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Environmental Impact on Variable Depth Sonar (VDS) System Performance

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ENVIRONMENTAL IMPACT ON VARIABLE DEPTH SONAR (VDS) SYSTEM PERFORMANCE

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ABSTRACT

A modeled based performance assessment of the collective acoustic and oceanographic characteristics of the Shallow Water Active Classification (SWAC) sea trials conducted in the Mediterranean Sea is provided. The assessment enables the determination of which environmental conditions (e.g., bottom characteristics) and VDS system parameters (e.g., source depth) significantly impact active sonar system performance for the purpose of identifying system parameters that could be adaptively exploited. Using the best available input data in a range-dependent model, extant conditions throughout four sea tests covering three geographical areas and two seasons were modeled to predict selected performance metrics. Operational performance was then assessed at frequencies near 600 and 3000 Hz to determine a) expected variability, b) sensitivity to perturbations in the modeled conditions and c) the correlation between system and acoustic parameters. In all the SWAC operating areas, bottom loss is the most significant parameter affecting reverberation and SIR. Reverberation, signal to interference ratio and multipath time spread were much more dependent on operating area than time of year. Furthermore, there was as much variability within test events spanning a few hours as was observed across seasons. Results from this assessment will be compared to measured system performance using the SWAC acoustic data at a future date.

INTRODUCTION

The SWAC sea trials, conducted by Supreme Allied Commander Atlantic (SACLANT) Centre and the Naval Undersea Warfare Center Division Newport (NUWCDIVNPT), collected an extensive and well documented acoustic database that is used by sonar engineers to develop and evaluate evolving sonar concepts. An assessment of the collective acoustic and oceanographic characteristics along with the interactions and dependencies of these data sets enhances their utility for the R&D community. The assessment provides awareness and understanding of the oceanic and system parameters most likely to affect detection and classification performance and identifies topic areas in which adaptive processing could improve performance. The objective of the model-based assessment was therefore to 1) determine the environmental conditions (e.g., bottom characteristics) and system parameters (e.g., source depth) which significantly impact performance, and 2) identify controllable system setup functions which could be adaptively modified to improve system performance.

Data were collected in the acoustically diverse littoral waters of the Malta Channel (shallow and deep), eastern Ionian Sea and western Mediterranean (W. Med.) off the southeastern coast of Spain. Tests were also conducted in the shallow water area of the Malta Channel on three separate occasions. The test thus enabled the establishment of a geographically and seasonally dependent database for use in developing and evaluating sonar systems. Seasonal dependence is not reported herein but can be found in the reference documents.

The Towed Vertically Directive Source system was used as the acoustic projector during all SWAC events. The tow body contained two vertically directive projector systems with resonant frequencies near 3000 (MF) and 600 (LF) Hz. The respective bandwidths for each projector were 800 and 200 Hz. The maximum source level for each system was 230 and 226 dB//uPa-m respectively; however, actual power levels were dependent on azimuthal angle, wavetrain type, bandwidth and duration. Each frequency band used a separate receiving array. The MF receiver contained 32 uniformly spaced acoustic sensors with an aperture of 5.6 m. The LF receiver contained 128 uniformly spaced sensors spanning 128 m. Array element data were amplitude shaded, beamformed, and further processed to form an empirical database.

Performance models use basic ocean and system parameters and provide fundamental acoustic predictions. System and oceanic parameters were used to describe and quantify sea trial conditions. They are, in essence, categorical representation of basic conditions that influence the received signal and interference in a sonar system. The following oceanic parameters were useful in relating fundamental ocean acoustic parameters to general acoustic propagation characteristics: sound speed profile; water depth; wind speed; bottom slope; surface and bottom loss; surface, bottom and volume backscattering coefficients; propagation modes and loss; acoustic arrival angles and multipath time spread. System parameters, such as reverberation, noise, signal to interference level (SIR), as well as source, target, and receiver depth were used to relate fundamental ocean acoustics to system performance.

METHODOLOGY

Approximately one-half (44 of 87) of the three hour test events were selected for modeling analysis. For each event, extant conditions for pings near the beginning, middle, and end were identified as modeling cases. Predictions of a set of selected performance metrics (reverberation, SIR, time spread) were generated for each ping using the best available input data and a U.S. Navy accepted range-dependent model (CASS/GRAB). The model was then re-run with modified sets of environmental and system inputs which were methodically varied to reflect expected system and environmental error margins. Operational performance was then assessed to determine the systems expected 1) variability (mean and standard deviation), 2) sensitivity to changes in environmental conditions, 3) correlation between system and acoustic parameters and 4) frequency dependence (LF vs. MF). Results are available in the references for each individual event, the different seasons and each geographic area.

The following selected parameters were independently modified, within reasonable uncertainty limits, to quantify system performance changes: source and target depths, wind speed, bottom loss, bottom and volume backscattering strengths. Obvious uncertainties, such as source level and target strength, do not require modeling.

RESULTS

Acoustical Characterization

The acoustical characterization is intended to provide a description of the ocean environment acoustics as it affects sonar performance within each sea test operating area. The baseline model results for three pings (approximately 1 hour apart) in each modeled event form the basis for establishing a general representation of acoustic performance for the extant conditions. The results are also used to establish a functional relationship between the sonar system model input parameters, and system performance and propagation metrics. The performance and propagation functions are: transmission loss, vertical arrival angles at the target and bottom, multipath time spread, ambient noise and signal to interference level.

Examples of the modeled SIR in the Malta Channel-shallow operating area and representative sound speed profiles (SSP) obtained in early November are illustrated in Figure 1.

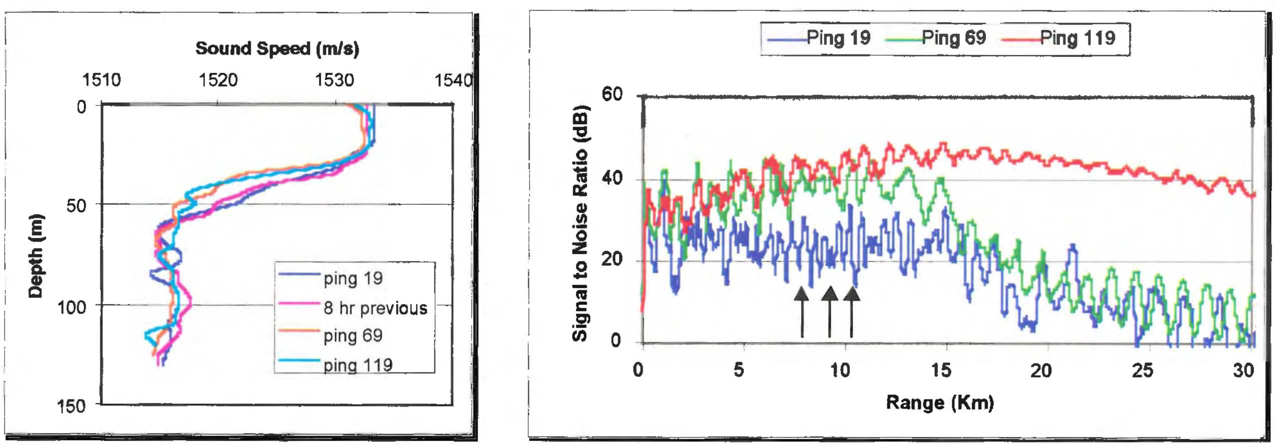

Figure 1. a.) (left) Representative SSPs and b.) (right) Modeled SIR for Three Pings in the Malta Channel Shallow

The source, target and receiver depths (60-85 m) are all located within the deep-water layer. Although they are nominally located near local sound speed minima, their exact depth significantly affects propagation to and from the target and the bottom which was typically about 125 m. A sampling of sound speed profiles during SWAC-1 event 22 shown in Figure 1a (left) reveals the dynamic nature of the sound speed minima. The overall results are spatially and temporally dependent weak ducts coupled with mild downward refracting conditions that produce an ever-present bottom limited propagation channel. Propagation conditions to the target generally change as a result of very small changes in source depth or sound speed profiles along the transmission path. Propagation loss as a function of range to the bottom usually increases rather monotonically unless the water depth decreases such that ducted energy begins to interact with the bottom.

In Figure 1b (right), the signal to interference ratios (SIR) during event 22 exhibit strong range dependencies within a transmission period (seconds) and are highly variable during an event (few hours). The arrows centered about 9 km, indicate target range and a 1 km interval to each side. As might be expected, the SIRs at the target ranges are greatest (>35 dB) in ducted conditions and lowest (<20 dB) when the acoustic channel only supports bottom limited propagation.

Geographic Dependence of Acoustical Characteristics

Mean and standard deviation of baseline model parameters and results over the entire sea test operating area were used as the basis for providing a characterization of each sea test operating area as well as making seasonal and geographic comparisons. SWAC-1 (Malta-shallow) and SWAC-3 (W. Mediterranean) both occurred during the fall but in different operating areas and thus represent the best data sets for geographic comparisons. The SWAC-4 tests conducted in the East Ionian Sea and Malta-deep also represent a significantly different operating environment but were conducted in the Spring. Even though these tests occurred in May, the seasonally dependent, upper portion of the water column is not a significant factor for the SWAC sonar parameters; hence they are guardedly included in this comparison.

As shown in Figure 2, all the profiles exhibit a very strong thermocline in the upper 50 m of the water column. Sound speed minima are different for each test but are typically located between 50 and 200 m. In general, the deep-water layer in the western Mediterranean and Ionian Sea was quite stable during the test periods. This was not the case in the Malta Channel where significant time and space variability in the deep water (below 50 m) layer was observed. The sound speed profiles in the Ionian Sea also indicate an increase in sound speed in the 50 to 150 m depth range. This gives rise to a well defined, but depth-limited, duct between 25 and 75m. Convergence zone propagation can occurs when the water depth exceeds the critical depth of ~1000 m.

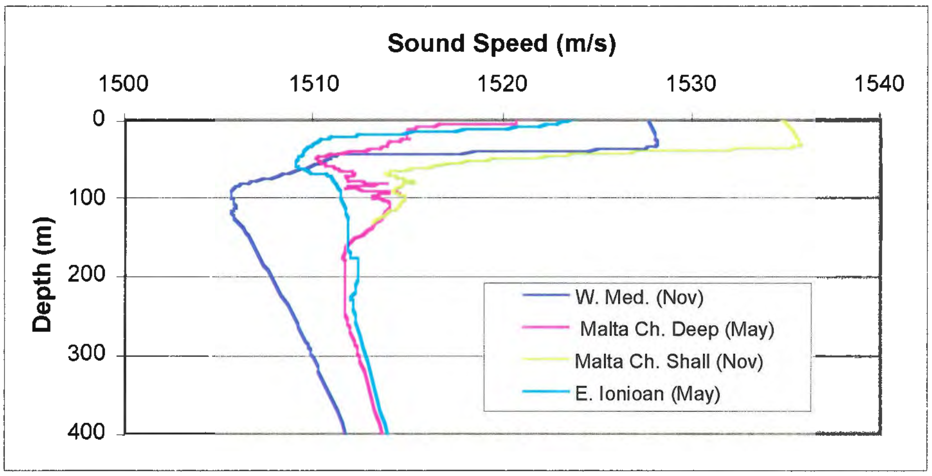

Figure 2. Representative Sound Speed Profiles of each SWAC Geographical Area

The MF mean and standard deviation values for SWAC-1 (Malta Channel-shallow), SWAC-3 (W. Med.), SWAC-4 (E. Ionian) and SWAC-4 (Malta Channel-deep) are shown in Figure 3.

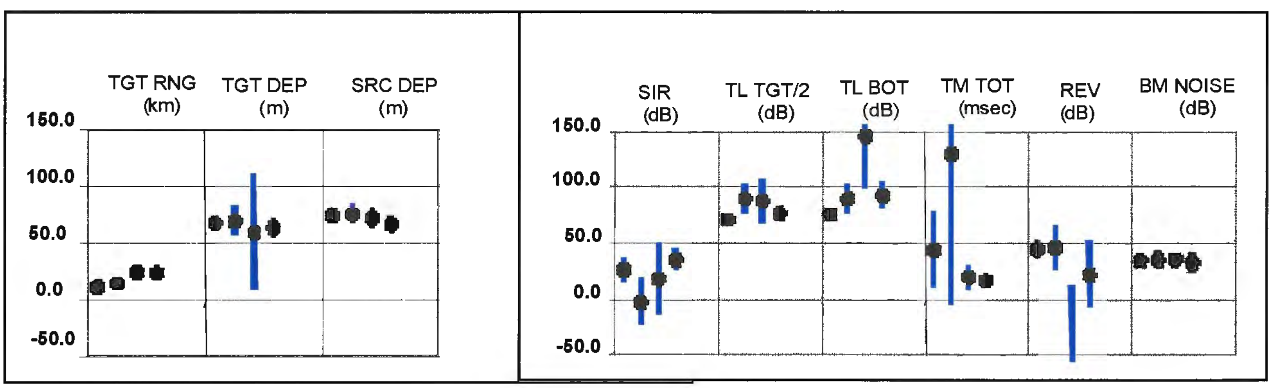

Figure 3. a.) (left) MF Mean and Standard Deviation of System Parameters and b.) (right) Acoustic Representations. Each group of four bars represent Malta-shallow, W. Med., E. Ionian Sea and Malta-deep respectively.

Figure 3a (left) shows little significant difference in mean target and source depths in any of the sea test operating areas. There are however, significant differences in the mean and variance of the acoustic parameters shown in Figure 3b (right). The mean transmission loss to the target (TL TOT/2) in the W. Med. and Ionian Sea is significantly higher and more variable than in either of the Malta Channel areas. This is one of the reasons the signal to interference ratios in the W. Med. and Ionian are dramatically lower than in the Malta Channel. Transmission loss to the bottom (TL BOT) is significantly higher in all the deep water regions than in the shallow water area of the Malta Channel. This results in a substantial reduction in reverberation (REV) for the Malta Channel-deep and Ionian Sea areas. Multipath time spread (TM TOT) is higher in the W. Med. area and lower in the Malta Channel-deep and Ionian Sea.

Parameter Sensitivity

The sensitivity of underwater acoustics to changes in oceanic conditions and system parameters is another important factor when developing, testing and evaluating robust sonar systems. In the SWAC sea tests, the principal factors affecting acoustic propagation were believed to be range, source depth, target depth, wind speed, bottom loss and bottom backscatter. To develop the database necessary to quantify and assess the expected variability within the SWAC sea trials, a single factor was decreased from the baseline value to reflect a reasonable lower bound and the model rerun. The factor was then increased from the baseline case and the model again rerun; then another factor was selected and the process repeated. The increments of the perturbations made in the model are provided in the second column of Table 1. The maximum difference of model output values between input parameter increments was recorded in the sensitivity table, e.g., the maximum difference in transmission loss to the target for source depths of 85, 75 and 95 m. For example, in the SWAC-1 environment, the average change in reverberation level (at the target range) as source depth was changed by 20 m in 10 m increments was 3.3 dB.

		REVERB LEVEL (dB//uPa)				SIR (TS=10dB) (dB)				TIME SPREAD @TGRT (10 ms)			
INPUT PARAMETERS		MALTA SHALL (SWAC 1)	W. MED (SWAC 3)	E.IONIAN (SWAC 4)	MALTA DEEP (SWAC 4)	MALTA SHALL (SWAC 1)	W. MED (SWAC 3)	E.IONIAN (SWAC 4)	MALTA DEEP (SWAC 4)	MALTA SHALL (SWAC 1)	W. MED (SWAC 3)	E.IONIAN (SWAC 4)	MALTA DEEP (SWAC 4)
		NOV.	NOV.	MAY	MAY	NOV.	NOV.	MAY	MAY	NOV.	NOV.	MAY	MAY
Target Depth	+/- 1 KM	4.3	8.1	33.3	25.3	3.5	9	13.8	5.5	1.5	3.7	0.9	1.1
Target Depth	+/- 10M					12.6	6.5	23.9	12.8	2.2	2.8	0.6	0.7
Source Depth	+/- 10M	3.3	5.3	10.3	9.9	15.8	8.4	6.6	10.2	2.2	2.5	0.7	0.9
Bottom Loss	-0.2, 5dB	36.9	26.9	28	26.3	16.4	31.9	6.9	9.1	3.7	5.9	0.6	3.3
Bottom Scatter	+/- 3dB	6	5.8	4.3	5.8	4.9	4.4	0.5	2.6				
Volume	-72, -200	10.4	5.4	36.8	1.5	10.2	4.8	3.6	1.5				
Sensitivity Color Key		BLANK < 1 unit	W 1-3 units	M 3-6 units	S >6 units								

Table 1. Geographic Dependence of MF Acoustic Performance Sensitivity to Perturbations of System and Environmental Parameters.

As seen in Table 1, **reverberation** is very sensitive to relatively small changes in range in environments with significant bottom slope (SWAC-3 and 4). It is also very sensitive to source location when depth excursions exceed the depth extent of localized sound speed minima. The sensitivity is somewhat less when the propagation paths are principally bottom-limited (SWAC-3). The shallow water area of the Malta Channel is the most homogeneous of the operating areas (low bottom slope and mixed propagation modes) and exhibits the least sensitivity. Reverberation is very sensitive to changes in bottom loss in all the operating areas. This can be related to the number of bottom interactions and incident grazing angle. On average, the SWAC-1 test had the highest number of bottom reflections and thus exhibited the greatest sensitivity. The sensitivity of reverberation is directly related to bottom scatter except in the Ionian Sea, where on occasion, the bottom is not the dominant scattering feature. For example, when bottom loss is changed by 6 dB/interaction and six bottom interactions occur between the source, bottom and back to the receiver, reverberation level changes 36 dB. An equal change in the backscatter coefficient changes the reverberation by only 6 dB. A uniformly distributed volume backscatter, if present at a nominal level of –72 dB, also strongly affects the total reverberation level.

There is strong geographic sensitivity dependence to volume reverberation upon the introduction of a nominal volume scattering strength. However, the variance of the sensitivity is very high and the cause quite subtle thus requiring a case by case analysis. Extreme changes in sensitivity within test areas often exceed average changes across operating areas. However, there are a few generalities. For example, the greatest sensitivity is in the Ionian Sea because the extant bottom backscatter is on average very small. The introduction of any reverberant results in large variations to the existing levels. In the deep-water portion of the Malta Channel there are only nine samples in the data set and six of those cases show no sensitivity to volume scattering; hence, the average sensitivity is quite small.

The sensitivity of **SIR** to target range indicates a geographic dependence similar to that of reverberation. As the number of bottom interactions increase, there is less change in propagation over small range intervals to the bottom and target; this results in decreased sensitivity to range changes. The sensitivity to target and source depth has nearly the same dependency as reverberation. However, the existence of numerous localized sound speed minima in SWAC-1 creates localized ducts. These significantly affect propagation to the target and the bottom, which in turn leads to the relatively high sensitivity observed in this scenario. Changes in bottom loss particularly affect SIR in non-ducting environments. Bottom backscatter has a moderate impact on SIR except in the Ionian Sea, where for the most part; ambient noise, not reverberation, is the dominant interference. The geographic dependence of SIR on volume scattering is similar to the trend observed for reverberation except that in the Ionian Sea, noise is the limiting interference and is seldom dominated by bottom or volume reverberation.

Multipath **time spread** is most sensitive to system and target parameters in SWAC-1 where localized sound speed minima exist and SWAC-3 where significant changes in bathymetry occur. During these two trials, relatively small range and depth changes result in changes to the multipath arrival structure which in turn affects the time spread estimate. In the Ionian Sea, the same small changes do not notably change the multipath structure hence there is little change in the time spread. There is a notable geographic dependence of time spread on bottom loss. Bottom loss changes affect time spread by stripping higher angle bottom reflection paths faster than lower angle arrivals, thus the more bottom interactions and higher dependence on grazing angle the greater the dependence of time spread on bottom loss. It follows that changes in bottom loss do not significantly affect time spread in ducted conditions such as found in the Ionian Sea.

Frequency Dependence

In order to establish the existence and occurrence of an optimal operating frequency and identify metrics most sensitive to center frequency, the modeling and analysis procedure was repeated using input parameters representative of conditions near 600 Hz (LF). As a first step, model predictions based on in situ conditions from similar areas and seasons were averaged and compared to the MF results found in figure 3b. This provided an indication of what should be expected from the measured data set. Because the LF and MF systems are significantly different, the predictions were normalized and again analyzed for differences as a function of frequency.

Frequency Normalization. *Even though most of the system level parameters remained the same throughout the SWAC trials, there are significant differences between the LF and MF sonar systems. This biases frequency comparisons of reverberation, noise, interference and SIR based solely on in situ conditions. For example, the directivity index (DI) of the MF towed array is about 9 dB less than the LF array. Similar differences exist for other system parameters. The in situ based model results were normalized to common values of source level, pulse length and receiver beamwidth and DI to obtain normalized values of reverberation, noise, interference and SIR. In addition, because the target strength of submarines is extremely complex and highly variable, a constant value of 10 dB was used throughout the modeling effort at both frequencies. An adjustment factor of* 10 *log(MF/LF) or 7 dB was also applied to the results to enable a more realistic assessment of the two frequency dependent systems.*

Normalized LF and MF modeled reverberation levels in the Ionian Sea and Malta Channel-deep area were low leading to noise limited interference conditions and SIR levels in excess of 24 dB. In the W. Mediterranean, acoustic interference was reverberation limited and SIR performance was less than 5 dB. In the Malta Channel-shallow area, interference was also reverberation limited but SIR estimates were greater than 25 dB. At each location, the dominant interference (noise or reverberation) is greater in the LF band.

As shown in Figure 4, the difference in performance between the LF and MF systems is very dependent on geographic location. The plots labeled with "ΔTS" are based on an assumed frequency dependent target strength difference of 7 dB. The set of values labeled with "TS10" is based on a target strength of 10 dB at both frequencies. Also note that the reported differences are based on average values and within each area, there are conditions that result in large variations. In the W. Med. and Malta-shallow areas, the greater differences in reverberation affecting LF, result in higher SIR for both "TS" cases at MF. For the Malta-deep area, it shows moderate SIR advantage at MF for the "ΔTS" case and no apparent advantage under the "TS10" case assumption. In the Ionian area, in spite of elevated noise levels affecting LF, it shows higher LF SIR performance. Though greatly simplified, it appears that under conditions where reverberation and relatively short ranges (<15 km) are encountered, the MF system should out-perform the LF system. For somewhat longer ranges (>20 km) and ducting conditions where noise is the limiting interference, the LF system is marginally better.

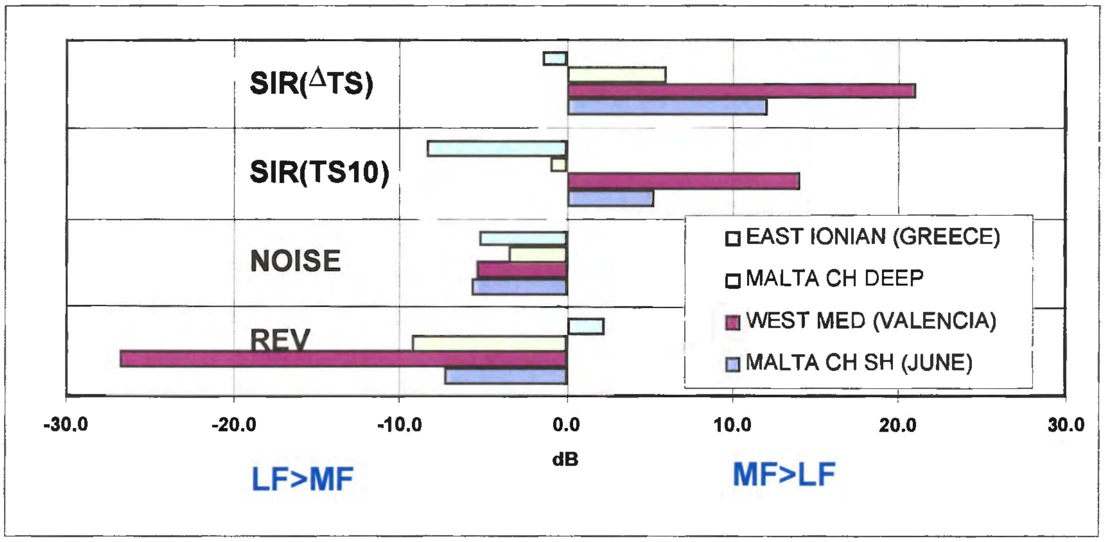

Figure 4. Performance of LF and MF Frequency bands across SWAC Geographic Areas

Conclusions

For a VDS system operating in the littoral waters of the Mediterranean Sea, the sensitivity of reverberation, SIR and multipath time spread to changes in system and environmental parameters is much more dependent on geographical area than time of year. In all the SWAC operating areas, bottom loss is the most significant parameter affecting reverberation and SIR. In the vicinity of local sound speed minima, sonar and target depths are also critical factors. Except in cases where the bottom is not insonified, bottom loss changes affect SIR and reverberation in a nearly one to one to relation. Of the independent parameters selected, multipath time spread is most affected by bottom loss in refracted bottom reflected conditions but only by a moderate amount.

Though not discussed, in the shallow waters of the Malta Channel, reverberation and signal to interference ratio are highly dependent on bottom loss because of the multiple interactions energy has with the bottom while propagating to and from the target. They are also affected by bottom and volume scatter factors but less so because scattering, as a single interaction event, only occurs once during the propagation of a pulse to and from the target. Because of relatively small and localized acoustic channels in the deep layer, SIR is also significantly affected by sonar and target depth changes of tens of meters. Multipath time spread is only moderately affected by path stripping. There does not appear to be any significant seasonal dependence (October/November vs. May/June) but large non-seasonal yet temporal (over hours and days) oceanic changes, such as caused by large storms or eddies, result in large variations.

The dependence of performance sensitivity on frequency is an indication of sonar robustness as a function of frequency. Overall, this modeling study shows a performance advantage at MF for the conditions encountered in the SWAC tests. However, it may be desirable under some circumstances to operate with a system with less optimal performance but more immune to changes in the environment. The LF system performance is less sensitive to all changes in operating conditions except volume scattering strength. Though not shown, the same trend exists for all the tests conducted in the shallow water region of the Malta Channel.

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