SURFACE DUCT PROPAGATION LOSS MEASUREMENTS AND MODEL PREDICTIONS AT LOW AND MID FREQUENCIES

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Abstract Side-by-side measurements of low- and mid-frequency propagation loss were obtained during a sea test conducted in the North Atlantic during February of 1992. These measurements are compared to each other and with model predictions calculated using the Generic Sonar Model (GSM). Supporting *in-situ* environmental data was used as inputs to the GSM. The three events selected for this analysis show, that in a variety of sea states the propagation loss predictions model the measurements fairly well. It is concluded that since the experiment took place in a surface duct, propagation loss is heavily dependent on small variations in the water temperature profiles near the surface and on changes in the wind speed.

1. Introduction

Analyses of at-sea performance of active sonar systems show that several obvious terms in the sonar equation are most important in determining the effectiveness of a system. The most dominant of these terms are target strength, background (noise and/or reverberation) level and propagation loss. Therefore, when a side-by-side sea test was conducted to compare a low frequency (nominally 1 kHz) and a mid-frequency (nominally 3 kHz) active sonar system, it was important to measure, analyze and model propagation loss during this test. In support of these measurements, one-way propagation loss measurements to a deep target were made during the test. The paper will analyze and discuss the results of the side-by-side propagation loss measurements. The data analyzed in this paper are taken from three selected events representing a variety of sea states and propagation ranges which vary from 7 to 87 m.

2. Background

The current active sonar system on US surface ships transmits in what is called the mid-frequency (MF) band of the active sonar frequency spectrum. Low frequency (LF) active sonar systems have been proposed to augment this current system.

Many paper studies have been conducted to contrast the current MF system and several variations of proposed LF systems. These studies usually involve acoustic performance prediction models, such as the Generic Sonar Model (GSM) [1], and battle group effectiveness simulation models. Results of these studies are all highly dependent on the models used and the assumed system parameters. Moreover, these studies have not necessarily used a common methodology for collecting the input data or analyzing the LF and the MF systems. This has led to some confusion and occasionally conflicting claims. Therefore, side-by-side sea tests were planned to collect MF and LF data simultaneously and then, to analyze these data using a common, consistent approach. An advantage of the Side by Side collection methodology is the close spatial and temporal correlations of the dual measurements. This methodology serves to reduce environmental ambiguities.

2.1 Test Site

The side-by-side sea test, involving the *USNS GLOVER* (the LF platform) and a US Navy destroyer (the MF platform), was conducted during February of 1992. The operating area consisted of two partially overlapping areas: Site A, approximately 320 km northwest of Bermuda, and Site B, south of Site A, in the northernmost region of the Hatteras Abyssal Plain. Figure 1 is a chart showing these test sites. The bottom depth of this operating area is approximately 5200 km. Historically, sound speed profiles for the test sites exhibited clearly defined surface ducts with layer depths of over 300 m and with sufficient depth excess to support convergence zone (CZ) propagation. In-situ measurements, in general, supported the historical data. The convergence zones were centered at approximately 67 km.

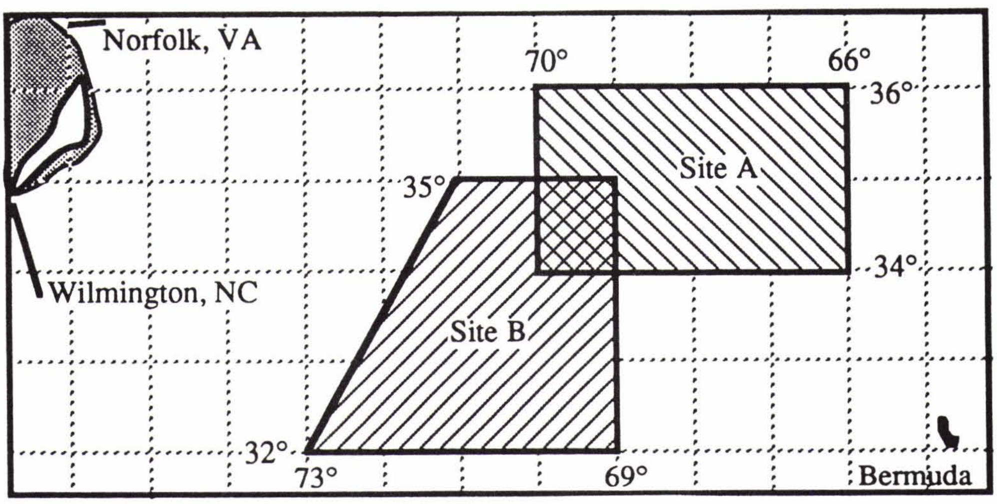

Figure 1. Location of Test Sites during the Side by Side Test

2.2 Platforms and Systems

The *USNS GLOVER* is a US Navy frigate operated for research purposes. The active sonar system on the *USNS GLOVER* is a prototype system, consisting of a low frequency planar hull transmit array, a reconfigurable multi-line towed array receiving system (RMES), and a computer workstation-based matched filter real-time signal processor and display. The source was a planar array mounted on the hull. The center of the transmit array was situated 5.5 m feet below the water's surface. The power amplifiers received beamformer outputs from a waveform generator and transmit beamformer. The RMES receiver on the *GLOVER* is a critical angle towed array system that contains up to nine acoustic array lines. For the Side-by-Side test, all nine lines were used whenever possible and configured in a cruciform arrangement.

During the sea test, the LF system transmitted two wavetrains of coded pulse (CP) and continuous wave (CW) signals. The first pair consisted of a 2 second, hyperbolic FM (HFM) pulse, followed by a 2 second, Hamming weighted, CW pulse. The other pair of signals was of the same type, but shifted to non-overlapping frequencies. For the events that covered ranges from 7 to 46 km, every 49 seconds the LF system transmitted one or the other signal pairs. The first wavetrain was transmitted followed 49 seconds later by the second wavetrain. For events covering the longer ranges, 41 to 87 km, a 75 second repetition interval was employed.

The active sonar system on the destroyer is a US Navy standard active sonar system. The transmitter and the receiver are co-located on a hull-mounted, cylindrical array. The center of the array is located 7.6 m below the surface of the water. The sonar system transmitted a 1 second linear FM slide followed by a 1 second CW. The propagation loss data analyzed for this paper examines the CP signals only.

The receiver was outfitted with data recording equipment to record received signals from both surface ships. These records were used to determine LF and MF transmission data from the two source platforms to the receiver. The receiver hydrophone was at a nominal depth of 180 m.

Both surface ships were outfitted with a satellite Global Positioning System (GPS) receiver to collect navigation data. The *USNS GLOVER* was outfitted with a data gathering system (DGS) that processed and stored ship's course, speed, and true wind speed data (the anemometer height was 25 m above the sea surface).

2.3 Description of Collected Data

The propagation loss data analyzed in this paper are one-way measurements from the transmitter of each ship to the receiver located at a depth of 180 m. The voltage out of a calibrated receiving hydrophone was recorded on magnetic tape along with appropriate calibration signals for each sonar transmission from the surface ships. The root-mean-squared (rms) summed pressure level over the entire pulse length of the CP signals was measured for each ping reception. Although the pressure levels were summed across the entire pulse length, because of spreading due to multipaths, not all energy was included in each measurement. One way propagation loss was calculated by subtracting the appropriate source levels. For details of this data collection procedure see [2].

2.4 Test Procedures

The sea test consisted of four run pairs or eight separate events. Each run pair consisted of a stepped opening geometry of approximately seven hour duration, followed by a two to three hour break, and then a stepped closing geometry of approximately seven hour duration. Figure 2 provides a view of the track for one of the run pairs. The LF and the MF platforms remained on steady parallel courses while the receiver maneuvered through the various steps of the geometry. For each event, MF platform was positioned 685 m astern and offset 90 m to starboard of the *GLOVER's* track. The receiver was near abeam of both surface ships at ranges specified for the particular event. Figure 3 shows the relative positions of the LF and MF platforms and the receiver (note that the figure is not to scale). The receiver executed the seven legs of each event, alternating between parallel legs and either opening or closing legs. The receiver's speed was increased during the opening (closing) legs to keep its speed of advance equal to the 10 knot speed of the surface ships. This paper will report on the analysis of transmission loss for 3 of these 8 events.

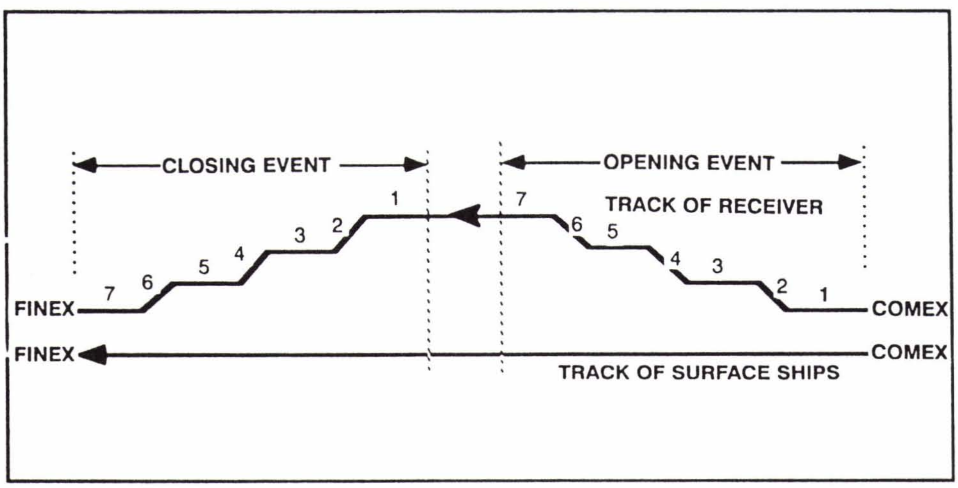

Figure 2. Geometry of Opening/Closing Event Pair

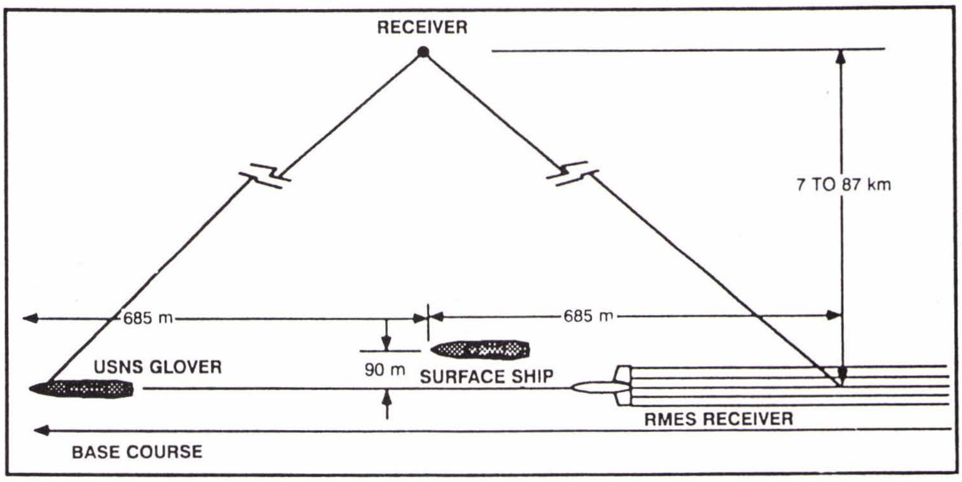

Figure 3. Relative Positions of LF and MF surface ships and receiver during all events (not shown to scale)

3. Approach

Three events are analyzed in this paper. Event 2, CLS1DA, is a closing short range event with building seas. Event 3, OPN2DA, is an opening long range event with very high winds. Event 8, CLS2DA, is a closing long range event with moderate wind speeds. The following paragraphs describe the rationale and the resulting assumptions made in modeling the propagation loss.

3.1 Track Reconstruction

Track reconstruction data were collected for each event. GPS, DGS and SINS data were used to calculate track reconstruction data values every 30 seconds for each event. These data were used to determine range to each propagation loss measurement.

3.2 Environmental Data

Expendable bathythermal traces (XBTs) were used to measure water temperature versus depth for the upper 450 m of the water. These XBTs were launched on both surface ships at the beginning of each event, sometime near the middle of the event, and at the end of the event. The resulting near-surface sound speed profiles and the DGS wind speed data were used in modeling the transmission loss.

One of the key factors influencing the modeling was the wind speed. Early in the test the winds were moderate (from 15 to 20 knots). They increased dramatically at the end of event 2 and peaked at around 40 to 45 knots during event 3. For the next three events, the winds decreased. Prior to the beginning of event 8, they averaged about 10 to 15 knots. As event 8 began, wind speed increased once again from 13 knots at the beginning of the event to 21 knots during most of the event. Figure 4 is a plot of the true wind speed measurements as they were recorded by the *GLOVER*'s DGS system every 2 minutes.

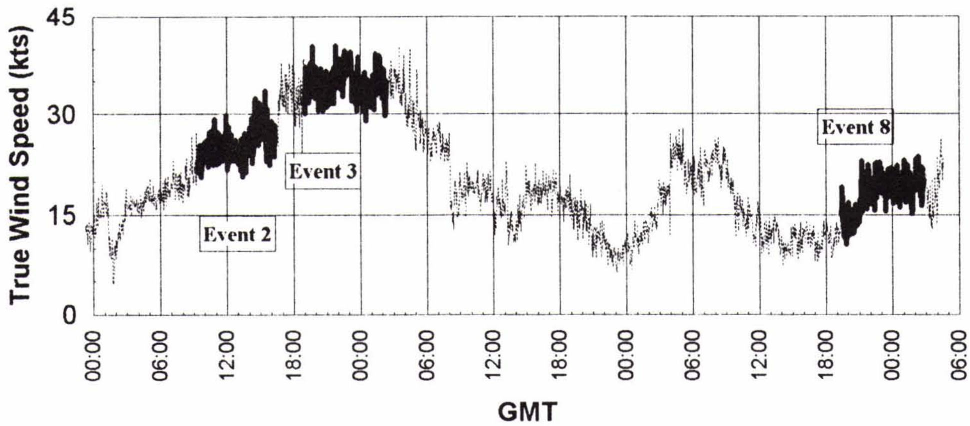

Figure 4. True Wind Speed Time History during Sea Test
(events analyzed shown in bold)

3.3 Assumptions in Performance Prediction Modeling

For each of the test events, there were three sound speed profiles available from each of the surface ships. These sound speed profiles were derived from the measured XBTs which were merged with one of Podeszwa's historical deep profiles [3]. The first step in the analysis consisted of evaluating these six profiles from the standpoint of validity. Any profile whose shallow portion had been merged with any historical deep profile other than Podeszwa's A17 or A18 was rejected as untrustworthy. On the other hand, profiles that appeared very similar, regardless of the ship from which they had originated, were included as a potentially useful input to GSM.

Sound speed profiles, whether obtained on the LF or MF platforms, were applied to both the LF and MF modeling analysis. Since each event extended over six to eight hours, environmental conditions such as those measured by wind speed and/or sound speed might change over an event. Therefore, it was found that modeling assumptions needed to account for changes in wind speed and sound speed.

During the sea test, the fathometer on the MF platform was operated to produce depth soundings. These did not provide the most accurate bottom-depth information in many cases. However, the LF reverberation data, by virtue of the transmitter array's vertical beam pattern, did exhibit a sharp spike associated with the first bottom return, thus giving a clue as to the correct water depth. This was corroborated by examining data on US Navy charts.

Table 1 shows the resulting environmental parameters determined for each event analyzed in this paper. The letter preceding the XBT denotes the ship from which it was launched:

LF platform (L) or MF platform (M). The number indicates whether it was launched at the beginning (1), in the middle (2), or at the end (3) of the event. The values of these parameters were input into the GSM to generate predictions for propagation loss.

Table 1. Best Fit Environmental Parameter Values for Events 2, 3, and 8 of Side-by-Side Sea Test

Event	Event Name	Wind Speed (knots)	XBT	Podeszwa Profile	Bottom Depth (m)	LF Freq (kHz)	MF Freq (kHz)	Time into Event (min)
2	CLS1DA	22	M-1	A18	5232	1	3	0-230
	CLS1DA	25	M-2	A18	5232	1	3	230-330
	CLS1DA	30	L-3	A18	5232	1	3	330-420
3	OPN2DA	30	L-1	A18	5201	1	3	0-210
	OPN2DA	35	L-2	A18	5201	1	3	210-450
8	CLS2DB	21	L-2	A18	5183	1	3	0-450

Figures 5, 6 and 7 show the upper 600 meters of the sound velocity profiles used in this analysis. Notice the complicated structure of these profiles, particularly those in events 2 and 3 where winds speeds were changing rapidly.

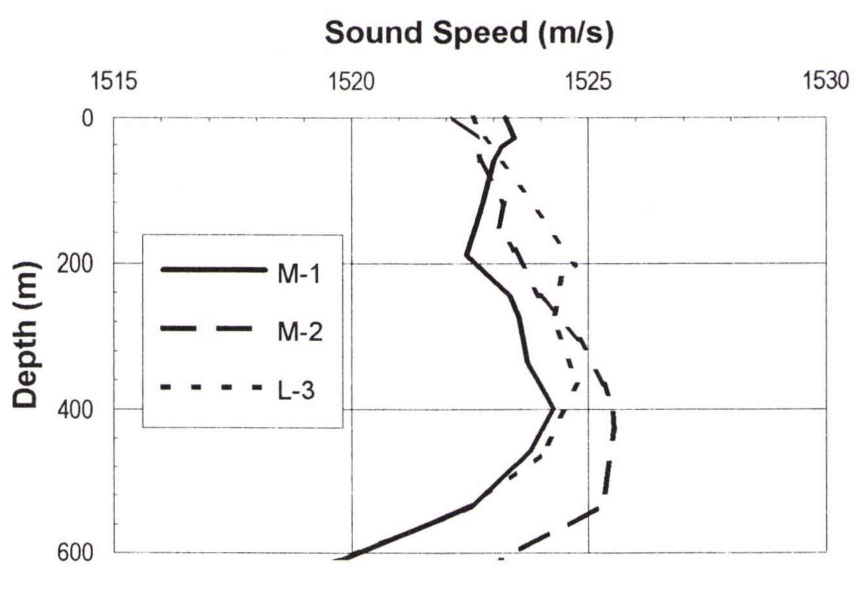

Figure 5. Shallow Sound Velocity Profiles showing Surface Duct Structure of Three Profiles used in Propagation Loss Analysis of Event 2

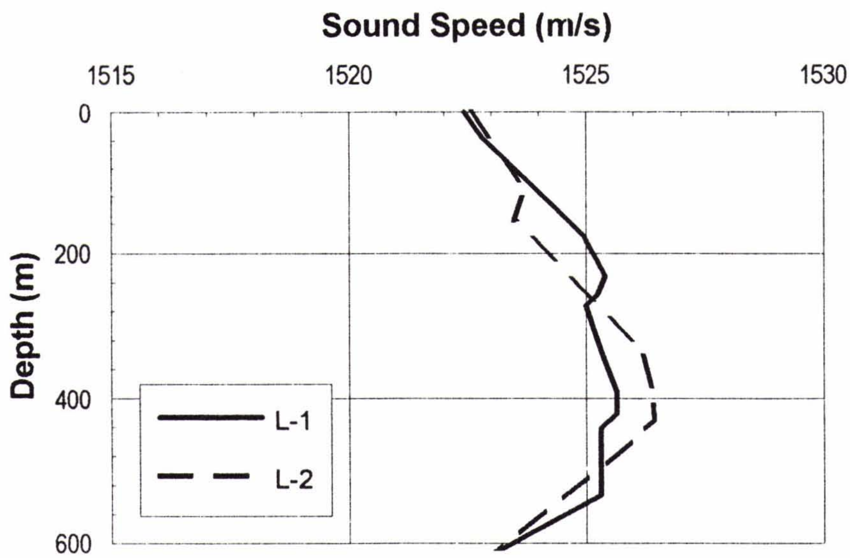

Figure 6. Shallow Sound Velocity Profiles showing Surface Duct Structure of Two Profiles used in Propagation Loss Analysis of Event 3

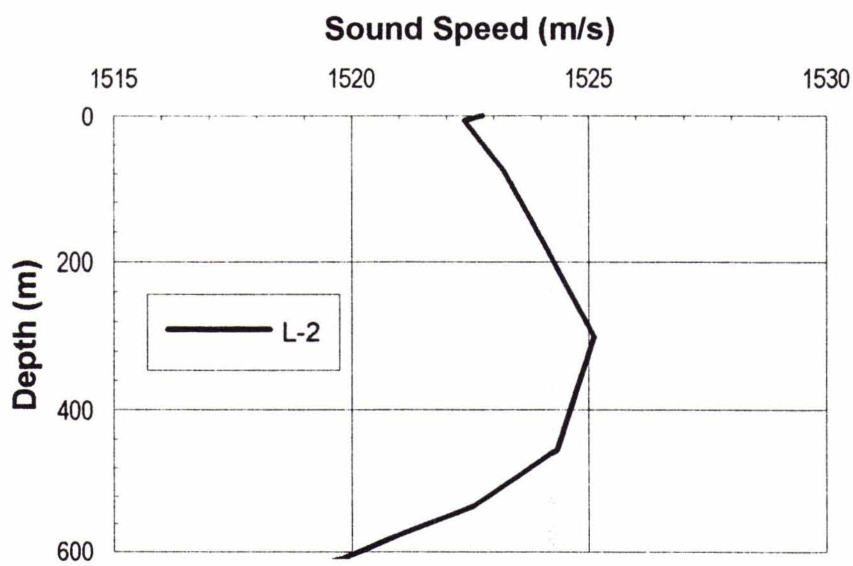

Figure 7. Shallow Sound Velocity Profile showing Surface Duct Structure of Profile used in Propagation Loss Analysis of Event 8

Figure 8 shows a ray trace using the M-2 XBT from event 2, plotting only those rays which had the most significant propagation loss. This ray trace was typical of ray traces using all SVPs from this analysis. It shows a combination of surface duct and convergence zone propagation. This figure also shows that convergence zone propagation extends from about 65 to 90 km.

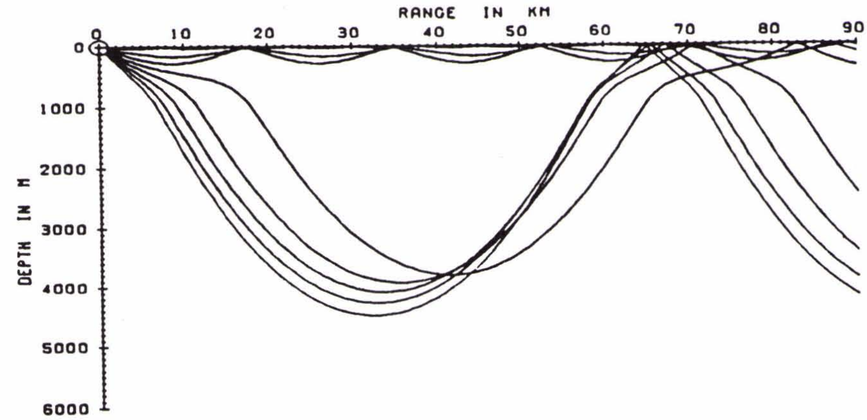

Figure 8. Ray trace using SVP from Event 2 and Source at 7.6 m Below the Surface. (Only Most Significant Rays are Shown.)

For each of these events, the MGS province bottom type was 6 (high loss). However, ray traces show there was very little bottom interaction. Therefore, bottom loss contributed very little to propagation loss. The frequencies in the table above refer to the modeling frequencies. For the LF system, the frequency used was the mean of the centers of the two HFM pulses. For the MF system, the center frequency of the LFM signals was used.

The Generic Sonar Model (GSM) was used to calculate propagation loss predictions. The GSM is a collection of acoustic and sonar system submodels. Table 2 shows the GSM submodels used to calculate the propagation loss predictions.

Table 2. GSM Submodels Used to Calculate Propagation Loss Predictions

Temperature/Sound Speed Conversion	CONGRATS
Sea State/Wind Speed Conversion	NAVOCEANO
Volume Attenuation	Thorp
Surface Reflection Loss	Beckmann-Spizzichino
Bottom Reflection Loss	MGS
Eigenray	FAME
Pressure	Incoherent

4. Analysis of Each Event

During the sea test, environmental conditions varied as each event progressed. Therefore, presenting measurement data and predictions versus time into an event, reveals the environmental variability of the data. Since the run geometry was a stair-step, time into event does not map linearly into target range. Therefore, for each event, two types of figures (figures 9 through 14) are shown. The first is the range of the surface ships to the target. Since the inter-ship range (approximately 700 m) is much less than the target ranges, the target ranges from each surface ship were assumed to be equal. The second figure contains two plots (one for LF and one for MF) comparing measured propagation loss data and predicted propagation loss versus time into event. Several types of propagation paths are identified on these figures. A sound channel propagation path is identified by **SC**. This path involves no interactions between the surface or the bottom and all the energy stays within the deep sound channel that was present for all events. A surface reflection path is identified as **SR.** This path type contains one or more interactions with the surface, but no bottom interactions. And finally, convergence zone paths which cross the layer, but contain no bottom interactions, are denoted by **CZ**. The effect of these propagation modes will be discussed in paragraph 4.4.

4.1 Event 2 Propagation Loss Comparisons

The wind speed increased from about 20 knots to more than 30 knots during Event 2. In addition to this, examination of the sound speed profiles indicate that the near surface temperature of the water was changing as the wind speed increased. Therefore, this event had to be modeled in three time segments.

The upper plot of figure 10, shows that during the first time segment (0-230 min), the predictions underestimate the measured propagation loss data for both LF and MF sets. A sound speed profile based on the first MF XBT was used and the wind speed was assumed to be 22 knots. After almost four hours, the wind speed was increased to 25 knots which is the mean of the initial wind speed and later wind speeds. At this time, the second MF XBT was used for the sound velocity profile. These values were used until the last 90 minutes of the event, when both the last XBTs of the event, wind speed measurements, and other reverberation measurements indicate that the surface conditions had changed drastically. At that time the last XBT launched on the *GLOVER* was used for the sound velocity profile. The wind speed was increased to 30 knots to reflect the high sea state conditions that were in effect at the end of this event. It should be noted here that these environmental values yield predictions that match fairly well with the data. However, when reverberation measurements are also considered there is some indication that lower wind speeds need to be invoked.

4.2 Event 3 Propagation Loss Comparisons

Throughout this event, the wind speed was very high - varying from 30 knots to more than 40 knots at the end of the event. For the first 3 hours of the event, a 30 knot wind speed was used for model predictions with the first XBT launched on the *GLOVER*. After that, the second XBT was used and the wind speed was increased to 35 knots

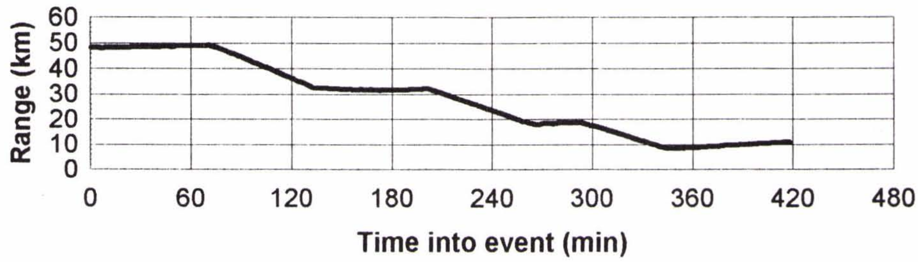

Figure 9. Event 2 Range to Propagation Loss Measurements versus Time into Event

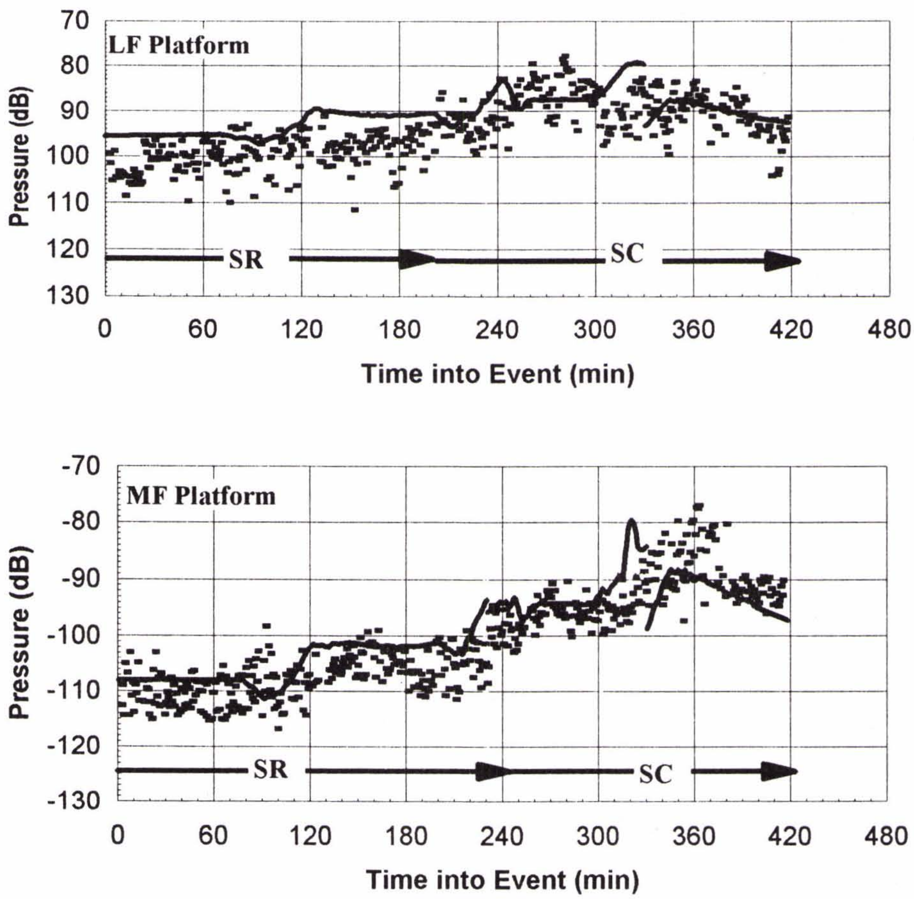

Figure 10. Comparison of Event 2 LF (upper plot) and MF (lower plot) Measured Propagation Loss Data and Predicted Propagation Loss versus Time Into Event

The MF data sets (figures 11 and 12) show unexplained variability in the first and third hours of this event. Most of this cannot be explained by a variation based on increasing range since for these time periods parallel legs were executed. Perhaps the high sea state contributed to this variability. The second half of the event shows more stability and better agreement with predicted propagation loss.

4.3 Event 8 Propagation Loss Comparisons

This event had the least environmental variability of the sea test. It was found that using the second XBT launched from the GLOVER and assuming a wind speed of 21 knots resulted in a good agreement of predictions to measured data.

During this event the propagation paths for the LF platform were dominated by surface duct, with some CZ propagation evident. This can be seen in the upper plot of figure 14. However, the MF data and predictions (lower plot of figure 14) show that the CZ propagation is the dominant propagation path.

4.4 Summary of Propagation Measurements

In order to better understand the accuracy of predictions to measurements, each event was broken up by dominant propagation mode type. Tables 3 and 4 show these mode types for LF and MF measurements.

Several statistical measures within these propagation modes were also calculated. The mean difference [denoted by m(p-m) in the table], which is the mean of the differences between the measured propagation loss and the corresponding modeled propagation loss, is shown. Also shown in these tables are standard deviations [σ(p-m) in the table] of the differences and data counts [n(m) in the table] of the measured propagation loss for each propagation mode type.

Table 3. Propagation Path and Statistical Summary of LF Measurements and Predictions for Events 2, 3, and 8 of Side-by-Side Sea Test

Event	Range (km)	Time into Event (min)	Propagation Mode	m(p-m) dB	σ(p-m) dB	n(m)
2	50-30	0-209	SR	5.6	4.1	212
	30-8	209-420	SC	1.8	5.3	217
3	40-65	0-202	SR	.6	5.5	124
	65-90	202-450	CZ	4.4	3.2	135
8	90-62	0-220	CZ,SR	5.3	3.6	166
	62-40	220-450	SR	4.7	5.4	123

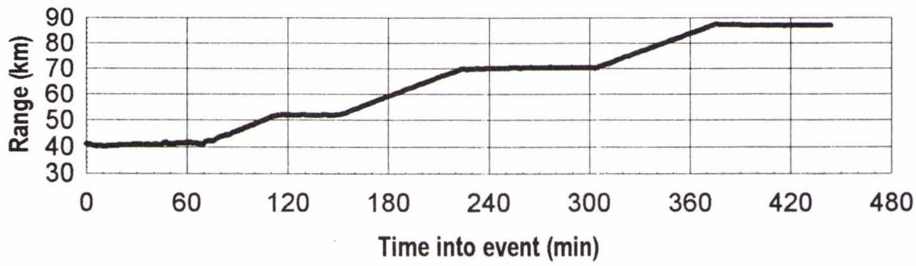

Figure 11. Event 3 Range to Propagation Loss Measurements versus Time into Event

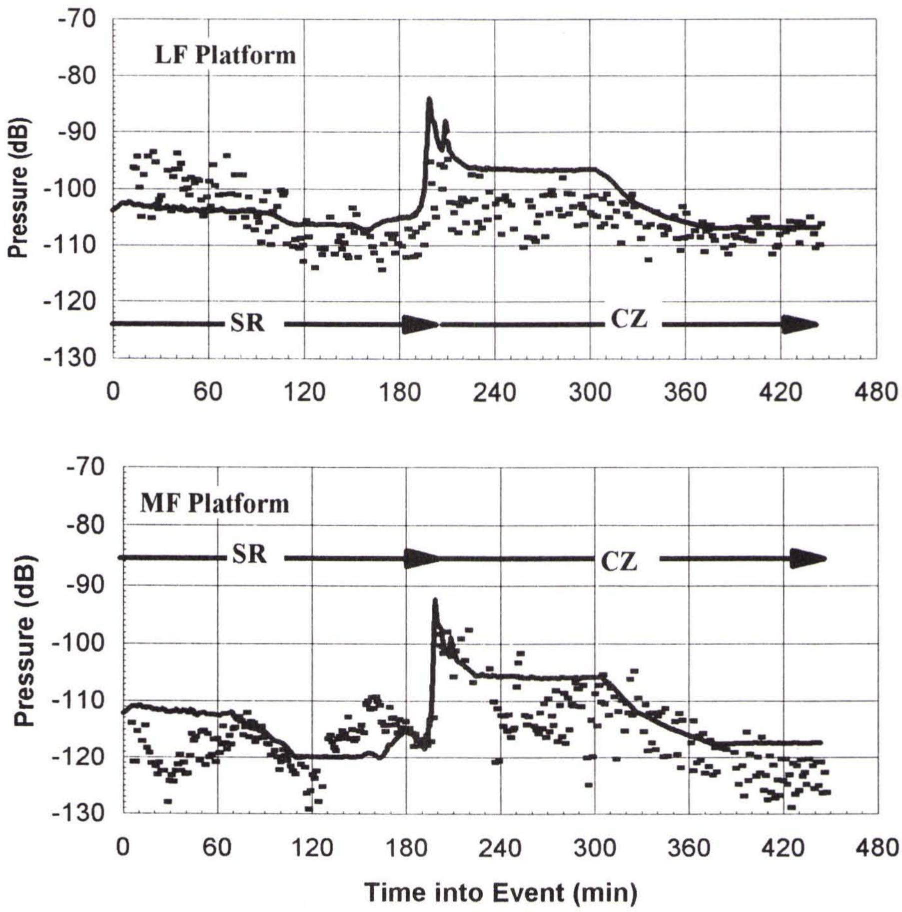

Figure 12. Comparison of Event 3 LF (upper plot) and MF (lower plot) Measured Propagation Loss Data and Predicted Propagation Loss versus Time Into Event

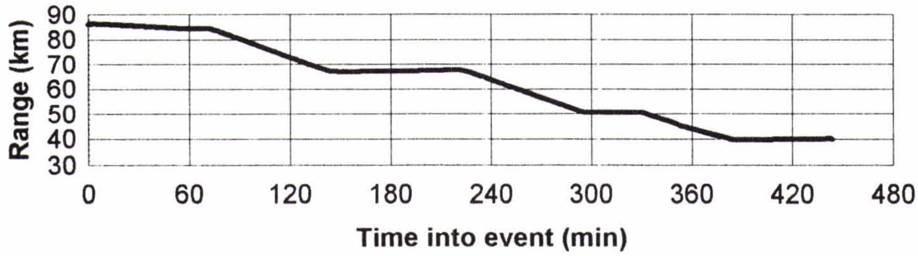

Figure 13. Event 8 Range to Propagation Loss Measurements versus Time into Event

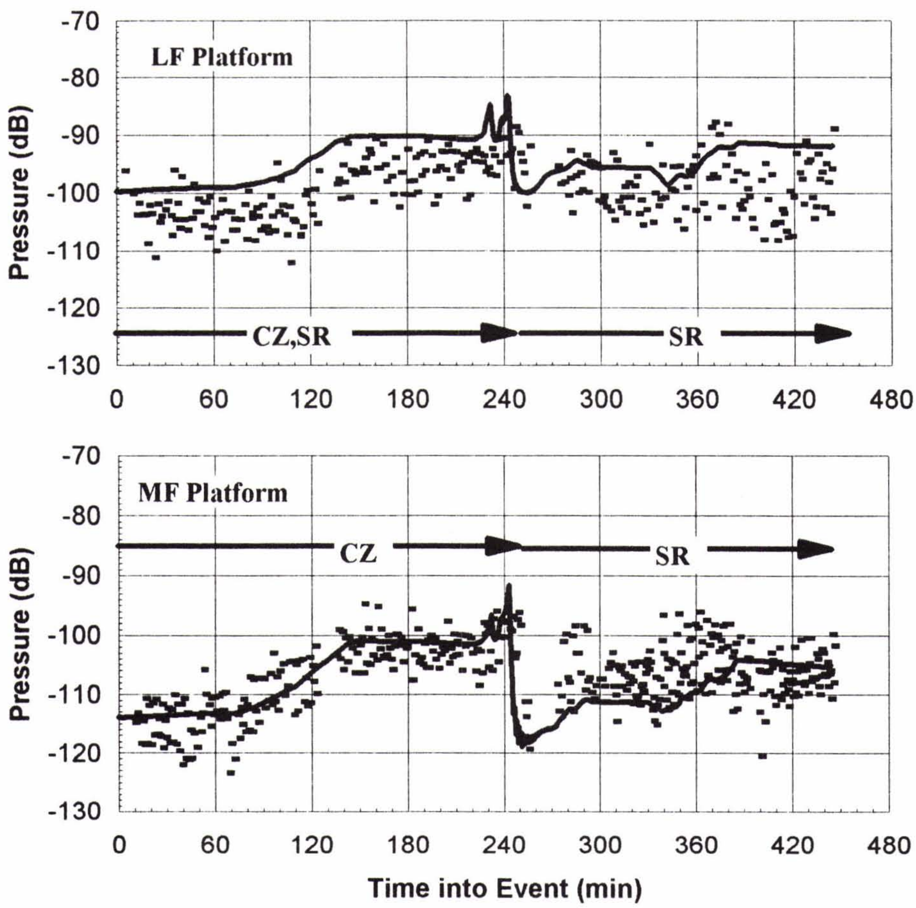

Figure 14. Comparison of Event 8 LF (upper plot) and MF (lower plot) Measured Propagation Loss Data and Predicted Propagation Loss versus Time Into Event

Table 4. Propagation Path and Statistical Summary of MF Measurements and Predictions for Events 2, 3, and 8 of Side-by-Side Sea Test

Event	Range (km)	Time into Event (min)	Propagation Mode	m(p-m) dB	σ(p-m) dB	n(m)
2	50-22	0-245	SR	-.2	5.5	185
	22-8	245-420	SC	2.9	3.7	282
3	40-65	0-202	SR	1.9	5.7	144
	65-90	202-440	CZ	4.5	4.5	154
8	90-64	0-240	CZ	.7	3.4	197
	64-40	240-450	SR	-2.3	5.4	236

In general, these tables show that both the LF and MF measurements have more propagation loss than predicted by the model. There are two basic reasons for these observations. As noted before, these measurements were made in a highly changing environment. Therefore, one reason for the error in predictions may be due to inaccurate inputs to the model - namely sound velocity profiles. Rapidly changing sound velocity profiles and/or inaccuracy in measured sound velocity profiles could account for discrepancies between the predictions and measurements. The other reason is that the surface loss model used to predict the propagation loss may not model the loss well for these frequencies and under these wind speed conditions. The details of this supposition are examined in the following paragraphs.

The tables indicate that during event 2, at intermediate ranges (approximately 25 to 50 km), the LF surface loss model does not predict enough surface loss to match the measurements. At these ranges, the model indicates that one surface reflection has occurred.

However examination of event 3 data, does not show a similar underprediction of surface loss predictions for intermediate range data. But caution should be used when drawing implications from this data set, since, for both LF and MF, figure 12 shows that the data are highly variable in this region. In CZ ranges, both LF and MF model predictions underestimate propagation loss. Once again, no bottom interactions are involved and boundary losses are due to the surface.

Analysis of event 8 propagation modes show that the surface duct is cut off under MF conditions. There is also a similar under-estimation of propagation loss for the LF case. As in the other cases, all under-estimations are due to inaccuracies in the surface loss model.

It is important to note, that other analyses of these data, indicate that if the surface loss model was modified to better estimate the measured data discussed in this paper, predicted reverberation using such a modified surface loss model would produce modeled reverberation which did not agree with measurements.

5.0 Summary

This paper presents measured propagation loss data at low frequencies and mid-frequencies. Propagation loss predicted by GSM is compared to these measurements. All the measurements were made under conditions that were dominated by surface duct and/or convergence zone conditions. Surface duct propagation was particularly dominant, however during high sea state conditions bubble scattering was not taken into account.

When events are characterized by propagation mode, propagation and surface loss accuracy and data variability can be examined.

The analysis shows that MF predictions appear to underestimate propagation loss when compared to measurements by about 1 to 2 dB. However, LF predictions show a much greater underprediction of loss. In addition, there is an increase of LF model error as range increases. This corresponds to the greater number of surface reflections as range increases. Another reason for the underprediction of propagation loss may be due to the nature of the propagation loss measurement technique. Summed rms measurements were restricted to the pulse length of the transmitted signal, however many multipath arrivals beyond the pulse length were observed.

This data set points to the need for accurate measurement of environmental parameters, such as wind speed, wave height, and sound velocity profiles measured at frequent intervals.

References

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[3] Podeszwa, E., *Sound Speed Profiles for the North Atlantic Ocean*, NUWC TD5447, 20 October 1976.