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MONTEREY, CALIFORNIA

THESIS

AN ANALYSIS OF THE EFFECTS OF ENERGY SPREADING LOSS AND TRANSMISSION LOSS ON LOW FREQUENCY ACTIVE SONAR OPERATIONS IN SHALLOW WATER

by

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Energy Spreading Loss (ESL) is qualitatively defined as the reduction in peak power level due to energy spreading of a transmitted acoustic pulse in time. An analysis of the impact of bathymetric geometry and sediment type on ESL and TL associated with the Low Frequency Active/Compact Low Frequency Active (LFA/CLFA) sonar operations was conducted utilizing the FEPE, FEPE_SYN, and EXT_TD programs to model the time spreading of the acoustic pulse due to multipath propagation in shallow water. Both a Blackman windowed pulse and a Continuous Wave (CW) pulse were used in this analysis. The Blackman pulse had a center frequency of 244 Hz with a bandwidth of 24 Hz. The CW pulse had a center frequency of 244 Hz with a bandwidth of 0.0625 Hz. Model inputs were a geoacoustic description of the Tanner Bank region off the coast of San Diego and a typical late summer sound speed profile taken from the MOODS database. ESL and TL's impact on low frequency active sonar operations was determined as a function of bathymetry, sediment type, sound speed profile, and pulse length.

The results showed that ESL is inversely related to pulse duration and at low frequencies is relatively uninfluenced by sediment type. When pulse lengths were reduced to less than 1 second, ESL became appreciable (> 6 dB one way) and was an important segment of the active sonar equation. TL was found to be the dominating factor in LFA/CLFA operations for pulse lengths greater than 1 second and was greatly influenced by sediment type and sound speed profile.

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I. INTRODUCTION

A. NAVY'S INTEREST IN LFA

During the late nineteen seventies and early eighties, the Soviet submarine fleet introduced technological advances in noise quieting that significantly decreased radiated acoustic signature source levels. These advances in quieting continue today and constitute a direct threat to the performance of the US Navy's passive ASW sonar systems. As a result, increased interest is now being placed on active acoustics for the Navy's underwater sonar surveillance systems. One component under investigation is the use of the Low Frequency Active (LFA) sonar system. This system has been tested as a part of the Critical Sea Test Program (CST), begun as a CNO urgent antisubmarine warfare (ASW) research and development program initiative in 1987 to address some of the unknown active acoustic research and development issues relating to the LFA sonar system's performance, generally anticipated to take place in a deep water environment.

With the end of the end of the cold war, the US Navy's ASW interests shifted from the open ocean, deep water SSN and SSBN threat to that of shallow water, diesel-electric submarines operated by second or third world countries in limited regional conflicts. This shift posed two major challenges to the ASW picture: 1) the high spatial and temporal variability of the ocean environment associated with the littoral region; and 2) the near lack of detectable acoustic signatures associated with a modern diesel-electric submarine operating on the battery. In addition, the advances in the air independent propulsion (AIP) submarine systems now allow modern diesel submarines to go weeks to more than a month without snorkeling.

Due to the substantial changes wrought by these two challenges, CST shifted its focus in 1991. During Phase II of the program, LFA was developed into a system called compact LFA (CLFA) which could be utilized for effective detection, localization, and prosecution of an underwater ASW threat in shallow water. One of these tests, CST 10, also called Magellan II, was conducted in the Southern California Operations Area (Socal Oparea) near Tanner and Cortez Banks with multiple air, surface, and subsurface bistatic and monostatic participants. The data from CST 10 was chosen by the Naval Space and Warfare Command as an area to analyze in this thesis effort because of its similarity to the Gulf of Oman, a possible littoral ASW threat region.

B. BACKGROUND

Predicting and understanding the performance of shallow water acoustics is extremely complex due to the highly variable spatial and temporal nature of environmental conditions encountered there. Shallow water coastal regions can be subject to river runoff, coastal upwelling/downwelling and a number of other factors effecting the water column temperature and salinity variability. Shallow water areas often contain areas of rapid bathymetric changes and highly variable sediment composition. At low LFA frequencies bottom and sub-bottom reverberation is greatly increased in shallow water and is highly dependent on the geoaccoustic sub-bottom properties. Additionally, the littoral is often an area rich in biologic activity which can be a source of ambient noise and volumetric reverberation, both of which are highly variable in time and phase.

Historically, most tactical active sonars have transmitted waveforms centered at several kilohertz frequencies, e.g., ~3 kHz. At these high frequencies the time stretching or pulse distortion caused by the multipath/multimode propagation generally encountered in shallow water causes a significant performance degradation, called energy spreading loss (ESL). At tactical sonar frequencies ESL is a 10 dB performance issue, not a 1 or 2 dB problem (Tanaka, 1996). This thesis will assess the performance impact of ESL and TL at the lower frequencies associated with LFA systems. LFA is subject to multipath refraction and diffraction within the sediment sub-bottom that are much different than those same interactions at higher mid-kilohertz frequencies. It is this multipath interaction and diffraction which require the use of full wave equation solutions at low frequencies in shallow water. This study uses the Finite Element Parabolic Equation (FEPE) propagation model [Collins, 1988] to solve the full wave equation. A time domain version of FEPE, FEPE_SYN [Collins, 1988] is used to predict the time arrival structure of a pulse with finite bandwidth at LFA frequencies. FEPE_SYN is only able to model the propagation results for an ideal waveform, which is not practical for active sonar systems transmitting complex waveforms. Therefore another program, EXT_TD (Rovero, 1992), using the FEPE_SYN output and the ocean transfer function verses frequency inputs extend the model estimate for any specified transmitted waveform.

Tactical active sonar system performance in shallow water has been demonstrated to be significantly degraded by the ESL phenomena. This phenomena has been studied and modeled [Tanaka, 1996] as it related to high/mid-kilohertz frequencies for pulses with Blackman weighting. It is the purpose of this analysis to extend this work to lower LFA frequencies and LFA transmitted pulse shapes.

This study will show that ESL will not cause significant LFA system performance degradation for the very long (2 to 5 second) pulse lengths associated with deep water deployment where very long detection ranges (hundreds of miles) is the objective. It is in shallow water regions where CLFA is utilized and shorter pulse lengths are required such that the first 3 to 5 km are not masked during pulse transmission that ESL becomes a concern.

The propagation environment examined was based on oceanographic and geoacoustic measurements in the Tanner/Cortez Banks region. To assess performance degradation, ESL has been treated as an active sonar equation parameter, being added as an additional loss to the standard deep water terms, (e.g., Urick, 1983). The models FEPE_SYN [Collins, 1988] and EXT_TD [Rovero, 1992] have been used to estimate the one way magnitude loss and time stretching characteristics of ESL experienced using both continuous wave (CW) and Blackman pulses from an LFA source for a variety of source and target depths. FEPE [Collins, 1988] was used to model transmission loss (TL) as a function of sediment type, sediment thickness, source/receiver depth, water depth, and sound speed profile characteristics. This analysis demonstrated that TL, not ESL, was the dominant factor in limiting sonar performance in the Tanner Bank region for pulse lengths greater than 2 seconds.

1. Definition of ESL and TL

Transmission Loss (TL) can be described as the reduction in peak power of an acoustic pulse due to geometric stretching, attenuation, scattering, etc. Energy lost due to these effects never reaches the receiver array and cannot be recovered. Energy spreading loss (ESL) can be described as the reduction in peak power due to the time stretching of the originally transmitted acoustic pulse due to multipath propagation and sub-bottom interactions. This time-stretched energy does reach the receiver array, but is an energy loss because matched filter or signal replica correlators used on current operational tactical active sonars are "matched" to the transmitted pulse, not the propagated pulse . This "matching" of the replica and transmitted pulses is a signal processing technique developed for deep water situations where time stretching is generally not a problem, i.e., the shape of the transmitted pulse and propagated pulse are generally quite similar. In shallow water, multipath influences may significantly alter the shape of the propagated pulse from that of the original transmitted pulse. This results in only a small portion of the available energy being processed at the receiver array. Future advanced processing methods such as inverse beamforming (IBF) [Nuttal and Wilson, 1991] and matched field processing (MFP) [Bucker, 1978], can be used to overcome the performance degradation due to ESL if the local oceanographic/geoacoustic shallow water environment can be modeled accurately and estimated using inverse techniques (IT) [Null et al, 1996].

2. Shallow Water Considerations

Shallow water regions have at least two important bathymetric geometries that are of concern in CLFA operations: the relatively flat continental shelf zone and the upslope region of transition from deep water up the continental slope and onto the continental shelf. These geometries were modeled during this study utilizing the Tanner Bank bathymetry. While Tanner Bank is steeper than the continental slope, it allows for a contrast in LFA/CLFA performance in these two geometries. Areas of additional concern during shallow water operations are the highly variable sediment structure as well as the plethora of factors influencing sound speed. As will be shown, sediment type and sound speed profile have very significant, but very different impacts on ESL and TL in these two environments.

3. Active Sonar Equation

In CLFA source placement tactics it is preferable to "stand off" in deep water at the greatest range possible and detect targets in the shallow water slope or shelf regions. In order to determine the extent to which this is possible it is necessary to examine the active sonar equation:

$$SE = SL - 2TL - 2ESL + TS - RL - DT \quad \text{(Reverberation Limited)} \qquad (1\text{-}1)$$

$$= SL - 2TL - 2ESL + TS - (AN-AG) - DT \quad \text{(Ambient Noise Limited)} \qquad (1\text{-}2)$$

where SE = signal excess (dB)

SL = source level (dB re 1m)

TL = transmission loss for one way propagation (dB)

ESL = energy spreading loss for one way propagation (dB)

TS = target strength (dB)

RL = CLFA beam reverberation (dB)

AN = ambient noise (dB)

AG = array gain (dB)

DT = detection threshold

A precise estimate of all terms in the active sonar equation for CLFA in the Tanner Bank region will not be attempted in this thesis. However, utilizing representative estimates of these parameters and setting SE = 0, a CLFA figure of merit (FOM) is calculated.

$$\tfrac{1}{2}\,\mathrm{FOM} = \mathrm{TL} + \mathrm{ESL} = \tfrac{1}{2}\,[\mathrm{SL} - \mathrm{RL} - \mathrm{DT}] \qquad \text{(reverberation limited)} \qquad (1\text{-}3)$$

$$= \tfrac{1}{2}\,[\mathrm{SL} - (\mathrm{AN} - \mathrm{AG}) - \mathrm{DT}] \qquad \text{(noise limited)} \qquad (1\text{-}4)$$

FOMs of 80 to 90 dB are reasonable for CLFA, assuming low to moderate reverberation or ambient noise levels. Detection ranges for which TL + ESL are > 100 dB are unrealistic for CLFA while FOMs < 80 dB are possible in areas of high reverberation or high ambient noise, both situations being prevalent in the littoral. Therefore, a CLFA FOM = 85 dB is chosen as the focus in the analysis to assess performance impact of ESL and TL.

4. Previous ESL Results

The effects of environmental acoustic parameters on ESL at tactical sonar frequencies were previously studied by Tanaka [1996] for varying sound speed profiles and sediment types found in Area Foxtrot, a shallow water test bed south of Long Island, NY. In his study, no attempt was made to vary the pulse shape or transmission time. His study showed ESL was highly dependent upon bottom type, target depth, and only moderately dependent on sound speed profile. He also found that the greatest increase in ESL occurred from the source out to some critical range (1600 m for his study), becoming relatively constant with increased range. This study is a continuation of Tanaka's work at lower frequencies, with the addition of increased water depth, increased sediment complexity, and the use of operational pulse shapes to measure the effects of ESL in a tactically realistic environment.

II. MODELING ESL AND TL IN SHALLOW WATER

A. ESL COMPUTATIONAL MODEL

ESL is the result of time stretching of the transmitted pulse due to multipath propagation in shallow water. The peak energy of the received pulse is reduced because of this time spreading. To compute ESL consider a pulse at some range from the source which has undergone no time stretching and which is symmetric in amplitude about its peak value in the time domain. This idealized non-stretched pulse at range, r, has the same duration as the transmitted pulse at range r = 1 m. The quantitative measure of ESL is based on the pulse source level or the total energy at 1 m from the source:

$$E_{source} = \int A^2(t)dt = \sum A^2_{source}(k) \qquad (2\text{-}1)$$

where E_{source} represents the total energy of the transmitted pulse, A represents the amplitude of the pulse at time t with a time increment dt and k is the number of time increments in the pulse, 8192 in this study. E_{source} is used to compare its magnitude to that of the received pulses. For this study, the Blackman windowed pulse and continuous wave pulse (CW) were used. The latter pulse was chosen to model actual pulses employed by the LFA/CLFA system.

In defining ESL quantitatively for the Blackman windowed pulse, the amplitude of an idealized, fictitious non-stretched pulse at range r was determined by compressing all of the pulse's time-stretched energy into a pulse having the same pulse length and shape as the original transmitted pulse. This time compressed pulse is termed $A_{compressed}$. In order to determine how much energy is lost due to time spreading, the squared amplitude of the compressed pulse is compared to the squared maximum amplitude of the time-stretched pulse and their ratio is defined as ESL:

$$ESL = 10\log_{10}\left(A_{compressed} / A^{max}_{stretched}\right)^2 \qquad (2\text{-}2)$$

where $A_{stretched}^{\max}$ is the absolute value of the peak amplitude of the time-stretched pulse. The value of $A_{stretched}^{\max}$ is determined from a computer model (to be described) which calculates the amplitude and shape of the stretched pulse as a function of range. The relationship of the peak values of the source, compressed, and stretched pulses is illustrated in Figure 1.

The amplitude of the ideal compressed pulse is computed based on the assumption that the shape of both the source and the time-compressed pulses are symmetric in amplitude and are related by the ratio:

$$r = A_{compressed}(k) / A_{source}(k) . \tag{2-3}$$

Since energy must be everywhere conserved, within the time window containing the received pulse, conservation principles require that

$$E_{compressed} = E_{stretched} = \sum A_{stretched}^2(k) \tag{2-4}$$

Substituting Equations (2-3) and (2-4) into Equation (2-1) yields

$$E_{compressed} = \sum A_{stretched}^2(k) = r^2 * E_{source} \tag{2-5}$$

Thus the factor r is given by:

$$r = \sqrt{\left(E_{compressed} / E_{source}\right)} \tag{2-6}$$

Therefore, one can obtain the amplitude of the compressed pulse, $A_{compressed}$ (k), from the known values of A_{source} (k) and E_{source} from equation (2-1) and $E_{compressed}$ as determined from Equation (2-5). The relationship of the peak values of the source, compressed and stretched pulses is illustrated in Figure 1.

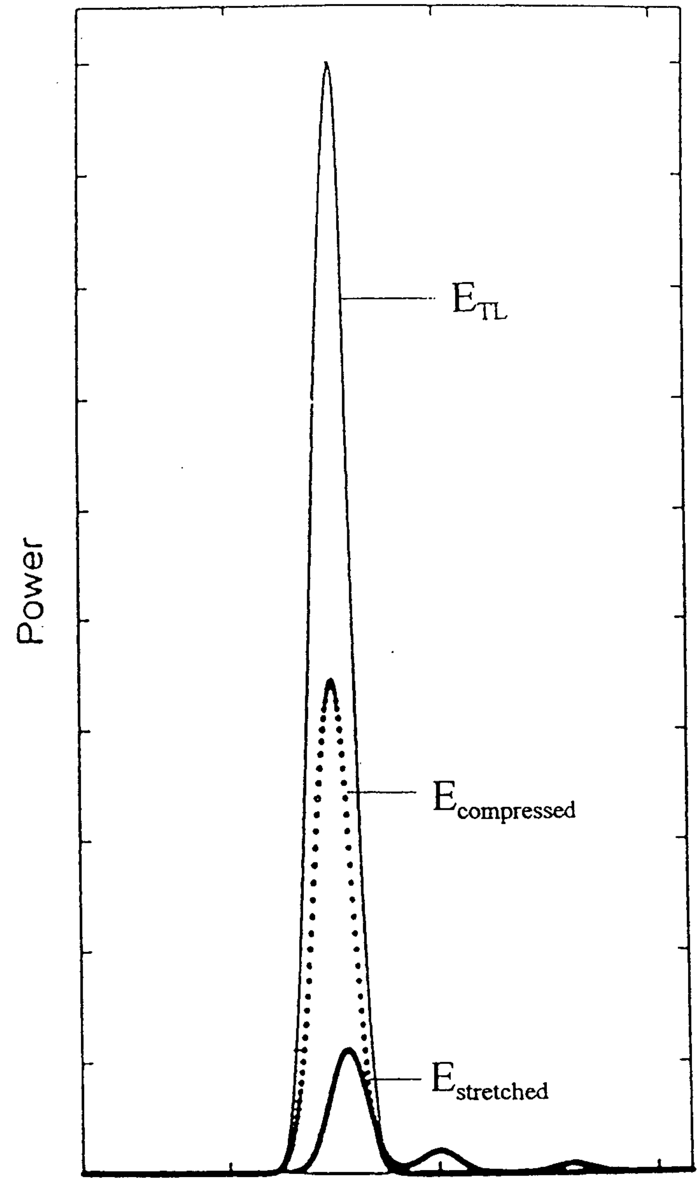

Figure 1. ESL is quantitatively determined by time compressing the time-stretched pulse into one having the same pulse length and shape as the transmitted pulse.

In defining ESL quantitatively for the CW waveform, we have again utilized the idealized pulse, compressing all of the time-stretched energy into a pulse with the same length (T) as the originally transmitted pulse.

$$A_{compressed} = \sum A_{stretched}(k) / T \qquad (2\text{-}7)$$

However, due to the shape of the CW pulse, it was not possible to utilize the symmetrical relationship assumption used with the Blackman pulse. Instead, the peak amplitude of the time stretched pulse ($A^{\max}_{stretched}$) was determined by taking a running average of the absolute amplitude of the resultant time series equal in length to the originally transmitted pulse (e.g., 5 seconds). The amplitudes of the pulses in the [5 second] window containing the greatest energy were then averaged, thus creating a square pulse equal in length to the originally transmitted pulse, but containing the energy associated with the largest of the time distorted pulses:

$$A^{\max}_{stretched} = \left(\int_t^{t+T} A^{\max}_{timeseries} \right) / T \qquad (2\text{-}8)$$

Utilizing Equations (2-7) and (2-8)

$$ESL = 20 * \log_{10}\left(A_{compressed} / A^{\max}_{stretched}\right) \text{ [dB]} \qquad (2\text{-}9)$$

A unique feature of the approach used in both of the previous cases is that the amount of energy spreading as a function of time is modeled using an accurate, full wave propagation model. Hence, no reverberation noise or artifacts contaminate the computation of ESL. Also, unlike previous studies (e.g., Jones, 1990), an assumed statistical distribution (e.g., Gaussian) for the time spread signal is not necessary. The energy contained in the stretched pulse is calculated directly. Indeed, our studies have shown that the time-stretched pulse takes on a variety of extraordinary shapes, continually changing with range as multipaths sum constructively or destructlively.

B. SIGNAL PROPAGATION MODELS

The key factor in computing ESL is to accurately calculate the shape and energy contained in the time-stretched pulse. The computation is made more complex and computer intensive in that the propagation of a transmitted pulse of finite bandwidth and known spectral shape must be simulated. This accomplished through the use of a multi-frequency version of the Finite Element Parabolic Equation (FEPE) developed by Collins (1988), termed FEPE_SYN, and a program EXT_TD, which incorporates the transmitted pulse shape characteristics. Together they produce accurate depictions of the energy spreading as the signal propagates in range.

FEPE_SYN is a range-dependent , full wave model which calculates the TL for each frequency within the bandwidth of the selected transmitted pulse (Collins, 1988). The output of this program is an ocean transfer function (OTF) which provides a file of the complex pressure, amplitude and phase as a function of range, depth and frequency.

Rovero (1992) developed a program, EXT_TD, to augment the frequency domain output of FEPE_SYN to provide a time domain depiction of a transmitted pulse at selected range and depth increments. The transmitted pulse, variable in duration and shape, is subjected to an FFT using the same resolution as the OTF. The result is multiplied by the complex conjugate of the OTF which incorporates the effects of both TL and phase interactions on the pulse as a function of range, depth, and frequency. An inverse FFT is then performed to provide a time-domain depiction of the energy distribution of the pulse at selected range intervals along the propagation path.

III. IMPACT OF ESL AND TL ESTIMATES ON CLFA PERFORMANCE

A. BACKGROUND

Two model runs were made simulating the acoustical environment of the Tanner Bank region off the coast of San Diego, which is the same shallow water region chosen for Critical Sea Test (CST) 10 (Magellan II) LFA sonar system measurements. This shallow water area was chosen due to its geoacoustic and bathymetric similarity to the Gulf of Oman with its rapid changes in bathymetry in an area covered with a thick layer of highly absorbent clay, silt, and fine sand (Table 1)(Figure 2).

Two distinct paths were chosen for the FEPE_SYN model runs. The first was from deep to shallow water, up the steep slope of Tanner Bank, thence crossing the relatively shallow depths on top of the bank (Figure 3). This case was chosen specifically to demonstrate the relative impact of sediment type, sound speed profile, and pulse length on TL and ESL in a region of rapid bathymetric change, ending over a relatively shallow water environment on top of Tanner Bank This path modeled the employment of CLFA in deep water searching for a target located on a slope or on a shallow slope. The second path was a diagonal transit across the top of Tanner Bank in fairly shallow water (Figure 4). This path was chosen to model CLFA performance for the source placed in shallow water to detect a shallow water target such as a bottomed diesel. The second path is similar to model runs made by Tanaka (1996), at 3.5 kHz in a shallow water area south of Long Island. This run will help assess the impact of sediment type on TL and ESL in shallow water, and comparison with Tanaka's ESL results will help determine the frequency dependence of ESL in shallow water. It is also emphasized that one way ESL calculated in this thesis must be "doubled" for CLFA performance calculations.

HAMILTON GEOACOUSTIC MODEL FOR TANNER AND CORTEZ BANKS

Depth (m)	ρ (g/cm^3)	k_p (dB/λ)	V_p (m/s)	V_s (m/s)	Lithology
0.0	1.58	.0900	1520.0	175	clay/silt
38	2.68	.4890	1562.5	240	very fine sand
122	2.68	.4890	1593.8	350	very fine sand
137	1.60	.0285	1625.0	350	clay/silt/sand
164	1.60	.0285	1656.3	400	clay/silt/sand
183	1.60	.0285	1703.1	425	clay/silt/sand
212	2.71	.5100	1703.1	425	coarse sand
243	2.71	.5100	1718.8	450	coarse sand
259	2.71	.5100	1718.8	450	coarse sand
381	2.73	.5100	1828.1	500	coarse sand
457	2.73	.0450	1890.6	550	volcanic
533	2.73	.0450	2125.0	700	volcanic

Table 1. Hamilton Geoacoustic Model for Tanner and Cortez Banks

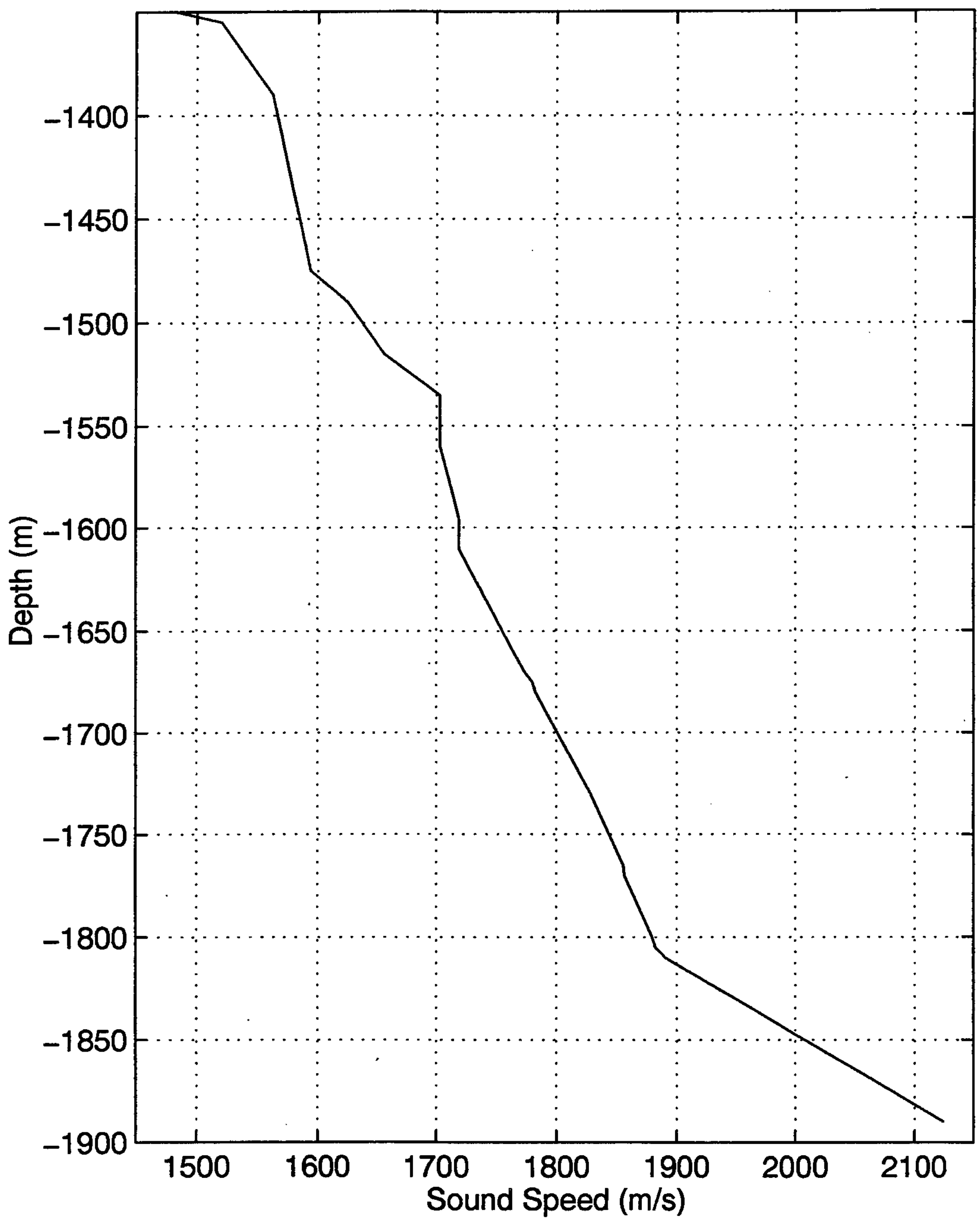

Figure 2. Sound Speed Profile for Tanner and Cortez Banks

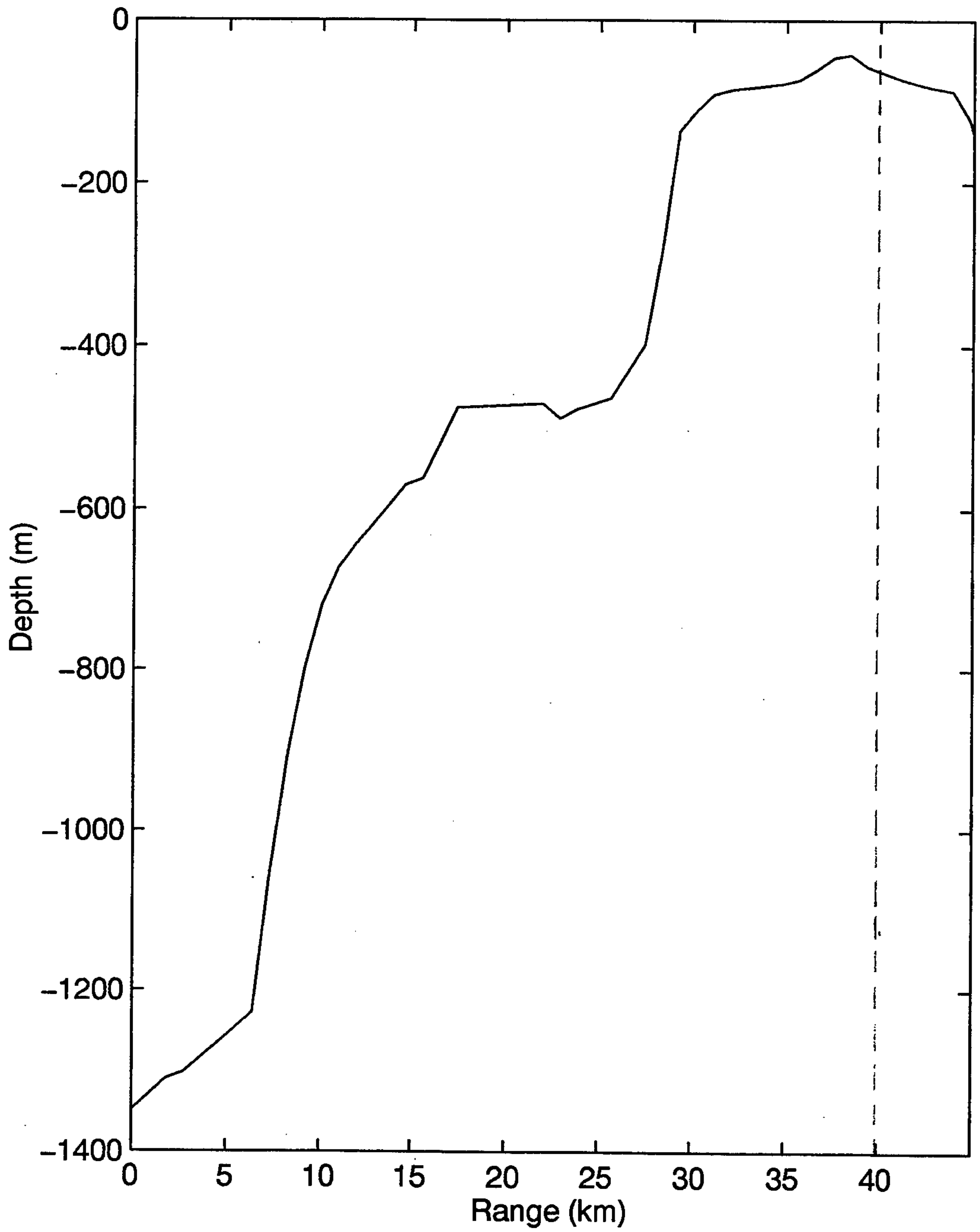

Figure 3. Deep water bathymetry of Tanner Bank. Dashed line indicates max range of model run.

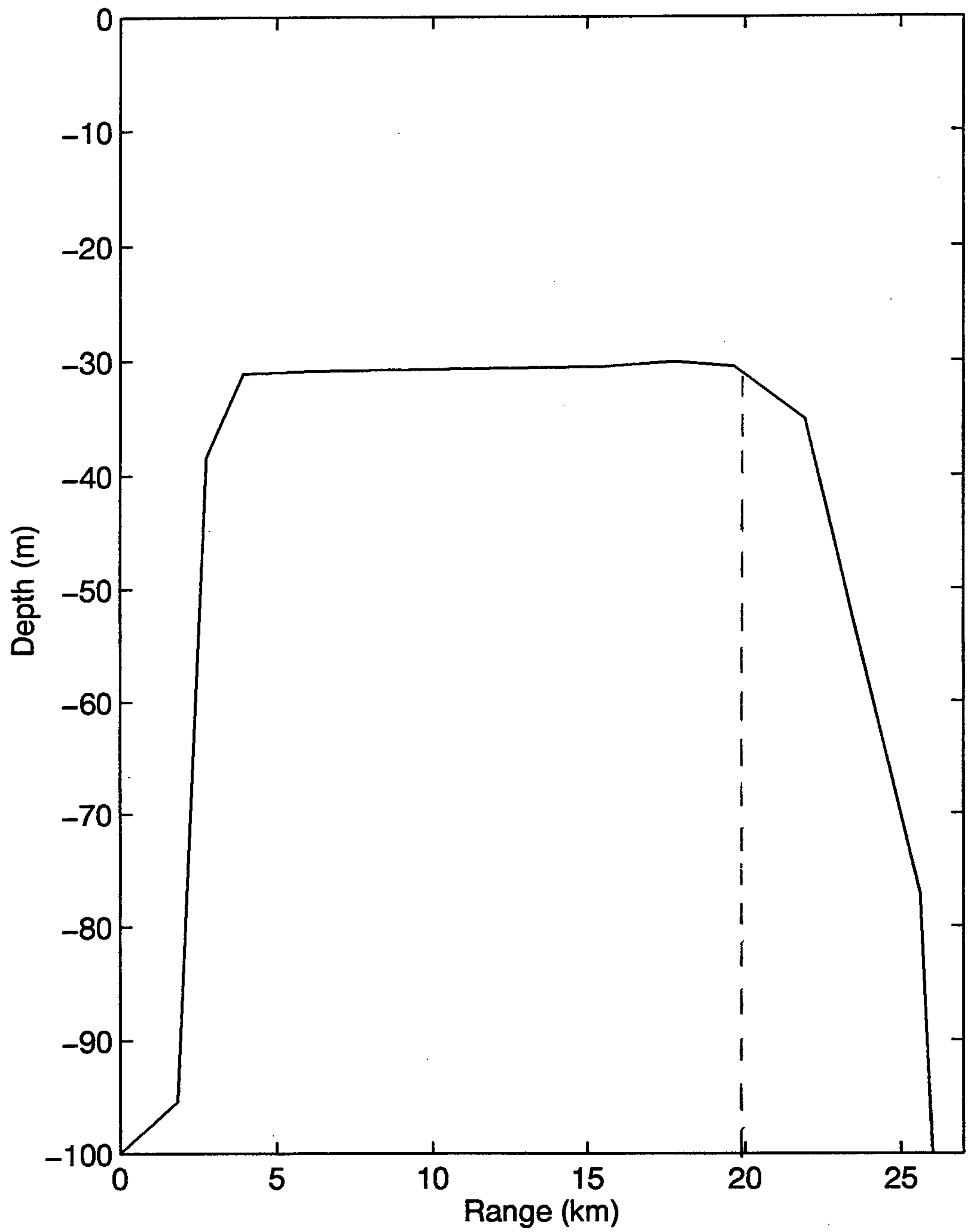

Figure 4. Shallow water bathymetry on top of Tanner Bank. Dashed line indicates max range of model run.

B. DEPENDENCE OF ESL ON PULSE TYPE AND PULSE DURATION

The pulses modeled in this study were the Blackman windowed pulse and the Continuous Wave (CW) pulse. In modeling the Blackman pulse (BP), a center frequency of 244 Hz with a 2 Hz bandwidth was used to achieve a pulse duration of ~5 sec. By increasing the bandwidth to 4 Hz, a pulse duration of ~3 sec was modeled. In modeling the CW pulse, a bandwidth of 1/16 Hz was used with pulse durations of 0.1 sec to 5 sec. A hyperbolic frequency modulated (HFM) sweep was planned to be analyzed for ESL in this thesis, but was omitted as little or no ESL difference was noted for the BP and CW pulses of equal pulse length. Hence, the research effort was redirected to study the large impact of pulse duration and sediment type on ESL. Only the CW pulse results will be shown in the analysis that follows since the results were similar for the Blackman pulse.

Pulse duration has an obvious effect on ESL that results primarily from the difference in group speeds among the dominant normal modes comprising the transmitted waveform. Although the speed of sound is frequency independent, the group speed of individual modes in shallow water can vary significantly from the speed of sound. Physically this results in time spreading of the transmitted pulse and is the cause of ESL.

ESL increases as pulse duration decreases for the shallow propagation path on top of Tanner Bank. Figure 5 is a summary of all the one way ESL calculations for CW pulse durations of 5 sec, 2 sec, 0.5 sec, and 0.1 sec showing the wide range of variance of ESL. For example, Figures 6 and 7 show the transmitted 5 sec CW waveform (range = 1 m) and the same waveform after propagating 6 km on top of Tanner Bank. Although the amplitude of the CW pulse is greatly reduced due to TL, the waveform shape shows little time stretching. The one way ESL is only 1 dB as calculated by the ESL definition in Section II.

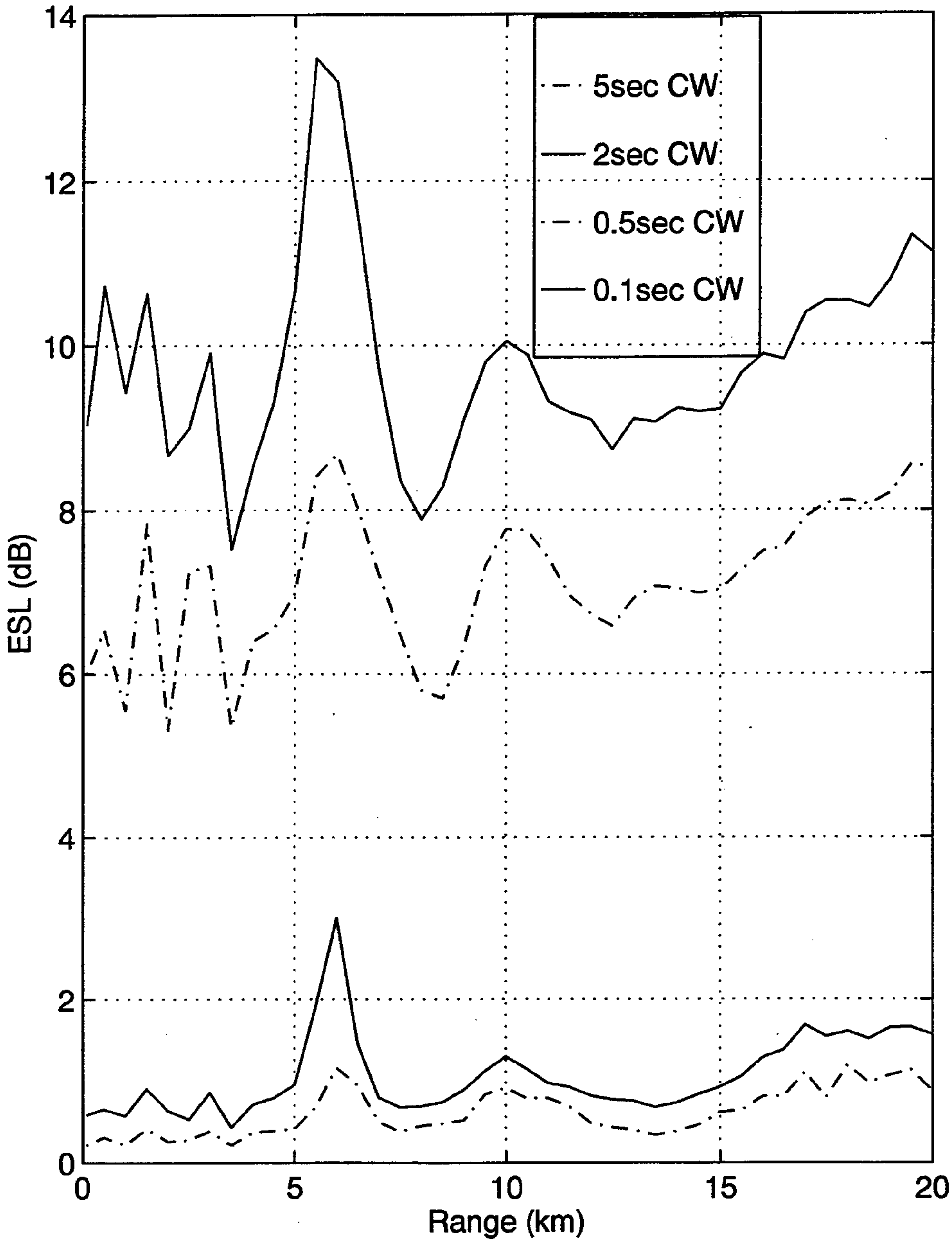

Figure 5. Dependence of ESL upon pulse duration in shallow water. ESL increases inversely with pulse length.

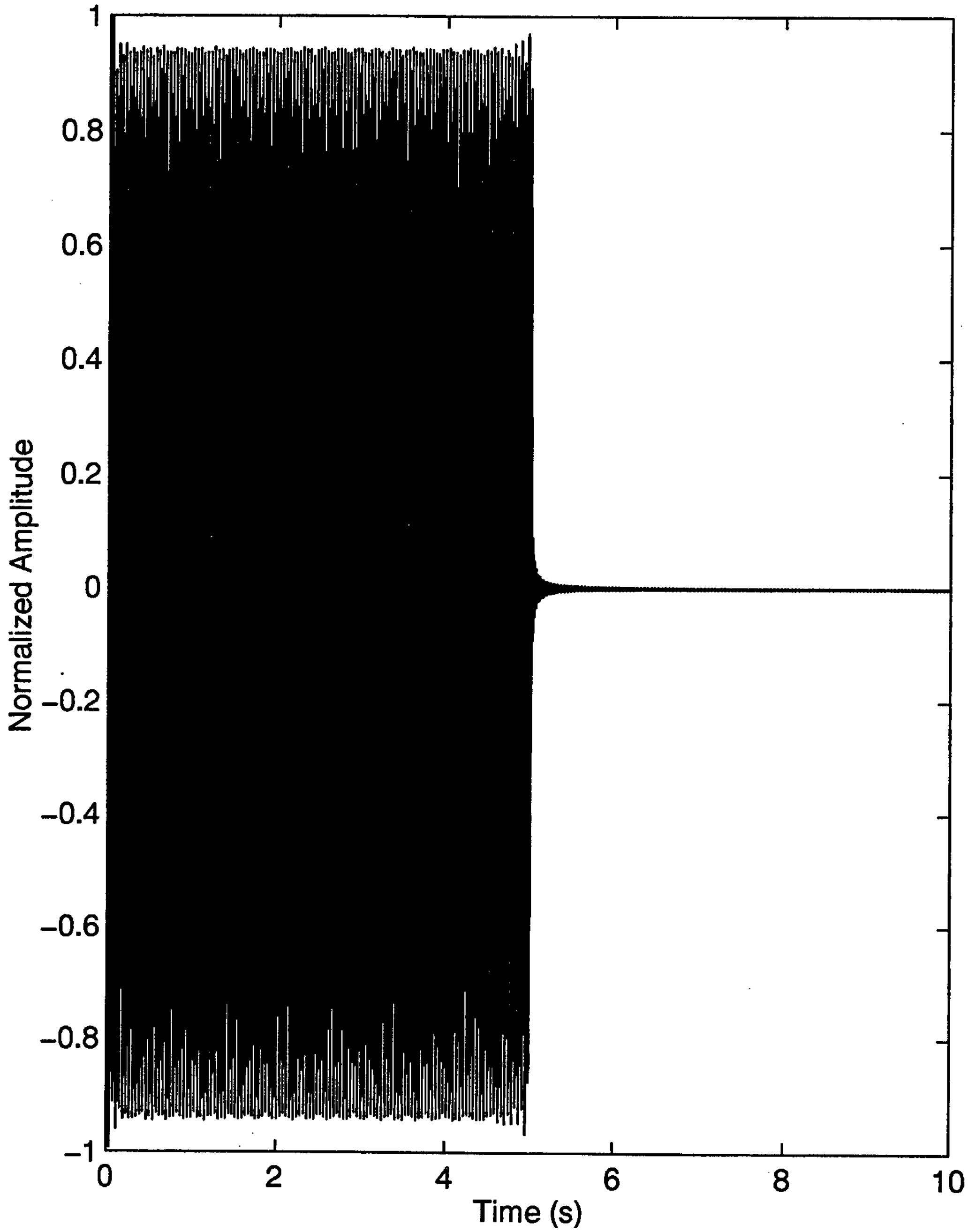

Figure 6. 5 sec Continuous Wave (CW) pulse, 1 m from source.

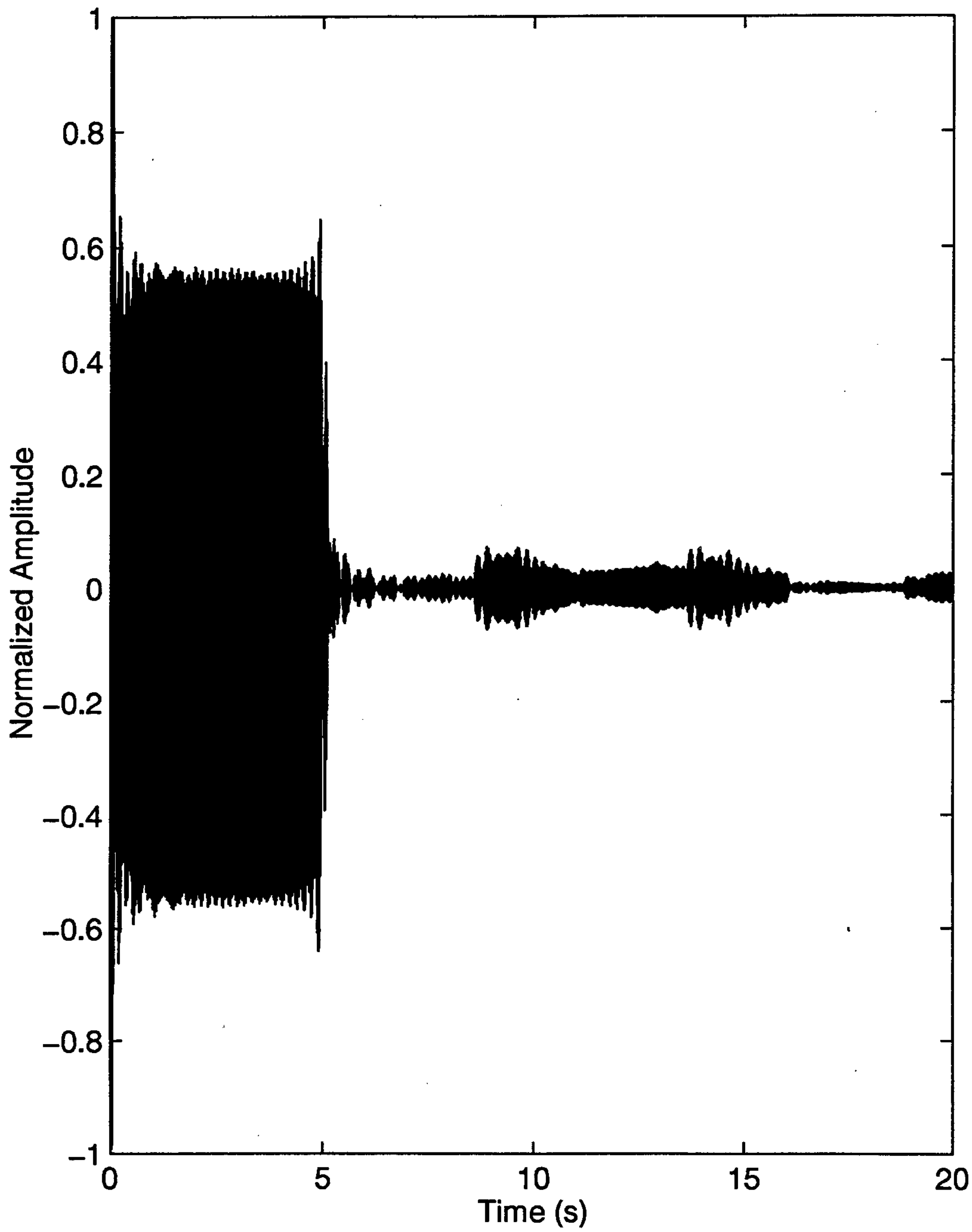

Figure 7. 5 sec CW pulse in shallow water at a range of 6000 m. Pulse has undergone minimal time stretching and has experienced 1 dB of ESL.

Figure 8 shows a 2 sec CW pulse after propagating for 6 km on top of Tanner Bank. The one way ESL has increased to 3 dB as evidenced by the greater pulse duration. Figures 9 and 10 show CW pulses of 0.5 and 0.1 sec durations, respectively, after propagating 6 km over Tanner Bank. One way ESL has increased to 8.5 dB and 13 dB, respectively, showing significant pulse distortions of the transmitted pulse.

This very large increase in ESL with decreasing pulse duration is independent of the transmitted waveform shape and is readily explained by modal. The dominant normal modes propagating along this shallow Tanner Bank path are determined solely by the environment and do not depend on the wave form transmitted. It will be shown that the largest difference in group speeds for this environment is approximately 100 m/s for the geoacoustic model used for Tanner Bank. For one way propagation to 6 km at an average sound speed of 1500 m/s, the total average one way travel time is 4 sec, and the travel time difference among modes with group speed differences on the order of 100 m/s is 0.25 sec. For a 5 sec or 2 sec CW pulse, this maximum time spread factor of 0.25 sec has minimal impact. However, for a 0.5 sec or 0.1 sec CW pulse this time spread factor distorts or stretches the transmitted pulse significantly as shown in figures 9 and 10 with one-way ESL values of 8.5 dB and 13 dB.

It is emphasized that these results are site specific and therefore must be estimated for each environment encountered. As a rule of thumb, in very deep (>1500 m) water at CFLA frequencies ESL is very low. For shallow, or intermittently shallow propagation paths ESL must be estimated using the modeling techniques developed in this thesis. For example, the upslope run (Figure 3) starting in mid-slope and ending on top of Tanner Bank shows one way ESL as a function of range (Figure 11) for 5 sec, 2 sec, and 0.5 sec CW pulses (the one way ESL for the 0.1 sec CW pulse was too large to fit on the Figure 13 scale). Figure 12 shows the bathymetry for this run. It is surprising that ESL degradation is, in general, worse for this upslope case than for the shallow water case shown in Figure 4 on top Tanner Bank. While Figure 11 shows that one way ESL still increases significantly with decreasing pulse duration, the values are larger for the upslope

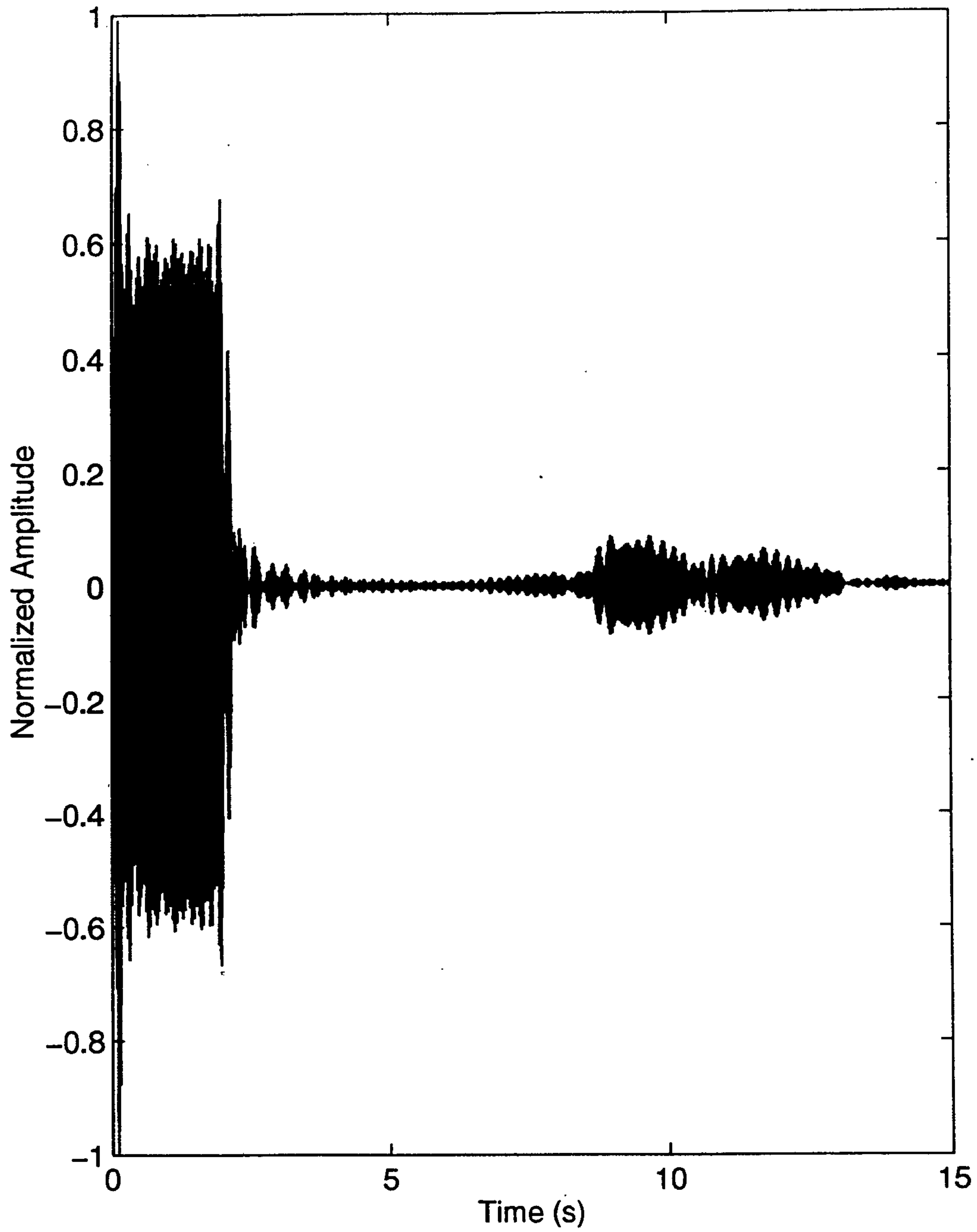

Figure 8. 2 second CW pulse in shallow water at a range of 6000 m. Pulse has undergone minimal time stretching and has experienced 3 dB of ESL.

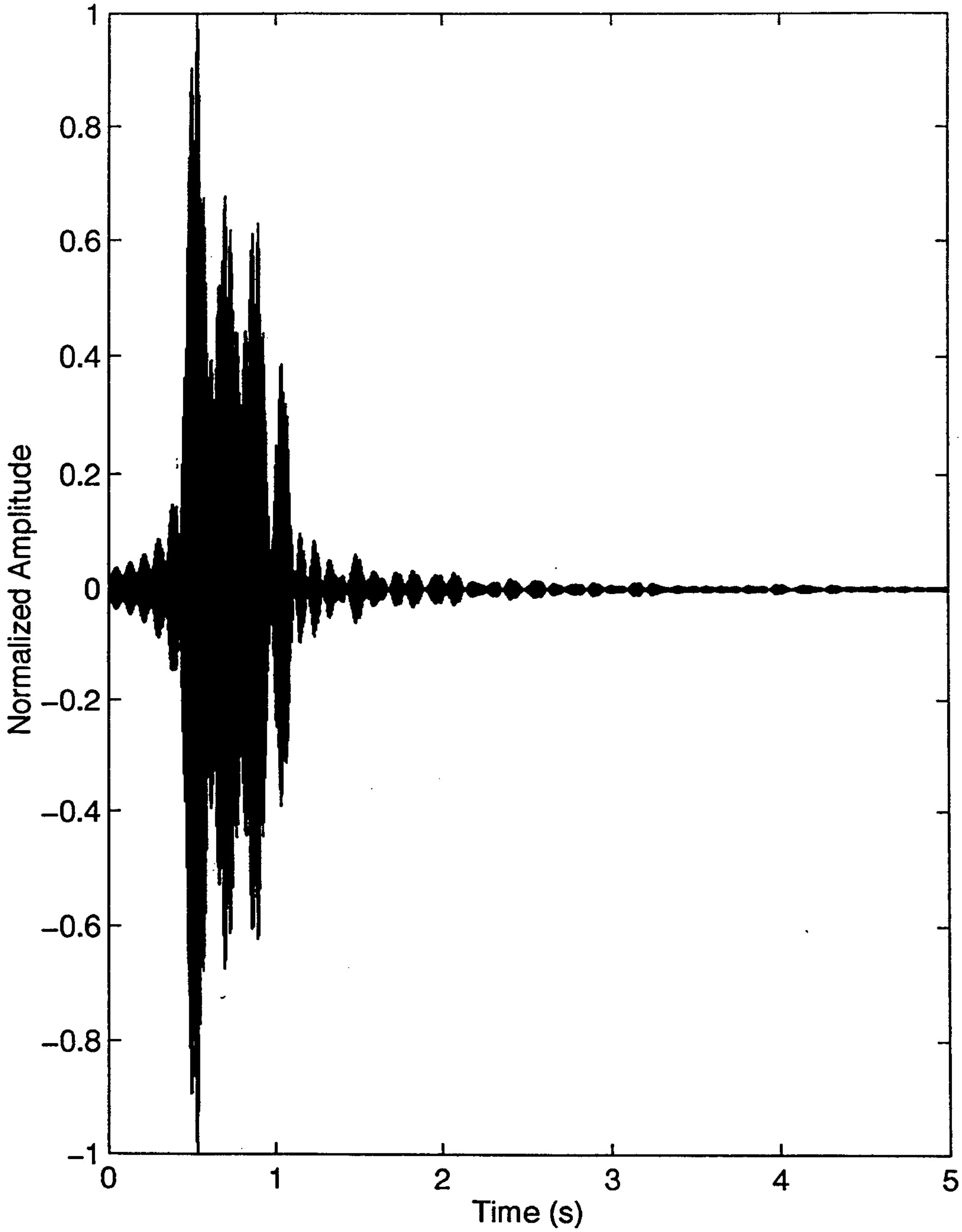

Figure 9. 0.5 sec CW pulse in shallow water at a range of 6000 m. Pulse has undergone significant time stretching and has experienced 8.5 dB of ESL.

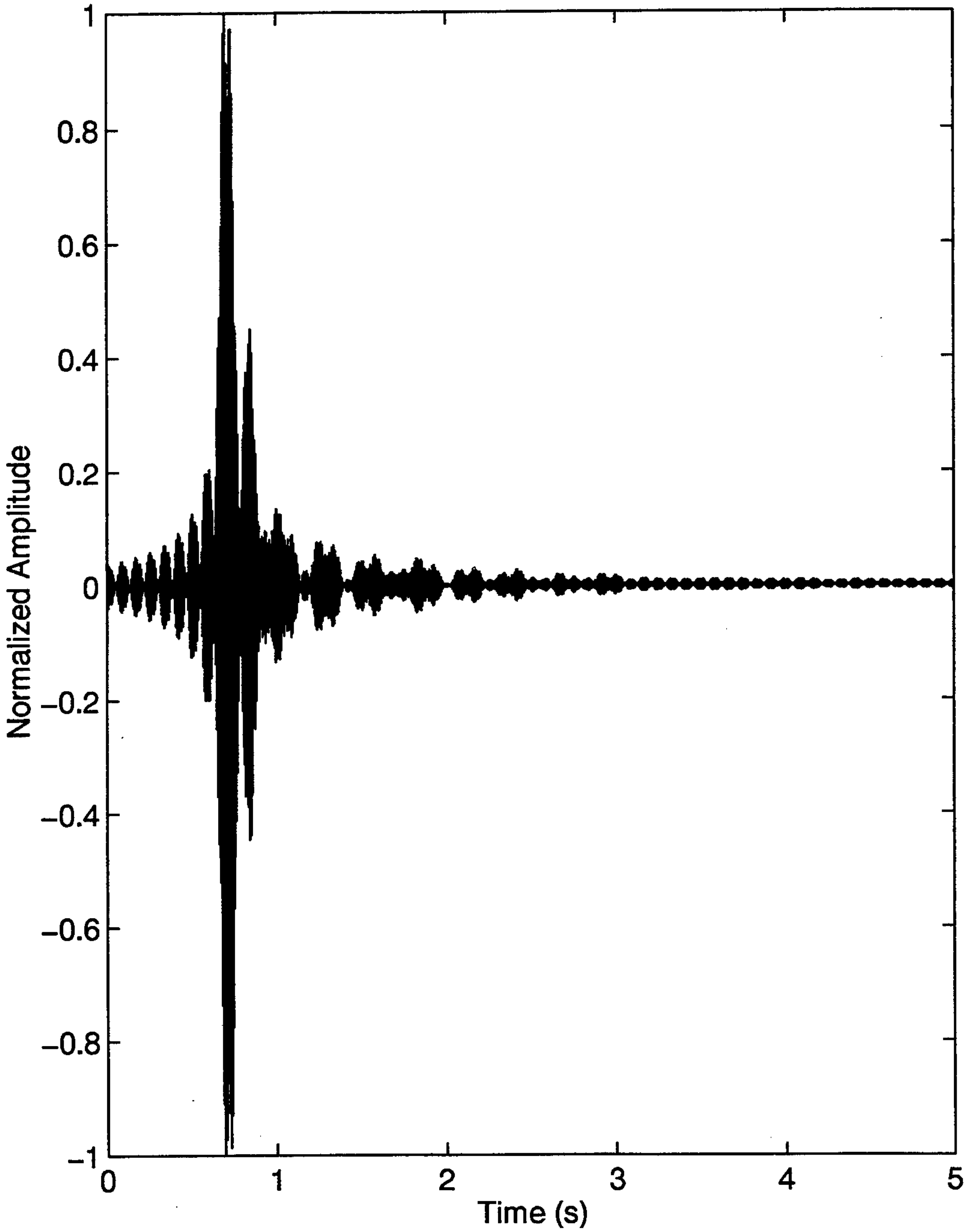

Figure 10. 0.1 sec CW pulse in shallow water at a range of 6000 m. Pulse has undergone significant time stretching and has experienced 13 dB of ESL.

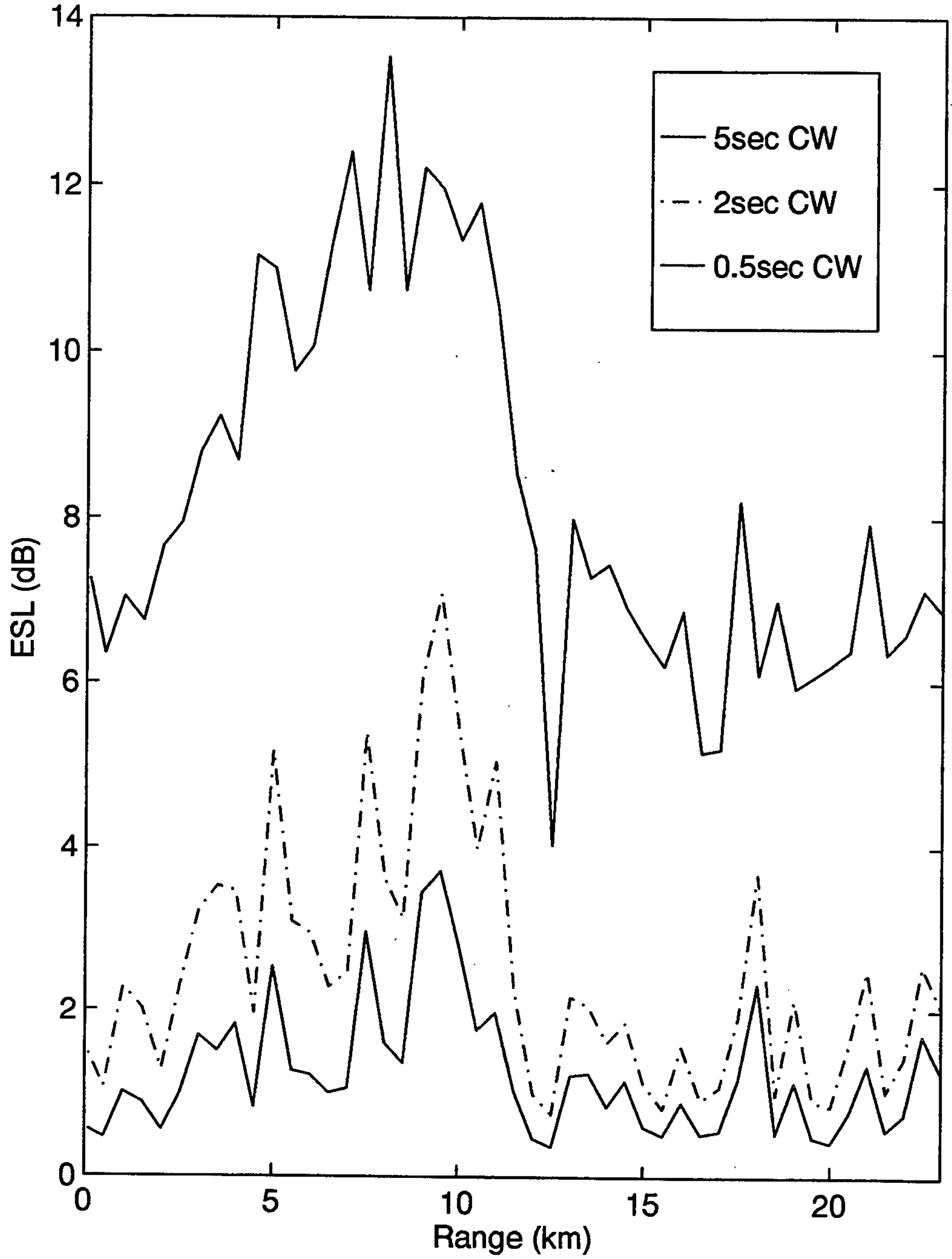

Figure 11. Dependence of ESL on pulse duration in intermediate depth water on Tanner Bank shelf break.

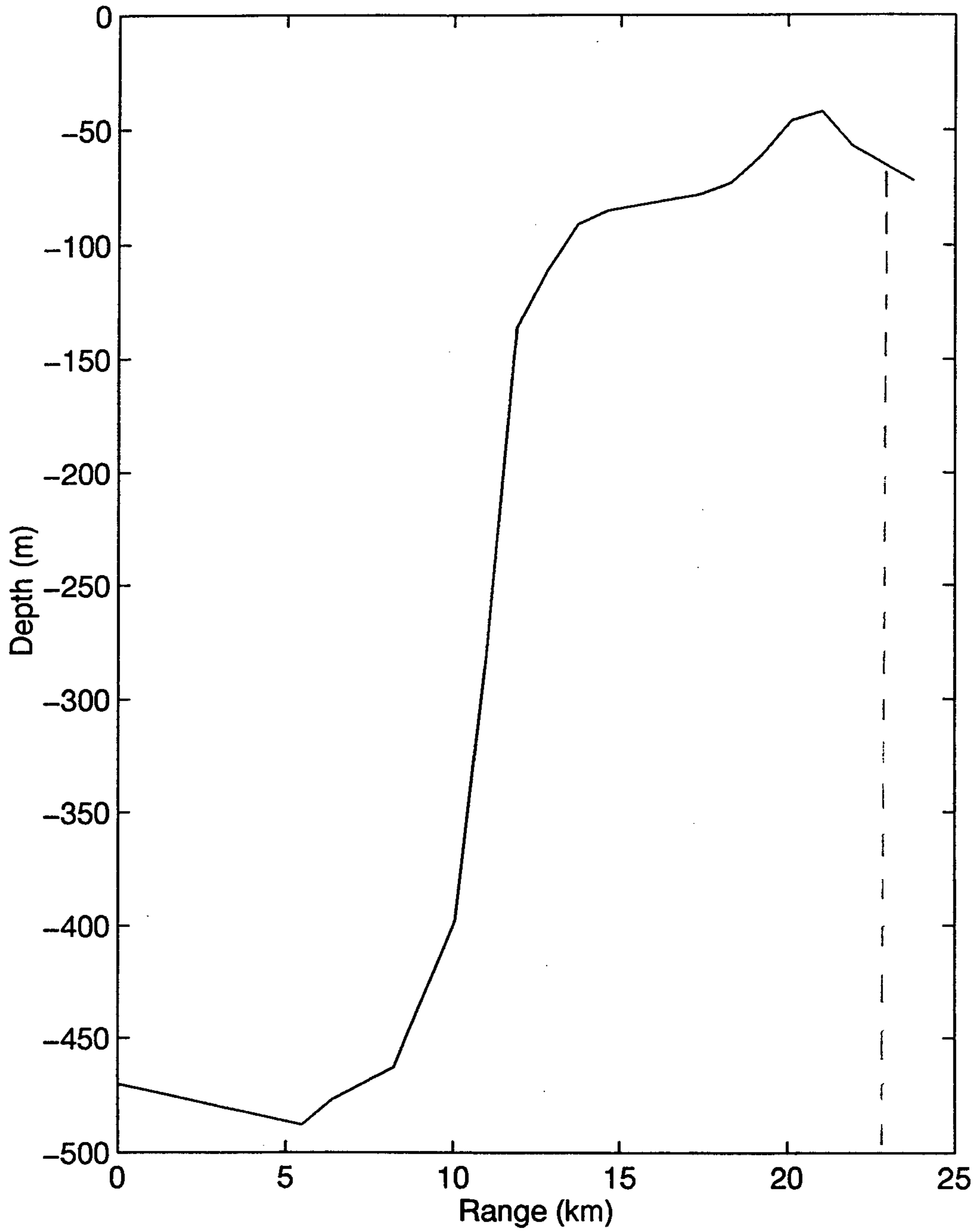

Figure 12. Tanner bank mid-shelf bathymetry. Dashed line indicates max range of model run.

path than the one way ESL along a path in shallow water (Figure 5). The reasons for this are based in normal mode theory and is complex for a range dependent (i.e., coupled mode) upslope environment. However, one can say that an upslope environment will cause energy to be transferred among modes, and that the dominant mode numbers will vary rapidly as the water depth shoals. This is why each environment must be modeled using accurate, full wave, range dependent models, such as FEPE_SYN.

Figures 13, 14, and 15 show a 2 sec CW transmitted pulse at the source, the CW pulse after propagating 5 km just prior to reaching the steepest slopes of Tanner Bank, and the CW pulse after propagating 9.5 km near mid-slope of Tanner Bank. The one way ESL at 5 km and 9.5 km are approximately 5 dB and 7 dB, respectively, with large pulse distortions observed .

The obvious tactical conclusion from the preceding analysis for the optimum employment of a CLFA system is to stand off in very deep water (~1500 m) and transmit 5 sec CW pulses to minimize ESL. When considering the entire active sonar equation (Section I.B.3), the detection ranges achieved are not great enough for CLFA to detect a target on top of Tanner Bank. However, an overriding consideration for not using a 5 sec pulse duration in shallow water CLFA operations is that the initial 7 km of range are "blanked out" for detection purposes. In the next section, ESL and TL will be modeled for CLFA locations starting in deep water toward Tanner Bank, starting mid-slope toward Tanner Bank, and on top of Tanner Bank.

C. IMPACT OF ESL AND TL ON CLFA PERFORMANCE IN THE TANNER BANK REGION

In the next three sections an FOM of 85 dB will be used to estimate CLFA detection ranges from TL and ESL estimates for three source locations: a source initially located in deep water propagating upslope, for a mid-shelf source propagating upslope, and for a source in shallow water on top of Tanner Ban. The FOM estimate of 85 dB is a

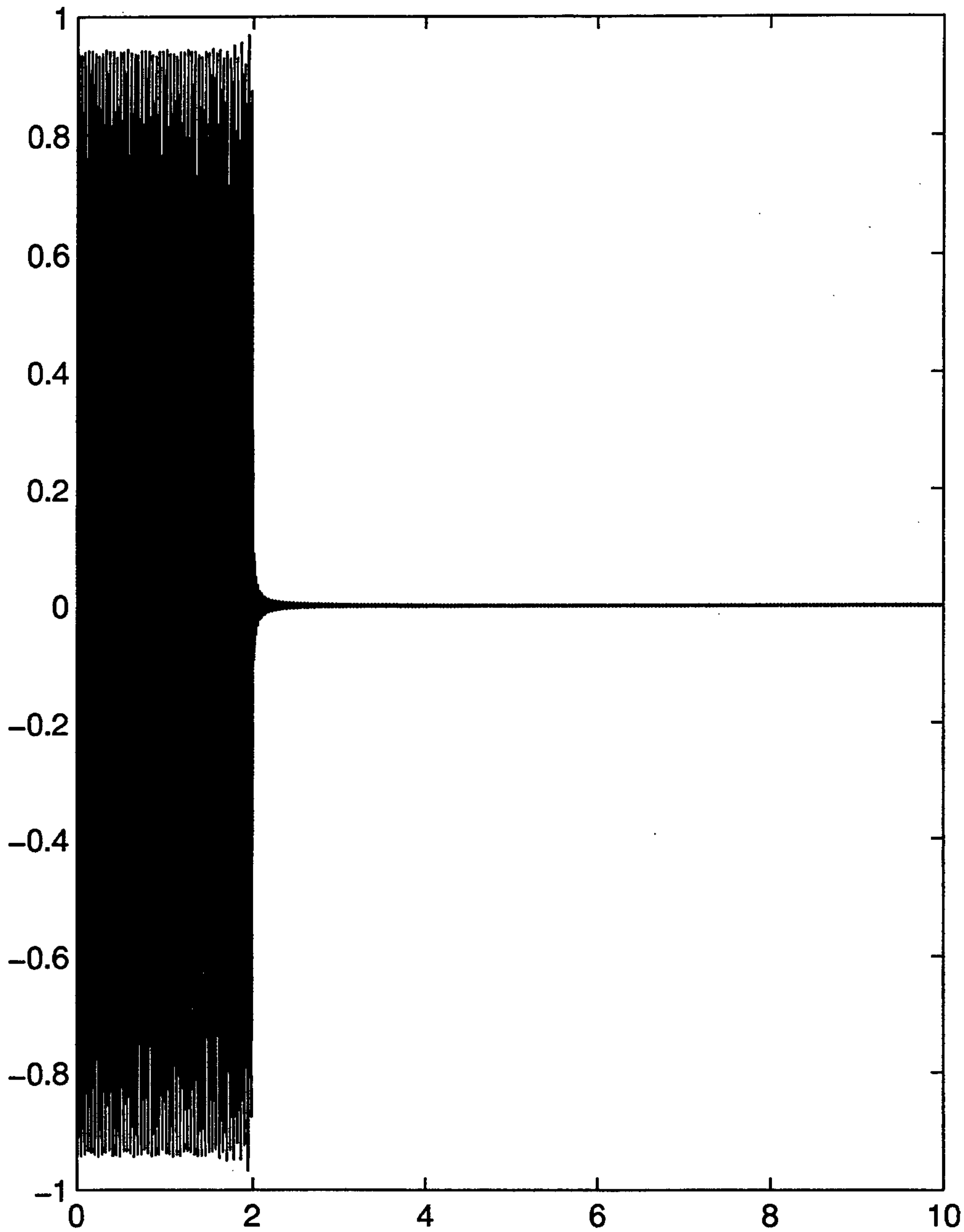

Figure 13. 2 sec Continuous Wave (CW) pulse 1 m from source.

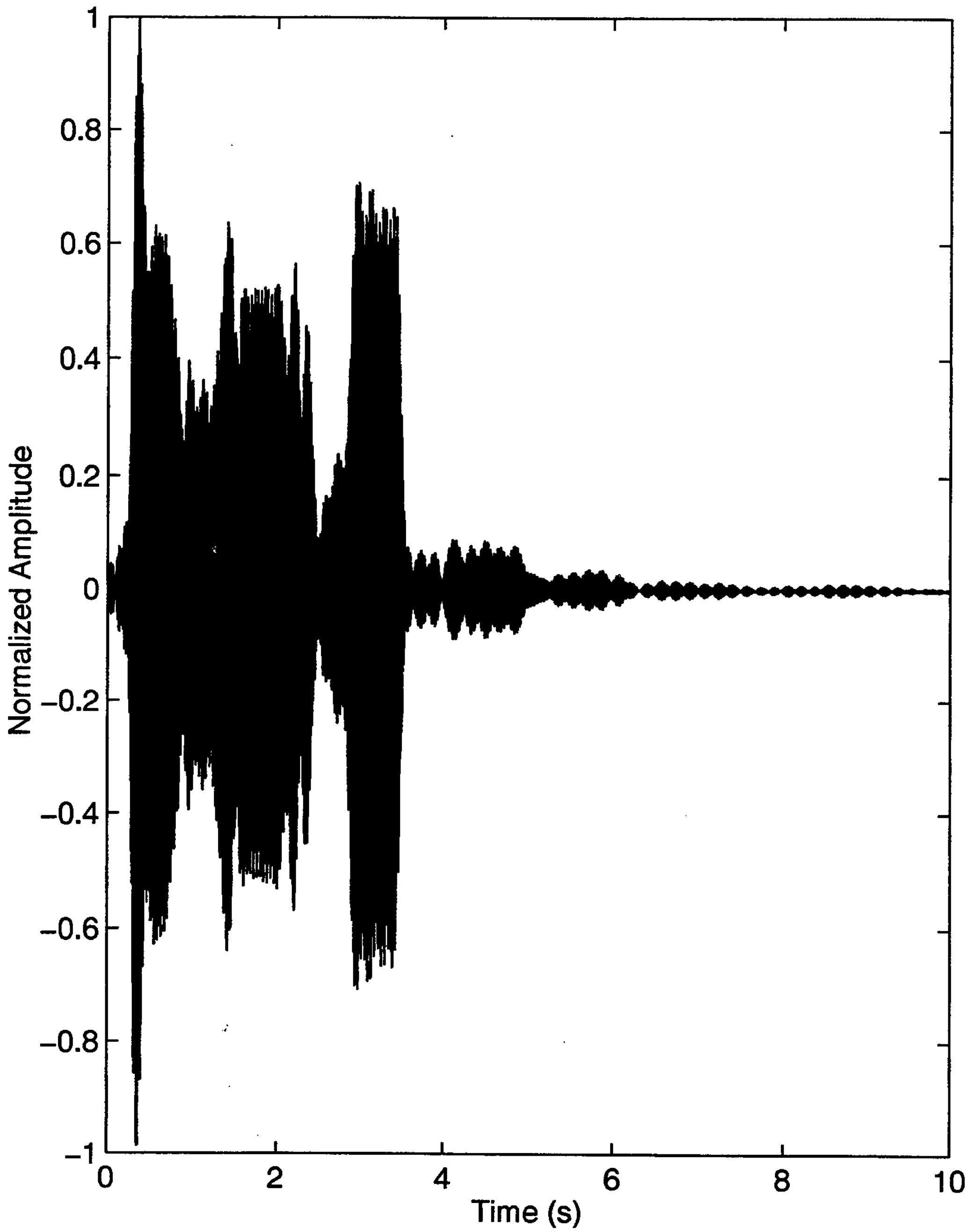

Figure 14. 2 sec CW pulse in mid-shelf water at a range of 5000m. The pulse has undergone significant time stretching and has experienced 5 dB of ESL.

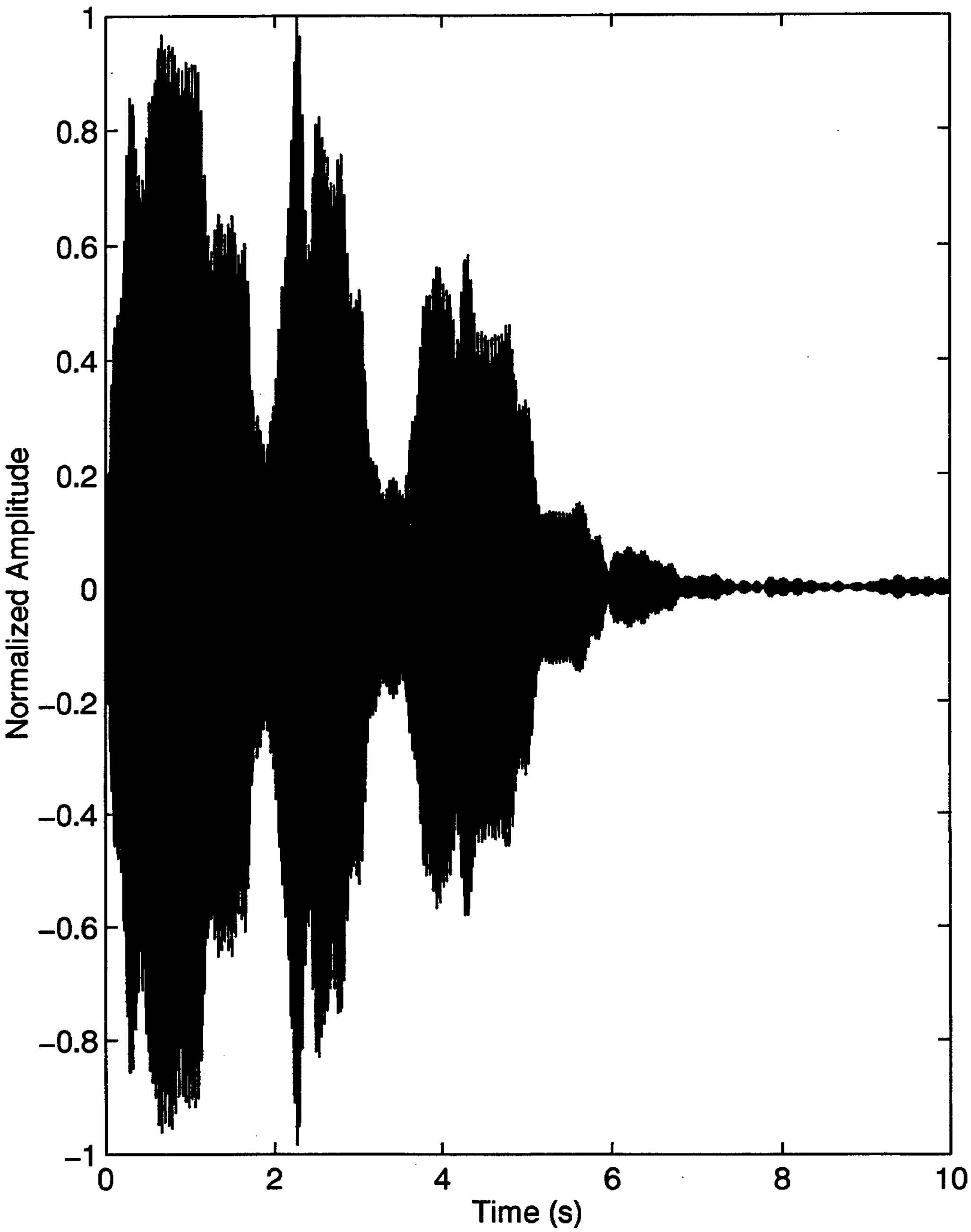

Figure 15. 2 sec CW pulse in mid-shelf water at a range of 9500 m. The pulse has undergone significant time stretching and has experienced 7 dB of ESL.

crude approximation (see Section I.B.3) and the reader can substitute his/her own CLFA FOM if it is deemed more accurate. A best case of ambient noise limited conditions was assumed. The detection ranges will be far less in a reverberation limited environment.

1. Deep Water Toward Tanner Bank Propagation Path

Assume a CLFA source is located in ~1400m of water west of Tanner Bank and a propagation path shown in Figure 3, that proceeds upslope and thence on top of Tanner Bank. A typical SSP for the summer months (Figure 16) is used for the initial model runs. Estimates of TL at 250 Hz along this propagation path are shown in Figure 17 for the geoacoustic model in Table 1 and source depth of 350 m (the optimal depth found for this case). It is important to emphasize that the FOM of 85 dB must be used with a combination of the TL plus ESL curves, and not just a TL curve. Therefore, consider a case where a 5 sec CW pulse (or any other pulse shape) is transmitted and ESL from Figure 11 (5 sec CW pulse) must be added to the TL values in Figure 17 for ranges of 25 km and greater. For ranges less than 25 km, ESL is assumed to be minimal (~1 dB). For the ideal case of ambient noise limited conditions, an FOM of 85 dB predicts good detection conditions within 25 km and then marginal to poor detection conditions beyond as TL and ESL (Figure 11 and 17) increase up the steep slopes of Tanner Bank. In reverberation limited conditions, the FOM needs only to decrease to 75 dB to make detection performance very poor indeed. No matter what the noise limiting condition is, detection of a target of interest over the steep slopes of Tanner Bank, or on top of Tanner Bank and beyond is highly unlikely.

Surprisingly, if the silt sediment of Tanner Bank were replaced by a hard sand sediment, with sediment compressional sound speed profile shown in Figure 18, the TL plot shown in Figure 19 becomes poorer. In this case, a detection range of only 15 km is predicted using an FOM of 85 dB and detection of a target of interest on top of Tanner Bank and beyond is highly improbable. In shallow water sand is generally considered a better "reflecting" bottom and silt/clay is considered a "poor" bottom. This proved to be

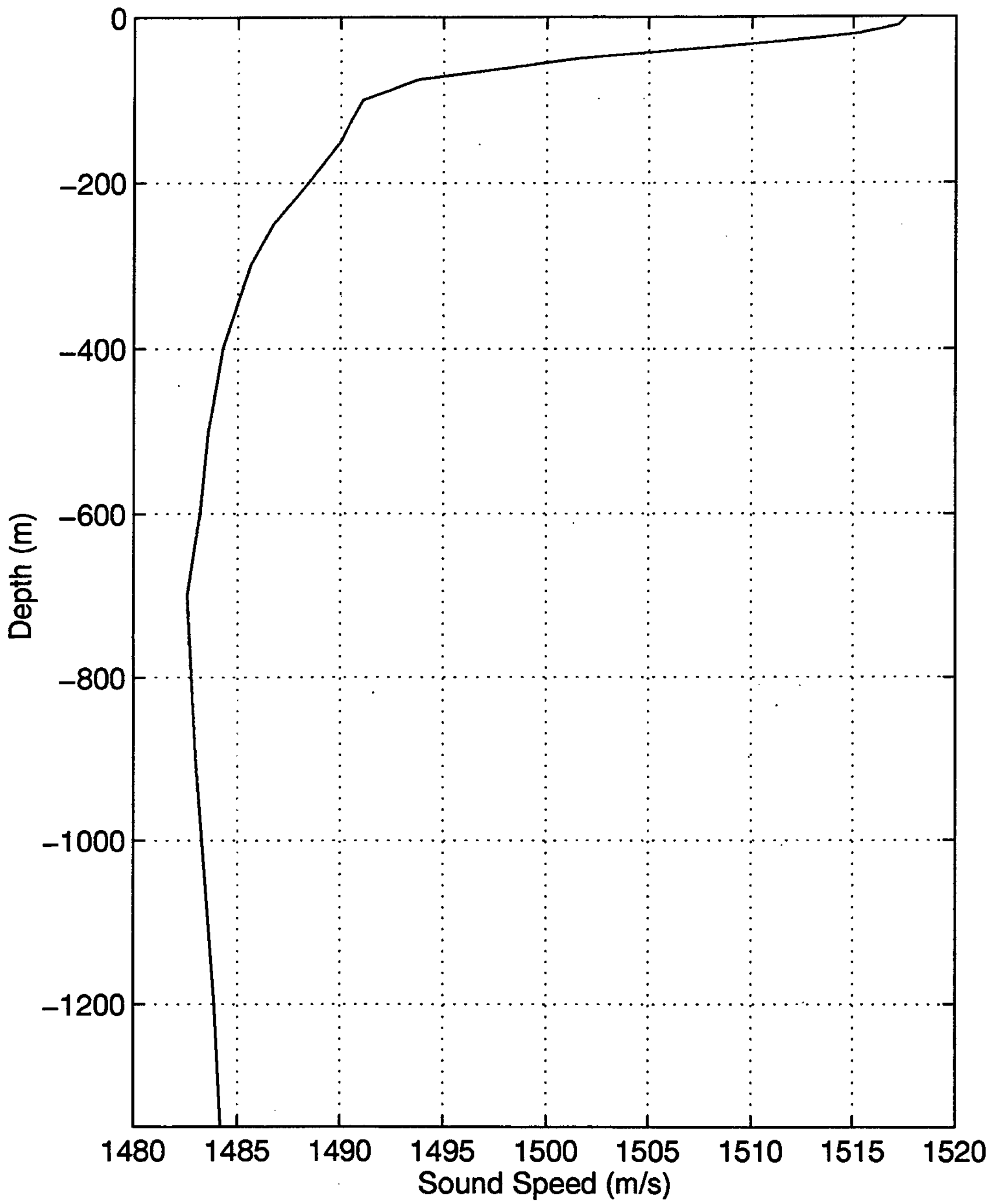

Figure 16. Typical July/August sound speed profile (SSP) for the Tanner Bank region with a strong negative gradient.

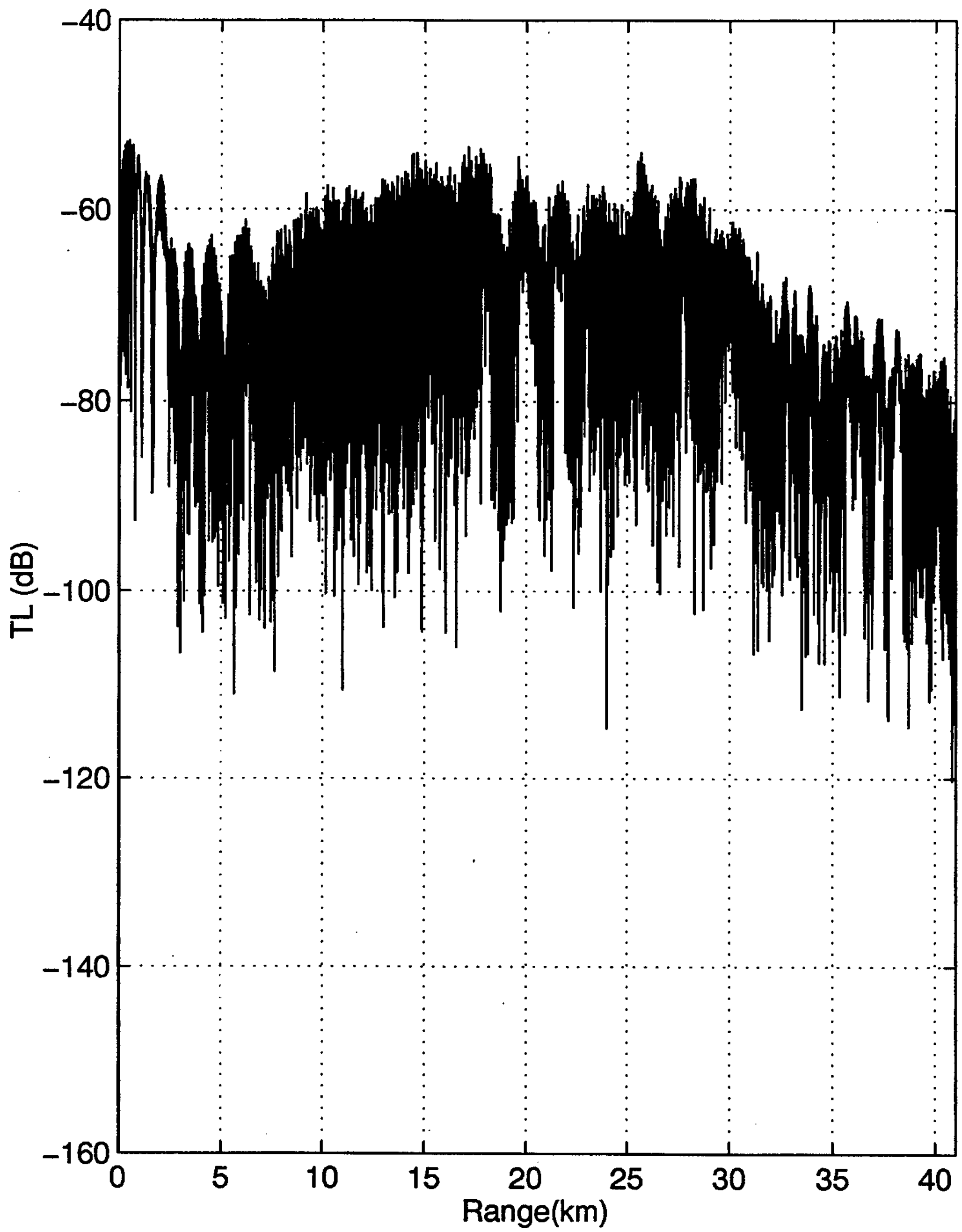

Figure 17. FEPE calculated TL values for deep water in the Tanner Bank region. Source depth is 350 m over a silt/clay sediment base with a strong downward refracting, negative gradient profile.

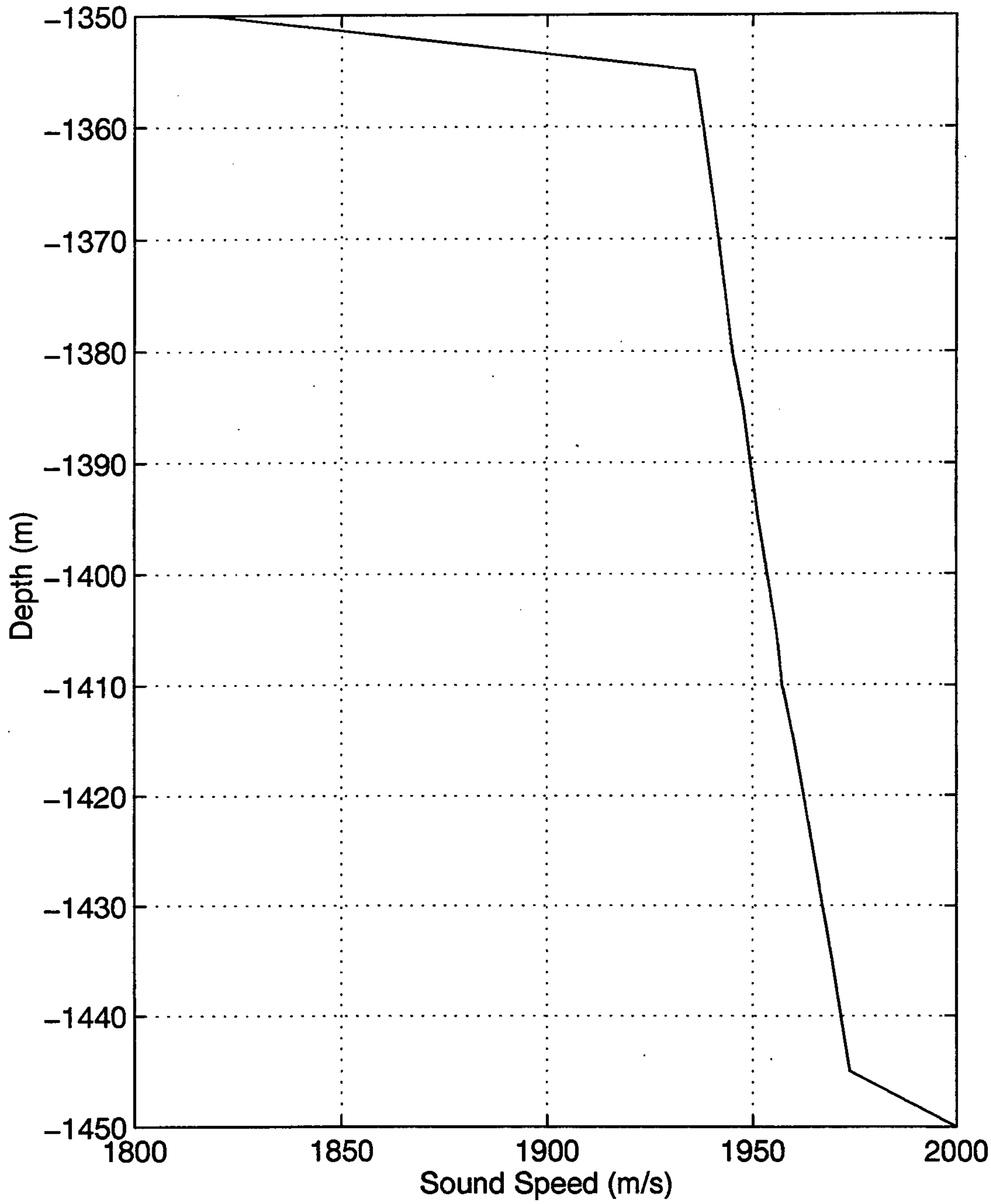

Figure 18. Sediment sound speed profile for the hard sand bottom of Area Foxtrot.

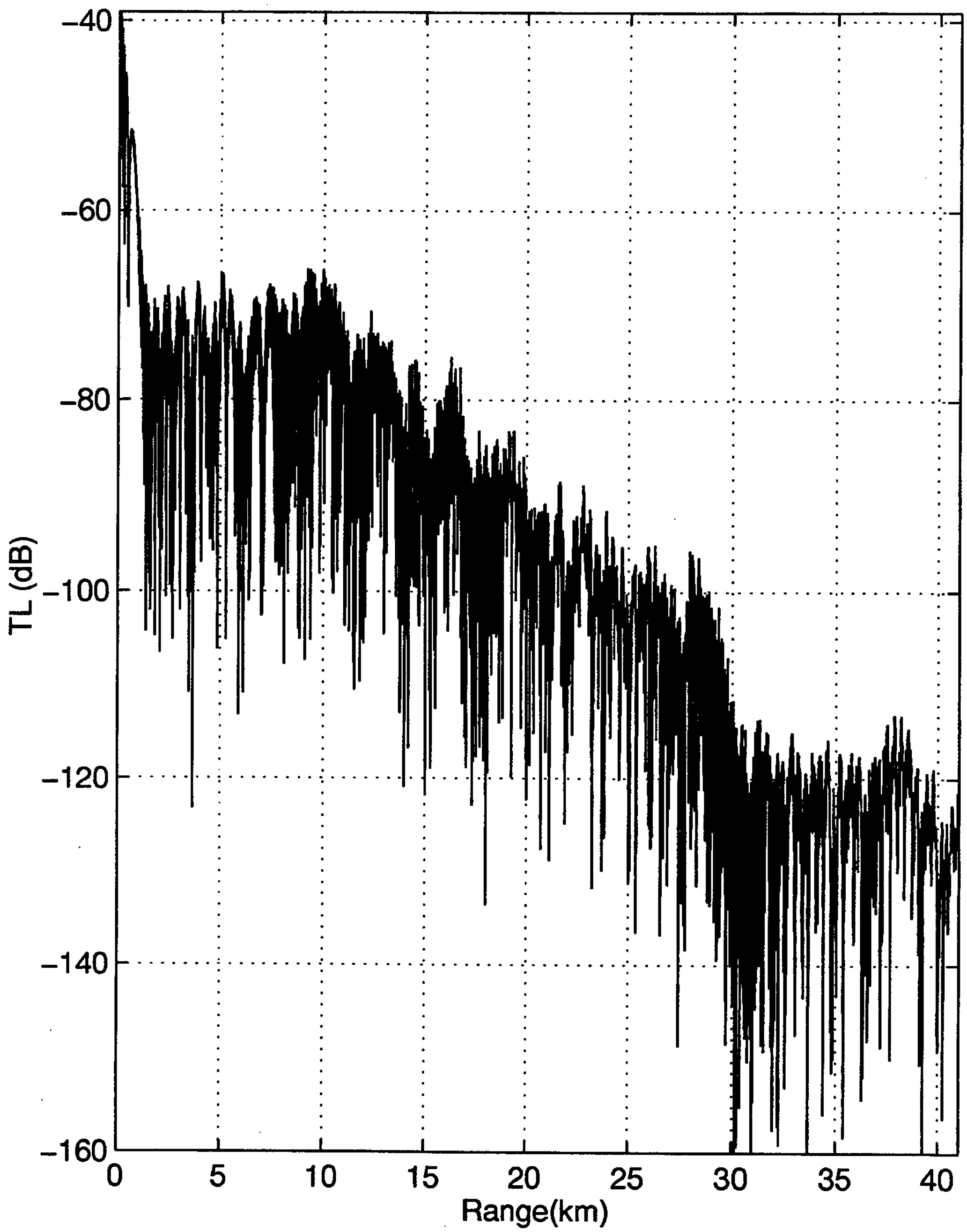

Figure 19. Same as Figure 16 with source depth of 75 m over a hard sand bottom.

the case in the range independent environment on top of Tanner Bank, but along the upslope path where the ray angles/mode order is ever increasing, the higher attenuation in sand than in silt/clay evidently dominates the better reflective properties normally associated with sand sediments.

This result was not expected and is currently being investigated further. However, FEPE has been benchmarked several times for upslope propagation paths using normal mode models and measured data and the FEPE results in Figure 19 are believed to be accurate. FEPE has been run in the same manner in the past for many different environmental conditions and has compared favorably with measured TL data (Duarte, 1994; Null et al., 1996). Thus, if the Tanner Bank region was comprised of a sand bottom, CLFA results would be worse, not better.

To examine if the shape of the SSP had an impact on CLFA performance results, an isothermal SSP (Figure 20) was used from the top of the water column to the ocean bottom. Actually, in wintertime over Tanner Bank a mixed layer (ML) develops only to approximately 20 m to 30 m (Dien, 1993). However, this ideal, but unrealistic, case of a ML extending to the ocean bottom was run to investigate how much an improvement in TL might result. Figure 21 shows the TL estimates for this ideal case. Depending on actual RL conditions, performance would improve for a FOM = 85 dB. However, this case is not likely to exist in reality over Tanner Bank and is run to set an upper limit on TL.

To establish a lower limit on TL, an infinite absorbing bottom and negative SSP TL model run was made. A comparison of this "worst" case and the preceding "best" case (compare Figure 22 and Figure 21) indicates over a 65 dB difference in TL at 25 km. This is why the use of inversion techniques (ITs) (Null et al., 1996) is strongly recommended to deduce the actual geoacoustic sediment properties and SSP in-situ from beam reverberation measurements. The geoacoustic model used is our "best guess" based

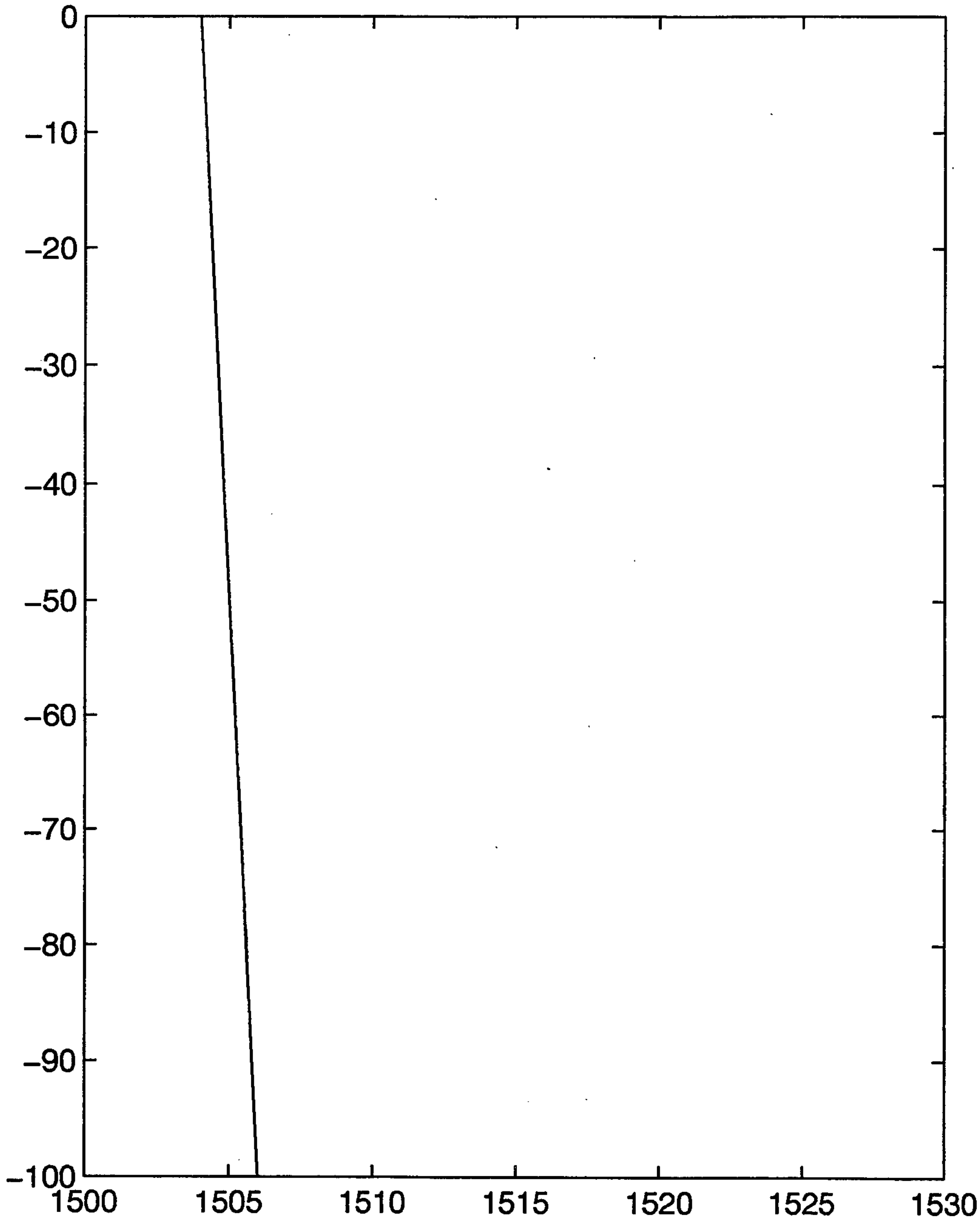

Figure 20. Isothermal sound speed profile.

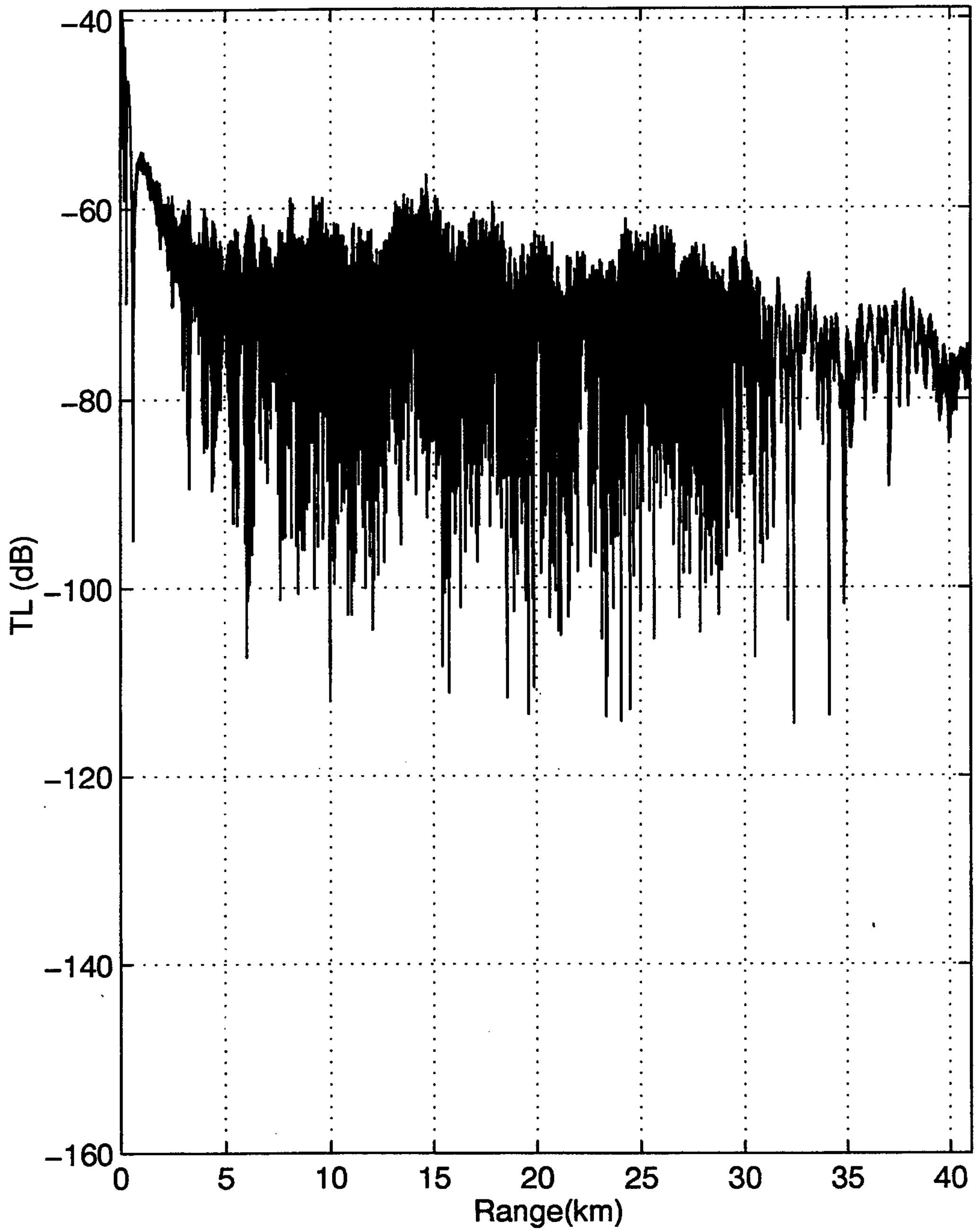

Figure 21. Same as Figure 16 with a source depth of 75 m and an upward refracting isothermal profile.

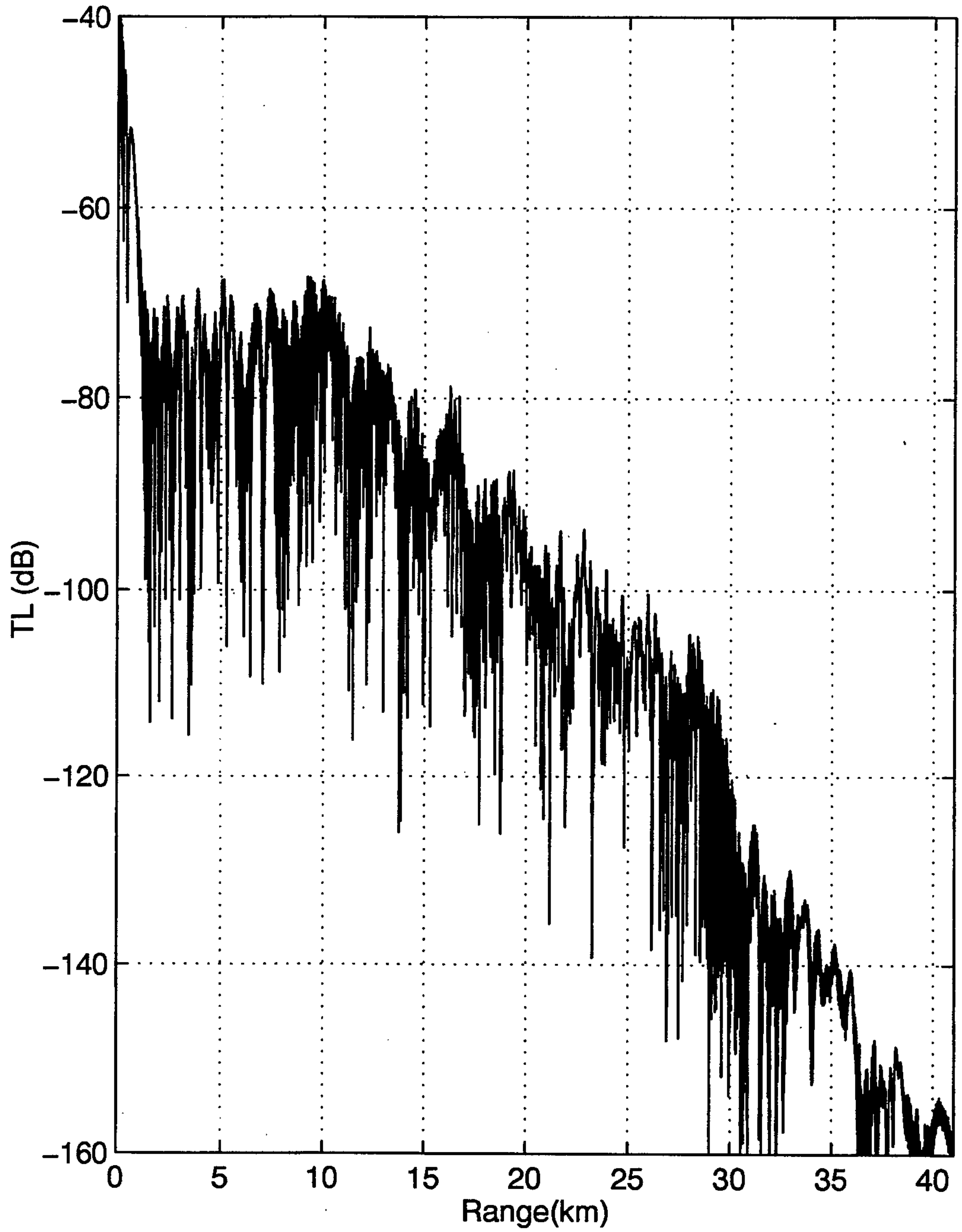

Figure 22. Same as Figure 16 with a source depth of 75 m over a silt/clay sediment depth of 2000 m to simulate an absorptive bottom of infinite depth.

will likely be highly variable spatially on a scale of 1-2 km (Scanlon 1996). The use of inverse technology must become a standard LFA/CLFA measurement technique to estimate performance accurately.

2. Mid-Shelf Toward Tanner Bank Propagation Path

If the CLFA source is moved toward Tanner Bank to the position shown in Figure 11, will CLFA improve? The answer is no, and one may not want to use a 5 sec pulse duration in case there are nearby targets of interest. If the pulse duration is decreased, ESL will increase significantly (Figure 10) and CFA performance will degrade at longer (> 4km) ranges.

Figure 23 shows a TL plot for the mid-shelf case. If it were not for ESL (shown in Figure 24 for a 5 sec CW pulse with sand and silt/clay bottoms), detection ranges may extend on top of Tanner Bank beyond 15 km range. Even for the ideal RL conditions assumed, the detection range will still not extend across the top of Tanner Bank and beyond.

A TL plot for the idealized ML case (Figure 25) indicates detection probability can potentially extend beyond Tanner Bank if both source and target are within the ML. Additional TL runs for both sand and perfectly absorbing bottoms suggest detection ranges similar to those for the deep water CLFA location (Figures 22 and 23).

3. Shallow Water Propagation Path Across the Top of Tanner Bank

A shallow water propagation path (Figure 4) on top of Tanner Bank was chosen to assess CLFA's performance in a continental shelf environment. This acoustic environment is quite different from the upslope propagation path discussed in the previous sections. Figures 26 and 27 show the TL estimates for a negative sound speed profile overlying a silt/clay and sand bottom, respectfully. The TL dependence on sediment type is reversed

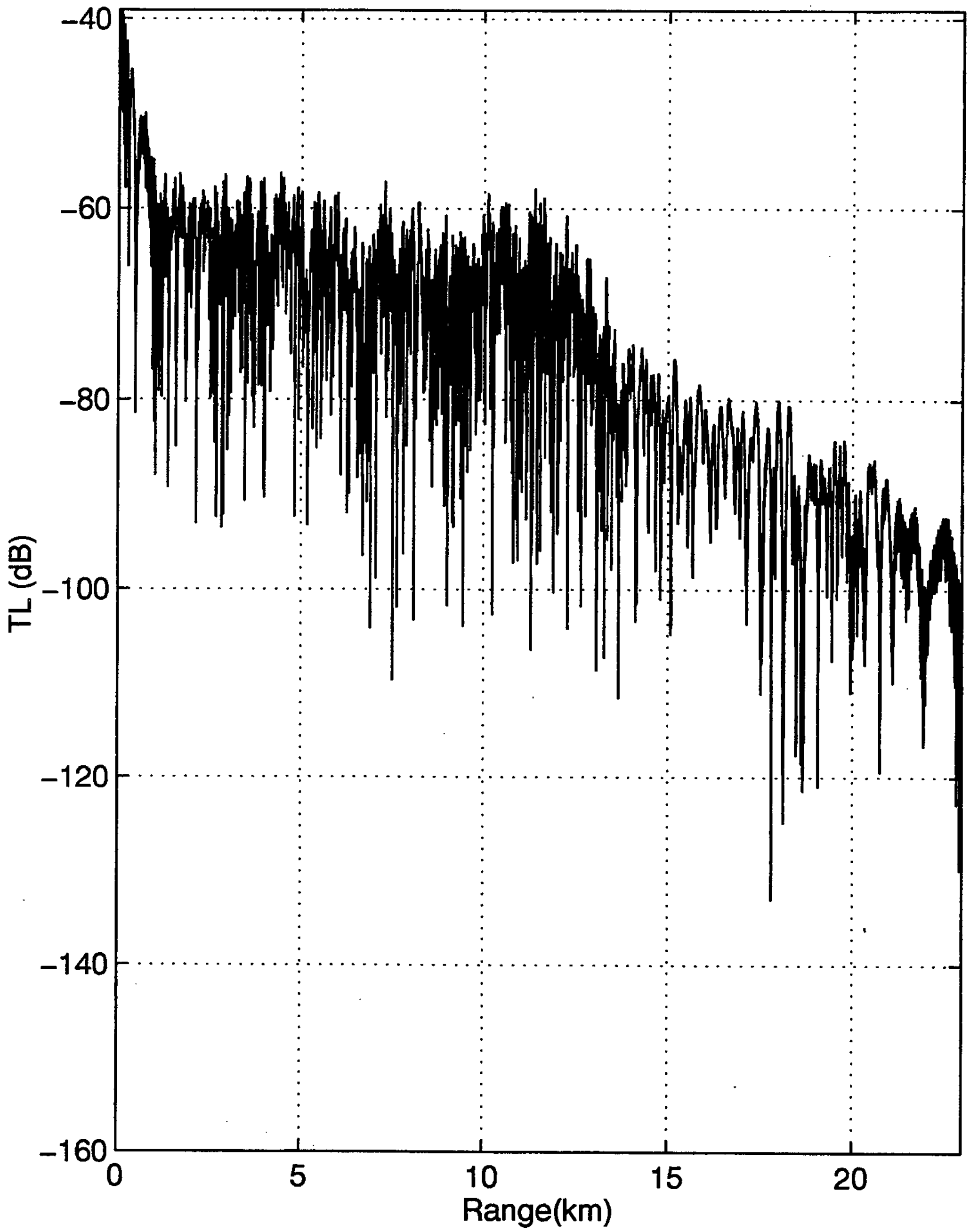

Figure 23. TL values for mid-shelf water with a silt/clay sediment base. Source depth of 75 m with a downward refracting, negative gradient profile.

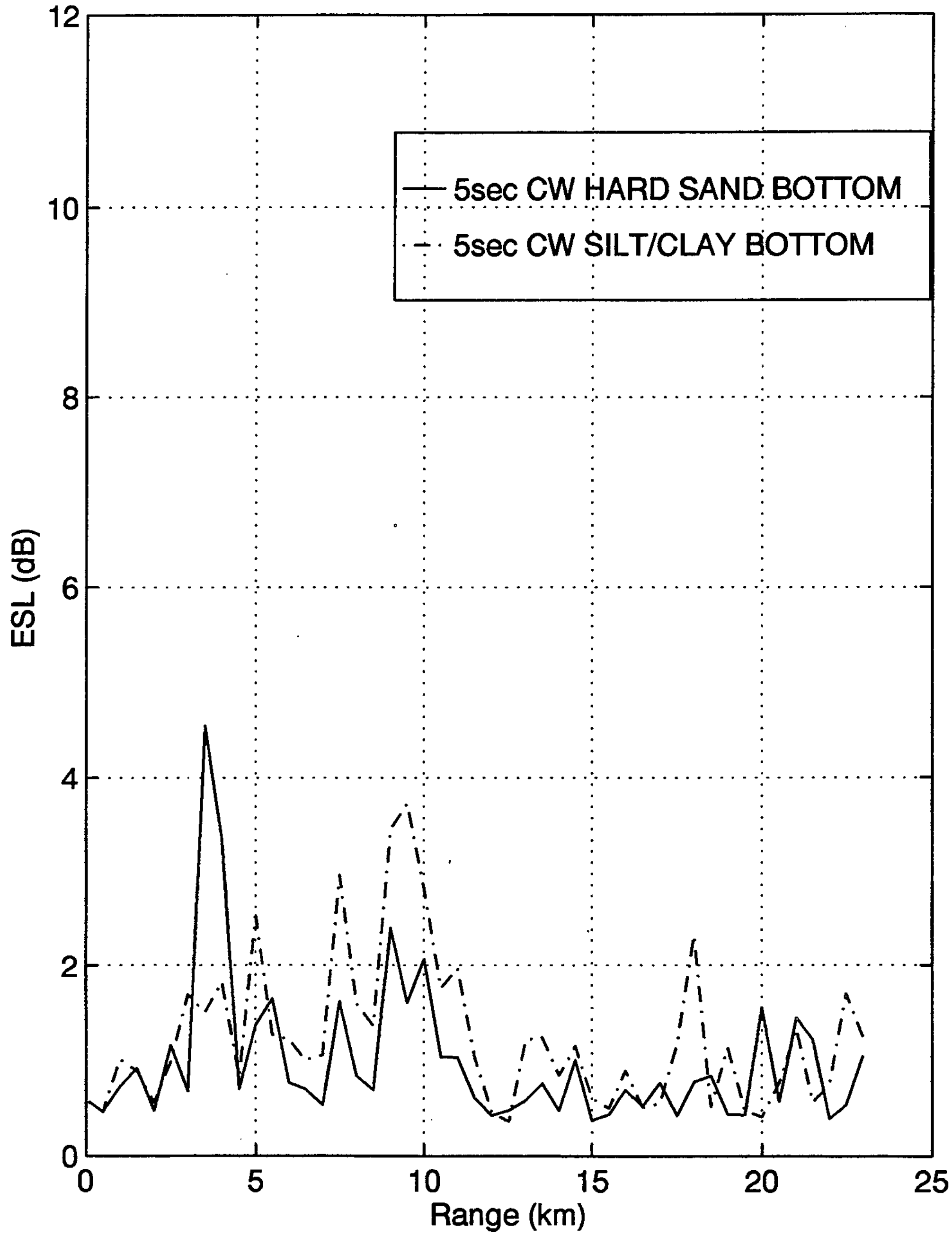

Figure 24. ESL dependence on sediment type in mid-shelf water. ESL appears to be little influenced by sediment composition.

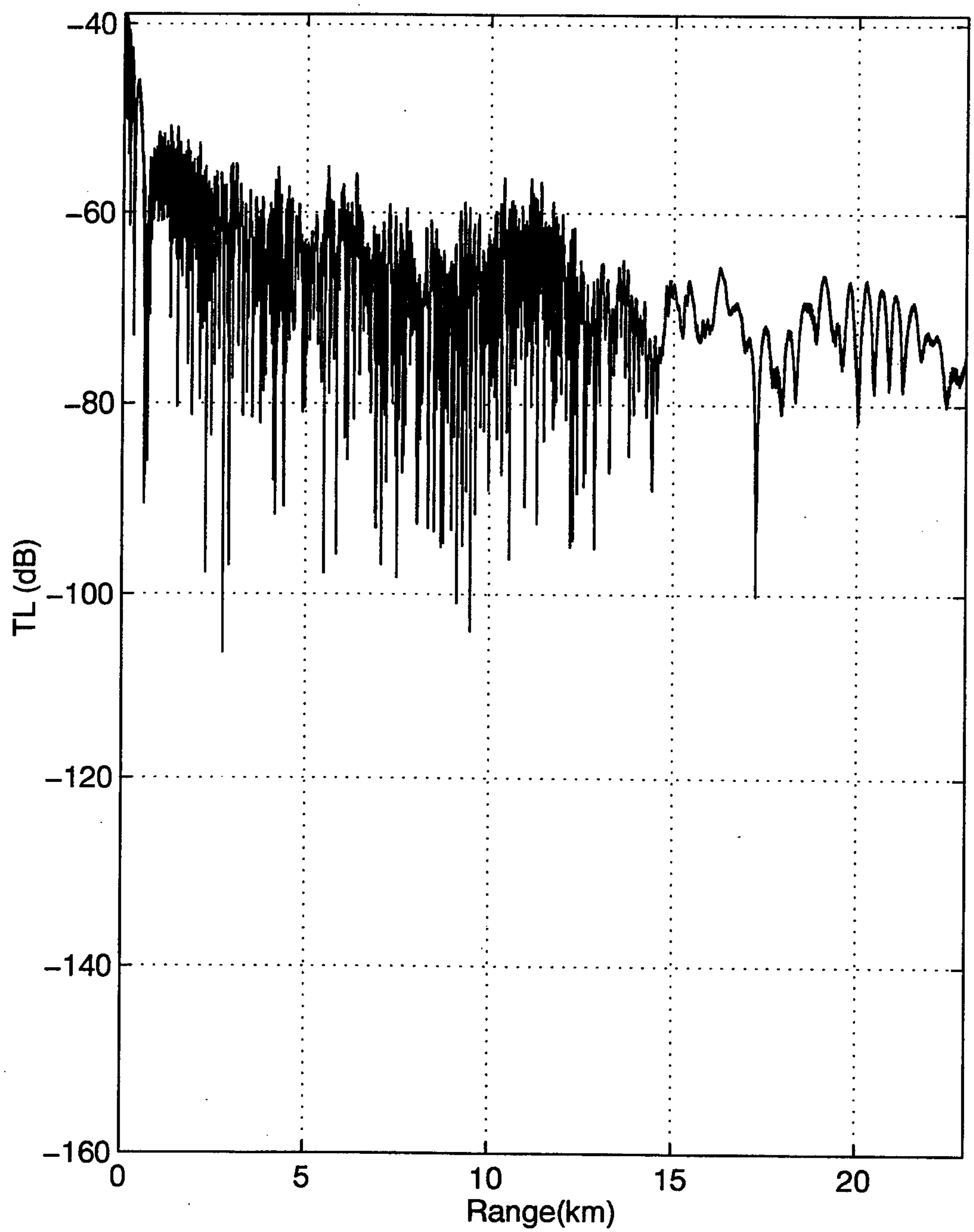

Figure 25. Same as Figure 23 with an isothermal profile. Dramatically improved TL values transiting the shallow water on top of Tanner Bank.

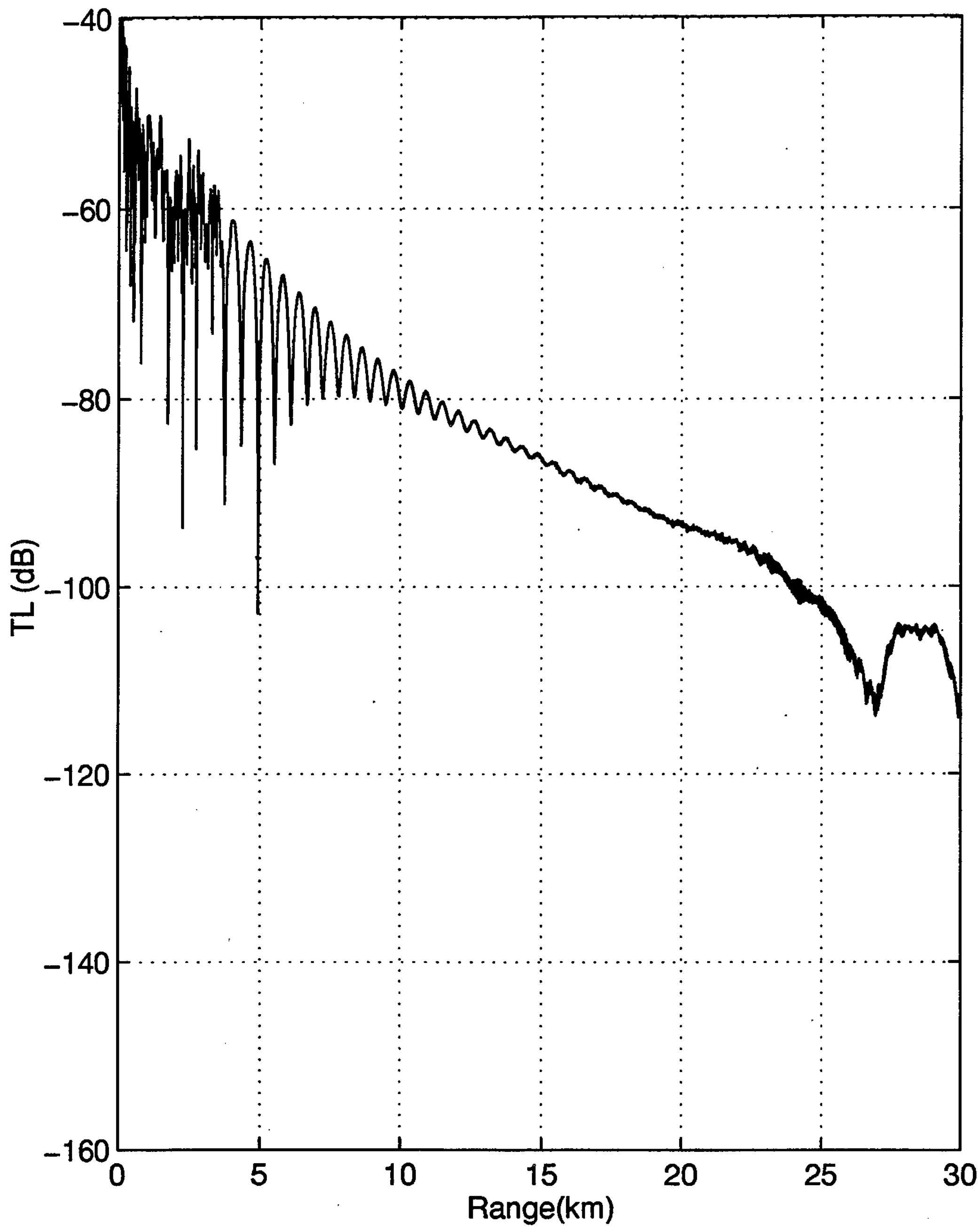

Figure 26. TL values for the shallow water on top of Tanner Bank with a depth of 75 m over a silt/clay bottom with a negative gradient.

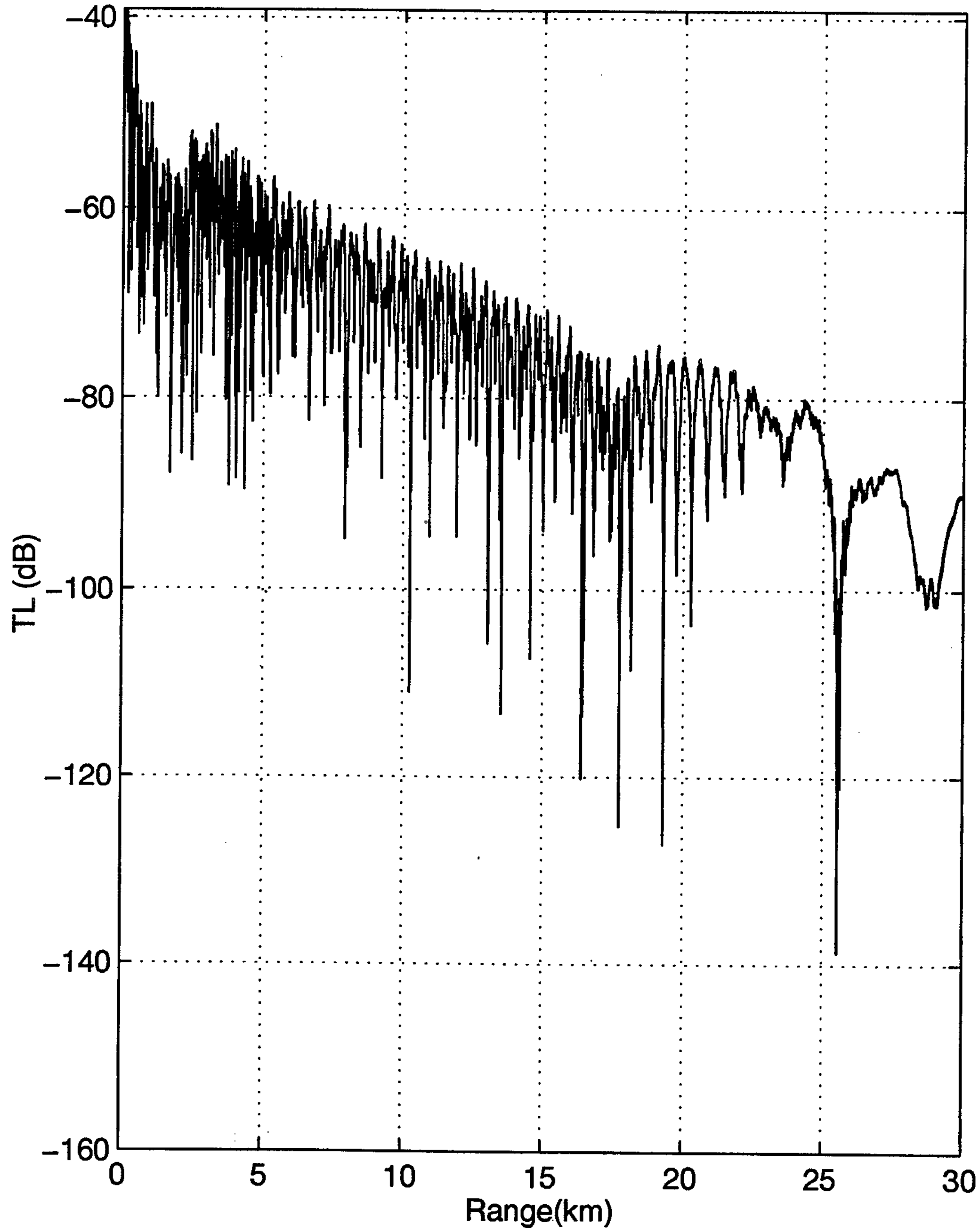

Figure 27. Same as Figure 26 with a hard sand bottom.

from that observed in the upslope case with the sand TL considerably better than for the silt/clay case. The improvement in TL associated with a sand bottom is consistent with most previous analyses of shallow water propagation. Where in silt/clay sediments are often termed "lossy bottoms" and sand sediments "reflective bottoms".

This again emphasizes the need to model each specific case on its own and not develop "thumb rules" for the complex shallow water environment. It also reinforces the necessity for using inversion techniques to deduce the local shallow water environmental geoacoustic and oceanographic properties.

ESL for this shallow water environment was relatively low and independent of sediment type (Figure 28) or SSP (ML vs negative profile) (Figure 29). Thus, for the negative SSP and an FOM of 85 dB, the TL + ESL values in Figures 26 thru 29 predict detection ranges of 25 km (across Tanner Bank) for the sand sediment case and less than 15 km for the more realistic silt/clay sediment layer on Tanner Bank. Again, these detection ranges are for the optimistic case of ambient noise limited conditions.

The effect that an upward refracting isothermal SSP exerts on TL for the silt/clay sediment cover on Tanner Bank is examined in a comparison of Figures 26 and 30 which shows that detection ranges are at least 5 km longer for the upward refracting profiles. This profile enhances water-borne propagation and reduces bottom interaction, thus reducing the TL. The need to reduce bottom interaction is even more dramatically illustrated in a comparison of Figures 26 and 31. For this latter figure the sediment layer has been increased in thickness to 2000 m, essentially infinitely thick. Penetration of low frequency energy into the bottom and its subsequent attenuation has limited detection ranges to ~3 km.

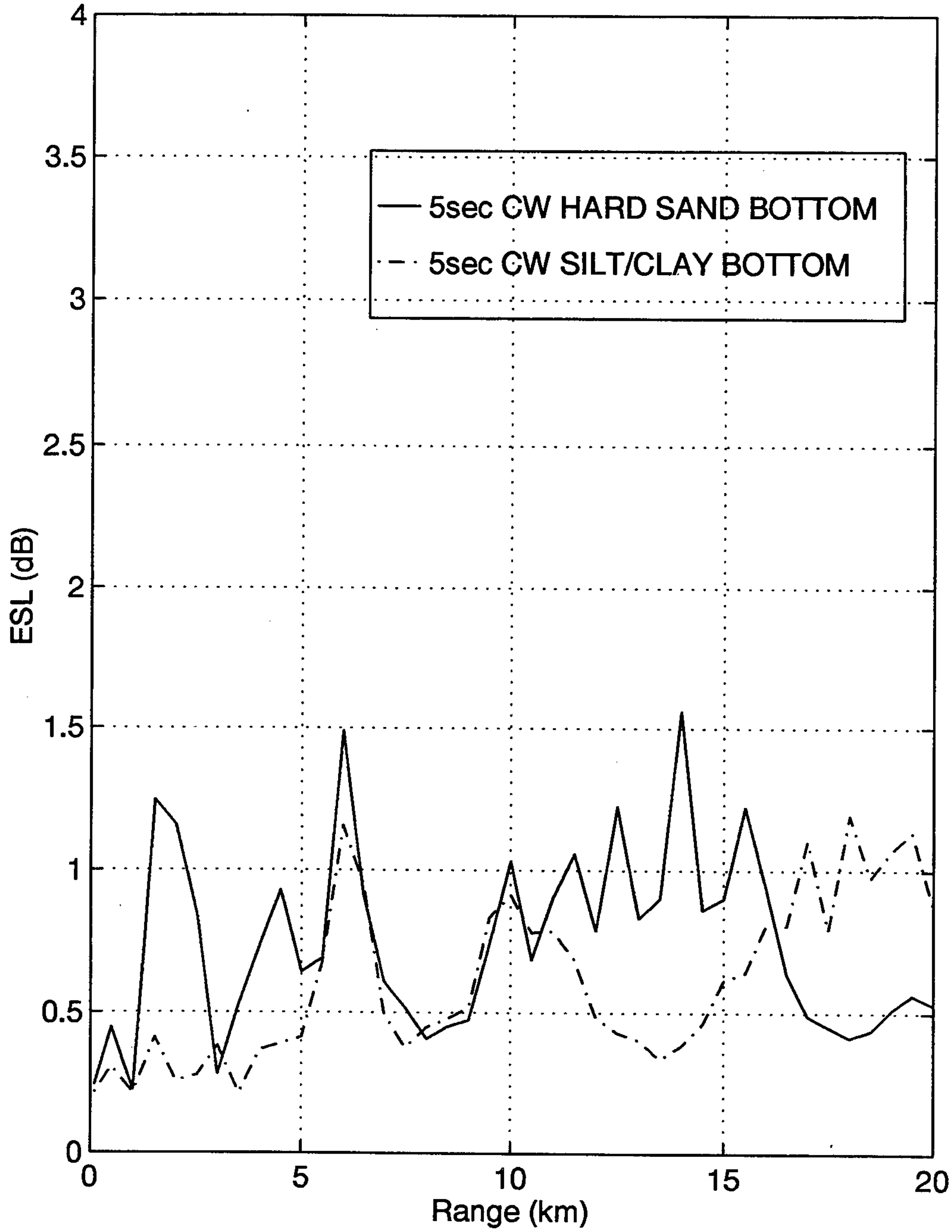

Figure 28. ESL dependence on sediment type in shallow water. ESL appears to be marginally less for a silt/clay bottom, but values are very close in magnitude.

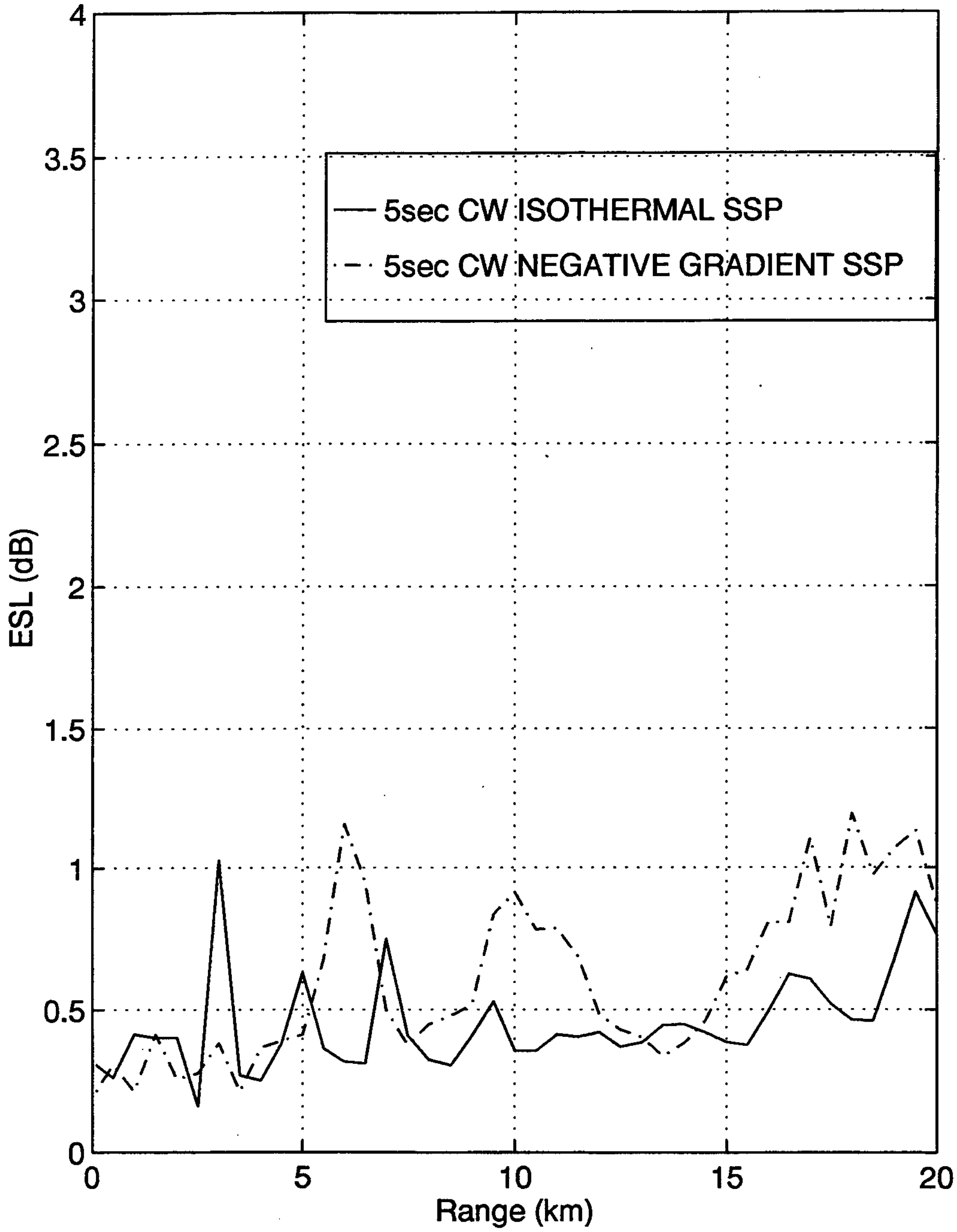

Figure 29. ESL dependence on sound speed profile in shallow water. SSP appears to have little impact on ESL values.

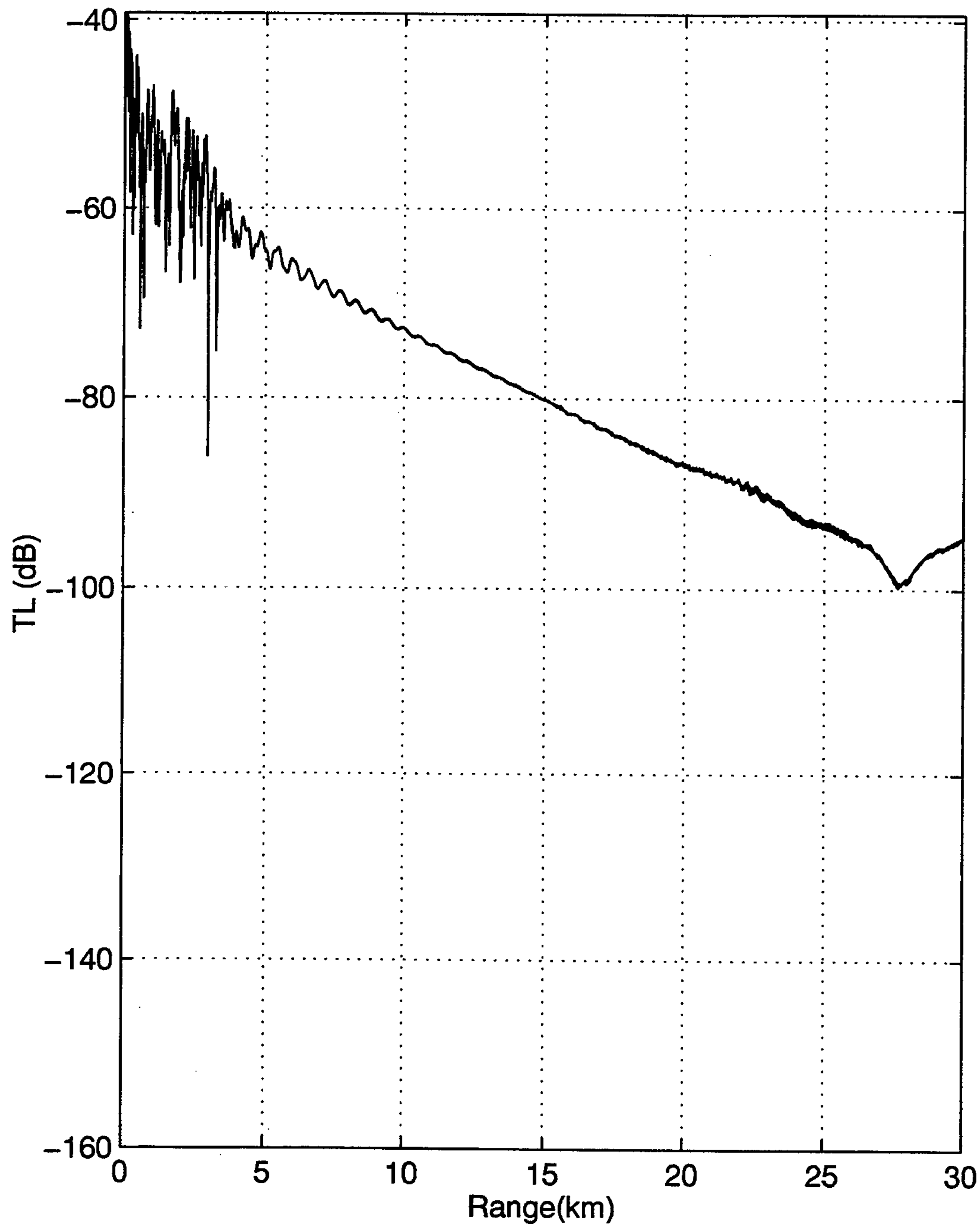

Figure 30. Same as Figure 26 with an isothermal gradient. TL values show a significant improvement with an isothermal gradient over a silt/clay bottom.

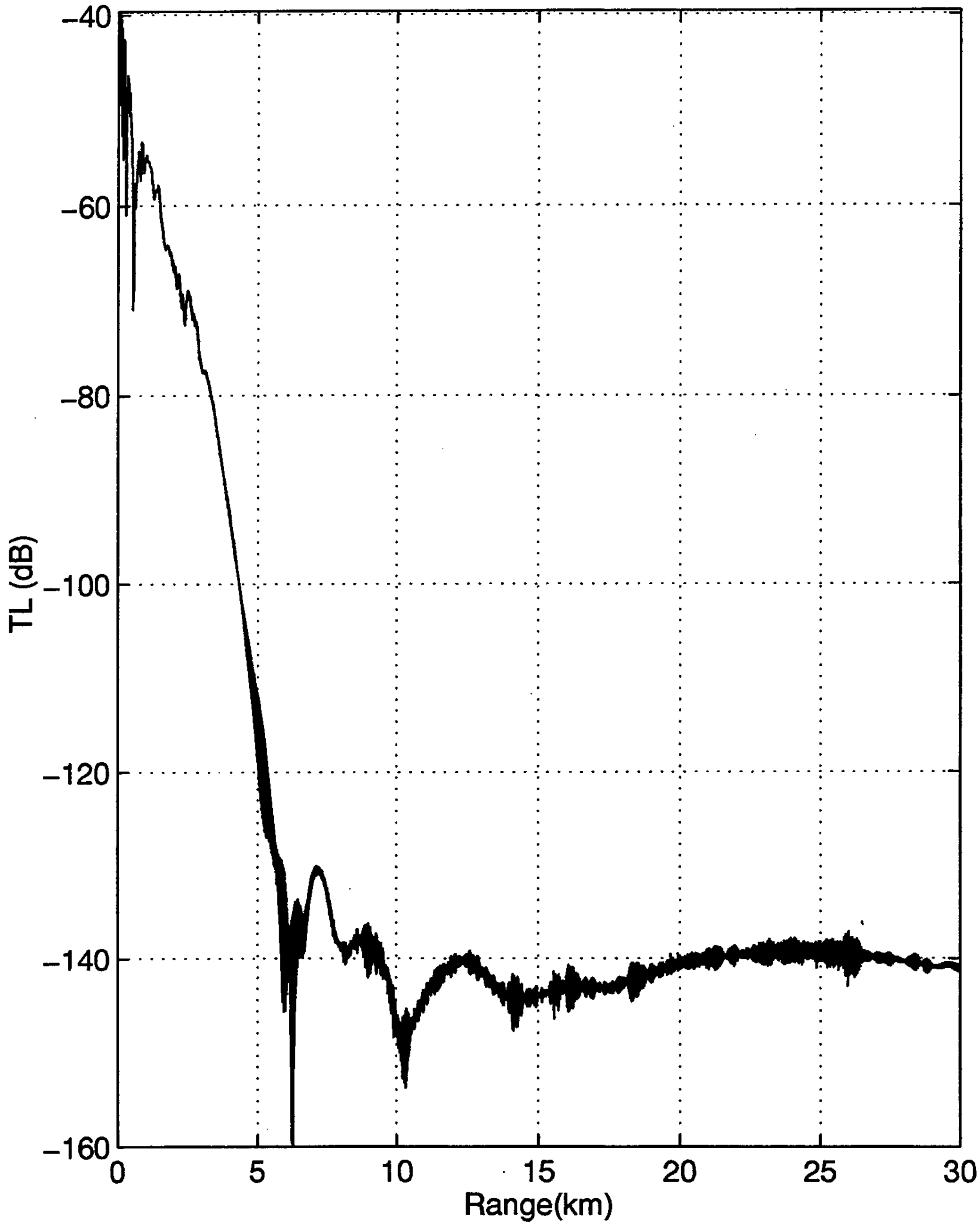

Figure 31. Same as Figure 26 with a silt/clay sediment depth of 2000 m.

IV. NORMAL MODE PROPAGATION THEORY

The previous section indicated that significant differences in TL in shallow water at LFA frequencies could occur due to changes in the geoacoustic nature of the sea bed. On the other hand, only relatively small variations in ESL were observed. To explain these responses one must introduce the concepts of normal mode propagation as it is not plane waves or ray paths but normal modes which propagate in shallow water.

To examine the effect of sediment composition on system performance, normal mode model (SUPERSNAP) runs for a 30 m constant depth were run for both sand and silt/clay sediment types. Hard sand has a very steep compressional sound speed gradient that effectively refracts bottom penetrating energy back into the water column with only limited penetration into the sediment. Thus, while the attenuation in sand, in dB/wavelength, is high relative to silt-clay (Table 1), the total bottom attenuation is low because the path length in the sand sediment is substantially shorter. For a silt/clay sediment structure the converse is true and the sedimentary layer must be considered an integral part of the propagation wave guide along with the water column. Consequently, the bottom attenuation is much more severe as shown by the TL estimate in Figure 26.

From a normal mode viewpoint, the highly reflective sand sediment supports the transmission of only propagating modes. These will have group speeds as shown in Figure 32. The critical issue is what modes are dominant which is a function of source and receiver depths, among other parameters. For example, if modes 6 and 10 were the dominant modes, there would be over a 500 m/sec difference in group speeds and ESL would be significantly more important.

The SNAP estimates of mode amplitudes versus water depth are shown in Figure 33. The sensitivity of ESL and TL to source/receiver depth is easily seen. For a 25 m depth source and receiver, one sees that modes 1 and 2 have relatively high positive

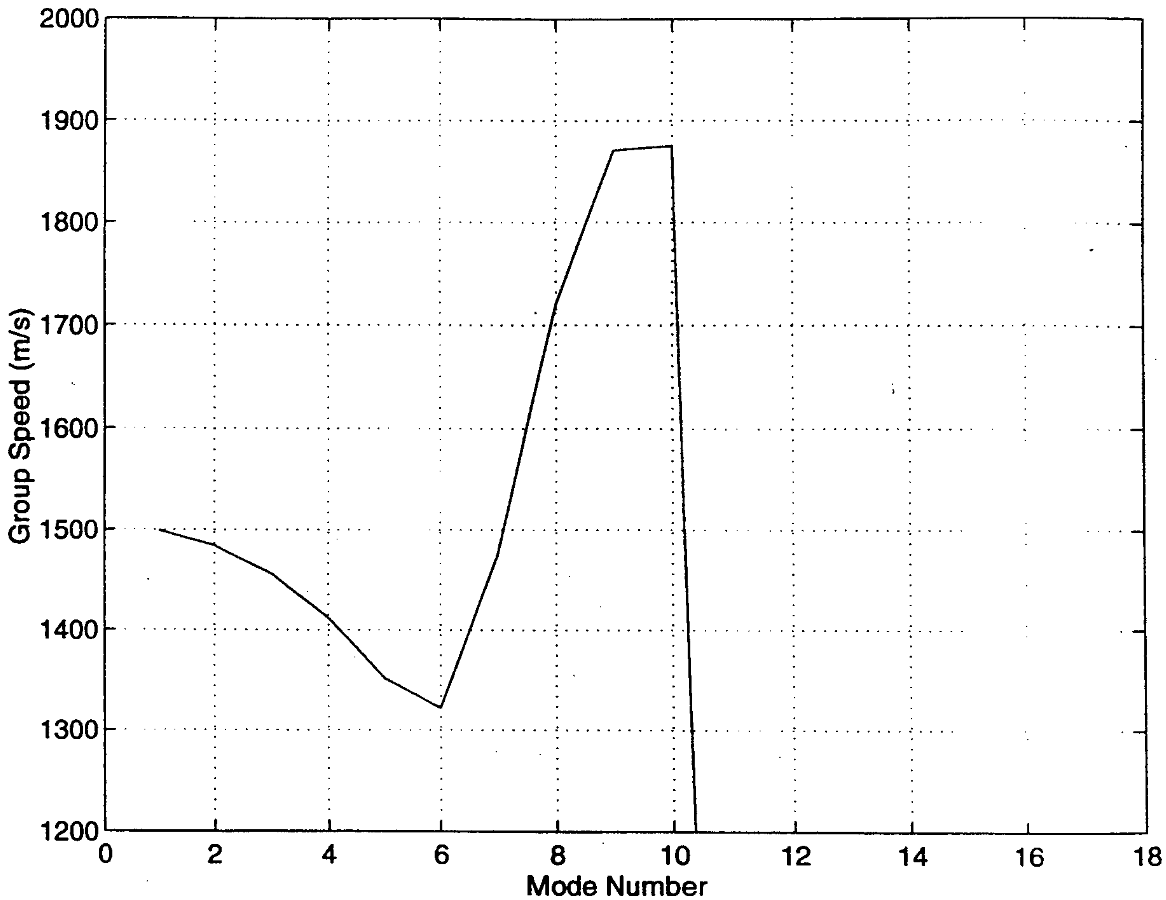

Figure 32. Modal group speeds for a 250 Hz source at a depth of 25 m over a hard sand bottom.

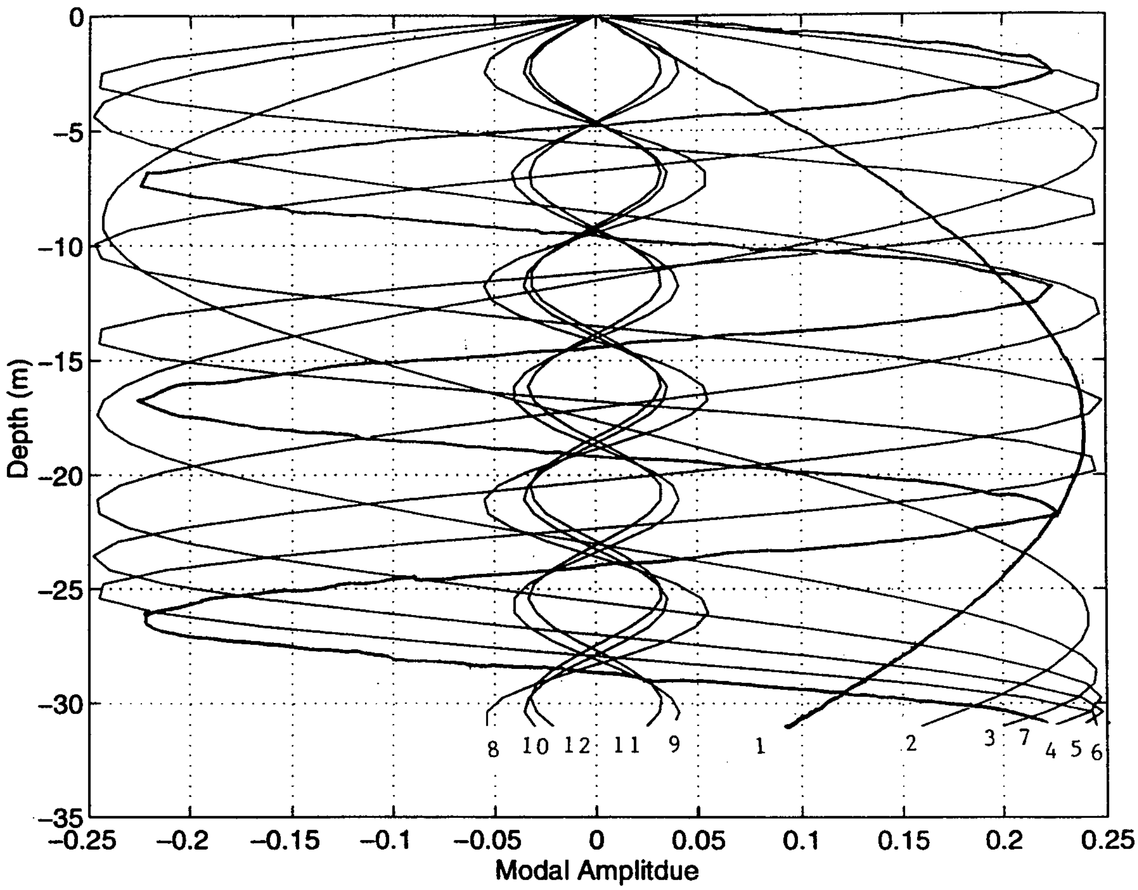

Figure 33. Modal amplitudes for a 250 Hz source at a depth of 25m over a hard sand bottom.

amplitudes while modes 5, 6, and 7 have large negative amplitudes. Modes 8, 9, 10, and higher have significantly lower amplitudes and the resultant pressure field is an interference pattern dominated by modes 1, 2, 5, 6, and 7 which have group speeds that are within 180 m/sec of each other (Figure 32). The very high group speeds of modes 8, 9, and 10 do not influence ESL because of their relatively low amplitudes. Thus, the dominant modes have group speeds whose differences can not be detected at short ranges in shallow water. For example, modes 1 and 5 have group speeds of approximately 1500 m/s and 1350 m/s, respectively, and their travel times difference for 15 km is less than 0.1 sec. For a 2 sec or 5 sec pulse length, this means there is virtually no effect on ESL.

To understand the relatively good TL characteristics for the sand sediment, it is instructive to introduce some of the standard isospeed, hard bottom results from the acoustics literature because the solution is deterministic, not numerical, for this simple case. The hard sand bottom parameters from Area Foxtrot approximate the hard bottom case accurately enough to explain why the TL is relatively low (Figure 27). The radial wave numbers, $\mathbf{k_{rm}}$, are given by:

$$k_{rm} = \sqrt{(\omega^2 / c^2) - [(m - 0.5)\pi / D]^2} \qquad (4\text{-}1)$$

where D is water depth, ω is the angular frequency $2\pi f$, c is sound speed, and m is the mode number. The modal group speeds, $\mathbf{U_m}$, are given by:

$$U_m = d\omega / dk_{rm} = (\sqrt{(\omega^2 / c^2) - [(m - 0.5)\pi / D]^2}\,(c^2 / \omega) \qquad (4\text{-}2)$$

The cutoff frequency (f_{co} = c/4D) is 12.5 Hz; no modes propagate in this 30 m channel below this frequency. Using the far field approximation to the Hankel function, the pressure as a function of range, r, and source and receiver depths, z_s and z_r, is given by:

$$P_{(r,zs,zr)} = i(\sqrt{8\pi})e^{-i0.25\pi} / [\sum_{m=1}^{m_{max}} \sin(k_{rm}zs)\sin(k_{rm}zr)e^{ik_{rm}r} / \sqrt{rk_{rm}}] \quad (4\text{-}3)$$

This is the solution to the wave equation for the isospeed hard bottom case. Propagating modes are defined as those for which k_{rm} is a real number in Equation (4-1). For mode numbers (m) ≥ 11, k_{rm} becomes imaginary (for f = 250 Hz and D = 30 m) and e^{ikrmr} in equation (4-3) becomes "exponentially decaying" with range. Modes for which k_{rm} is real are termed oscillatory (standing waves or propagating modes) because no attenuation occurs other than geometric spreading with range. When k_{rm} is imaginary, the modes are termed evanescent and decay exponentially with range. For other than isospeed, hard bottom environments, k_{rm} is a complex number with both real and imaginary components and ideal propagating modes do not exist. In practice, the terminology relating to the ideal wave guide is still used in the sense that low angle/low order modes are called propagating, while higher angle/higher order modes that interact with the bottom are called "leaky" or evanescent modes.

The TL of these propagating modes is given by:

$$TL_{(r,zs,zr)} = 10\log_{10}\left|P^2_{(r,zs,zr)} / P^2_{(r,zs,zr)}\right| \quad (4\text{-}4)$$

Setting $z_s = z_r$ = 25 m, D = 30 m, f = 250 Hz, and with k_{rm} determined by Equation (4-1) yields a TL that closely approximates the FEPE estimates of TL in Figure 27. The exceptionally low TL values for the sand bottom case result from the 10 propagating modes having relatively small attenuation which can be thought of as k_{rm} values with very small imaginary parts, or low exponential decay with range. It would be very difficult to select z_s and z_r values in Figure 34 such that TL would not be good because there are no depths where all mode amplitudes go to zero.

When considering the silt/clay sediment values that approximates the Tanner Bank region, the normal mode description is much different than for the sand sediment environment above. The silt/clay sediments and water column must be considered as one propagation channel, and, as Figure 35 shows, there are almost 80 modes to consider. All the modes interact with the sub-bottom. Figure 35 shows that all dominant modes have modal group speeds with difference of less than 200 m/s. This difference is too small to result in any appreciable time stretching.

The important point made by this study is that ESL and TL are related to normal mode concepts in shallow water and that sediment type is the dominant factor in modeling ESL and TL accurately for LFA performance issues. The local geoacoustic environment should be determined by measurements from LFA reverberation tests using inverse techniques [Scanlon et al., 1996; Null et al., 1996] now being developed. It will be unlikely that one can use a historical data base for geoacoustic information that will be accurate on the small spatial scales necessary to model ESL and TL accurately. In many shallow water regions the sediment environment can change from sand to silt/clay in less than 1 km. For Tanner Bank a realistic Hamilton geoacoustic model was derived (Table 1) based on historical data, but the local variations in this geoacoustic model are expected to vary significantly on small spatial scales. As this section shows, LFA performance can also vary significantly based on the geoacoustic environment encountered.

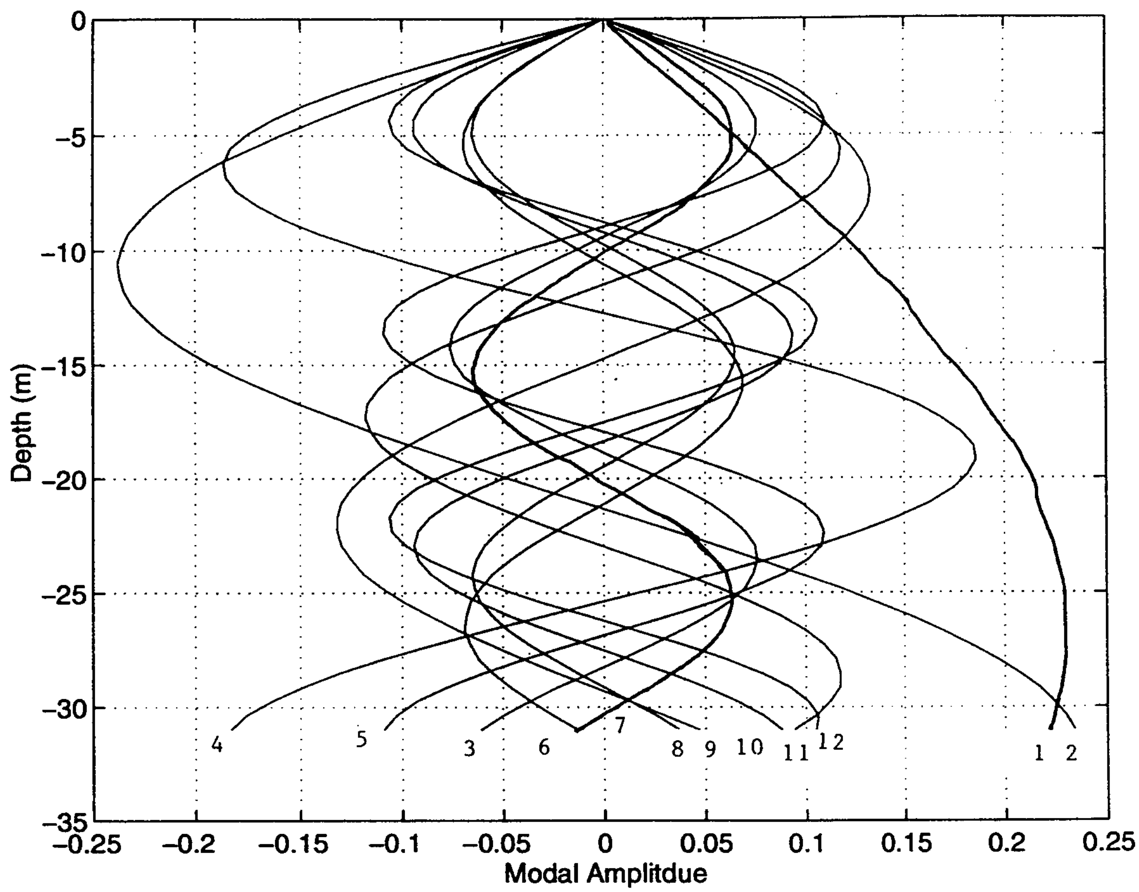

Figure 34. Modal amplitudes for a 250 Hz source at a depth of 25 m over a silt/clay bottom. Only the first 12 modes (of ~80) are shown due the minimal amplitudes of higher order modes.

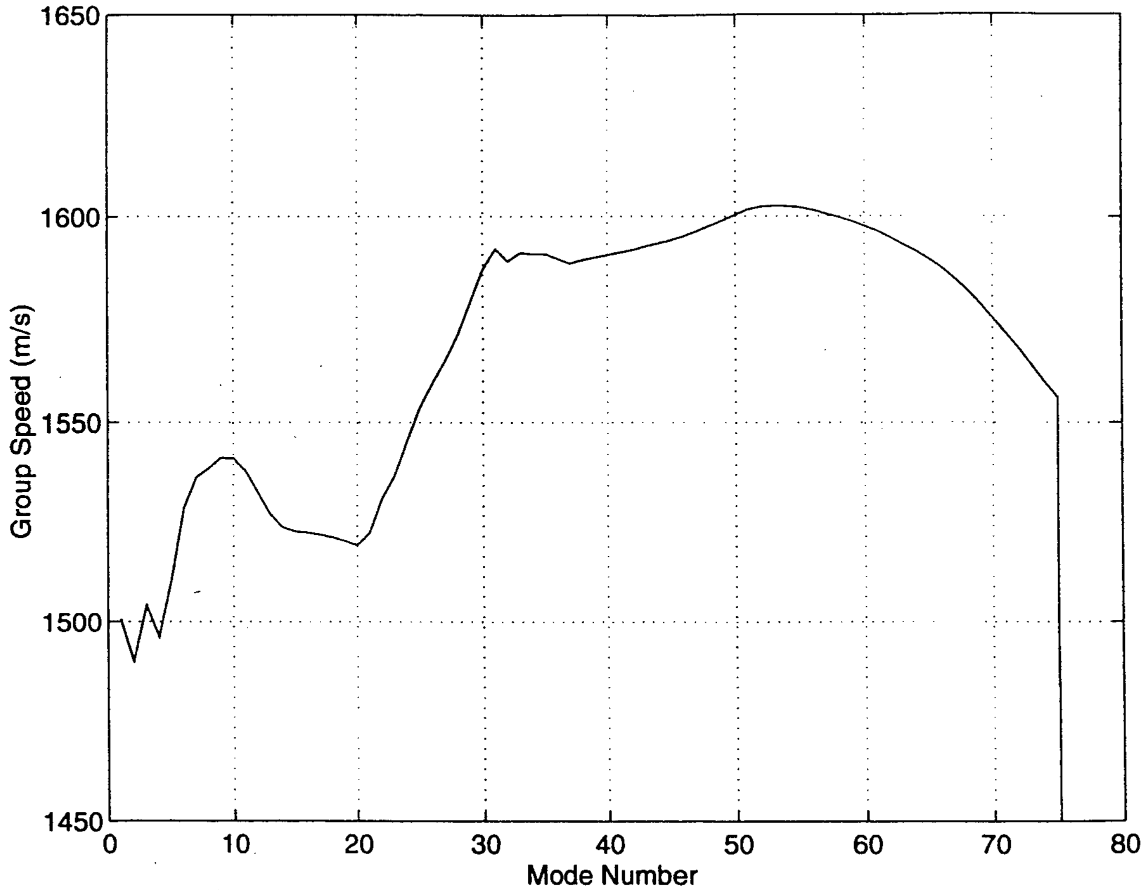

Figure 35. Modal group speeds for a 250 Hz source at a depth of 25 m over a silt/clay bottom.

A. CONCLUSIONS

- The multipath nature of acoustic propagation in shallow water leads to time stretching of active sonar pulses. This thesis examined the one way propagation losses associated with this time stretching phenomenon known as energy spreading loss (ESL) as a function of bathymetry, range, sediment type, and sound speed profile for the low frequencies associated with the CLFA system. Both ESL and TL values were used to evaluate CLFA system performance in the rapidly changing bathymetry of the Tanner Bank region off southern California. It was found that TL is the dominant feature for system performance in a shallow water environment.

- ESL was found to be inversely related to pulse duration. At the comparatively long pulse lengths associated with CLFA (2 to 5 sec pulses were modeled) ESL was found to be minimal (< 2 dB) while in midshelf water depths. In shallow water, ESL values averaged ~ 4 dB. When pulse lengths were shortened to less than 1 sec, the values for ESL increased to average of 7 dB for a 0.5 sec pulse and 10 dB for a 0.1 sec pulse in midshelf water depths. In shallow water the ESL values were even higher.

- ESL was found to be relatively independent of sediment type and sound speed profile for the low frequencies of the CLFA system. ESL values mostly varied by less than 1 dB for both a highly absorptive silt/clay sediment and for a highly reflective hard sand bottom. Two sound speed profiles, a strong downward refracting negative gradient and an upward refracting isothermal gradient, produced very similar results with the ESL plots following the same curves and varying by less that 0.5 dB.

- ESL is independent of waveform. Evaluations of both the Blackman windowed pulse (BW) and the continuous wave (CW) pulse resulted in near identical values over a wide variety of sediment type, pulse duration, and bathymetric geometries.

- ESL is independent of waveform. Evaluations of both the Blackman windowed pulse (BW) and the continuous wave (CW) pulse resulted in near identical values over a wide variety of sediment type, pulse duration, and bathymetric geometries.

- Transmission loss, modeled for the single center frequency of 244 Hz, was the dominant feature in system performance. TL was strongly influenced by bathymetry, sediment type, and sound speed profile. In shallow water the best TL values resulted from an upward refracting SSP which allowed limited bottom interaction. If the acoustic path involved large numbers of bottom interaction, the highly reflective sand bottom preserved most of the acoustic energy for good TL values, while the silt/clay bottom attenuated the signal and produced poor detection ranges. In midshelf depths these roles are surprisingly reversed, with the silt/clay sediment preserving more of the acoustic signal than the reflective bottom.

- Shallow water sound propagation is highly variable by region. Mean or climatological values do not do an accurate job of predicting sonar system performance within a particular area. Local geoacoustic environment measurements are essential in the calculation of FOM and probable detection ranges.

B. RECOMMENDATIONS

- Conduct inversion technique studies of Tanner Bank region to map sedimentary changes within the region.

- Continue model evaluations of TL dependence on sediment type in regions of rapid bathymetric change.

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