Sonar coverage mapping

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Abstract--**The objective is to indicate on a map the level of coverage achieved in a minehunting operation. The accuracy of the map is a function of many variables, including target strength statistics, propagation loss, background reverberation and noise, and navigation errors. With careful control of errors and using real-time measurements of reverberation and sound speed profiles, it is possible to achieve the necessary accuracy, and produce meaningful maps of coverage levels.**

Index Terms-- **sonar performance, coverage map.**

INTRODUCTION

IN underwater minehunting, the desired result is to have detected and identified all mines in a given area. Unfortunately, at the current state-of-the-art, it is often not possible to achieve this result with absolute certainty. In practice, the achievable result is a percentage level of coverage. For example, a level of 99% means that, for every 100 mines present, 99 are expected to be detected, and one missed. Search procedures can be designed to meet a prescribed level of coverage based on probabilistic theories, but they are heavily dependent on environmental acoustic models. The clearance level is currently computed from bottom roughness, clutter density, and lane spacing for a specific threat. Shallow water environments are not well-understood and current acoustic models often inaccurate. One method for overcoming this difficulty is to replace the most inaccurate model predictions with measurements. Specifically, the total noise and reverberation level (N) experienced by the mine-hunting sonar should be measured. This is a low-cost solution since it does not require additional underwater hardware, and it makes use of data from the existing sonar, which would otherwise be discarded. The only requirement is a calibrated sonar capable of taking accurate acoustic level measurements, and sound velocity profile (SVP) information. The noise level is subtracted from the expected signal level (S) to give the total signal-to-noise ratio (SNR). The expected signal level is computed from known target signal statistics, a measured SVP and the bathymetry of the mission area. The result is an estimate of SNR that accurately tracks the sonar's performance, as a function of bearing and range. This information, combined with the geodetic position and heading of the sonar from an external reference, such as GPS, may be used to map out the area covered by the sonar and the coverage level achieved. The resulting coverage map may be used to track the progress of a minehunting mission in real-time, both aboard the minehunter and at the command center. The data may also be used for post-mission analysis.

THEORY

Detection performance may be quantified in terms of the SNR, in the standard sonar equation.

$$\mathrm{SNR} = \mathrm{S} - \mathrm{N} \tag{1}$$

where S and N are the signal and total noise levels, in dB re 1 μPa. The signal is the echo from the expected target. The noise includes all kinds of interference, including ambient noise, self-noise, and reverberation. The signal level is usually expressed as,

$$\mathrm{S} = \mathrm{SL} + \mathrm{TS} - 2\mathrm{TL} \tag{2}$$

where TS is the representative target strength of the expected target and 2TL is the two-way propagation loss, in dB, from sonar to target and back; SL is source level, in dB re 1 μPa at 1m. In practice, the target strength is aspect dependent, and should be treated as a random process. The transmission loss is primarily a function of the sound path through the water, which is dependent on the sound speed profile. The total noise may be expressed as,

$$\mathrm{N} = 10\log(10^{\mathrm{NA}/10} + 10^{\mathrm{NS}/10} + 10^{\mathrm{RS}/10} + 10^{\mathrm{RB}/10} + 10^{\mathrm{RV}/10}) \tag{3}$$

where NA is the ambient noise level, which varies as a function of sea state, NS is the self-noise of the system; the RX parameters denote reverberation of which there are three components, surface reverberation RS, bottom reverberation RB and volume reverberation RV. The surface reverberation RS includes sound scattered by ripples and waves and the subsurface bubble clouds that breaking waves tend to generate. The bottom reverberation RB includes sound scattered by bottom roughness and other scatterers associated with the bottom such as biological life forms and related structures. The volume reverberation includes fish schools and plankton layers.

ACCURACY

The accuracy with which the above components may be estimated varies widely. Great strides have been made in improving accuracy. The source level SL is exact. It is the

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sound power projected by the sonar and it can be precisely measured. Its error is negligible. The target strength (TS) can be estimated from models, based on shape and size. The accuracy achievable depends on the actual target in question. A simple spherical target with a thick metallic shell can be modeled quite accurately, to within a decibel. For a complicated target, like some of the modern bottom mines, the models are probably accurate to a standard deviation of 6 dB. In practice, it is best to acquire the mine types of interest and measure the target strength as a function of aspect and frequency in a well-controlled environment. The measurements can be accurate to within 1 dB.

The coherent transmission loss (2TL) is a function of the environment. In some areas where the water is known to be well mixed, the spherical spreading model can be used to accurately predict propagation loss. In most practical cases, there will be a non-uniform SVP which has to be measured, in order to accurately compute propagation loss. Historical data measured in the same geographical area has been used in the past but with little success, because there is too much variation about a historical mean profile. The probable standard error is of the order of 10 dB at the longest detection ranges achievable. It is not practical to directly measure 2TL. The usual practice is to compute 2TL from a measured SVP. For the detection ranges that are typically associated with mine-detection, the standard error achievable with a measured SVP, is probably in the region of 3 dB, with a few exceptions. The exceptions are caustics, shadow zones, and the presence of obstruction, such as fish schools, which will be ignored for the purposes of this study. The total error of S is the incoherent sum of the errors in TS and 2TL. The estimated errors are summarized below.

Table I. Standard error (dB) of target signal related components

Quantity	Model	Measurement
TS	6	1
2TL	10	3
S	11.7	3.2

The total noise level N is often more difficult to estimate than the signal S. The ambient noise NA, is the isotropic ambient noise less the sonar array gain. The isotropic noise is well characterized in the deep ocean according to sea-state. In shallow water, deviations from the standard deep water curves of up to 5 dB have been observed [1]. There will be deviations from isotropy. For the same sea state, variations between 5 and 10 dB have been observed [2]. A standard deviation of 6 dB would be a reasonable guess. In a well designed sonar, the self-noise is insignificant, and for this study it will be ignored.

The main problem in littoral waters is the reverberation. It is usually much stronger than the noise, and it varies proportionally with source level. Surface reverberation RS is determined by the source level, array directivity, surface scattering strength and the incoherent propagation loss from sonar to surface and back through a variety of paths. The array directivity is not subject to random errors. There are models that predict surface scattering strength from the wind speed. For the same wind speed, there can be significant variations that are speculated to be due to temperature, salinity, and suspended biological matter [3]. The random variations are of the same order as that of ambient noise. The error in estimating the propagation loss using a historical average SVP would be in the region of 10 dB. With a measured SVP, it would be closer to 3 dB. Taking the lower figure for the propagation loss error, a total incoherent standard error of 6.7 dB is estimated. The bottom reverberation is a combination of source level, array directivity, bottom scattering strength and the incoherent propagation loss from sonar to the bottom and back. The bottom scattering strength is often modeled as a function of bottom type, e.g. gravel, sand, silt, or clay. However, within each type, there are variations that overlap. Historical data show a standard error of about 7 dB [4] within each bottom type. The standard error in propagation loss is similar to that of the surface reverberation, giving a total incoherent standard error of 7.6 dB. Volume reverberation is a combination of source level, array directivity, volume scattering strength and propagation loss. The volume scattering strength is difficult to know in advance. A fish school can present a high value of volume scattering strength. Fish schools have to be treated as a random process. Knowledge of the local fish population is very important. Their presence may be seasonal, such as annual spawning seasons, and diurnal as they follow their sources of food. For this study they will be ignored, and the volume scattering strength will be treated as negligible. The situation is summarized in Table II. Since the noise components are incoherently additive, the standard error of the result is largely dependent on the dominant components. The self-noise component will be ignored because it is never the dominant component. The volume reverberation will be ignored because it is often small compared to the others, and on those occasions when it is dominant it is very difficult to predict; it is an important issue which is beyond the scope of this small study. Therefore, the total standard error must lie between that of ambient noise, at 6 dB, and bottom reverberation, at 7.6 dB. The measurement accuracy issues will be addressed in the next section.

Table II. Standard error (dB) of noise related components

Quantity	Model	Measurement
NA	6	
NS	0	
RS	6.7	
RB	7.6	
RV	-	
N	≥ 6; ≤ 7.6	2

SONAR PERFORMANCE MONITORING

A sonar performance monitoring system (SPMS), that quantifies sonar performance as a function of range and bearing within the sonar sector was demonstrated at the MIREM9 exercise aboard the USS Pioneer in 1999, and aboard the USS Champion in 2000. SPMS uses background noise and reverberation statistics (N) measured directly through the sonar (TTS), and a computed target signal level (S), to produce values of SNR as a function of position within the sonar field of view. Instead of attempting to quantify the components of the noise separately, N was measured directly and in real-time. Since it is a direct measurement, the estimated error is only dependent on the accuracy of the sonar calibration, which typically has a standard error of about 2 dB. The total SNR standard error is the incoherent sum of the errors in S and N, as given by Tables I and II, and summarized in Table III. It is evident that the model predictions are going to have a total standard error of at least 13 dB. For example, at a probability of false alarm of 0.00001, the difference in SNR between a 10% and 99.9% probability of detection is only 7 dB for a non-fluctuating target in Gaussian noise[5]. In this context, an error of 13 dB or more would make it impossible to render meaningful estimates of coverage level. Using measured values, as provided by a system like SPMS, the SNR estimate is expected to have a total standard error in the region of 4 dB. The 10% and 80% levels of detection probability are separated by a 4dB difference in SNR. From 80% to 99% is another 3 dB. A smaller standard error is certainly desirable but this value is close to adequate for distinguishing coarse levels of coverage achieved. Most of the error comes from the coherent transmission loss estimation for target signal estimation. Future improvements are possible using more sophisticated three-dimensional propagation codes instead of the two-dimensional codes currently in use.

Table III. Standard error (dB) of SNR

Quantity	Model	Measurement
S	11.7	3.2
N	$\geq 6;\ \leq\ 7.6$	2
SNR	$\geq 13;\ \leq\ 14$	3.8

SONAR PERFORMANCE MAPPING

Having established that SNR can be quantified at an acceptable level of accuracy, the next step in the process of mapping sonar coverage level is to associate every point in the operating area with the appropriate value of SNR. In this task, there are elements of space and time to consider. The spatial element concerns the accuracy with which a point on a sonar display, and the associated value of SNR, can be projected into a corresponding point in geodetic space. The accuracy is dependent on the navigational aids that are used, such as the global positioning system (GPS) and differential GPS. In general, the spatial coordinate system is a three-dimensional one. In practice, a two-dimensional geodetic coordinate system of latitude and longitude is preferred. While N is measured as a function of azimuth and time, S is computed also for a range of depths reflecting possible moored mine positions. For each resolvable point in latitude and longitude, the minimum value of SNR (MSNR) over a selected range of depths will be retained. The mapping of MSNR is illustrated in Fig. 1, with data collected aboard USS Pioneer. The target to which the values apply and the sonar configuration are omitted.

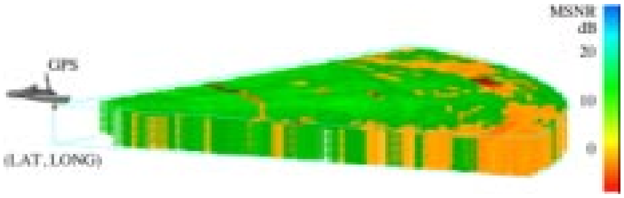

Fig. 1. Illustration of MSNR mapping at each ping

The element of time needs special consideration. A new MSNR value is produced every ping for each geodetic point, but a detection is rarely made on the basis of just one ping. A more realistic indicator of performance is a moving average of MSNR (MAMSNR), over a time window that corresponds to the time it takes for a sonar operator, a computer-aided-detection algorithm, or both, to make a positive detection, at each geodetic point. The final indicator of coverage level is the peak value of the MAMSNR (PMAMSNR) achieved. An example of a coverage map, showing the PMAMSNR, was generated for illustration purposes from data collected aboard USS Champion, as shown in Fig. 2.

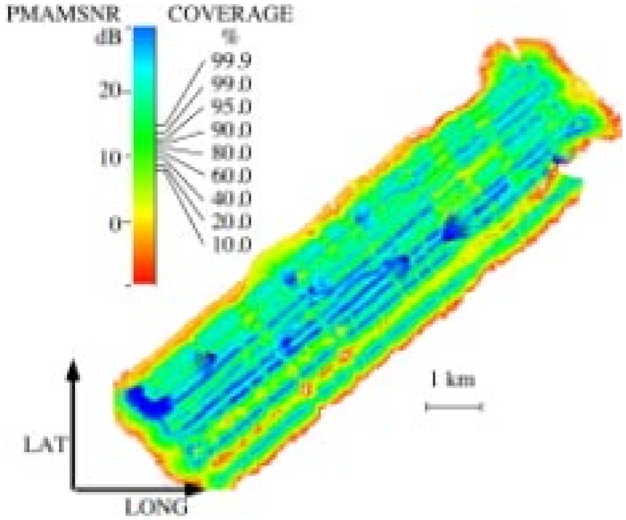

Fig. 2. Illustration of a coverage map

The PMAMSNR was plotted as a function of latitude and longitude. The target characteristics for which the values apply and the sonar configuration are omitted. The illustration only serves to show the qualitative nature of the information that can be obtained. The map shows a grid of tracks that was followed by the sonar to cover the designated area. The color scale shows the PMAMSNR values, which may be converted to corresponding levels of probability of detection (PD), using standard detection theory [5]. The PD can be used to compute the level of coverage. For example, a level of 99% means that, for every 100 mines present, 99 are expected to be detected. The map shows good coverage down the center of each track, of better than 99.9%. On both sides of each track line, the coverage degrades smoothly. There are a few ridge structures running perpendicular to the tracks that present some problem areas. These have been analyzed and they appear to be ridges of high bottom scattering strength that locally depressed the PMAMSNR values. The result is reduced coverage over the ridge structures. Where the ridges intersect the marginal areas between the track lines, gaps in the coverage are indicated. In the larger gaps, the indicated PD values are less than 10%. This is a fictional illustration, and not a reflection of the mine-hunting performance of the ship on which the data was collected.

CONCLUSIONS

The ability to map coverage level during a mine-hunting operation is very desirable. In real-time, it allows the progress of the operation to be monitored and problems to be detected at an early stage. As a post-mission analysis tool, it allows a constructive analysis of the achievements of the operation and coverage gaps. Accuracy of the coverage level is a critical factor. The accuracy allowed by modeling and historical databases alone is not adequate to distinguish the basic levels of coverage. The Sonar Performance Monitoring System (SPMS) can provide the necessary accuracy in measuring the noise component of the SNR equation that would allow meaningful estimates of coverage levels, thus, demonstrating the feasibility of sonar coverage mapping.

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