SINGLE-PHONE SOURCE TRACKING IN A VARIABLE ENVIRONMENT

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Internal tides commonly occur along ocean coasts. They are internal waves driven by the usual tidal force and generated by scattering at a sharp bottom feature such as the shelf break. The internal tides are dramatic features with crests typically 10-30 km apart and wave heights of 20 m. On the ocean surface they cause only a gentle ripple about 10 cm high but they affect the shine of the surface. As a result, astronauts often see them as the tides propagate away from the shelf break. In June 1996, a shallow-water tomography experiment (INTIMATE 96) was conducted off the coast of Portugal to observe these internal tides and learn about their acoustic effects. A source was towed around a vertical hydrophone array to produce acoustic sections along several slices. The experiment also provided an ideal opportunity for testing model-based source tracking. Acoustic sections taken parallel to the Portuguese coast allowed us to understand the propagation physics in a range-independent area. With this we have been able to develop a matched-field algorithm suitable for use in the far more complicated downslope direction which, being perpendicular to the crests of the internal tides, also experiences strong ocean-temperature variations. We will discuss both the approach and the source tracking.

1. INTRODUCTION

The INTIMATE 96 experiment was designed primarily as an acoustic tomography experiment for monitoring internal tides[1]. The internal tides recently have renewed importance as a means of understanding how the ocean dissipates the lunar energy[2]. The internal tides appear to be a key link in the cascade of energy from the large to the small scale.

The effects of internal tides have been seen several times in tomography experiments[3][4][5][6] but INTIMATE is the first series of experiments specifically designed to tomographically image them. Preliminary results on the oceanographic inverse problem have been presented elsewhere[7]. Our focus in this paper is instead the inverse problem for source position. In applications the source might be any of a variety of things such as a marine mammal or an autonomous undersea vehicle. In our experiment the source is a towed transducer transmitting chirps in the 300-800 Hz band that were received on a 4-phone vertical array. In this paper we shall discuss data from only the deepest phone at 115 m.

The ray trace from the 115-m phone shown in Fig. 1 gives a feel for the environment. Rays are traced from that lowest receiver out to 10 km, which was the maximum range of interest. The ray plot has been superimposed on a transmission loss plot calculated at 1 kHz using an incoherent addition of rays[8][9].

The receiver was deployed on the continental shelf off the coast of Portugal while the source was deployed over the continental slope at a depth of 90 m and at a range of about 6.5 km. In this fashion the source-receiver plane cuts a slice roughly perpendicular to the internal tides.

The sound speed profile is downward refracting so that all of the rays interact with the bottom, which raises questions about the bottom type. A set of 8 corings revealed the usual suspects: silts, sands, mud, shells, and combinations thereof at different locations and depths.

The internal tides cause large displacements of the isotherms with a corresponding impact on the ocean sound speed structure. The time evolution of this is shown in Fig. 2 using CTD data taken at the receiver location. The period is about 12.5 hours, which corresponds to the lunar tide.

2. MODEL-BASED TRACKING

There is now an enormous literature on model-based tracking (or matched-field processing) but only scarce and modest experimental successes. However, especially promising results have been achieved in recent years. A good introduction to the field is Ref. [10]. Work most closely related to this paper is given in Refs. [11][12][13][14][15].

With regard to model-based tracking, this environment presents many challenges. There is significant variation in bottom depth; the downward refracting environment means all paths are bottom interacting; and there is tremendous oceanographic variability due to the tides. To develop a robust tracking algorithm, we first form the log-envelope:

$$r_{le}(t) = \max\{0, 20\log\left[env\left(r(t)\right)\right] - a\}$$

where *r(t)* is the ‘correlogram’ which is computed by correlating the received waveform with a replica of the transmitted waveform. The constant, *a*, is a clipping threshold set at 30 dB.

This much of the processing is fairly standard. In free-space, the replica-correlation of a chirp with itself yields a sharp peak whose duration is related to the bandwidth. In the ocean channel, the replica-correlation peaks at times corresponding to each of the echoes. The result is the channel impulse response. The envelope eliminates the phase information and the log balances weak and strong arrivals as discussed in Ref. [15]. We then align the leading edges and average 10 such waveforms together to reduce the noise.

It should be emphasized here that this processing assumes the knowledge of the source waveform in detailed (phase-amplitude) form. This information is generally available in bistatic, active scenarios. There are also important monostatic, passive applications where it is available. In our application the waveform was estimated using a tank measurement of the transducer amplitude response but neglecting phase variations across frequency.

Next we use an acoustic model to simulate this entire process and write

$$g_{le}(t;r,z) = \max\{0, 20\log\left[env\left(g(t;r,z)\right)\right] - a\},$$

where the modeled response, *g(t;r,z),* is calculated over a grid of plausible source ranges, *r*, and depths, *z*. A wide variety of reliable ocean-acoustic models are suitable for that[8].

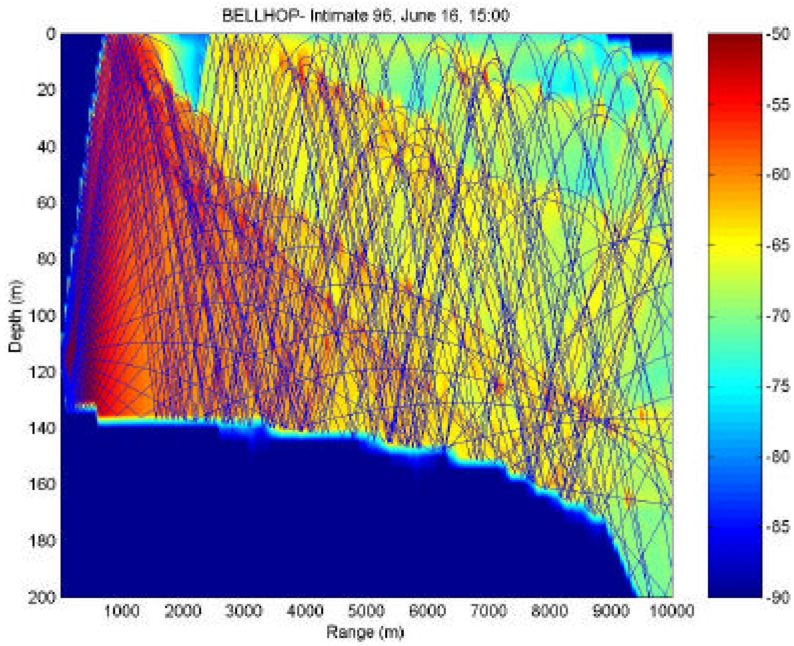

Figure 1 Ray trace and transmission-loss.

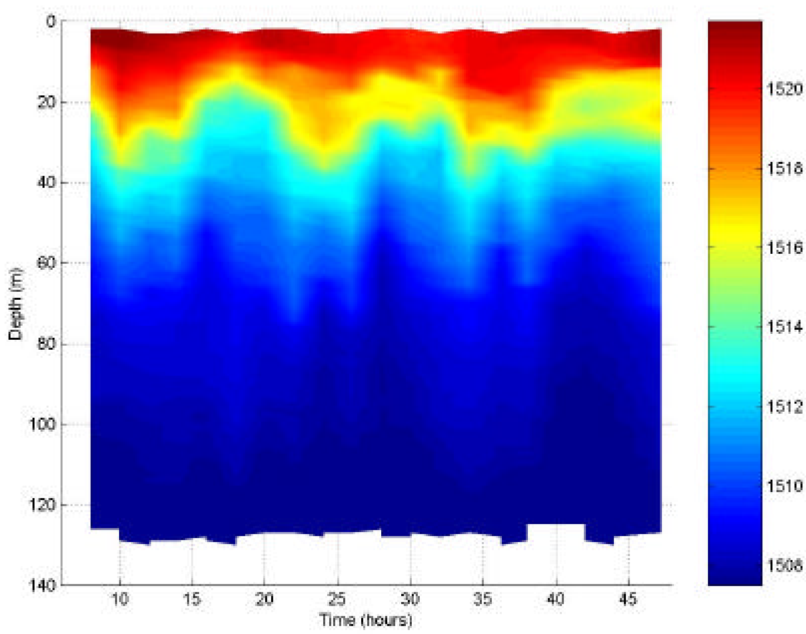

Figure 2 Sound speed profile over time at the receiver.

In the following we have used the BELLHOP ray-beam model (briefly described in Ref. [9]) which is particularly convenient for these sorts of broadband, range-dependent problems. In principle, one does a broadband calculation to predict the waveform response and then correlates the result with the chirp. However, to save time, we take advantage of the linearity of this process and use the code to propagate the autocorrelation of the chirp directly. The computer time for calculating *g(t;r,z)* for 500 ranges and 11 depths required about 10 seconds on a laptop computer. The measured bathymetry was used; however, the sound-speed profile was taken statically using a single measurement from the CTD section shown earlier. The ocean bottom is modeled as a half-space with sound speed of 1750 m/s.

Next we do a sort of fingerprint match, comparing the ensemble of modeled waveforms to the actual received waveform. The comparison is done by correlation:

$$c(t;r,z) = \int r_{le}(t)\, g_{le}(t - t;r,z)\, dt \;,$$

and searching for the maximum of the correlation,

$$P(r,z) = \max_t \left| c(t;r,z) \right| ,$$

identifies the best fit.

This calculation is repeated for every chirp transmitted. Since chirps were transmitted every 8 seconds over several days and since each chirp is matched against an ensemble of modeled waveforms, there is quite a bit of processing involved. The processing of the entire 3 days of experimental data required several hours on a laptop computer.

3. RESULTS

The correlation surface, *P(r, z)*, is calculated every time a chirp is sent yielding a 3-dimensional function of range, depth, and time that is awkward to render in print. We seek its maximum over depth and thereby project it onto the range-time plane. The result shown in Fig. 3 shows the range of the source over the 25-hour period of this phase of the experiment. There is a clear ridge in the correlation that meanders around a range of about 6.7 km. This is in good agreement with the source ship’s actual range of about 6.4 km. The apparent oscillation is a sort of mirage due to both the surface and internal tides. The slight range bias is probably a consequence of errors in the bathymetry.

We can also project the correlation through the range axis yielding a depth-time record of the source, which is shown in Fig. 4. With 10 depths, the surface is slightly undersampled but nevertheless, agrees very well with the true source depth of 90 m.

4. CONCLUSIONS

Using data from the INTIMATE 96 experiment, we have shown single-phone, continuous, range-depth tracking at 7 km range in a highly variable shallow-water environment. The acoustic modeling is not burdensome relying on a simple ray-beam model for the channel simulations. Indeed, the processing is done on a laptop computer with enough speed to be practical in real-time.

There is not space to discuss the complete data set; however, the algorithm has been successfully applied to the entire data set demonstrating tracking on all 4 of the hydrophones in the array over a several day period while the source completed two 25-hour stations and an 18-hour bow-tie pattern to beyond 10 km in range. The tides show up as an interesting feature in that they cause a sort of mirage that makes the source appear to move back and forth in range. The results are not presented here, but a similar tidal oscillation was seen in the cross-slope track[16].

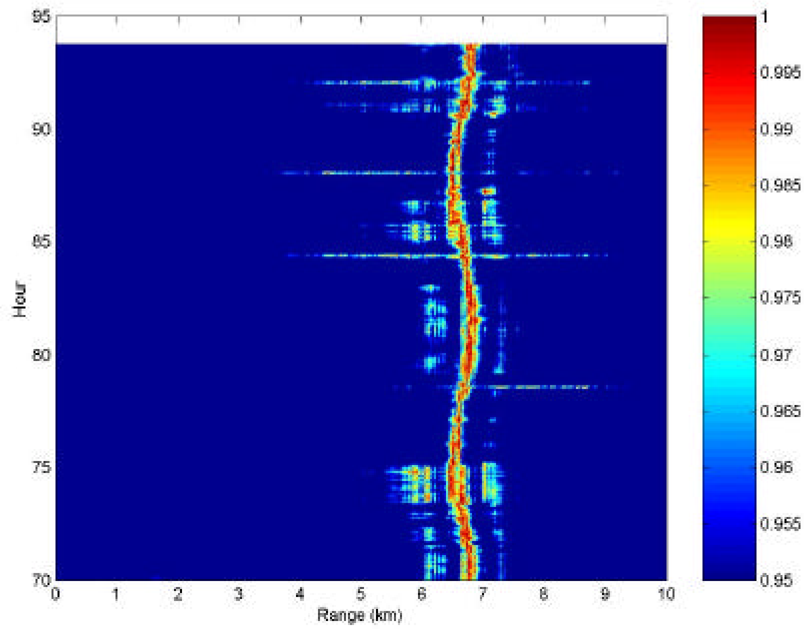

Figure 3 Range-time ambiguity surface.

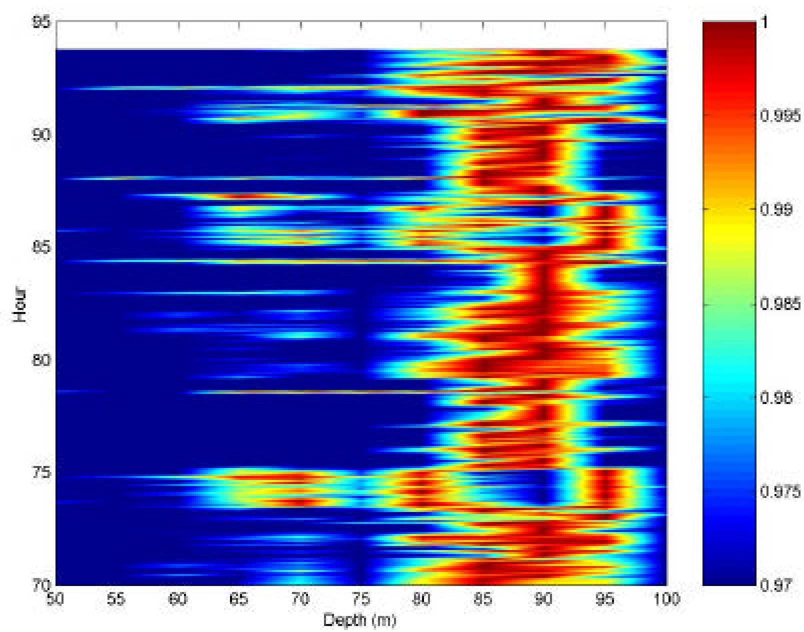

Figure 4 Depth-time ambiguity surface.

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REFERENCES

[1] Open University Course Team, *Waves, Tides, and Shallow-Water Processes*, Open University press (1989).
[2] W. Munk and C. Wunsch, "The Moon, of course …", *Oceanography*, **10**, No. 3 (1997).
[3] N.L. Weinberg, J.G. Clark, and R.P. Flanagan, "Internal tidal influence on deep-ocean acoustic ray propagation", *J. Acoust. Soc. Amer.*, **56**(2), 447-458 (1974).
[4] W. Munk, B. Zetler, J. Clark, S. Gill, D. Porter, J. Spiesberger, and R. Spindel, "Tidal effects on long-range sound transmission", *J. Geophys. Research*, **86**(C7), 6399-6410 (1981).
[5] F.R. Martin-Lauzer, Y. Stéphan, and F. Evennou, "Analysis of tomographic signals to retrieve tidal parameters", *Proceedings of the Second European Conference on Underwater Acoustics*, Ed. L. BjØrnØ, European Commission, 1051-1056 (1994).
[6] B.D. Dushaw, B.D. Cornuelle, P.F. Worcester, B.M. Howe, and D.S. Luther, "Barotropic and baroclinic tides in the central North Pacific Ocean determined from long-range reciprocal acoustic transmission", *J. Phys. Oceanography*, **25**(4) 631-647 (1995).
[7] X. Démoulin, Y. Stéphan, S. Jesus, E. Coelho, and M. Porter, "INTIMATE96: A shallow-water tomography experiment devoted to the study of internal tides", *Proceedings of the Shallow Water Acoustics Conference*, Beijing, China (1998*) in press*.
[8] F. Jensen, W. Kuperman, M. Porter and H. Schmidt, *Computational Ocean Acoustics*, American Institute of Physics, (1994).
[9] M. B. Porter, *The KRAKEN normal mode program*, SACLANT Undersea Research Centre Memorandum (SM-245) / Naval Research Laboratory Mem. Rep. 6920 (1991).
[10] A. Tolstoy, *Matched-Field Processing for Underwater Acoustics*, World Scientific, Singapore, (1993).
[11] Evan K. Westwood and David P. Knobles, "Source track localization via multipath correlation matching", *J. Acoust. Soc. Amer.*, **102**(5), 2645-54 (1997).
[12] L.N. Frazer and P.I. Pecholcs, "Single-hydrophone localization", *J. Acoust. Soc. Amer.*, **88**, 995-1002 (1990).
[13] R.K. Brienzo and W.S. Hodgkiss, "Broadband matched-field processing", *J. Acoust. Soc. Amer.*, **94**(5), 2821-2831 (1993).
[14] Z.H. Michalopoulou, M.B. Porter, and J. Ianniello, "Broadband source localization in the Gulf of Mexico", *Journal of Computational Acoustics*, **2**(3),361–370 (1996).
[15] M. Porter, S. Jesus, Y. Stéphan and X. Démoulin, E. Coelho, "Exploiting reliable features of the ocean channel response", *Proceedings of the International Conference on Shallow Water Acoustics* held in Beijing, China, April 22-25 (1997) *in press.*
[16] M.B. Porter, Y. Stephan, S. Jesus, E. Coelho, "Shallow-water tracking in the Sea of Nazaré", *Proceedings of the 1998 International Symposium on Undersea Technology*, April 15-17, Tokyo, Japan, IEEE Catalog Number 98EX101, 29-34 (1998).