CHANNEL-ADAPTED SOURCE FOR SHALLOW WATER

Donald F. Gingras

SACLANT Undersea Research Centre, Viale San Bartolomeo 400, 19138 La Spezia (SP), Italy

Abstract In shallow water areas the utilization of active sonar is complicated by the fact that in these environments the performance of active systems is degraded by source signal interaction with channel boundaries. These boundary interactions result in increased reverberation. In this paper a method for reducing backscatter through the use of single mode excitation is evaluated via simulation. It is shown that a vertical array of sources, whose amplitude and polarity are determined by the mode one eigenfunction, can significantly reduce backscatter in shallow water environments. The backscattered energy, as computed using a two-way parabolic equation (PE) model, is computed for a variety of source array configurations and compared to that generated by a single source.

1. Introduction

We consider the problem of reducing the backscattered energy from bottom features in shallow water by matching a vertical array of sources to the channel characteristics. In shallow water the forward and backscattered fields are strongly dependent on the channel characteristics such as: sound velocity profile in the water, the surface and bottom boundaries and the structure of the bottom. A clever active system can exploit these channel characteristics to reduce the undesirable backscatter from boundaries. In this paper it is shown that by using the channel characteristics to define the amplitude and polarity for a vertical array of sources that are 'matched' to the mode one eigenfunction the backscattered energy from the bottom boundary can be reduced significantly.

There has been a significant amount of work conducted on the use of a vertical array of receivers and/or sources to isolate individual modes in a underwater channel, see for example Refs. [1–6] and references therein. Clay [1] provided the theoretical framework for understanding the use of vertical arrays as mode filters. Ingenito [2] showed that mode separation could be achieved experimentally in shallow water for both range-independent and range-dependent environments. King [3] reported on experimental results aimed towards individual mode enhancement. In Ref. [4] Gazanhes et al. reported on successful experimental mode identification work in a reduced scale model waveguide. Clay and Huang [5] also reported on experimental work in a scale model waveguide where the first mode was excited by shading a vertical array in amplitude to match the mode one eigenfunction. Finally in Ref. [6] Gazanhes et al. reported on a comprehensive set of mode excitation and filtering experiments in a scale model waveguide where mode interference and mode conversion was also examined.

Most of the early work reported in Refs. [1–6] was directed towards the demonstration that in an acoustic channel individual modes could be excited or identified. The effect of single mode excitation on the forward or backscattered field was not investigated. With the availability of large scale computing and highly efficient numerical models for computing both the forward and backscattered energy, research investigating the relationship between mode excitation and backscatter can be conducted via computer simulation. In this paper a two-way parabolic equation (PE) model for acoustic backscattering, see Ref. [7], was used to investigate the impact of mode excitation on backscatter from the bottom boundary for range-dependent environments. The approach involves the use of a vertical array of sources which span most of the water column where the amplitude of each source is determined by the amplitude of the mode one eigenfunction at the source depth. In a series of simulations in range-dependent shallow water environments it is shown that the use of a properly weighted vertical array of sources reduces the backscatter significantly with respect to that generated by a single omnidirectional source.

In Section 2 normal mode theory is used to provide a brief overview of the fundamental theory affecting individual mode excitation in shallow water. Section 3 discusses the two-way PE based backscatter model and the modifications that were incorporated. Section 4 presents the simulation results obtained when vertical source arrays are used in a simple and a complex range-dependent shallow water environment. Finally in Section 5 some conclusions are presented.

2. Mode Excitation

In this section, in order to simplify the discussion, it is assumed that the ocean waveguide is horizontally stratified, i.e., the sound speed varies only with depth. In the subsequent sections this assumption is eliminated. It is well established that under the stratified assumption the solution of the wave equation and boundary conditions can be expressed as a sum of normal modes. Assuming azimuthal symmetry and using cylindrical coordinates the horizontal distance from the origin to some point in the channel is r, and the depth with respect to the ocean surface is z with the depth axis pointing downward. For a harmonic point source at the origin at depth z_0 the pressure field in the far field at the point r, z can be expressed as

$$p(r, z; z_0) = \sum_{m=1}^{\infty} \phi_m(z)\phi_m(z_0)H_0^{(1)}(\kappa_m r), \tag{1}$$

where the normalized mode eigenfunctions $\{\phi_m\}$ and the mode eigenvalues $\{\kappa_m\}$ are solutions of the equations

$$\frac{d^2\phi_m(z)}{dz^2} + \left[\left(\frac{\omega}{c(z)}\right)^2 - \kappa_m^2\right]\phi_m(z) = 0, \tag{2a}$$

$$\int_0^\infty \rho(z)\phi_n(z)\phi_m(z)dz = \delta_{n,m}, \tag{2b}$$

and boundary conditions. $\delta_{n,m}$ is the Kronecker delta function, $H_0^{(1)}$ is the zeroth-order Hankel function of the first kind, and $\rho(z)$ is the density vs depth function.

The mode orthonormality condition of Eq. (2b) provides the basis for the single mode excitation. Assume there is a vertical array of sources at the origin located at depths $z_1, z_2, \ldots, z_L$. Furthermore assume that only a finite number of modes M propagate to the point r, z in the field. In this case by applying Eq. (1) the pressure field at the point r, z due to the array of sources is written as

$$p(r, z; z_1, z_2, \cdots, z_L) = \sum_{j=1}^{L} a_j \sum_{m=1}^{M} \phi_m(z_j)\phi_m(z)H_0^{(1)}(\kappa_m r), \tag{3}$$

where the set of coefficients $\{a_j\}$ $j = 1, 2, \ldots, L$ are the shading or weighting coefficients for each of the L sources in the array. Let the weighting coefficients be defined by the eigenfunction of the nth mode sampled at the source depths, that is

$$a_j \equiv \phi_n(z_j) \; j = 1, 2, \ldots, L. \tag{4}$$

In this case the pressure field at the point r, z due to the source array is given by

$$p(r, z; z_1, z_2, \cdots, z_L) = \phi_n(z)H_0^{(1)}(\kappa_n r)\sum_{j=1}^{L} \phi_n^2(z_j) + \sum_{\substack{m=1 \\ m\neq n}}^{M} \gamma_{mn}\phi_m(z)H_0^{(1)}(\kappa_m r), \tag{5}$$

where $\gamma_{mn} \equiv \sum_{j=1}^{L} \phi_m(z_j)\phi_n(z_j)$; note that γ_{mn} is a discrete approximation of the integral of Eq. (2b). The first term of Eq. (5) represents the field contribution at the point r, z due to mode n, the second term represents the cross-mode contributions. By the mode orthonormality condition of Eq. (2b) it would be expected that the cross-mode contributions would be small. The magnitude of these contributions are governed by two factors: (1) the spatial sampling scheme used in the source array and (2) that the discrete approximation is carried out over the depth range of 0 to z_L rather than the full range of 0 to ∞.

In Section 4 the effect of these approximations will be investigated via simulation by examining the effect of spatial sampling on the energy in the backscattered field.

3. Backscatter Modelling

It is well known that the parabolic equation (PE) method is efficient for solving acoustic propagation problems with range-dependent environments. Recently the PE method was extended to handle reverberation from deterministic deformations in the boundaries, this version is referred to as the two-way PE [7]. The two-way PE is based on a single-scattering approximation and the approach of two-way coupled modes in which range-dependent environments are approximated by a sequence of range-independent regions. At the vertical boundaries between regions the solution of the two-way PE is required to satisfy continuity conditions. In addition to providing an accurate backscattered field, the two-way PE provides a high degree of accuracy for the forward field. It should be noted that, as mentioned in Ref. [7], the two-way PE is implemented as a line source in plane geometry rather than the usual point source in cylindrical geometry and the spreading factor $r^{-1/2}$ is not included in the field computation.

The two-way PE method, as currently implemented, is limited to backscatter from deterministic bottom deformations and does not handle backscatter from sloping bottoms or from the ocean surface. While the two-way PE model does not handle all types of reverberation generating mechanisms, it does handle the one mechanism which is dominant in shallow water. It should also be noted while most reverberation models compute only the mean reverberation intensity the two-way PE model computes the coherent forward and backscattered pressure fields. This feature makes the two-way PE very useful for signal processing studies since coherent processing can be applied to the forward and backscattered fields.

As with all PE based propagation codes the forward propagation is initiated with a 'starting-field'. In the two-way PE a mode-based starting-field which is a function of the source depth is used. For the channel adapted source work reported herein a vertical array of sources is used rather than a single omni-directional source. Thus the PE starting-field was modified to incorporate the multiple sources as follows. Let $\mathbf{w}_j(z)$ be the starting-field pressure vector for a source at depth z_j, i.e., pressure vs depth sampled on some grid as generated by the mode-based field starter. Then by Eq. (3) it follows that the total starting-field vector $\mathbf{u}(z)$ for a source array with sources at depths $z_1, z_2, \ldots, z_L$ is given by

$$\mathbf{u}(z) = a_1\mathbf{w}_1(z) + a_2\mathbf{w}_2(z) + \cdots + a_L\mathbf{w}_L(z), \tag{6}$$

where the weighting coefficients a_j $j = 1, 2, \ldots, L$ are defined by the eigenfunction of the nth mode, see Eq. (4). To facilitate comparing backscattered fields for various array source configurations the weighting coefficients were normalized for constant power, i.e., $\sum_{j=1}^{L} a_j^2 = 1$.

Given the starting-field $\mathbf{u}(z)$ the PE solution is obtained in two steps. Starting at the source array, $r = 0$, the outgoing PE is used to propagate the forward field across the range-independent regions. In regions in which backscattering is expected to be important, transmitted (forward-scattered) and reflected (backscattered) fields are computed at the vertical interfaces between range-independent regions. The reflected fields are stored for later use. After this process has reached the maximum range, the incoming PE is used to propagate the incoming reflected fields. At each vertical interface, the appropriate stored reflected field is coherently added to the incoming field.

With the modified two-way PE method discussed above the forward and backscattered fields can be computed for range-dependent environments for arbitrary vertical arrays of sources with arbitrary source weighting.

4. Shallow Water Simulations

In this section we present the results obtained using the two-way PE for computing the backscattered field for two range-dependent environments. The usefulness of employing vertical arrays of sources weighted by individual mode eigenfunctions is investigated. In all cases each source is a unit line source (plane geometry) emitting a frequency of 250 Hz.

4.1. Flat With Step Case

In this section a simple range-dependent environment is considered, see Fig. 1. The bathymetry is flat with a depth of 130 m from $r = 0$ to $r = 10$ km, at $r = 10$ km there is a 10 m step decrease in depth. Figure 2 provides the sound speed profile, a typical Mediterranean winter profile, the bottom parameters and the mode shapes for the first six modes obtained using a normal mode solution for a constant channel depth of 130 m at a frequency of 250 Hz.

Figure 3 provides a color contour representation for the forward field as computed using the two-way PE for two different source configurations, recall that there is no spreading loss in the two-way PE calculation. The color scale indicates loss in dB ($20 \log |p|$) relative to a unit source at 1 m plotted as a function of receiver range and depth. Figure 3a illustrates the forward field as a function of range and depth for a single source at a depth of 50 m. Note at $r = 10$ km, the location of the step, that forward energy is spilled into the bottom. Figure 3b illustrates the same situation except in this case the source is a vertical array of sources. There are six sources with an inter-element spacing of 20 m, the top source is at 10 m. The sources are weighted by the mode one eigenfunction. It is apparent that in this case the sound pressure in the water column is focused away from both the surface and the bottom boundaries and into the center of the water column. Also note there is considerably less energy spilled into the bottom at the step, indicating that there is less energy directed towards the step thus reducing backscatter.

Figure 4 illustrates the backscatter produced by the environment of Fig. 1 for a single source at 50 m. Figure 4a illustrates the backscatter for a single receiver at 50 m as a function of range, while Fig. 4b illustrates the backscatter as a function of range and depth across the channel. The backscatter for source depths of 25 m, 75 m, and 100 m was also computed, the variability in backscatter as a function of source depth was small. Figures 5a and 5b illustrate the same situation when the source is an array of sources; six sources spaced at 20 m, top source at 10 m, mode one eigenfunction source weighting. Comparing Figs. 4a and 5a it is seen that the use of the vertical array of sources weighted to emphasize mode one has reduced the average backscatter by about 18 dB across the entire backscattered field from $r = 0$ to $r = 10$ km for a receiver at 50 m. Comparing Figs. 4b and 5b it is seen that the reduction in backscatter is fairly uniform across the field in range and depth.

This simple range-dependent example illustrates the usefulness of properly weighted vertical array of sources in terms of backscatter reduction.

4.2. Canyon Case

Figure 6 illustrates a somewhat more realistic range-dependent situation. A range-dependent track was extracted from a shallow water area in the Mediterranean north of Elba Island. The source is placed in a fairly flat region of depth 130 m. The propagation is downslope (0.34°) across a canyon of depth 180 m and then upslope (0.69°) to a flat region of depth 120 m over a range of 14 km. The range-dependent slopes are represented by a sequence of range-independent stair-steps where at each step the depth change is on the order of 5 m. Figures 7a and 7b illustrate the winter and summer sound speed profiles and bottom parameters used in the simulations and the shape of the mode one eigenfunctions. Figure 8a illustrates the forward field as a function of range and depth for a single source at a depth of 50 m. Figure 8b illustrates the forward field for a vertical array of sources containing 12 sources spaced at 10 m weighted by the mode one eigenfunction. It is apparent that the energy is effectively focused down the center of the channel and away from the surface and bottom boundaries.

Figure 9a illustrates the backscatter as a function or range and depth for a single source at 50 m for the winter environment. It is apparent that the upslope region is generating a considerable amount of backscatter. Figure 9b illustrates the same situation when an array of sources was used. The source array contained 12 sources spaced at 10 m with the top source at a depth of 10 m weighted by the mode one eigenfunction. For this case the reduction in backscattered energy is dramatic, on the order of 20 dB over the entire region. An array consisting of six sources spaced at 20 m with mode one eigenfunction weighting was also considered but the degree of backscatter reduction was minimal.

For the summer environment Fig. 10a illustrates the forward field as a function of range and depth for a single source at a depth of 50 m. Figure 10b illustrates the forward field for a vertical array of sources containing 12 sources spaced at 10 m weighted by the mode one eigenfunction. It is seen that with the summer downward refracting profile the focusing away from the boundaries is not nearly as effective as it was for the winter case.

Figures 11a and 11b illustrate the backscatter when the summer profile was used with the bathymetry of Fig. 6. From the mode shapes of Figs. 7a and 7b it is seen that for the summer environment the mode one eigenfunction has its largest amplitude near the bottom. Thus, intuitively, we may expect that the for the summer environment the mode one eigenfunction weighting may not be as effective for backscatter reduction. Figure 11a illustrates the case for a single source at 50 m. Comparing Fig. 11a with Fig. 9a it is seen that when the summer downward refracting profile was used the backscatter from the upslope region increased considerably. Figure 11b illustrates the case when a source array of 12 sources spaced at 10 m with mode one eigenfunction weighting was used. Comparing Figs. 11a and 11b it can be seen that the backscatter is reduced by about 5 to 7 dB over the range/depth plane. As expected the degree of backscatter reduction is considerably less for the summer profile case than it was for the winter profile case.

5. Conclusions

The use of vertical arrays of sources in shallow water has been investigated using backscatter, as generated by the two-way PE model, as a measure of performance. It appears that when the amplitude and polarity of the sources are matched to the mode one eigenfunction a considerable reduction in the backscatter produced by deterministic bottom deformations can be realized. These simulation results strongly indicate that the overall performance of active systems in shallow water can be improved through the use of vertical arrays of sources. In shallow water with depth on the order of 130 m and source frequency of 250 Hz. the simulation results indicate that somewhere between six and twelve sources distributed throughout the water column are required in order to significantly reduce backscatter.

References

[1] Clay, C.S. Use of arrays for acoustic transmission in a noisy ocean. *Reviews of Geophysics*, **4**, 1966: 475–507.

[2] Ingenito, F. Excitation, propagation, and attenuation of acoustic normal modes in shallow water. *In*: Hastrup, O.F. and Olesen, O.V. Sound propagation in shallow water. Proceedings of a conference held at SACLANTCEN on 23–27 September, 1974. Volume 2: Unclassified papers, SACLANTCEN CP-14. La Spezia, Italy, SACLANT Undersea Research Centre, 1974: pp.224–234.

[3] King, L.A. Enhancement techniques in transmitting and receiving underwater acoustic modes. *In*: Hastrup, O.F. and Olesen, O.V. Sound propagation in shallow water. Proceedings of a conference held at SACLANTCEN on 23–27 September, 1974. Volume 2: Unclassified papers, SACLANTCEN CP-14. La Spezia, Italy, SACLANT Undersea Research Centre, 1974: pp.224–234.

[4] Gazanhes, C., Sessarego, J.P. and Garnier, J.L. Identification of modes in some conditions of sound propagation in shallow water. *Journal of Sound and Vibration*, **56**, 1978: 251–259.

[5] Clay, C.S., and Huang, K. Single mode transmission and acoustic backscattering measurements in a laboratory waveguide. *Journal of the Acoustical Society of America*, **67**, 1980: 792–794.

[6] Gazanhes, C., Garnier, J.L. Experiments on single mode excitation in shallow water propagation. *Journal of the Acoustical Society of America*, **69**, 1981: 963–969.

[7] Collins, M.D. and Evans, R.B. A two-way parabolic equation for acoustic backscattering in the ocean. *Journal of the Acoustical Society of America*, **91**, 1992: 1357–1368.

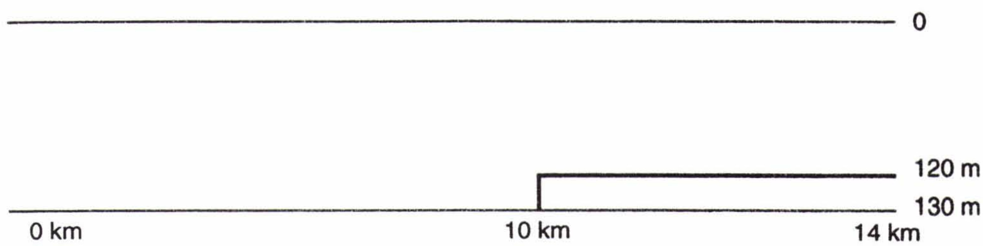

Figure 1 *The range-dependent bathymetry for the 'step case' example.*

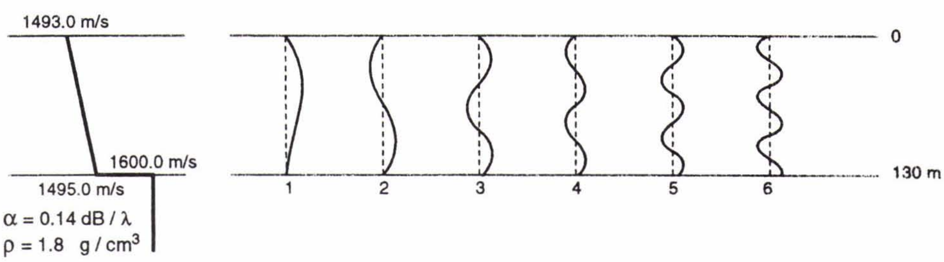

Figure 2 *The winter sound speed profile and bottom parameters with eigenfunctions for modes 1 to 6 at a frequency of 250 Hz for a flat channel of depth 130 m.*

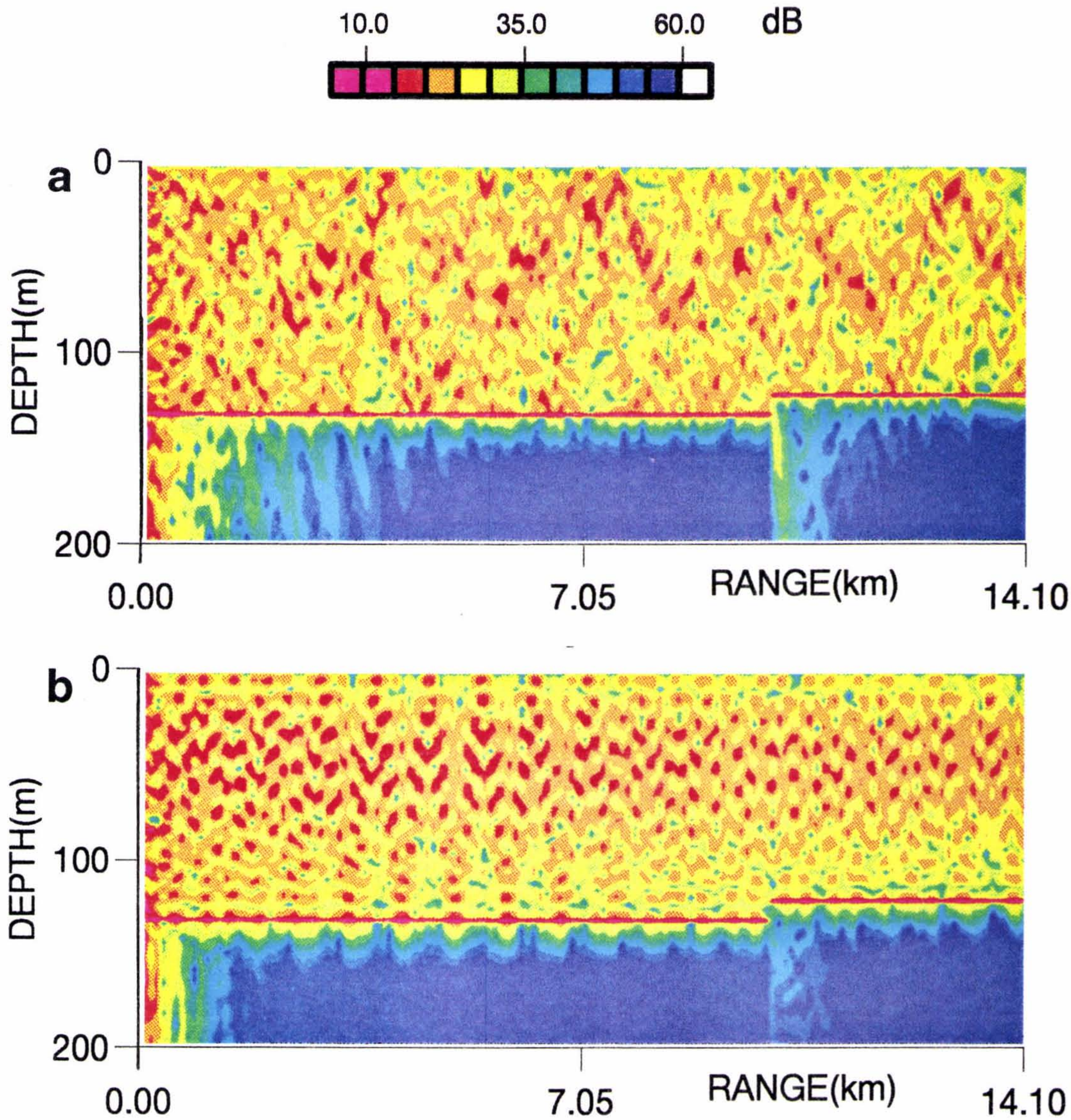

Figure 3 *The modulus of the forward pressure field as a function of range and depth for the 'step case' bathymetry, winter environment; (a) a single source at 50 m, and (b) a vertical array of sources consisting of 6 sources spaced at 20 m matched in amplitude and polarity to the mode one eigenfunction.*

intentionally blank page

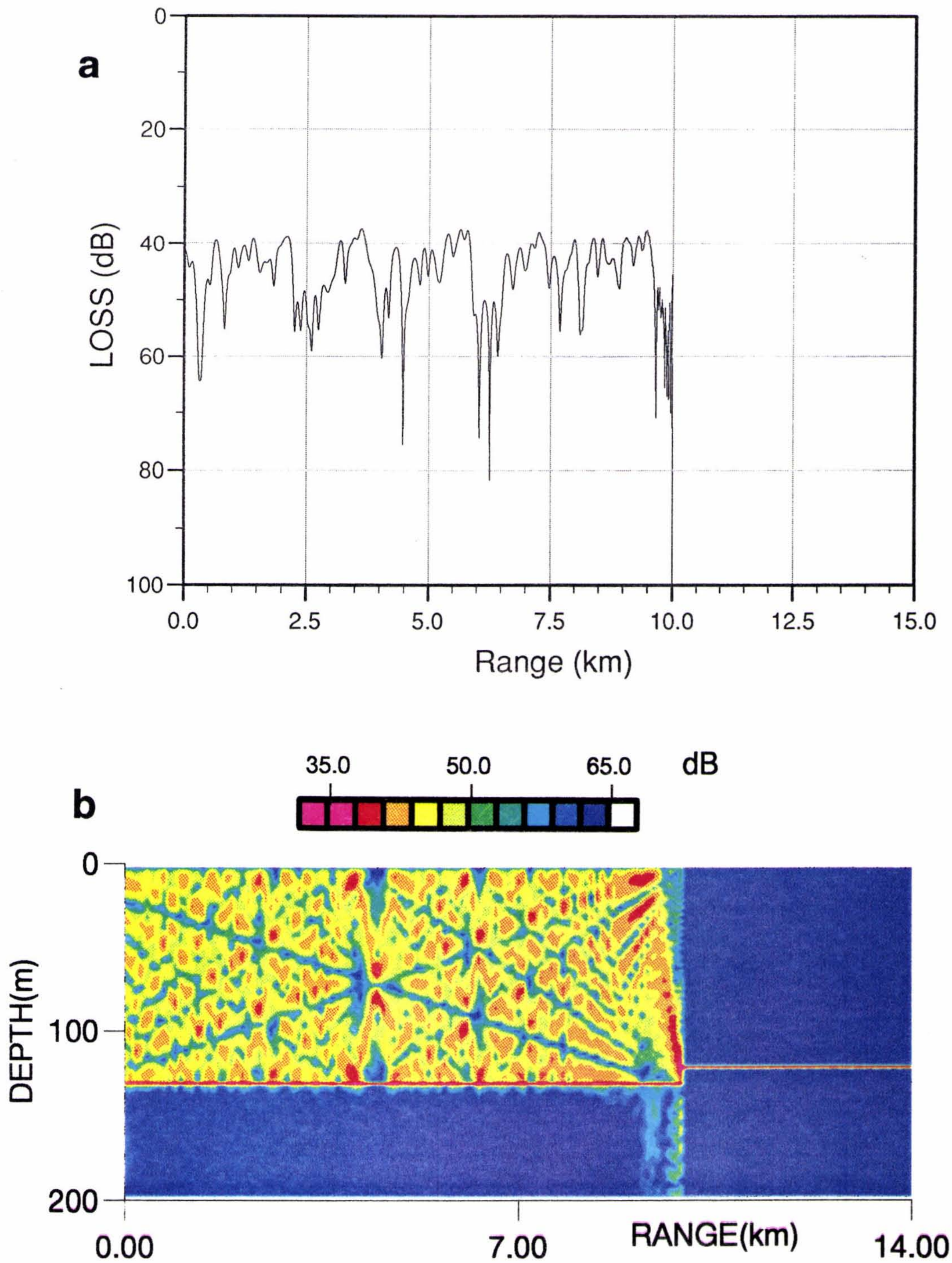

Figure 4 *The modulus of the backscattered pressure field for the 'step case' bathymetry, winter environment, for a single source at 50 m; (a) backscatter vs range for a receiver at 50 m, and (b) backscatter vs range and depth.*

intentionally blank page

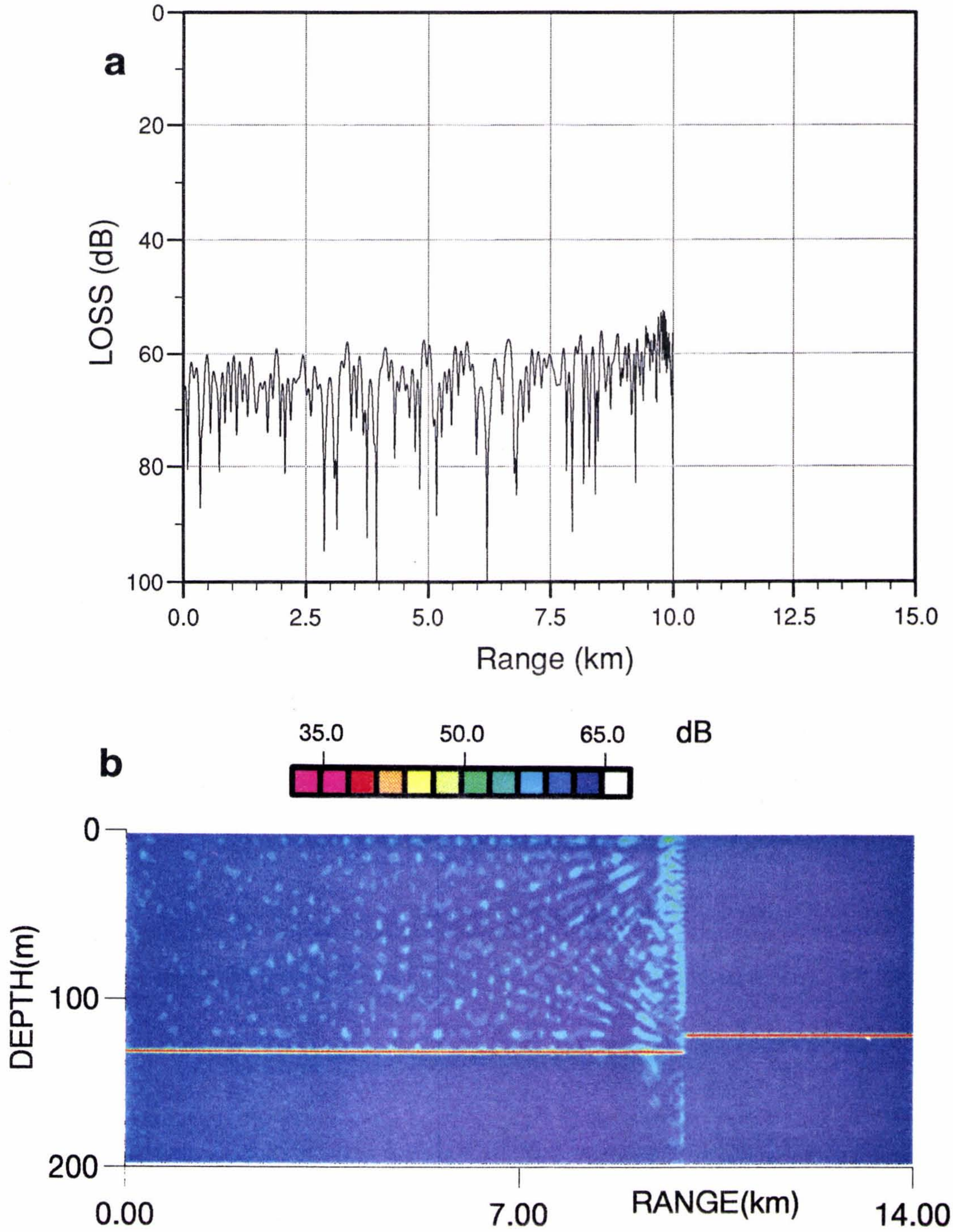

Figure 5 *The modulus of the backscattered pressure field for the 'step case' bathymetry, winter environment, for a vertical array of sources containing 6 sources spaced at 20 m matched in amplitude and polarity to the mode one eigenfunction; (a) backscatter vs range for a receiver at 50 m, and (b) backscatter vs range and depth.*

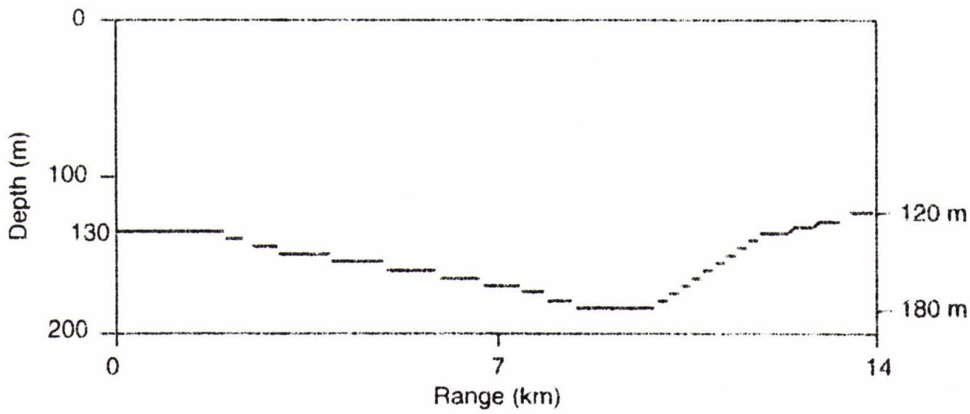

Figure 6 *The range-dependent bathymetry for the 'canyon case' example.*

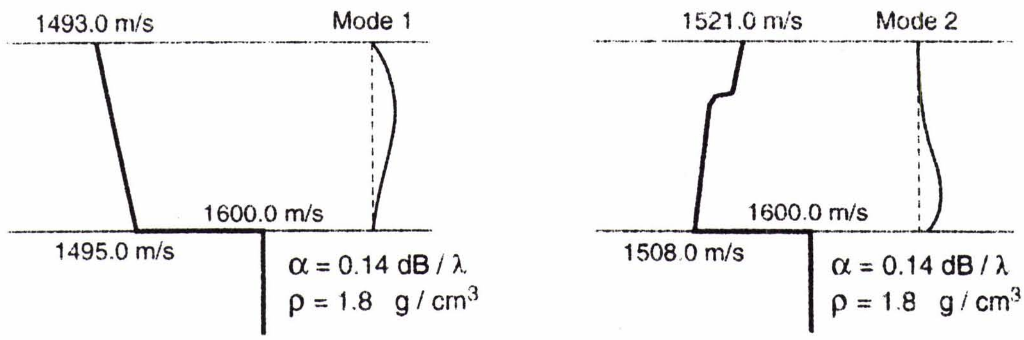

Figure 7 *The environments used for the 'canyon case', (a) winter and (b) summer.*

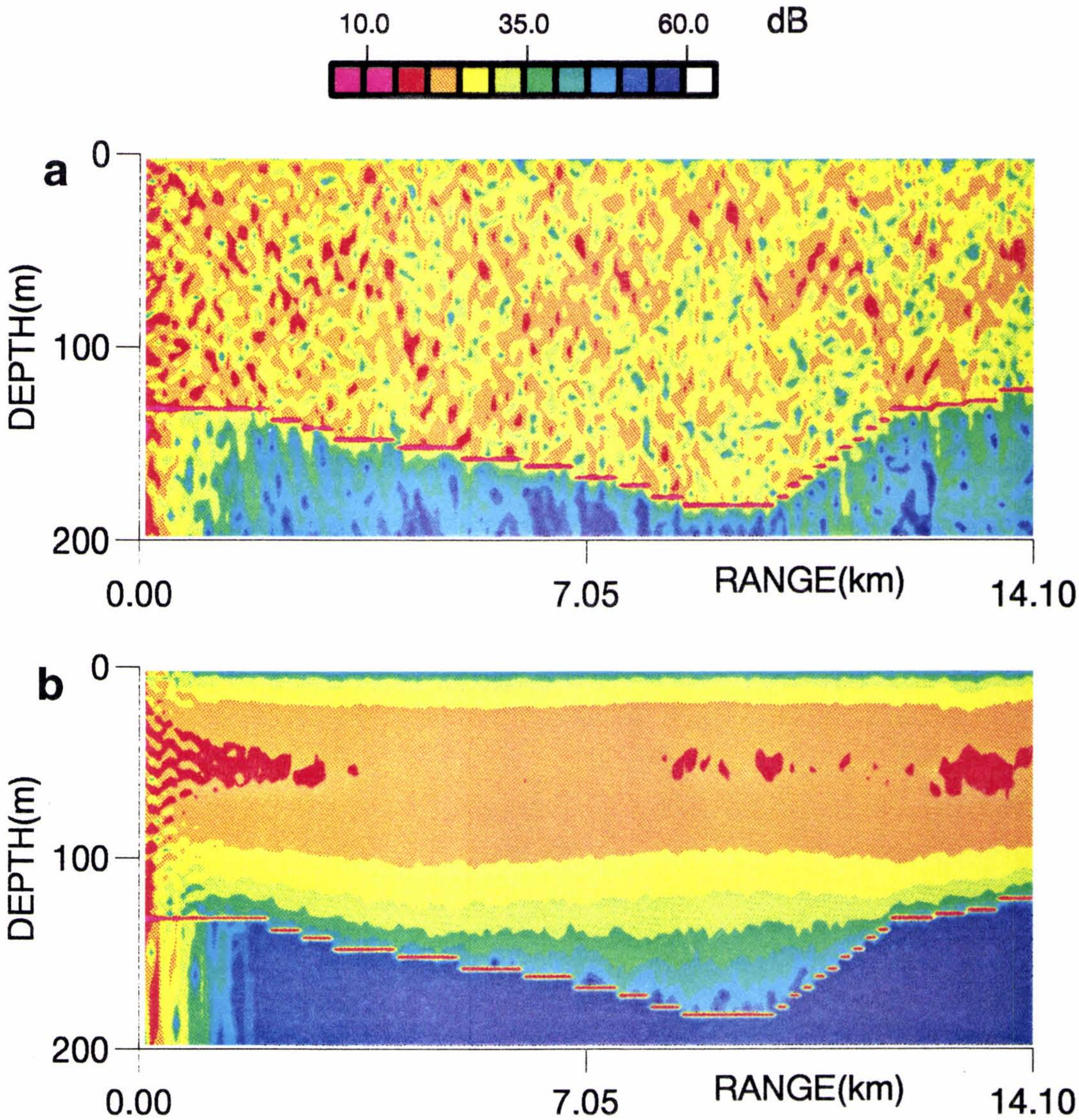

Figure 8 *The modulus of the forward pressure field as a function of range and depth for the 'canyon case' bathymetry, winter environment; (a) a single source at 50 m, and (b) a vertical array of sources consisting of 12 sources spaced at 10 m matched in amplitude and polarity to the mode one eigenfunction.*

intentionally blank page

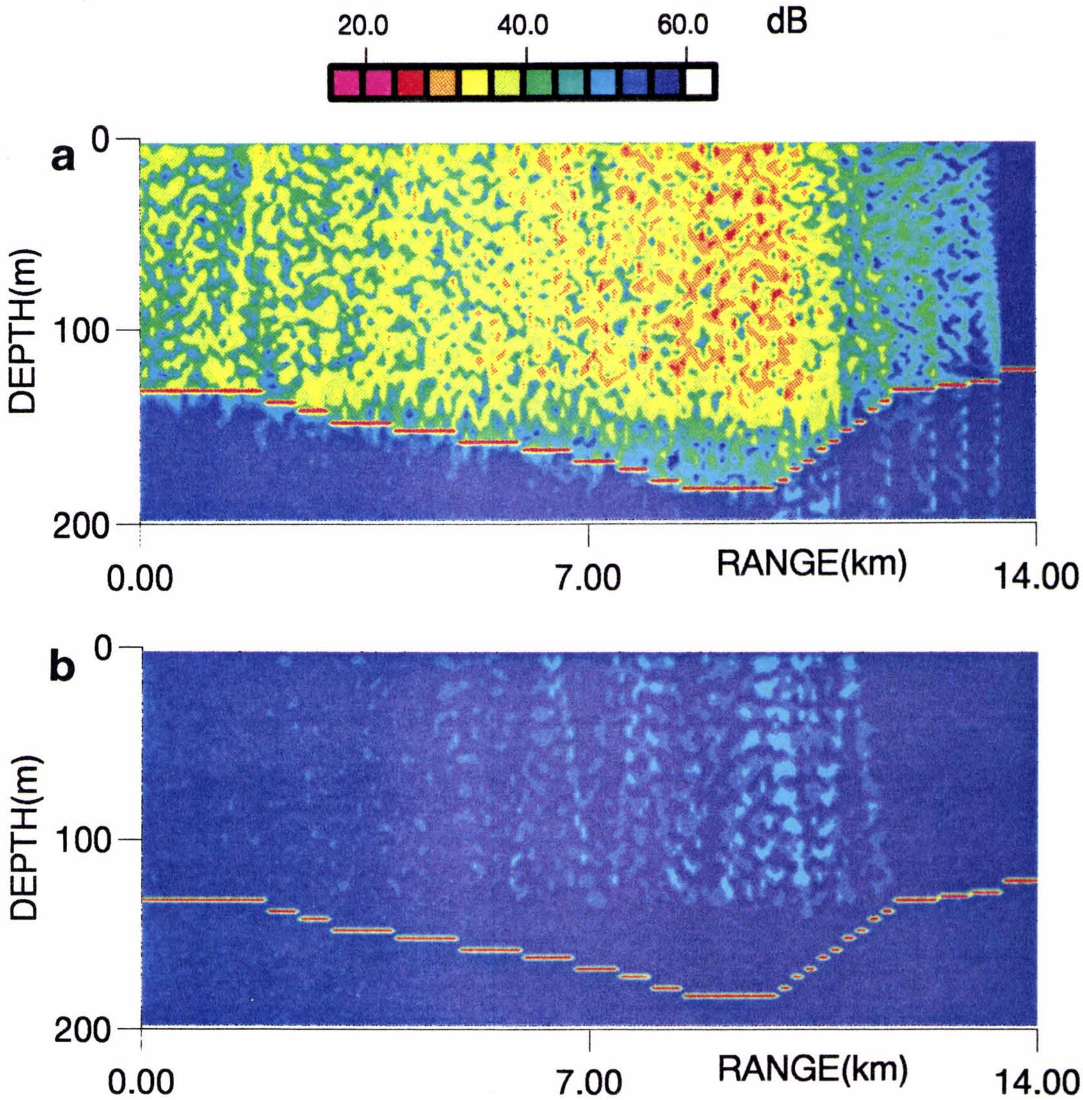

Figure 9 *The modulus of the backscattered pressure field for the 'canyon case' bathymetry, winter environment; (a) a single source at 50 m and (b) a vertical array of sources containing 12 sources spaced at 10 m matched in amplitude and polarity to the mode one eigenfunction.*

intentionally blank page

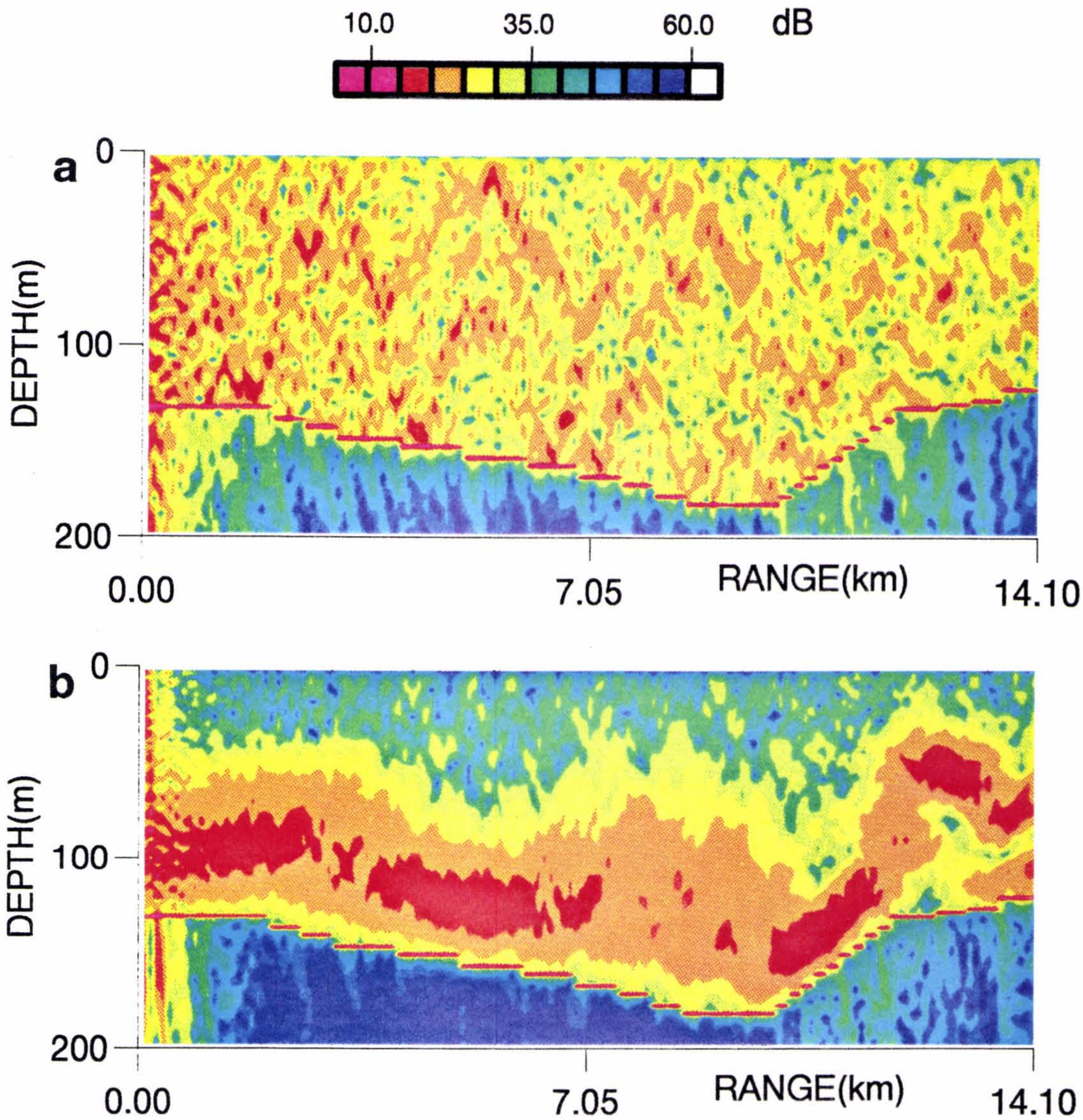

Figure 10 *The modulus of the forward pressure field as a function of range and depth for the 'canyon case' bathymetry, summer environment; (a) a single source at 50 m, and (b) a vertical array of sources consisting of 12 sources spaced at 10 m matched in amplitude and polarity to the mode one eigenfunction.*

intentionally blank page

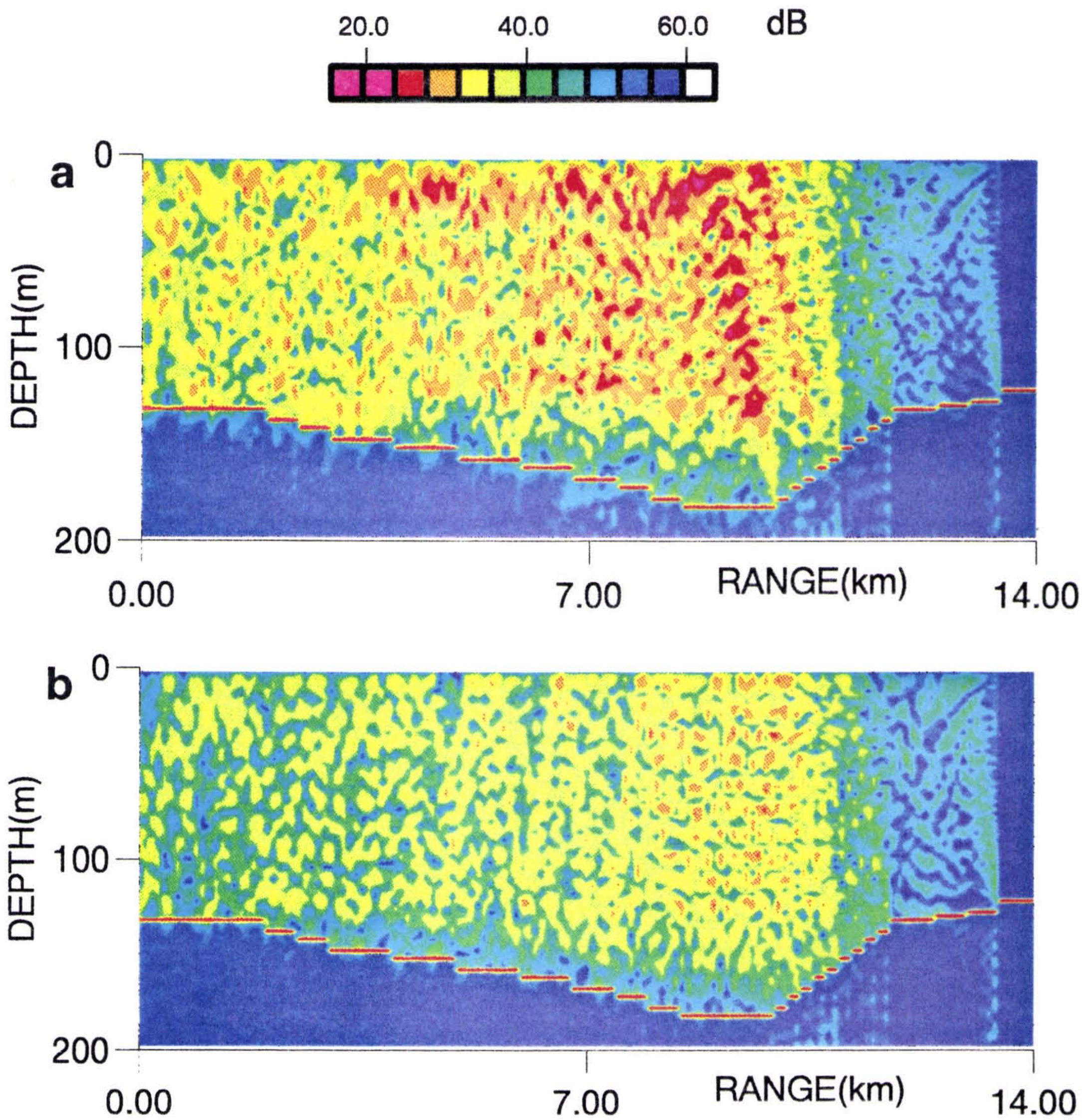

Figure 11 *The modulus of the backscattered pressure field for the 'canyon case' bathymetry, summer environment; (a) a single source at 50 m and (b) a vertical array of sources containing 12 sources spaced at 10 m matched in amplitude and polarity to the mode one eigenfunction.*

intentionally blank page