

**DETECTION OF T-PHASES AT ISLAND SEISMIC STATIONS:  
DEPENDENCE ON SEAFLOOR SLOPE, SEISMIC VELOCITY AND ROUGHNESS**

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**ABSTRACT**

The hydroacoustic segment of the International Monitoring System (IMS) currently being installed for use in verifying compliance with the Comprehensive Nuclear Test Ban Treaty (CTBT), will consist of six hydrophone stations and five supplemental T-phase stations. The ability to detect acoustic signals at T-phase stations relies on an understanding of the acoustic to seismic coupling mechanisms. In this paper, we model upslope propagation of acoustic energy at a sloping wedge using an elastic parabolic equation (PE) modeling method. We synthesize both vertical and horizontal displacement waveforms for broadband sources, and show that the signal amplitudes are strongly dependent on the properties of the offshore slope. For all slope types, the signal amplitudes at onshore seismic stations decrease rapidly with increasing frequency. This decrease with frequency is most pronounced for sources with high mode number content at a shallow sloping wedge. Finally, we show that a significant amount of energy can be lost to surface shear waves at the sloping wedge. We investigate the dependence of surface shear wave excitation on seafloor roughness.

**Key words:** hydroacoustics, acoustic to seismic transmission

# Report Documentation Page

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## OBJECTIVE

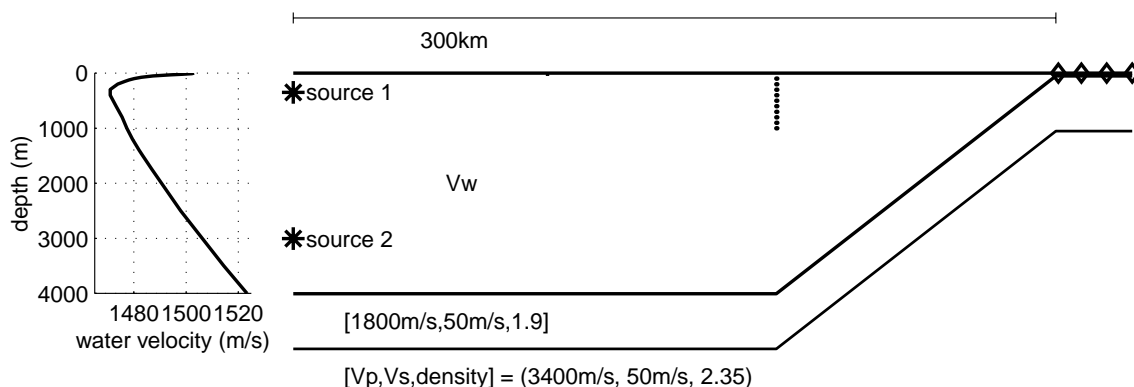
The hydroacoustic component of the International Monitoring System (IMS), currently being installed for use in verifying compliance with the Comprehensive Nuclear Test Ban Treaty (CTBT), will consist of six hydrophone stations and five supplemental T-phase stations (Lawrence and Grenard, 1998). The T-phase stations, which will be located on islands where acoustic transmission is partially blocked, will each be equipped with one to three seismometers designed to detect seismic phases generated by conversion of hydroacoustic waves at the island boundary. Although the T-phase stations are significantly less sensitive than hydrophones to ocean-borne acoustic energy, because of the relatively high attenuation of the seismic phase within the crust, their anticipated lower cost makes their use desirable.

There are several physical processes that can impede routine discrimination between underwater explosions and naturally-occurring events. For instance, at T-phase stations, discriminants based on spectral characteristics are hindered by the frequency dependent attenuation of seismic energy within the crust, which makes detection of high frequency T-phases difficult. A further difficulty with T-phase stations is that signal amplitudes depend on the azimuth of the arriving T-phase (Hanson, 1998) and may vary with physical parameters at the land/ocean interface, such as seismic velocities or slope gradients. Thus, accurate calibration of T-phase stations requires a better understanding of acoustic to seismic conversion at the island boundary. In this paper, we describe acoustic to seismic coupling in terms of the upslope propagation of acoustic modes impinging on a sloping wedge. We demonstrate the effect of slope and bottom velocity on predicted waveforms using PE modelling, and show that the results are in agreement with acoustic mode theory.

## RESEARCH ACCOMPLISHED

We have examined the effect on the recorded signal of several physical parameters, including the slope of the ocean/shore boundary, the modal content of the incoming acoustic phase, and the distance between the seismic station and shoreline.

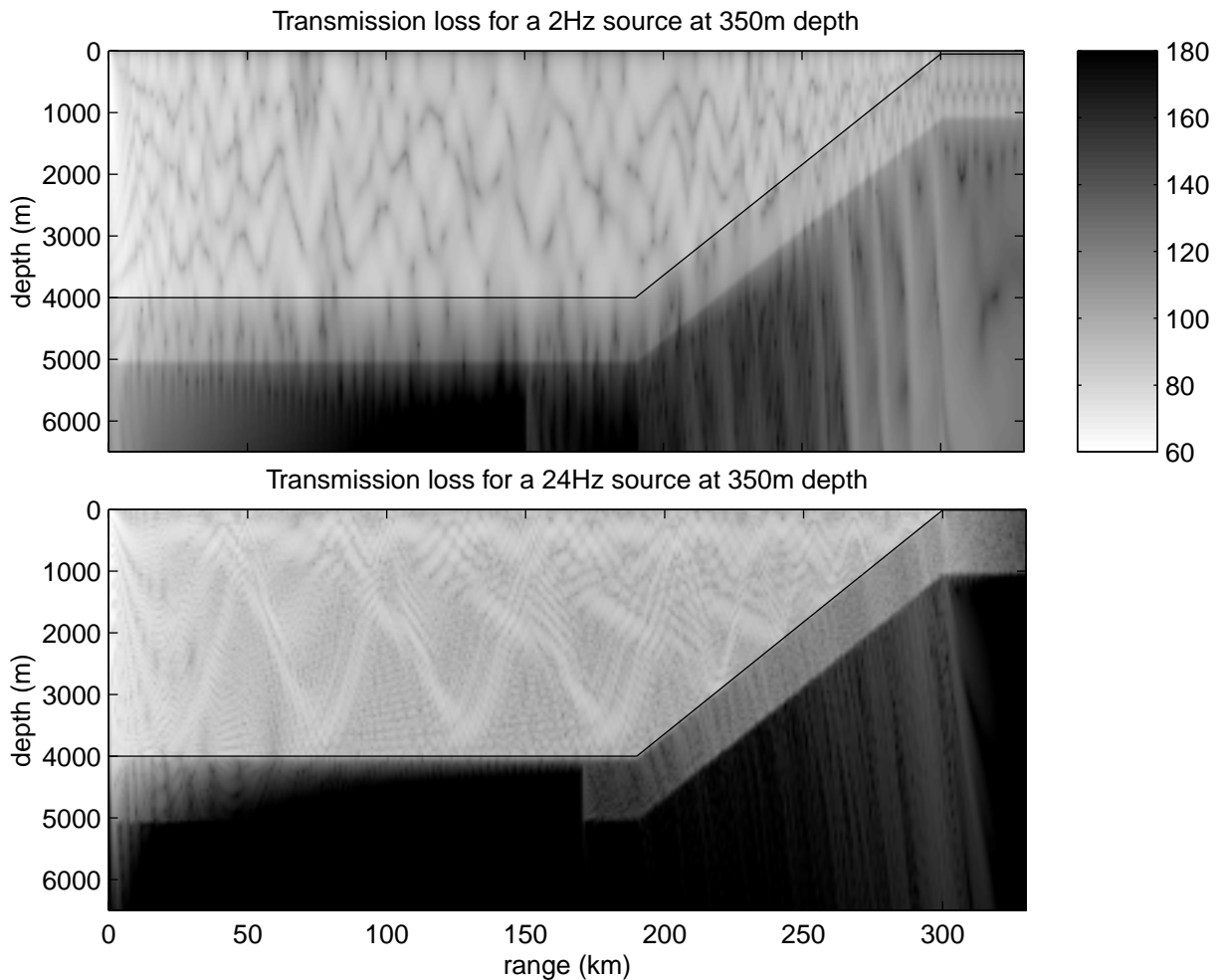
We model acoustic to seismic coupling along a sloping wedge using an elastic parabolic equation (PE) code developed by Collins (1993), which allows for simultaneous computation of compressional potential and vertical displacement,  $u_z$ . We examine the compressional potential and  $u_z$  for four scenarios, with varying slope angles and source depths. In each case, the velocity model is as shown in figure 1, and computations are performed for a range of frequencies between 2 and 24Hz. Both the seafloor and land section of the model feature a 1km thick “sedimentary” layer, with a P-velocity of 1800m/sec, over a faster basement. The distance between the source and the “shoreline”, (*i.e.*, where the



**Figure 1** Environmental model for PE computations. The water velocity profile used for all computations is shown at left. The diamonds denote seismometer locations, recording vertical displacement, and the asterisks denote the 2 source locations used in the modeling. The position of a vertical hydrophone array is marked by the dotted line.

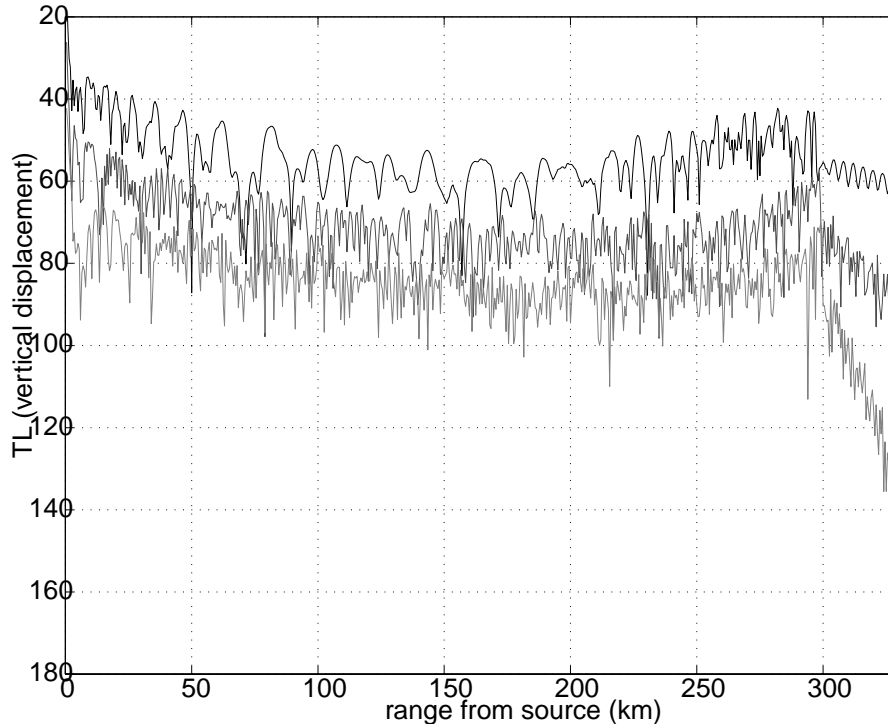
ocean depth decreases to zero) is fixed at 300km for all computations. The P-wave attenuation is set to 0.1 dB/wavelength and the S-wave attenuation is set to 1 dB/wavelength. The water depth is constant at 4 km up to the base of the slope. The model is extended 30 km past the shoreline to model the effects of transmission loss with distance inland. The S velocity was held at a very low value, 50 m/sec, to limit the analysis to coupling of acoustic energy to P waves.

The dB loss in compressional potential for a source at 350 m depth, is shown as a function of depth and range from the source in figure 2 for a slope of 2°. Results for a 2Hz source are shown above and for 24 Hz, below. At both frequencies, some energy couples into the basement within the first 50 km. As the ocean depth decreases, acoustic energy is absorbed into the seafloor at different ranges corresponding approximately to the modal cutoff depths. Some energy couples into beams that radiate directly into the basement; the remainder becomes trapped in the sediment layer and propagates along this attenuative waveguide to the land. For the 2 Hz source, the ranges corresponding to low order mode cutoff depths are indicated by regions of significant intensity in the bottom. For the 24 Hz source, much of the energy is trapped within the top 1km of the ocean, and couples into the waveguide very near the shoreline.



**Figure 2** Transmission loss plots for a 2Hz (top) and 24Hz (bottom) source at 350m depth, for a 2° slope.

The decrease in  $u_z(z=0)$  as a function of range from the source, is shown in figure 3, for 2 Hz, 8 Hz and 24 Hz sources. For each source,  $u_z$  decreases almost linearly with distance beyond the range at which the ocean depth vanishes. The decrease is most rapid at high frequencies, as shown, since the attenuation (in dB) is nearly linear with frequency within the bottom.



**Figure 3** Decrease in vertical displacement (in dB) for 2 Hz (black), 8 Hz (gray), and 24 Hz (light gray) sources at 350 m depth.

For comparison, the decrease in potential energy for an identical model, but with a source at 3000 m depth, is shown in figure 4 for frequencies of 2 Hz and 24 Hz. In this case, the results for 2Hz are nearly identical to those above, but at 24 Hz frequencies, the acoustic energy within the ocean propagates as surface interacting rays, which then couple into the waveguide at a distance of greater than 10km from the shore. The decrease in  $u_z(z=0)$  as a function of range from the source is shown in figure 5, at frequencies of 2, 8 and 24Hz. As shown, the results are nearly identical to those for the shallow source at 2Hz. However, the total dB loss in  $u_z$  is much greater at high frequencies as compared to the results for the shallow source, since the path length through the attenuative waveguide is longer.

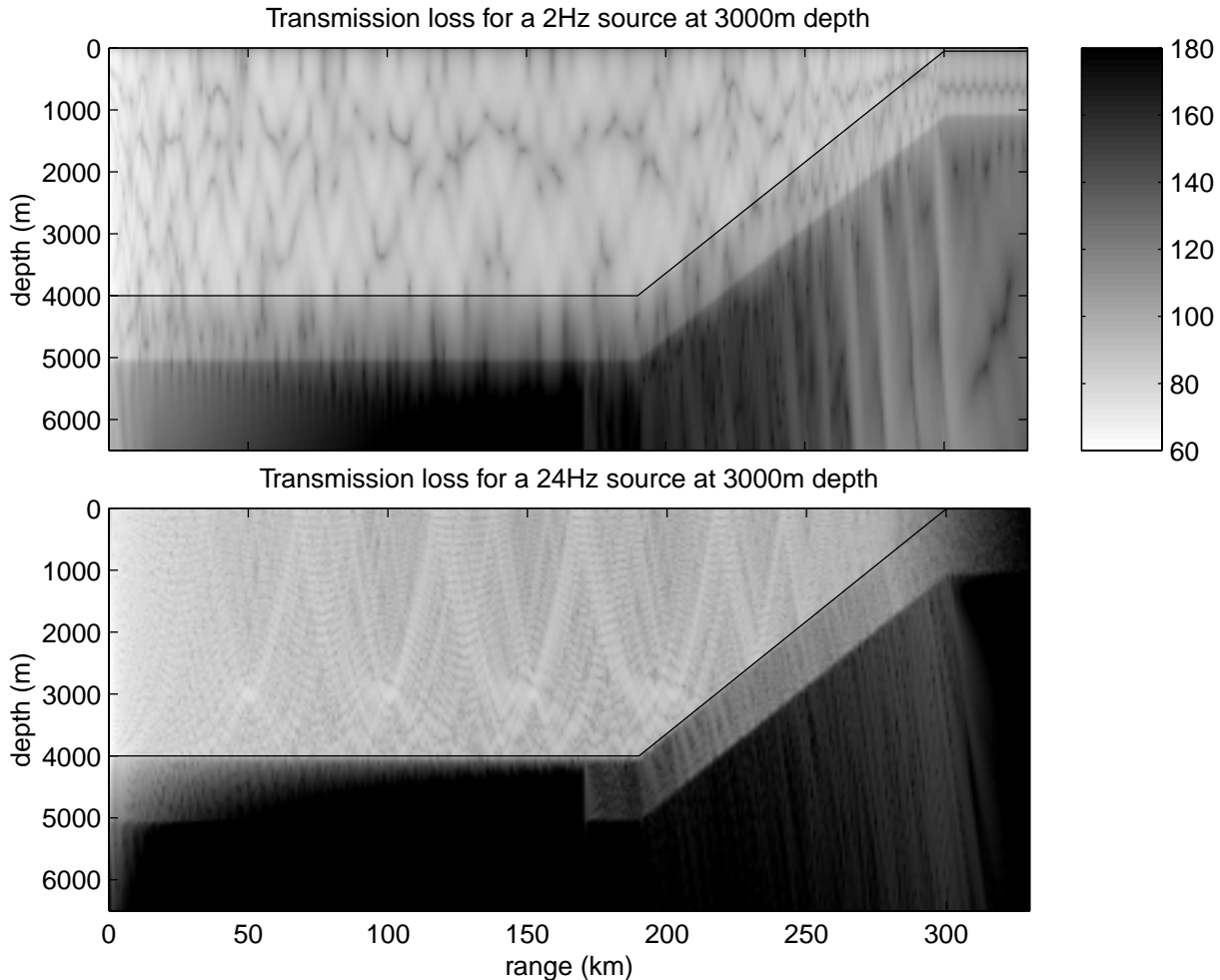
The frequency dependence of the recorded signals at varying distances inland is summarized in figure 6, for the sources at 350m and 3000m depth. As shown, signal strengths at 2Hz are nearly identical at the 2 source depths, but the falloff in amplitude with increasing frequency is far more severe for the deep source than for the shallow source. In comparison, the average dB loss in the compressional potential at a vertical hydrophone array at a range of 190km from the source is nearly uniform as a function of frequency.

The attenuation in  $u_z$  may be interpreted in terms of the acoustic modes excited by the source. Since acoustic energy propagates in the ocean with negligible transmission loss, the signal amplitudes recorded at T-phase stations will decrease with increasing distance traveled by the converted seismic phase. For a simple wedge model, the depth, and

hence, range at which the acoustic energy becomes trapped in the sediment waveguide depends on slope of the wedge, as well as the modal composition and frequency of the source. The depth at which a given mode couples into the bottom is given approximately by the cutoff depth for a Pekeris waveguide (Pekeris, 1948), *i.e.*

$$d_m = (m-0.5) c_1 c_2 / (2f(c_2^2 - c_1^2)^{1/2}), \quad (1)$$

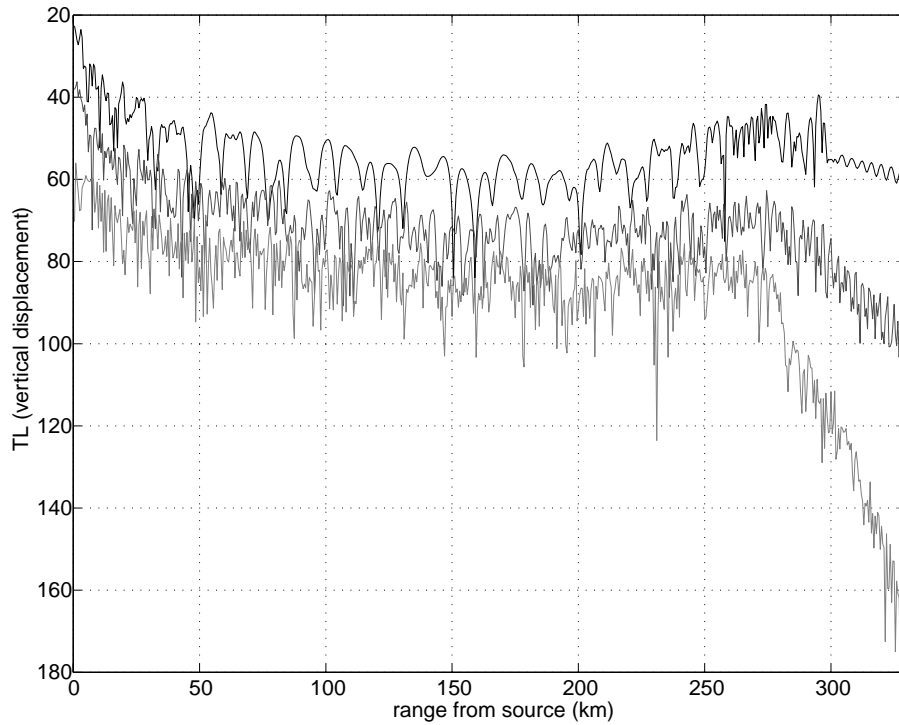
where  $m$  is the mode number,  $f$  is the frequency of the source, and  $c_1$  and  $c_2$  are the velocities of the fluid layer and fluid halfspace, respectively. For a slope of angle  $\alpha$ , the range from the shore at which the acoustic mode couples to the seismic mode is given approximately by  $d_m / \tan(\alpha)$ . Thus, the lowest order modes at any given frequency couple to seismic waves nearest to the shore, so the recorded amplitude at a T-phase station will depend on the mode content of the acoustic signal, particularly at high frequencies that are strongly attenuated by propagation through land.



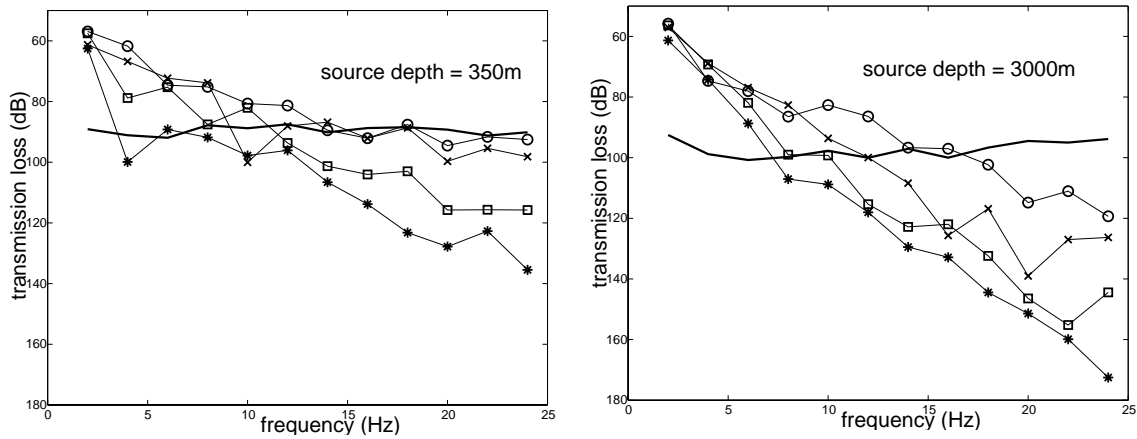
**Figure 4** As in figure 2, but for a source at 3000 m depth.

Figure 7 shows several discrete normal modes that exist in the flat region of the model at 2Hz (a) and 24Hz (b). A particular mode can be excited only if the modal depth function at the source is non-zero, thus at 2Hz, the lowest order modes can be excited by both shallow and deep sources. At 24Hz, low order modes can be excited only by the shallow source. Figure 8 shows the approximate amplitude wave-number spectra excited by the 2Hz and 24Hz sources at depths of 350 and 3000m. As shown, the first 10 modes are not excited by the deep 24Hz source, thus coupling takes place much further from the shoreline and is hence attenuated far more than for the shallow source. On the other hand, since the modal composition of lower frequency sources is less strongly dependent on depth, and since intrinsic attenuation is

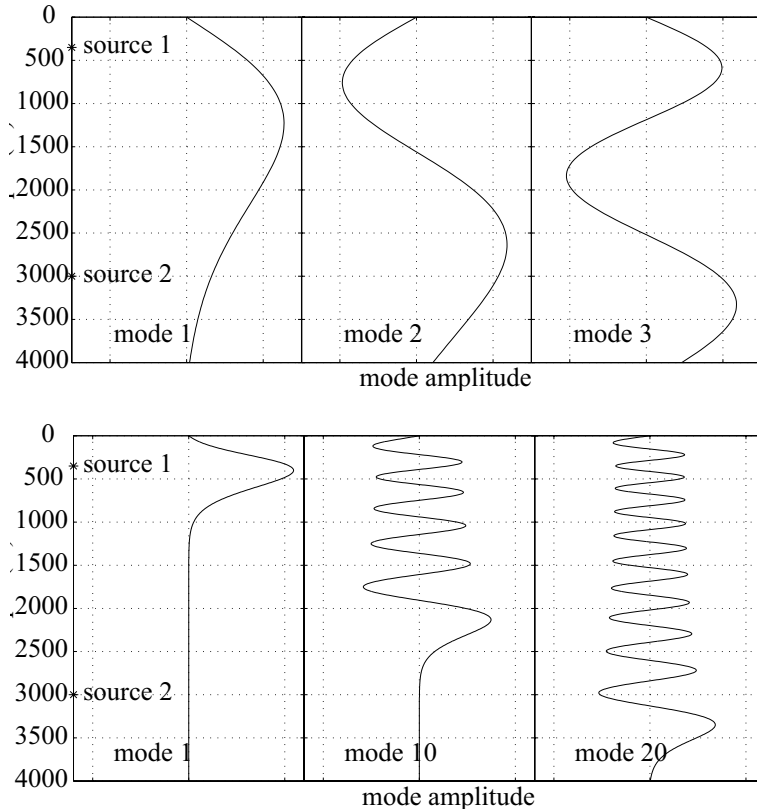
not as severe at low frequency, recorded T-phases are correctly predicted to be less strongly influenced by the modal composition of the source.



**Figure 5** As in figure 3, but for a source at 3000 m depth.



**Figure 6** The dB loss in  $u_z$  as a function of frequency for sites located 1 km (circles), 10 km (x'es), 20 km (squares), and 30 km (asterisks) inland. a) results for a source at the sound channel minimum incident on a  $2^\circ$  slope. b) results for a source below the reciprocal depth incident on a  $2^\circ$  slope. The average transmission loss in compressional potential to a vertical array extending from 100-900 m depth at a range of 190 km from the source is shown for comparison, and is marked by the heavy lines.

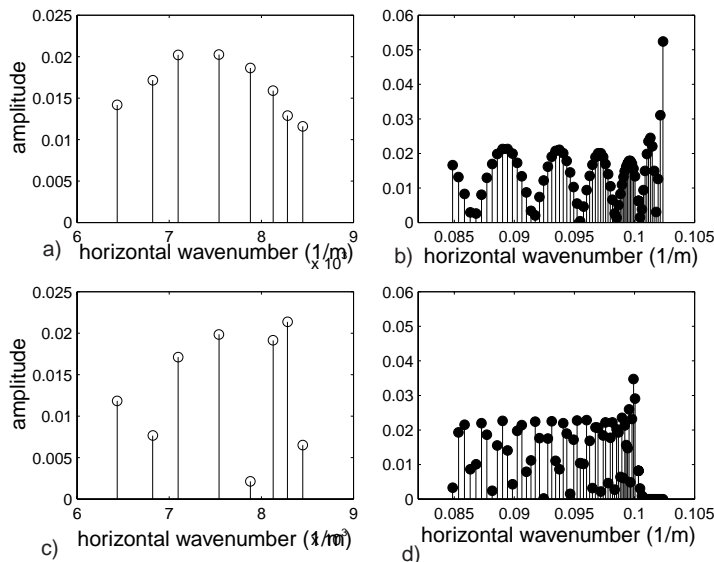


**Figure 7** Several modal depth functions in the flat part of the ocean for a) 2 Hz, and b) 24 Hz.

frequency. This corresponds to a narrower distance range for a steep slope than at a shallow one, thus, as discussed in de Groot-Hedlin and Orcutt (1999), the duration of any given mode may be greater at a shallow slope than at a steep one, and its amplitude correspondingly lower.

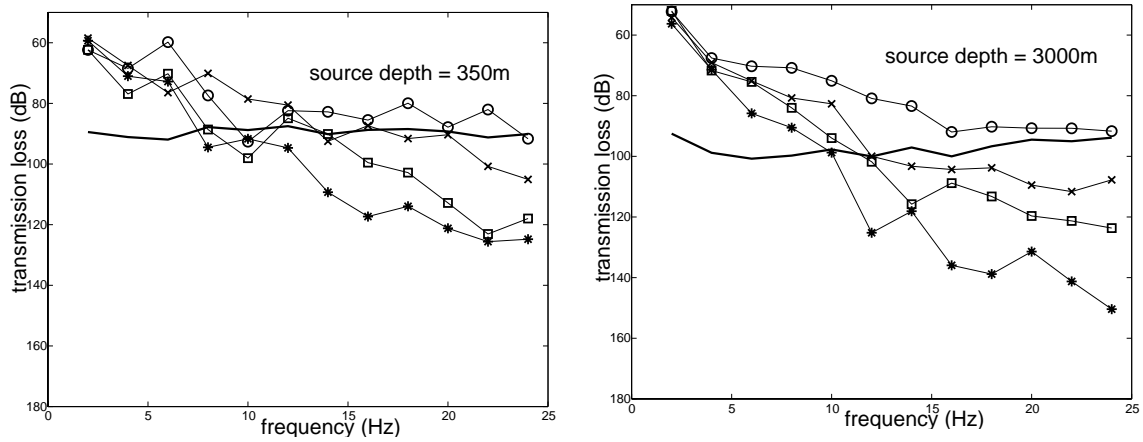
Since low order modes are cutoff at shallow depths near the shore, the effect of slope angle on the recorded signal is expected to be small, in the frequency domain, for sources composed primarily of low order modes. Figure 9a summarizes the frequency dependence of the signals for onshore stations, for a model with a  $6.6^\circ$  slope. As predicted, the decrease in signal strength as a function of frequency is similar to that of the  $2^\circ$  slope, as shown in figure 6a. Conversely, for sources which generate high order modes, the effect of slope is expected to be significant, since the path length through the attenuative waveguide is much shorter for steeper slopes. This is confirmed by the results shown in figure 9b. Comparing these results with those of figure 6b, for a  $2^\circ$  slope, it can be seen that the signal decreases much more slowly as a function of frequency for the steeper slope.

Finally, it should be noted that, although the effect of slope on total transmission loss is small for low order modes, this does not negate the possibility that detection of T-phases depends on slope. As shown by Jensen and Kuperman (1980), each mode couples over a narrow depth range at about the cutoff frequency.



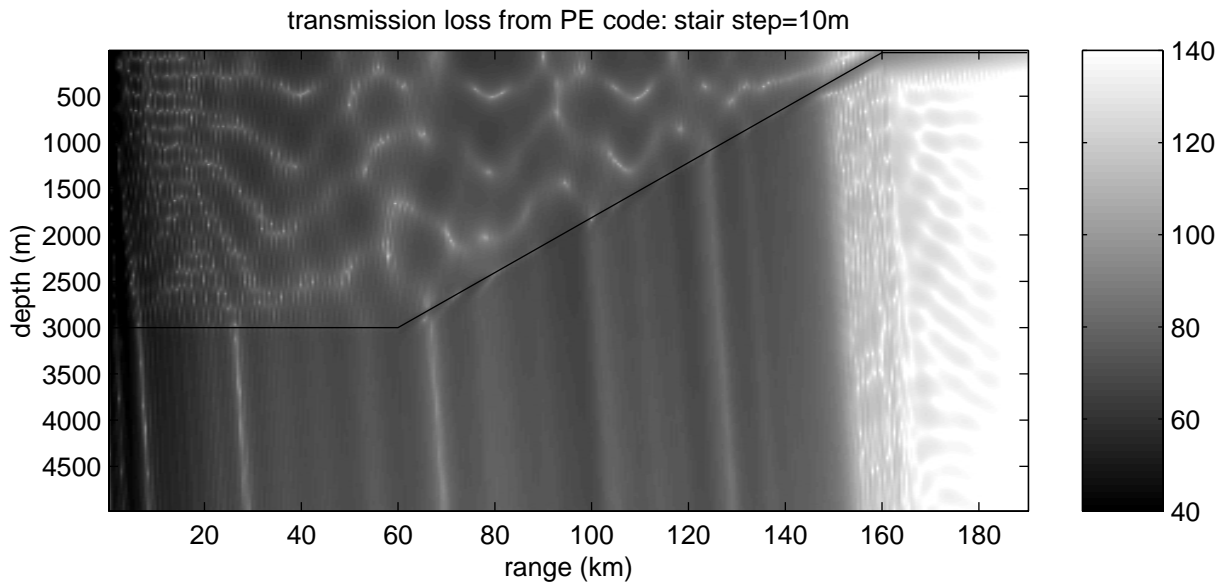
**Figure 8** Approximate pressure wave-number spectra for a source at 350 m depth at a) 2 Hz and b) 24 Hz, and for a source at 3000 m at c) 2 Hz and d) 24 Hz. We show only the peaks corresponding to the normal modes of the ocean waveguide.



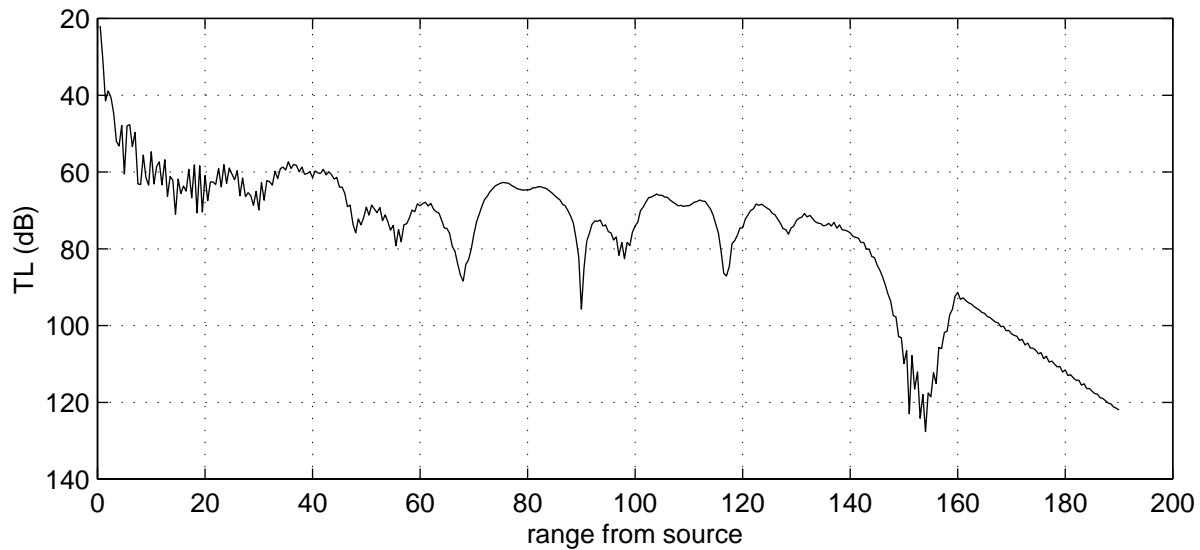


**Figure 9** As in figure 6, but for a model with a steeper slope of  $6.6^\circ$ .

In comparison, for a model with significant shear velocity in the bottom, much of the T-phase energy is converted to surface waves, which propagate along the ocean, seafloor boundary, and are rapidly attenuated. Vertical displacement losses for a model with a (constant) seafloor P-wave velocity of 2400m/sec and S-wave velocity of 1200m/sec are shown in figure 10, for a frequency of 5Hz. The displacements along the surface are shown in detail figure 11. As shown, surface waves are attenuated rapidly with distance along the coast.



**Figure 10** Transmission loss at  $f=5\text{Hz}$  for model with seafloor P-velocity of 2400m/sec and S-velocity of 1200m/sec. The water velocity profile is shown in figure 1. The source is 350m, i.e. at the sound channel minimum.



**Figure 11** Loss in vertical displacement along the surface for elastic seafloor.

## **CONCLUSIONS**

The transformation of acoustic to seismic modes can also be described in terms of mode coupling. Low modes couple to the seafloor at shallow depths, and higher order modes couple into seismic energy at increasing depths, and hence ranges from the coast. Since attenuation increases both with increasing frequency and with distance propagated through the attenuative crust, T-phase signal amplitudes decrease most rapidly with increasing frequency for sources comprised of high order acoustic modes coupling to seismic energy near a shallow coastline.

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