MODELING HYDROACOUSTIC WAVEFORM ENVELOPES: IMPLICATIONS FOR TEST BAN TREATY MONITORING

Jay J. Pulli, Robert Bieri, and Eugene Dorfman[†]
GTE/BBN Technologies, 1300 N 17th St, Suite 1200, Arlington, VA 22209
[†]GTE/BBN Technologies, 70 Fawcett St, Cambridge, MA 02140

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ABSTRACT

Test ban treaty monitoring in the world's oceans is aided by the fact that the ocean environment is known to a degree of detail that is much finer than in the solid earth. Raypaths, traveltimes, and amplitudes can thus be accurately predicted. But additional information about the source and path may be contained in the received waveform envelope. This modeling effort has been undertaken to determine whether or not it is practical to extract information such as source depth and type from the waveform envelope, and how this may be used in a CTBT context.

To compute the waveform envelopes, a truncated set of normal modes is summed over a finite bandwidth to obtain an approximate time series. The normal mode code KRAKEN is used to compute modal shapes and wavenumbers for a set of frequencies, and the time series is then recovered using the Fast Fourier Transform. The model has been used to illustrate the factors that contribute to the shape of the received hydroacoustic waveform envelope, including the locations of the source and receiver with respect to the sound channel axis, the bottom conditions, and the bathymetry.

As expected, the largest amplitude is produced when both the source and receiver are in the middle of the sound channel axis. In this situation, path bathymetry determines the number of trapped (low loss) modes. As expected for typical SOFAR sound speed profiles, a buildup of signal energy with time is predicted, culminating in the large mode 1 arrival (this signal shape is often called "classic SOFAR"). Higher order modes are increasingly important as the source and/or receiver are moved away from the SOFAR axis. Bottom conditions are only an issue for the case of a bottom mounted hydrophone.

Modeling results are presented for a number of events, including the Chase21 ship scuttling explosion on June 25, 1970 off the New Jersey coast; nuclear explosions on Mururoa Atoll; and Japanese exploration explosions.

Key Words: Hydroacoustics, long-range propagation, modeling, normal modes

OBJECTIVE

Test ban treaty monitoring in the world's oceans is aided by the fact that the ocean environment is known to a degree of detail that is much finer than in the solid earth. Raypaths, traveltimes, and amplitudes can thus be accurately predicted. But additional information about the source and path may be contained in the received waveform envelope. This modeling effort has been undertaken to determine whether or not it is practical to extract information such as source depth and type from the waveform envelope, and how this may be used in a CTBT context. These capabilities have now been integrated into the program HydroCAM, which has been developed under DOE funding (Farrell and LePage, 1996) to estimate the performance of hydroacoustic networks for the CTBT. In this study, we are interested in the gross features of the waveform envelope, such as its duration, rise time, and shape (skewness). Ranges of interest are on the order of thousands of kilometers; frequencies are less than 100 Hz.

RESEARCH ACCOMPLISHED

Theory

The long-range propagation of sound in the ocean is usually described in terms of normal mode theory (Brekhovskikh and Lysanov, 1991). In normal mode theory, the far field pressure p at a range r and depth z_r due to a point source located at (r=0, z=z_s) is given by the coherent mode sum

$$p(t,r,z) = \sum_{n=1}^{\infty} p_n(t,r,z)$$

Modal pressure $p_n(t,r,z)$ is given by

$$p_n(t,r,z) = \sqrt{\frac{2\pi}{k_n r}}\, e^{i\pi/4} \int_{-\infty}^{\infty} P_s(\omega)\Psi_n(\omega,z_s)\Psi_n(\omega,z_r) e^{i\omega t - ik_n(\omega)r}\, d\omega$$

where Ψ_n and k_n are the shape and wavenumber of mode n, respectively, and $P_s(\omega)$ is the source spectrum. For a point source we have

$$p_n(t,r,z) = \frac{1}{2\pi}\frac{1}{\rho(z_s)\sqrt{8\pi k_n r}}\, e^{i\pi/4} \int_{-\infty}^{\infty} P_s(\omega)\Psi_n(\omega,z_s)\Psi_n(\omega,z_r) e^{i\omega t - ik_n(\omega)r}\, d\omega$$

The corresponding pressure level PL is

$$PL = 20\log\frac{\langle p^2 \rangle}{p_{ref}^2}$$

In long range propagation, environmental fluctuations (sound speed changes) result in pressure level fluctuations around the mean value PL_0. In this case, the average received pressure and mean pressure level are often modeled as an incoherent sum, which is

$$p_{RMS}^2 = \sum_{n=1}^{\infty} p_{n,RMS}^2(\omega,r,z)$$

Normal mode shapes and wavenumbers were computed using the program KRAKEN (Porter, 1995) for a frequency band of 1-100 Hz and a frequency increment of 1 Hz. To increase the efficiency of the calculation, we use a grid of modal parameters created once using the program KRAKEN (Porter, 1995); these modal parameters are stored and used for all subsequent calculations. We also use interpolation, since the modal wavenumbers are generally smooth functions of frequency. These are computed and stored for a sparse grid of frequencies, then interpolated to a denser frequency grid to prevent aliasing.

Overview of the Model

The computation of the waveform envelope can be broken down into nine steps (see *Figure 1*):

- The first step is to calculate the path based on the source and receiver locations. This is accomplished within the framework of HydroCAM using the bent ray approach (refraction included)
- Next the modal wavenumbers are extracted
- Next the time interval of the waveform envelope is computed (since we do not want the entire time series from the origin time to the receiver time)
- Transfer functions for each of the modes are then calculated
- Each transfer function is multiplied by the source spectrum
- Then we extract the mode shape at the source and receiver
- Modal amplitudes are then used to scale each modal transfer function
- An inverse Fourier transform is taken to compute the modal time series
- Finally the modes are summed to compute the waveform envelope

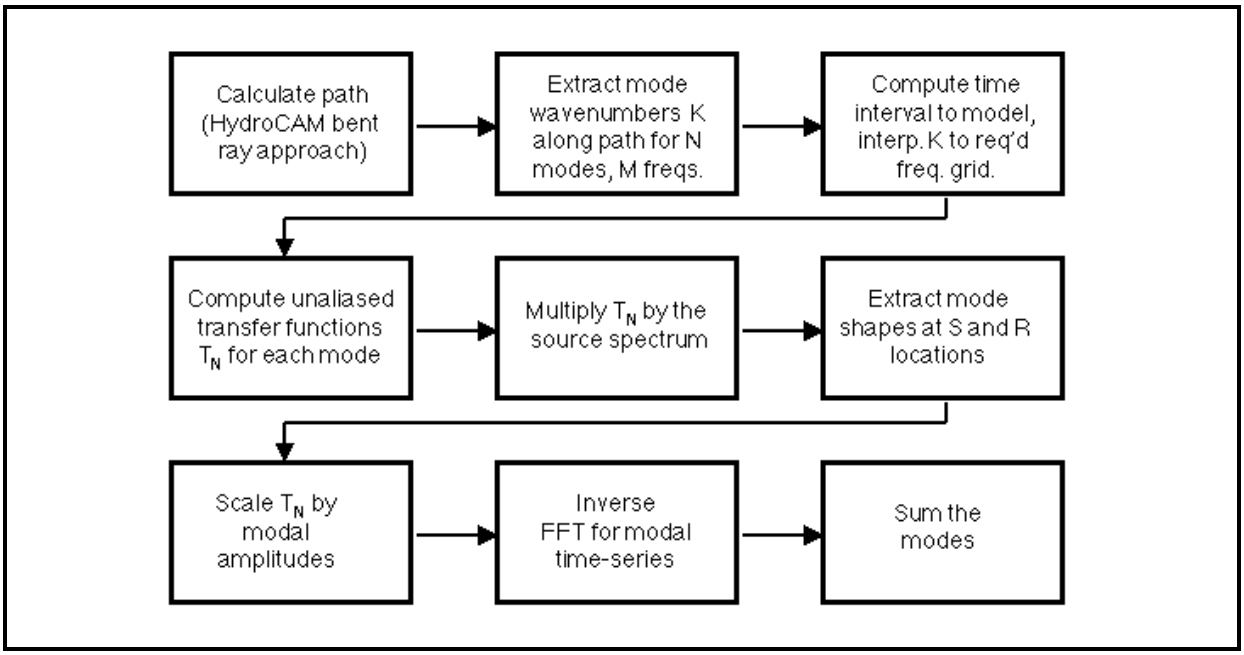

Figure 1. Flowchart of the waveform envelope modeling procedure.

Running the Model

The waveform modeling is accomplished from within the framework of HydroCAM and thus uses the same graphical user interface structure. The first interface is that of the Environment Form, shown in *Figure 2*. Here we select the bathymetric database to be used, the sound speed profile database (tied to the season), and the bottom conditions.

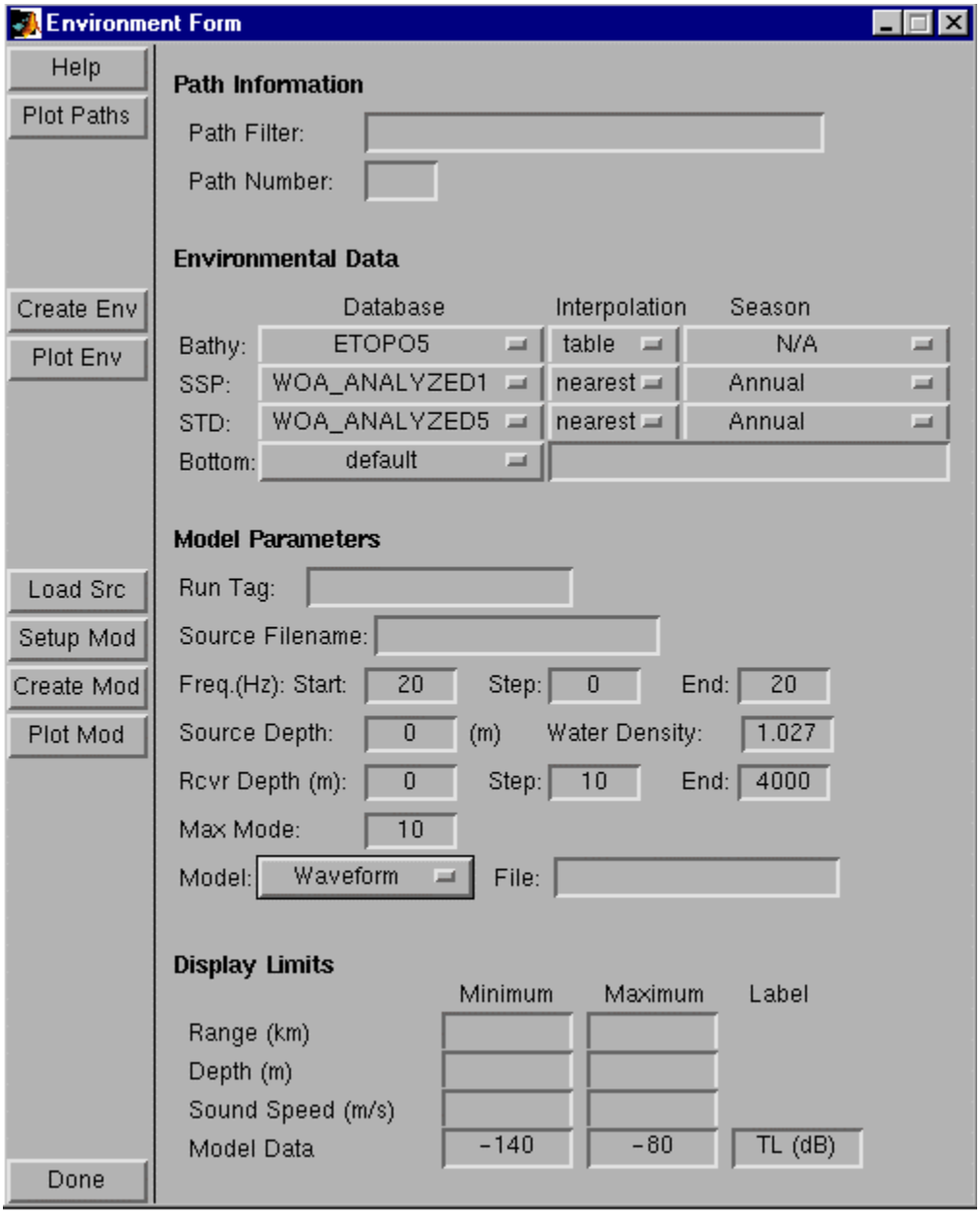

Figure 2. The path environment form used to select the databases and to create the environment (bathymetry and sound speed).

We then switch to the Kraken Parameter form, shown in *Figure 3*. This is where we set type of interpolation for the sound speed profiles, the surface and bottom conditions, the attenuation, phase speed limits, and maximum range.

When these are loaded, we return to the first panel (*Figure 2*) to load the source parameters, source depth, and receiver depth. Calculations are then begun. Results are saved in CSS Version 3 format, controlled under the Waveform Plot panel, shown in *Figure 4*. The user can specify origin information (times, station code, database prefix) as well as the frequency range and number of modes. Modes are saved separately and as a sum (envelope).

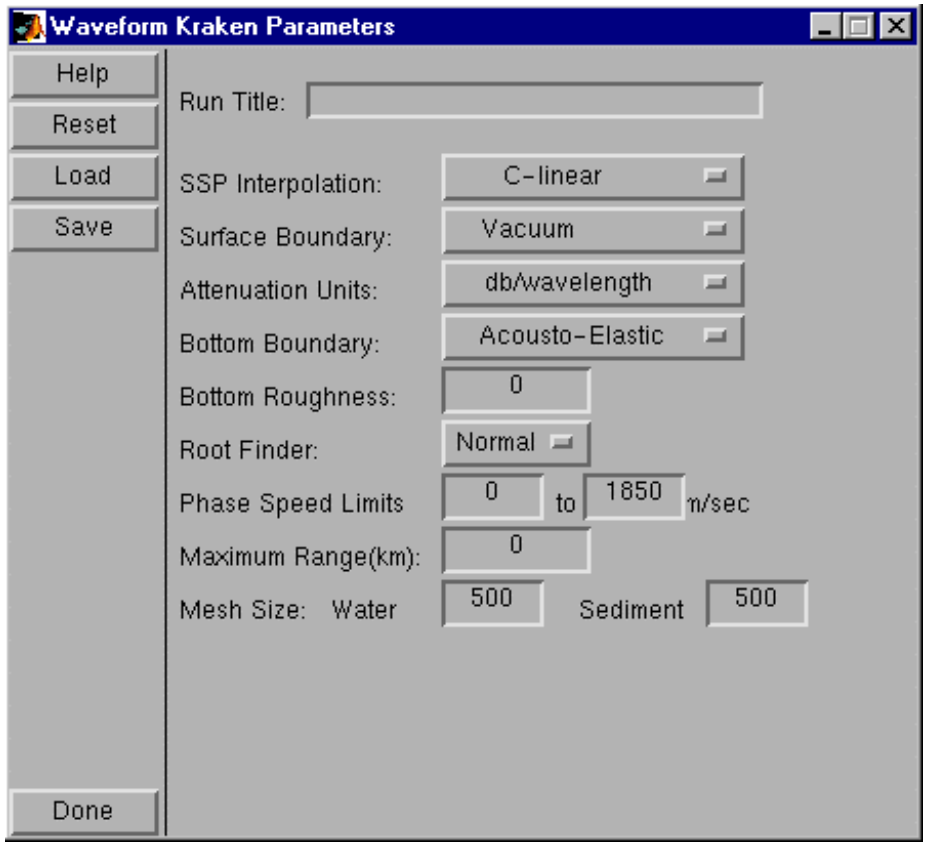

Figure 3. Kraken run options form. Options include sound speed interpretation, attenuation, and bottom conditions.

Examples

Figure 5 shows the results of a simple deep-water long range path calculation. In all three cases, the source was located on the sound channel axis (SCA), which provides the largest excitation of modal amplitudes. The waveform envelopes for three receiver locations are shown. When the receiver is also located on the SCA, large mode 1 amplitudes are observed in the waveform envelope. When the receiver is located above the SCA, higher modes begin to contribute to the waveform envelope and the entire waveform envelope is of lower amplitude. Very little energy is propagated below the SCA and the signal amplitude is greatly diminished.

Figure 6 shows the relative modal contribution to the waveform envelope for the path from Mururoa Atoll to Point Sur, CA. This is a case where only the first few modes contribute to the waveform envelope. It is a deep water path at a long range, and thus the low order modal contributions provide little sensitivity to determining the source depth from the waveform envelope. *Figure 7* illustrates an example where there is a greater sensitivity to source depth. This is the path from the Chase 21 explosion off the coast of New Jersey to the Ascension Island receiving station. The source was relatively shallow, on the continental shelf, and as the figure illustrates, there are numerous higher order modes excited from this shallow source. For comparison, a modal excitation plot is also shown for a deep source at this site. Only the lower order modes are excited in this case.

Source duration (as well as source time function) can be specified in the model. *Figure 8* shows the effect of source duration on the resulting waveform envelope for the Chase21 to Ascension path. A simple 3-cycle overshoot source is used with the source duration varying from 0.1 to 0.3 seconds. The longer source duration not only produces a larger signal (more source energy) but also contributes to more higher mode energy reaching the receiver. This increases the duration of the received signal.

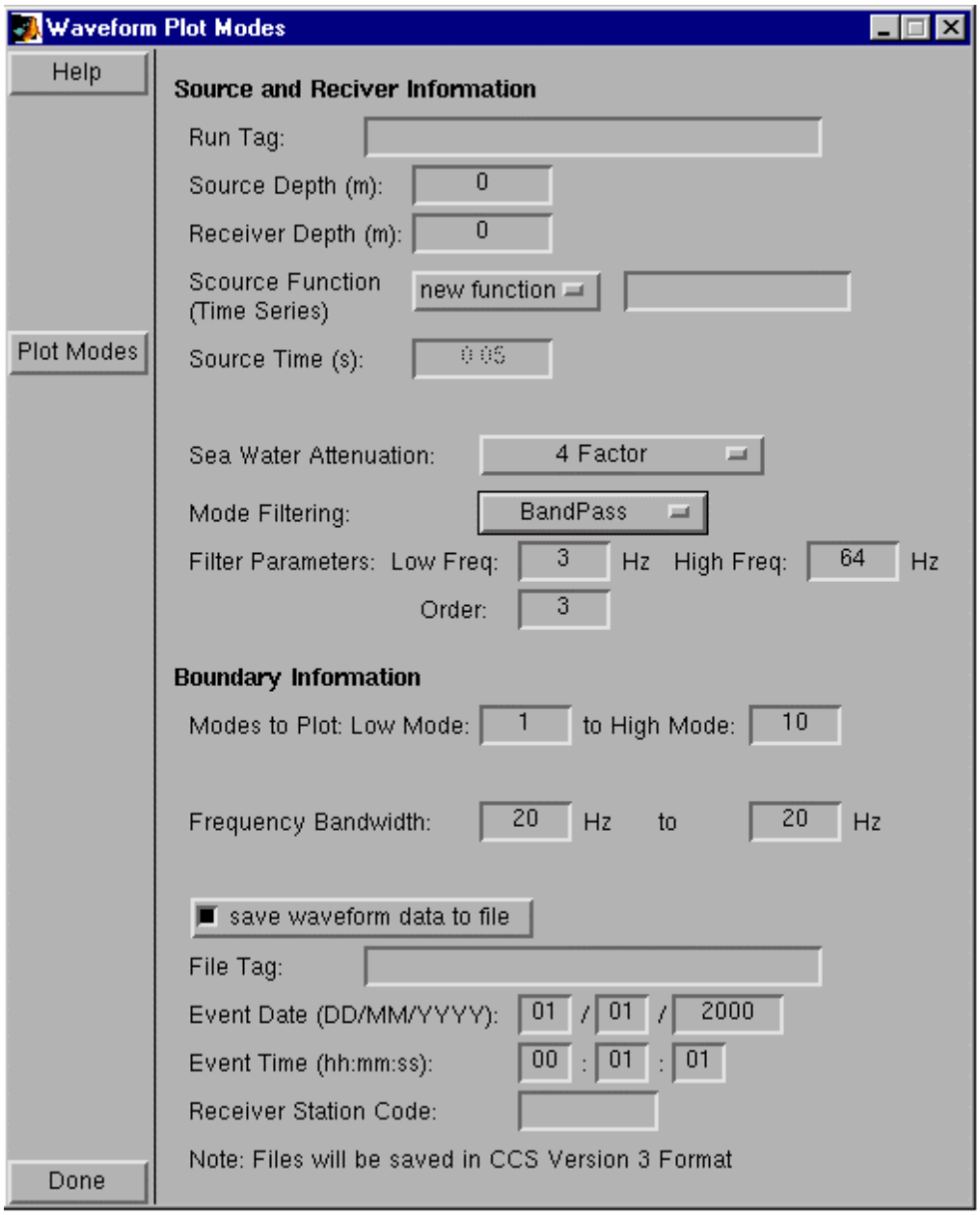

Figure 4. Waveform analysis option and plotting form. Here you input source and receiver depth, source functions, attenuation models, and output prefix for the CSS database.

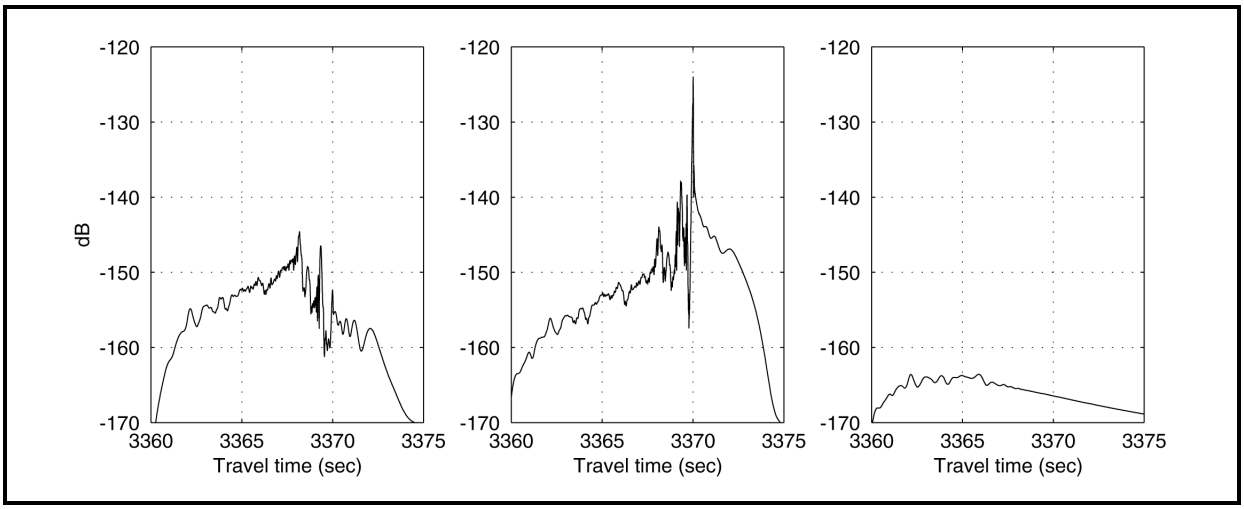

Figure 5. Sample calculation for a deep water path, source on the sound channel axis (SCA). The waveform envelope is shown for three receiver depths: above the SCA (left), on the SCA (middle) and below the SCA (right).

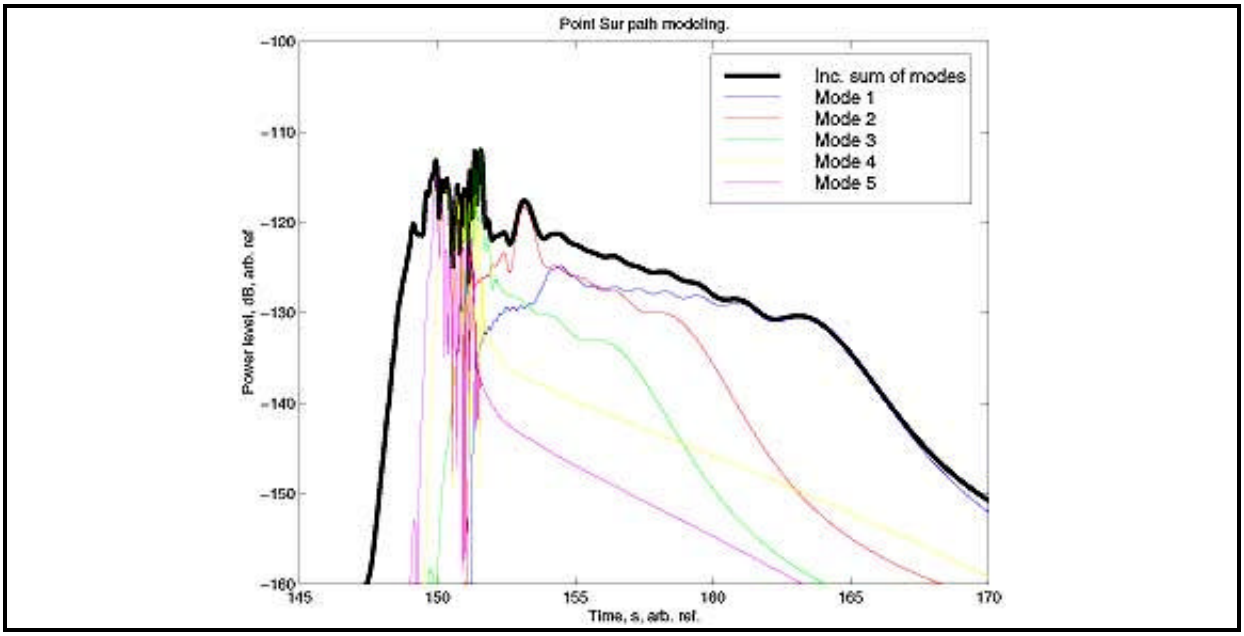

Figure 6. Modal contributions for the path from Mururoa Atoll to Point Sur, CA.

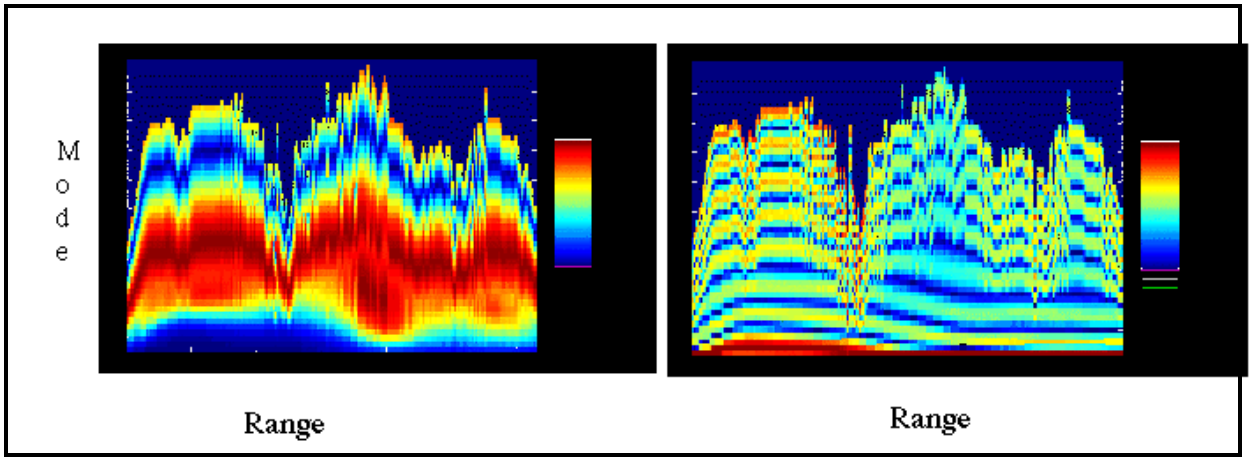

Figure 7. Modal excitation as a function of range for the path from the Chase 21 explosion off the coast of New Jersey to Ascension Island. The plot on the left shows the modal excitation of a shallow source (higher modes excited) whereas the plot on the right is for a deep source, which excites primary the lower order modes.

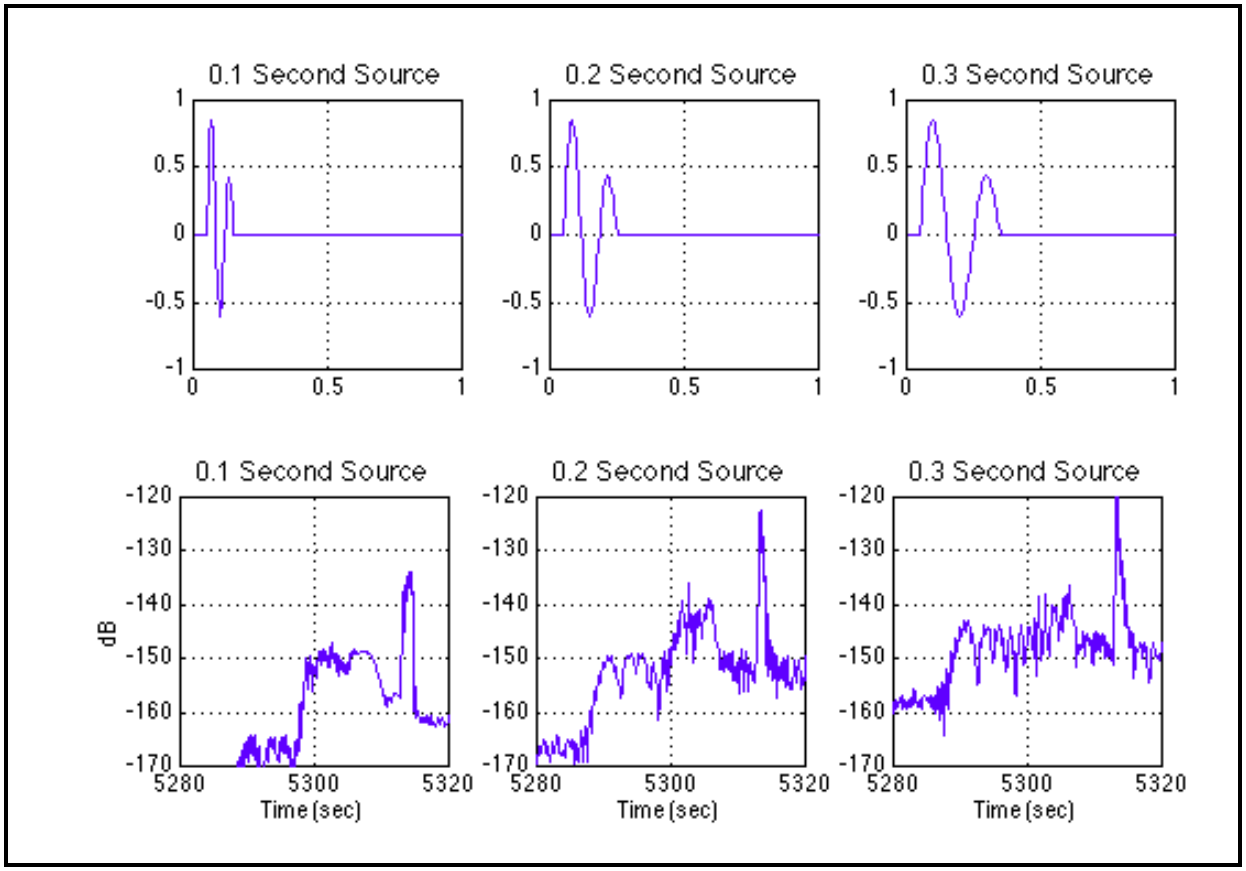

Figure 8. Effect of source duration on the waveform envelope for the Chase 21 to Ascension Island path.

CONCLUSIONS AND RECOMMENDATIONS

We have added a waveform envelope modeling capability to the program HydroCAM, which will now allow the utilization of waveforms as well as arrival times in the analysis of hydroacoustic events. Until now, we have compared the calculations with recordings of events that occurred in complicated environments, or may be seismic events which couple to waterborne acoustic energy (T-waves). Efforts are now underway to validate the calculations using sources in the ocean, which are not only simpler but more appropriate for the model. The modeling capability opens for study numerous effects such as absorption, bottom conditions near the source and receiver, mode coupling, source size region, etc. Eventually, a worldwide grid could be calculated and stored which would be used to examine the waveform envelopes of any source/receiver pair, and enable the user to

REFERENCES

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