

1. INTRODUCTION

ORCA is an acoustic propagation model for multi-layered acousto-elastic ocean environments based on normal mode theory.^{1,2} It has been designed to be easy to run for those who are unfamiliar with normal mode theory, but it also allows more advanced users to have considerable control over how the calculations are performed. Unlike most propagation modeling codes, the user need not specify depth, range, or wavenumber sampling parameters. For most options in the input file, the user may specify the default value, which causes the model to decide, for example, how many modes need to be computed. The two main parameters the user needs to decide upon for a specific run are: (1) the minimum range of interest, and (2) whether shear wave modes are desired.

Model outputs, such as transmission loss versus range and depth or mode function value versus mode number and depth, are written in Hierarchical Data Format (HDF) files.³ The HDF files may be read into Matlab using built-in functions or into Fortran using the HDF library subroutines.

For a given problem, ORCA uses one of two basic approaches to find modes: one where modes are found in the complex k plane, and one where modes are found on the real k axis. The user specifies which approach is to be used. The complex k plane algorithm must be used for problems involving elastic layering and for problems where accurate results at short ranges are required. The algorithm finds both trapped and leaky modes exactly in the complex k plane. The leaky modes account for propagation at steep angles of propagation and are necessary to obtain accurate results at short range. The real k axis algorithm is more efficient, but may only be used for fluid problems. The algorithm finds only the trapped modes and approximates the modal attenuations using perturbation theory. Inaccurate results may be obtained at short ranges and for problems involving moderate to large material attenuations.

The eigenvalue finding algorithm for the complex k -plane approach is based on an intuitive normal mode criterion, which states that modal eigenvalues correspond to plane wave angles for which constructive interference occurs between upgoing and downgoing plane waves. Therefore, plane wave reflection coefficient computations lie at the heart of the algorithm. Complex modal eigenvalues are computed in order to account for the loss of energy

from the waveguide due to any of the following mechanisms: attenuation in the media, partial reflection/partial transmission at the waveguide boundaries, or shear wave conversion at the waveguide boundaries. The fact that “leaky modes,” which correspond to plane waves that are partially reflected at the waveguide boundaries, are included means that ORCA is valid even at very short ranges. Modes corresponding to interface waves, such as Scholte and Stonely waves, may also be found, making the model useful at very low frequencies as well.

The eigenvalue finding algorithm for the real k axis uses the same basic eigenvalue criterion equation as is used by MODELAB,⁴ but employs a more efficient and robust root-finding technique and assures that all modes are found by counting the zero-crossings of the mode functions. The real k -axis algorithm is generally 4–6 times faster than the complex k -plane algorithm.

ORCA also has a feature designed to assure accurate results even when a mode is near the branch point corresponding to the sound speed in one of the two halfspaces (see, for example, Sec. II E of Ref. 1). An option exists to automatically insert a false bottom layer having the properties of the original halfspace, followed by a new halfspace with a slight gradient in the attenuation. The branch cut is eliminated, and the branch line integral contribution is efficiently represented by additional modes.

Besides its ease of use, another characteristic that makes the ORCA model unique is that its computation time increases roughly linearly as a function of frequency and waveguide thickness. In contrast, the time required by models that solve the wave equation numerically (in layers a fraction of a wavelength thick) typically increase quadratically. This characteristic can be extremely important for problems where a large number of modes are involved.

2. ORCA INPUT FILES

Running ORCA requires the user to edit two input files: (1) the **SVP** file that contains the geoacoustic description of the environment, and (2) the **OPT** file that contains the source-receiver geometry and user options. In both of these files, an asterisk as the first character on a line is used to indicate that the next line contains data to be read by the program. An explanation of the data expected by ORCA is given by text on and before each asterisk line. When editing input files, the user may *not* delete or add an asterisk line, but *may* insert or modify lines before an asterisk line for additional comments. Except where noted, the program inputs

the data with *unformatted* read statements, so numbers can be separated by commas, spaces, or even carriage returns. Separating numbers with several spaces improves readability. The asterisk lines in each file are numbered so that when the program encounters an error or illegal parameters, the resulting error message indicates the line number.

2.1 The SVP Input File

An example **SVP** file, which may be found in **inputs/benchmark_svp**, is given in Table 2.1. The input items in the **SVP** file are:

(1) SVP VERSION NUMBER AND TITLE.

- (i) *ver_no* is the version number of the **SVP** file, which is used to allow future versions of ORCA to be able to read input files from previous versions. Do not change this number. Note that the **SVP** file version number does not have to match the **OPT** file version number.
- (ii) title of profile (64 characters maximum, in single quotes).

(2) GEOACOUSTIC PARAMETERS OF UPPER HALFSPACE.

- (i) compressional velocity, c_p . Set $c_p < 0$ to make the first top layer given in Line (9) the upper halfspace. This feature allows the experienced user to specify an upper halfspace that has a gradient.
- (ii) shear velocity, c_s .
- (iii) density, ρ .
- (iv) compressional wave attenuation, a_p .
- (v) shear wave attenuation, a_s .
- (vi) compressional wave attenuation frequency exponent \bar{a}_p
- (vii) shear wave attenuation frequency exponent \bar{a}_s .

For air, $c_p = 343$ m/s, $\rho = .00121$ g/cm³, $c_s = a_p = a_s = 0$. To simulate a truly pressure-release interface, ρ should be set to a small number, such as 10^{-10} .

(3) SOUND SPEED PROFILE IN WATER.

- (i) N_{SVP} is the number of sound velocity profile (SVP) points in the ocean (2 N_{SVP}). The program will read this number of lines in Line (4).
- (ii) c_{tol} is the tolerance used in fitting SVP to eliminate layers. Set $c_{tol} = 0$ to keep all layers.

(4) DEPTH, SOUND VELOCITY POINTS IN WATER.

- The first depth must be 0 (the ocean surface); the last depth is the (positive) depth of the ocean.
- *The first line must also include:* the density and compressional wave attenuation

of the water (typically, $\rho_w = 1.05$ and $\alpha_w = 0$).

(5) NUMBER OF LAYERS IN OCEAN BOTTOM (0 N_{LAY}).

- This number of lines is read in Line (6).

(6) GEOACOUSTIC PARAMETERS FOR EACH BOTTOM LAYER.

- (i) *TYPE* of compressional velocity profile (1= $1/c^2$ linear; 2,3,4=BLUG).
- (ii) layer thickness, h .
- (iii) compressional velocity at top of layer, c_{p1} .
- (iv) • *TYPE* = 1, 3, or 4: compressional velocity at bottom of layer, c_{p2} .
• *TYPE* = 2: velocity gradient at top of BLUG layer, g .
- (v) shear velocity at top of layer, c_{s1} .
- (vi) shear velocity at bottom of layer, c_{s2} .
- (vii) density at top of layer, ρ_1 .
- (viii) density at bottom of layer, ρ_2 .
- (ix) compressional attenuation at top of layer, a_{p1} .
- (x) compressional attenuation at bottom of layer, a_{p2} .
- (xi) shear attenuation at top of layer, a_{s1} .
- (xii) shear attenuation at bottom of layer, a_{s2} .
- (xiii) • *TYPE*=1: dummy (must include a dummy number – do not skip).
• *TYPE*=2,3: BLUG parameter, β .
• *TYPE*=4: velocity gradient at top of BLUG layer, g .
- (xiv) • *TYPE*=1: dummy (must include a dummy number – do not skip).
• *TYPE*=2,3,4: sound speed error tolerance c_{tol} between $1/c^2$ linear layers used in model and BLUG layer specified. Recommended values for c_{tol} are 5–20 m/s. Smaller values of c_{tol} result in larger numbers of layers and longer CPU times.
- (xv) • compressional wave attenuation frequency exponent \bar{a}_p
- (xvi) • shear wave attenuation frequency exponent \bar{a}_s .

(7) GEOACOUSTIC PARAMETERS FOR SUBSTRATE [same format as Line (2)].

Note: Set $c_p < 0$ to make the last bottom layer given in Line (6) the lower halfspace. This feature allows the experienced user to specify a lower halfspace that has a gradient.

(8) NUMBER OF LAYERS ABOVE OCEAN (0 N_{TLAY}).

- This number of lines is read in Line (9).

(9) GEOACOUSTIC PARAMETERS FOR EACH TOP LAYER [same format as Line (6)].

TABLE 2.1: Example SVP file.

```

### SVP FILE FOR ORCA NORMAL MODE MODEL ###
### ENTER DATA AFTER LINES WITH * IN FIRST COLUMN ###
### USE OTHER LINES FOR COMMENTS ###
Note: ap,as = p-wave, s-wave attenuations (pos~dB/m/kHz, neg~dB/wavelength,
      999 ~ Thorpe attenuation in seawater)
*(1) ver_no  'SVP TITLE':
      3.0  'Example SVP'
-----
*(2) cp      cs      rho      ap      as      For Upper Halfspace:
      343.0   0.0   .00121   0.0    0.0
-----
nsvp = number of SVP points in ocean to be read on Line (4)
ctol = tolerance used in fitting SVP to eliminate layers (0=keep all layers)
*(3) nsvp  ctol
      9     0
-----
Ocean SVP Profile (add constant rho, ap in ocean on 1st line):
*(4)   z      cp
      0  1540   1   999
      30  1520
      45  1511
      50  1510
      85  1506
      100 1506.5
      200  1510
      300 1512.5
      500 1518.0
-----
*(5) nbot (# bottom layers to be read in Line 6):
      2
-----
Layer Profiles: type: 1=linear, 2=blug, 3=blug, 4=blug;  examples:
[Note: type<0 ==> add attn freq exponents (fexpp,fexps) at end of line]
1  h  cp1 cp2 cs1 cs2 rho1 rho2 ap1 ap2 as1 as2 dum dum fexpp fexps
2  h  cp1  g cs1 cs2 rho1 rho2 ap1 ap2 as1 as2 beta ctol fexpp fexps
3  h  cp1 cp2 cs1 cs2 rho1 rho2 ap1 ap2 as1 as2 beta ctol fexpp fexps
4  h  cp1 cp2 cs1 cs2 rho1 rho2 ap1 ap2 as1 as2  g ctol fexpp fexps
*(6)
      1  50 1540,1540  0,0  1.2,1.2  -.1,-.1  0,0
      1 300 1600,1800  0,0  1.3,1.5  -.1,-.1  0,0
-----
*(7) cp      cs      rho      ap      as      For Lower Halfspace:
      5000.0  2200.0   2.1   -.05   -.05
-----
*(8) ntop (# Top Layers to Be Read on Line 9):
      0
-----
*(9) Top Layer Parameters [(same format as line (6))]

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The BLUG profile (see, for example Ref. 6) in the ocean bottom is a three-parameter curve given by

$$c_p(z) = \sqrt{c_{p1}^2(1 + \beta)^2 + 2gc_{p1}(1 + \beta)z} - \beta c_{p1}, \quad (2.1)$$

where the depth z varies from 0 to the layer thickness h , c_{p1} is the sound speed at the top of the layer, g is the sound velocity gradient at the top of the layer, and β is the curvature parameter. By setting *TYPE*=2 in item (6)(i), the user may choose to specify c_{p1} , g , and β , which are the parameters usually specified in databases. Alternatively, the user may specify the BLUG curve by c_{p1} , c_{p2} , and β (*TYPE*=3) or by c_{p1} , c_{p2} , and g (*TYPE*=4). In summary, the three different *TYPE* options for the BLUG profile are designed to allow the user to specify the three BLUG parameters most readily available. The relationships between the BLUG parameters are given by the following expressions:

$$c_{p2}(c_{p1}, \beta, g, h) = \sqrt{c_{p1}^2(1 + \beta)^2 + 2gc_{p1}(1 + \beta)h} - \beta c_{p1} \quad (2.2)$$

$$g(c_{p1}, c_{p2}, \beta, h) = \frac{c_{p2} - c_{p1}}{h} \left[1 + \frac{c_{p2} - c_{p1}}{2c_{p1}(1 + \beta)} \right] \quad (2.3)$$

$$\beta(c_{p1}, c_{p2}, g, h) = \frac{(c_{p2} - c_{p1})^2}{2c_{p1}(c_{p1} - c_{p2} + gh)} - 1 \quad (2.4)$$

Attenuation values are normally given in the **SVP** file in units of dB/m/kHz. However, setting an attenuation value negative causes ORCA to interpret the attenuation value to be in units of dB/ [where $\alpha_{\text{dB/m/kHz}} = (1000/c)\alpha_{\text{dB/}}$].

ORCA allows the user to specify a non-unity power law frequency dependence for the compressional and shear wave attenuations in each layer.⁷ The p-wave and s-wave frequency exponents $\bar{\alpha}_p$ and $\bar{\alpha}_s$ are read from **SVP** file. For a given frequency f , the attenuation in dB/m is then computed as

$$\alpha_{\text{dB/m}} = \alpha_{\text{dB/m/kHz}} (f/f_o)^{\bar{\alpha}} f_o, \quad (2.5)$$

where $f_o = 1000$ Hz. Ultimately, ORCA uses the attenuation to compute the imaginary part of the medium wavenumber K as:

$$\text{Im}(K) = \frac{\alpha_{\text{dB/m}}}{20 \log e}. \quad (2.6)$$

The standard units assumed by ORCA in the **SVP** and **OPT** files are: depth and thicknesses in m, horizontal ranges in km, sound speed in m/s, density in g/cm^3 , attenuation in dB/m-kHz, velocity gradient in s^{-1} , and frequency in Hz. As noted at the start of the **SVP** file, negative values of attenuation are assumed to be in units of dB/ , where λ is the wavelength.

2.2 The OPT Input File

An example **OPT** file, which may be found in **inputs/benchmark_opt**, is given in Table 2.2. The input items in the **OPT** file are:

(1) TYPE(S) OF COMPUTATIONS DESIRED.

- (i) *ver_no* is the version number of the **OPT** file, which is used to allow future versions of ORCA to be able to read input files from previous versions. Do not change this number. Note that the **OPT** file version number does not have to match the **SVP** file version number.
- (ii) *iicw* is the option for mode computations: 0=none, 1=CW (single frequency), 2=broadband.
- (iii) *iikpl* is the option for complex k -plane images of reflection coefficient quantities: 0=none, 1 = $\ln(R_1R_2)$, 2 = $\ln(1-R_1R_2)$, -1 = R_1R_2 , 2 = $1-R_1R_2$. R_1 and R_2 are the downward and upward reflection coefficients, respectively, computed at the reference depth. Enter parameters on Line (12).
- (iv) *iirc* is the option for calculations of reflection coefficient versus angle and frequency: 0=none, 1= R versus grazing angle θ and frequency f , 2=FFT file.
- (v) *iiparm* is the option to perform a parameter study (0=no, 1=yes). This option allows one to vary one or more geoacoustic parameters in the environment and repeatedly perform the calculations specified by *iicw*, *iikpl*, and/or *iirc* above.
- (vi) n_{env} is the option to output the geoacoustic profile as a function of depth (ASCII file with suffix **_prof**). The number of depth points is n_{env} , and the six columns represent z , c_p , c_s , ρ , a_p , and a_s .
- (vii) *iifmt* specifies the format of the output files (0=all formats, 1=HDF files, 2=Matlab .mat files, 3=ASCII files).

(2) MODE COMPUTATION GENERAL PARAMETERS (*iicw* = 0 on Line (1)).

- (i) *iirx* determines the type of mode-finding algorithm: 0=complex k -plane algorithm, 1=real k -axis algorithm. The real k -axis algorithm (*iirx*=1) handles only fluid environments, finds only the trapped modes, and computes modal attenuations approximately using perturbation theory. For *iirx*=1, any elastic properties specified in the **SVP** file are set to zero, the upper halfspace is assumed to be a

vacuum, and the maximum modal phase speed is the p-wave speed of the lower halfspace.

- (ii) $c_{ph\min}$ is the minimum phase speed desired when searching for modes. For $c_{ph\min} = 0$, the minimum p-wave sound speed is used. For $c_{ph\min} = -1$, seismic modes are searched for also.
- (iii) $c_{ph\max}$ is the maximum phase speed desired when searching for modes.
 - $0 < c_{ph\max}$: Find modes with phase speeds up to $c_{ph\max}$ (in m/s).
 - $-90 < c_{ph\max} < 0$: Find modes corresponding to plane wave grazing angles up to $|c_{ph\max}|$ (in deg).
 - $c_{ph\max} = 0$: Find enough modes such that field is valid at r_{\min} (see next item).
- (iv) r_{\min} is the minimum range of interest in km, which is used to determine when to stop finding modes.
 - 999 r_{\min} : Use $c_{ph\max}$ criterion (see previous item).
 - $0 < r_{\min} < 999$: Find enough modes such that field is valid at r_{\min} km.
 - $r_{\min} = 0$: Set r_{\min} to the minimum range from the source-receiver geometry given.
 - $r_{\min} < 0$: Find a maximum of $|r_{\min}|$ modes. This option is *not recommended*, but may be useful when the user needs to limit the number of modes used in the solution to a specific value (see discussion in Sec. 5.2).

NOTE: The mode search must be limited by either $c_{ph\max}$ or r_{\min} , but not both.

- (v) r_{\max} is the maximum range of interest, which is used to determine how closely each eigenvalue needs to be found. Set $r_{\max} = 0$ to have the program compute r_{\max} automatically from the source-receiver geometry.
- (vi) $phfac$ is the phase step parameter. In going from one mode to the next, steps of $(2\pi)/(phfac)$ are used. Set $phfac=0$ to get the default value of 4.
- (vii) db_cut determines the cutoff level for weak modes. For a given range, any mode weaker than the strongest mode by db_cut is not included in the mode summation. Set $db_cut=0$ to get the default of 50 dB, which is quite conservative. Values between 30 and 60 are recommended.
- (viii) $iifb$ is the option to insert a false bottom. For $iifb=1$, a $3-\lambda$ thick layer having the properties of the original halfspace is inserted, where λ is the compressional-wave wavelength at the lowest frequency in the problem. For complex k -plane computations ($iirx=0$), the new halfspace is given a gradient in the attenuation. Additional modes are introduced that account for the branch line integral. For real k -axis computations ($iirx=1$), the sound speed in the lower halfspace is set

according to $c_{ph\max}$ [see Line (2)(ii)], which allows steeper angles of propagation to be included. For $iifb > 1$, the thickness of the layer is set to $iifb(\lambda)$.

- (ix) *iigbs* is the option to create a Gaussian beam source (0=point source as usual, 1=Gaussian beam source). For *iigbs*=1, insert beam characteristics after the usual source/receiver on Line (5). This option only works for the complex k -plane algorithm (*iirx*=0).
- (x) *iidiag* is the option to print diagnostic messages to the screen during the run. This option is designed for the experienced user when problems arise.

For *iicw*=1 on Line (1), CW mode parameters are to be specified on the next four lines.

(3) FREQUENCIES.

- (i) N_f is the number of frequencies, followed by the frequencies.
 - For $N_f > 0$, list the frequencies f_1, f_2, \dots, f_{N_f} .
 - For $N_f < 0$, list f_1 and f_{N_f} , and a set of N_f uniformly spaced frequencies will be computed.

(4) CW MODE OUTPUT OPTIONS.

- (i) *iitl* is the option to output transmission loss (in dB) versus range and depth: 0=none, ± 1 =list source/receiver depths and ranges on Line (5), ± 2 =use source track and receiver array specified on Line (10) and Line (11). Set *iitl* negative to obtain the phase of the field (in degrees) as well as the magnitude.
- (ii) *iimf* is the option to output mode functions versus depth and mode number: 0=no, 1=p-wave mode functions only, 2=s-wave mode functions only, 3=both p- and s-wave mode functions. Enter depths on Line (6).
- (iii) *iisig* is the option to output vertical and horizontal displacements, u_z and u_x , and normal and tangential stresses, σ_{zz} and σ_{zx} , as a function of depth and mode number. These quantities are continuous across solid-solid interfaces. Enter depths on Line (6).
- (iv) *iimt* is the option to output an ASCII file containing the mode trajectory in the complex k plane. This option is designed for the experienced user.
- (v) *iidc* is the option to output dispersion curves: 0=no, 1=group velocity v_g , 2=phase velocity v_{ph} , 3=both group and phase velocity. The quantities are computed as functions of frequency and mode number.
- (vi) *iikn* is the option to output the real and imaginary parts of the eigenvalues k_n (as a function of frequency for multiple frequency runs).
- (vii) *iieig* is the option to output an ASCII file containing a list of mode characteristics, including phase velocity v_{ph} , group velocity v_g , turning depths, and attenuation in dB/km.

- (viii) *ikrak*, *ioas*, *iifepe*, *iimlab* are options (0=no, 1=yes) to output ASCII input files for KRAKEN (or KRAKENC), OASES, FEPE, or MODELAB, respectively. If *ikrak*>10 the number of KRAKEN mesh points per wavelength is set to *ikrak*.

A file with the suffix **_modes** containing the complex mode eigenvalues, phase speeds, and group velocities is always produced when *iicw*=1 is chosen.

(5) SOURCE/RECEIVER GEOMETRY PARAMETERS (for *iitl*=1 on Line (4)).

- (i) N_{zs} is the number of source depths. Enter a positive number to list depths (in m) sequentially, or a negative number to list the first and last values with $|N_{zs}|$ evenly spaced values.
- (ii) N_{zr} is the number of receiver depths. Enter a positive number to list depths (in m) sequentially, or a negative number to list the first and last values with $|N_{zr}|$ evenly spaced values.
- (iii) N_r is the number of source-receiver ranges. Enter a positive number to list ranges (in km) sequentially, or a negative number to list the first and last values with $|N_r|$ evenly spaced values.
- (iv) For Gaussian beam source only [*iigbs*=1 on Line (2)]: re-enter N_{zs} , followed by the distances b (in m) in complex space to place the source(s).
- (v) For Gaussian beam source only [*iigbs*=1 on Line (2)]: re-enter N_{zs} , followed by the beam grazing angle(s) θ_{gbs} (in deg, positive for upward-pointing).

(6) MODE FUNCTION PARAMETERS (for *iimf*=1 or *iisig*=1 on Line (4)).

- (i) *iir/i* is the option to output real and/or imaginary parts of the mode functions: 0=neither, 1=real parts only, 2=imaginary parts only, 3=both real and imaginary parts.
- (ii) *iim/p* is the option to output the magnitude and/or phase of the mode functions: 0=neither, 1=magnitude only, 2=phase only, 3=both magnitude and phase.
- (iii) N_{zm} is the number of depths at which to compute and output mode functions. Enter a positive number to list depths (in m) sequentially, or a negative number to list the first and last values with $|N_{zm}|$ evenly spaced values.

(7) BROADBAND MODE COMPUTATION PARAMETERS (*iicw*=2 on Line (1)).

- (i) f_s is the sample rate (in Hz).
- (ii) $+N_{\text{FFT}}/-T_w$ determines the number of points in the discrete FFT. Enter N_{FFT} as a positive (power of 2) integer, or the time window duration T_w (in s) as a negative real number. In the latter case, N_{FFT} is computed automatically such that the time window N_{FFT}/f_s is at least T_w .
- (iii) $f_{\text{min}}, f_{\text{max}}$ is the frequency band. The frequency resolution is given by $f = f_s/N_{\text{FFT}}$.

- (iv) *iiff* is the option to output an FFT file: 0=no, 1=list source/receiver depths and ranges on Line (8), 2=use source track and receiver array specified on Line (10) and Line (11). The format of the FFT file is given in Sec. 4.1.
- (v) *iiout* is the option to output broadband eigenvalues and mode functions to a binary file (same options as for *iiff* above). The depths at which the mode functions are output are determined by the depths specified on Line (8) for *iiout*=1 or on Line (10) and Line (11) for *iiout*=2. The output file has the suffix **_bbeig** and may be used by other programs to compute the field at any range.
- (vi) *iift* is the option to output an ASCII file containing the mode eigenvalues in the k plane as a function of frequency. This option is designed for the experienced user.
- (vii) *iimt* is the option to output an ASCII file containing the mode trajectory in the complex k plane at the highest frequency f_{\max} . This option is designed for the experienced user.
- (viii) *iidc* is the option to output dispersion curves as a function of frequency and mode number: 0=none, 1= v_g , 2= v_{ph} , 3=both v_g and v_{ph} . A Matlab script may be used to plot the curves.
- (ix) *iimf* is the option to output mode functions versus depth, mode number, and frequency: 0=no, 1=p-wave mode functions only, 2=s-wave mode functions only, 3=both p- and s-wave mode functions. Enter depths on Line (6).

Note: When the real k -axis algorithm is selected (*iirx* = 0 on Line (2)), the broadband calculations are carried out using either a frequency interpolation algorithm (*iirx*=1), or a “brute-force” loop over frequency (*iirx*=2). The frequency interpolation method is usually more efficient.

(8) SOURCE/RECEIVER GEOMETRY PARAMETERS.

- Read when *iiff*=1 or *iiout*=1 on Line (7). Same format as Line (5).

(9) MODE PARAMETER STUDY OPTIONS (for *iiparm*=1 on Line (1)).

- (i) N_{run} is the number of runs to perform.
- (ii) N_{parm} is the number of parameters to vary (maximum of 25).
- (iii) r_{seed} is the seed of a random number generator. Set $r_{\text{seed}} = 0$ to obtain deterministic values for the parameters between initial and final values given below. Otherwise, uniformly distributed values between initial and final values are chosen.
- (iv) For each of the N_{parm} parameters to vary, the following values are given next:
 - *obt* specifies the medium: 0=ocean, 1=bottom layers, 2=top layers.
 - *nlay* specifies which layer in the medium.

- *ktb* specifies the top ($|ktb| = 1$) or the bottom ($|ktb| = 2$) of the layer. Set *ktb* negative to keep the gradient of the parameter in the layer the same as it was originally.
- *pc* is the parameter code: $0=h$, $1=c_p$, $2=c_s$, $3=\rho$, $4=a_p$, $5=a_s$.
- *val1*, *val2* are the initial and final values for the parameter ($r_{seed} = 0$), or the interval over which the parameter is randomly varied ($r_{seed} = 0$).

(10) SOURCE/RECEIVER GEOMETRY FOR SOURCE TRACK AND RECEIVER ARRAY.

- Read when *iitl*=2 on Line (4), *iiff*=2 on Line (7), or *iiout*=2 on Line (7).
- (i) z_s is the source depth (in m).
- (ii) n_{srcseg} is the number of straight-line source track segments to be read on Line (11).
- (iii) Name of array geometry file (maximum 64 characters, in single quotes). See Sec. 2.3 for the format of this file.

(11) SPECIFICATION OF SOURCE TRACK SEGMENTS (n_{srcseg} lines to be read).

- (i) *TYPE* of source track specification: 1=polar form; 2=*x*-*y* form.
- (ii) • *iic*=0 makes the current leg independent (not continuous with) the previous leg. For *TYPE*=1, T_1 and T_2 are measured with respect to the CPA point. For the first leg *iic* is automatically set to zero.
- *iic*=1 makes the current leg continuous with the previous leg. For *TYPE*=1, CPA is ignored; for *TYPE*=2, X_1 and Y_1 are ignored. The total time along the current leg is taken to be $T_2 - T_1$.
- (iii) v is the source velocity (in m/s).
- (iv) T_1 is the start time of the leg (in min). For *TYPE*=1, setting $v=0$ implies that T_1 and T_2 are given as distances (in km) along track.
- (v) T_2 is the end time of the leg (in min). For *TYPE*=2, non-zero v means that this value is computed automatically.
- (vi) *+dt/-nt* determines the track sampling: positive values are interpreted as *dt*, the time in min between which samples of the source track are taken; negative values are interpreted as *nt*, the total number of points at which to sample the leg $nt = 2$.
- (vii) • *TYPE*=1: CPA is the range in km from the origin to the closest point of approach of the source. Positive CPA defines a track that is clockwise relative to the origin, negative CPA defines a track that is counterclockwise.[†]
- *TYPE*=2: X_1 is the starting *x*-coordinate in km.

[†]Note that this is different from the ray model GAMARAY.

- (viii) • TYPE=1: PHI is the direction of the source track (in deg E of N)[†].
 - TYPE=2: Y_1 is the starting y-coordinate in km.
- (ix) • TYPE=1: Dummy argument, set to zero.
 - TYPE=2: X_2 is the final x-coordinate in km.
- (x) • TYPE=1: Dummy argument, set to zero.
 - TYPE=2: Y_2 is the final y-coordinate in km.

(12) k -PLANE IMAGE PARAMETERS (for $iikpl = 0$ on Line (1)).

- (i) $freq$ is the frequency (in Hz).
- (ii) $iivar$ determines the variable to image: $1=R_1R_2$, $2=(R_1R_2)/(k)$, $3=(R_1R_2)/(\omega)$. Separate files for the real and imaginary parts of the complex quantities are produced. The most useful choices are to set $iikpl=1$ and $iivar=1$, in which case the real and imaginary parts of $\ln R_1R_2$ are imaged. Modes are defined by $R_1R_2 = 1$, which implies $\text{Re}(\ln R_1R_2) = 0$ and $\text{Im}(\ln R_1R_2) = 0$. To find eigenvalues, ORCA follows the “mode trajectory” defined by $\text{Re}(\ln R_1R_2) = 0$ from right to left in the complex k plane (see Ref. 1).
- (iii) $iikf$ determines the form for kr and ki that follow: $1=k/k_{ref}$ (where $k_{ref} = \omega/c_{pmin}$, $2=k$, $3=(k_r/k_{ref}), (k_i \text{ dB/km})$). The most intuitive choice is $iikf=3$ because $k_r/k_{ref} = \cos\theta_{ref}$, where θ_{ref} is the grazing angle of the plane wave with horizontal wavenumber k_r at the reference depth (where the minimum sound speed occurs), and k_i in dB/km gives the modal attenuation.
- (iv) $kr1, kr2, nkr$ are the initial and final values of the real part of k (in units defined above by $iikf$) and the number of sample points.
- (v) $ki1, ki2, nki$ are the initial and final values of the imaginary part of k (in units defined above by $iikf$) and the number of sample points. For viewing in Spyglass Transform, make $ki1 > ki2$ so that ki increases upward on the image.
- (vi) $nduct$ determines which duct, as counted from top to bottom, to take as the reference depth. Set $nduct=0$ to use the duct with the lowest sound speed.
- (vii) $iiph$ determines the interval to use when computing the phase of complex numbers: $1 = (-180^\circ, 180^\circ)$, $2 = (0^\circ, 360^\circ)$.
- (viii) $iishp, iishs$ are the Riemann sheets (+1 or -1) for the p-wave and s-wave branch cuts, respectively. Set both to +1 for typical applications.

(13) REFLECTION COEFFICIENT VERSUS f AND ANGLE (for $iirc=1$ on Line (1)).

- (i) $freq1, freq2, nfreq$ are the initial and final frequencies (in Hz) and the number of

[†]Note that this is different from the ray model GAMARAY.

frequency samples.

- (ii) *iilog* is the option for logarithmic spacing: 0=linear, 1=logarithmic.
- (iii) $\theta_1, \theta_2, N_\theta$ are the initial and final grazing angles (in deg) and the number of grazing angle samples.

(14) FFT FILE OF R VERSUS f AND ANGLE (for *iirc*=2 on Line (1)).

- (i) *freq1, freq2* are the initial and final frequencies (in Hz).
- (ii) f_s is the sample rate.
- (iii) N_{FFT} is the number of points in the discrete FFT. The frequency spacing is then $f = f_s / N_{\text{FFT}}$.
- (iv) $\theta_1, \theta_2, N_\theta$ are the initial and final grazing angles (in deg) and the number of grazing angle samples.

The output FFT file has a single “sequence” with N_θ “receivers,” each of which corresponds to a grazing angle. See Sec. 4.1 for the format of the `_fft` file.

2.3 Array Geometry File

An array geometry file may be specified in Line (10). Array geometry files are useful when simulating the field on specific vertical, horizontal, or volumetric arrays. An example array geometry file may be found in `inputs/benchmark_array` and is given in Table 2.3. The input items in the array geometry file are:

(1) Type of receiver array.

- $II_{\text{ARR}} = 1$ for a uniformly spaced receiving array.
- $II_{\text{ARR}} = 2$ for a nonuniformly spaced receiving array.

Note: The center of the array for the purposes of defining the source CPA is at $(x, y, z) = (0, 0, ZR_1)$. Array locations are specified in m.

(2) Receiver array specification for $II_{\text{ARR}} = 1$.

- The array elements are centered at the origin in the x - y plane.
 - (i) ZR_1 is the depth of the *top* of the array.
 - (ii) N_x is the number of elements in the x -direction.
 - (iii) N_y is the number of elements in the y -direction.
 - (iv) N_z is the number of elements in the z -direction.
 - (v) x is the element spacing in the x -direction.
 - (vi) y is the element spacing in the y -direction.
 - (vii) z is the element spacing in the z -direction. Note: negative z makes ZR_1 the depth of the *bottom* of the array.

(3) Receiver depths for $II_{\text{ARR}} = 2$.

TABLE 2.2: Example OPT file.

```

##### OPTION FILE FOR ORCA NORMAL MODE MODEL #####
### ENTER DATA AFTER LINES WITH * IN FIRST COLUMN ###
##### USE OTHER LINES FOR COMMENTS #####
==> TYPE(S) OF COMPUTATIONS DESIRED:
ver_no = Version Number of Option File (DO NOT CHANGE THIS);
iicw   = Mode Computations (0=no; 1=CW; 2=Broadband);
iikpl  = Complex k-Plane Images [0=no; 1=ln(R1*R2); 2=ln(1-R1*R2)];
iirc   = PW Reflection Coeff (0=no; 1=R vs angle,f; 2=FFT file vs. angle);
iiparm = Parameter Study Using iicw,iikpl,iirc above (0=no; 1=yes);
n_env  = Geoacoustic Profile (_prof) Output File (0=no; pos=# depth pts);
iifmt  = Output Format (1=HDF;2=MAT;3=ASCII;0=all);
*(1) ver_no iicw iikpl iirc iiparm n_env iifmt
      1.6   1     0     0     0     0     1
-----
==> MODE COMPUTATION GENERAL PARAMETERS (iicw>0 on Line 1):
      SET ALL TO 0 TO FIND MODES AUTOMATICALLY
iirx   = Real axis version (0=no, 1=yes);
cphmin = Min Phase Speed (0=p-wave modes only; -1=seismic modes also);
cphmax = Max Phase Speed [0=use rmin; pos=speed; neg=max angle(deg)];
rmin   = Min Range of Interest in km [>999=use cphmax; 0=use S/R geom];
rmax   = Max Range of Interest in km (0=use S/R geom);
phfac  = Phase Step Parm: Step by 2*pi/phfac (set to 4-8, 0=default==>4);
db_cut = Modes Weaker By db_cut Ignored (set to 30-60, 0=default==>50);
iifb   = False Bottom (0=no, 1=def, >1=thickness in lambda);
iigbs  = Gaussian Beam Source (0=no,1=yes) [iirx=0 only; add beam angle
      and beamwidth for each source depth in lines (5) or (8)];
iidiag = Print Diagnostic Msgs;
*(2) iirx cphmin cphmax rmin rmax phfac db_cut iifb iigbs iidiag
      0     0     0     0     0     4     50     0     0     0
-----
CW MODE PARAMETERS ON NEXT 5 LINES (iicw=1 on Line 1)
Frequencies (nf>0 ==> List f's; nf<0 ==> List first,last f):
*(3) nf f1 f2 ...
      1 50
-----
CW Mode Output Options:
iitl   = TL (0=no;1=zs,zr,r on Line 5; 2=src track/rec array on Line 10)
iimf   = Mode Functions (0=no,1=p-wave,2=s-wave,3=both). Enter depths on Line 6.
iisig  = Disp uz,ux and Stress sigzz,sigzx (0=no,1=yes). Enter depths on Line 6.
iimt   = Mode Trajectory in k-plane (ASCII file).
iidc   = Disp Curves(0=no,1=vg,2=vph,3=both);
iikn   = Mode Eigenvalues Re(kn),Im(kn);
iieig  = List of eigenvalue characteristics;
iikrak,iioas,iifepe,iimlab = Output Kraken, OASES, FEPE, MODELAB input files;
*(4) iitl iimf iisig iimt iidc iikn iieig iikrak iioas iifepe iimlab
      1   1   0   0   0   0   1   0   0   0   0
-----
For iitl=1, Enter Source Depths, Receiver Depths, Ranges:
*(5) nzs zs1 zs2 (m) ... nzs zr1 zr2 (m) ... nr r1 r2 (km) ...
      1 50
      -100 5 500
      -200 .05 10
-----
For iimf>0 or iisig=1, enter Re/Im(0-3), Mag/Phase(0-3) Options and Depths:
*(6) iir/i iim/p nzm zml zm2 ...
      0   1 -201 0 600
-----

```

TABLE 2.2 (cont'd): Example OPT file.

```

BB MODE COMPUTATION PARAMETERS (iicw=2 on Line 1):
fs      = Sample f;
nfft/Tw = pos=NFFT (power of 2); neg=Time Window in s;
iifft   = Output FFT File (0=no;1=zs,zr,r on Line 8; 2=read file on Line 10);
iiout   = Output BB Eigenvalues and Functions (same options as iifft above);
iift    = Freq Traj(ASCII); iimt = Mode Traj(ASCII);
iidc    = Disp Curves (0=no,1=vg,2=vph,3=both);
iimf    = Mode Functions at Rec Depth on Line 8 (0=no,1=2D HDF,2=3D HDF);
*(7) fs  nfft/Tw  fmin fmax iifft iiout iift iimt iidc iimf
      200    -2.5   10  50    1    0    0    0    0    0
-----
For iifft=1, iiout=1, or iimf>0, enter src depths, rec depths, ranges:
*(8) nzs zsl zs2 (m) ... nzs zr1 zr2 (m) ... nr r1 r2 (km) ...
      1 100 1 200 -20 .05 10
-----
PARAMETER STUDY (iiparm=1 on Line 1):
nrun   = # of CW mode runs;
nparm  = # of parameters to vary;
rseed  = Random # seed (integer) [0=none (vary linearly from vall to val2)];
obt    = Medium (0=ocean, 1=bottom layers, 2=top layers);
nlay   = Layer #;
ktb    = Bottom/Top of Layer (1=top, 2=bottom, neg=maintain gradient);
pc     = Parm Code (0=h, 1=cp, 2=cs, 3=rho, 4=ap, 5=as);
vall, val2 = First, Last Values of Parameter;
*(9) nrun nparm rseed [(obt nlay ktb pc vall val2), j=1, nparm]
      10    1    0    0    1    2    0    200    100
-----
S/R GEOM FOR SRC TRACK AND REC ARRAY (iitl=2 on Line 4 or iifft=2 on Line 8)
*(10) zs  n_src_seg  'array_geom_file_name'
      20    1    'nosc_v1'
-----
Source Track: v~m/s; t,dt~min; cpa,x,y~km; phi~deg E of N (see manual)
      1 iic  v    t1    t2 +dt/-nt  cpa  phi                (POLAR FORM)
*(11) 2 iic  v    t1    t2 +dt/-nt  x1   y1   x2   y2                (X-Y FORM)
      1  0  5    0    60 -100    2   45
-----
==> k-PLANE IMAGES (iikpl>0 on Line 1)
iiivar = Variable to Image [1=R1*R2, 2=d(R1*R2)/dk, 3=d(R1*R2)/dw];
iikf   = Form for kr,ki (1=k/kmin, 2=k, 3=kr~kr/kmin,ki~dB/km);
kdud   = Duct Number for Reference Depth (0 for min cp in ocean);
iihp   = Phase Wrap (1=-180,180; 2=0,360);
iishp,iishs = Riemann Sheet for p/s Branch Cuts (+1 or -1);
*(12) freq iiivar iikf  kr1  kr2  nkr  ki1  ki2  nki nduct iiph iishp iishs
      25    1    1    .8  1.0  101  .1  0  101  0    2    1    1
-----
==> REFLECTION COEFFICIENT VS f (Hz) AND GRAZING ANGLE (deg)
R vs Frequency and Angle (iirc=1 on Line 1):
*(13) freq1  freq2  nfreq  iilog  theta1  theta2  ntheta
      10    50    41    0    90    0    91
-----
FFT File of R vs. Frequency and Angle (iirc=2 on Line 1):
*(14) freq1  freq2    fs  nfft  theta1  theta2  ntheta
      10    50    100  512    90    0    91

```


- (i) N_{zr} is the number of receiver depths. Enter a positive number to list depths sequentially, or a negative number to list the first and last values with $|N_{zr}|$ evenly spaced values.
- (4) Receiver array specification for $II_{ARR} = 2$.**
- Specification of the (x, y) locations of the receivers. One set of the following items must be given for each of the N_{zr} depths given in Line (3).
 - (i) N_{xy} is the number of receivers in the (x, y) plane at the current depth.
 - (ii) $x_1, y_1; x_2, y_2; \dots, x_{N_{xy}}, y_{N_{xy}}$ are the (x, y) locations of the N_{xy} receivers at the current depth.
- (5) Average sound speed.**
- This item is not used by ORCA.

TABLE 2.3: Example array geometry file.

```

### ARRAY GEOMETRY FILE FOR ORCA NORMAL MODE MODEL ###
### ENTER DATA AFTER LINES WITH * IN FIRST COLUMN ###
### USE OTHER LINES FOR COMMENTS ###
*(1) RECEIVER ARRAY SPECIFICATION: IIARR (1=uniform, 2=nonuniform)
2
IIARR=1: uniformly spaced receiver array
*(2) zr1 nx ny nz dx dy dz [dx,dy,dz are element spacings in m]
    271. 1 1 1 20. 20. 20.
IIARR=2: receiver depths in m (nZR>0 ==> List zr's; nZR<0 ==> List first,last zr):
*(3) nZR zr1 zr2 ...
    1 100
IIARR=2: specify (x,y) receiver positions in m for each of the nZR depths:
*(4) nxy x(1),y(1) x(2),y(2) ... x(nxy),y(nxy) [nZR pairs]
16 -80,0 -70,0 -60,0 -50,0 -40,0 -30,0 -20,0 -10,0
    10,0 20,0 30,0 40,0 50,0 60,0 70,0 80,0
*(5) Average sound speed (not needed for ORCA)
1500.0

```

3. RUNNING ORCA

To run ORCA, create a file named **orca_in**, place the name of the desired **SVP** file on the first line, the name of the desired **OPT** file on the second line, and the name of the output file root on the third line. Then run the model by executing ORCA. A summary file with suffix **_out** is always produced. The file contains the starred lines and the lines read from the input files so that a new run with exactly those parameters may be made at a later date. It also contains the date and time the run was made, the amount of CPU time taken for the run, and any informative or warning messages produced during the run. For CW mode runs, a file with the suffix **_modes** is also produced and contains a list of the modes found. The output data files

for the HDF, Matlab, and ASCII formats have the suffixes **_hdf**, **.mat**, and **_asc**, respectively. HDF and Matlab files should be FTPed in binary mode. The names of the other output files have the following suffixes: **_eig** for the text file containing the mode list, and **_fft** for the binary file containing the source-receiver transfer functions.

4. OUTPUT FILES

4.1 The **_fft** Output File

An **_fft** file is generated when $iiff > 0$ in Line (7) or when $iirc = 2$ in Line (1) of the **OPT** file. The **_fft** file contains the transfer functions for each source-receiver range. The program opens the file with the FORTRAN statement:

```
open(16,file=nnn_fft,access='direct',recl=4*(22+NFBINS)) ,
```

where $NFBINS$ is the number of frequency bins at which the field has been calculated.

The file is generated by the following FORTRAN direct-access file write commands:

```
write(16,rec=irec) (XH(j),j=1,20),(conjg(TF(j)),j=NF1,NF2) ,
```

where $XH(20)$ is a real*4 header, TF is the complex*8 array containing the transfer function from frequency f_{\min} to f_{\max} . The transfer function indices are computed as

$$NF1 = \text{nint}((f_{\min} / f) + 1); NF2 = \text{nint}((f_{\max} / f) + 1), \quad (4.1)$$

where $f = f_s / N_{\text{FFT}}$. For each source-receiver range, the **_fft** file contains a 20-word header and an $NFBINS$ -word complex transfer function.

Note that the conjugate of the field computed by ORCA is written to the **_fft** file. The suppressed time dependence of the original acoustic field is $\exp(-i\omega t)$. Conjugation just before output changes the time dependence to $\exp(i\omega t)$. As a result the inverse discrete Fourier transform of the spectrum in the **_fft** file should be performed using the kernel $\exp(-i\omega t)$.

The 20-word `_fft` file header contains the following information:

TABLE 4.1: Structure of `_fft` file header.

Index	Variable	Index	Variable
1	-1	11	No. of Receivers N_{rec} or N_{zr}
2	0	12	1
3	Source Number	13	0
4	Receiver Number	14	T_{ref}
5	N_{FFT}	15	First Frequency Bin Offset: $NF1 - 1$
6	f_s	16	Last Frequency Bin Offset: $NF2 - 1$
7	No. of Frequency Bands (set to 1)	17	Source-receiver range R in m
8	0	18	z_r
9	0	19	z_s
10	0	20	No. of Source Positions

The reference time T_{ref} in Word 14 indicates the time at which the impulse response (the inverse FFT of the transfer function) begins relative to an impulse at time zero at the source. T_{ref} is chosen so that a mode whose group velocity is the minimum p-wave sound speed in the water arrives 10% of the way into the time window. For each source position, the reference time T_{ref} is the same for all receivers. Thus one can perform crosscorrelations between receivers without the need to time delay the FFT files.

An FFT with its header is written for each source-receiver pair. For `iifft=1` the number of receivers is taken to be the number of receiver depths N_{zr} specified in Line (8), and the number of source positions is taken to be the number of ranges N_r . The order in which the FFTs appear is as follows: for each source position along the source track, an FFT is output for each of the N_{rec} receivers in the array.

5. HINTS FOR RUNNING ORCA

5.1 Preparing the SVP File

When applying the ORCA model to a particular acoustic propagation problem, the first step is to create the **SVP** file appropriate for the area being modeled. The sound velocity profile in the water column may be obtained from a database or from measurements. The geo-

coustic profile of the ocean bottom may be obtained from the BLUG database, from seismic studies of the area, or from the literature. A classic reference for geoacoustic modeling appears in Ref. 5.

Before finalizing the **SVP** file, it is worthwhile to study a plot of the SVP and eliminate points that are not needed. ORCA will do this automatically if c_{tol} in Line (3) is set to a positive number, such as 0.5 or 1.0 m/s.

The BLUG database⁶ for ocean bottom geoacoustic parameters was compiled by fitting ray model calculations to experimental measurements of bottom loss. Bottom loss was obtained by detonating shots and frequency-averaging the received spectra. The database provides the following geoacoustic parameters for the sediment layer:

- (1) The ratio of the sound speeds at the sediment surface and the water above it, c_{p1}/c_w ,
- (2) The surface density ρ_1 (assume $\rho_2 = \rho_1$ if no other information is available),
- (3) The initial sound velocity gradient g ,
- (4) The curvature parameter β for the p-wave sound speed profile,
- (5) The surface compressional wave attenuation a_{p1} ,
- (6) The attenuation gradient, from which one may obtain a_{p2} , and
- (7) The basement reflection coefficient, which is not usable by ORCA.

The sediment layer thickness h is not given and must be obtained from the two-way travel time τ_2 . An approximate formula to convert τ_2 to thickness h is (see Sec. IE of Ref. 5):

$$h = \frac{c_{p1}(e^{\bar{g}\tau_2/2} - 1)}{\bar{g}}, \quad (5.1)$$

where \bar{g} is the average gradient in the layer. Shear speeds and attenuations are not available from the database. Unusually high p-wave attenuations may be an indication that shear wave speeds are significant and cause high loss.

Also given in the BLUG description of the ocean bottom are the thickness and density of a thin layer above the sediment. Except for the density, the thin layer is assumed to have the same parameters as the surface of the sediment layer. The thin layer was included in the database to account for anomalously low bottom losses observed at certain sites and at certain (steep) angles and (high) frequencies. When the density of the thin layer is unrealistically high, it is an indication that mechanisms outside the scope of the BLUG database are responsible.

When a BLUG profile is specified, ORCA finds the maximum difference c_{\max} between the BLUG profile and the $1/c^2$ linear profile assumed by ORCA. If $c_{\max} > c_{\text{tol}}$ [given in Line (6)(xiv)], then the layer is subdivided at the depth where c_{\max} was found. The procedure is then repeated on all the layers produced until the $1/c^2$ linear profiles match the BLUG profile within c_{tol} m/s. Recommended values for c_{tol} are 5–20 m/s.

5.2 Preparing the OPT File

The second step in preparing to run ORCA is to edit the **OPT** file. For mode computations, the only inputs that require special consideration are the mode parameters on Line (2). For the inexperienced user, all these parameters may be set to the default value of 0, in which case ORCA chooses conservative, but reasonable, values for the parameters.

Two of the parameters on Line (2), $c_{ph\max}$ and r_{\min} , are similar in that they are used to determine how many modes are computed. To compute the correct field at short ranges, more modes (having higher attenuations and, usually, higher phase velocities) need to be found and included in the mode summation. Only one of the two parameters may be used to determine when the mode search is terminated. The best (and strongly recommended) approach is to set $c_{ph\max} = 0$, which eliminates the phase velocity criterion, and to set r_{\min} to the minimum range for which an accurate field is required. Setting $r_{\min} = 0$ causes ORCA to compute r_{\min} automatically from the source-receiver geometry specified (for TL calculations, for example). Using r_{\min} to limit the mode search causes ORCA to check the imaginary parts of the eigenvalues and ignore modes that have too much attenuation at the minimum range of interest. When positive, r_{\min} should not be set to a value lower than is actually required since more computations will be required.

Setting $r_{\min} = -n$ causes ORCA to limit the number of modes to n . This option is *not* recommended because, for multiple duct environments, the first n modes found may not be the first n modes in order of increasing phase velocity. Limiting the number of modes using the $c_{ph\max}$ or negative r_{\min} parameters is only recommended when the user desires to compare results with another model or to artificially limit the number of modes or source aperture.

The $c_{ph\min}$ parameter on Line (2) allows the user to request that seismic and interface modes be found. Under typical circumstances, it is recommended that $c_{ph\min}$ be set to 0, in which case only the usual modes that propagate in the water column are found. Only when the ocean bottom is elastic, the frequency is low (such that few or no trapped modes are present), and the source and receiver are within a wavelength or two of the bottom is it recom-

mended that the seismic and interface modes be requested (by setting $c_{phmin} = -1$). When $c_{phmin} = -1$, the mode search is started at a phase speed of $0.9c_{smin}$, where c_{smin} is the minimum shear speed in the environment. c_{phmin} is *not* meant to be used to ignore low-order trapped modes; therefore it should not be set to a value above the minimum water sound speed.

The final three parameters on Line (2) are straightforward. r_{max} is used to determine how accurately each mode eigenvalue k_n needs to be found and should be set to the maximum range at which the field is computed. ORCA uses the r_{max} parameter to assure that the phase error in the complex exponential $\exp(ik_n r_{max})$ is less than $2\pi/360$, or 1° . However, setting r_{max} somewhat higher than necessary does not significantly increase computation time. The *phfac* option determines the step size ORCA uses in going from one mode to the next in the complex k plane. It is recommended to set *phfac*=0, which results in the default value of 4. Experienced users may wish to use values of 8–32 in order to obtain finely sampled mode trajectory plots or to check that no additional modes are found. Finally, the *db_cut* parameter should be set to a value between 30 and 60, where higher values result in greater accuracy. Set *db_cut*=0 to obtain the default value of 50 dB.

When entering source-receiver geometries (and ocean sound speed profiles), the user should keep in mind that depths are taken to be in m, while ranges are taken to be in km. The most common mistakes are to give r_{min} , r_{max} , or source-receiver ranges in m rather than km. Another common mistake is in specifying multiple frequencies, depths, or ranges. When uniformly spaced sets are desired, the convention is to set the integer to a negative number and specify the first and last values. Positive integers imply that all the values will be listed.

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3. The HDF library and documentation may be obtained from NSCA via telnet at the address "ftp.ncsa.uiuc.edu". The only subroutines that use the HDF library are in out_writex.f, which may be modified to output any type of format desired.

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