Measurement and Modeling of Downslope Effects on Long-range Propagation

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Abstract- **Ocean Acoustic Tomography (OAT) utilizes the sound speed structure of the deep ocean to permit the efficient propagation of low-frequency sound to very long ranges. The measurement of travel time on basin-scales is being used to estimate temperature variations in the North Pacific [Worcester, et. al, JASA 105 (6), 1999]. In order to eliminate the need for accurate source location systems for long-term experiments, the source for the NPAL (North Pacific Acoustic Laboratory) experiment was moored near the sound channel axis off the Island of Kauai. The received signals at the NPAL site off the coast of Monterey California arrived on the order of 1s late. Propagation modeling, and a measurement of the sound just off the coast of Hawaii show that at least 0.5s delay in propagation down the slope occurs because of interaction with the sea floor.**

I. INTRODUCTION

The presence of a sound channel in the deep ocean makes possible the transmission of low frequency acoustic energy to very long distances[1]. In 1993 the Heard Island Feasibility Test demonstrated that sound could be effectively transmitted across the globe and that the travel times could be measured with sufficient accuracy to permit the accurate measurement of ocean temperatures (acoustic thermometry) using travel time tomography. From 1995 through 1998 the ATOC (Acoustic Thermometry of the Ocean Climate) experiment transmitted sound from a source off Monterey California and one moored on Hawaii to a Vertical Line Array (VLA) moored off Hawaii and to Navy SOSUS receivers across the Pacific Basin.

This paper is a brief overview of the analysis effects of seafloor scattering near the source for a long-range acoustic transmission. It is organized as follows. The NPAL experiment is briefly presented in Section II. Propagation modeling of the Downslope propagation is presented in Section 3. The Kauai Near-Source Test (KNST) experiment, in which transmissions were recorded downslope of the Kauai source, is presented in Section IV. Section IV also includes initial comparisons of the received signal and range-dependent Parabolic Equation modeling. Section V concludes with a description of the modeling and experimental approach being undertaken to address this issue.

II. THE NORTH PACIFIC ACOUSTIC LABORATORY EXPERIMENT

The Kauai source for the NPAL experiment is mounted on the seafloor, at a depth of 900m, 25 nautical miles northeast of Kauai. In addition to receiving the transmitted signals on the US Navy SOSUS network, a set of 5 vertical line arrays were deployed in 2000m of water on the continental slope off the coast of Monterey California. The arrays were deployed broadside to the expected arrival angle for the purpose of measuring horizontal coherence lengths for very long-range propagation experiments.

The source location was chosen to meet the constraints of being close to shore (for power) and being a location where the bathymetry intersected the sound channel axis. The sound channel axis in the central Pacific ranges from 900m to 1200m in depth. The source is placed on the axis so that it excites acoustic energy in all propagation angles and this provides the best sampling of the water column for ocean acoustic tomography. The bathymetry from the source into deep water is shown in Fig. 1.

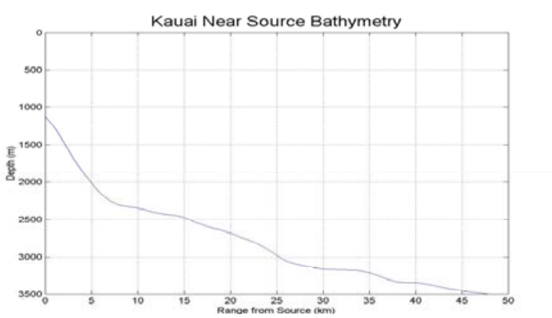

Fig. 1 Downslope bathymetry near Kauai Source

The source transmits 40 periods of a pseudo-random m-sequence covering the frequency band of 60 to 90 Hz. The center frequency of the source is 75 Hz. Each period is 27.2s long, yielding a roughly 20 minute transmission. The transmission schedule was designed to satisfy marine mammal mitigation concerns and permit the accurate estimation of the tidal component. Every 4 days, there are 6 transmissions, separated by 4 hours.

The analysis of the NPAL receptions, and the associated ocean acoustic tomography, is being conducted by researchers at the Scripps Institution of Oceanography and the Applied Physics Laboratory – University of Washington and will be published elsewhere. The significant issue addressed here is that after matched-filtering and vertical beamforming, the received signal arrived at the vertical line arrays nearly 1s later than expected from both ray modeling and adiabatic mode modeling[2]. The timing algorithms on the source and receiver arrays were double-checked and there were no apparent errors in the timing. The same signal processing was performed during the ATOC experiment, where the source was mounted on a seamount near Monterey, and in that experiment there was no significant disagreement between modeled and measured propagation times.

This paper is a presentation of the investigation into the effects of the downslope near the source and it's proposed explanation of the 1s mismatch between predictions and measurements.

III. MODELING DOWNSLOPE PROPAGATION

In order to examine the effects of the bathymetry near the bottom mounted source on acoustic transmissions into deep water, broadband Parabolic Equation (PE) runs were performed using RAM[3]. The impulse response of the channel was computed at 25km for various assumptions about the sediment geo-acoustics. At this point, with the exception of internal wave scattering effects, we presume that the propagation in deep water is well understood.

The difficulty with precise modeling of the downslope propagation is the lack of knowledge of the geo-acoustic parameters. Given the volcanic creation of the island of Kauai, we can assume that the basement is basalt, with a very high compressional sound speed on the order of 3500 m/s. Uncertainty in the exact compressional speed is not an important issue due to the severe sound speed contrast between the speed of sound in water and in basalt. The two issues are the presence and speed of the shear wave in the basalt and the extent to which sediment has settled and covered the hard basement.

Initial attempts to run the RAM-S code, with shear-waves included were not successful, partly because of the difficulty in coming up with a stable simulation for the PE in an environment that includes shear and is strongly range-dependent. To address the issue of sediment geo-acoustics, we simply performed the propagation runs with several generic sediment profiles (silt over basalt/ sand over basalt/ exposed basalt). For this problem, it is the strength of the first and second bottom bounce, and how much they are scattered into lower propagation angles that is critical.

Fig. 2 and 3 show the transmission loss at 75 Hz (the center frequency of the source transmission) for two different sediment assumptions. In Fig. 2, with a 10m silt sediment overlying a basalt basement, it is clear that the bottom interacting energy is completely stripped from the water column. For this sediment, the approximation that all bottom interacting energy is gone and only rays which do not bottom interact are present and contain significant energy is not a poor approximation.

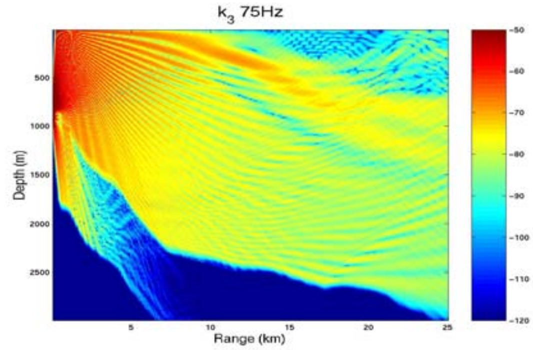

Fig 2. Transmission Loss 25km downslope for sand sediment.

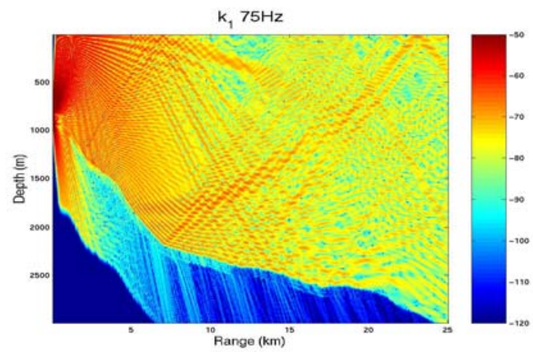

Fig 3. Transmission Loss 25km downslope for exposed basalt.

For the exposed basalt sediment, shown in Fig. 3, however, the conclusion is quite the opposite. It is clear that there is significant acoustic energy at high-angles and sound does survive after interacting with the sediment. For this case, the non-bottom interacting rays will arrive at the receiver, but the assumption that they contain all of the energy is not valid. A full-field, broadband, range-dependent propagation run is required to fully understand how much energy is contained in each set of ray arrivals.

The impulse response for the soft sediment and the exposed sediment at 25km are shown in Figs 4 and 5. With the soft sediment layer, the bottom bounce is present, but it is weak and does not compete with the direct path. For the exposed basalt (and although not shown, for a more reflective sand sediment over a basalt basement) the first order bottom bounce has as much energy as the direct path. This is significant to the tomography problem because this energy will propagate to long ranges and arrive at the receiver 0.5 s behind the direct path.

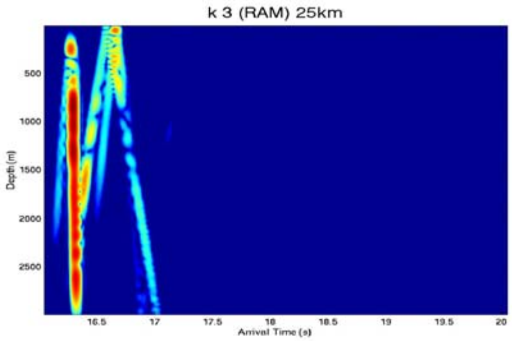

Fig 4. Impulse response 25km downslope for sand sediment.

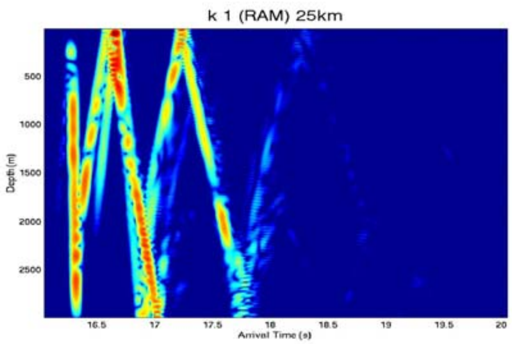

Fig 5. Impulse response 25 km downslope for exposed basalt.

There are two mechanisms at work here to permit sound to come off the shelf and arrive at the receiver (on the other end of the basin) delayed by 0.5s. The first is a shallow water propagation phenomenon. In deep water the water column dispersion is such that the group velocity is driven by refraction of the sound speed profile and therefore higher angle rays (or higher modes) have higher group velocities because they spend time (and turn) in regions with higher compressional sound speeds. In shallow water, the opposite is true. In shallow water propagation, the steep angles refract little, and their group velocity is dominated by interaction with the bottom and effectively becomes $v_o\cos\theta$. While the sound is propagation down the shelf, interacting with the bottom in the first 5 km, the propagation is effectively shallow water, giving the high angle energy very slow group velocities. Horizontal group velocities can be as low as 1300 m/s for high angle energy. Once in deep water, the modal dispersion switches to the more common SOFAR propagation and the high angle energy is now the fastest. We postulate that there will be a range at which most of the energy collapses into a single pulse. In order to have the sound effectively propagate to the receiver at great distances, the sound cannot continue to interact with the bottom. The second mechanism, which permits sound to arrive at the end of the basin late, is the angle conversion (or mode coupling) that occurs with each bottom bounce on the continental shelf. As the high angles hit the seafloor, they are scattered to lower angles. They propagation off the bottom and there is a set of propagation angles that are delayed by 0.5s and are scattered to angles that are no longer bottom interacting.

IV. THE KAUAI NEAR SOURCE TEST

In April 2002, the Kauai Near-Source Test was conducted to test the accuracy of the source timing, and to observe if the bottom interacting energy was observable at ranges of 25 and 50km. A short (100m) vertical line array was deployed to a depth of 100m from a small boat off the coast of Kauai. There were six transmissions of the NPAL source successfully recorded on the vertical line array. The transmissions were recorded at ranges of 0.25, 3.2, 5, 26, 38 and 52km from the source.

For all of the recordings the Signal-to-Noise (SNR) was high enough to see the transmission on a single element spectrogram without matched filtering the impulse response. After applying the m-sequence matched filter, and summing over 4 periods, rather than all 20 transmitted periods, the SNR ranged from 40 dB down to 25 dB. The single element spectrogram for the first reception is shown in Fig. 6.

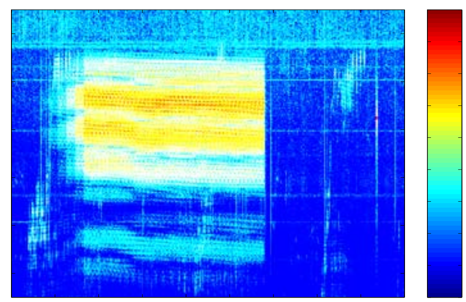

Fig 6. Single Channel Spectrogram of Kauai Source Transmission

The first, and possibly primary, result of the KNST was that there was no error in the source clock timing. Extra care was taken to sync the clocks of the recording system with a GPS satellite IRIG-B clock to make sure that we could measure travel time from the source to the receiver array exactly. For transmission 2, at a distance of 3.2 km, the estimated propagation time was 2.15s from broadband PE modeling and the measured arrival time was at 2.2s.

The received signal for Transmission 2, at a range of 3.2 km is shown in Fig. 7, along with PE predictions for 3 sediment types. In the data, shown in blue, there are two clear arrivals separated by 0.8 s corresponding to the direct path (and surface reflection) and the bottom bounce path. The PE simulation captures both of these paths quite well. The structure in the bottom path that is in the data is not observed in the PE simulations. The third arrival, corresponding to the second bottom bounce path is not clearly resolved in the data.

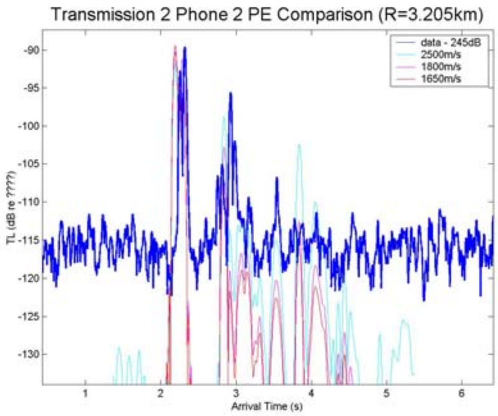

Fig. 7. Measured and Modeled reception at 3.205 km.

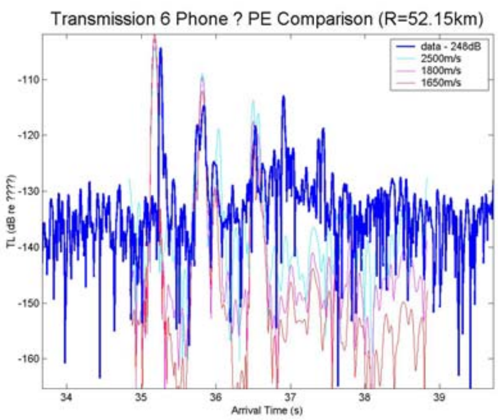

Fig. 8. Measured and Modeled reception at 52 km.

V. CONCLUSION AND FUTURE PLANS

The effects of interaction with the seafloor on long-range acoustic transmissions from a bottom-mounted source have been investigated. The approach has been a combination of long-range acoustic tomography (the NPAL experiment), near source computational acoustic modeling and measurements of transmissions near the source. The so-called “1-second Problem”, where the predictions of acoustic travel time at over 3000 km is 1 second less then the measured time, was investigated. Any form of source timing error was ruled out by direct acoustic measurements over the source. It was confirmed that the bottom bounce path has comparable energy to the direct path. This energy takes roughly 0.5s behind the direct path when the sound enters deep water. Comparisons of broadband PE computations with the measurement show qualitative agreement, although the full geo-acoustic inversion has not been completed.

The work planned to investigate this problem can be broken into three areas. Firstly, a more thorough analysis of the KNST data is required, including beamforming of the vertical line array data, processing more periods to improve the Signal-to-Noise Ratio, and striation based geo-acoustic inversions from the observed striation patterns in the single element spectrograms. The second area of effort will involve computational acoustic modeling of the downslope propagation problem using the new RD-OASES code and compare these results with the RAM-S model. In addition to the data analysis and the computational modeling, a sea-test is planned for the late summer of 2004. This test will be a substantially more thorough investigation of the phenomenon than the KNST. The RV Kilo Moana will be used, permitting examination of the signal out to ranges of 1000km. The Office of Naval Research FORA (Five Octave Research Array) will be deployed, permitting both horizontal and vertical measurements to be taken with a dense sampling of a 200m-aperture array. The combination propagation modeling, including effects of shear, and direct measurement at a variety of ranges will provide us with the opportunity to fully investigate the complex interaction of sound with the seafloor as it propagates from shallow water to deep water. This issue is important in the understanding of source excitation for long-range ocean acoustic tomography as well as the structure of ambient noise in the deep ocean basins.

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