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Performance assessment of the MUSCLE synthetic aperture sonar

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UW43. Performance Assessment of the MUSCLE Synthetic Aperture Sonar

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Synthetic Aperture Sonar (SAS) systems are quickly becoming fundamental tools for seabed mapping applications, as they provide high resolution imagery independent of range from the sensor, with high area coverage rates. Fundamental in many SAS processing algorithms is the Displaced Phase Center Antenna (DPCA) algorithm, one variant of which uses range-dependent ping-to-ping cross-correlations to help estimate platform movement, which is then used in reconstructing array element locations in order to beam form across the synthetic aperture. SAS image quality can be estimated as a function of signal to noise ratio (SNR), which can be derived from the cross-correlation values obtained in the DPCA processing. This paper investigates the performance of the NATO Undersea Research Centre MUSCLE vehicle, equipped with a 300 kHz interferometric SAS with a 60 kHz bandwidth. Performance assessments are shown for a variety of environmental parameters using data collected during four sea trials. SNR measurements are then compared to the values obtained with the NATO sonar performance prediction model ESPRESSO.

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1 INTRODUCTION

Synthetic aperture sonar (SAS) systems are quickly becoming fundamental tools for seabed mapping applications, as they provide high resolution imagery independent of range from the sensor, with high area coverage rates [1, 2]. Fundamental in many SAS processing algorithms is the displaced phase center antenna (DPCA) algorithm, one variant of which uses range-dependent ping-to-ping correlations to help estimate platform movement. SAS performance, measured in terms of the maximum sonar range guaranteeing quality imaging, can be estimated as a function of these ping-to-ping correlations. This paper investigates the performance of the NATO Undersea Research Centre (NURC) MUSCLE vehicle, equipped with a 300 kHz interferometric SAS with a 60 kHz bandwidth. Performance assessments are presented for different sea trials using real correlation data collected at sea. These real measurements are then compared to values obtained with the NATO sonar performance prediction model Espresso to identify similarities and discrepancies.

The remainder of this paper is organized as follows. Section 2 presents performance measurements obtained during various sea trials. Section 3 introduces the sonar performance prediction model Espresso and conducts a sensitivity analysis for some key input parameters. Section 4 compares the ping-to-ping correlation coefficients measured at sea to the values obtained with the Espresso model. Concluding remarks are made in section 5.

2 SONAR PERFORMANCE MEASUREMENTS

2.1 PING-TO-PING CORRELATION

For this paper, the SAS measure of performance considered is the maximum sonar range to which quality sonar data can be collected. The minimum imaging range is assumed to be fixed at 40 m. When planning mapping or search operations, the knowledge of the maximum imaging range achievable is critical to ensure operational effectiveness. If this range is underestimated in a survey, the same area of seabed is imaged multiple times, decreasing the coverage rate. If this range is overestimated, there will be a lack of quality sonar data for portions of the search area, resulting in an incomplete survey.

The maximum SAS imaging range can be estimated from the ping-to-ping normalized peak correlation computed during the DPCA motion estimation process. The cross-correlation between two consecutive sonar pings, $p_k(t)$ and $p_{k+1}(t)$, is given by $\zeta_{k,k+1}(\tau) = \left\langle p_k(t) p^*_{k+1}(t+\tau) \right\rangle$, where τ is a time shift. The normalized peak correlation ρ is then [2]:

$$\rho = \max_{\tau} \left| \frac{\zeta_{k,k+1}(\tau)}{\sqrt{\zeta_{k,k}(0)\zeta_{k+1,k+1}(0)}} \right| . \tag{1}$$

This normalized correlation ρ is directly proportional to the signal-to-noise (SNR) ratio (in dB) [1]:

$$\text{SNR} = 10\log_{10}\left[\frac{\rho}{1-\rho}\right] , \tag{2}$$

where the SNR is defined as the ratio of the direct bottom reverberation ($\text{BR}_{\text{direct}}$) over the sum of the incoherent background noise and the multipath arrivals ($\text{BR}_{\text{multipath}}$). The incoherent background noise includes the surface reverberation (SR), the volume reverberation (VR) and the noise (N). The SNR, with all variables expressed in linear units, is therefore given by:

$$\text{SNR} = \frac{\text{BR}_{\text{direct}}}{\text{BR}_{\text{multipath}} + \text{SR} + \text{VR} + \text{N}} . \tag{3}$$

Being related, both the correlation coefficients and the SNR can be used to identify the maximum imaging range. For the remainder of this paper, the correlation coefficients are used. By estimating the correlation coefficients as a function of range and setting a threshold under which data is considered to be of insufficient quality, one can estimate the maximum imaging range achievable. As in [3], the imaging quality threshold for this study is set to a minimum correlation coefficient value of 2/3 (corresponding to a SNR threshold of 3 dB).

2.2 MEASUREMENTS AT SEA

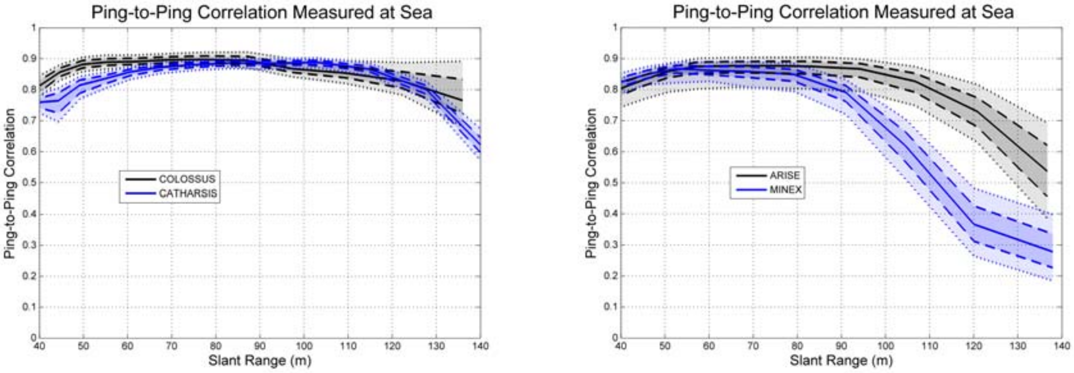
Since 2008, NURC has been conducting experiments and collecting data with the MUSCLE autonomous underwater vehicle (AUV) equipped with an interferometric SAS. The MUSCLE SAS can achieve a resolution of 2.5 cm along track and 1.5 cm across track. The data considered in this study was obtained using two sonar modes, modes 100 and 100c. The common characteristics of these sonar modes are summarized in Table 1. The only difference between the two modes lies in how the sonar receiver is used. The receiver of the MUSCLE SAS is divided into two sections. The upper section has a vertical beamwidth of 5°, while the lower section has a vertical beamwidth of 10° and is oriented a further 4° downwards in addition to the already existing mechanical steer. Mode 100c uses only the lower section of the receiver, while mode 100 uses both sections (with the switch from the lower to the upper section happening at 125 ms).

Parameters	**Mode 100/100c**
Frequency (kHz)	300
Bandwidth (kHz)	60
Source Level (dB)	211.7
Pulse Repetition Interval (ms)	250
Pulse Length (ms)	14
Pulse Type	LPM
Pulse Width (deg)	20
Rx Horizontal Beamwidth (deg)	6
Mechanical Steer (deg)	6
Electronic Steer (deg)	7

Table 1: Sonar mode characteristics.

Four SAS sea trials are of special interest for assessing the performance of the MUSCLE SAS. The representative subsets of ping-to-ping correlation coefficients as a function of range selected from each sea trial are summarized in Figure 1. The observed variability of the correlation coefficients is due in part to the motion of the AUV, the variation of the surface condition and the variation of the local seabed composition. At short ranges, near field effects can also induce variations. This variability is summarized in Figure 1 by using the median (solid line), the 25th and 75th percentiles (dashed lines) and the 9th and 91st percentiles (dotted lines) of each dataset. If the observed distributions were Gaussian, these five curves would be uniformly spaced.

The details of each trial are summarized in Table 2. All four trials were conducted in areas where the seabed was flat and while the sea state was calm. The COLOSSUS and CATHARSIS trials were held in areas where the water depth was relatively deep for high frequency sonar systems. Figure 1(a) shows that the correlation coefficients for COLOSSUS remained above the $\rho = 2/3$ threshold for the entire range considered, reaching a maximum imaging range in excess of 140 m. In the case of the CATHARSIS trial, the median correlation coefficient curve fell below the data quality threshold at a range of approximately 135 m. In contrast, the third sea trial, ARISE, was held in a shallow water area having a maximum water depth of 17 m. Figure 1(b) shows that the median correlation coefficient curve for ARISE fell below the data quality threshold at shorter range of approximately 127 m. This illustrates the impact of the increased multipath contribution in shallow water environment, which reduces the value of the correlation coefficients.



(a) (b)

Figure 1: Correlation coefficients measured at sea during four sea trials. (a) COLOSSUS and CATHARSIS trials; (b) ARISE and MINEX trials.

Characteristics	**COLOSSUS**	**CATHARSIS**	**ARISE**	**MINEX**
Water Depth (m)	47	34	17	17
Sonar Altitude (m)	13	13	11	11
Seabed (approximation)	Sand	Mud	Silt	Silt
Pings Considered	3051	2382	4272	4032
Sonar Mode	100	100	100c	100c

Table 2: Trials summary.

In addition to multipath, significant vehicle motion can also have a negative impact on the quality of the data collected and reduce the value of the correlation coefficients. In particular, large variations in sway and yaw can severely degrade the quality of the sonar coverage [1]. To illustrate this phenomenon, the fourth sea trial chosen was the Italian Navy Mine Hunting Exercise (MINEX) held in the same area as the ARISE sea trial. During this trial, increased currents induced adverse vehicle motion and decreased the maximum imaging range achievable. This phenomenon can be clearly observed in Fig. 1(b), the median correlation coefficient curve for MINEX falling below the $\rho = 2/3$ threshold at only 105 m.

3 SONAR PERFORMANCE MODELING

3.1 ESPRESSO MODEL

When planning seabed mapping operations, sonar performance prediction models can be used to estimate the maximum imaging range achievable. One such model is the Espresso (*E*xten*s*ible

*Pe*rformance and *E*valuation *S*uite for *So*nar) model [4] developed by NURC. It was designed as a minehunting sonar performance prediction tool built to interface with NATO minehunting mission planning and evaluation tools. Espresso uses beam-tracing [5] to model the performance of forward or side-looking sonars. The various model inputs are grouped in four categories: environment, platform, sonar and target. These inputs allow users to replicate specific environmental conditions (such as water depth, windspeed and sound speed profile) and specific sonar system operating parameters (sonar altitude, frequency, bandwidth, etc.). The APL94 sub-models [6] are used for bottom scattering and reflection, as well as for surface scattering and reflection.

A large number of outputs can be obtained with Espresso, including for instance reverberation estimates, target echoes and probabilities of detection. The output of interest in this study is the ping-to-ping correlation coefficients as a function of range (or equivalently, the SNR as a function of range). As any sonar performance model, Espresso has limitations users need to be aware of. First, the seabed is assumed to be flat and homogeneous. Also, sonar motion is not included in the model. For SAS systems, one should therefore consider the outputs of Espresso as upper bounds on the achievable performance as adverse sonar motion potentially degrading this performance is not considered. Finally, one needs to be careful when using high frequencies (such as the MUSCLE SAS 300 kHz frequency) for which the scattering sub-models might not be entirely accurate [6].

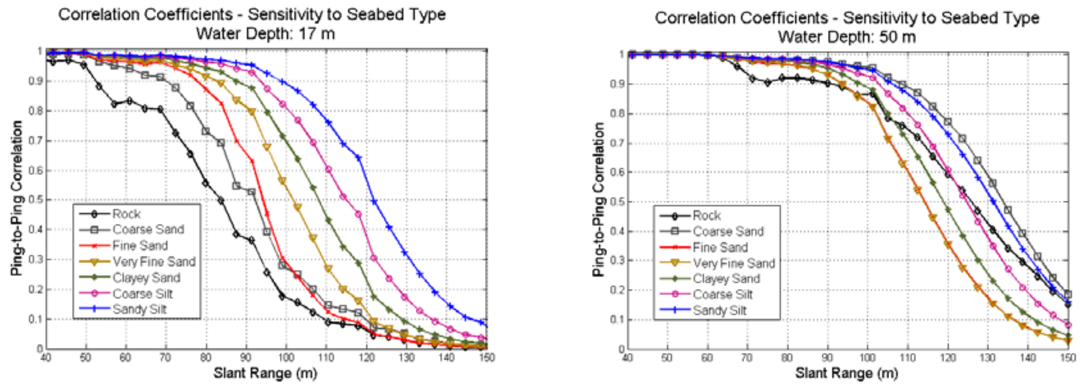
3.2 SENSITIVITY ANALYSIS

Before using Espresso to model correlation coefficient curves, an analysis needs to be conducted to identify how sensitive the modeled results are with respect to variations of the input parameters. If the output is very sensitive to a given input parameter, the estimate of this input parameter needs to be as accurate as possible to obtain relevant modeled results. As correlation coefficient curves are related to the SNR according to equation 2, the key parameters to consider are the ones influencing the variables in equation 3. The volume reverberation was found to have a negligible effect compared to the bottom reverberation, the surface reverberation and the noise level, so it was excluded from our sensitivity analysis. This analysis was conducted using the MUSCLE SAS parameters listed in Table 1, mode 100c and an assumed constant sound speed profile with $c = 1500$ m/s.

The key parameter influencing bottom reverberation (direct and multipath) was identified as the seabed characterization. The sensitivity analysis results with respect to the seabed type are shown in figure 2. Two water depths were considered: a shallow water environment of 17 m with a sonar altitude of 11 m, and a deep water environment of 50 m with a sonar altitude of 13 m. In the shallow water case, it can be seen that the correlation curves are highly sensitive to the seabed type. Results for the deep water case show a reduced sensitivity. This is to be expected, the multipath contribution being lower for deeper waters.

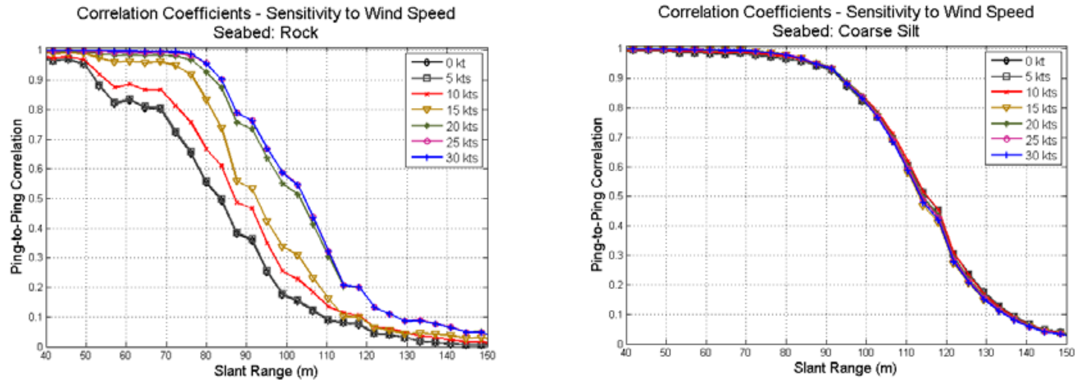
Another key input parameter was determined to be the wind speed. This input influences the level of surface reverberation [7] and, more significantly in shallow water environments, the level of multipath through the surface reflection loss [6]. For the wind speed analysis, the seabeds “rock”, with a high sound reflectivity, and “coarse silt”, with a low sound reflectivity, were chosen as they were observed to be representative examples. The sensitivity results obtained for the rock seabed are similar to results observed for other highly reflective seabeds, including for instance very coarse sand and cobble. The same principle applies for the coarse silt seabed, generating similar sensitivity results as low reflectivity seabeds like very fine silt and coarse clay. Results for the wind speed sensitivity analysis are shown in Figure 3 for a shallow depth. It can be seen that in the rock seabed case, the correlation curves were showing large variations with respect to the wind speed. This phenomenon was not observed for the coarse silt seabed. This is due to the impact of multipath for highly reflective seabeds. By increasing the wind speed, and therefore the surface reflection loss, the multipath contribution was reduced and the correlation values were increased.

Finally, the sensitivity to the total noise level was considered. This noise level included ambient, platform and receiver noises. As with the wind speed analysis, the representative rock and coarse silt seabeds were used in conjunction with a shallow depth. Results are summarized in Figure 4. These results show that the correlation curves are highly sensitive to the noise level in the case of the coarse silt seabed, but not in the case of the rock seabed. This is due mainly to the fact that correlation curves are limited by the multipath contribution for highly reflective seabeds, while they are noise limited for low reflectivity seabeds. Overall, these sensitivity results indicate that when using Espresso, one has to be very careful when estimating the seabed type, the wind speed and the noise level.



(a) (b)

Figure 2: Sensitivity of the correlation coefficients to the seabed characterization (wind speed: 5 kts, noise level: 84 dB). (a) water depth: 17 m; (b) water depth: 50 m.



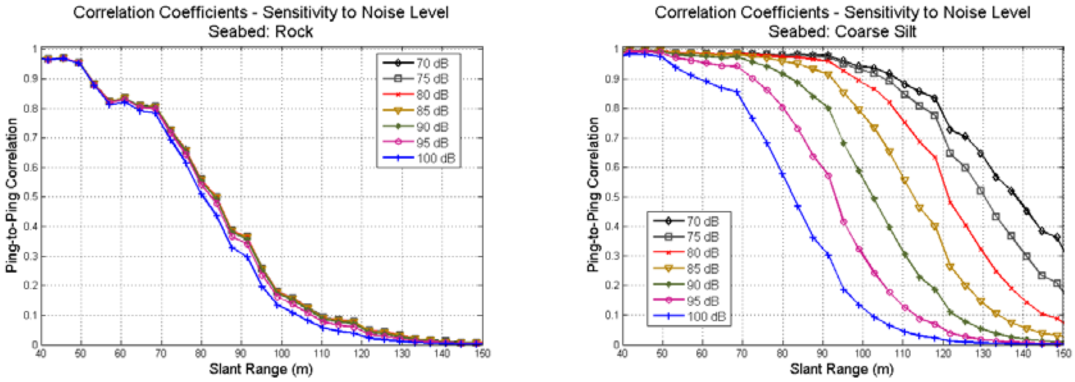
(a) (b)

Figure 3: Sensitivity of the correlation coefficients to the wind speed (water depth: 17 m, noise level: 84 dB): (a) seabed: rock; (b) seabed: coarse silt.

4 COMPARATIVE RESULTS

To investigate if the Espresso model can be used to accurately predict the behavior of the correlation coefficient curves, and therefore to accurately estimate the maximum imaging range achievable, some of the data presented in Section 2.2 is now compared to the modeled values obtained with Espresso. For this comparative study, the data from the ARISE trial was selected as this trial was conducted in a challenging shallow water environment where multipaths degraded the maximum imaging range achievable.

As was shown in Section 3.2, the correct characterization of the seabed is critical to obtaining meaningful outputs from the Espresso model. To accurately compare the ARISE data to the Espresso model results, NURC conducted a series of seabed measurements in the area where ARISE was held. Five core samples of the sea bottom were taken and the composition of each sample was studied. Results for a representative sample are shown in Figure 5. Each sample was divided in four



(a) (b)

Figure 4: Sensitivity of the correlation coefficients to the noise level (water depth: 17 m, wind speed: 5 kts): (a) seabed: rock; (b) seabed: coarse silt.

sub-samples having different depths. At each depth, the cumulative distribution function of the grain sizes was obtained and the median grain size was used to characterize the seabed type [8]. Using a frequency of 300 kHz, the upper layer between 0-3 cm is assumed to be the most significant layer.

The results shown in Figure 5 illustrate that while only the median is used to characterize the seabed type, there exists a large variation of grain sizes within a given sample. This suggests that to obtain realistic results with Espresso, a set of seabed types should be used instead of a single type. This observation was reinforced by the results from the other core samples showing that the seabed type was not homogeneous throughout the search area. Based on the seabed measurements from the ARISE trial area, it was concluded that the correct characterization of the sea floor should be somewhere between very fine silt and coarse silt.

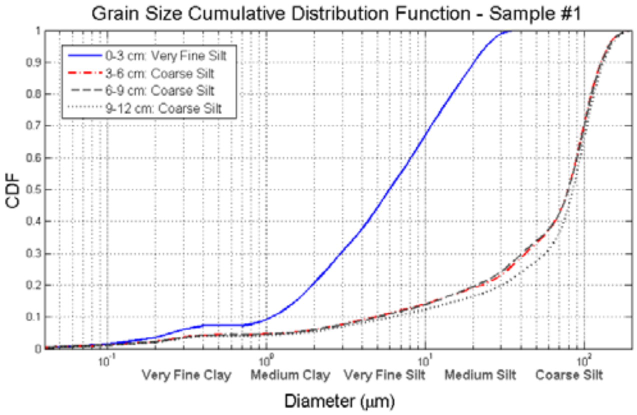


Figure 5: Cumulative distribution functions of grain size measurements for four different depths.

As the results of the seabed type estimation show that the seabed composition should be either very fine silt or coarse silt, the sensitivity analysis of Figure 4(b) indicates that the noise level used in the Espresso model can have a significant impact on the modeled correlation coefficient curves. To account for this sensitivity and to obtain accurate noise values, noise level measurements were conducted by NURC. It was found that the main source of noise for the MUSCLE SAS was the receiver electronic noise. The total noise level was estimated to be around 84 dB, but with a large uncertainty of about ±10 dB.

The wind speed during the ARISE trial was less than 4 knots, so this parameter is not expected to have a significant impact on the modeled curves as shown in Figure 3(b). The sea state during the trial was very calm and the measured sound speed profile was close to constant, with an average sound speed of $c = 1522$ m/s. The sonar parameters summarized in Table 1 were used in conjunction with the sonar mode 100c using only the lower section of the receiver. The total water depth was 17 m and the sea bottom was flat. Finally, the MUSCLE vehicle was operating at an altitude of 11 m.

The results of the comparative study are shown in Figure 6. The measurements from the ARISE sea trial are represented in black. The Espresso results for coarse silt and very fine silt seabeds, combined with a 84 dB noise level, are represented in red. The curves in blue are the pair of coarse / very fine silt curves having the best statistical fit (minimizing the sum of squared distances) with the 25th and 75th percentiles of the ARISE data. This best fit was observed for a noise level of 72 dB. Knowing that the noise level measurements might not have been accurate enough, a lower noise level of 72 dB cannot be rejected for this comparative study.

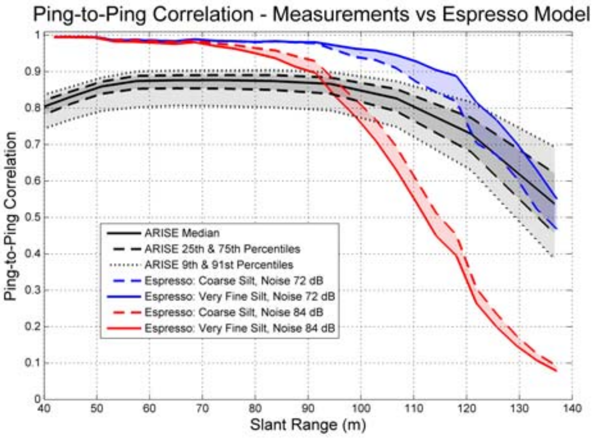


Figure 6: Measurements from the ARISE sea trial compared to results from the Espresso model.

At short ranges, for both the 72 and 84 dB noise levels, the Espresso model yields higher values of the correlation coefficients than was measured. This can be explained by the higher impact of sonar motion at short range, not modeled in Espresso, reducing the measured correlation values. Furthermore, the range window used to calculate the correlation values during the DPCA process might be too long and introducing too much near field variations reducing the measured correlation coefficients. After being relatively constant for short ranges, the measured correlations begin to decrease at a range of about 90 m. This phenomenon is accurately modeled in the case of the 72 dB noise level, but not in the 84 dB case. At long ranges, the comparative results indicate that when using a noise level of 84 dB, Espresso underestimates the correlation coefficients, and therefore the maximum imaging range achievable. However, if a noise level of 72 dB is used, it appears that Espresso can yield results comparable to measurements at sea.

Given the great sensitivity to the input parameters and the imprecisions in the measured noise levels, a definitive statement on the accuracy of the correlation coefficient curves modeled with Espresso is difficult. Discrepancies between measured and modeled data could be explained by the fact that this comparative study used a sonar frequency of 300 kHz, above the recommended range of the reverberation and reflection sub-models [6]. Furthermore, the accuracy of the multipath modeling, critical for a shallow environment, could also be a factor explaining differences. A previous preliminary comparative study [9] identified that the multipath modeling in Espresso can be limited by the current sonar modeling which does not handle diffuse surface and bottom scattering.

5 CONCLUSIONS

The ability to correctly estimate the imaging performance of a sonar system is fundamental when planning mapping operations or assessing their efficiency upon their completion. This paper investigated the performance of the NURC MUSCLE 300 kHz SAS system. Performance assessments were presented for different sea trials using real correlation coefficient data collected at sea. It was observed that environmental and operational conditions introduce variability in the maximum range to which quality sonar data can be collected. In particular, multipath in shallow water environments and adverse vehicle motion were shown to significantly degrade the maximum imaging range achievable. The correlation coefficient measurements were then compared to the values obtained with the NATO sonar performance prediction model Espresso. It was shown that the Espresso outputs can be highly sensitive to the input parameters related to the seabed type, the wind speed and the noise level. Still, when using realistic parameters, it was observed that Espresso could adequately replicate the behavior of the correlation coefficient curves observed at sea.

To increase the accuracy of the Espresso model, NURC is currently conducting research in improved modeling of forward scattering and in higher fidelity multipath modeling for high frequency systems [10]. This research effort also intends to extend the modeling to more complex bathymetries, allowing for sloped seabeds and ripple fields. Further SAS data collection for model validation is also planned during sea trials scheduled for August and October 2012.

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