Contact Depth Localization- Sensitivity to Environmental Variability

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***Abstract*-- A contact depth recognition technique has been developed which uses the multipath structure of a point target echo and hence the channel structure as a discriminator. The technique uses a template matching approach of predicted multipath structure. Multipath structure is predicted using the Comprehensive Acoustic Sonar Simulator (CASS) model. Inputs to the model, such as sound speed profile, bottom bathymetry and boundary reflection coefficients are modeled using the variability observed in real world environments. This paper addresses the sensitivity of contact depth localization to environmental uncertainty. A method to parameterize environmental uncertainty has been developed and it is used to derive the statistical characterization of the performance of the depth estimation algorithm. Robust depth localization performance is demonstrated for oceanographic variability scales consistent with real world operating environments.**

I. INTRODUCTION

The subject of this paper is the development and evaluation of a contact depth localization technique which uses a template matching or pattern recognition approach applied to the contact echo response received on an active sonar system. The method compares modeled target echo responses with measurements to classify a contact as in the water column (volume target) or at/near the bottom (bottom clutter).

The template matching approach evaluated in the present work is considered over more rigorous approaches (such as generalized matched field) due to its simplicity and natural extension to pattern recognition techniques. It is well known that matched field techniques are generally sensitive to environmental uncertainty. The purpose of the present study is to determine if the template matching technique can offer reliable depth localization under environmental uncertainty.

With the advent of high speed computing architectures on board Navy tactical platforms, contact impulse response templates for a large set of depth/range bins can be generated in near real-time using numerical modeling such as is available from the Computational Acoustic Sonar Simulator (CASS). These templates in turn can be compared to multipath echo responses from high SNR (>15 dB) targets. Resolving multipath echo structures from small mine-like objects requires a temporal resolution on the order of a few milliseconds. In practice, this 'highlight structure' can be resolved with transmit bandwidths on the order of a few hundred Hertz and through matched filter processing of the received target echo.

The feasibility of the contact depth localization algorithm is examined by evaluating its nominal performance in 2 real world operating environments defined by their sound speed profiles, bottom loss, and bottom depth; and assessing its performance under uncertain information in these environmental parameters. The environments selected for this study are the Korea Straits, and Straits of Hormuz.

II. APPROACH

The template matching approach is used to make the binary decision of whether a target echo emanates from within the water column (e.g. moored, mine-like object) or from the bottom (e.g. bottom clutter) by comparing observed versus modeled target echo responses. Contact impulse response modeling is done using the range-dependent eigenray outputs of CASS to predict the echo response as a function of range, depth and sound speed profile. Echo responses were typically generated on a 2 m depth grid. The technique is particularly well suited for small object detection because target echo temporal extent is relatively small, and nearly all of the echo response can be modeled by multipath propagation to/from the target of interest. For this reason, a point reflector target is assumed.

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The contact depth estimation algorithm uses modeling parameters (frequency, system/sensor parameters, sound speed profile, bottom loss, bottom depth, wind speed, and waveform) to predict the echo responses for simulated contacts on a uniform grid of ranges and depths and across a range of sound speed profiles representative of the given environment. Given that a contact is detected at some range, the echo measurement of the observed received data (observed) is compared with the predicted echo response templates for simulated contacts near the measured range. The contact depth of the predicted echo response that matches most closely to the received echo measurement, as determined by the closest least squares fit, is the depth estimate of the detected contact. Figure 1 illustrates the algorithm concept.

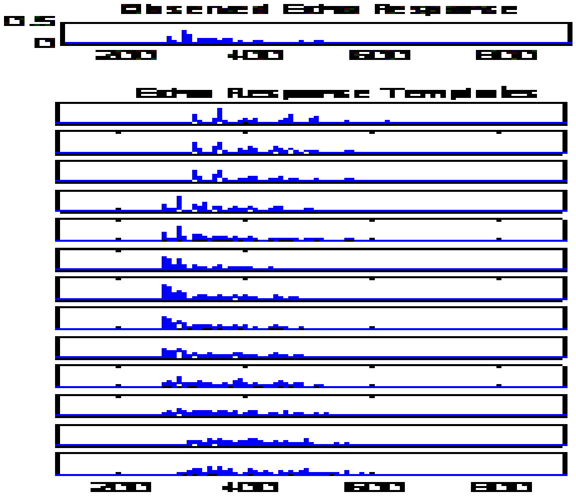

Figure 1. Impulse response template matching technique. Observed echo response is compared to a set of templates using a nearest neighbor (least squares) approach.

An in-volume target is declared for a best match to a template that is not within 10 meters of the bottom, and a bottom target is declared otherwise.

To assess the sensitivity to environmental uncertainty, observed echo responses were simulated for cases with imperfect knowledge of the environment. Specifically, bottom depth was allowed to vary by up to 10%, and sound speed profiles were allowed to vary consistent with real world operating environments as described below. Echo response from these ‘uncertain environments’ were then compared to the templates using the described method.

III. DESCRIPTIONS OF ENVIRONMENTS AND ENVIRONMENTAL VARIABILITY

To evaluate the performance of the depth discrimination algorithm in the presence of oceanographic variability, two operating environments were considered. These were (1) the Korean Straits and (2) the Straits of Hormuz, both during summer conditions. These operating areas were selected for both their operational significance as well as for the acoustically challenging (e.g. strong downward refraction) characteristics.

Historic water column profile data for the two environments were acquired from the National Oceanographic Data Center (NODC) archives (http://www.nodc.noaa.gov). Regional profiles for the two operating areas were sorted by date, time and location to yield contiguous time series of water column profiles (i.e. XBTs or CTDs) collected on the smallest available spatial and temporal scales. In this way, the impact of time-late XBTs on algorithm performance could be simulated and evaluated. A short description of the two operating environments as well as the observed variability in the selected profile data are discussed below.

A. Korea Straits Operating Environment

The Korea Straits has been characterized as an area of extreme oceanographic variability attributed primarily to its geographic location and influences from both cold and warm currents (Carey et al. 2002). Warmer, Kuroshio Current waters are advected into the region via the Tsushima Warm Current from the southwest. These waters in turn mix with the relatively cold waters of the Korean peninsula, which are fed from the Yellow sea. Bucca et al (1997) have measured the vertical temperature field in this area and these results have shown strong variability at the thermocline region modulated by internal waves processes, tidal oscillations and inter-fingering of frontal water masses. Well defined frontal boundaries were observed via CTD measurement.

The NODC profile data selected for this environment were 11 successive CTD casts from June of 1990 taken over a 15 hour period centered approximately 45 nautical miles south of the South Korean Coast. The location of these profiles, over-layed on bathymetric contours, is shown in figure 2.

Historically, cooler South Korean Coastal waters extend into the northern part of this area, while the southern area includes appreciable mixing from the warm Tsushima Current waters. NODC temperature, salinity and converted sound speed profiles for this area are shown in figure 3. Conversion to sound speed was done using the Del Grosso equation (Del Grosso, 1974). These profiles clearly show that temperature variability in the area is the dominant source for sound speed profile variability.

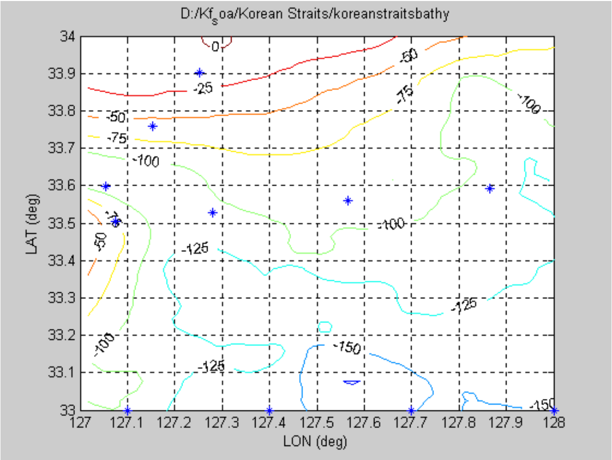

Figure 2. Geographic location of profile data used for Korean Straits environment (bathymetric contours in meters).

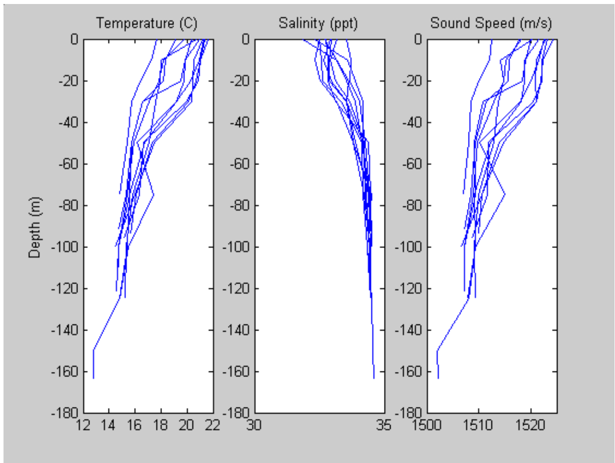

Figure 3. Temperature, salinity and derived sound speed profiles for Korean Straits environment.

Sound speed profile variability for this environment was quantified by means of a simple Euclidean distance metric for each profile compared to the first. This was done in (1) sound speed space and (2) sound speed gradient space as shown in figure 4. Because the profiles were of varying length, they were all truncated to 75 m and 6 points total in order to extract a meaningful distance metric.

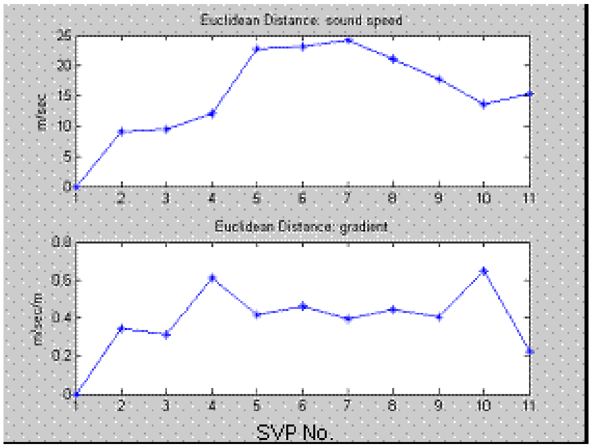

Figure 4. Euclidean distance metric for Korea Straits profiles. A measure of dissimilarity between profiles.

B. Straits of Hormuz Environment

The Straits of Hormuz are another operationally significant area in which local oceanography effects create significant features in the water column profiles. In general, this environment consists of warm, saline water and strong gradients due circulation between the Persian Gulf and the Gulf of Oman.

Deep, saline outflow from the Straits into the Gulf of Oman have been reported by Abdelrahman et al (1995) and Abdelrahman (1998). This water is in turn replaced by surface inflow along the Iranian coast, which becomes more saline and dense (due to evaporation) and sinks. Wind forcing and wind variability are significant drivers for circulation in this area.

The profiles selected from the NODC database were 10 contiguous XBT casts, occurring in July of 1993. These profiles were converted to sound speed using a single salinity profile from the same area and time. The location of the XBTs is shown in figure 5 in an area on the western side of the Straits in roughly 60 meters of water. The temperature, salinity and derived sound speed profiles are shown in figure 6. The vertical stratification in temperature and salinity are consistent with the ocean circulation patterns of the area.

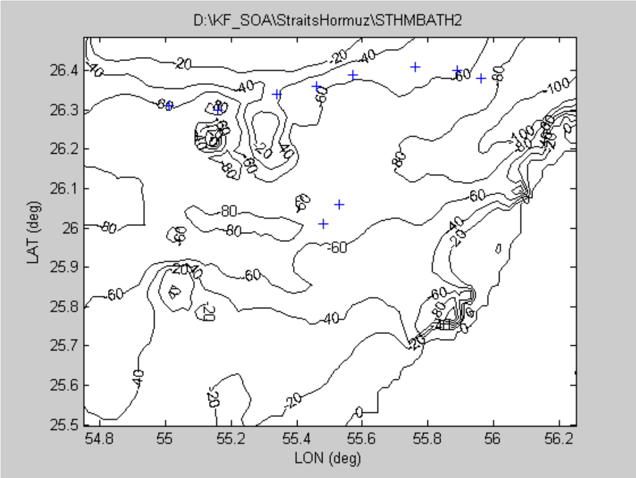

Figure 5. XBT locations in Straits of Hormuz (bathymetric contours in meters).

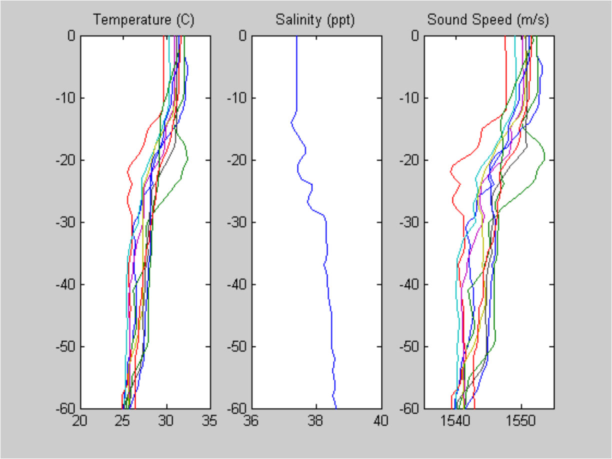

Figure 6. Temperature, salinity and derived sound speed profiles for Straits of Hormuz environment.

Figure 7 shows the Euclidean distance metrics for each sound speed profile from the Straits of Hormuz data set, referenced to profile number 1. The top panel shows normalized distance in sound speed space, and the lower panel shows normalized distance in gradient space.

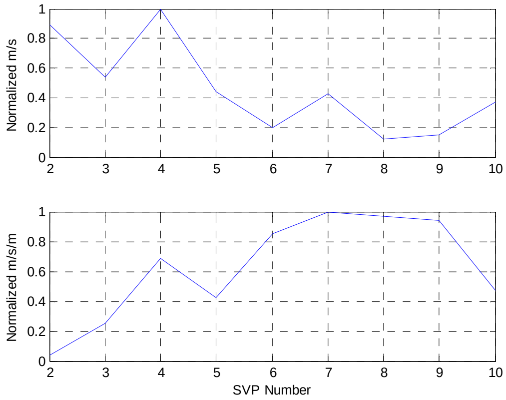

Figure 7. Normalized distance metrics for Straits of Hormuz sound speed profiles (top: sound speed, bottom: gradient).

IV. RESULTS

A. Korea Straits Results

Target depth classification results are shown in figure 8 as a function of sound speed profile used and at 3 ranges (2000, 4000 and 6000 yards). SVP1 is the matched environment case, in which hypothesized and observed sound speed profiles are identical and therefore 100% correct classification results. SVPs 2 through 10 represent the perturbations in sound speed profile from the matched case. 'AVG' represents the average result across all sound speed profiles.

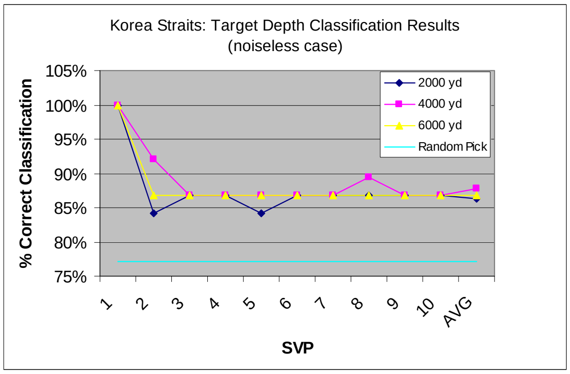

Figure 8. Target depth classification results simulated using CASS for Korea Straits environment.

These results indicate correct classification rates of between 85 and 90% for this noiseless case, as compared to 77% for a random pick. Further, the results are relatively insensitive to sound speed profile variability. As a result, there is no apparent correlation between these performance results and the SVP dissimilarity metrics of figure 4. This implies that for the range of profile variability observed (up to 25 m/sec mean square distance in sound speed and 0.7 m/s/m mean square distance in gradient space), there is little to no sensitivity on algorithm performance.

B. Straits of Hormuz Results

Results from the Straits of Hormuz sound speed profiles are shown in figure 9. Here again, profile 1 is the matched case (perfect knowledge of the environment) and results from profiles 2 through 10 are the prior contiguous (e.g. time late) sound speed profiles. Contrasting these results with those from the Korea Straits shown earlier, we find a much stronger dependency between classification performance and environment (SVP). We also note more variability in performance at the three range bins modeled.

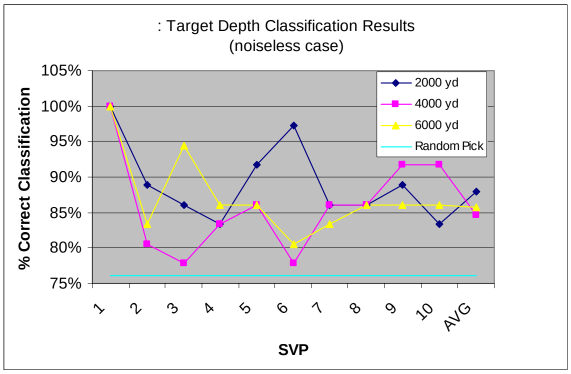

Figure 9. Target depth classification results Straits of Hormuz environmental variability.

For the 2000 yard range case, best classification performance is found using SVP6 as the mismatched profile. However, at both 4000 and 6000 yards, SVP6 yields poor classification performance; marginally better than the random pick. Referring back to figure 7, we find that SVP6 was relatively 'similar' in sound speed space to the matched case (SVP1), however in gradient space, it was one of the most dissimilar profiles.

While strong dependencies exist in the Straits of Hormuz study with respect to classification performance and sound speed profile, there is no distinguishable trend or correlation between algorithm performance and the profile similarity metrics selected for the current study. This suggests that the dissimilarity metrics chosen for the profiles may not be capturing the important differences between environments.

V. DISCUSSION

The results of this environmental sensitivity study suggest that a complex relationship exists between algorithm performance and sound speed profile variability. The range of environments modeled and the metrics used to capture environmental variability do not adequately describe the algorithm performance bounds. This is due to the nature of the binary classifier, which strips much of the environmental information by virtue of its nearest neighbor assignment algorithm. In particular, the algorithm assigns in-volume target if the nearest neighbor is any of the templates from the upper water column, and bottom target otherwise. Thus structural differences in impulse responses from within the same class (in-volume or bottom) are not significant.

For the Korea Straits environment, the algorithm performance is reasonably robust across the sound speed profiles. Performance is generally in the vicinity of 85% correct classification, independent of profile used. We conclude from this that over the range of variability sampled with these profiles, the depth estimation algorithm is relatively insensitive to profile uncertainty. We do not learn from these results however, what degree of profile variability causes algorithm performance degradation.

Unlike the Korea Straits results, the Straits of Hormuz environment shows strong sensitivity between sound speed profile and algorithm performance, as shown in figure 9. However, the dissimilarity metrics used to describe the environments do not correlate with classification performance. This unanticipated result is at present unexplained and requires further analysis. The fact that algorithm performance is not consistent across the 3 range bins selected suggests that the lack of correlation between performance and profile dissimilarity may be at least partially due to the non-monotonic fall off of signal excess with range, and the variability of this function across the profiles selected. Further analysis will seek to quantify this.

VI. CONCLUSIONS

The environmental sensitivity of a contact depth estimation algorithm suitable for small object avoidance has been evaluated. The algorithm, based on a multipath template matching approach, was conceived to offer robust performance across uncertainty in the environment. Algorithm performance was shown to be relatively insensitive to environment in the case of Korea Straits operating area. For this environment correct classification results were typically in the 85 to 90% range. This result is contrasted strongly with the Straits of Hormuz results, in which a strong dependency was observed between algorithm performance and sound speed profile. Although this dependency was observed in the performance results, there was no observed correlation to the environment dissimilarity metrics used. Further study is required to quantify the relationship between algorithm performance and environmental uncertainty.

The result that depth localization performance from the algorithm did not significantly degrade across the range of sound speed profiles sampled provides some encouragement for more general matched field depth estimation techniques. In particular, discussions with J.L.Krolik have indicated that an approach to matched field depth localization that uses multiple pings is relatively insensitive to bottom depth uncertainty. If the sound speed insensitivity observed in the current study can be extended to their work, there is hope for robust depth localization for small object avoidance.

Confirmation of this assertion will require further study.

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