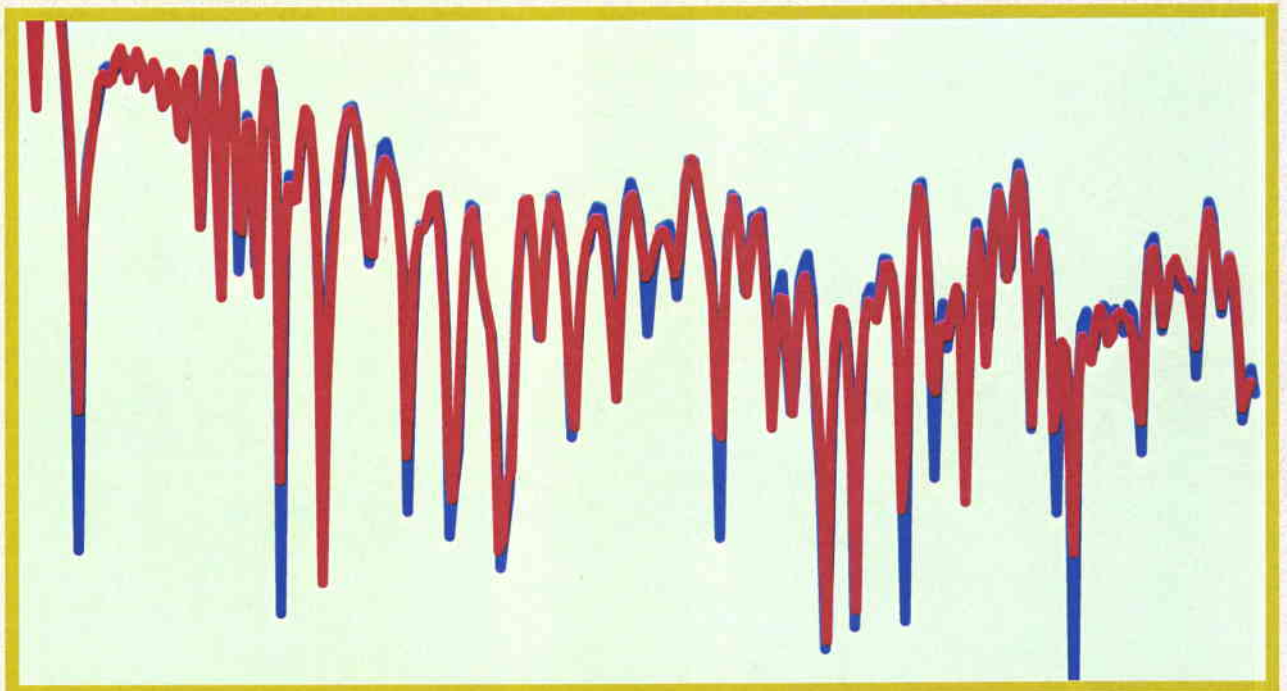


SACLANT UNDERSEA RESEARCH CENTRE REPORT



PROSIM broadband normal-mode model *A users' guide*



*Francesco Bini-Verona, Peter L. Nielsen
and Finn B. Jensen*

February 2000

PROSIM Broadband
Normal-Mode Model
A user's guide

F. Bini-Verona, P.L. Nielsen
and F.B. Jensen

The content of this document pertains
to work performed under Project 04-D of
the SACLANTCEN Programme of Work.
The document has been approved for
release by The Director, SACLANTCEN.



Jan L. Spoelstra
Director

SACLANTCEN SM-358

intentionally blank page

PROSIM Broadband Normal-Mode Model

A user's guide

F. Bini-Verona, P.L. Nielsen and F.B. Jensen

Executive Summary: Broadband sonar performance prediction in range-dependent shallow-water areas can be computationally intensive. The execution time of range-dependent propagation models is directly related to the complexity of the acoustic environment and the number of frequencies considered in the transmitted signal. This report describes an adiabatic range-dependent propagation model built with the main objective of being particularly easy to handle, fast and accurate compared with existing normal-mode models. The simple adiabatic approximation has been implemented in order to give a more realistic treatment of the ocean environment, where either the water depth, the sound speed profile or the bottom properties vary moderately along the propagation channel. The range-dependent problem is described by dividing the environment into a sequence of range-independent segments and using a sum of modes to represent the acoustic field in each segment. The performance of the propagation model is orders of magnitude faster than traditional normal-mode models for broadband calculations in range-dependent shallow-water scenarios. The model is written in the programming language FORTRAN, and it can easily be ported to any platform with a FORTRAN compiler.

SACLANTCEN SM-358

intentionally blank page

PROSIM Broadband Normal-Mode Model

A user's guide

F. Bini-Verona, P.L. Nielsen and F.B. Jensen

Abstract:

PROSIM is a layered normal-mode model approach for adiabatic broadband range-dependent sound propagation. The kernel of this model is based on a recently developed range-independent model called ORCA, which includes a very efficient eigenvalue solver and frequency interpolation technique. The implementation of range-dependency involved special handling of the range segments and the frequency interpolation to minimize hardware requirements and still keep the efficiency of the model. The computational speed of PROSIM is a function of the number of layers describing the environment in depth and the influence of the maximum frequency and bandwidth considered; nevertheless the calculation of broadband transfer functions up to 10 kHz in shallow water acoustic waveguides involving hundreds of modes and thousands of frequency components is performed in a few minutes on a state-of-the-art workstation.

Keywords: normal modes ◦ numerical modeling ◦ range dependence

Contents

1	Introduction	1
2	Model Overview	3
2.1	Deterministic acoustic modeling	3
2.2	Frequency interpolation	4
2.3	The range-dependent environment	6
2.4	Directional source	10
2.5	Attenuation	11
3	Installation of PROSIM	12
4	Running PROSIM	14
4.1	Input structure	14
4.2	Environmental inputs	14
4.3	Computational outputs	17
5	Numerical Verification and Examples	20
6	Conclusions	27
	References	29
	Annex A - Output options	30

1

Introduction

Sound propagation in the ocean can be described, in principle, by numerically solving the acoustic wave equation. Although simply stated, the computer implementation is generally difficult due to the complexity of the ocean-acoustic environment.

In the last decades a variety of numerical techniques have been developed for computing sound fields in the ocean [1]. Many of the existing ocean-acoustic numerical propagation models are highly sophisticated and take several hours to run on fast workstations or are very fast but not sufficiently accurate for scientific applications. Thus the development of a broadband (10 Hz - 10 kHz) acoustic propagation model requires special attention to accuracy, robustness and efficiency.

The broadband, deterministic propagation model **PROSIM** is based on a model called **ORCA** developed recently by Westwood et al., see Refs. [2, 3]. The model is based on a layered normal mode approach assuming that the inverse of the sound speed squared varies linearly with depth in each layer. Only real eigenvalues are included in the calculations, and the model only handles fluid sediment layers. Prediction of broadband sound propagation may in general be determined by a brute-force frequency-by-frequency analysis to establish the transfer function of the waveguide. However, this technique is not practical for determining very broadband transfer functions because of the computation time. The actual propagation model requires only an accurate determination of eigenvalues and mode functions for a subset of frequencies in the frequency band of interest. The eigenvalues and mode functions are then interpolated in frequency between this subset of calculated frequencies in order to obtain a specific sample of the transfer function. The interpolation technique is not applicable to all environments as, for instance, double duct problems, where modes are shifted from one duct to the other. In this case the frequencies and the corresponding modes where the shifting appears are identified, and the accurate brute-force frequency-by-frequency technique is applied only for those frequencies and modes. A demonstration of the efficient eigenvalue and mode solver is given in Ref. [3].

The **PROSIM** model is able to handle range-dependent environments within the adiabatic approximation, i.e. coupling of energy between modes caused by the range dependency is neglected. The range-dependent environment is divided into a sequence of range-independent segments. The eigenvalues and mode functions are evaluated for each segment and for a frequency sub-band of the total frequency band of interest. Hereafter the frequency sub-band is changed, and the calculations start at the first segment and proceed out to the last segment. The procedure

SACLANTCEN SM-358

continues until all the frequency sub-bands have been analyzed.

Moreover, the propagation model is able to approximate a source beam with a constant Gaussian shape independent of frequency by decomposing the source field into a sum of normal modes each multiplied by the appropriate shading coefficients. The beam is parameterized by the aperture and tilt.

The computational speed of the model is a function of the number of layers describing the environment in depth and the maximum frequency and bandwidth considered; nevertheless the calculation of transfer functions up to 10 kHz of shallow water acoustic waveguides involving hundreds of modes and thousands of frequency components is performed in a few minutes on a state-of-the-art workstation.

In its current configuration on a Compaq XP1000 workstation, the simulator is able to handle frequencies from 10 Hz up to 10 kHz with maximum 1100 modes, 12000 frequency components in the frequency band of interest, a maximum of 100 receivers in range and a maximum of 200 range segments.

The following sections give a brief description of the eigenvalue and mode solver, and explain how these elements are embedded into an adiabatic range-dependent version of the PROSIM propagation model. Finally, some examples of the application of this range-dependent model are given, where the received energy levels and time series obtained by using PROSIM are compared to reference solutions generated by the coupled-mode model C-SNAP developed at SACLANTCEN [4].

2

Model Overview

Normal-mode approaches have been widely used in underwater acoustics and are derived from an integral representation of the wave equation. The acoustic pressure $p(r, z)$ as a function of range r and depth z is obtained, by applying the separation of variables technique, as the product of a depth function $\Psi(z)$ and a range function $\Phi(r)$. After substituting into the Helmholtz equation and dividing by $\Psi(z)\Phi(r)$ we obtain [1]:

$$\frac{1}{\Psi} \left[\frac{1}{r} \frac{d}{dr} \left(r \frac{d\Psi}{dr} \right) \right] + \frac{1}{\Phi} \left[\rho(z) \frac{d}{dz} \left(\frac{1}{\rho(z)} \frac{d\Phi}{dz} \right) + \frac{\omega^2}{c^2(z)} \Phi \right] = 0 \quad (1)$$

where ρ and c is density and sound speed respectively, and ω the angular frequency of the acoustic signal. Equation 1 leads to the modal equation:

$$\rho(z) \frac{d}{dz} \left(\frac{1}{\rho(z)} \frac{d\Psi_m}{dz} \right) + \left(\frac{\omega^2}{c^2(z)} - k_{rm}^2 \right) \Psi_m(z) = 0 \quad (2)$$

for range-independent environments. The eigenvalues, which are the resulting values of the separation constants, are identified by k_{rm}^2 and the Ψ_m is the m^{th} normalized eigenfunction. Then we write the pressure as sum of the normal modes:

$$p(r, z) \simeq \frac{i}{\rho(z_s) \sqrt{8\pi r}} e^{-i\frac{\pi}{4}} \sum_{m=1}^{\infty} \Psi_m(0, z_s) \Psi(r, z) \frac{e^{ik_{rm}r}}{\sqrt{k_{rm}}} \quad (3)$$

for a single frequency, and at a source depth of z_s .

2.1 Deterministic acoustic modeling

In order to optimize the efficiency of the PROSIM propagation model, the ORCA model has been reduced to include only the procedures necessary for handling real wavenumbers. The broadband calculations are more efficient when real wavenumbers are used, because the problem of finding the eigenvalues is reduced from a 2D

to a 1D search space. Shear properties of the ocean bottom have been neglected in the PROSIM model development, while the ORCA model was set-up for handling both fluid and elastic properties of the waveguide. These procedures, forming the starting point of the development of the deterministic propagation module, are the engine of PROSIM. Moreover, the size of the arrays for the wavenumbers and mode functions have been increased to contain hundreds of modes needed for high frequency sound propagation. All the variables in the program containing wavenumbers, mode functions, source and receiver positions are kept in arrays which avoid any time consuming I/O operations. The eigenvalue solver is the same regardless of whether single frequency or broadband calculations are required. In the latter case the eigenvalue solver is called repeatedly until a necessary number of frequency components have been analyzed. The eigenvalue solver is in general based on switching between bisection [5] and cubic spline of the characteristic equation. As an eigenvalue is bracketed by the bisection method, the characteristic equation is approximated by a cubic spline, and an estimate of the eigenvalue is given by the root of this spline. There is a complex procedure to check if the estimated eigenvalue is found with sufficient accuracy, and if any modes are missing in the search interval, see Ref. [6].

2.2 Frequency interpolation

The PROSIM propagation model requires the accurate determination of the eigenvalues and mode functions for only a limited number of discrete frequency components. Between these discrete frequencies the eigenvalues and mode functions are interpolated with confidence for all environments as shown schematically in Fig. 1.

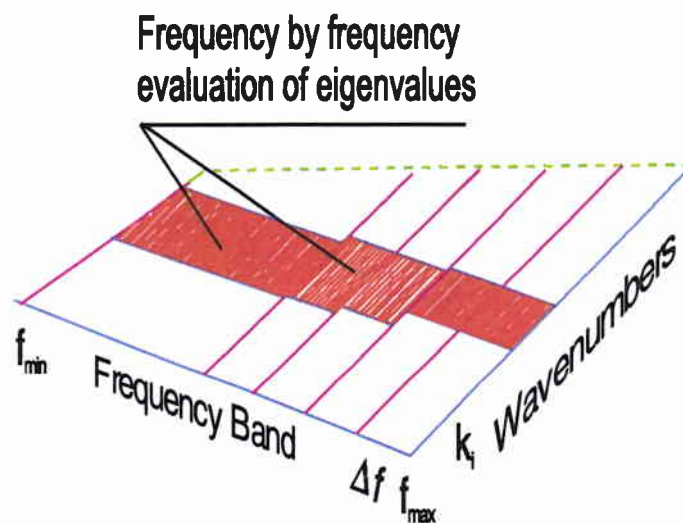


Figure 1 Schematic of the interpolation technique, where the frequency band of interest is divided into sub-bands. Interpolation of wavenumbers and mode functions are performed within each sub-band.

In double duct problems, for example, some of the modes shift from one duct to the other, which causes difficulties applying the interpolation scheme for those particular modes. In these cases the eigenvalues and mode functions are determined accurately for all frequencies by using the brute-force technique (the shaded regions in Fig. 1). A schematic of the interpolation technique is shown in Fig. 1, which is used both in the range-dependent PROSIM model as well as for range-independent environments. The frequency band of interest is divided into a certain number of frequency sub-bands (originally equal in size). The limits of each frequency sub-band define the frequencies, where the eigenvalues are determined accurately. The algorithm works as follows: All eigenvalues and mode functions are determined accurately at the highest frequency f_{max} , and at the lower limit of the first sub-band at the frequency $f_{max} - \Delta f$, see Fig. 1. Between the two frequency sub-band limits the eigenvalues and mode functions are interpolated. The interpolated mode functions are evaluated at a sufficient number of frequency components within the sub-band to construct the required time window. The actual sub-band is shifted to the next, and the interpolation of the mode functions starts again. This sequence is followed until the frequency band of interest has been fully analyzed. However this scheme has been improved observing that at higher frequencies the modes are smooth functions of frequency.

Therefore, it is not optimal to divide the frequency band of interest into equidistant frequency sub-bands as indicated in Fig. 1. The PROSIM model has an interpolation scheme, where the size of the sub-bands decreases by a logarithmic function as the frequency decreases, see Fig. 2.

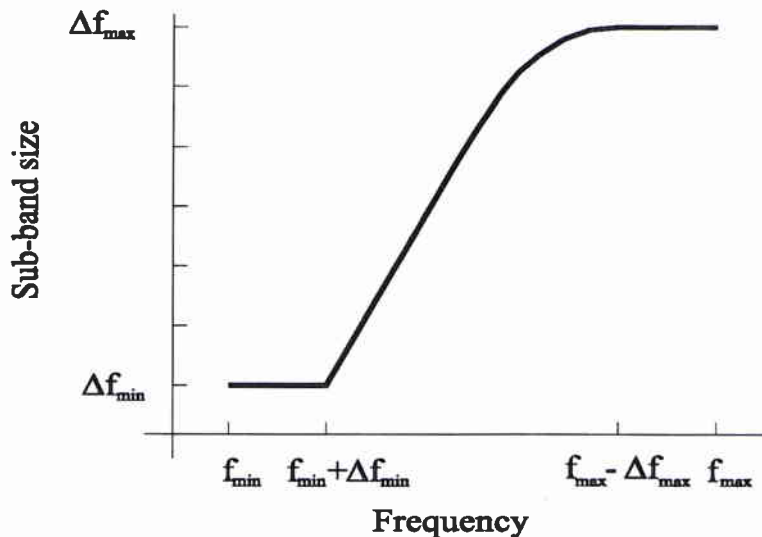


Figure 2 *Logarithmic change of the frequency sub-band sizes as the frequency decreases in the interpolation scheme.*

The size of the sub-band at the beginning of the interpolation is determined by evaluating the number of modes at the highest frequency and estimating for which Δf this number is reduced by 2 modes; the minimum size of the sub-bands at the lower frequencies is fixed to 15 Hz as in the original model.

As an example it is seen in Fig. 1 that the number of brute-force calculations is constant within the first two frequency sub-bands from the highest frequency (shaded regions). However, at the third sub-band the lowest and highest mode number decreases. If a frequency sub-band includes a jump of this type, the number of brute-force calculations is increased from the minimum mode number in the third sub-band to the maximum mode number in the first or second sub-band. Therefore, unnecessary brute-force calculations will be carried out for a certain number of mode functions in the three sub-bands considered. This will increase the execution time of the program. The introduction of the logarithmic decrease of Δf , which maintains the difference in the number of modes between two adjacent sub-bands to less than 2, has enhanced the performance by approximately 33% for range-independent environments.

2.3 The range-dependent environment

As shown in Fig. 3, a range-dependent environment is simulated by dividing the full range into a number of segments with different range-independent properties.

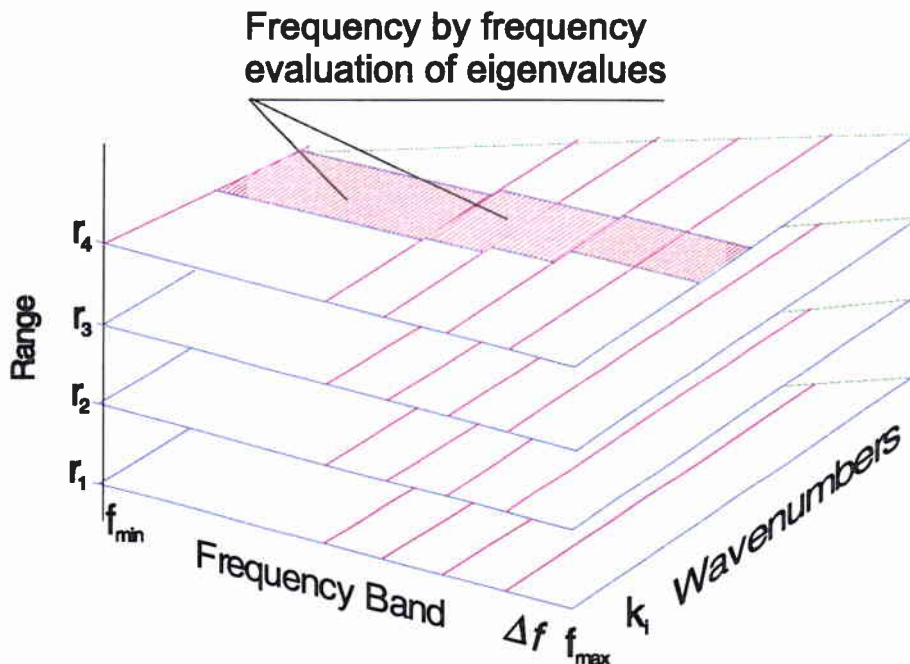


Figure 3 The interpolation of wavenumbers and mode functions are performed within each sub-band and in range.

Since the wavenumbers and the corresponding mode set are computed in each segment, there is no significant difference between computing modal properties for range-independent and range-dependent environments. Hence the differences arise when summing up the modes, since several parameters change from segment to segment. In the actual implementation of range-dependence in the PROSIM model cross-coupling terms, which allow energy to transfer from one mode to another are neglected. This approximation leads to the following well-known expression for the complex pressure, see Ref. [1].

$$p(r, z) \simeq \frac{i}{\rho(z_s)\sqrt{8\pi}} e^{-i\frac{\pi}{4}} \sum_{m=1}^M \Psi_m(0, z_s) \Psi(r, z) \frac{e^{i \int_0^r k_m(r') dr'}}{\sqrt{\int_0^r k_m(r') dr'}} \quad (4)$$

where M denotes the lowest number of modes existing in any segment between source and receiver. The eigenvalues and eigenfunctions are normally evaluated at a discrete set of ranges, while the values at intermediate ranges are calculated by linear interpolation.

As seen in Eq. 4, the integral of the wavenumbers is used in the adiabatic formulation of the range-dependent environment. This integration is always performed analytically assuming that k_m varies linearly between two adjacent segments. The environment is approximated by a series of range-independent segments with a sloping bottom described by a staircase approximation. In Fig. 4 is shown an example with four range segments S_{i-1} , S_i , S_{i+1} and S_{i+2} with two arrays of receivers A1 and A2 and the source placed at a depth of 30 m.

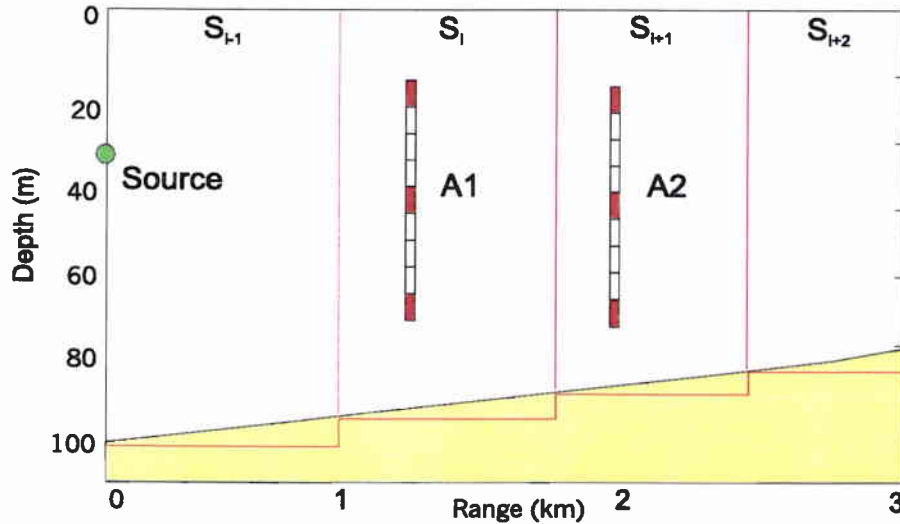


Figure 4 The range-dependent environment is composed of several range-independent segments. The symbols S_{i-1} , S_i , S_{i+1} , S_{i+2} are the range-independent segments used for representing the sloping (or simply changing) environment with a staircase approximation.

The eigenvalues and mode functions for the segment S_{i-1} and the first frequency sub-band are determined as for the range-independent case. The same procedure is applied for the adjacent segment S_i . The information of the eigenvalues and mode functions for these two segments are stored in arrays to perform wavenumber integration or interpolation of the mode functions in range.

The acoustic pressure is calculated if any receivers are present within the first segment, and all variables related to the first segment are reset and used for storage in the third segment. This procedure continues until the last segment in the environment is reached. Hereafter the frequency sub-band is changed, and the calculations start at the first segment and proceed out to the last segment. The procedure continues until all the frequency sub-bands have been analyzed. Figure 4 illustrates a case for an up-slope bottom, but the method also applies to down-slope and any other combination of slopes, range-dependent sounds speed profiles, bottom properties, etc.

The mode sets and the pressure fields over depth within the segment are obtained by linear interpolation of the mode amplitudes evaluated at the beginning of two adjacent sectors: The so-called *virtual* receivers. This strategy keeps the program size to a reasonable level and eliminates the need of I/O operations. Due to changes in the bathymetry, the receivers contained in each sector have to be associated to the right depth of the corresponding *virtual* receivers located at the vertical boundaries of the segment.

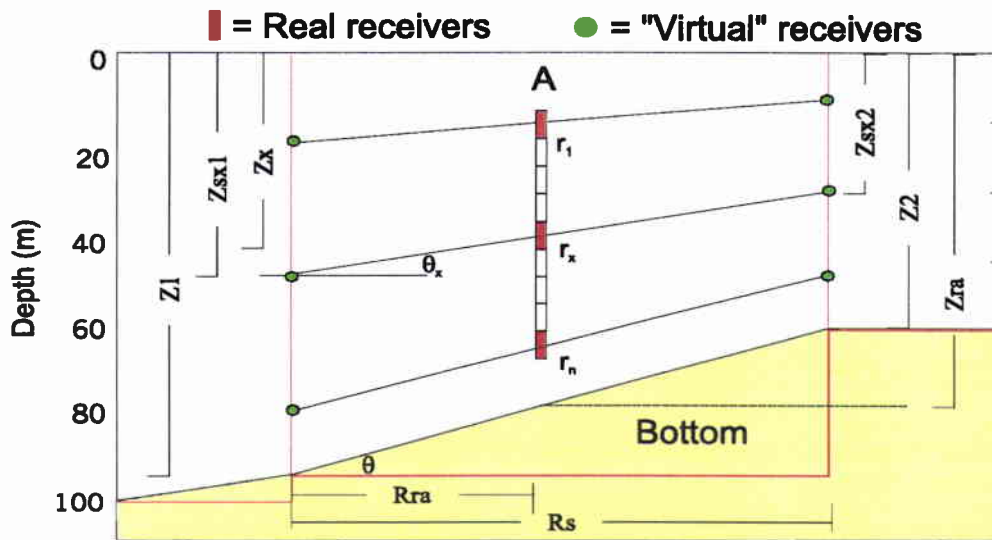


Figure 5 The evaluation of virtual receivers in a range-dependent environment.

As depicted in Fig. 5, such *virtual* receivers are found by applying the following expressions:

$$\begin{aligned}
 H &= Z_1 - Z_2 \\
 \Theta &= \tan^{-1} \left(\frac{H}{R_s} \right) \Leftrightarrow \tan \Theta = \left(\frac{H}{R_s} \right) \\
 Z_{ra} &= Z_1 - \tan \Theta R_{ra} \\
 \tan \Theta_x &= \frac{Z_x}{Z_{ra}} \tan \Theta \\
 Z_{sx1} &= Z_x + \tan \Theta_x R_{ra} \\
 Z_{sx2} &= Z_x + \tan \Theta_x (R_s - R_{ra})
 \end{aligned} \tag{5}$$

where Z_1 and Z_2 are the depth at the beginning of sectors 1 and 2, respectively and H is their difference, Z_{sx1} and Z_{sx2} are the depth of the *virtual* receivers at the beginning of the two adjacent sectors 1 and 2 respectively, Z_x is the depth of the real receiver r_x , Z_{ra} is the depth evaluated in the segment at the distance R_{ra} , and Θ_x and Θ are the angles between the *virtual* and real receivers and of the sloping bottom with respect to horizontal, respectively. Note that the angle Θ_x changes continuously in depth from zero at the sea surface to Θ at the water-bottom interface. In the case of a constant water column, the *virtual* and the real receivers share the same depth, so the preceding expressions are not applied.

Since the evaluation of wavenumbers and mode amplitudes is the most time consuming part of the program, the *virtual* receivers are evaluated for the current as well as for the adjacent segment at the same time in order to improve the overall performance of the model. This procedure is shown schematically in Fig. 6.

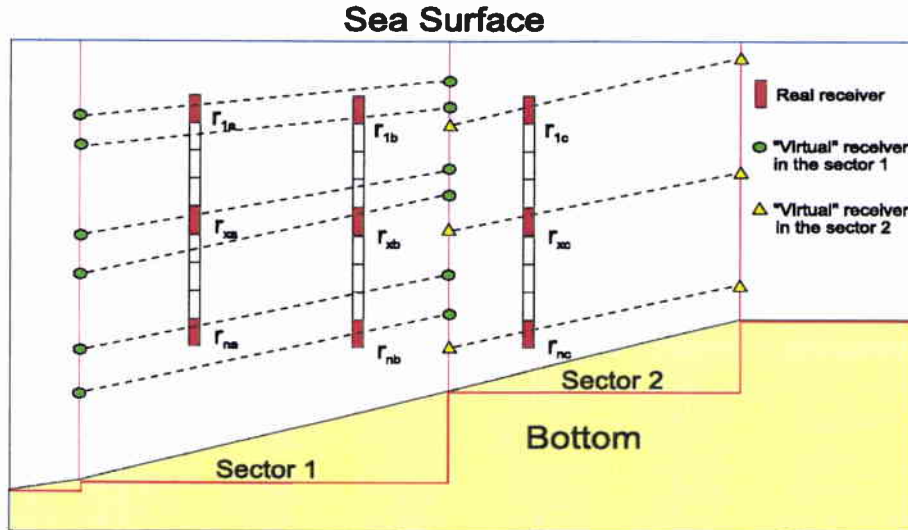


Figure 6 The *virtual* receivers of the two adjacent sectors are found and stored.

The program checks if any real receivers are placed in the two adjacent sectors S_1 and S_2 . If any real receivers exist in the two sectors, the model evaluates the corresponding depth of the *virtual* receivers by applying Eq. 5. The resulting mode amplitudes are stacked in an array to be used later for the interpolation.

2.4 Directional source

Sometimes it is important to address specifically the bottom interaction problem: In this case PROSIM includes a directional beam with a Gaussian shape, which is assumed constant for all the frequencies:

$$\Psi_G(z) = \sqrt{k_0 \tan(\theta_1)} e^{-\frac{k_0^2}{2}(z-z_s)^2 \tan^2(\theta_1)} e^{ik_0(z-z_s)\sin(\theta_2)} \quad (6)$$

where θ_1 and θ_2 are the half beam width aperture and tilt angle respectively, z_s is the source depth, k_0 is the wavenumber ($k_0 = \omega/c_0$, $\omega = 2\pi f$ is the angular frequency with $f = (f_{max} - f_{min})/2$, f_{max} and f_{min} are the limits of the frequency band, and c_0 is the sound speed at the source depth). The Gaussian shape is expressed as a sum of normal modes $\Psi_m(z)$ each multiplied by the appropriate shading coefficients α_m :

$$\Psi_G(z) = \sum_{m=1}^M \alpha_m \Psi_m(z) \quad (7)$$

where M is the maximum number of modes for the assigned frequency.

The $\{\alpha_m\}$ are determined by applying the operator:

$$\int_0^D (\cdot) \frac{\Psi_m(z)}{\rho(z)} dz \quad (8)$$

where D is the water depth and $\rho(z)$ is the density. Then we have:

$$\int_0^D \Psi_G(z) \frac{\Psi_m(z)}{\rho(z)} dz = \int_0^D \left\{ \sum_{m=1}^M \alpha_m \Psi_m(z) \right\} \frac{\Psi_m(z)}{\rho(z)} dz = \alpha_m \int_0^D \frac{\Psi_m^2(z)}{\rho(z)} dz \quad (9)$$

Since modes are orthonormal we have:

$$\int_0^D \frac{\Psi_m^2(z)}{\rho(z)} dz = 1 \quad (10)$$

Then the coefficients are given by the following equation:

$$\alpha_m = \int_0^D \Psi_G(z) \frac{\Psi_m(z)}{\rho(z)} dz \quad (11)$$

The shading coefficients are evaluated in the subroutine `rx_mode_gauss.f`. The shape obtained summing up the normal modes, each multiplied by the appropriate shading coefficients, is compared with the original given shape Ψ_G . If the error obtained does not fulfill the threshold implemented, a message is provided to the user that the modes found are not sufficient for the approximation. The error criteria implemented, is the Mean Squared Error (MSE) which is:

$$MSE = \frac{\sum_{i=1}^N (\Psi_G(z_i) - \sum_{m=1}^M \alpha_m \Psi_m(z_i))^2}{N} \quad (12)$$

where z_i is the i^{th} depth in the water column, N is the number receivers in depth used for sampling the water depth, and M is the number of normal modes obtained for the assigned frequency. The actual threshold for the MSE is 0.5 which has been observed as a good choice for several shallow water environments.

2.5 Attenuation

Volume attenuation (absorption) in the water column, sediment layer and subbottom is treated by a perturbation theory introducing a small imaginary component to the total wavenumber. Then we have:

$$K = \frac{\omega}{c} \left(1 + \frac{i\alpha c}{40.000 \pi \log(e)} \right) \quad (13)$$

The attenuation coefficient α is a constant expressed in units of dB/(m-kHz). However, the model is able to evaluate the attenuation for the water column as a function of frequency and the expression implemented is [1]:

$$\alpha(f) = 3.3 \cdot 10^{-3} + \frac{0.11 f^2}{1 + f^2} + \frac{44 f^2}{4100 + f^2} + 3.0 \cdot 10^{-4} f^2 \quad (14)$$

where f is the frequency in kHz.

3

Installation of PROSIM

PROSIM is written in Fortran 77 and runs under several Unix operating systems. It has been developed with a minimum number of deviations from ANSI F77 in order to guarantee portability. Compilation and linking of the model on different platforms is obtained through the flag -f in the make command line. For example, to compile on a HP station the user should type: make -f Makefile.unix, uncommenting in the Makefile.unix file the lines that have to be used by the HP fortran compiler.

PROSIM uses a number of include files to control the array sizes and pass variables through the various program units. The main parameters determining the program size are defined in the `Parms.com`. The maximum value of each parameter, i.e. the storage requirements, depends on the computer used to run the code. If the program is not compiled successfully, or once compiled is not able to run, then the storage requirements are too big and the user must decrease the size of some of the parameters. Conversely, if the user receives a "storage exceeded" message, the dimension of the array which caused that message must be increased. With the Compaq XP1000 workstation the maximum number of modes allowed and the maximum number of receivers are 1100 and 100, respectively. The bandwidth is 10 Hz-10 kHz, with 12000 frequency components. The maximum number of range segments is 200. The following list explain the parameters used in the program and defined in the `Parms.com` file.

NLMAX - This parameter is used for dimensioning the geo-acoustic arrays (total number of layers in SVP, bottom, and top + 2)

NSRMAX - Determines the total number of receivers (number of receivers in the array by the number of arrays in range)

NVRMAX - Is used for determining the total number of virtual receivers. This parameter is strongly related to the total number of real receivers placed in two adjacent segments: The number of virtual receivers ≥ 2 times the number of real receivers in the actual segment + the number of real receivers in the adjacent segment. Then the user must evaluate before the compilation for which segments this number assumes the maximum and set this parameter accordingly.

NM_MAX - Maximum number of modes.

NFMAX - Maximum number of frequencies in CW computation.

NFCMAX - The maximum number of frequency components allowed in each frequency sub-band for broadband calculation.

NFBBMAX - The number of frequencies used to compute the transfer function $nfft = (f_{max} - f_{min}) / f_s$, for broadband calculations.

RGMAX - Maximum number of segments used in range-dependent environments.

Some parameters have been hardwired internally and the user must edit the appropriate subroutines if changes to these parameters are needed.

c_{phmin} - Is the minimum phase speed used when searching for modes. The default value is 0 (defined in `opt_read.f`).

c_{phmax} - Is the maximum phase speed desired when searching modes (defined in `opt_read.f`).

$c_{phmax} > 0$: Find modes with phase speed up to c_{phmax} (in m/s).

$c_{phmax} < 0$: Find modes which correspond to plane wave grazing angles up to $|c_{phmax}|$ (in deg.).

$c_{phmax} = 0$: Find enough modes such that the field is valid at r_{min} .

The default value is -89.9.

r_{min} - Minimum range of interest (in km), which is used to determine when to stop finding modes. The default value is $r_{min} = 0$ in order to have the program computing this parameter automatically from the source-receiver geometry (defined in `svp_read.f`).

r_{max} - Maximum range of interest, which is used to determine how close each eigenvalue needs to be found. The default value is $r_{max} = 0$ in order to have the program computing this parameter automatically from the source-receiver geometry (defined in `opt_read.f`).

db_{cut} - Determines the cutoff level for weak modes. For a given range, any modes weaker than the strongest mode by db_{cut} is not included in the mode summation. The default value is 50 dB, which is quite conservative. Values between 30 and 60 are recommended (defined in `opt_read.f`).

$attfq$ - Is a logical variable set to TRUE: The attenuation in water is considered as a function of frequency (defined in `svp_read.f`).

$bintrf$ - The transfer function output file is written in a binary (`bintrf` set to TRUE) or in a ASCII format (`bintrf` set to FALSE). The default value is FALSE (defined in `bb_fft_out.f`).

4

Running PROSIM

Running PROSIM requires the user to edit one input file which contains both the geo-acoustic description of the environment and the source-receiver geometry. The program reads the data with unformatted read statements allowing numbers to be separated by commas, spaces or carriage returns. The description of the environment and the required computational outputs must be supplied through an input file named "*filename*".*dat*, where "*filename*" is a user specified name of the input file. The program is launched by running a shell script as *runprosim "filename"* on the command line. The output files are named "*filename.ext*", where the extension of the output files "*ext*" depends on the computational options. The results of a run are displayed by a UNIRAS based graphic software.

4.1 Input structure

We have adopted the input structure similar to that used for C-SNAP. However, a few differences are unavoidable because some parameters are not used (such as the internal number of range subdivisions required to approximate a sloping bottom or a range varying sound velocity profile, and the range coordinate of every new input profile).

4.2 Environmental inputs

A description of the environmental inputs is shown in the following list. All the inputs are read through a list-directed Fortran statement, with every row in the list indicating an input record. Parameters belonging to the same record must be separated by either commas or blanks and may be supplied by using more than one line. Each of the various input profiles required to describe a range-dependent environment must always initiate with the input record (see Table A1 in Annex A)

H0, S0, S1, RB, N2

and terminate with the input record

B2S, C2S

The last input profile is considered to extend in range, with constant properties, as far out as necessary to complete the evaluation of complex pressure (if any receivers are placed in such a segment). Obviously if only one range segment is given in the input, PROSIM will treat the case as a range-independent environment. The following list is a description of the environmental inputs and source-receivers geometrical configuration. It is worth to mention that some dummy values have been inserted in order to maintain the compatibility with the C-SNAP input format. The environmental input parameters for the propagation model is summarized in Table A1.

TITLE - The title of run that will appear as heading on all printed and plotted outputs.

NF - Number of source frequencies used for the CW calculations. If NF is equal to 0, the source frequencies are not used: The broadband calculation is performed and a dummy frequency must be inserted. For $NF \geq 1$, this parameters gives the number of frequencies used for CW calculations.

F(1), ..., F(NF) - Source frequencies in Hz. Frequency values can be given in any order, but the program starts with the highest.

MIN, DM, DM - Minimum order mode in the source field; DM are dummy values.

DM, DM - Dummy values, normally set to 0.

H0, S0, S1, RB, N1 - **H0** represents the thickness of water column in meters; **S0, S1, N1** are the dummy values; **RB** is the range in km to the end of the current input profile. As an example, if in the first range segment this value is 5 and in the second range segment is 10, then the first range starts at 0 km and after 5 km it ends and the environment is **updated**, while the second range start at 5 km (10 - 5 km) and after 5 km it is maintained constant.

Z0(i), C0(i) - Sound speed profile in the water column. The first value given must be at the sea surface ($Z0(1)=0$) and the last value at the seafloor ($Z0(M)=H0$).

H1, R1, B1 - **H1** is the thickness of sediment layer in meters. This layer can be omitted by setting H1 equal to zero. In this case the profile must be omitted, while R1 and B1 are dummy. **R1** is the density of the sediment in g/cm^3 . **B1** is the compressional wave attenuation in the sediment assumed to be in units of dB/ λ if it is a negative number or assumed in units of dB/(m-kHz) otherwise.

Z1(i), C1(i) - Sound speed profile in the sediment layer. The first value given must be at the water/sediment interface ($Z1(1)=0$) and the last value at the sediment/subbottom interface ($Z1(N)=H1$).

R2, B2, C2 - **R2** is the density of subbottom in g/cm^3 . **B2** is the compressional wave attenuation in the subbottom assumed in dB/ λ if it is a negative number, or considered in units of dB/(m-kHz) if positive; **C2** is the compressional speed in the subbottom in m/s.

SACLANTCEN SM-358

B2S, C2S - Dummy values, usually set to 0.

PULSE - Code word example used to separate the description of the environment from the description of the geometry of the source and receiver arrays. A complete list of code words for PROSIM is given in Table A2.

GA, GT - These parameters are used to evaluate the Gaussian beam. **GA** is the half-beam width and **GT** is the tilt (positive downward) in degrees.

FFT, MINF, MAXF, SW - **FFT** determines the size of fast Fourier Transform, **MINF, MAXF** give the frequency band limits for broadband computation, **SW** determines the sampling frequency if **SW** < 0 or the time window if **SW** > 0.

P1, PNA, NA - **P1** is the initial array position in km; **PNA** is the final array position in km; **NA** represents the number of arrays (equally spaced) in range.

D1, DNR, NR - **D1** is the initial receiver depth in meters from the sea surface; **DNR** is the final receiver depth in meters; **NR** represents the number of receivers (equally spaced) in the array.

SD - Source depth in m.

"AXIS" - X-, Y-, and Z-axis information depending on the computational option.

The following text is an example of an input file named *example.dat*.

```

PROSIM EXAMPLE      !Title
1                   !number of freq. NF: 0=broadband >0 multi cw
106. 110.           !List of frequencies (F(1)-F(NF)) for multi cw
1 500 500           !minimum modes number MIN, dummy, dummy
0 0                 !dummy,dummy
100 0 0 5. 0        !w. depth H0,dummy,dummy,sector length RB, dummy
0.0000 1530.00      !Z0,C0
10.0000 1531.00     !Z0,C0
20.0000 1533.00     !Z0,C0
30.0000 1512.00     !Z0,C0
40.0000 1500.00     !Z0,C0
100.0000 1500.00    !Z0,C0
2.00 1.80 -0.50     !sediment thickness H1,density R1,attenuation B1
0.0000 1520.00      !Z1,C1
2.0000 1550.00      !Z1,C1
2.0 -0.50 1600.00   !sub-bottom density R2, att. B2, sound speed C2
0 0                 !dummy,dummy
90 0 0 10. 0        !w. depth H0,dummy,dummy,sector length RB, dummy
0.0000 1530.00      !Z0,C0
10.0000 1531.00     !Z0,C0
20.0000 1533.00     !Z0,C0
30.0000 1512.00     !Z0,C0
40.0000 1500.00     !Z0,C0

```

```

90.0000 1500.00      !Z0,C0
2.00   1.80   -0.50 !sediment thickness H1,density R1, attenuation B1
0.0000 1520.00      !Z1,C1
2.0000 1550.00      !Z1,C1
2.0    -0.50 1600.00 !sub-bottom density R2, att. B2, sound speed C2
0      0              !dummy,dummy
PULSE                !Computation option
0., 0.0              !Gaussian half-beam angle GA,tilt (+downward) GT
4098, 450, 480, -4098. !fft size,min freq, max freq, samp. freq/Time W.
0.5 10 10            !min range, max range, No. of ranges
5 70 2               !min rec. depth, max rec. depth, No. of receiver
50                   !Source depth

```

4.3 Computational outputs

The basic building blocks required to identify the computational outputs consist of a sequence of code words and numerical values specified in the input file. The code words are used to define the required output options, calculation type and the preferred output type. Code words are also used to define plot axes; in this case four or five numerical values need to be specified on the same line in the input file. As a general rule, all the code words must be given in upper case letters, and the lowercase character strings appearing on the same line as some of the code words should be replaced by numerical values. The source characteristics ([GA,GT]), frequency information ([FFT,MINF,MAXF,SW]), receiver geometry ([P1,PNA,NA] and [D1,DNR,NR]) and source depth ([SD]) must follow immediately after the code word. Hereafter the axes information must be defined depending on the computational output.

4.3.1 Output options, calculation, and output type code words

The output options, calculation, and output type code words must be given on the same input line, with the output option first and followed by a choice of calculation and output code words in any order. Each code word must be separated by either a single blank character or a comma. As illustrated in Table A2, they consist of either five- or three-character uppercase strings. Though in principle their association is intended to be as free as possible, in practice there are some limitations. For instance, the code words COH and INC are meaningless in conjunction with option PROF and MODES and, the default output type for the CONDR and PROF output options is set to PLT. Table A3 shows the allowed combinations of the above code words.

The output option PULSE is not associated with any calculation and output type code words. The result file from the PULSE option is composed by a header and the transfer function as complex pressure. The header contains the geometrical information of the run (title of the run, name of the model, center frequency, source

SACLANTCEN SM-358

depth, the geometrical properties of the arrays, the FFT size, the frequency band and the time sampling); the transfer function part contains the complex pressure starting from the first receiver in range and depth for the lowest frequency component in the frequency band. This means that the transfer function part has as many lines as the number of receivers by the number of ranges by the number of frequency components. The following text is an example of the output file named *example.trf*.

```

PULSETRF      !This corresponds to the prosim_in input file
PROSIM        !This is the name of the forward model
              1      !This is a dummy value
              1      !This is a dummy value
PROSIM EXAMPLE !The title of the run (as in the 1st line of the input)
+             !This is a dummy value
  465.2271     !Center frequency
  50.00000     !Source depth
  5.00000     70.00000     2   !min depth, max depth, No of receivers
  0.5000000   1.611111     10  !min rng, rng increment, No of rng
  4096 451 481 2.4402147E-04 !FFT size, 1st and last freq., time sampl.
              0             !This is a dummy value
  0.0000000E+00 !This is a dummy value
              1             !This is a dummy value
              1             !This is a dummy value
              1             !This is a dummy value
              0             !This is a dummy value
              0             !This is a dummy value
  0.0000000E+00 !This is a dummy value
  0.0000000E+00 !This is a dummy value
  0.0000000E+00 !This is a dummy value
  0.0000000E+00 !This is a dummy value
  0.0000000E+00 !This is a dummy value
  2.5066293E-03 -2.0956792E-04 !The transfer function starts HERE
  4.5080206E-04 -8.9323043E-04 !The complex pressure is written looping
-4.4582186E-05 -1.9822469E-04 !on the number of receivers, then on the
  5.1937343E-05 1.5288928E-04 !number of ranges and finally on the number
  1.6913076E-04 -1.8372151E-04 !of frequencies.

```

The program starts in writing the data from the first receiver in the first array for the lowest frequency component in the band to the last receiver in the last array for the highest frequency component as described in the following pseudo-language procedure:

```

for n_freq=1:FFT
  for n_array=1:NA
    for n_rec=1:NR
      write the transfer function component
    end
  end
end
end

```

The output structure of the transfer function is compatible with the SACLANTCEN and MIT pulse plotting package for pulse processing and display of received time series. The format of the transfer function file can be changed between ASCII and BINARY by changing the hardwired logical variable `bintrf` to false (ASCII) or true (BINARY) in the subroutine `bb_fft_out.f`. The transfer function file can be obtained for single-frequency or broadband computations leaving maximum flexibility of post-processing to the user.

4.3.2 *Plot axis code words*

The plot axis code words consist of five uppercase character strings followed on the same line by four or five numerical values as shown in Table A4. Three-dimensional plots are produced for options CONDR, CONFR and CONFD with contour lines or colours. In this case the third axis (ZAXIS) is used to indicate the contour levels and the number of smoothings required. Also a two-dimensional smoothing of the transmission loss surface is available and is performed by the contour package. The specification of the plot axis is optional. If omitted, the default values shown in Table A4 are used instead.

A summary of all possible computational outputs is given in Table A5a–h (Annex A).

4.3.3 *Numerical considerations*

Applying the PROSIM model to range-dependent environments requires a convergence test of the solution. This is simply performed by increasing the number of range-independent segments to describe the range-dependent environment until the solution is stable. In cases where the continuous spectrum is important, it is necessary to include a false bottom with a high compressional sound speed. This high-speed false bottom increases the number of modes propagating above the critical angle in the original problem and, therefore, discretizes the continuous spectrum. However, the false bottom has to be defined sufficiently deep to prevent reflections back into the water column from the interface at the false bottom.

5

Numerical Verification and Examples

An important difference between C-SNAP, the SACLANTCEN coupled normal mode model, and the PROSIM model is the way the depth-dependent wave equation is solved. C-SNAP uses the finite difference method, subdividing the environments into layers: The sound speed profile is entered as a discrete set of points, and a linear interpolation is performed between the profile depths in order to determine the sound speed in all the incremental layers. PROSIM assumes that the inverse of the sound speed squared varies linearly with depth in each layer, and the acoustic field is evaluated analytically as a sum of two independent Airy functions in the layers.

In order to validate the model we have defined three different environments (see Fig. 7) for a total of five test cases: Tests A and B have been done to compare PROSIM and ORCA for computational speed, since we have introduced some improvements in the kernel of the model; tests A, B and C have been done to compare PROSIM and C-SNAP for computational speed and accuracy. The maximum water depth considered is 100 m in all test cases.

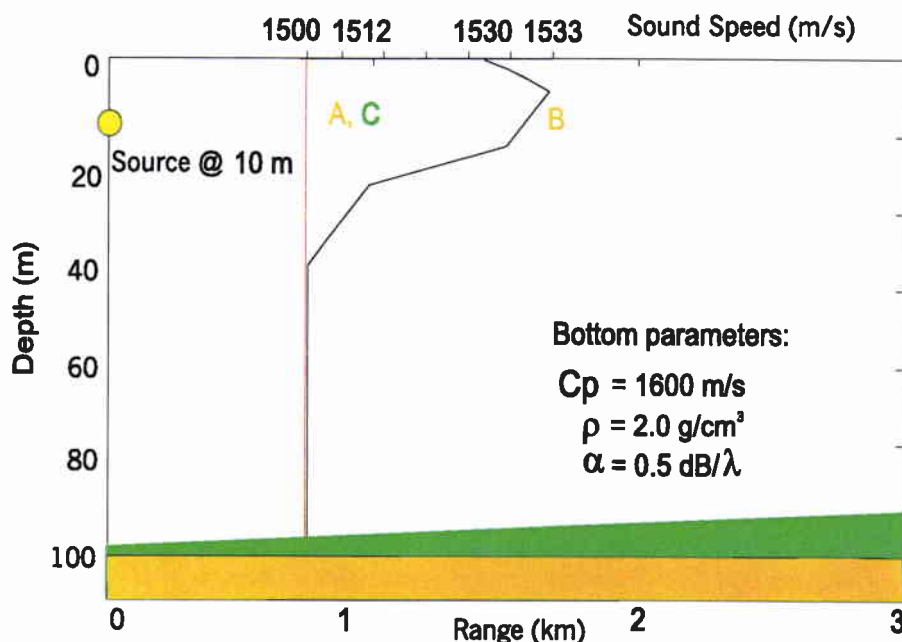


Figure 7 The environmental parameters used for testing PROSIM.

Table 1 *The sound speed profile used in test B.*

Depth <i>m</i>	<i>c</i> <i>m/s</i>
0	1530
10	1531
20	1533
30	1512
40	1500
100	1500

Table 2 *Elapsed time of PROSIM vs. ORCA on a Compaq XP1000 workstation in the frequency band 12–10000 Hz. The tests are done with the following sound speeds: (A) iso-speed, (B) sound speed profile as indicated in Table 1.*

Δf	(A)		(B)	
	PROSIM	ORCA	PROSIM	ORCA
15 Hz	10.1 s	11.8 s	50.9 s	50.9 s
25 Hz	-	8.4 s	-	41.9 s
50 Hz	-	7.1 s	-	37.0 s
75 Hz	-	6.4 s	-	38.6 s
100 Hz	-	6.1 s	-	31.9 s
125 Hz	-	6.1 s	-	28.5 s
150 Hz	-	5.6 s	-	32.8 s
175 Hz	-	6.3 s	-	36.4 s
log scale	5.5 s	-	28.2 s	-

As depicted in Fig. 7, test A includes an iso-velocity waveguide with a sound speed of 1500 m/s and a density of 1.0 g/cm³, test B includes a waveguide divided into 6 layers caused by a typical depth-dependent sound speed for shallow water as indicated in Table 1. In both cases there is a homogeneous bottom with sound speed, density and attenuation of 1600 m/s, 2.0 g/cm³ and 0.5 dB/λ, respectively. Test C includes an iso-velocity waveguide with a sound speed of 1500 m/s and a density of 1.0 g/cm³, the bottom is a homogeneous 1° up-slope again with sound speed, density and attenuation of 1600 m/s, 2.0 g/cm³ and 0.5 dB/λ, respectively. The source is placed at a depth of 10 m and is transmitting sound at frequencies between 12 Hz and 10 kHz. The maximum number of modes found is 464 in the iso-velocity case and 439 with the depth dependent sound speed; the number of frequency components is 1364 in both cases. A complete profiling of the model has been performed and the analysis showed that 25% of the total execution time was spent by the sub-routines calculating the Airy functions, 16% was spent in the sub-routine calculating the propagator matrix for the layers, and 15% of the total time was used for multiplication of the propagator matrices for all the layers. Evaluating the mode amplitudes is approximately half the time of the total elapsed time, while the remaining 44% is used to perform the interpolation. Thus the improvement in the interpolation method can reduce considerably the time spent for the simulations.

As we can see from Table 2 for fixed Δf the two models have approximately the same performances, while the introduction of the logarithmic reduction of the subbands has increased the computation speed. Thus the model has been able to find the best Δf for any assigned environment and this reduces the total time devoted to the evaluation of mode amplitudes accurately.

For the last three performance tests, the benchmark problems defined comprise both

a range-independent as well as a simple acoustic range-dependent environment. At present it has been chosen only to consider the bathymetry as range-dependent, but as stated before PROSIM can handle any range-dependent environment, e.g. sound speed profile, density, attenuation, sediment thickness etc., within the limitations of the adiabatic approximation. C-SNAP is used to generate the reference solution in terms of the received time series. However, the C-SNAP model allows coupling of energy between modes, and hence a notable difference between the solutions is expected for strongly range-dependent environments.

In test C we have a sloping bottom with an angle of 1° up-slope; an iso-velocity water column with a sound speed of 1500 m/s and a density of 1.0 g/cm^3 ; a homogeneous bottom with sound speed, density and attenuation of 1600 m/s, 2.0 g/cm^3 and $0.5 \text{ dB}/\lambda$, respectively. The received energy level (coherent transmission loss) as a function of range for the range-dependent test C obtained by C-SNAP and PROSIM with option TLRAN (Table A5g) is shown in Fig. 8. The transmission loss is given for a receiver depth of 25 m and a frequency of 600 Hz.

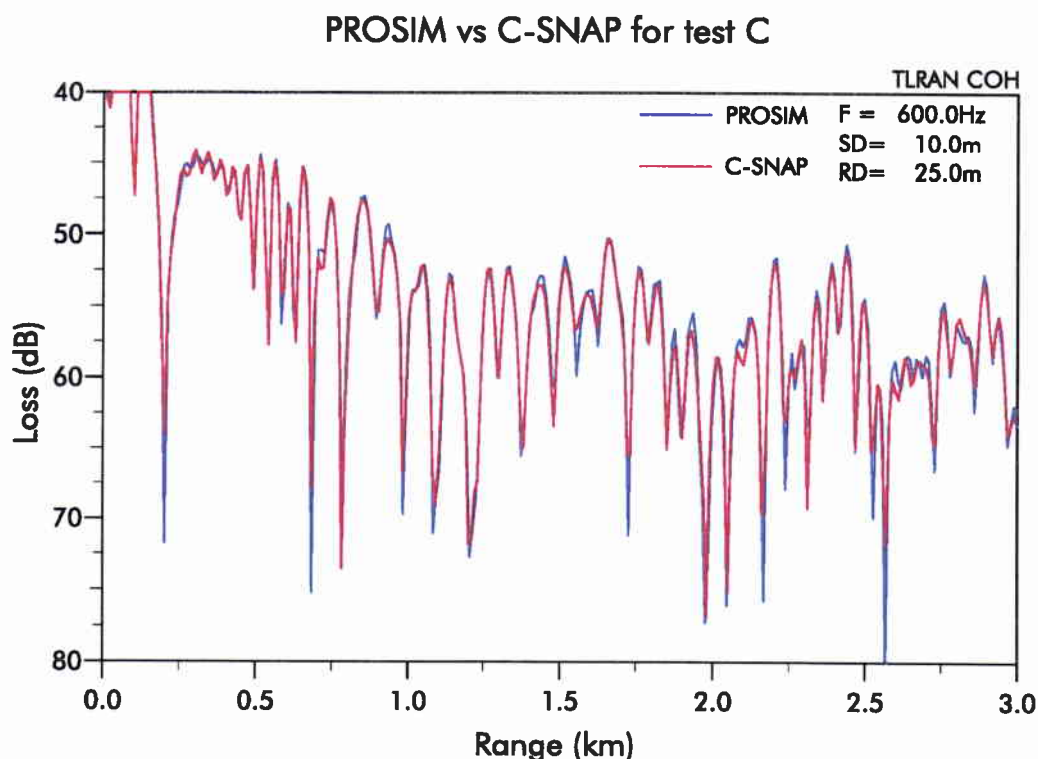


Figure 8 Transmission loss as a function of range at a receiver depth of 25 m and a frequency of 600 Hz calculated by PROSIM and C-SNAP for test C.

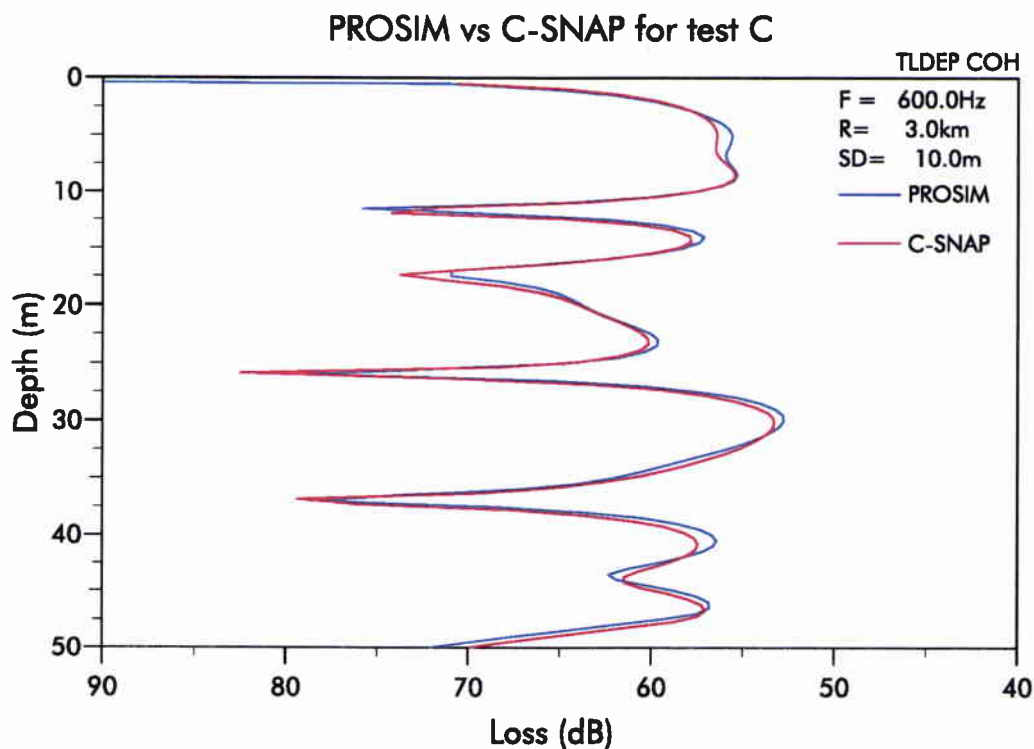


Figure 9 Transmission loss as a function of depth at a range of 3 km and a frequency of 600 Hz calculated by PROSIM and C-SNAP for test C.

The transmission loss as a function of depth (option **TLDEP** in Table A5f) at a range of 3.0 km and a frequency of 600 Hz is plotted in Fig. 9. A good agreement is seen between the two models, which verifies that the adiabatic approximation is sufficient to model received energy levels for this particular range-dependent environment and frequency.

In all cases of modelling received time series the frequency bands considered were 100-500 Hz, 100-1000 Hz and 100-3000 Hz. The source is placed at a depth of 10 m; the maximum water depth is again 100 m, and the acoustic field is propagated out to a maximum range of 3 km. The source pulse used is a Hanning weighted sine wave with a duration corresponding to the desired bandwidth. The ratio between the execution times obtained by using C-SNAP and PROSIM for all the frequencies together with the maximum number of excited modes is given in Table 3. For the maximum bandwidth, the PROSIM model is about 66 times faster than C-SNAP for test A, about 52 times faster for test B and about 36 times faster for test C. This ratio increases with frequency, because the execution time increases linearly with frequency for the PROSIM model whereas it follows a squared law for C-SNAP.

Table 3 *Ratios of C-SNAP vs. PROSIM execution times. Test A refers to the iso-speed range-independent environment, test B to a range-independent environment with a depth-dependent sound speed as indicated in Table 1, while test C refers to a 1° up-slope iso-speed environment.*

Frequency (Hz)	A	B	C
100-500	6 (23 modes)	4 (28 modes)	5 (23 modes)
100-1000	9 (46 modes)	13 (52 modes)	11 (46 modes)
100-3000	66 (139 modes)	52 (55 modes)	36 (139 modes)

Therefore, at low frequencies and many layers the performance of the two models is almost identical, but the new simulator becomes more and more efficient as the frequency increases.

Range-stacks of the received signals out to a range of 3 km obtained by PROSIM and C-SNAP for the range-independent environment (test A) in the frequency band of 100-500 Hz are shown in Fig. 10. It is seen that the result obtained by using the two numerical models is almost identical.

In Fig. 11 the received time signals are shown at a range of 3 km obtained by PROSIM and C-SNAP for the range-dependent environment (test C) and in the frequency band of 100-1000 Hz. It is seen in Fig. 11 that the results from the two numerical models only have minor discrepancies in amplitude and in arrival time. In this case the maximum number of modes is 46, and the number of frequency components is 1367. Dividing the environment into 128 range-independent segments the computation time is 182 seconds for the C-SNAP model and 15 seconds for the PROSIM model on a Compaq XP1000 workstation. Increasing the bandwidth for test C to 100-3000 Hz, the maximum number of modes becomes 139. The environment is again divided into 128 range-independent segments and the computation time is now 4353 seconds for the C-SNAP model and 121 seconds for the PROSIM model: The PROSIM model is thus about 36 times faster than C-SNAP.

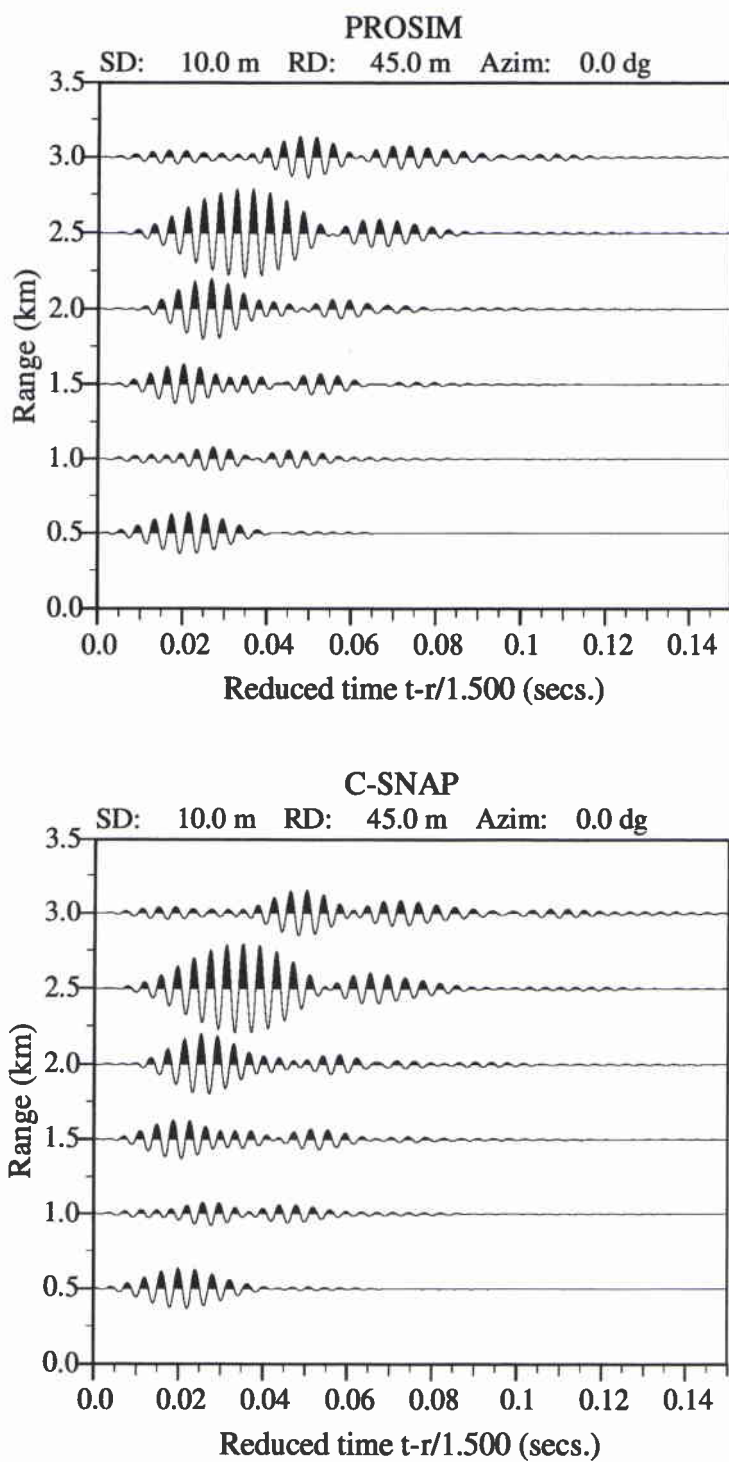


Figure 10 Comparison of the output from PROSIM (upper panel) and C-SNAP (lower panel) for test A.

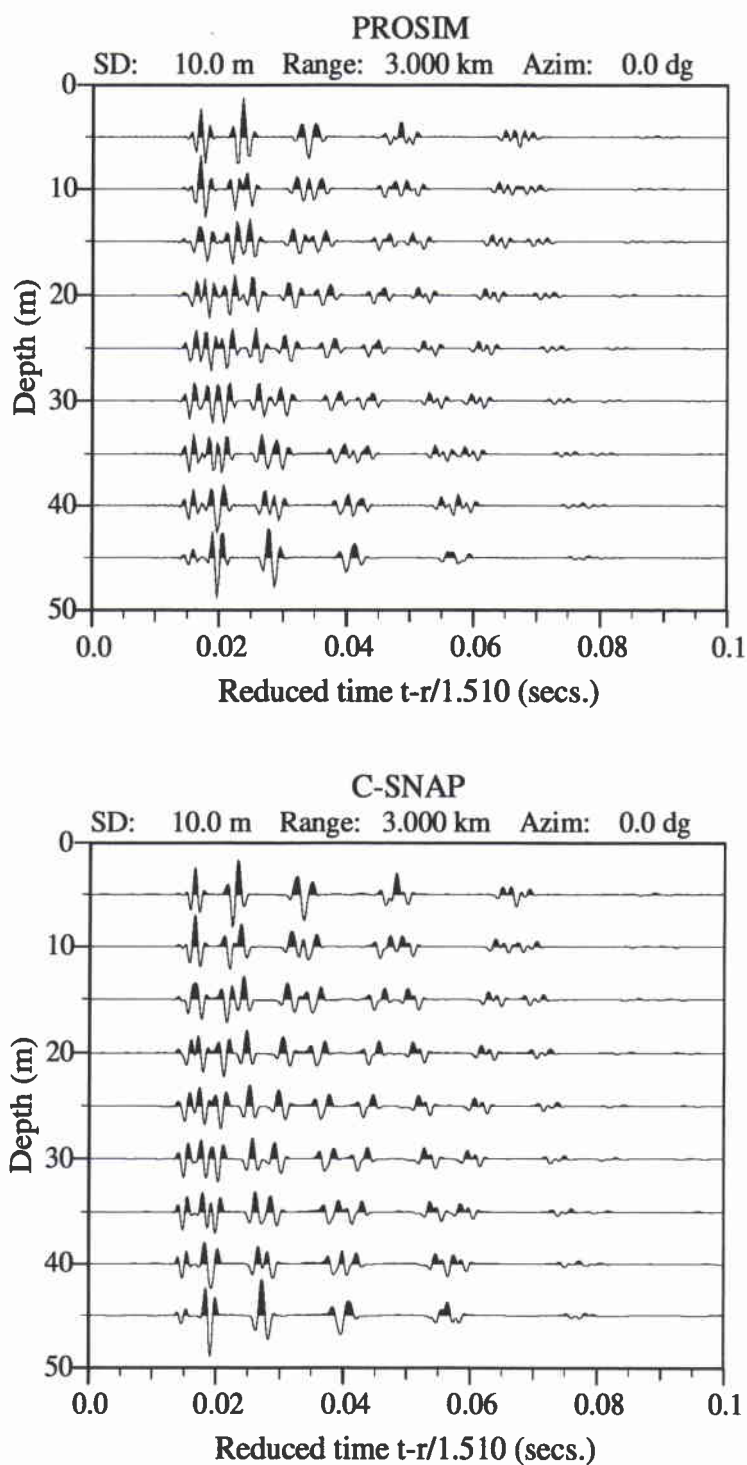
SACLANTCEN SM-358

Figure 11 Comparison of the output from PROSIM (upper panel) and C-SNAP (lower panel) for test C.

6

Conclusions

The PROSIM range-dependent, broadband propagation model has been developed based on the adiabatic approximation. An existing propagation model ORCA has been used as the engine of the PROSIM propagation model. Only real wavenumbers are included, so the PROSIM model does not include shear properties in the bottom. A gain of about 33% is obtained in computation speed by introducing a logarithmic variation of the size of the frequency sub-bands in the frequency interpolation scheme. The simulator is able to handle frequencies up to 10 kHz with maximum 1100 modes, 12000 frequency components in the frequency band of interest, maximum 100 receivers in range and maximum 200 range segments.

The accuracy and efficiency of PROSIM has been checked against C-SNAP for shallow water test cases. As an example we considered the bottom as range dependent consisting of a 1° up-slope and is discretized by using 128 stair steps. It was found that PROSIM is faster than C-SNAP by a factor from 30-100 depending on the environmental properties, and that the differences between adiabatic and coupled mode solutions are small for the considered test environments. It is concluded that PROSIM is an efficient and accurate broadband propagation model for a class of moderately range-dependent shallow water propagation scenarios.

SACLANTCEN SM-358

Acknowledgment

This work was partially funded by the EU under the MAST-III, project PROSIM, contract no. MAS3-CT95-0008.

References

- [1] F. B. Jensen, W. A. Kuperman, M. B. Porter and H. Schmidt, *Computational Ocean Acoustics*, AIP Series in Modern Acoustics and Signal Processing, American Institute of Physics, New York, 1994.
- [2] S. J. Levinson, E. K. Westwood, R. A. Koch, S. K. Mitchell and C. V. Sheppard, *An efficient and robust method for underwater acoustic normal-mode computations*, Journal of Acoustic Society of America, 97 (3), March 1995, pp. 1576-1585.
- [3] E. K. Westwood, C. T. Tindle, and N., R. Chapman, *A normal mode model for acoustoelastic ocean environments*, Journal of Acoustic Society of America, 100 (6), December 1996, pp. 3631-3645.
- [4] C. M. Ferla, M. B. Porter and F. B. Jensen, *C-SNAP: Coupled SACLANTCEN normal mode propagation loss model*, SACLANTCEN Memorandum SM-274, December 1993.
- [5] W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical recipes in FORTRAN, the art of scientific computing*, Second edition, Press Syndicate of the University of Cambridge, 1992.
- [6] E. K. Westwood, *Improved Narrow-band and Broadband Normal Mode Algorithms for Fluid Ocean Environments*, Journal of Acoustic Society of America, 99 (4), Pt. 2, April 1996 p. 2524.

Annex A

Output options

Table A1 Summary of PROSIM environmental inputs.

PARAMETER	EXPLANATION	UNIT	LIMIT
TITLE	Text on plots	-	≤ 64 chars
NF	No. of source frequencies (CW solution)	-	$NF \geq 1$
	broadband computation	-	$NF \leq 60(1)$ $= 0$
F(1) ... F(NF)	Source frequencies	-	≥ 0
MIN,DM,DM	MIN: min order mode in source field DM: dummy value	-	≥ 1
DM,DM	DM: dummy value	-	
H0,S0,S1	H0: water depth	m	≥ 0
RB,N1	S0,S1,N1: dummy values RB: the range from the source to the beginning of a new input profile	km	> 0
Z(1),C0(1)	Z(1): first ssp depth (=0) C0(1): first value of ssp in water	m m/s	- -
.	.	.	.
Z(M),C0(M)	Z(M): last ssp depth (=H0) C0(M): last value of ssp in water	m m/s	(2) -
H1,R1,B1	H1: thickness of sediment layer R1: density of sediment B1: compressional wave attenuation	m g/cm^3 dB/λ $dB/(m-kHz)$	≥ 0 $B1 \leq 0$ $B1 \geq 0$
Z1(1),C1(1)	Z1(1): first ssp depth (=0) C1(1): first value of ssp in sediment	m m/s	- -
.	.	.	.
Z1(N),C1(N)	Z1(N): last ssp depth (=H1) C1(N): last value of ssp in sediment	m m/s	(2) -
R2,B2,C2	R2: density of bottom B2: compressional wave attenuation C2: compressional sound-speed in bottom	g/cm^3 dB/λ $dB/(m-kHz)$ m/s	> 0 $B2 \leq 0$ $B2 \geq 0$ > 0
B2S,C2S	B2S,C2S: dummy values	-	-

Table A1 Continued.

PARAMETER	EXPLANATION	UNIT	LIMIT
"CODE WORD"	The code word depends on the computational requirements		
GA,GT	GA: width of Gaussian beam (3)	Degrees	$0 \geq \text{GA} < 90$
	GT: tilt of beam (+ downwards)	Degrees	$0 \geq \text{GT} < 90$
FFT,MINF,MAXF,SW	FFT: Fast Fourier Transform size	-	-
	MINF: minimum source frequency	Hz	-
	MAXF: maximum source frequency	Hz	-
	SW: sampling frequency ($\text{SW} < 0$)	Hz	(4)
P1,PNA,NA	SW: total time window ($\text{SW} > 0$)	s	(4)
	P1: minimum range in calculation	km	≥ 0
D1,DNR,NR	PNA: maximum range in calculation	km	-
	NA: No. of equally spaced ranges	-	(5)
SD	D1: minimum receiver depth	m	≥ 0
	DNR: maximum receiver depth	m	-
	NR: No. of equally spaced receivers	-	(6)
SD	SD: source depth	m	$0 \geq \text{SD} \geq \text{H0}$

- (1) The number of frequencies **NF** in a multi-frequency continuous wave solution is limited by **NFMAX** defined in **Parms.com**, see section 3.
- (2) The number of layers in depth $M + N + 2$ is limited by **NLMAX** defined in **Parms.com**, see section 3.
- (3) An omni-directional point source is assumed if both **GA** and **GT** are ZERO
- (4) The number of frequency components in a broadband solution $(\text{MAXF} - \text{MINF}) \cdot \text{FFT} / \text{SW} + 1$ for $\text{SW} < 0$ or $(\text{MAXF} - \text{MINF}) \cdot \text{SW} + 1$ for $\text{SW} > 0$ is limited by **NFBBMAX** defined in **Parms.com**, see section 3.
- (5) The number of receivers in range **NA** is limited by **NSRMAX**, **NVRMAX** and **RGMAX**, see section 3.
- (6) The number of receivers in depth **NR** is limited by **NSRMAX** and **NVRMAX**, see section 3.

SACLANTCEN SM-358

Table A2 *Output options, calculations and output types.*

OUTPUT OPTION	EXPLANATION
CONDR	Contured transmission loss versus depth and range
CONFR	Contured transmission loss versus frequency and range
CONFD	Contured transmission loss versus frequency and depth
MODES	Individual modes versus depth
PROFL	Sound speed and bathymery versus depth and range
TLDEP	Transmission loss versus depth
TLRAN	Transmission loss versus range
PULSE	Broadband pulse propagation

CALCULATION TYPE	EXPLANATION
COH	Coherent addition of modes
INC	Incoherent addition of modes

OUTPUT TYPE	EXPLANATION
COL	Colour contour plots through UNIRAS software
PLT	Plotted output (line contour plot for option CONDR , CONFR and CONFD)
PRT	Printed output

Table A3 *Allowed combinations of code words.*

	COH	INC	COL	PLT	PRT
CONDR	YES	YES	YES	YES	
CONFR	YES	YES	YES	YES	
CONFD	YES	YES	YES	YES	
MODES				YES	YES
PROFL				YES	
TLDEP	YES	YES		YES	
TLRAN	YES	YES		YES	
PULSE					YES

Table A4 *Axis identifier code words.*

CODE WORD	EXPLANATION	UNIT	DEFAULT
SAXIS s1,s2,s3,s4	Sound speed axis: s1: sound speed minimum s2: sound speed maximum s3: axis length s4: tickmark spacing	m/s m/s cm m/s	1450 1650 3 25
XAXIS x1,x2,x3,x4,x5	Horizontal axis: x1: lowest data value x2: highest data value x3: axis length x4: tickmark spacing x5: number of data points in smoothing window (2)	(1)	(1)
YAXIS y1,y2,y3,y4	Vertical axis: y1: lowest value y2: highest value y3: axis length y4: tickmark spacing	(1)	(1)
ZAXIS z1,z2,z3,z4	Loss values: z1: minimum contour level z2: maximum contour level z3: level increment z4: number of smoothings	dB dB dB -	60 110 5 0

- (1) In this case units and default values are dependent on the particular output option they refer to. They are given in Tables A5a-h.
- (2) Applicable to option **TLRAN** only

SACLANTCEN SM-358

Table A5a Contoured loss versus depth and range.

INPUT PARAMETER	EXPLANATION	UNIT	DEFAULT
CONDR,OP1,OP2,etc	OP1,OP2, etc (1): any allowed choice from Table A3		
GA,GT	GA: width of Gaussian beam (1) GT: tilt of beam (+ downwards)	Degrees Degrees	- -
FFT,MINF,MAXF,SW	FFT: Fast Fourier Transform size MINF: minimum source frequency MAXF: maximum source frequency SW: sampling frequency (SW < 0) SW: total time window (SW > 0)	- Hz Hz Hz s	- - - - -
P1,PNA,NA	P1: minimum range in calculation PNA: maximum range in calculation NA: No. of equally spaced ranges	km km -	- - -
D1,DNR,NR	D1: minimum receiver depth DNR: maximum receiver depth NR: No. of equally spaced receivers	m m -	- - -
SD	SD: source depth	m	-
XAXIS x1,x2,x3,x4	Range axis: x1: minimum range x2: maximum range x3: axis length x4: tickmark spacing	km km cm km	P1 PNA 16 (PNA-P1)/5
YAXIS y1,y2,y3,y4	Depth axis: y1: minimum depth y2: maximum depth y3: axis length y4: tickmark spacing	m m cm m	0 $H_{max}(3)$ 10 $H_{max}/5$
ZAXIS z1,z2,z3,z4	Loss values: z1: minimum loss z2: maximum loss z3: loss increment z4: No. of smoothings	dB dB dB -	60 110 5 0

- (1) At least one calculation type (**COH,INC**) must be specified.
- (2) An omni-directional point source is assumed if both **GA** and **GT** are ZERO
- (3) Maximum water depth from the entire environmental input

Table A5b *Contoured loss versus frequency and range.*

INPUT PARAMETER	EXPLANATION	UNIT	DEFAULT
CONFR,OP1,OP2,etc	OP1,OP2, etc (1): any allowed choice from Table A3		
GA,GT	GA: width of Gaussian beam (1) GT: tilt of beam (+ downwards)	Degrees Degrees	- -
FFT,MINF,MAXF,SW	FFT: Fast Fourier Transform size MINF: minimum source frequency MAXF: maximum source frequency SW: sampling frequency (SW < 0) SW: total time window (SW > 0)	- Hz Hz Hz s	- - - - -
P1,PNA,NA	P1: minimum range in calculation PNA: maximum range in calculation NA: No. of equally spaced ranges	km km -	- - -
D1,DNR,NR	D1: minimum receiver depth DNR: maximum receiver depth NR: No. of equally spaced receivers	m m -	- - -
SD	SD: source depth	m	-
XAXIS x1,x2,x3,x4	Range axis: x1: minimum range x2: maximum range x3: axis length x4: tickmark spacing	km km cm km	P1 PNA 16 (PNA-P1)/5
YAXIS y1,y2,y3,y4	Frequency axis: y1: minimum frequency y2: maximum frequency y3: axis length y4: No. of sub-divisions per octave	Hz Hz cm -	MINF MAXF 10 1
ZAXIS z1,z2,z3,z4	Loss values: z1: minimum loss z2: maximum loss z3: loss increment z4: No. of smoothings	dB dB dB -	60 110 5 0

(1) At least one calculation type (COH,INC) must be specified.

(2) An omni-directional point source is assumed if both GA and GT are ZERO

SACLANTCEN SM-358

Table A5c *Contoured loss versus frequency and depth.*

INPUT PARAMETER	EXPLANATION	UNIT	DEFAULT
CONFD,OP1,OP2,etc	OP1,OP2, etc (1): any allowed choice from Table A3		
GA,GT	GA: width of Gaussian beam (1)	Degrees	-
	GT: tilt of beam (+ downwards)	Degrees	-
FFT,MINF,MAXF,SW	FFT: Fast Fourier Transform size	-	-
	MINF: minimum source frequency	Hz	-
	MAXF: maximum source frequency	Hz	-
	SW: sampling frequency (SW < 0)	Hz	-
	SW: total time window (SW > 0)	s	-
P1,PNA,NA	P1: minimum range in calculation	km	-
	PNA: maximum range in calculation	km	-
	NA: No. of equally spaced ranges	-	-
D1,DNR,NR	D1: minimum receiver depth	m	-
	DNR: maximum receiver depth	m	-
	NR: No. of equally spaced receivers	-	-
SD	SD: source depth	m	-
XAXIS x1,x2,x3,x4	Depth axis:		
	x1: minimum depth	m	0
	x2: maximum depth	m	$H_{max}(3)$
	x3: axis length	cm	16
	x4: tickmark spacing	m	$H_{max}/5$
YAXIS y1,y2,y3,y4	Frequency axis:		
	y1: minimum frequency	Hz	MINF
	y2: maximum frequency	Hz	MAXF
	y3: axis length	cm	10
	y4: No. of sub-divisions per octave	-	1
ZAXIS z1,z2,z3,z4	Loss values:		
	z1: minimum loss	dB	60
	z2: maximum loss	dB	110
	z3: loss increment	dB	5
	z4: No. of smoothings	-	0

- (1) At least one calculation type (COH,INC) must be specified.
- (2) An omni-directional point source is assumed if both GA and GT are ZERO
- (3) Maximum water depth from the entire environmental input

Table A5d *Individual mode functions versus depth.*

INPUT PARAMETER	EXPLANATION	UNIT	DEFAULT
MODES,OP1,OP2	OP1,OP2 (1): any allowed choice from Table A3		
GA,GT	GA: width of Gaussian beam (1) GT: tilt of beam (+ downwards)	Degrees Degrees	- -
FFT,MINF,MAXF,SW	FFT: Fast Fourier Transform size MINF: minimum source frequency MAXF: maximum source frequency SW: sampling frequency ($SW < 0$) SW: total time window ($SW > 0$)	- Hz Hz Hz s	- - - - -
P1,PNA,NA	P1: minimum range in calculation PNA: maximum range in calculation NA: No. of equally spaced ranges	km km -	- - -
D1,DNR,NR	D1: minimum receiver depth DNR: maximum receiver depth NR: No. of equally spaced receivers	m m -	- - -
SD	SD: source depth	m	-
XAXIS x1,x2,x3,x4	Mode amplitude axis: x1: lowest data value x2: highest data value x3: axis length (accommodates 6 modes) x4: tickmark spacing	(3) (3) (3) (3)	-0.2 0.2 16 0.2
YAXIS y1,y2,y3,y4	Depth axis: y1: minimum depth y2: maximum depth y3: axis length y4: tickmark spacing	m m cm m	0 H0(4) 10 H0/5

(1) At least one calculation type (**PLT**, **PRT**) must be specified.

(2) An omni-directional point source is assumed if both **GA** and **GT** are ZERO.

(3) $m/\sqrt{kg}$

(4) Water depth at the origin.

Table A5e *Sound-speed profile versus range and depth.*

INPUT PARAMETER	EXPLANATION	UNIT	DEFAULT
PROFL,PLT	The only output type is PLT		
GA,GT	GA: width of Gaussian beam (1) GT: tilt of beam (+ downwards)	Degrees Degrees	- -
FFT,MINF,MAXF,SW	FFT: Fast Fourier Transform size MINF: minimum source frequency MAXF: maximum source frequency SW: sampling frequency ($SW < 0$) SW: total time window ($SW > 0$)	- Hz Hz Hz s	- - - - -
P1,PNA,NA	P1: minimum range in calculation PNA: maximum range in calculation NA: No. of equally spaced ranges	km km -	- - -
D1,DNR,NR	D1: minimum receiver depth DNR: maximum receiver depth NR: No. of equally spaced receivers	m m -	- - -
SD	SD: source depth	m	-
XAXIS x1,x2,x3,x4	Range axis x1: minimum range x2: maximum range x3: axis length x4: tickmark spacing	km km cm km	0 RB(2) 16 RB/5
YAXIS y1,y2,y3,y4	Depth axis y1: minimum depth y2: maximum depth y3: axis length y4: tickmark spacing	m m cm m	0 $H_{max}(3)$ 10 $H_{max}/5$
SAXIS s1,s2,s3,s4	Sound speed axis s1: minimum sound speed s2: maximum sound speed s3: axis length s4: tickmark spacing	m/s m/s cm m/s	1450 1550 3 20

- (1) An omni-directional point source is assumed if both **GA** and **GT** are ZERO.
- (2) Range at the beginning of the last input sound speed profile.
- (3) Maximum water depth from the entire environmental input.

Table A5f *Propagation loss versus depth.*

INPUT PARAMETER	EXPLANATION	UNIT	DEFAULT
TLDEP,OP1,OP2, etc	OP1,OP2, etc (1): any allowed choice from Table A3		
GA,GT	GA: width of Gaussian beam (1)	Degrees	-
	GT: tilt of beam (+ downwards)	Degrees	-
FFT,MINF,MAXF,SW	FFT: Fast Fourier Transform size	-	-
	MINF: minimum source frequency	Hz	-
	MAXF: maximum source frequency	Hz	-
	SW: sampling frequency ($SW < 0$)	Hz	-
	SW: total time window ($SW > 0$)	s	-
P1,PNA,NA	P1: minimum range in calculation	km	-
	PNA: maximum range in calculation	km	-
	NA: No. of equally spaced ranges	-	-
D1,DNR,NR	D1: minimum receiver depth	m	-
	DNR: maximum receiver depth	m	-
	NR: No. of equally spaced receivers	-	-
SD	SD: source depth	m	-
XAXIS x1,x2,x3,x4	Loss axis		
	x1: minimum loss	dB	60
	x2: maximum loss	dB	120
	x3: axis length	cm	16
YAXIS y1,y2,y3,y4	Depth axis		
	y1: minimum depth	m	0
	y2: maximum depth	m	$H_{\max}(3)$
	y3: axis length	cm	10
	y4: tickmark spacing	m	$H_{\max}/5$

- (1) At least one choice for the calculation type (COH,INC) and one for the output type (PRT, PLT) must be made.
- (2) An omni-directional point source is assumed if both GA and GT are ZERO.
- (3) Maximum water depth from the entire environmental input.

The SACLANT Undersea Research Centre provides the Supreme Allied Commander Atlantic (SACLANT) with scientific and technical assistance under the terms of its NATO charter, which entered into force on 1 February 1963. Without prejudice to this main task - and under the policy direction of SACLANT - the Centre also renders scientific and technical assistance to the individual NATO nations.

This document is approved for public release.
Distribution is unlimited

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

tel: +39 0187 527 (1) or extension
fax: +39 0187 527 700

e-mail: library@saclantc.nato.int

NORTH ATLANTIC TREATY ORGANIZATION