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TITLE

TRACKING OF AN UNDERWATER SOUND SOURCE IN RANGE, DEPTH AND BEARING IN SHALLOW PACIFIC WATER

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Tracking of an Underwater Sound Source in Range, Depth and Bearing in Shallow Pacific Water

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Introduction

In this paper, we present matched-field inversion and tracking results for data collected in a Pacific shallow water environment. The data were collected with a Vertical Line Array (VLA) in September 1993 as part of the PACIFIC SHELF Sea Trial in a co-operative trial by Defence Research Establishment Pacific (DREP), Victoria, B.C. and Applied Research Laboratory (ARL), University of Texas at Austin. The primary objective of this Trial was to evaluate Matched-Field Processing (MFP) techniques in a Pacific shallow water environment.

The data analysed here was collected while a Continuous Wave (CW) source was towed downslope towards the VLA. MFP can be used to localize such sources by exploiting knowledge of the environment. This is accomplished by matching the measured data with an acoustic field prediction based on a model of the environment. The best match will indicate the most likely source position. Alternatively, if the source position is known, the best match for a selection of environmental models would indicate the most likely environment. This process, otherwise referred to as Matched-Field Inversion (MFI), can determine environmental parameters. These inversions are particularly effective when the position of the source and geometric configuration of the receiving array are well known.

In this paper, parameters describing the mean geometric configuration of the VLA during the time of the experiment were found by using MFI. The parameters were: the tidal depth of the water column, the VLA position on the continental slope, the array depth and the orientation of the measured array tilt. The tidal depth accounts for an increase of water depth for the entire region as a result of tides. The success of the inversion was measured by results from a 2-D Efficient Linear Tracker (ELT).

Previous 2-D and 3-D tracking ([17], [8], [9]) predicted ranges within 200 m of the measured ranges demonstrating the robustness of MFP techniques. However, as a result of an initial lack of knowledge of the array geometry and environment, the track headings found were offset from the known headings. In this paper, we attempt to procure better track estimates with a refined array geometry model from the inversion results. Results from a 3-D ELT were compared in order to determine whether the tracking improved with the inverted array geometry information.

1 Data

For the experiment analysed here, a CW source emmitted 3 frequencies simultaneously at 45, 70 and 72 Hz while it was towed by the CSS W.E. RICKER towards the VLA receiver. The source levels at 45 Hz and 70 Hz were typical of a strong line from a merchant vessel while the 72 Hz line was 20 dB lower. The VLA consisted of 16 equispaced hydrophones with a separation distance of 15 m which spanned the water depths between about 85 m and 310 m where the water column depth was $\sim$ 375 m. This VLA was designed to be anchored at one position and was attached to a free-floating electronics canister with a 100 m tether line. From this electronics canister, the data were multiplexed and transmitted to the CFAV ENDEAVOUR where the data were recorded. The Global Positioning System (GPS) position of the electronics canister, and the output of array tilt and depth sensors were also recorded. The tether line introduced an array position uncertainty of up to 100 m.

The source track [9] began 11.9 km from the array, on the continental shelf at a water column depth of $\sim$ 160 m and proceeded down the continental slope towards the VLA at a constant linear velocity, while maintaining a source depth of $\sim$ 30 m. After 43 min, there was a change of heading and the source proceeded downslope again at a constant linear velocity for another 22 min.

Both the source and receiver positions were recorded from GPS and radar which each have errors of $\sim$ 100 m. However, the range estimate between two GPS measurements (e.g., the source and reciever) sampled at the same time have only $\sim$ 30 m uncertainty.

The uncertainty of the VLA's geometry was complicated by the fact that throughout the trial, the VLA did not remain anchored. Therefore an average over time of the GPS position would not be indicative of the true VLA position. As well, the tilt and depth sensors would not be indicative of a complicated array shape. From a previous study [17], the linear array tilt was found to be approximately 2.0° to 2.5° which was consistent with the measured tilt of about 1.0°. The orientation of this tilt was not available.

The sea state was very calm during the time that this data were collected. Therefore it is possible, that for the data analysed here, the array remained stationary, while the free-floating electronics box drifted.

Noise levels during the time of the experiment were high since there was considerable shipping traffic.

The initial environment model used here is based on an XSV (Expendable Sound Velocimeter) measurement which was cast eighty minutes prior to the experiment's start time. The bottom acoustical properties were based on seismo-acoustic results from another PACIFIC SHELF experiment [1] which resulted in an estimate for the sediment thickness and compressional speeds of the sediment layer and bottom halfspace. Other bottom parameters were based on typical values for the environment (e.g. Ref. [11], [4] and [5]). More detailed information for the environment model and the data is given in [9].

2 Analysis Techniques

The geometric inversion and the 3-D tracking results for the strong line (45 Hz) are presented here.

The adiabatic normal mode approximation was used to calculate the range-dependent replica fields. This method is fast and efficient if the acoustic modal data are precomputed. This approach does not include effects due to mode-coupling, and inaccuracies commonly associated with these effects for a range-dependent environment were addressed for this experiment in [9]. It was found that mode-coupling inaccuracies were negligible except at the steepest slopes of the environment, consistent with other results in [2]. For a wedge-like environment, it has been found [3] that 3-D modelling is required in order to account for 3-D refraction properly. This is a limitation of the analysis completed here but since the true source track is directly upslope, this problem is not as significant. The replica fields for matching were generated at 40 m increments in range for ranges up to 16 km and at 10 m increments in depth for depths from the sea-surface to the bottom. For the 3-D tracker, there were N radials at 1° increments between 0° and 90°.

The normal mode program, ORCA [12], [13], [14] was used for pre-calculating the environment's modal data prior to calculating the range-dependent replica field [9]. ORCA was chosen because it models an elastic bottom and gradients that are usually encountered in sediments [10].

For the inversions presented here, the acoustic fields used in the analysis were approximated in a 2-D calculation along a radial instead of a 3-D calculation. This was accomplished by including a phase correction to the adiabatic normal mode approximation [6] in order to approximate the effect of the horizontal aperture from a tilted array.

Since the VLA was not stationary we wanted to determine the VLA configuration (array position, orientation of the tilt and depth) which would best represent the data for the entire track. For this set of inversions, the mean VLA configuration was determined by weighting matches equally for a distributed set of points throughout the entire track analysed. This was accomplished by using as a cost function the estimated track Signal-to-Noise Ratio (SNR) results from a 2-D Efficient Linear Tracker (ELT). The ELT finds the most statistically significant constant speed linear tracks. Consequently, the ELT analysis was performed separately for data before and after the mid-track change of heading. This ELT operated on a collection of Bartlett ambiguity surfaces ([9], [15] and [16]) which were sampled in time. In this study, we inverted for each parameter separately because of computational constraints. For each inversion, the parameter value that produced the highest estimated track SNR was chosen as the true parameter value.

Previous 2-D tracking results [9] at the mean bearing of the entire track resulted in measured track ranges very near the true track's ranges. When the problem was extended to a 3-D volume [8], but using only basic array geometry information, the track ranges again were within the uncertainty of the GPS track, and the ELT discriminated from the entire 3-D volume the correct region of the true track. However, the track headings were not near the true headings.

3 Inversion Results: Geometric

Inversions were completed for various tidal depth perturbations ranging from -20 to 20 m. As can be seen in Figure 1 there is a peak at about -6 m. At the time of the experiment the bathymetric depth change from the tide was probably less than 1 m. The negative tidal depth perturbation indicated a VLA position which would be further upslope.

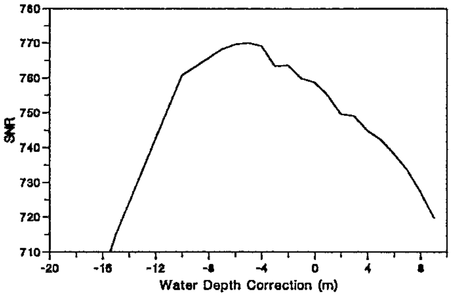

Figure 1: The maximum track SNR (linear scale) at 45 Hz for the 2-D ELT as a function of bathymetric depth.

For this reason we then inverted for a VLA position which is upslope of the GPS position. The VLA position uncertainty of 200 m could represent as much as 7 m difference in bathymetric depth. The results of this inversion, in Figure 2 indicates a VLA position about 200 m upslope. For further inversions, the VLA position was moved upslope 210 m.

In Figure 3, the inversion results for the orientation of the array tilt, assuming an array tilt of 2.5°, indicate a peak SNR estimate at about 35° from the 2-D analysis plane which was the mean bearing of the entire track.

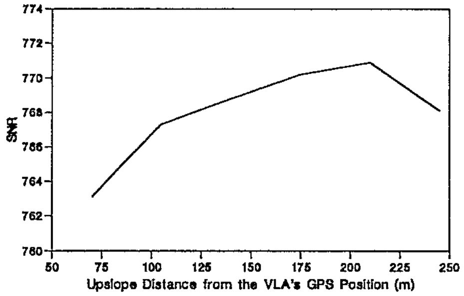

Figure 2: The maximum track SNR (linear scale) at 45 Hz for the 2-D ELT as a function of upslope distance from the VLA GPS measurement.

The array depth inversion results shown in Figure 4 indicate the top hydrophone's depth to be about 83 m.

The highest correlations obtained during the final inversions for high SNR data were about 0.95.

After the geometric inversions were completed, the inverted parameter values were used to update the environmental model. The N × 2-D acoustic field and 3-D track results were then re-calculated. The 45 Hz track results before and after the inversions are shown in Figures 5 and 6 respectively. The 45 Hz track bearings were much closer to the true track bearings for both the near and far range tracks than for the previous results. The low SNR (72 Hz) track results (not shown) also improved with the updated VLA geometry. For both frequencies, the highest track SNR occurred within 10 m of the true source depth. Environmental mismatch [7], the adiabatic approximation and the presence of coloured noise may be responsible for the remaining discrepancy.

4 Conclusions

Track SNR estimates from a 2-D Efficient Linear Tracker (ELT) were used as the cost function in an inversion for the geometry of the Vertical Line Array (VLA). The updated VLA configuration was then used to determine whether the 3-D track from a 3-D ELT improved. The estimated track positions and their estimated track SNRs did improve for both the low and high SNR data. This indicates that a 2-D ELT can be employed for inversions in a 3-D environment to improve environmental model estimates. Mismatch in

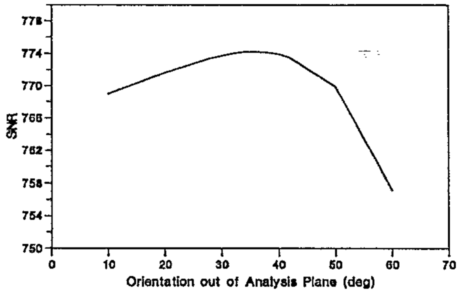

Figure 3: The maximum track SNR (linear scale) at 45 Hz for the 2-D ELT as a function of the orientation of the array tilt relative to the plane of analysis.

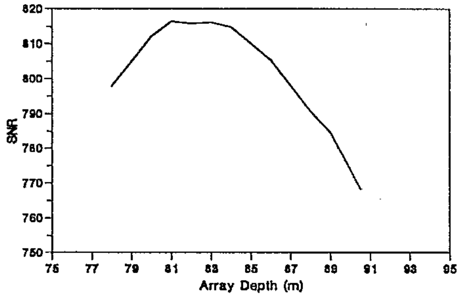

Figure 4: The maximum track SNR (linear scale) at 45 Hz for the 2-D ELT as a function of array depth from the sea surface.

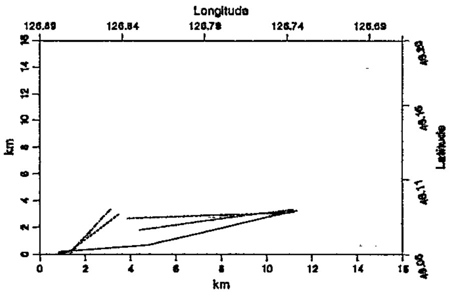

Figure 5: The GPS track (solid) and the top 2 track (dashed, dotted) estimates at 45 Hz before the geometric inversions, are shown within the search area.

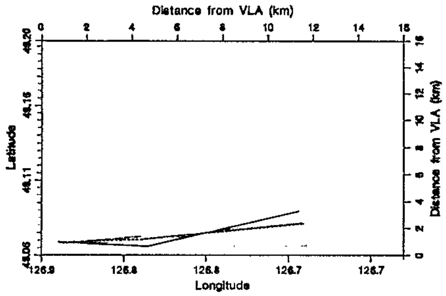

Figure 6: The GPS track (solid) and the top 2 track (dashed, dotted) estimates at 45 Hz after the geometric inversions, are shown within the search area.

bottom geo-acoustic parameters, the adiabatic approximation and the presence of coloured noise are probably responsible for the remaining discrepancy between the true track and the ELT track estimates. The first stage in future work will be devoted to improving the 3-D track results by inverting for the environment's geo-acoustic parameters.

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