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Vertical Array Passive Geo-Acoustic Inversion in Range-Dependent Environments

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ABSTRACT

Antisubmarine Warfare (ASW) is often conducted in shallow-water, where seabed geophysical properties are complicated, and often unknown. In the absence of good seabed characterization, tactical planning is seldom optimal or efficient. Survey techniques for geo-acoustic bottom characteristics are expensive and time consuming. The U.S. Navy has investigated several inversion techniques to characterize seabed sediments, most of which use an active sonar approach that is limited to areas near the receiver. Passive techniques offer the potential to remain covert and greatly extend the area of seabed characterization. This paper describes a new approach, called Passive Geo-Acoustic Inversion Techniques (PGAIT) that uses coherent and incoherent matched-field processing on signals from ships of opportunity for geo-acoustic characterization. There is no need to know the source spectrum. Broadband and temporal averaging techniques are used to reduce ambiguities and to increase the output Signal-to-Noise Ratio (SNR). The algorithms are robust to environmental model mismatch and usually produce an output with at least 10 dB SNR, which is sufficient to identify sediment types. The performance of PGAIT is demonstrated at frequencies between 30 and 50 Hz in several sediment conditions, ranging from very soft to very hard. The results show that: 1) the vertical aperture should contain at least 3 hydrophones per wavelength to ensure high quality inversions; 2) coherent (phase-only) matched-field processing outperforms standard intensity processing by about 2 dB in good input SNR conditions; and 3) incorrect assumptions about the assumed sound-speed profile (*e.g.,* a bias or incorrect mixed-layer-depth) do not significantly affect the inversion results.

INTRODUCTION

The US Navy is able to dominate any “blue-water” area of strategic importance. Such battlespace dominance is not so readily achieved in littoral regions. The number of different environmental factors that impact Naval operations markedly increases in the littoral, as does their magnitude and rate of change in space and time. The complexity and dynamics of the littoral zone are especially challenging with respect to both mission planning and performance of acoustic sensors. PGAIT was conceived as a solution to this important near-shore ocean monitoring problem. A notional PGAIT sensor suite would include a string of vertical hydrophones to monitor acoustic signatures from passing ships and thermistors to observe temperatures.

The value of such a buoy system can be judged by the impact of the data collected on improving tactical sensor performance. For example, if an area is assumed to have “average” water conditions, from historical databases, and typical silty-sand sediments, then “average” detection ranges will be computed. If actual water conditions are warmer and if the sediments are softer than assumed, then the extra downward refraction and attenuation in the soft sediments could lower the actual detection range by at least an order of magnitude. The environmental variability can be large and therefore, the potential value of PGAIT can be significant.

PGAIT CONCEPT

PGAIT uses signals from ships of opportunity to simultaneously estimate ship range, bottom depth, and sediment geoacoustic properties. Typical ship spectra are strongest in the 30-100 Hz band and contain broadband noise generated by flow, cavitation, etc., superimposed with multiple tonals generated by machinery. This first analysis concentrates on the 30-50 Hz band.

The estimation process requires several reasonable assumptions. First, each ship has constant velocity and source level during the processing period (several tens of minutes). Second, the hydrophone array is straight and vertical or the hydrophone positions can be measured. Third, the general bearing of the ship is known to within about +/-20 deg by cross-processing pairs of buoys. Fourth, the local geoacoustic properties are homogeneous within a few kilometers of the sensors. Ultimately all signatures are processed to produce new geoacoustic estimates or reduce uncertainty in previous estimates, but in a range-ordered sequence, which overcomes errors in standard geoacoustic inversion processing.

Matched correlation processing is performed between the received field and predictions for all possible ship ranges and geoacoustic types obtained from an acoustic model. The different geoacoustic models are based on sediment types from hard and reflective (coarse sand) to soft and absorbant (silty-clay). The sediment types are defined by their mean grain-size, in ‘phi units,’ where phi = -$\log_2$[grain size in mm]. The phi values for coarse sand and silty-clay are 1 and 8.5, respectively.

Fig. 1 shows the effects that three different sediment types have on low-frequency (40 Hz) acoustic propagation. The colors represent Transmission Loss (TL) from 60 dB (white) to 85 dB (blue). The vertical scale is depth, showing the full 200-m water column and the upper 100 m of sediments. (A 500-m thick sediment layer was used in the model calculations.) The horizontal scale is range from 0 to 10 km. The source is located at 7-m depth to simulate a large surface ship. The environment is shallow-water with a flat bottom at 200-m depth and a summer, downward-refracting water sound-speed profile that forces a significant amount of sound penetration into the bottom. The three images illustrate how the softer bottoms absorb significantly more energy than the harder bottoms. The TL in the water is much less over a hard (coarse sand) sediment than it is for a soft (silty clay) sediment.

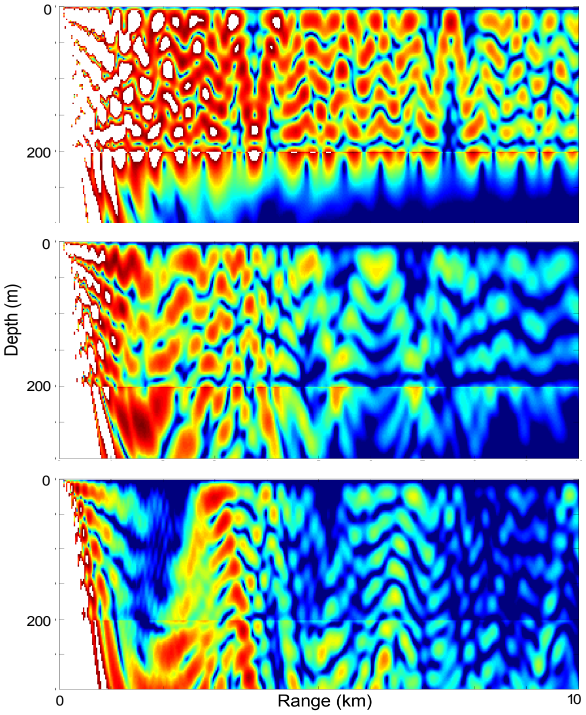

Figure 1. TL at 40 Hz in range-independent environment with 200-m water depth; fine sand (upper), silt (middle), and silty clay (lower).

Geoacoustic property estimation begins when a PGAIT correlation function indicates that a ship is within a close range, wherein we can assume homogeneous sediment properties. We created several realistic environments to evaluate the processing algorithms. We assume that a vertical array with 72 hydrophones spaced 2m apart from 8-150m in depth is deployed in 200-m water depth. We assume that a ship is passing 4 km from the array. We choose a set of frequencies from the ship spectrum centered around 40 Hz to analyze. Then, estimated bathymetry and measured temperature profiles are used to predict acoustic fields from a sequence of sources placed at ranges from 0 to 20 km, for multiple frequencies, and for each sediment type. For each frequency, we correlate the received signal (from the vertical array) with range-independent model predictions at each range, for each sediment type, using several different correlation techniques. Then we incoherently average the correlograms over frequency to reduce ambiguities. The highest peak of the averaged correlations indicates which sediment type and range best match the received signal.

We quantified the correlogram results in terms of their output Peak-to-Background Ratios (PBR), defined as the highest peak value minus the mean background level divided by the standard deviation of the background. We expect that PBR should be greater than 5 dB in order to have high quality estimates of phi and range. We hypothesized that bandwidth averaging and coherent phase correlation techniques would both be needed to significantly reduce ambiguities and improve our capability to correctly estimate phi and range.

Fig. 2 shows a comparison between PBR vs. bandwidth for both incoherent TL (lower curve) and coherent phase (upper curve) correlation processing in a range-independent, phi=4.5 (silty-sand) environment. The correlations between the received signals for each sediment type and the corresponding model fields at the true range of 4 km are averaged to produce the TL and phase curves shown. For all bandwidths, the phase correlations produce PBR’s at least 2 dB higher than the PBR’s for TL correlations. The narrow peaks associated with phase correlations may account for this improvement, which occurs because the phase of the received signal changes more rapidly with range than does amplitude.

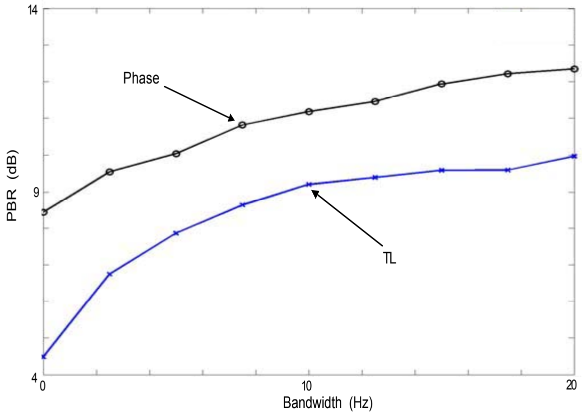

Figure 2. PBR vs bandwidth for TL and phase correlations.

The number of hydrophones required to achieve adequate inversion performance is an important consideration with respect to cost and deployment for a practical system. In this work we started with 72 hydrophones covering about 3/4 of the water column, from 8 to 150-m depth. We then reduced the number of hydrophones, while maintaining an equal spacing and still spanning 142 m in the water column, and recomputed the PBR for both correlators (TL and phase) in the phi=4.5 environment with full 9-frequency bandwidth averaging. The results are shown in Fig. 3.

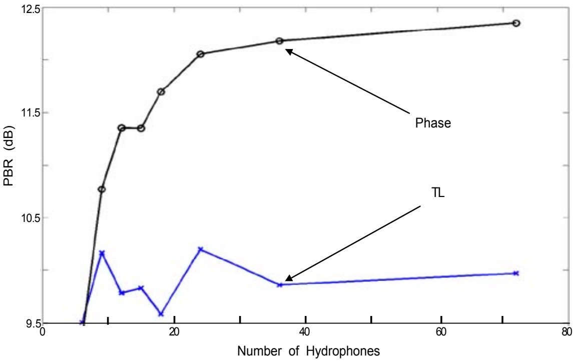

Figure 3. PBR vs number of hydrophones for TL and phase correlations.

For TL processing, the PBR remains at about 10 dB for any number of hydrophones above 10. For phase processing, PBR increases dramatically from 9.5 to 12.1 dB when the number of hydrophones increases from 6 to 24. With additional hydrophones, PBR increases slowly. A good compromise seems to be at about 15 hydrophones where PBR = 11.4 dB. The fully packed case with 72 vertical hydrophones at 2-m spacing provided about 19 samples per wavelength at 40 Hz, which is clearly overkill. The sparse case, with 15 hydrophones at 10-m spacing, provides about 4 samples per wavelength, which seems reasonable. Assuming that these results extend to other environments, PGAIT will not require an excessive number of hydrophones to produce satisfactory inversion results. Note that with 9-frequency averaging, the 2-dB advantage that phase processing has over TL remains for all significant numbers of hydrophones.

ERROR ANALYSIS

In practice, the water sound-speed profile will not be known exactly. Therefore, we performed an error analysis by creating a mismatch between the assumed sound-speed environment and the real environment so that an error would be introduced into the correlation process. In this section, the sound-speed errors will not be accounted for and thus they will degrade the correlations.

The summer sound-speed profile is shown in Fig. 4 (red curve), along with others that were used to describe a range-dependent sound-speed environment to test robustness against mismatch. The insert shows the upper 25 m of the profiles.

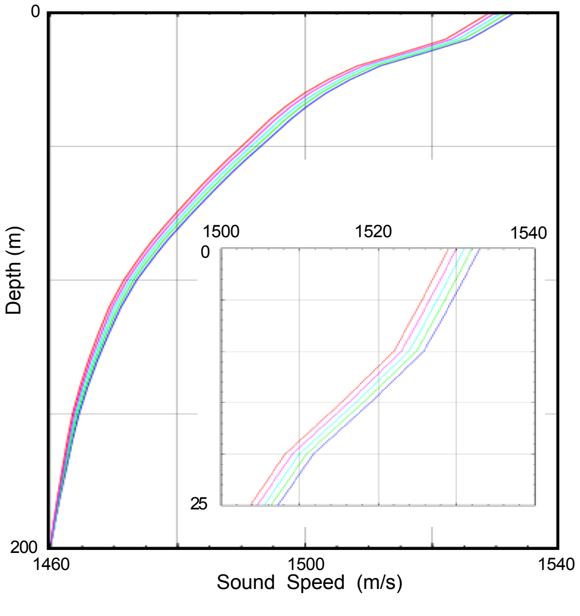

Figure 4. Range-dependent sound speed profiles.

The spread in sound speeds was determined by examining historical variability. We determined that in a typical shallow-water area the standard deviation of sound speed was about 4 m/s at the sea surface and negligible at 200-m depth. We assumed that the original profile was correct at the buoy location and that it changed gradually out to a distance of 4 km where we placed a passing ship over a phi=4.5 sediment. We perturbed the surface sound speed by 1 m/s at 1 km, by 2 m/s at 2 km, by 3 m/s at 3 km, and by 4 m/s at 4 km range. We used proportionally less change as a function of depth. We made acoustic calculations over all possible fixed sediment types with a range-independent (false assumption) and then with a range-dependent (real assumption) about sound-speed profiles and performed cross-correlations between the two sets. Since we have already decided that only about 15 hydrophones, spanning 8 to 150-m depths, are needed to achieve a good result in an error-free (no mismatch) environment, we decided to perform the error analysis with this reduced set of hydrophones.

The range-dependent, sound-speed mismatch results for 15 hydrophones, using the phase correlation approach, are given in Figure 5 for two “true” sediment cases; phi=3 on the left and phi=7 on the right. The range interval shown is from 2 to 6 km from the simulated PGAIT array, which in this figure is labelled SEALOG. The degraded peak is clearly seen with the correct sediment type estimation (phi=3 and 7) at the correct range (4 km) with acceptable PBRs of 8.3 and 8.8 dB, respectively. We consider this to be a very good result because with thermistors on the buoy to eliminate any initial temperature bias and a large 4 m/s sound speed error at a 4 km range, we are able to correctly characterize the sediment and ship range without ambiguity. We expect real sound-speed mismatches at 4 km range to be much less than the 4 m/s used here. This result is significant because experimental applications of matched-field processing in the real world usually fail because a) mismatch errors are not accounted for properly and b) the goal of characterizing multi-layer environmental detail is too ambitious. Our short-range, broadband, phase correlation approach for coarse property characterization is robust to expected unknowns and natural uncertainties in the real world.

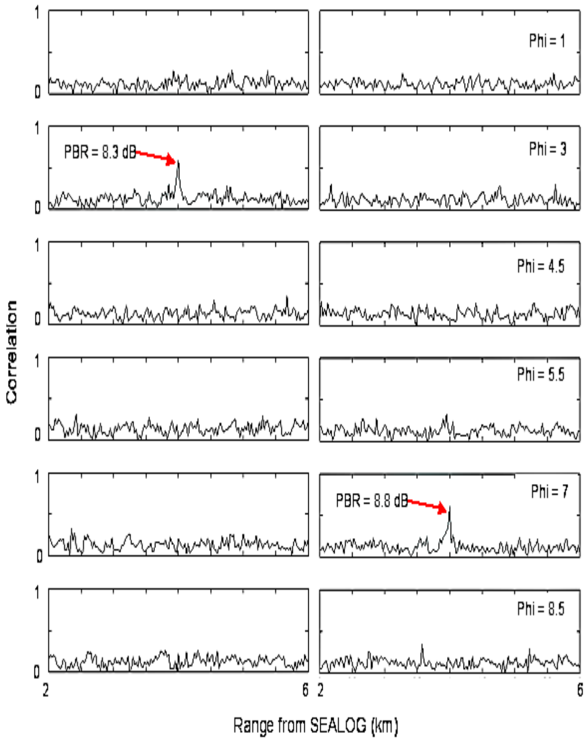

Figure 5. Water sound-speed mismatch results.

SUMMARY

We have shown the potential for geo-acoustic property estimation using passing ships of opportunity and new matched-phase, broadband correlation techniques. The passive, low frequency acoustic approach, enhanced by local temperature measurements has been shown to provide accurate estimates of sediment type. The novel aspect of identifying and then processing only nearby ships in the initial stages is a key to success, because it allows a set of range-independent assumptions to be used. Expansion to range-dependent property estimation at longer ranges would be straightforward, once the confidence on nearby geo-acoustic properties is sufficiently high.

In the correlation / inversion analysis, we have shown a detailed analysis of the use of a single vertical array. Multiple arrays in a given area would result in both more accurate estimates of geo-acoustic parameters as well as estimates over a larger area. Our initial expectation is that a single array at a 200-m water depth location would be capable of sediment characterization to about 15-20-km range and therefore cover about 1000 km^2. Once the sediments are correctly characterized, the array would then be able to monitor and characterize the 3-D sound-speed field out to the same ranges with high accuracy, and beyond with reduced accuracy.

The error analysis showed that an unknown, range-dependent water sound-speed field, with a one standard deviation error at 4-km range would not significantly degrade the correlation analysis and that the correct sediment type and ship range could still be estimated with a peak-to-background ratio as low as 8.3 dB.

ACKNOWLEDGEMENT

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