LOW FREQUENCY ACTIVE SONAR (LFA) BOTTOM LOSS REQUIREMENTS

Edmond P. Jensen and Fernando Sabbadini

Naval Undersea Warfare Center
New London Detachment
New London, Connecticut 06320
USA

Abstract A bottom interaction simulator was developed to investigate LFA bottom bounce losses, i.e., the mismatch losses, which occur in matched filter processing of bottom and target reflected signals due to the time spreading (dispersion) of the signal caused by these boundaries. The motivation behind this was the need to address bottom loss data base deficiencies to aid in future upgrades which would support LFA sonar. The simulator provided a "tool" to examine the mismatch issue and determine the mismatch losses in a low cost/low risk approach to bound the problem. The mismatch loss, the additional loss over that of a non-spread signal, is given for a number of realistic situations where measured impulse response functions represent the spreads in a series of convolutions. The target was a 100:1 scale model of a simple cylindrical shape with rounded endcaps. The bottom was represented by previously obtained SACLANT Undersea Research Center impulse response data. The results indicate that only under ideal (no spread) conditions will a total energy bottom loss data base support LFA sonar performance predictions where coherent processing is used. This highlights the need for the bottom loss data base to include the effects of these spreads.

1. Introduction

When low frequency bottom bounce signals are transmitted and received in an active sonar detection process, the signal is often spread in time (dispersion) due to its penetration and reflection from the bottom. In active sonar, the detection process of these signals typically involves coherent processing. This usually means that a mirror image of the transmitted signal, which has been shifted to the right by its duration (pulse length), is used to filter the received signal. This is called the matched filter. The convolution process of matched filtering is equivalent to correlation using a replica of the source, hence the terminology of replica correlation. The matched filter is optimum in cases were there is no time spreading of the signal caused by the medium. However, as a result of the bottom interaction caused time spread, the received signal becomes "mismatched" to the matched filter and performance becomes degraded.

The amount of degradation in performance is known as the mismatch loss (MML). It is a quantity which needs to be accounted for in the sonar equation in some reasonable way. It is important to be able to determine the potential magnitude of the MML and to relate it to the bottom loss data base, since most of the dispersion of the signal is caused by bottom interaction. The contribution to time spread caused by reflection from the target also adds to MML. The first step in dealing with the MML for LFA sonar is to determine the magnitude of this quantity and its dependence on the sources of time spreading, the bottom and the target. Analytical treatments are not readily available to examine this phenomena. Sea tests are expensive and so are not an option. Simulation of the process is a viable means to determine the magnitude of the MML.

An active sonar bottom interaction simulator was developed to have a tool with which to assess the sonar performance "mismatch" issue under bottom interaction conditions. The need to do this was driven by requirements to specify a LFA bottom loss data base. The simulator has been used with certain acquired sets of bottom impulse response data to obtain the MML due to matched filter processing. It represents a low cost alternative to expensive sea tests to bound the problem and provide inputs to the development of a LFA bottom loss data base.

This report provides some early processing results showing the additional losses that might be needed in a sonar performance estimation of LFA bottom bounce sonar. As such it is part of a somewhat continuing effort to determine the bottom loss requirements for different sonar conditions.

For the purposes of this report, the simulator utilizes archived bottom impulse response data [1] obtained several years ago from the SACLANT Undersea Research Center and 100:1 scale model target impulse response data [2] obtained from tank measurements at the Naval Undersea Warfare Center Division, Newport. The target was a simple cylinder with rounded endcaps. On scaling to full size, the target provided simple representations of the effects of target echo spreading with aspect angle.

The MML, the additional loss due to time spreading of the signal over that of a non-spread signal, is given for a number of cases using samples of data from the SACLANT data set and target aspects of bow, broadside, and quarter. Various source waveforms are included in the simulator, with an LFM pulse being the waveform used here.

2. Active Sonar Bottom Interaction Simulation

Simulation of a given process is often undertaken to obtain a particular insight to the process. It often represents a low cost approach when compared to sea tests etc. In the area of bottom interaction acoustics, questions are often asked such as: Do you think a generalized forward scattering function representation of the bottom impulse response function will be a suitable product for the next upgrade to the standard data base to support LFA sonar? Will a characterization based on bottom types be reasonable? How can one address such questions? Simulation of the process is a reasonable approach to obtain information to address the question. On the Navy side, this sort of effort is imperative in order to be smart buyers.

The above questions being the motivation of the simulator, the LFA bottom interaction simulator (LFABS) is being continually developed. The LFABS scenario represents a deep water situation, where at least one target and two bottom interactions are typical in an arrival and other multipath are gated out in time or space. In shallow water regions, where more than two bottom interactions are common, multipath overlap can be expected. This situation has not been addressed at this time.

2.1 Simulation Overview
A cartoon of the simulation situation is presented in figure 1.

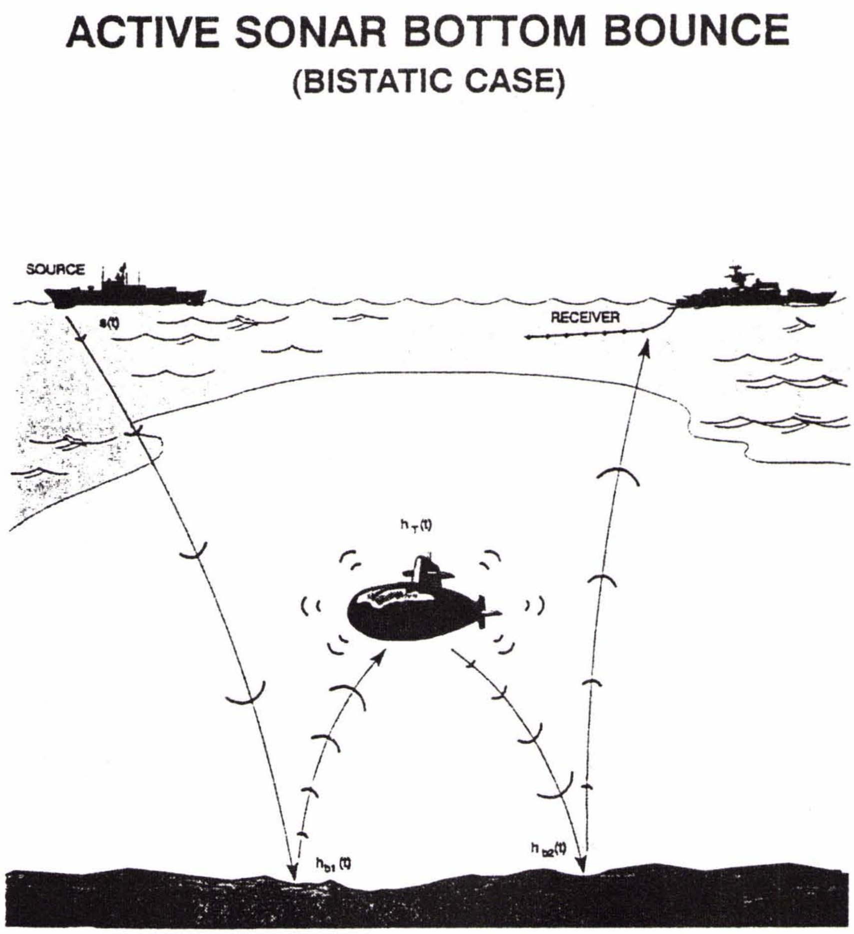

Figure 1. Cartoon of the LFA sonar bottom interaction simulation scenario. One target and two bottom interactions are considered.

The transmitted signal, s(t), propagates through the ocean and has two interactions with the bottom and one interaction with the target before being received. The water column does cause some dispersion, but it is being neglected in comparison to the bottom and target. In general the two bottom interactions are not collocated because of ship movement or bistatics. The simulation is given by a series of convolutions as shown in figure 2.

ACTIVE SONAR BOTTOM BOUNCE SIMULATION

SOURCE => MEDIUM BOTTOM $_1$ => TARGET => MEDIUM BOTTOM $_2$ => MATCHED FILTER

$$s(t) \otimes h_{b1}(t) \otimes h_T(t) \otimes h_{b2}(t) \otimes mf(t)$$

Figure 2. Functional diagram of the simulation showing convolutions of the source, bottom and target terms being matched filtered.

At the output of the matched filter, the MML is calculated. For the purposes of calculation of the MML, the amplitudes of the signals are not important, only the shapes are needed. Therefore, propagation loss doesn't enter into the calculation as will be seen.

2.2 Matched Filtering Overview

Matched filtering is the optimum processing under conditions of a known signal in white noise [3]. Under ideal conditions, the output of the matched filter will peak at a value corresponding to the total energy of the input, i.e., the sum of the squares of the input. This is the advantage of matched filtering. The matched filter, under ideal conditions, compresses the total energy of the input signal over time into one filter resolution cell of the matched filter. When the signal is mismatched, the output peak is less than the ideal total energy.

2.3 Matched Filtering Notes

Let mf(t) be the matched filter reference. Typically, for optimum performance when no dispersion exists, mf(t) = s(PL-t) where s(t) is the source waveform and PL is the pulse length. The output of the matched filter, y(t), is given through convolution by:

$$y(t)=(x(t) + n(t)) \otimes mf(t)$$

where the signal input, x(t) is given by:

$$x(t)=s(t) \otimes h(t)$$

and n(t) is the assumed input white noise. The medium response is combined from the individual terms through:

$$h(t)=h_{b1}(t) \otimes h_T(t) \otimes h_{b2}(t)...$$

indicating the convolution of the individual impulse responses of the bottom and the target.

It can be shown that:

$$SNR_{peak}=\frac{\left(\sum_k mf(k)x(p-k)\right)^2}{\frac{N_0}{2}\sum_k (mf(k))^2}$$

[e.g., see Burdic]

p indicates the position of the output time sequence where the peak occurs and N_0 is the white noise spectral noise density (e.g., watts/Hz).

Under ideal "matched conditions, mf=x and p corresponds to the pulse length resulting in:

$$SNR_{ideal}=\frac{2\ E}{N_0}$$

where E is the total energy of the input.

2.4 Measure of Effectiveness: The Mismatch Loss (MML)
In order to determine the system related performance degradation define the MML as follows:

$$MML=10\log_{10}(\frac{SNR_{peak}}{SNR_{ideal}})$$

Using the above results this becomes:

$$MML=10\log_{10}\left(\frac{(\sum_k mf(k)x(p-k))^2}{E\sum_k (mf(k))^2}\right)$$

This can be simplified by recognizing that:

$$E=\sum_k x^2(k)$$

and factoring out the magnitude of the above vectors we find:

$$MML = 20\log_{10}(|\sum_{k} mf_n(k)x_n(p-k)|)$$

$$= 20\log_{10}(|peak\ value|)$$

where the "n" subscripts indicate normalization of the input and the matched filter. It is interesting to see that MML depends on the shape of the input and the reference, but not the magnitude, alleviating the need to be concerned about the propagation loss along a path. It is also interesting to note that the "peak" within the logarithm of the last equation appears as a "voltage" type term, even though under ideal "matched" conditions, the peak value out of the filter equals the total energy of the input, a voltage squared term. Intuitively, this is the expected result because we are dealing with the output of a filter which is a voltage.

Examining the above analysis, it is seen that under ideal "matched" conditions, a total energy bottom loss data base will support bottom bounce sonar performance predictions. On the other hand, under dispersive conditions the total energy data base will be optimistic by an amount equal to the MML. It is therefore necessary to quantify the magnitude of the MML to determine its importance.

3. Target Inclusion Rationale

First though, being a bottom interaction study, some words are needed to defend the inclusion of target spreads. Two points are given to show why it is important. First, consider whether the following equation is true:

$$MML(2\ bottom + 1\ Tgt\ interaction) = MML(2\ bottom) + MML(1\ Tgt)$$

If it is true, the spreads are independent in the MML calculation and can be studied that way. If not, the target must be included. This can best be seen by thinking of the case where the impulse response function is a delta function in time. In this special case, convolution is the same as multiplication and the above equation holds. However, we are not dealing with delta functions and the examples to be shown demonstrate that the above equation doesn't hold.

Secondly, it is important to include the target to determine whether the target time spreads might dominate the MML, in which case the LFA bottom loss data base specification may be relaxed regarding time spreads.

4. Simulator Inputs

4.1 Bottom Inputs

As mentioned previously, bottom impulse response functions were obtained from archived SACLANT CENTER data. This data set consists of 6 sites in the Mediterranean Sea, with several different bottom impulse responses as a function grazing angle at each site. The data set impulse responses were obtain by deconvolution using the direct and bottom reflected paths. The data are broadband (.05 to 5 kHz). Testing of the simulation processing was done using data from what appeared to be the worst case (site 6 located SW of Crete in about 2700 m of water) based on time spread (figure 3). Three impulse response functions, h_{b1}, h_{b2}, h_{b3}, were chosen from this site in order to demonstrate the bottom interaction simulation. These are shown in figures 4a, b and c. The bottom grazing angles were 20, 22, and 24 degrees.

4.2 Target Inputs

The rationale to include the target spreads in the process was explained above. In order to obtain representative target impulse responses for the simulation, 100:1 scale model echoes were obtained from tank measurements and deconvolved using the echo and incident pulse. The scaled down frequency for these measurements ranged from .75 to 1.2 kHz. For the simulation examples to be presented here, monostatic impulse responses were obtained for bow (0°), broadside (90°), and quarter (46°) aspects. These are referred to as T_{00}, T_{90}, and T_{46} respectively. The scale model target in this case was a clean (no features such as a sail etc.) surface cylinder as mentioned earlier. Since it is featureless, at the frequencies being considered, e.g., 1 kHz, the spreads from it were perhaps less than would be expected from a more complex target. The rescaled to full size impulse responses are shown in figures 5a, b and c. The broadside aspect gives the least spread and the bow the most, as would be expected.

5. Simulation Results

5.1 Examples

In order to demonstrate the simulation process, examples of the matched filter input and output are given for various combinations of the following terms: s(t), $h_{b2}(t)$, $h_{b3}(t)$, $T_{46}(t)$, and mf(t). The source was a 1.5 sec LFM sweep from 950 to 1050 Hz. The combination of all these terms represented a worst case scenario with a MML = 7.7 dB. Individual steps will be shown. Figure 6a gives the source waveform. Figure 6b shows the source convolved with T_{46}. The source convolutions with the individual bottom responses are

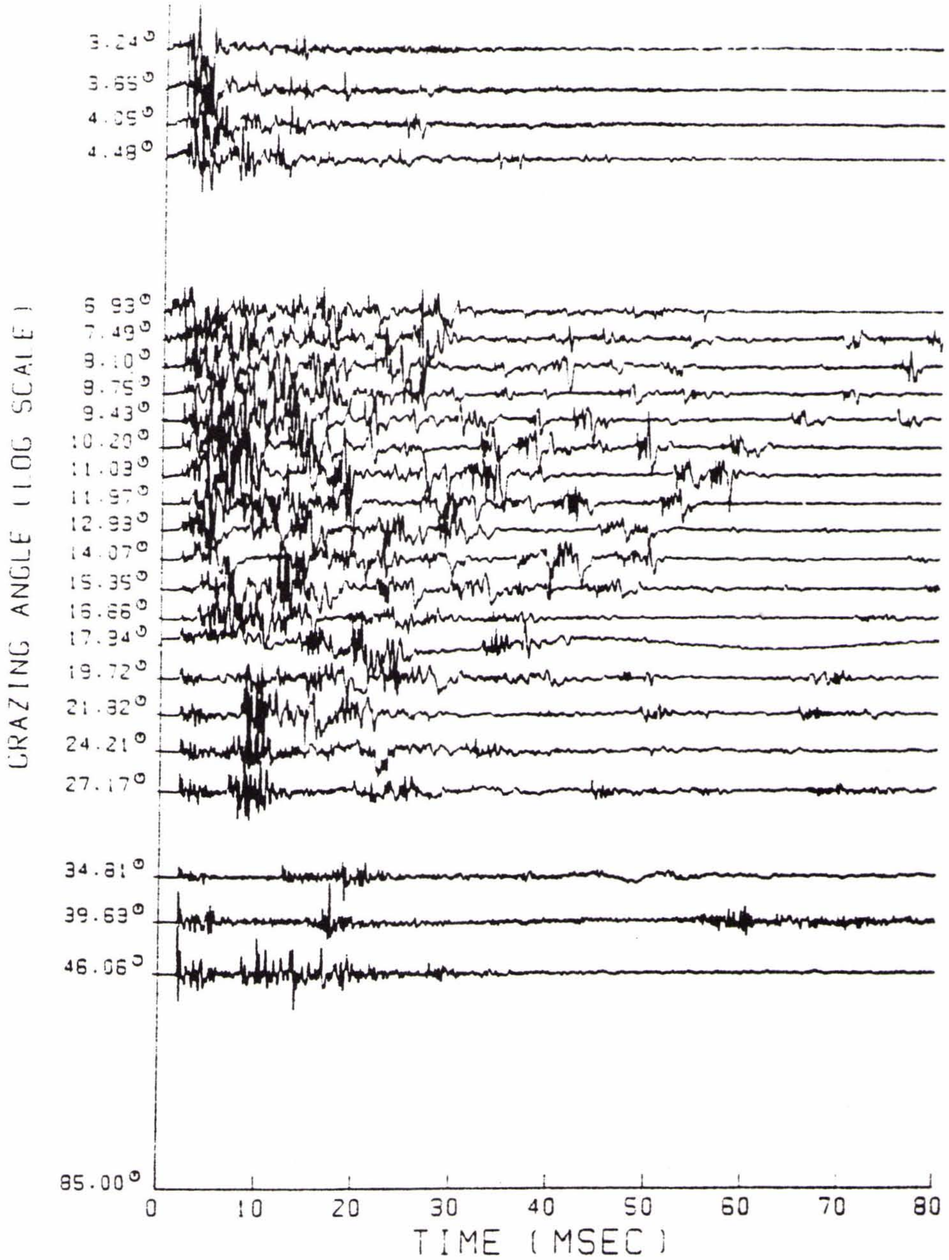

Figure 3. SACLANTCEN data set of broadband impulse response functions.

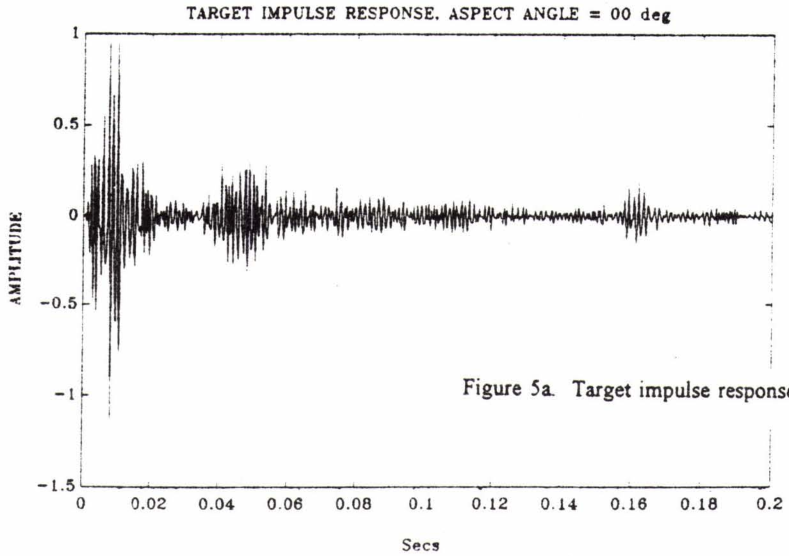

Figure 5a. Target impulse response function, $T_{00}(t)$, bow aspect.

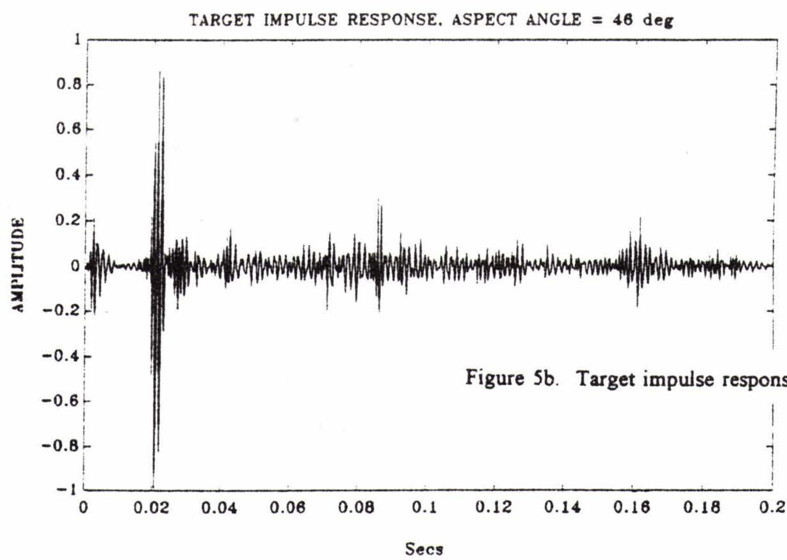

Figure 5b. Target impulse response function, $T_{46}(t)$, quarter aspect.

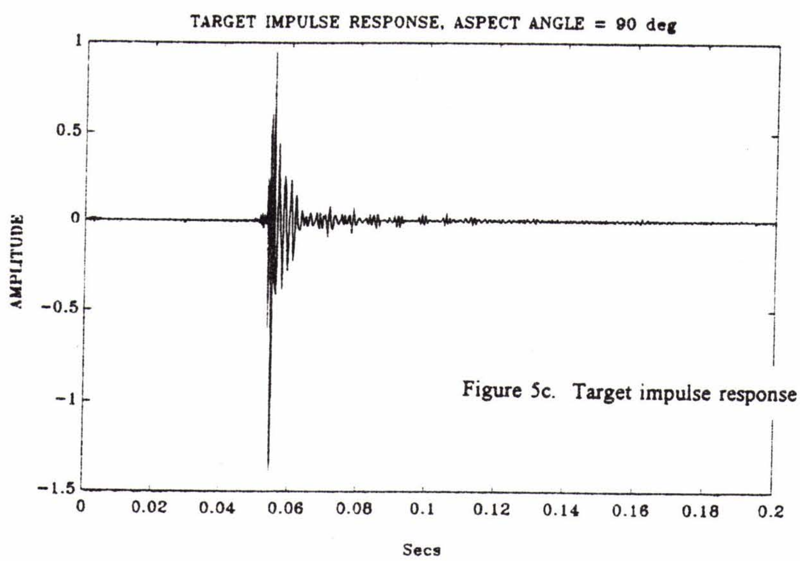

Figure 5c. Target impulse response function, $T_{90}(t)$, broadside aspect.

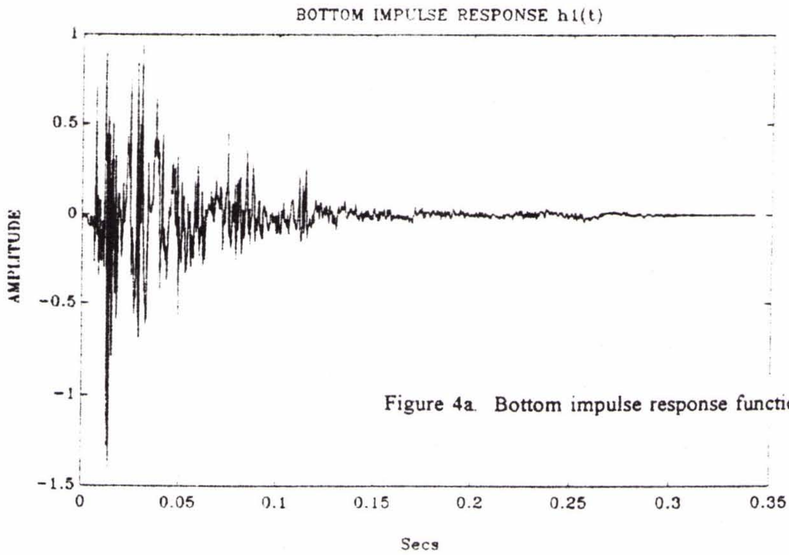

Figure 4a. Bottom impulse response function, $h_{b1}(t)$, at 22° grazing angle.

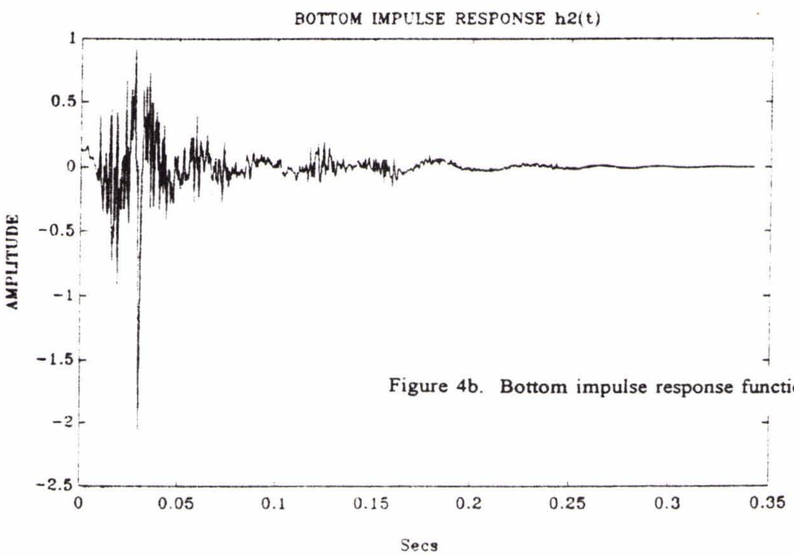

Figure 4b. Bottom impulse response function, $h_{b2}(t)$, at 24° grazing angle.

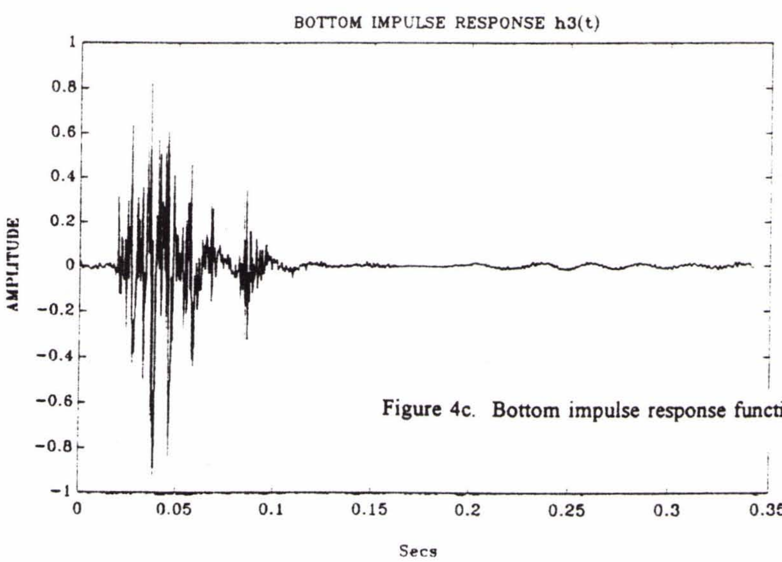

Figure 4c. Bottom impulse response function, $h_{b3}(t)$, at 20° grazing angle.

shown in figures 7a and 7b. The source convolutions with the two bottom interactions first with no target and then with a target is shown in figures 8a and 8b. The matched filter outputs for these cases are shown in the figures 9a,b and 10a,b. The MML is given on each figure. The output for the input of the case in figure 6b is not plotted, but the MML was 1.6 dB.

5.2 Tabulated Results

Several combinations of the h's and T's were examined in the simulation for up to two bottom and one target interaction for the source waveform described above. The simulation provided the values of MML for each of the cases shown in Table 1. An asterisk (*) denotes the terms used in the convolution process in each case. A double, **, indicates that the same bottom interaction was used twice, indicating a double bottom interaction with the outgoing and return path being the same, i.e., a pure monostatic case. The other multiple bottom interaction cases are quasi monostatic in that the return path is slightly different than the outgoing path.

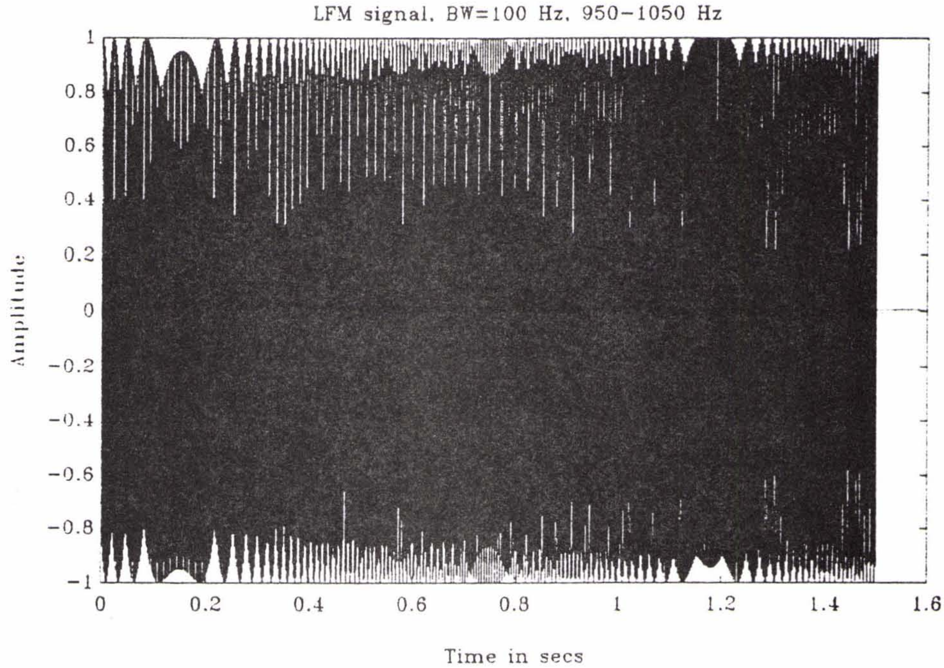

Figure 6a. The LFM source waveform, s(t).

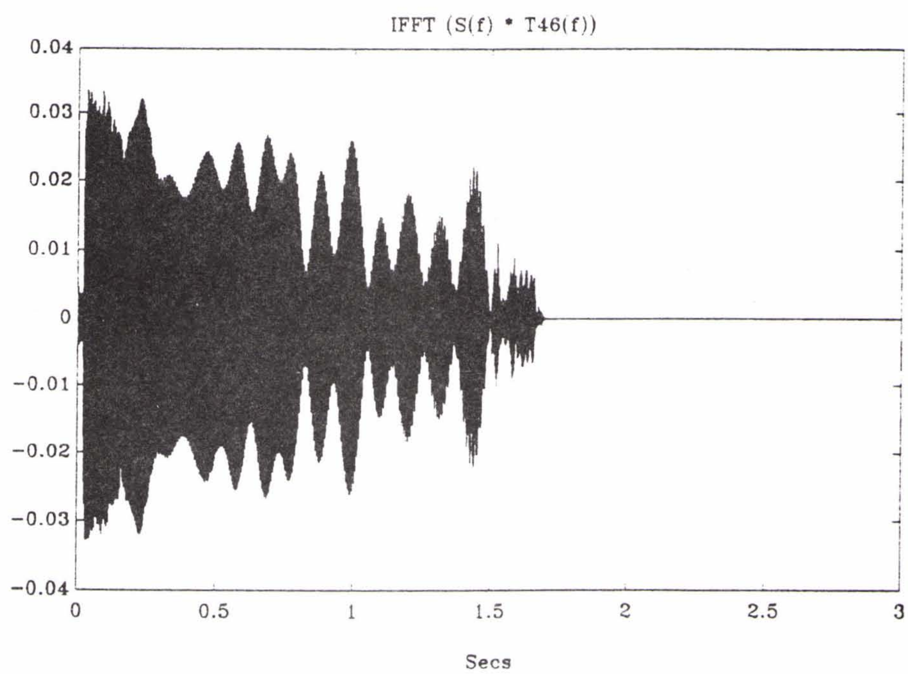

Figure 6b. The source waveform convolved with $T_{46}(t)$.

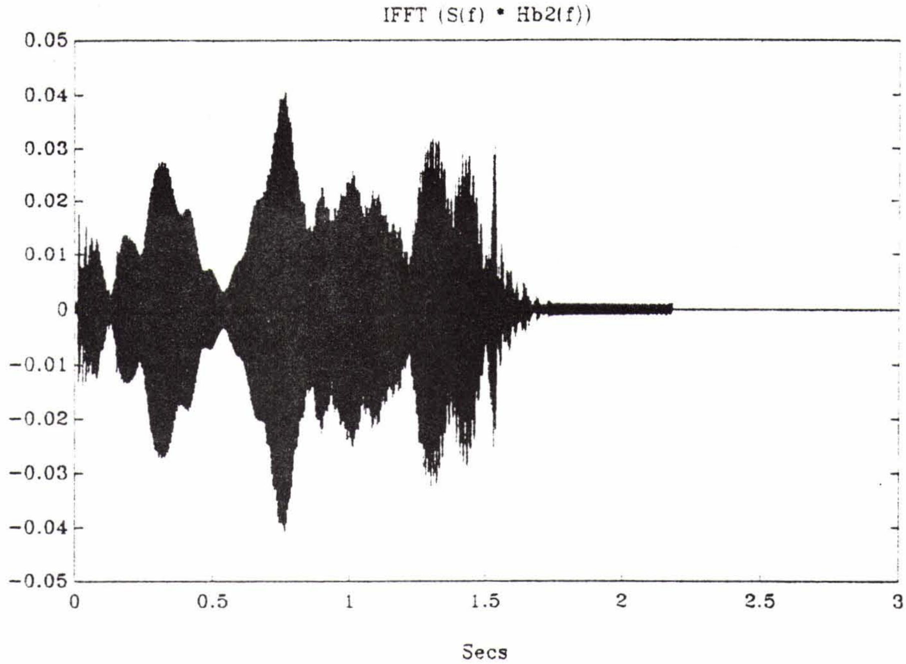

Figure 7a. The source waveform convolved with $h_{b2}(t)$.

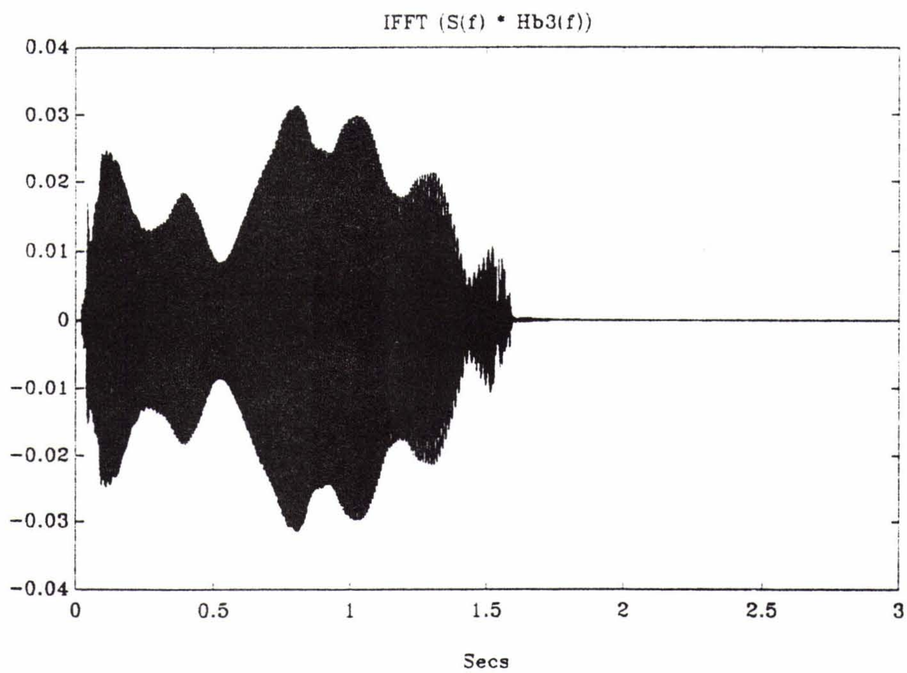

Figure 7b. The source waveform convolved with $h_{b3}(t)$.

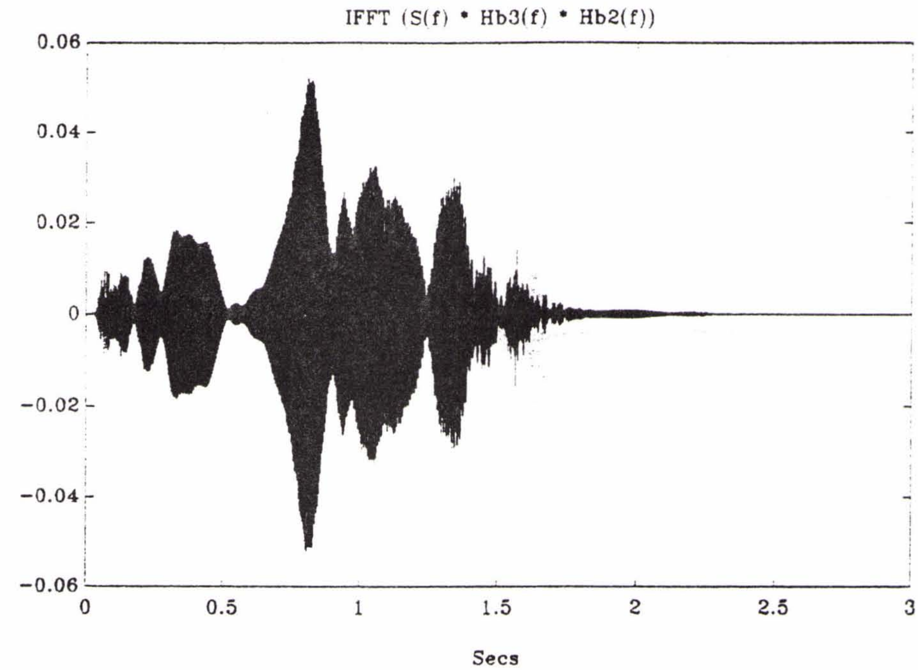

Figure 8a. The source waveform convolved with h_{b2} and h_{b3}.

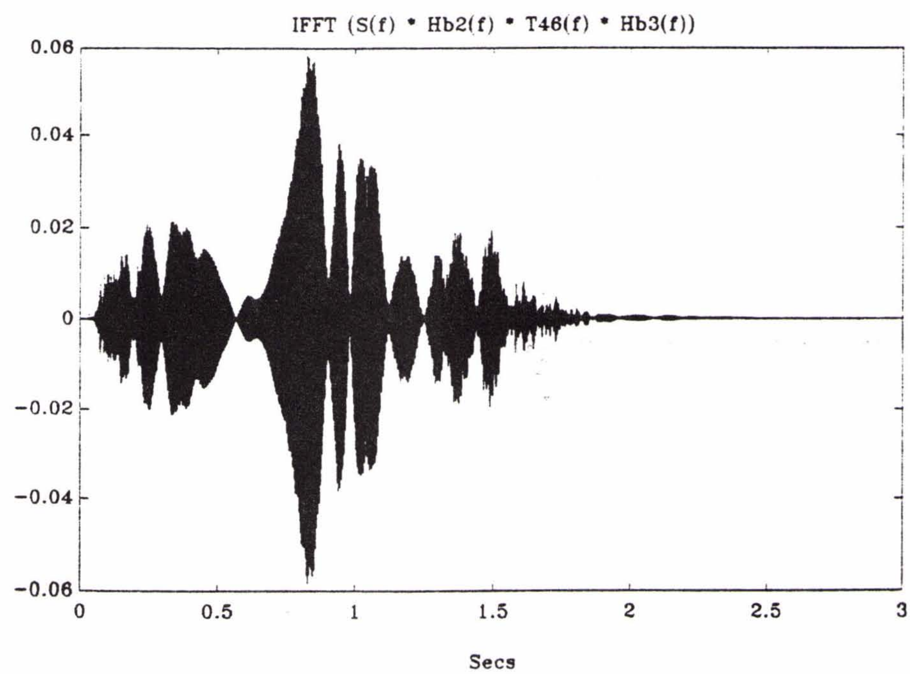

Figure 8b. The source waveform convolved with h_{b2}, h_{b3}, and T_{46}.

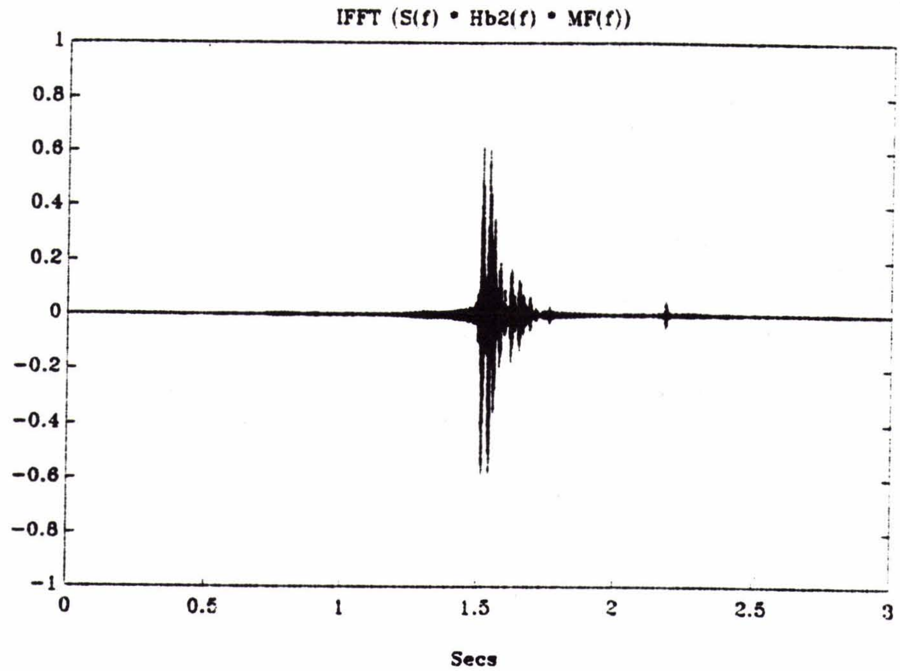

Figure 9a. Matched filter output of input from figure 7a. The MML is 4.2 dB.

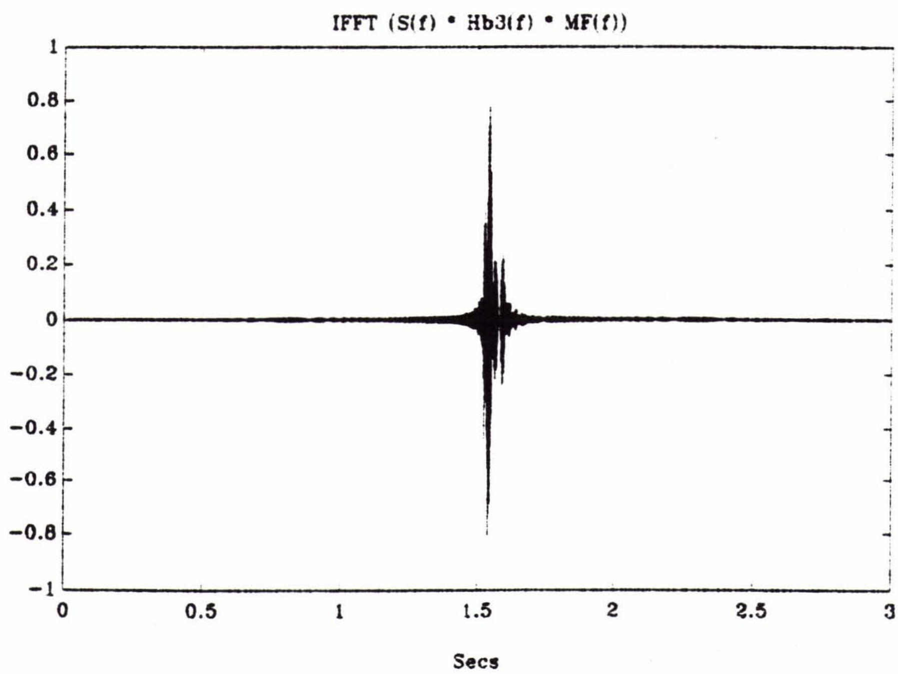

Figure 9b. Matched filter output of input from figure 7b. The MML is 1.8 dB.

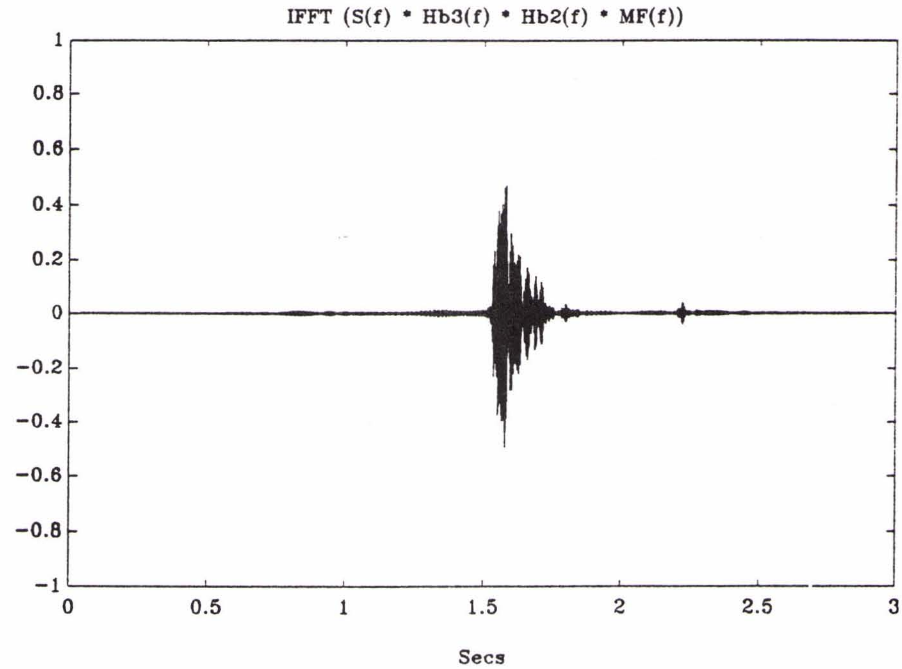

Figure 10a. Matched filter output of input from figure 8a. The MML is 6.1 dB.

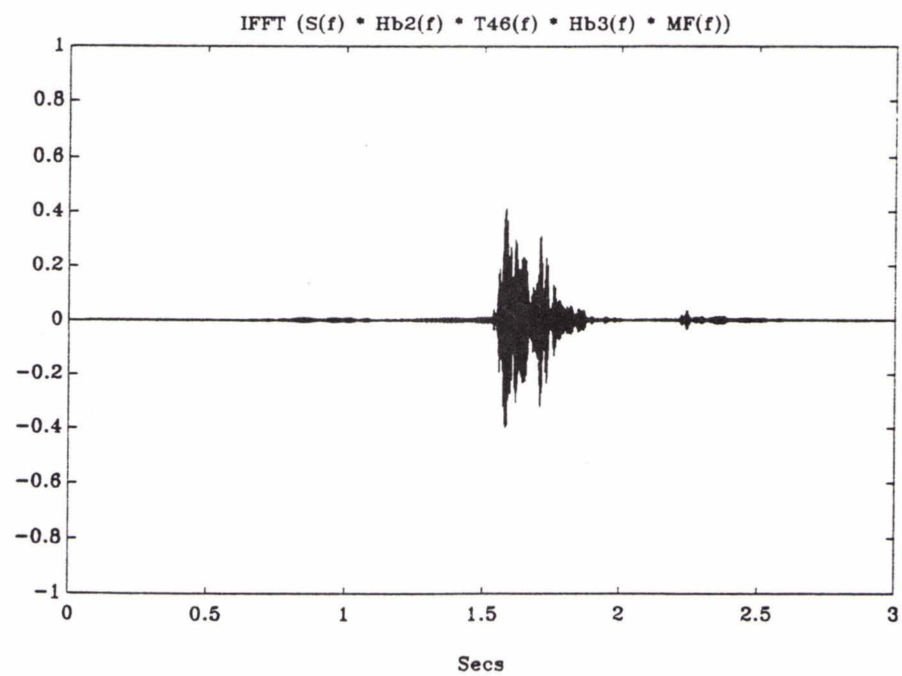

Figure 10b. Matched filter output of input from figure 8b. The MML is 7.7 dB.

TABLE 1
MISMATCH LOSSES FOR SEVERAL COMBINATIONS OF INPUT

PROCESS

s(t)	h_{b1}(t)	h_{b2}(t)	h_{b3}(t)	T_{00}(t)	T_{46}(t)	T_{90}(t)	mf(t)	MML(dB)
*	*						*	4.3
*		*					*	4.2
*			*				*	1.8
*				*			*	4.7
*					*		*	1.6
*						*	*	0.2
*	**						*	5.1
*		**					*	5.1
*			**				*	5.3
*	**			*			*	7.1
*	**				*		*	6.6
*	**					*	*	5.6
*	*	*					*	5.2
*	*		*				*	5.7
*		*	*				*	6.1
*	*	*		*			*	6.2
*	*	*			*		*	7.4
*	*	*				*	*	5.3
*	*		*	*			*	6.9
*	*		*		*		*	7.0
*	*		*			*	*	6.2
*		*	*	*			*	7.2
*		*	*		*		*	7.7
*		*	*			*	*	7.2

An examination of Table 1 provides examples of the need to include the target spreads in the simulation. The need for this is greater when the target's spread is large. With small spreads, such as T_{90}, the target's impulse response approaches a delta function in time and tends to separate out, although the last process in the Table seems to be an exception to this by about .9 dB. The result is that if individual MML terms are added together to obtain the total, significant differences can occur from that obtained by treating the process as a whole.

The convolutions of all the above processes were done in the frequency domain, but checks were made using time domain processing with the results being identical, but much slower in computational speed, in one case by a factor of forty.

6. Conclusions

The results indicate that only under the ideal conditions of no dispersion will a total energy bottom loss data base support LFA sonar performance predictions when coherent processing is used. If ideal conditions are not present, mismatches are seen to potentially contribute to a significant amount of additional losses which must be accounted for in the bottom loss data base. Otherwise bottom bounce performance predictions will be inadequate. A methodology needs to be developed to include the effect of time spreads in the data base. Furthermore, although it isn't the main topic of this paper, these spreads will degrade operational performance. Performance predictions will improve as the data bases are upgraded. However, in order to improve operational performance, a means to capture back the losses due to mismatching needs to be found. Ultimately, this could lead to developing an environmental acoustic based matched filter which has ability to adapt in a robust way to the input that it is receiving, thus taking on the characteristics of matched field processing. Some success has been attained recently in adapting to ducted water column dispersion [4]. The bottom may be more of a challenge. Nevertheless, the recaptured gains associated with this are bound by the MML.

References

[1] Hastrup, O. F., and Akal, T. Acoustic Reflectivity of the Sea Floor in the Central Mediterranean (U)," SACLANTCEN SR-27. La Spezia, Italy, SACLANT Undersea Research Centre, 1978 (NATO RESTRICTED).

[2] Godoy, C., "Private Communication," Naval Undersea Warfare Center Division, Newport, Rhode Island.

[3] W. S. Burdic, Underwater Acoustic System Analysis, Prentice Hall, Inc., Englewood Cliffs, NJ, 1991, 2nd ed., pp. 366-368.

[4] Hermand, J-P., and Roderick, W.I., Channel-adaptive reception of wideband acoustic signals, *In* Proc. of the European Conference on Underwater Acoustics, pp. 71-74.