separable in time. The observed pulse arrivals closely match the prediction. The arrivals persist for a two week period even in the presents of strong and weak internal wave activity. The fundamental difference between the Florida Straits experimental geometry and the Mid-Atlantic Bight is the depth to range ratio of; $D/R = 1.5 \times 10^{-2}$ and 5×10^{-3} respectively. The D/R is an indicator of the number of bottom interactions and the Florida Straits propagation paths are far less coupled to the bottom so modes are less affected by bottom variations.

Straightforward models that include small scale bottom bathymetry variability seem to account for the observations. The hypothesis and modeling approaches are being pursued. The result should help to extend the fixed system predictions to moving platforms.

PE Prediction of 800 Hz. Pulse Response

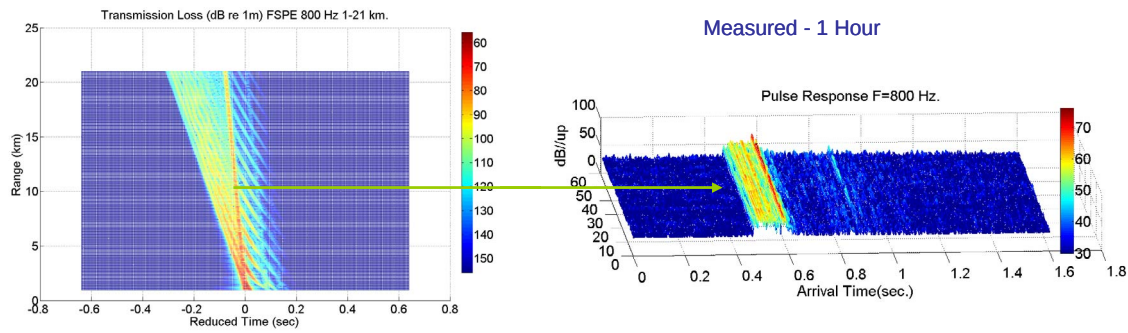


Figure 4. Pulse response time histories. Right, Florida Straits 800 Hz data, Left, PE model prediction

IMPACT/APPLICATIONS

Basic research on acoustic propagation in both deep and shallow oceans has focused on acoustic variability caused by internal waves for the past several decades. The classic experiment, repeated over and over, is transmission from a fixed (moored) source to a fixed receiver in order to observe the effects of oceanographic variability. But, the primary cause of fluctuations is often not internal waves but rather a combination of source/receiver motion and variability of bottom and sub-bottom bathymetry. The later topic is mostly unexplored by the basic research community. The relevant unanswered question is this: At what speed do fluctuations from motion diminish signal temporal and spatial coherence below usable levels.

The results described here challenge the conventional wisdom – towed systems must be mostly concerned internal waves for low frequencies signals (<100 Hz) whereas, fixed systems cannot avoid the influence of bottom irregularities on coherence in both space and time for higher frequencies even though the sources and receivers are fixed.

TRANSITIONS

A most important enabling technology of the underwater acoustic basic research has been M-sequence signal processing introduced to underwater acoustics in the early sixties. By spreading signal energy evenly in time and frequency lower sound pressure level in the ocean result. Pulse compression after reception constructs an intense short pulse with properties that are linear in time and frequency and are phase coherent. In this way precise probe signals can be transmitted over very long ranges in the ocean without excessive sound pressure levels that might interfere with marine mammals. Without m-sequence transmissions there would be no precision measurements of coherence and fluctuations at ranges beyond 50 km in the deep ocean and 5 km for shallow water.

Applying M-sequence to active sonar could reduce sound pressure levels in the ocean and thereby mitigate marine mammals concerns. To this end, a signal processing approach was developed and published in Journal of Underwater Acoustics. The approach eliminates Doppler leakage that usually swamps target returns.

Geo-acoustic petroleum exploration industry has similar marine mammal problems with the use of high sound pressure level impulsive sources in the sea. Exxon Mobile has initiated a collaboration the goal of adapting m-sequence processing to off shore oil exploration in an effort to eliminate Airgun sources. Early efforts are focusing on developing a suitable broadband source. These developments may, in the end, lead to better source capabilities for basic acoustics research.

RELATED PROJECTS

The Acoustic Observatory experiments were conducted shortly after the SW06 experiments. The experimental site and infrastructure (very long HLA) were combined with fixed and towed source transmissions of M-sequences. The resulting data sets are comparable with the SW06 data and provide the opportunity to compare propagation under two different types of internal wave fields. Also, some very long transmissions were possible (80 km.) which exhibited micro-multipath formation with a unique relation between arrival time and horizontal angle of arrival. The internal wave environments of the two sites differ if the New Jersey site is inside of a retrograde front that blocks the propagation of offshore IW on to the shallow shelf. As a result the IW's at the site are locally generated solitary waves followed by quiescent periods. The Florida site, is inside a prograde front that allows offshore IW to propagate producing a continuous saturated IW field. Nearly identical signals and formats allows direct comparisons for data sets for the two sites to extend the conclusions of the SW06 analysis to other areas with different bathymetry and bottom properties and internal wave fields.

PUBLICATIONS

1. H. A. DeFerrari, J. F. Lynch, and A. Newhall, "Temporal coherence of mode arrivals". JASA Express Letters _DOI: 10.1121/1.2968304_ Published Online December 2009
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4. J. M Collis,, T. F. Duda, J. F. Lynch, and H. A. Deferrari, Observed limiting cases of horizontal field coherence and array performance in a time-varying internal wavefield, *J. Acoust. Soc. Am.*, 124, EL97, 2008.