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EXPLOITING RELIABLE FEATURES OF THE OCEAN CHANNEL RESPONSE

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INTRODUCTION

Modelling sound propagation in shallow water is notoriously difficult. The main difficulties are, of course, ocean variability characteristic of coastal waters and the typically downward refracting profiles that make the acoustic field extremely sensitive to the bottom characteristics. Meanwhile accurate prediction of transmission loss curves at a single frequency requires that the relative phase of each surface and bottom echo is predicted with precision. It is a daunting task even for systems that will operate in carefully surveyed areas.

On the other hand, certain features of the channel response are extremely robust. A long, broadband chirp can be compressed to the equivalent of a short

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[1] work performed as a visiting professor at the University of the Algarve

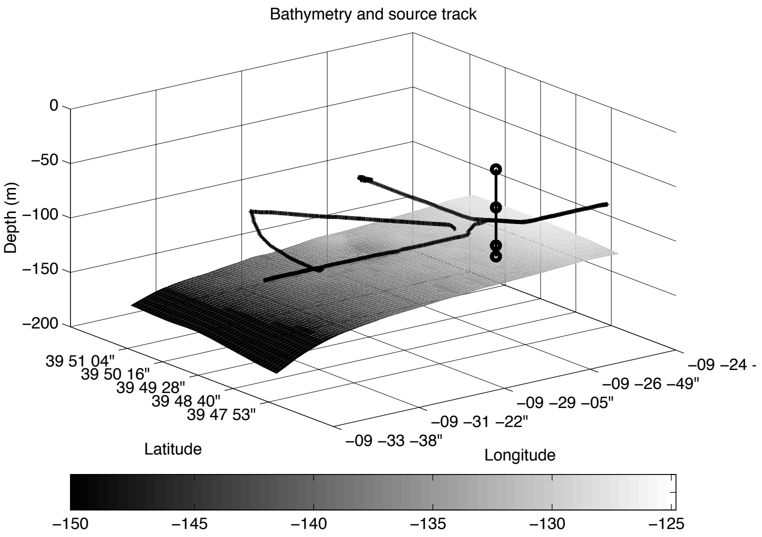

Figure 1: Source track and array position relative to bottom topography.

ping which is heard as a sequence of distinct surface and bottom echoes. The resulting pattern of echoes is extremely robust with respect to ocean and bottom variations.

Using data from the INTIMATE '96 tomography experiment we show how these characteristics can be exploited in the signal-processing to provide robust tracking of a source over several days. This includes periods where the ship travels both cross-slope and down-slope and where the environment changes radically due to internal tides.

EXPERIMENTAL SCENARIO

The INTIMATE 96 shallow water tomography experiment was primarily designed to image internal tides. The experimental configuration is illustrated in Fig. 1. The SPTA (Source Pour Tomographie Acoustique) was towed at a depth of about 90 m by the French oceanographic ship, d'Entrecasteaux. The acoustic signal was received on the SACLANTCEN portable array which had four hydrophones at depths of approximately $35, 70, 105, \text{and} 115\,\text{m}$. A more complete background in provided elsewhere in this volume[1].

INTIMATE 96 was conducted near the shelf break where the internal tides tend to be strongest. The position of the vertical array relative to the bottom topography is shown in Fig. 1. Note that the horizontal axes show latitude and

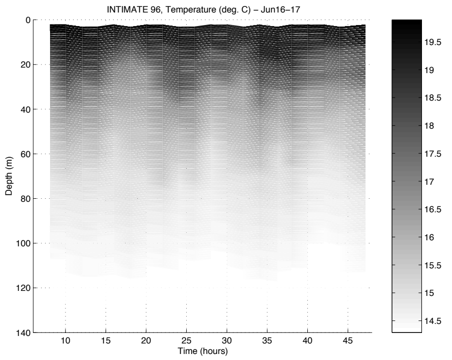

Figure 2: Ocean temperature vs. time from CTD measurements at the array.

longitude and the coast of Portugal would be some 20 km to the east.

To sample the internal tide field along several interesting axes, the source ship traced out a pattern of 4 radials and 1 arc. The precise track was measured by GPS data and is also shown in Fig. 1. (The source depth actually varies between 50 and 100 m but is here shown at the nominal 90 m depth.) Note that the topography under the source ship shows 30 m variation providing an unusual challenge for model-based tracking.

A CTD survey conducted during the experiment revealed the anticipated internal tide. The associated 25 hour cycle is clearly seen in the displacements of the isotherms in Fig. 2. Of course, the experiment was specifically designed to capture this internal tide feature; however, the associated oceanographic variability presents an additional difficulty for matched-field processing of the data.

The source transmitted chirps in the $300 - 800$ Hz band. The received signals were then correlated with an estimate of the transmitted waveform. This waveform was based on a laboratory measurement of the power spectrum (but not the phase spectrum) of the projector. The spectrograms of the received signals on each of the 4 phones are shown in Fig. 3. Examining the time axis, we can see that the chirps lasted for 2 seconds and were repeated every 8 seconds. On the frequency axis, we see the linear increase in frequency of the chirp. In the upper left panel the signal is almost impossible to discern. In fact, this phone had become flooded with salt water and was initially disregarded as a dead phone.

After replica correlation and forming an envelope of the resulting time series we obtain what is effectively a measurement of the impulse response of the ocean channel. This is shown in Fig. 4. A horizontal slice through this figure shows

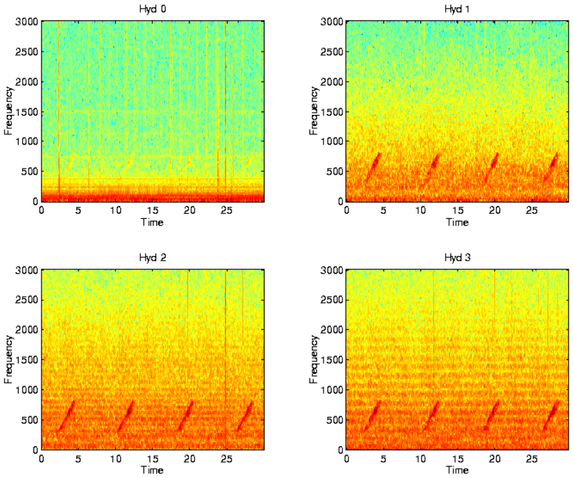

Figure 3: Spectrograms of the received signal on each of the 4 phones.

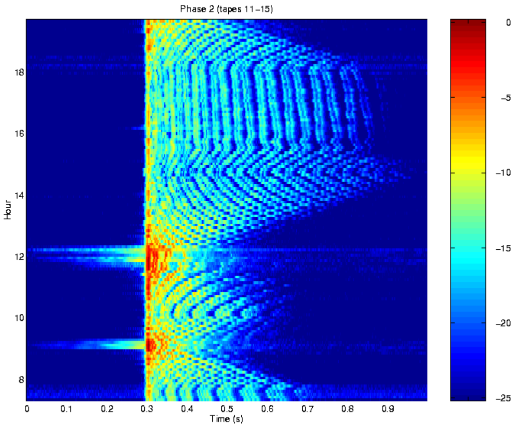

Figure 4: Replica correlograms during the 12 hours of ship maneuvers.

the impulse response for a single ping. The pings were repeated many times over the 12 hour period studied here, allowing us to observe the change in the echo pattern over time. This echo pattern of surface and bottom bounces varies with source range; at larger ranges we see more echoes and a longer impulse response.

Matched-field processing

The use of matched-field processing[2] for source localization has been compared to 'making a trick shot in pool'. It is assumed to require very precise predictions of the acoustic amplitude and phase so that the multiple surface and bottom bounces all coalesce at the source location. This in turn relies on a detailed knowledge of the environment. Indeed, if we apply conventional matched-field processing algorithms to this data without great care to measure the environmental data, one obtains disastrous results.

Clearly there is something wrong with the standard processing, since even the untrained eye can examine the pattern of echoes in Fig. 4 and accurately range the source ship. It helps to know that the bottom is sandy with a sound speed of about 1750 m/s but this number does not need to be known precisely. The sequency of opening and closing approaches is clearly manifest in the lengthening and shortening of the echo pattern. Furthermore, the period in the afternoon (15:00-18:00) when the source ship traced out an arc of roughly constant radius is easily identified by the stable echo pattern during that period.

Thus, it is the arrival pattern that provides a robust feature for localization. Because we have formed an envelope in Fig. 4 we have eliminated the sensitivity to the phase of the bottom reflection coefficient. Meanwhile, the logarithmic dB scale allows us to plot the results in a way where the eye can readily make out both the strong leading arrivals and the weak later arrivals.

The logarithmic scale is particularly important here because the leading arrivals which last for just 10% of the time series, contain 85% of the energy and completely overwhelm a conventional correlation-based scheme. The problem is akin to trying to range the source with all but the leading part of the time series masked out in Fig. 4. The shape of that leading part is definitely sensitive to source range, but it is represents a delicate interference of many arrivals and is also highly sensitive to errors in bottom depth, ocean temperature, etc. On the other hand, if we mask out the leading part, we can still reliably track the source from a visual inspection of the pattern of trailing arrivals.

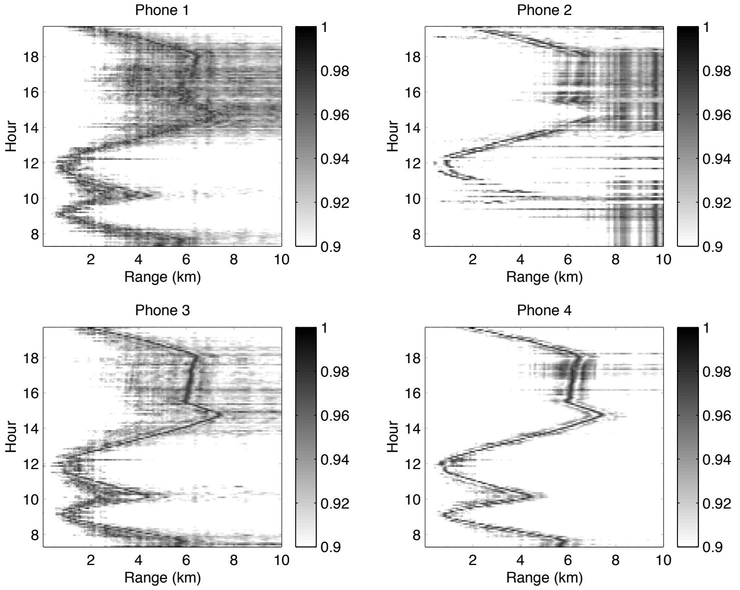

Figure 5: Range-time surfaces for each of the hydrophones.

Exploiting this in the signal processing is straightforward. We simply correlate the logs of the envelopes between model and data. In other words, we use the data plotted in Fig. 4 (which is in log-envelope form) for the correlation. The modeled log-envelopes can be predicted using a variety of acoustic models; here we have used the KRAKEN normal mode program[3]. The resulting range-time surfaces for each hydrophone are shown in Fig. 5.

Looking first at the lower-right panel, we can clearly make out the track of the source ship with its various opening and closing approaches. The exact track (not shown) is available from GPS data and agrees to within about 10%. Thus, the processing is successful in tracking the source continuously over the 12 hour period of ship maneuvers. Using the same processing, we have also localized the source continuously over two 25 hour periods while it was on station at about 6 km range. These surfaces represent projections of a full range-depth ambiguity volume; depth-time surfaces also reveal that the source has been correctly tracked in depth over the same periods.

It is noteworthy that these results were obtained in an environment with great variation in both bottom topography and ocean temperature. A simple flat bottom model was used even though there is some 30 m in depth variation. In addition, a single sound speed profile was used based on the measurement at the start of the experiment, even though the profile varied significantly during this 12 hour period. (The slight degradation seen in the afternoon period while the ship traced out an arc, is probably due to it having moved into the downslope area.)

Our initial attention was focused on this particular phone because it was located in the more stable part of the water column and there was some intuition that that position would be favorable. However, an examination of the other panels in Fig. 4 shows that the source is tracked on all the phones including the 'dead phone' with extremely low SNR. (In this figure the phones have been plotted in order of depth so the dead-phone corresponds to the upper-right panel.)

SUMMARY

One can model this data with great precision using any of a number of off-the-shelf (or more precisely, off-the-net) acoustic models. Accurate modeling requires accurate topographic and oceanographic information. The latter bodes well for our other objective of tomographically imaging the internal tides.

On the other hand, we have seen that with suitable processing we can exploit the 'reliable features' and obtain virtually perfect tracking with very coarse information about the environment and even at very low SNR. Of course, in a short paper we have found it necessary to omit many details. It should be noted that the processing assumes some knowledge of the source spectrum. This is an important but not much studied case. However, when the source spectrum is known poorly, the processing can be done with the cross-correlation between phones.

The standard approach for ocean acoustic tomography also exploits this arrival-time information (though variations that are sensitive to the phase of the arrivals and full matched-field approaches have also been studied). For both the tomographic and source localization problems the choice of approach depends on the degree to which parameters which are not part of the inverse problem are aliased into those that are. For typical localization problems, it appears that the arrival-time processing is more robust. Meanwhile, the correlation in log-space provides a convenient alternative to peak tracking algorithms, especially at low SNR.

Acknowledgment

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