A Shallow Water System for Maximizing Echo to Reverberation Ratio

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Abstract A method for increasing incident energy on mid-depth targets while at the same range reducing boundary reverberation for shallow water ducts has been devised. The basis of the approach is couched in range dependant normal mode theory, exploiting the interference between modes to form nulls, called the Modal Interference Method (MIM). By making use of a long vertical array of sound sources, selected modes can be excited and their amplitudes and relative phases can be controlled by the pulsed-cw input waveforms to the individual sources. This control allows formation of nulls in the field at specified range/depth pairs. The source array emits a sequence of pulses, each pulse designed for optimizing a particular range. Thus the sequence sweeps out a range segment of interest. For reverberation reduction, nulls for a particular range are placed on or near the boundaries of the duct. For low and mid frequencies, this is where most of the scattering is generated. Since the scattered energy is proportional to the incident energy, scattered energy is also nulled. This has an additional effect of causing intensity maxima in depth to exist interior to the boundaries. Furthermore, by controlling the waveforms such that additional nulls are selectively placed within the water column, a sharp single maximum can be formed at one depth. Thus both the echo can be maximized and the reverberation can be minimized. The governing equations for such a system have been derived and are presented. The straight forward application of MIM requires knowledge of some modal environmental parameters. These parameters can be estimated based on sound speed profile and bottom acoustic property measurements. However, two other approaches that do not require those measurements are presented, using feedback information to adapt to the environment. One involves direct down range field measurements tied into the system. The second uses a search in modal amplitude and phase space to minimize the received (reverberation) energy. Acoustic field calculations for some shallow water areas are described. Environmental mismatch has been simulated for a few situations, indicating that the approach seems to be fairly robust. Degradations from theoretical mode formation occur when a realistic source array is used. The method of calculating these degradations is given, along with results of applying the method to several realizable configurations. Finally, results using a linear gradient search algorithm are presented.

1. Background

Active systems in shallow water are plagued by multi-path structure complexities and reverberation. Controlling the modal excitation may present advantages over conventional approaches. Exploiting some of the shallow water sound channel's characteristics by the use of modal methods was explored much earlier (King, 1974). In that work, a mode's excitation was approximated by a short vertical source array near the surface steered downward at a particular angle, and a second array near the bottom steered upward at the same angle. Different steered angles would tend to excite different modes. The results tended to improve signals. However, good separation of modes probably did not occur due in part to the ray-angle to mode approximation and due to the short aperture of the two source arrays. To gain substantial control of modes, a near full water column of sources is required so that separation of adjacent modes is accomplished, and elements need to be spaced closely enough so that the various desired modes do not have aliased images at higher mode numbers. Another approach (Laval, 1974) describes a conceptual system using a modal conversion method for the indication of submerged targets. A vertical array of sources is used to send a single mode or a small number of modes. A vertical array of receiving elements is used to modally analyze the returns. The presence of a target would generate converted modal energy. The modal pattern of the return would have information as to the target's range and depth. This paper presents a different approach, believed to be unique, that both null's the reverberation at boundaries while maximizing (vertical focusing) acoustic energy within the water column on potential target depths.

Due to recent advances in source technology, and in particular the slotted cylinder, a system using a long source string with many elements is now much more feasible. At mid-frequencies, the reverberation is generated primarily at the surface and bottom, and is proportional to the acoustic energy incident on those boundaries. Control of that incident energy can be achieved by a complex weighting of the drive to the vertical sources, so as to minimize, or to "null" the incident boundary energy (and therefore the reverberation). At the same time, it maximizes the energy near middle depths. In the shallow water duct, discrete modes propagate out in range from a source. At certain range-depth locations, the modes can destructively interfere, creating nulls in the acoustic field. The locations of these nulls can be controlled if the relative amplitudes and phases of a few chosen modes are manipulated. By placing the nulls on or near the boundaries, reduction in reverberation should occur. Additionally, at the same range, maxima in the field can be formed so as to maximize an echo at a particular depth. In a simple implementation, the system would be operated in a pulsed-cw mode like many conventional active sonars. However, a sequence of pings would be emitted, each with a different optimum search range, thus sweeping out the ranges of interest. A horizontally directional receiver array would allow the system to work in horizontally anisotropic environments. It is recognized, therefore, that searches would need to be done in azimuthal sectors as well as range for those environments. Since that is but a system complexity (albeit perhaps a major one), the concept is described in this paper without the complication of the azimuthal component.

2. Mathematical basis for the Method

We make use of the normal mode equations:

$$P(r,d) = \sum_m c_m U_m(d) e^{ik_m r} \qquad \text{(EQ 1)}$$

where
r = range,
d = depth,
m = mode number,
c_m = unknown complex modal coefficients which will produce the nulls as specified in (2),
U_m = real modal function,
k_m = complex modal wavenumber.

For n null (zero pressure) constraints at (r_i,d_i) i = 1,...., n:

$$P(r_i,d_i) = U_1(d_i) e^{ik_1 r_i} + \sum_{m=2}^{n+1} c_m U_m(d_i) e^{ik_m r_i} = 0 \qquad \text{(EQ 2)}$$

We choose to use the first n+1 modes. Therefore there are n unknowns (the c_m), and the n linear equations (2), which are easily solved. We further note that the U_m and k_m can be range dependant, so ***this method is not limited to range-independent environments.*** Any other n+1 modes could have been chosen, but the lowest modes in general have less attenuation, are less sensitive to the environmental unknowns and fluctuations, and should produce the largest nulling area.

Alternatively, we can write (2) in terms of the ***relative*** environmental parameters $\hat{U}_m = U_m/U_1$ and $\Delta k_m = k_m - k_1$.

$$P(r_i,d_i) = \sum_{m=2}^{n+1} C_m \hat{U}_m(d_i) e^{i\Delta k_m r_i} = -1 \qquad \text{(EQ 3)}$$

3. Modeling results and discussion

Figure 1 displays the acoustic field at 750 Hz in which only modes 1 and 2 are propagating. Mode 2's complex amplitude is equal to that of mode 1. The modal functions and wavenumbers are obtained by using the normal mode model KRAKEN (Porter, 1991) for iso-velocity water of 200 m overlying a sand bottom with the appropriate density and sound speed. The upper box displays the propagation loss (in dB with respect to a mode 1 source level of unity) versus range and depth. The lower boxes show line plot "slices" through the same field. We note that the modes interfere with each other at three regions. ***The central theme in MIM is to change the complex modal weights so as to place these***

regions near the boundaries which should cause reduction in reverberation at those ranges.

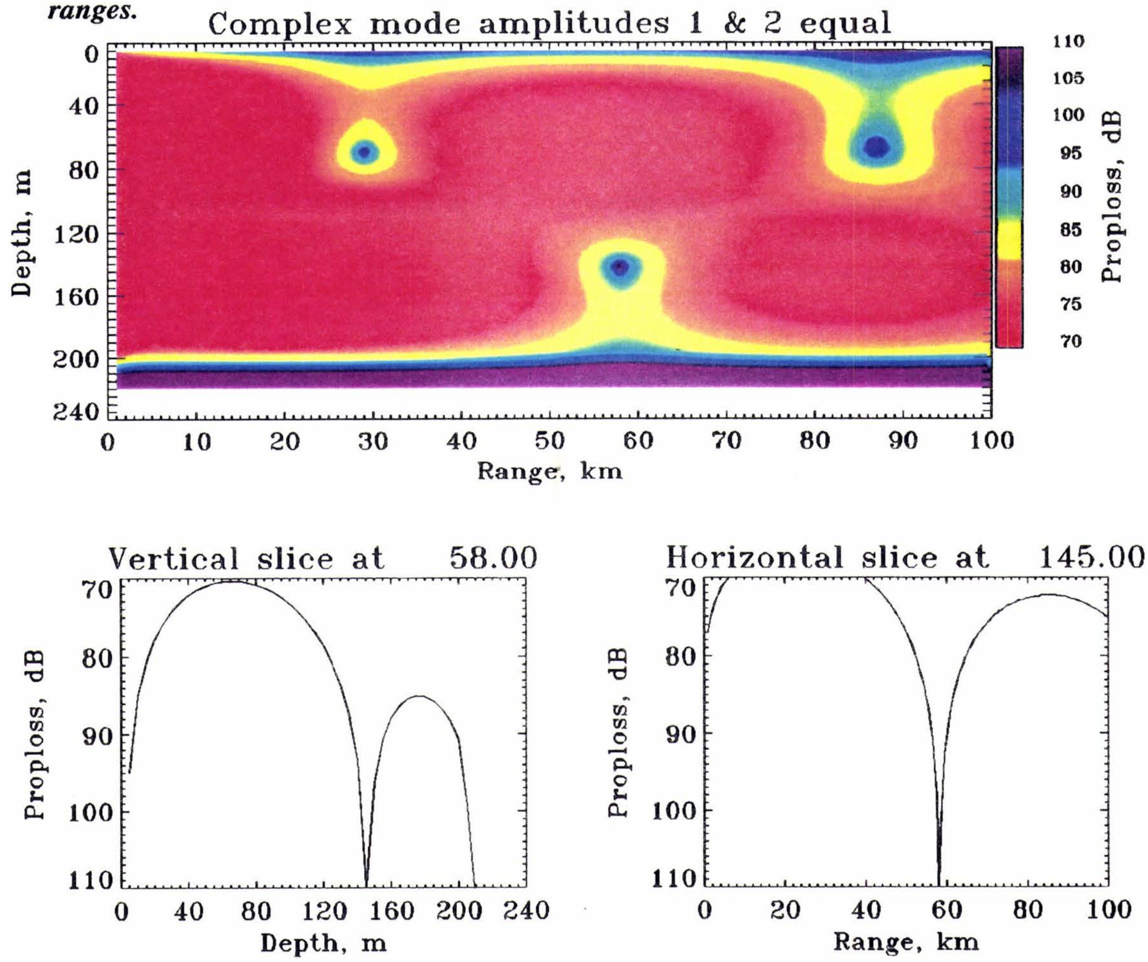

FIG. 1. The field is composed of modes 1 and 2, showing the interference patterns when the complex modal amplitudes are equal. By using different amplitudes, the nulls can be moved within the field.

In figure 2, the complex weights have been changed by using a single constraint (n=1 in equations 2 and 3) in order to form a null at 50 km range on the bottom (200 m). A single constraint uses 2 modes, modes 1 and 2. The lower left box plots a vertical profile at 50 km, showing a peak (modes 1 & 2 in phase) at 60 m depth, while the lower right displays the field on the bottom vs. range. Notice the desired null at 50 km. It is important that the width of the null be wide (over 5 km at 20 dB down into the null in this case). This is an important parameter, since we need the null to be as wide as possible, and certainly much wider than a target of interest. Notice also the repeating pattern of nulls at other ranges. A system can therefore use one design pulse for multiple ranges reducing search time.

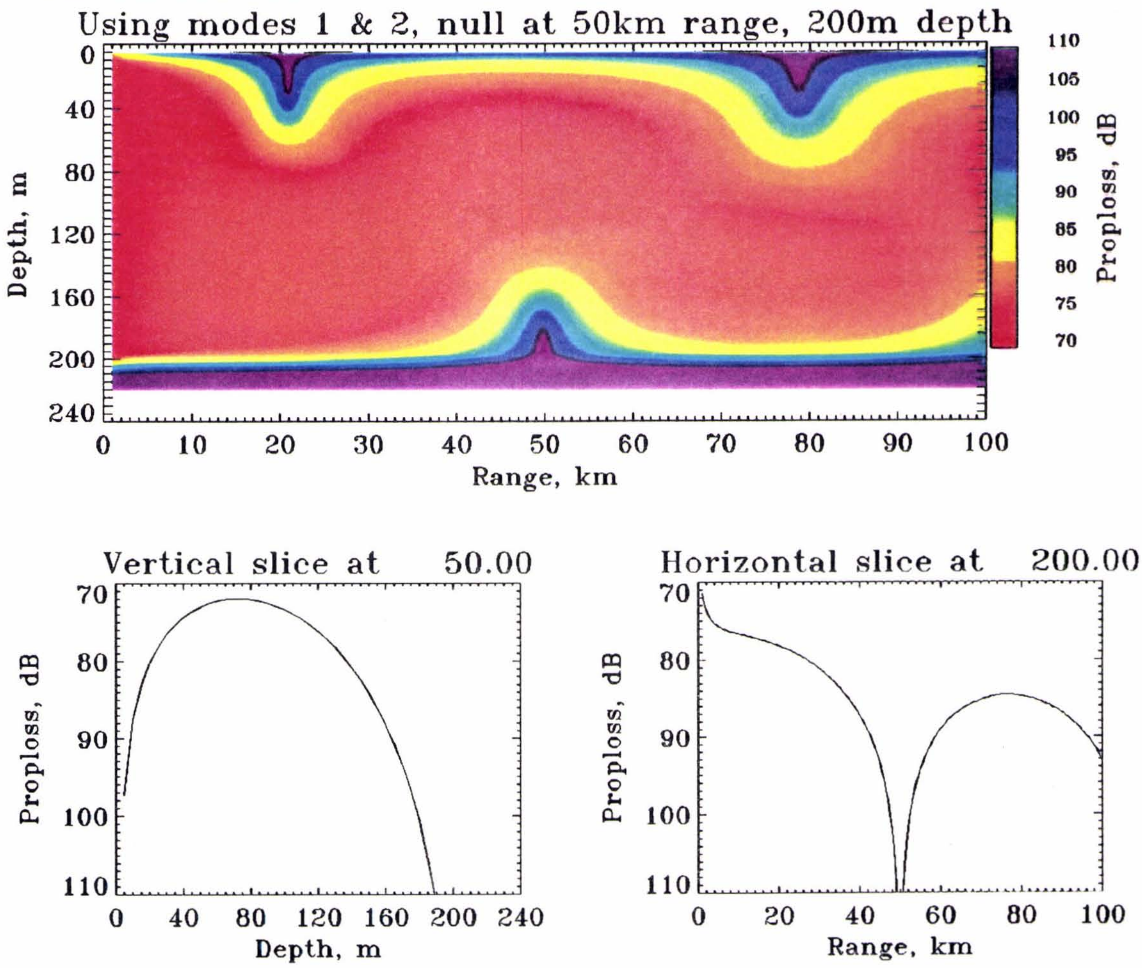

FIG. 2. Using MIM, the null has been moved to the bottom at a 50 km range. Placing a null on the bottom should reduce reverberation at that range.

Figure 3 uses two constraints or three modes. Here a null is also put near the surface to reduce surface reverberation at the same range where bottom reverberation is being suppressed. All three modes are about in phase at 100 m, and therefore a peak exists. This peak in depth is relatively wide. However, one can put additional nulls within the water column to cause a narrowing and further peaking. Therefore, additional echo-to-reverberation ratio (ERR) can be gained by adding more nulls in different parts of the water column. However, this then requires searching in depth by a series of pulses. This becomes a systems issue how best to trade off better performance at the expense of search time, but note that the system does allow this trade off. In fact, the system, seeing a potential target, could shift from a search state to spend additional pings with higher ERR so as to make a better determination of the potential target.

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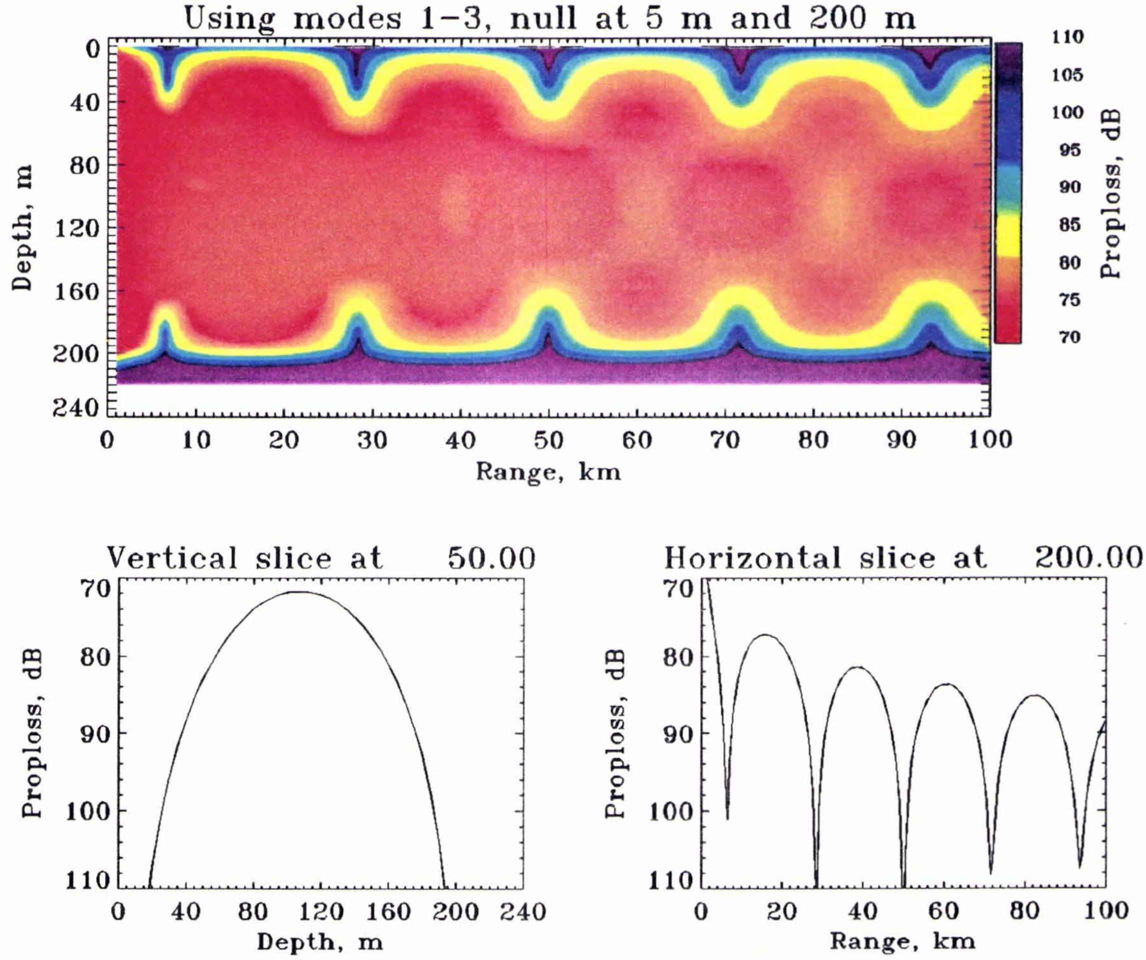

FIG. 3. Placing an additional null at 5 m depth at a range of 50 km should reduce both bottom and surface reverberation. Notice the peaking of the field at about 110 m, which will maximize the echo from targets there. That peak can be moved up and down by adding more modes with the proper constraints.

Figure 4 shows results using the summer environment from adventure bank southwest of Sicily. There is a strong downward refraction in the upper 100 m, and a weak upward one in the lower 100 m overlying sand (Figure 5). Nulls have been placed at 45 m and 200 m. The MIM concept works well here, since the lowest modal functions are almost zero in the upper 40 m and below 150 m. This environment would then require only the 40-150 m depths to have source elements, making a system less costly.

4. Modal purity calculations

The modeling results shown above have assumed compact full channel strings. We now consider the effects of realistic source strings by analyzing the modal degradation as one intentionally blank page

increases the elemental spacing and removes elements unpractically close to the bottom and surface. Since the modal functions that are output from KRAKEN are orthogonal (after dividing by the square root of the density), we use them as a basis vector set to form a modal spectrum. The array data to be analyzed is formed by first copying from the basis set a desired modal function to be used, and then setting the values of the unpopulated locations to zero. The modal spectrum is then calculated by the inner product of that vector with each modal basis vector. Figure 6 shows the results of an array with elements starting at 15 m from the surface, and extending down to 5 m above the sediment. The array is being driven with only mode 1. In this case, the 40 dB modal "sidelobes" would probably not produce a measurable problem. When the elemental spacing is extended to 10 m between elements, "aliased" modes appear around mode 40. This very well could be a problem, depending on the relative attenuation levels between mode 1 and 40. The particular uses and ranges need to be analyzed for a given situation.

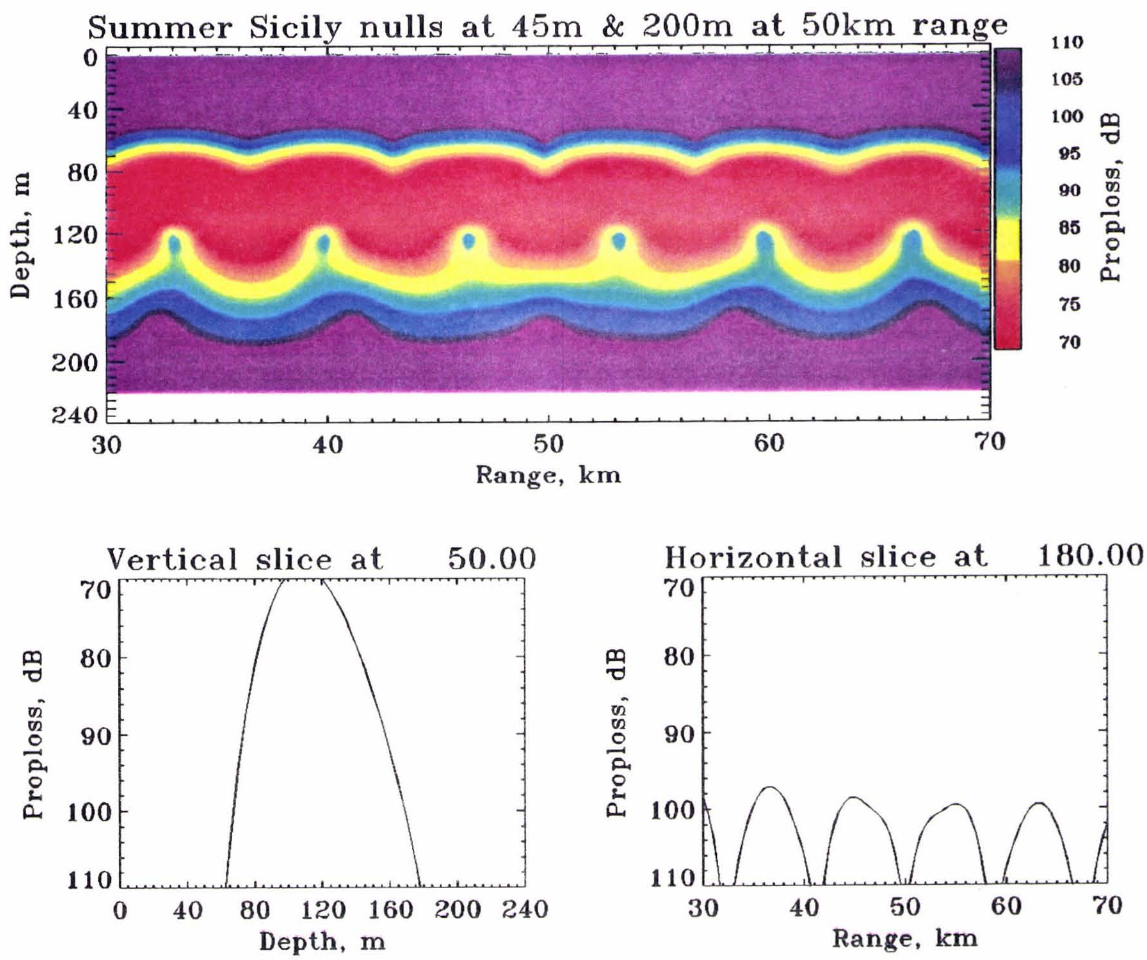

FIG. 4. The field using a summer sound speed profile south of Sicily. The lowest modes are trapped within depths between 50 and 150 m, causing the narrower peaking at 110 m, and much lower field at the 200 m bottom.

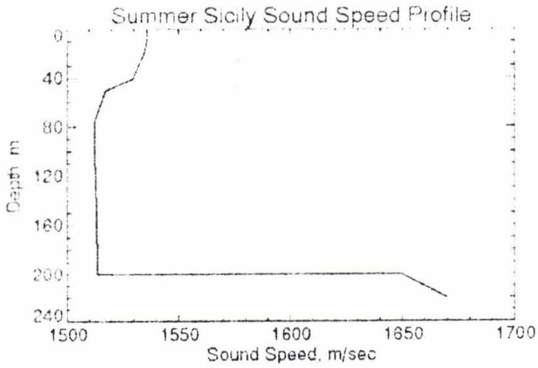

FIG. 5. Sound speed profile, including the 1650 m/sec sandy bottom.

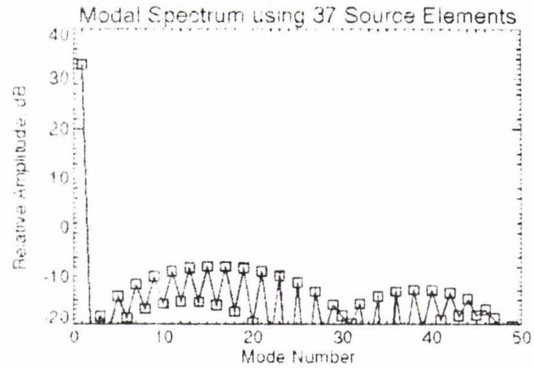

FIG. 6. Modal spectrum when mode 1 is driven using 37 source elements that are placed from 15 to 195 m in the vertical at an element spacing of 5 m.

5. Environmental mismatch

Some simulations have been done in intentionally mismatching the environment, to see the degradation. The bottom sound velocity was changed by 40% in the field calculations, but the design for the pulses made use of the original values. Surprisingly, there was only a 5% shift in the range of the null, and almost no shift in vertical position of the null. If this is indicative in real situations, then the system can be used by first observing a "notch" in the reverberation versus time for a pulse, and adjusting the analysis for that "notched" range, rather than using the designed range for that pulse. However, bathymetry mismatches will occur as well, so it is recognized that adaptive methods will need to be sought.

6. Adaptive techniques

Some work has also gone into the development of an adaptive approach, mitigating the need for environmental knowledge, particularly for each range. Given incorrect knowledge of the environment, we send out a pulse of, say, modes 1 and 2 with the intention of nulling a particular range of bottom reverberation. (Assume, for simplicity, that there is only bottom reverberation.) Due to the mismatch, the null appears at a different range and not on the bottom, which will not minimize the reverberant energy at that range. The adaptive problem is, using the received (reverberant) time history (derived from a collocated receiving array), to find the modal amplitudes and phases that will cause the minimization of that received energy for the desired range. It appears that, for at least mildly range dependent environments, the adaptive two dimensional search space (modal amplitude and phase) can be separated into two single dimensions, vastly reducing the adaptive time. It may also be possible that an adaptive method would allow an "inversion" of the environment, producing environmental parameters. We initially approached the

search problem by using a simulated annealing technique (Metropolis, et al, 1953). However, we found that the relative phase variations shifted the range of the null, but only very weakly modified the vertical position of the null. Likewise, relative amplitude variations shifted the vertical position of the null, but not the range of the null. We therefore adopted a simpler linear gradient search method, which converges after just a few iterations. Figure 7 shows the extent of the null at the bottom increase with each of three passes. Using an initial (rather poor) guess of equal complex amplitudes for modes 1 and 2, the null is up in the water column at 145 m at a range of 58 km (see figure 1). The null is successively successfully moved onto the bottom by the three iterations.
Another possible approach, but adding to system complexity, would have pressure sensors down range that would directly measure th: field produced by the pulses. These data would be used in the search algorithm rather than the receiver array data.

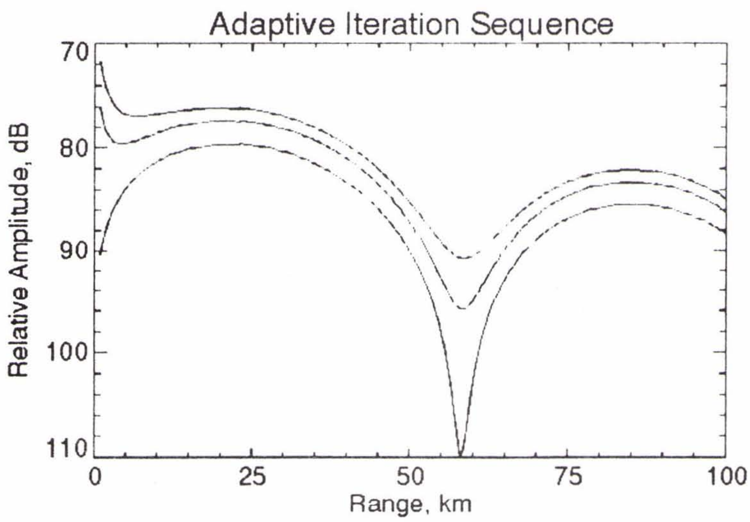

FIG. 7. The acoustic pressure on the bottom vs. range when the adaptive algorithm is attempting to form a null at 58 km. The deep null is obtained after only 3 iterations.

7. Conclusions

A shallow water system using modal control of a vertical array of sources that both minimizes the reverberation and maximizes the echo from submerged targets has been devised and modeled for some environments. An adaptive approach to minimizing the environmental uncertainties has been shown to work well on modeled data. Analysis of the length and spacing of the source array requires many elements, but a modern technology (slotted cylinder) allows for such an array to be practical. Although more modelling is called for, the next major step is to field an experiment to validate the concept and quantify the echo to reverberation enhancements.

8. Acknowledgments

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9. References

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