OASES
Version 3.1
User Guide and Reference Manual

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Contents

1 Introduction

OASES is a general purpose computer code for modeling seismo-acoustic propagation in horizontally stratified waveguides using *wavenumber integration* in combination with the *Direct Global Matrix* solution technique [1, 2, 3]. It is basically an upgraded version of SAFARI [4]. Compared to SAFARI version 3.0 distributed by SACLANTCEN, OASES provides improved numerical efficiency, and the global matrix mapping has been re-defined to ensure unconditional numerical stability in the few extreme cases where the original SAFARI has proved unstable. OASES is downward compatible with SAFARI, and the preparation of input files follows the guidelines of the SAFARI manual [4]. The SAFARI manual focused on VMS implementation, but this note will assume UNIX to be the operating system. However, the bulk of the code is operating system independent and is easily implementyed under VMS, MS-DOS etc.

2 Installing OASES

OASES is available on all nodes of the computational environment of the MIT/WHOI acoustics group. The information on installation provided in this section is therefore only intended for recipients of new export versions. The MIT/WHOI user should proceed to Section 3.

2.1 Loading OASES files

For recipients running UNIX, the whole OASES directory tree will be shipped in compressed **tar** files, compressed with the standard `compress` and `gzip` utilities, respectively.

```
oases.tar.Z
oases.tar.gz
```

The "export" subset of oases is available via anonymous ftp from `ftp@keel.mit.edu.` or via the World-wide-Web: *ftp://keel.mit.edu/pub/oases/* The files are placed in the `pub/oases` directory, which also contains a `README` file..

To install, download the tar file(s) in your desired root directory $HOME and issue the commands

```
uncompress oases.tar.Z
tar xvf oases.tar
mv oases_export oases # Only for Export package
```

or, if you use `gzip` use the command

```
gunzip -c oases.tar.gz | tar xvf -
mv oases_export oases # Only for Export package
```

which will install the directory tree:

$HOME/oases	OASES root directory
$HOME/oases/src	Source files for 2-D OASES
$HOME/oases/src3d	Source files for 3-D OASES
$HOME/oases/bin	OASES scripts and destination of executables
$HOME/oases/lib	Destination of OASES libraries
$HOME/oases/tloss	Data files for OAST
$HOME/oases/pulse	Data files for OASP
$HOME/oases/rcoef	DATA files for OASR
$HOME/oases/plot	Source files for FIPPLOT
$HOME/oases/contour	Source files for CONTUR
$HOME/oases/mindis	MINDIS graphics library
$HOME/oases/pulsplot	Source files for Pulse Post-Processor
$HOME/oases/doc	This document in LaTeX format

2.2 Building OASES Package

Version 2.1 shipped after May 5, 1997 have a new Master `Makefile` in the oases root directory $HOME/oases, which automatically detects the platform type and sets compiler options accordingly. The only modification needed to this file is the specification of the `bin` and `lib` directories for the executables and libraries, respectively. The defaults are $HOME/oases/bin and $HOME/oases/lib. For Linux platforms a few aditional changes may necessary, as described below. The entire package is installed by the statement

```
make all
```

which will recursively execute all the individual makefiles in the package.

In version 2.3 shipped after Feb. 11, 2000 the makefile `$HOME/oases/Makefile` uses the environment variables `$HOSTTYPE` and `$OSTYPE` to determine platform-specific compiler flags, object and library paths etc.. This allows for using a single OASES root directory on networks with different platform and operating systems, for example Alpha workstations running either OSF or Linix. The following platform/OS combinations are supported at present:

`alpha-osf1`	Alpha workstations running OSF1
`alpha-linux`	Alpha workstations running Linux
`decstation`	DEC RISC workstations (e.g. 5000/240)
`sun4`	SUN SPARC workstations
`i386-linux-linux`	PC platforms running Linux
`i486-linux-linux`	PC platforms running Linux
`iris4d`	SGI workstations

Any other platform is easily added by editing `Makefile` as described in the following section.

Once the package is built, include the executable directory in your path, e.g. in your `.cshrc` file:

```
setenv OASES_SH ${HOME}/Oases/bin                    # OASES scripts
setenv OASES_BIN ${OASES_SH}/${HOSTTYPE}-${OSTYPE} # OASES executables
set path = ( $OASES_SH $OASES_BIN $path )
```

2.2.1 Compiler Definitions

The compiler options are set in the master makefile **Makefile** in the OASES root directory. Hosts not supported may by added by including in `Makefile` a block with the compiler/linker definitions, e.g. for a `HOSTTYPE hosttype`, running `OSTYPE ostype`

```
############################################################
#
# host-type Workstations
#
############################################################
#
# Compiler flags
#
# Fortran statement
FC.hosttype-ostype = f77
# CC Flags
CFLAGS.hosttype-ostype = -O
# Linker/loader flags
LFLAGS.hosttype-ostype =
# ranlib definition
RANLIB.hosttype-ostype = ranlib
# Additional run-time libraries
LIB_MISC.hosttype-ostype =
# Run-time library emulation
MISC.hosttype-ostype =
#
```

The default works on most platforms, but for LINUX some changes may be necessary, depending on which compiler you are using. For example, if you use the Absoft FORTRAN compiler on a Linux box `(HOSTTYPE = i386-linux, OSTYPE = linux)`, then the Linux header in Makefile should look as follows:

```
############################################################
#
# PC HARDWARE RUNNING LINUX
#
############################################################
#
# Compiler flags
#
#
# For the ABSOFT FORTRAN compiler, un-comment the following
# lines:
#
FC.i386-linux-linux = f77  -f -s -N2 -N9 -N51
LIB_MISC.i386-linux-linux = -lV77 -lU77
MISC.i386-linux-linux =
#
# For the standard F2C FORTRAN compiler, un-comment the following
# lines:
#
# FC.i386-linux-linux = fort77
# LIB_MISC.i386-linux-linux =  $(LIBDIR)/libsysemu.a
# MISC.i386-linux-linux = misc.done
#
CFLAGS.i386-linux-linux = -I/usr/X11R6/include
LFLAGS.i386-linux-linux = -L/usr/X11R6/lib
RANLIB.i386-linux-linux = ranlib
```

After performing the changes, set the default directory to the OASES root directory, and compile and link by issuing the command:

```
make objdir
make all
```

2.2.2 Parameter settings

If the default parameter settings are insufficient they may be altered in the parameter include file

```
$OASES_ROOT/src/compar.f
```

The controling parameters are

Parameter	Description	Default
NLA	Max number of layers	200
NPEXP	Max number of wavenumber and time samples is 2^{NPEXP}	16
NRD	Max number of receiver depths	101

2.3 Building PLOTMTV

PLOTMTV is a public domain package, producing high quality colour graphics. It is available on the OASES web site:

`<ftp://keel.mit.edu/pub/Plotmtv/>`

Download the two files:

```
Plotmtv1.4.1.tar.gz
mtvpatch.tar.gz
```

Place these two files in a temporary directory, e.g. `/tmp`. Then execute the commands:

```
gunzip -c Plotmtv1.4.1.tar.gz | tar xvf -
gunzip -c mtvpatch.tar.gz | tar xvf -
```

Then follow the instructions in the README file. Once you have executed the `make` command, remember to move the executable `plotmtv` to a directory in your path, e.g. `/usr/local/bin`.

3 System Settings

Before using `OASES` you must change your `.login` to properly.

3.1 Executable Path

First of all, include the directory containing the `OASES` scripts and executables in your `path`, e.g using the statement

```
setenv OASES_SH ${HOME}/Oases/bin                     # OASES scripts
setenv OASES_BIN ${OASES_SH}/${HOSTTYPE}-${OSTYPE} # OASES executables
set path = ( $OASES_SH $OASES_BIN $path )
```

In the MIT/WHOI computational environment the paths to the OASES executables and scripts are

Node	Path	CPU
keel	/keel0/henrik/Oases/bin	Alpha OSF
boreas	/keel0/henrik/Oases/bin	Alpha Linux
frosty1	/fr1/henrik/Oases/bin	Alpha OSF
frosty2	/fr1/henrik/Oases/bin	PC Linux
frosty3	/fr3/henrik/bin	PC Linux
arctic	/keel0/henrik/Oases/bin	Alpha OSF
acoustics	/keel0/henrik/Oases/bin	PC Linux
reverb	/reverb0/henrik/Oases/bin	PC Linux
vibration	/reverb0/henrik/Oases/bin	PC Linux
sonar	/keel0/henrik/Oases/bin	Alpha Linux
monopole	/dipole0/henrik/Oases/bin	Alpha Linux
dipole	/dipole0/henrik/Oases/bin	PC Linux

3.2 Environmental Parameters

You may want to set your terminal type to avoid having to specify it everytime you use `mplot` or `cplot`. If you are running X-windows, set the DISPLAY environmental variable properly and insert the statement

```
setenv USRTERMTYPE X
```

in your `.login` file or simply type it in if you are not usually using X-windows.

If you are running from a Tektronix 4100-series terminal or emulator, replace 'X' by 'tek4105'. Similarly, for the Tektronix 4000-series, replace 'X' by 'tek4010' or 'tek4014'.

The default contour package is MINDIS, creating black and white line contour plots. To make PLOTMTV your default contour package, execute the command, either manually or in your `.login` file:

```
#
# MTV environment
#
setenv CON_PACKGE MTV
setenv MTV_WRB_COLORMAP "ON"
setenv MTV_COLORMAP hot
setenv MTV_PRINTER_CMD "lpr"
setenv MTV_PSCOLOR "ON"
```

The 'hot' colour scale is chosen in this case, overwriting the WRB colorscale which is a red-to-blue colorscale close to the classical one used e.g. in acoustics, e.g. in Ref. [3]. The other variables should be self-explanatory. The 'hot' colourscale has the advantage that it yields a gradual greytone scale when printed on a b/w printer. The default MATLAB color scale is 'jet'.

Similarly, version 2.1 and later include a filter `plp2mtv` which translates the line plot `plp` and `plt` files to an `mtv` file and executes `plotmtv.` This filter may be used directly as a plot command instead of `mplot file`

```
plp2mtv file
```

Alternatively, `plotmtv` may be chosen as the default line plot package used by the `mplot` command by setting an environment variable:

```
setenv PLP_PACKGE MTV
```

It should be noted that some `mplot` options may not be fully supported by `plp2mtv.`

4 OASES - General Features

4.1 Environmental Models

OASES supports all environmental models available in SAFARI, i.e. any number and combination of isovelocity fluids, fluids with sound speed gradients and isotropic elastic media. In addition, as a new feature any number of transversely isotropic layers may be specified (all with vertical symmetry axis). Further, media with general dispersion characteristics can be included.

Version 2.0 of OASES in addition allows for stratifications including an arbitrary number of poro-elastic layers, with the propagation described by Biot's theory. This modification has been performed by Morrie Stern [5] at the University of Texas at Austin, in collaboration with Nick Chotiros and Jim tencate at ARL/UT. Nick and Morrie suggested I include their modifications in the general OASES export package, for the use and benefit of the general underwater acoustics community. This is a significant additional capability of OASES, and the contribution of the Austin group in that regard is highly appreciated.

4.1.1 Transversily Isotropic Media

A transversely isotropic layer is flagged by stating the usual parameter line for the layer:

$$D \quad c_c \quad c_s \quad \alpha_c \quad \alpha_s \quad \rho \quad \gamma \quad [L]$$

with $c_c < 0$ as a flag. Here only the interface depth D has significance. The other parameters for the transversely isotropic layer should then follow in one of two ways, depending on the value of c_c:

$c_c = -1$: The medium is specified as a periodic series of thin layers as per Schoenberg:

NC						Number of constituents (≤ 3)
c_c	c_s	α_c	α_s	ρ	h	Speeds, attns., density, fraction
c_c	c_s	α_c	α_s	ρ	h	Speeds, attns., density, fraction

$c_c = -2$: The 5 complex elastic constants and the density of the transversely isotropic medium are specified directly after the flagged layer line:

Value	Value	Units
Re(C_{11})	Im(C_{11})	Pa
Re(C_{13})	Im(C_{13})	Pa
Re(C_{33})	Im(C_{33})	Pa
Re(C_{44})	Im(C_{44})	Pa
Re(C_{66})	Im(C_{66})	Pa
ρ		g/cm3

If option **Z** was specified in the option line, then a slowness diagram is produced for each transversely isotropic layer.

4.1.2 Dispersive Media

For pulse problems where causality is critical, non-zero attenuation must be accompanied by frequency-dependent wave speeds. Since this is of main importance for seismic problems with relatively high attenuation, the specification of dispersive wave speeds has been limited to elastic media only. A dispersive layer is again flagged by a negative value of c_c:

$c_c = -3$: A dispersive layer is specified as followsin the file **input.dat**:

$D \quad -3 \quad 0 \quad 0 \quad 0 \quad \rho \quad \gamma \quad [L]$

LTYP

The only significant parameters for the layer are the depth D, the density ρ and the roughness parameters γ and L. The parameter **LTYP** is a type-identifier for the layer. The frequency dependence of the wave speeds and attenuations should be specified in the file **input.dis**, which may contain several dispersion laws. The file should contain a block of data in the form of a frequency table, for each value of **LTYP** specified in **input.dat**, with the first block corresponding to **LTYP** = 1, the second corresponding to **LTYP** = 2 etc. The format for each block is asfollows:

```
NF                                                # Number of freqs.
F(1)     CC(1)     CS(1)     AC(1)     AS(1)     # Freq, speeds, atten.
F(2)     CC(2)     CS(2)     AC(2)     AS(2)     # Freq, speeds, atten.
 :         :         :         :         :
F(N)     CC(N)     CS(N)     AC(N)     AS(N)     # Freq, speeds, atten.
```

The table does not have to be equidistant. OASES will interpolate to create a table consistent with the frequency sampling specified in **input.dat**.

4.1.3 Porous Media

As an additional feature of the OASES 2.0 environmental model layers modelled as fluid saturated porous media (Biot model) may be included with other layer types. The Biot model and its implementation is described in Appendix A.

A porous sediment layer is flagged by stating the usual parameter line for the layer in the environmental data block:

$$D \quad c_c \quad c_s \quad \alpha_c \quad \alpha_s \quad \rho \quad \gamma \quad [L]$$

with negative values for both c_c and c_s. Only the interface depth D has significance and must be stated correctly; the other parameters listed on this data line are dummy. This line is immediately followed by a line containing the 13 parameters specifying the properties of the porous sediment layer in the order:

$$\rho_f \quad K_f \quad \eta \quad \rho_g \quad K_r \quad \phi \quad \kappa \quad a \quad \mu \quad K \quad \alpha_s \quad \alpha_c \quad c_m$$

where

ρ_f	is the density of the pore fluid in $\mathrm{g/cm^3}$
K_f	is the bulk modulus of the pore fluid in Pa
η	is the viscosity of the pore fluid in kg/m-s
ρ_g	is the grain (solid constituent) density in $\mathrm{g/cm^3}$
K_r	is the grain bulk modulus in Pa
ϕ	is the sediment porosity
κ	is the sediment permeability in $\mathrm{m^2}$
a	is the pore size factor in m
μ	is the sediment frame shear modulus in Pa
K	is the sediment frame bulk modulus in Pa
α_s	is the sediment frame shear attenuation
α_c	is the sediment frame bulk attenuation
c_m	is a dimensionless virtual mass parameter

The sediment frame properties pertain to the drained structure and are assumed to be dissipative. In particular, for harmonic motion the frame shear and bulk moduli are taken to be complex in the form $\tilde{\mu} = \mu(1+i\mu')$, $\tilde{K} = K(1+iK')$. The imaginary parts of the moduli are specified through $\alpha_s = 20\pi\mu' \log e$ and $\alpha_c = 20\pi K' \log e$ where α_s corresponds to the attenuation measured in dB/Λ of shear waves in the sediment frame (as in the data specification for elastic layers) when the attenuation is low; α_c is related to the attenuation of both compression and shear waves. However, it should be noted that in contrast to the elastic layer case, the Biot porous sediment model will yield complex wavespeeds even if the frame is elastic since dissipation is inherent in the relative motion of the pore fluid with respect to the frame.

The pore size parameter a is treated as an empirical constant which depends on the average grain size and shape; for spherical grains of diameter d the value $a = \phi d/3(1-\phi)$ has been suggested[6]. The virtual mass parameter c_m (called the 'structure factor' or 'tortuosity' by some authors and often denoted α) is also treated as an empirical constant which depends on the pore structure of the frame. For moderate frequencies (long wave length compared to 'average pore size') and porosities from 25% to 50%, Yavari and Bedford[7] have made finite element calculations which suggest that Berryman's relation $c_m = 1 + 0.227(1-\phi)/\phi$ may be used in the absence of more reliable data. More thorough discussions of the material parameters defining the Biotmodel may be found in other references[8].

If the **K** option is invoked, then recievers in a porous sediment layer will output (negative) pore fluid pressure rather than bulk stress as called for in other fluid or solid layers. The **Z** option, which creates a velocity profile plot, shows the zero frequency limit wavespeeds in porous sediment layers. Note that at present the modifications do NOT permit sources in Biot layers.

The following presents a modification of SAFARI-FIP case 3 to replace the elastic sediment layer by a poro-elastic layer,

```
SAFARI-FIP case 3. Poroelastic.
N C A D J
30 30 1 0
5
  0    0      0     0   0   0   0
  0 1500   -999.999 0   0   1   0 # SVP continuous at z = 30 m
 30 1480 -1490      0   0   1   0
100 -1 -1 0 0 0 0 0               # Cp<0 Cs<0 flag poro-elastic layer
1 2.E9 .001 2.65 9.E9 .4 2.E-9 1.E-5 3.13E8 5.14E9 .8 1.55 1.25
120 1800   600      0.1 0.2 2.0 0

50
0.1 120 41 40
1350 1E8
-1 1 950
0 5 20 1
20 80 12 10
0 120 12 20
40 70 6
```

4.1.4 Continuous Sound Speed Profiles

OASES version 1.7 allows for specifying a continuous sound speed profile through a flag rather than specifying the negative of the actual value at the bottom of the layer in the shear speed field as in SAFARI (OASES still supports this form also). The flag specification is particularly useful when running through many values of sound speed at a certain depth, such as for matched field inversion for SVP.

The continuity of the SVP at the *bottom of a layer* is activated by the usual parameter line for the layer:

$$D \quad c_c \quad c_s \quad \alpha_c \quad \alpha_s \quad \rho \quad \gamma \quad [L]$$

with $c_s = -999.999$ as a flag, i.e. by setting the shear speed for the layer to -999.999. All OASES modules will then set the sound speed at the bottom of the layer equal to the speed specified for the top of the next layer below.

As an example, the following is the OAST file `saffip3.dat` corresponding to the SAFARI test case 3 with the SVP being continuous at 30 m depth:

```
SAFARI-FIP case 3
N C A D J
30 30 1 0
5
  0    0      0      0   0   0   0
  0 1500  -999.999 0   0   1   0 # SVP continuous at z = 30 m
 30 1480 -1490     0   0   1   0
100 1600   400     0.2 0.5 1.8 0
120 1800   600     0.1 0.2 2.0 0

50
0.1 120 41 40
1350 1E8
-1 1 950
0 5 20 1
20 80 12 10
0 120 12 20
40 70 6
```

4.1.5 Stratified Fluid Flow

OASES version 1.8 allows for computing the field in stratified flow. This option is only valid in the 2-D versions, handling flow parallel to the direction of propagation only (downstream or upstream). Flow is only allowed in *isovelocity fluid layers*!

The flow is activated by specifying the usual parameter line for the layer:

$$D \quad c_c \quad c_s \quad \alpha_c \quad \alpha_s \quad \rho \quad \gamma \quad [L]$$

with $\alpha_s = -888.888$ as a flag, i.e. by setting the shear attenuation for the layer to -888.888. The flow speed in m/s is in a separate line immidiately following the layer data line.

The sign convention is *positive* for *flow from source to receiver (downstream propagation)* and *negative* for *flow from receiver towards source (upstream propagation).*

As an example, the following is the OAST file `saffip1.dat` corresponding to the SAFARI test case 1 with a flow in the water column of 5 m/s towards the source (upstream propagation):

```
SAFARI FIP case 1. Flow -5 m/s.
J N I T
5 5 1 0
4
  0    0    0     0    0      0   0
  0 1500    0     0 -888.888 1.0 0
-5.0                              # flow speed 5 m/s towards source
100 1600  400     0.2  0.5   1.8 0
120 1800  600     0.1  0.2   2.0 0
95
100 100 1 1
200 1E8
-1 1 1000
0 5.0 20 1.0
20 80 12 10
```

5 OASR: OASES Reflection Coefficient Module

OASR is downward compatible with SAFARI-FIPR Version 3.0 and higher, and therefore supports all options and features described in the SAFARI manual. A couple of new options have been added.

5.1 Input Files for OASR

The input data are structured in 9 blocks. The first 5 blocks, shown in Table 1, specify the title, options, environmental parameters, together with the desired grazing angle and frequency sampling. The last 4 blocks, outlined in Tables 1 and 2, contain axis specifications for the graphical output. Some of these blocks should always be included and others only if certain options have been specified. The single blocks and parameters are described in detail in the following.

5.1.1 Block I: Title

The title printed on all graphic output generated by OAST.

5.1.2 Block II: OASR options

In addition to supporting the SAFARI options described in [4], OASR supports several new options.

- B This option replaces the default P-P wave reflection or transmission coefficient by the P-Slow wave coefficient. Only allowed for Biot layers.
- C Loss contours plotted in frequency and grazing angle.
- L Generates a plot of reflection loss in dB in addition to the default linear magnitude plot vs frequency or angle.
- N This is the default option, which therefore never needs to be specified. It calculates the P-P reflection loss as function of angle and frequency.
- P Phase angle of reflection coefficient plotted in addition to the default magnitude.
- S This option replaces the default P-P wave reflection or transmission coefficient by the P-SV wave reflection coefficient.

Input parameter	Description	Units	Limits
BLOCK I: TITLE			
TITLE	Title of run	-	$\leq$ 80 ch.
BLOCK II: OPTIONS			
A B C	Output options	-	$\leq$ 40 ch.
BLOCK III: ENVIRONMENT			
NL	Number of layers, incl. halfspaces	-	NL≥ 2
D,CC,CS,AC,AS,RO,RG,CL	D: Depth of interface.	m	-
.	CC: Compressional speed	m/s	CC≥ 0
.	CS: Shear speed	m/s	-
.	AC: Compressional attenuation	dB/Λ	AC≥ 0
.	AS: Shear attenuation	dB/Λ	AS≥ 0
	RO: Density	g/cm^3	RO≥ 0
	RG: RMS value of interface roughness	m	-
	CL: Correlation length of roughness	m	CL> 0
	M: Spectral exponent		¿ 1.5
BLOCK IV: FREQUENCY SAMPLING			
FMIN,FMAX,NRFR,NFOU	FMIN: Minimum frequency	Hz	FMIN> 0
	FMAX: Maximum frequency	Hz	FMAX> 0
	NRFR: Number of frequencies	-	NRFR≥ 1
	NFOU: Plot output increment	-	NFOU≥ 0
BLOCK V: ANGLE/SLOWNESS SAMPLING			
AMIN,AMAX,NRAN,NAOU	AMIN: Minimum angle/slowness	dg/(s/km)	AMIN≥ 0
	AMAX: Maximum angle/slowness	dg/(s/km)	AMAX≥ 0
	NRAN: Number of angles/slownesses	-	NRAN≥ 1
	NAOU: Plot output increment	-	NAOU≥ 0
BLOCK VI: ANGLE/SLOWNESS AXES			
ALEF,ARIG,ALEN,AINC	ALEF: Left border, angle/slws axis	dg/(s/km)	-
RALO,RAUP,RALN,RAIN	ARIG: Right border, angle/slws axis	dg/(s/km)	-
(only for NFOU> 0)	ALEN: Length of angle/slws axis	cm	ALEN> 0
	AINC: Distance between tick marks	dg/(s/km)	AINC> 0
	RALO: Lower border of R-loss axis	dB	-
	RAUP: Upper border of R-loss axis	dB	-
	RALN: Length of loss and phase axes	cm	RALN> 0
	RAIN: R-loss axis tick mark interval	dB	RAIN> 0

Table 1: Layout of OASR input files: I. Calculation and plot parameters.

Input parameter	Description	Units	Limits
BLOCK VII: LOSS/FREQUENCY AXES			
FLEF,FRIG,FLEN,FINC	FLEF: Left border of frequency axis	Hz	-
RFLO,RFUP,RFLN,RFIN	FRIG: Right border of frequency axis	Hz	-
(only for NAOU> 0)	FLEN: Length of frequency axis	cm	FLEN> 0
	FINC: Distance between tick marks	Hz	FINC> 0
	RFLO: Lower border of R-loss axis	dB	-
	RFUP: Upper border of R-loss axis	dB	-
	RFLN: Length of loss and phase axes	cm	RALN> 0
	RFIN: R-loss axis tick mark interval	dB	RAIN> 0
BLOCK VIII: LOSS CONTOUR PLOTS (Option C)			
ALEF,ARIG,ALEN,AINC	ALEF: Left border, angle/slws axis	dg/(s/km)	-
FRLO,FRUP,OCLN,NTKM	ARIG: Right border, angle/slws axis	dg/(s/km)	-
ZMIN,ZMAX,ZINC	ALEN: Length of angle/slws axis	cm	ALEN> 0
(only for option C)	AINC: Distance between tick marks	dg/(s/km)	AINC> 0
	FRLO: Lower border of frequency axis	Hz	FRLO> 0
	FRUP: Upper border of frequency axis	Hz	FRUP> 0
	OCLN: Length of one octave	cm	OCLN> 0
	NTKM: Number of tickmarks pr octave	-	NTKM> 0
	ZMIN: Minimum contour level	dB	-
	ZMAX: Maximum contour level	dB	-
	ZINC: Contour level increment	dB	ZINC> 0
BLOCK IX: SVP AXES			
VLEF,VRIG,VLEN,VINC	VLEF: Wave speed at left border	m/s	-
DVUP,DVLO,DVLN,DVIN	VRIG: Wave speed at right border	m/s	-
(only for option Z)	VLEN: Length of wave speed axis	cm	VLEN> 0
	VINC: Wave speed tickmark distance	m/s	VINC> 0
	DVUP: Depth at upper border	m	-
	DVLO: Depth at lower border	m	-
	DVLN: Length of depth axis	cm	DVLN> 0
	DVIN: Depth axis tickmark distance	m	DVIN> 0

Table 2: Layout of OASR input files: II. Plot parameters.

T Generates a table of computed complex reflection coefficients. The file is in ASCII format and will be given the same name as the input file, but extension `.rco` .

Z Plot of velocity profiles.

p Calculates and plots reflection coefficients vs horizontal slowness rather than the default grazing angle. This option allows for computing "reflection coefficients" in the evanescent regime. When this option is specified, the sampling in Block V should be given in slowness in s/km, and similarly for the plot parameters in Blocks VI and VIII.

s Generates a file with boundary discontinuities for the rough interfaces. Used by OASS for computing scattering kernels.

t Computes transmission coefficients instead of the default reflection coefficients. The transmission coefficients refer to the lowermost halfspace.

5.1.3 Block IV: Environmental Model

OASR supports all the environmental models allowed for SAFARI as well as the ones described above in Section 4.1. The significance of the standard environmental parameters is as follows

NL: Number of layers, including the upper and lower half-spaces. These should Always be included, even in cases where they are vacuum.

D: Depth in m of upper boundary of layer or halfspace. The reference depth can be choosen arbitrarily, and D() is allowed to be negative. For layer no. 1, i.e. the upper half-space, this parameter is dummy.

CC: Velocity of compressional waves in m/s. If specified to 0.0, the layer or half-space is vacuum.

CS: Velocity of shear waves in m/s. If specified to 0.0, the layer or half-space is fluid. If CS()<0, it is the compressional velocity at bottom of layer, which is treated as fluid with $1/c(z)^2$ linear.

AC: Attennuation of compressional waves in dB/λ. If the layer is fluid, and AC() is specified to 0.0, then an imperical water attenuation is used (Skretting & Leroy).

AS: Attenuation of shear waves in dB/λ

RO: Density in g/cm^3.

RG: RMS roughness of interface in m. RG(1) is dummy. If RG<0 it represents the negative of the RMS roughness, and the associated correlation length CL and spectral exponent should follow. If RG>0 the correlation length is assumed to be infinite.

CL: Roughness correlation length in m.

M: Spectral exponent of the power spectrum as defined by Turgut [25], with $1.5 < \mathrm{M} \leq 2.5$ for realistic surfaces, with $\mathrm{M} = 1.5$ corresponding to the highest roughness, and $\mathrm{M} = 2.5$ being a very smooth variation. For 2-D Goff-Jordan surfaces, the fractal dimension is $\mathrm{D} = 4.5 - \mathrm{M}$ Insignificant for Gaussian spectrum (option **g** not specified) but a value must be given.

5.2 Execution of OASR

As for FIPR, filenames are passed to OASR via environmental parameters. In Unix systems a typical command file **oasr** (in $HOME/oases/bin) is:

```
#                              the pound sign invokes the C-shell
setenv FOR001 $1.dat         # input file
setenv FOR019 $1.plp         # plot parameter file
setenv FOR020 $1.plt         # plot data file
setenv FOR028 $1.cdr         # contour plot parameter file
setenv FOR029 $1.bdr         # contour plot data file
setenv FOR022 $1.rco         # reflection coefficient table
setenv FOR023 $1.trc         # reflection coefficient table
setenv FOR045 $1.rhs         # scattering output file
oasr1                        # executable
```

After preparing a data file with the name **input.dat**, OASR is executed by the command:

\> **oasr input**

5.3 Graphics

Command files are provided in a path directory for generating the graphics.

To generate curve plots, issue the command:

\> **mplot input**

To generate contour plots, issue the command:

\> **cplot input**

5.4 Output Files

With option **T** specified, OAST will generate a file 'input'.rco containg the magnitude $|R|$ and phase ϕ of the complex reflection coefficient $R = |R| \exp \phi$. Assume you add option T to `saffipr1.dat` , and also add option p to select slowness sampling:

```
SAFARI FIPR case 1.
P Z T p
3
0 1500 0 0 0 1 0
0 1600 400 0.2 0.5 1.8 0
20 1800 600 0.1 0.2 2.0 0
50 50 1 1
0.1 4.0 200 0              # Slowness sampling 0.1 - 4 s/km
0 4 20 1                   # Slowness axes
0 15 12 5
0 2000 10 1000
-20 40 10 20
```

Then, after issuing the command

> **oasr saffipr1**

the file `saffipr1.rco` will be generated:

```
      50.000      50.000   1   1
       50.000   200  # Frequency, # of slownesses
       0.100000       0.339462     -15.996886
       0.119598       0.342714     -15.640528
       0.139196       0.346415     -15.196492
       0.158794       0.350498     -14.655071
       0.178392       0.354880     -14.006412
       0.197990       0.359469     -13.240785
       0.217588       0.364159     -12.349057
       0.237186       0.368833     -11.322515
       0.256784       0.373363     -10.153061
       0.276382       0.377615      -8.832868
       0.295980       0.381445      -7.354058
       0.315578       0.384707      -5.707997
       0.335176       0.387249      -3.883928
       0.354774       0.388919      -1.867177
```

```
   .               .               .
   .               .               .
   .               .               .
```

Note that the reflection coefficients are listed vs *horizontal slowness* in s/km, and phase angles are stated in *degrees*.

Another output file `input.trc` will be generated, identical to the `input.rco` file, except for the reflection coefficients being listed vs grazing angle in degrees. The format of both these output files is compatible with the one required by `OAST` as input for options `t` and `b` . The file `input.trc` generated by the input file above is as follows

```
50.000      50.000   1   2  # fr1, fr2, nf, slowns/angle(1/2)
 50.000   200               # Frequency, # of angles
81.373070       0.339462     -15.996886
79.665359       0.342714     -15.640528
77.948311       0.346415     -15.196492
76.220207       0.350498     -14.655071
74.479210       0.354880     -14.006412
72.723396       0.359469     -13.240785
70.950676       0.364159     -12.349057
69.158813       0.368833     -11.322515
67.345337       0.373363     -10.153061
65.507576       0.377615      -8.832868
63.642544       0.381445      -7.354058
61.746929       0.384707      -5.707997
59.816971       0.387249      -3.883928
57.848427       0.388919      -1.867177
   .               .               .
   .               .               .
   .               .               .
```

Note that the slowness/angle sampling is identified by the last number in the first line, with 1 indicating slowness sampling, and 2 indicating angle sampling.

5.5 OASR - Examples

As an example of the use of OASR for computing seismo-acousticreflection coefficients, the following datafile reproduces the results presented for a sand bottom in Stoll and Kan's paper [22]:

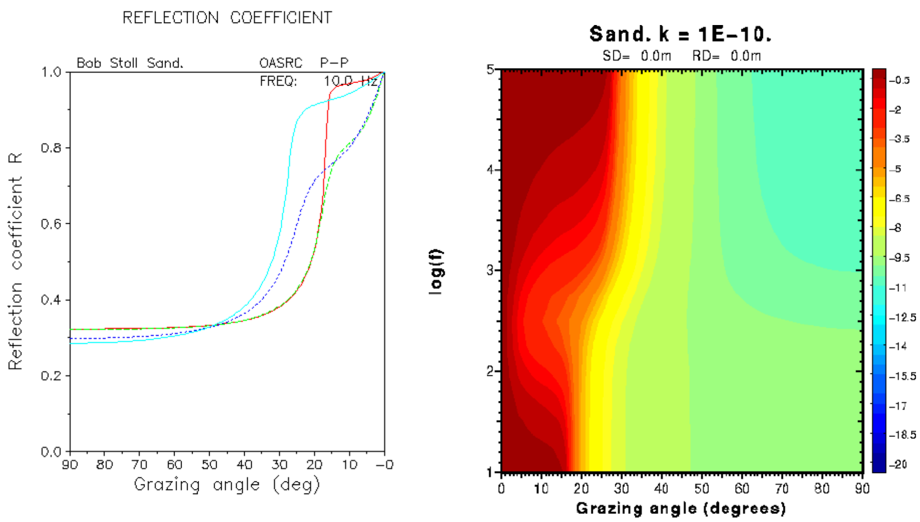

Figure 1: Reflection coefficients vs frequency and angle for porous sand halfspace, reproducing results of Stoll and Kan.

```
Sand. Stoll and Kan 81.
N C Z
2
0 1414 0 0 0 1 0
0 -1800 -600 0.1 0.2 2.0 0
1. 2.E9 .001 2.65 3.6E10 .47 1.E-10 3.9E-5 2.61E7 4.36E7 1.3 1.3 1.25
10 100000 17 4
0 90 181 0
90 0 10 10
0 15 12 5
0 90 12 15
10 100000 1 1
1 20 0.5
0 2000 12 500
-10 10 12 5
```

Assembled in one plot, Fig. 1, the resulting reflection coeffiecients at the 5 frequencies 0.01, 0.1, 1, 10, and 100 kHz reproduce exactly the results shown in Fig. 4 of Stoll and Kan's paper. In addition, the datafile produces the contour plot in Fig. 1 of reflection coefficients vs angle and frequency.

OASES handles arbitrary poro-elastic stratifications, and Fig. 2(a) shows the equivalent frequency-angle contours of the reflection coefficient of a 1 m thick layer of sand overlying

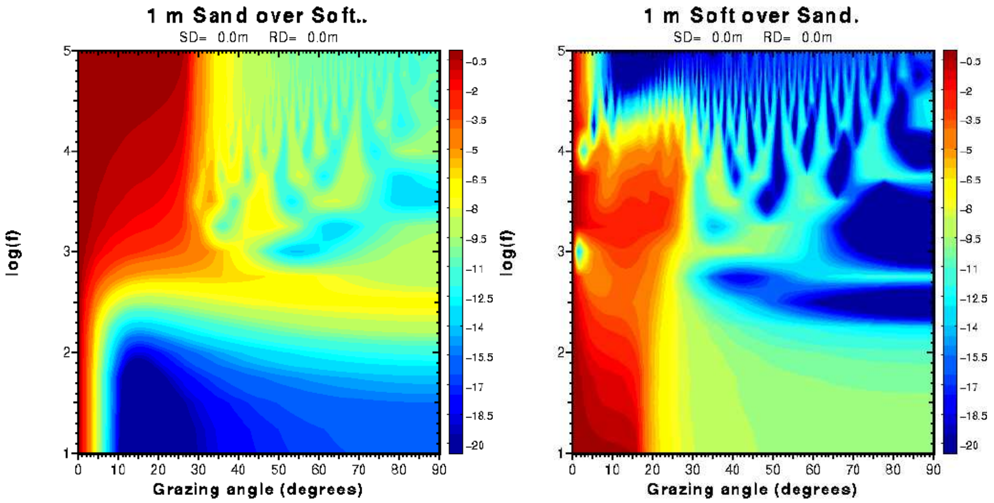

Figure 2: Reflection coefficients vs frequency and angle for (a) a 1 meter layer of porous sand overlying a "soft" halfspace, and (b) a 1 meter thick "soft" layer overlying a sand halfspace. Prameters for both media are consistent with those given by Stoll and Kan.

Stoll and Kan's "soft" sediment. Similarly Fig. 2b) shows the reflection coefficients for a 1 meter "soft" layer over sand. The datafile for generating Fig. 2(a) is

```
1 m Sand over Soft.
N C Z
3
0 1414 0 0 0 1 0
0 -1800 -600 0.1 0.2 2.0 0
1. 2.E9 .001 2.65 3.6E10 .47 1.E-10 3.9E-5 2.61E7 4.36E7 1.3 1.3 1.25
1.0  -1800 -600 0.1 0.2 2.0 0
1. 2.E9 .001 2.65 3.6E10 .76 1.6E-15 1.56E-7 2.21E7 3.69E7 4.3 4.3 1.25
10 100000 17 4
0 90 181 0
90 0 10 10
0 15 12 5
0 90 12 15
10 100000 1 1
1 10 0.5
0 2000 12 500
-10 10 12 5
```

6 OAST: OASES Transmission Loss Module

Except for the specification of frequencies, OAST is downward compatible with SAFARI-FIP Version 3.0 and higher, and therefore supports all options and features described in the SAFARI manual. In addition to improved speed and stability, OAST offers several new options.

6.1 Input Files for OAST

The input files for OAST is structured in 12 blocks, as outlined in Tables 3 and 4. In the following we describe the significance of the various blocks, with particular emphasis on differences between SAFARI-FIP and OAST.

6.1.1 Block I: Title

The title printed on all graphic output generated by OAST.

6.1.2 Block II: OAST options

In addition to supporting the SAFARI options described in [4], OAST supports a wide suite of new options.

- **A** Depth-averaged transmission loss plotted for each of the selected field parameters. The averaging is performed over the specified number of receivers (block VI).
- **C** Range-depth contour plot for transmission loss. Only allowed for one field parameter at a time.
- **F** In versions earlier than 2.3a Filon-FFT is applied to evaluate the wavenumber integrals instead of the default FFP. However, this overestimates the transmission loss and provides no benefit for transmission loss calculations if the sampling criteria are satisfied. In fact it yields up to 3 dB error for automatic sampling and has therefore been disabled in the newer versions of OAST.
- **G** Rough interfaces are assumed to be characterized by a Goff-Jordan power spectrum rather than the default Gaussian.
- **H** Horizontal velocity calculated.
- **I** Hankel transform integrands are plotted for each of the selected field parameters.

Input parameter	Description	Units	Limits
BLOCK I: TITLE			
TITLE	Title of run	-	$\leq$ 80 ch.
BLOCK II: OPTIONS			
A B C $\cdots$	Output options	-	$\leq$ 40 ch.
BLOCK III: FREQUENCIES			
FR1,FR2,NF,COFF,[V]	FR1: First frequency	Hz	> 0
	FR2: Last frequency	Hz	> 0
	NF: Number of frequencies		> 0
	COFF: Integration contour offset	dB/Λ	COFF≥ 0
	V: Source/receiver velocity (only for option d)		
BLOCK IV: ENVIRONMENT			
NL	Number of layers, incl. halfspaces	-	NL≥ 2
D,CC,CS,AC,AS,RO,RG,CL	D: Depth of interface.	m	-
.	CC: Compressional speed	m/s	CC≥ 0
.	CS: Shear speed	m/s	-
.	AC: Compressional attenuation	dB/Λ	AC≥ 0
.	AS: Shear attenuation	dB/Λ	AS≥ 0
	RO: Density	g/cm^3	RO≥ 0
	RG: RMS value of interface roughness	m	-
	CL: Correlation length of roughness	m	CL> 0
	M: Spectral exponent		¿ 1.5
BLOCK V: SOURCES			
SD,NS,DS,AN,IA,FD,DA	SD: Source depth (mean for array)	m	-
	NS: Number of sources in array	-	NS> 0
	DS: Vertical source spacing	m	DS> 0
	AN: Grazing angle of beam	deg	-
	IA: Array type	-	1 $\leq$IA$\leq$ 5
	FD: Focal depth of beam	m	FD$\neq$SD
	DA: Dip angle. (Source type 4).	deg	-
BLOCK VI: RECEIVERS			
RD1,RD2,NR,IR	RD1: Depth of first receiver	m	-
	RD2: Depth of last receiver	m	RD2>RD1
	NR: Number of receivers	-	NR> 0
	IR: Plot output increment	-	IR≥ 0
BLOCK VII: WAVENUMBER SAMPLING			
CMIN,CMAX	CMIN: Minimum phase velocity	m/s	CMIN> 0
	CMAX: Maximum phase velocity	m/s	-
NW,IC1,IC2	NW: Number of wavenumber samples	-	NW$= 2^M, -1(auto)$
	IC1: First sampling point	-	IC1≥ 1
	IC2: Last sampling point	-	IC2$\leq$NW

Table 3: Layout of OAST input files: I. Computational parameters.

Input parameter	Description	Units	Limits
BLOCK VIII: RANGE AXES			
RMIN,RMAX,RLEN,RINC	RMIN: Minimum range on plots	km	-
	RMAX: Maximum range on plots	km	-
	RLEN: Length of x-axis for all plots	cm	RLEN> 0
	RINC: Distance between tick marks	km	RINC> 0
BLOCK IX: TRANSMISSION LOSS AXES (Only for Options A,D,T)			
TMIN,TMAX,TLEN,TINC	TMIN: Minimum transmission loss	dB	-
	TMAX: Maximum transmission loss	dB	-
	TLEN: Length of vertical TL axes	cm	TLEN> 0
	TINC: Distance between tick marks	dB	TINC> 0
BLOCK X: DEPTH AXES (Only for Options C,D)			
DUP,DLO,DLN,DIN	DUP: Min. depth for plots	m	-
	DLO: Max. depth for plots	m	-
	DLN: Length of depth axes	cm	DCLN> 0
	DIN: Distance between tick marks	m	DCIN> 0
BLOCK XI: CONTOUR LEVELS (Only for Option C,f)			
ZMIN,ZMAX,ZINC	ZMIN: Minimum contour level	dB	-
(	ZMAX: Maximum contour level	dB	-
	ZINC: Contour level increment	dB	ZINC> 0
BLOCK XII: SVP AXES (Only for Option Z)			
VLEF,VRIG,VLEN,VINC	VLEF: Wave speed at left border	m/s	-
DVUP,DVLO,DVLN,DVIN	VRIG: Wave speed at right border	m/s	-
	VLEN: Length of wave speed axis	cm	VLEN> 0
	VINC: Wave speed tick mark distance	m/s	VINC> 0
	DVUP: Depth at upper border	m	-
	DVLO: Depth at lower border	m	-
	DVLN: Length of depth axis	cm	DVLN> 0
	DVIN: Depth axis tick mark distance	m	DVIN> 0

Table 4: Layout of OAST input files: II. Plot parameters.

J Complex integration contour. The contour is shifted into the upper halfpane by an offset controlled by the input parameter COFF (Block III).

K Computes the bulk pressure. In elastic media the bulk pressure only has contributions from the compressional potential. In fluid media the bulk pressure is equal to the acoustic pressure. Therefore for fluids this option yields the negative of the result produced by option N or R.

L Linear vertical source array.

N Normal stress σ_{zz} ($= -p$ in fluids) calculated.

P Plane geometry. The sources will be line-sources instead of point-sources as used in the default cylindrical geometry.

R Computes the radial normal stress σ_{rr} (or σ_{xx} for plane geometry).

S Computes the stress equivalent of the shear potential in elastic media. This is an angle-independent measure, proportional to the shear potential, with no contribution from the compressional potential (in contrast to shear stress on a particular plane). For fluids this option yields zero.

T Transmission loss plotted as function of range for each of the selected field parameters.

V Vertical velocity calculated.

Z Plot of velocity profile.

a Angular spectra of the integration kernels are plotted. A $0 - 90°$ axis is automatically selected representing the grazing angle ($0°$ corresponds to horizontal propagation). NOTE: The same wavenumber corresponds to different grazing angles in different media!. The vertical axis is selected automatically, representing the angular density (as opposed to the wavenumber density for integrand plots (option I).

b Solves the depth-separated wave equation with the lowermost interface condition expressed in terms of a complex reflection coefficient. The reflection coefficient must be tabulated in a input file `input.trc` which may either be produced from experimental data or by the reflection coefficient module OASR as described on Page 30. See also there for the file format. The lower halfspace must be specified as vacuum and the last layer as an isovelocity fluid without sources for this option. Add dummy layer if necessary. Further, the frequency sampling must be consistent. Therefore, if this option is combined with option `f` , the input file must have cosistent logarithmic sampling. Using `OASR` this is optained by using option `C` with the same minimum and maximum frequencies, and number of frequencies. Note: Care should be taken using this option with a complex integration contour, option `J` . The tabulated reflection coefficient must clearly correspond to the same imaginary wavenumber components for `OAST` to yield proper results. `OASR` calculates the reflection coefficient for real horizontal wavenumbers.

c Contours of integration kernels as function of horizontal wavenumber (abcissa) and receiver depth (ordinate). The horizontal wavenumber axis is selected automatically, whereas the depth axis is plotted according to the parameters given for option C. The contour levels are determined automatically.

d Source/receiver dynamics. OAST v 1.7 handles the problem of source and receiver moving through the waveguide at the same speed and direction. The velocity projection V onto the line connecting source and receiver must be specified in Block III, as shown in table 3. Since source and receiver are moving at identical speeds there is no Doppler shift, but the Green's function is different from the static one, as described by Schmidt and Kuperman[9].

f A full Hankel transform integration scheme is used for low values of kr and tapered into the FFP integration used for large kr. The compensation is achieved at very low computational cost and is recommended highly for cases where the near field is needed.

o Contours of transmission loss plotted vs frequency and range, i.e. the traditional 'optimum frequency' contour plots. Requires NFREQ > 1 (see below). A logarithmic frequency axis is assumed for this option. Requires ZMIN, ZMAX and ZINC to be specified in Block XII (same contour levels as for option **C** which may be specified simultaneously).

g Rough interfaces are assumed to be characterized by a Goff-Jordan power spectrum rather than the default Gaussian (Same as G).

l User defined source array. This new option is similar to option **L** in the sense that that it introduces a vertical source array of time delayed sources of identical type. However, this option allows the depth, amplitude and delay time to be be specified individually for each source in the array. The source data should be provided in a separate file, **input.src**, in the format described below in Section 6.1.5.

s Outputs the mean field discontinuity at a rough interface to the file 'input'.rhs for input to the reverberation model OASS.

t Solves the depth-separated wave equation with the top interface condition expressed in terms of a complex reflection coefficient. The reflection coefficient must be tabulated in a input file `input.trc` which may either be produced from experimental data or by the reflection coefficient module `OASR` as described on Page 30. See also there for the file format. The upper halfspace must be specified as vacuum and the first layer as an isovelocity fluid without sources for this option. Add dummy layer if necessary. Further, the frequency sampling must be consistent. Therefore, if this option is combined with option `f` , the input file must have cosistent logarithmic sampling. Using `OASR` this is optained by using option `C` with the same minimum and maximum frequencies, and number of frequencies. Note: Care should be taken using this option with a complex integration contour, option `J` . The tabulated reflection coefficient must clearly correspond to the same imaginary wavenumber components for `OAST` to yield proper results. `OASR` calculates the reflection coefficient for real horizontal wavenumbers.

Number $(1-4)$ specifying the source type (explosive, forces, moment) as described in Section 6.1.5

6.1.3 Block III: Frequencies

A frequency loop has been incorporated in OAST to allow for computation of transmission loss over a wide frequency band in one run. The frequency specification (Block III in SAFARI Manual) has therefore been changed to:

```
FR1 FR2 NF COFF [V]
```

where FR1 and FR2 are the minimum and maximum frequencies, respectively. NF is the number of frequencies, spaced equidistantly between FR1 and FR2, except if option **f** was specified; then the frequencies will be spaced logarithmically. COFF is the complex wavenumber integration contour offset. To be specified in dB/λ, where λ is the wavelength at the source depth SD. As only the horizontal part of the integration contour is considered, this parameter should not be chosen so large, that the amplitudes at the ends of the integration interval become significant. In lossless cases too small values will give sampling problems at the normal modes and other singularities. For intermediate values, the result is independent of the choice of COFF, but a good value to choose is one that gives 60 dB at the longest range considered in the FFT, i.e.

$$\mathrm{COFF} = \frac{60 * \mathrm{CC(SD)}}{(\mathrm{FREQ} * \mathrm{R}_{max})}$$

where the maximum FFT range is

$$\mathrm{R}_{max} = \frac{\mathrm{NP}}{\mathrm{FREQ} * (1/\mathrm{CMIN} - 1/\mathrm{CMAX})}$$

This value is the default which is applied if COFF is specified to 0.0.

The optional parameter V is the identical speed of source and receiver relative to the medium, projected onto the radial vector connecting them. This parameter is only used for option **d**.

6.1.4 Block IV: Environmental Model

OAST supports all the environmental models allowed for SAFARI as well as the ones described above in Section 4.1. The significance of the standard environmental parameters is as follows

NL: Number of layers, including the upper and lower half-spaces. These should Always be included, even in cases where they are vacuum.

D: Depth in m of upper boundary of layer or halfspace. The reference depth can be choosen arbitrarily, and D() is allowed to be negative. For layer no. 1, i.e. the upper half-space, this parameter is dummy.

CC: Velocity of compressional waves in m/s. If specified to 0.0, the layer or half-space is vacuum.

CS: Velocity of shear waves in m/s. If specified to 0.0, the layer or half-space is fluid. If CS()< 0, it is the compressional velocity at bottom of layer, which is treated as fluid with $1/c(z)^2$ linear.

AC: Attennuation of compressional waves in dB/λ. If the layer is fluid, and AC() is specified to 0.0, then an imperical water attenuation is used (Skretting & Leroy).

AS: Attenuation of shear waves in dB/λ

RO: Density in g/cm^3.

RG: RMS roughness of interface in m. RG(1) is dummy. If RG< 0 it represents the negative of the RMS roughness, and the associated correlation length CL and spectral exponment M should follow. If RG> 0 the correlation length is assumed to be infinite.

CL: Roughness correlation length in m.

M: Spectral exponent of the power spectrum as defined by Turgut [25], with $1.5 <$ M ≤ 2.5 for realistic surfaces, with M $= 1.5$ corresponding to the highest roughness, and M $= 2.5$ being a very smooth variation. For 2-D Goff-Jordan surfaces, the fractal dimension is D $= 4.5 -$ M Insignificant for Gaussian spectrum (option **g** not specified) but a value must be given.

6.1.5 Block V: Sources

OAST supports the same sources as SAFARI-FIP, i.e explosive sources in fluids or solids or vertical point forces in solids (option X). Multible sources in a vertical array are supported. If sources with horizontal directionality are desired, the 3-dimensional version OASP3D must be used. The significance of the source parameters are as follows

SD: Source depth in m. If option 'L' has been specified, then SD defines the mid-point of the vertical source array.

NS: Number of sources in the array.

DS: Source spacing in m.

AN: Specifies the nominal grazing ANG of the generated beam in degrees. $ANG > 0$ corresponds to downward propagation.

IA: Array type

1. Rectangular weighted array
2. Hanning weighted array
3. Hanning weighted focusing array
4. Gaussian weighted array
5. Gaussian weighted focusing array

FD: Focal depth in m for an array of type 3 and 5.

DA: Dip angle in degrees for dip-slip sources (type 4).

Source Types

As in SAFARI the default source type in OAST is an explosive type compressional source. In addition to the optional vertical point force, and axisymmetric seismic moment source has been added to OAST. The source type is specified by a number $(1-3)$ in the option field (line 2). The translation is as follows:

1. Explosive source (default) normalized to unit pressure at 1 m distance.

2. Vertical point force with amplitude 1 N.

3. Horizontal (in-plane) point force with amplitude 1 N.

4. Dip-slip source with seismic moment 1 Nm. Dip angle specified in degrees in block V, following the other parameters.

5. Omnidirectional seismic moment source representing explosive source. Same as type 1, but all three force dipoles have seismic moment 1 Nm.

Source Normalization

In SAFARI, the source strength was normalized to yield unit pressure (in Pa) at a distance of 1 m from the source (for solids the negative of the normal stress 1 m below the source).

In OASES, the same source normalization has been maintained for point sources (explosive sources) in fluid media. For solid media, however, the sources are normalized to unit volume (1 m^3) injection for explosive sources and unit force 1 N for point sources or 1 N/m for line sources.

User defined Source Arrays

Version 1.6 of OAST has been upgraded to allow a user-defined source array through option **l**.

Option **l** is intended for general physical arrays with uneven spacing or special shadings, As for the built-in arrays, such user-defined arrays may be present in fluid as well as elastic media. The array definition should be given in the file **input.src** in the following format

```
LS
SDC(1)  SDELAY(1)  SSTREN(1)    # Depth (m), Delay (s), Amplitude
SDC(2)  SDELAY(2)  SSTREN(2)
SDC(3)  SDELAY(3)  SSTREN(3)
  :         :          :
  :         :          :
SDC(LS) SDELAY(LS) SSTREN(LS)
```

6.1.6 Block VI: Receivers

The default specification of the receiver depths is the same as for SAFARI, i.e. through the parameters RD1, RD2, NR and IR in Block VI, with

RD1 Depth of uppermost receiver in m

RD2 Depth of lowermost receiver in m

NR Number of receiver depths

IR Depth increment for options I and T

By default, the NR receivers are placed equidistantly in the vertical.

Non-equidistant Receiver Depths

In OASES the receiver depths can optionally be specified individually. The parameter NR is used as a flag for this option. Thus, if NR $<$ 0 the number of receivers is interpreted as –NR, with the individual depths following immidiately following Block VI. As an example, SAFARI FIP case 2 with receivers at 100, 105 and 120 m is run with the following data file:

```
SAFARI-FIP case 2.
N I T J Z
30 30 1 0
5
```

```
  0    0      0 0   0   0   0
  0 1500 -1480 0   0   1   0
 30 1480 -1490 0   0   1   0
100 1600   400 0.2 0.5 1.8 0
120 1800   600 0.1 0.2 2.0 0
50
100 100 -3 1        # 3 receiver depths
100.0 105.0 120.0             # Receiver depths in meters
700 1E8
1024 1 512
 0  5 20  1
20 80 12 10
1450 1550 10 25
   0  100 10 20
```

6.1.7 Block VII: Wavenumber Integration

This block specifies the wavenumber sampling in the standard SAFARI format. The critical issues involved in selecting the wavenumber sampling is described in the SAFARI manual [4], but even more detailed in *Computational Ocean Acoustics* [3]. The structure of this input block is as follows:

CMIN: Minimum phase velocity in m/s. Determines the upper limit of the truncated horizontal wave- number space:

$$k_{max} = \frac{2\pi * \text{FREQ}}{\text{CMIN}}$$

CMAX: Maximum phase velocity in m/s. Determines the lower limit of the truncated horizontal wave- number space:

$$k_{min} = \frac{2\pi * \text{FREQ}}{\text{CMAX}}$$

In plane geometry (option P) CMAX may be specified as negative. In this case, the negative wavenumber spectrum will be included with $k_{min} = -k_{max}$, yielding correct solution also at zero range. In contrast to SAFARI, OAST allows for complex contour integration (option J) in this case.

NW: Number of sampling points in wavenumber space. Should be an integer power of 2, i.e. NWN= 2^m. The sampling points are placed equidistantly in the truncated wavenumber space determined by CMIN and CMAX.

IC1: Number of the first sampling point, where the calculation is to be performed. If IC1> 1, then the Hankel transform is zeroed for sampling points 1,2. . .IC1-1, and the discontinuity is smoothed.

IC2: Number of the last sampling point where the calculation is to be performed. If IC2<NWN, then the Hankel transform is zeroed for sampling points IC2+1,. . .NW, and the discontinuity is smoothed by Hermite polynomial extrapolation.

Automatic wavenumber sampling

OAST Version 1.5 has been supplied with an automatic sampling feature, making it possible for inexperienced users to obtain correct answers in the first attempt without the usual convergence testing. The automatic sampling is activated by specifying the parameter NW = -1 and it automatically activates the complex wavenumber integration contour even though option J may not have been specified. The parameters IC1 and IC2 have no effect if the automatic sampling is selected.

As an example, to run the SAFARI-FIP case 2 problem with automatic sampling, change the data file as follows:

```
SAFARI-FIP case 2. Auto sampling.
N I T J Z
30 30 1 0
5
  0    0      0 0    0   0   0
  0 1500 -1480 0    0   1   0
 30 1480 -1490 0    0   1   0
100 1600   400 0.2 0.5 1.8 0
120 1800   600 0.1 0.2 2.0 0
50
100 100 1 1
1300 1E8                        # CMIN = 1300
-1 0 0                          # NW   =   -1
 0  5 20  1
20 80 12 10
1450 1550 10 25
   0  100 10 20
```

6.2 Execution of OAST

As for SAFARI, filenames are passed to the code via environmental parameters. In Unix systems a typical command file **oast** (in $HOME/oases/bin) is:

```
#                              the pound sign invokes the C-shell
setenv FOR001 $1.dat         # input file
setenv FOR002 $1.src         # Source array input file
setenv FOR019 $1.plp         # plot parameter file
```

```
setenv FOR020 $1.plt        # plot data file
setenv FOR023 $1.trc        # reflection coefficient table (input)
setenv FOR028 $1.cdr        # contour plot parameter file
setenv FOR029 $1.bdr        # contour plot data file
setenv FOR045 $1.rhs        # file for scattering discontinuities
oast2                       # executable
```

After preparing a data file with the name **input.dat**, OAST is executed by the command:

> **oast input**

6.3 Graphics

Command files are provided in a path directory for generating the graphics.

To generate curve plots, issue the command:

> **mplot input**

To generate contour plots, issue the command:

> **cplot input**

7 RDOAST: OASES Range-dependent TL Module

RDOAST is the **range-dependent** version of OAST. RDOAST uses a Virtual Source Approach for coupling the field between range-independent sectors, basically using a *vertical source/receiver array*, and a *single-scatter*, *local plane wave* handling of vertical discontinuities. In contrast to the similar approach of the elastic PE, VISA properly handles seismic conversion at the vertical boundaries. The solutions compare extremely well with PE solutions for week contrast problems, and with full boundary integral approaches for several canonical elastic benchmark problems [20, 21].

7.1 Input Files for RDOAST

The input files for RDOAST are very similar to those of OAST , with the main differences being the extra environmental blocks, and two receiver specifications, one for the marching source/receiver array and contour plots, and one for TL vs range etc. As for OAST, the input file is structured in 12 blocks, as outlined in Tables 5 and 6.

7.1.1 Block I: Title

The title printed on all graphic output generated by RDOAST.

7.1.2 Block II: RDOAST options

In addition to supporting all the OAST options, RDOAST has a few additional ones.

A Depth-averaged transmission loss plotted for each of the selected field parameters. The averaging is performed over the specified number of receivers (block VI).

B Computes backscattered field in single-scatter approximation.

C Range-depth contour plot for transmission loss. Only allowed for one field parameter at a time.

F This option activates the FFP integration within each sector. The default is direct integration. Use option F only in cases where each sector has a large number of receiver ranges ($\Delta R = 2\pi/(k_{max} - k_m in)$). Note that the effect of this option is different than in OAST.

G Rough interfaces are assumed to be characterized by a Goff-Jordan power spectrum rather than the default Gaussian.

Input parameter	Description	Units	Limits
BLOCK I: TITLE			
TITLE	Title of run	-	$\leq$ 80 ch.
BLOCK II: OPTIONS			
A B C $\cdots$	Output options	-	$\leq$ 40 ch.
BLOCK III: FREQUENCIES			
FR1,FR2,NF,COFF,[V]	FR1: First frequency	Hz	> 0
	FR2: Last frequency	Hz	> 0
	NF: Number of frequencies		> 0
	COFF: Integration contour offset	dB/Λ	COFF≥ 0
	V: Source/receiver velocity (only for option d)		
BLOCK IV: ENVIRONMENT			
NSEC	Number of sectors	-	NSEC≥ 1
NL, SECL	Sector 1: No. layers, length	-, km	NL≥ 2
D,CC,CS,AC,AS,RO,RG,CL	D: Depth of interface.	m	-
.	CC: Compressional speed	m/s	CC≥ 0
.	CS: Shear speed	m/s	-
.	AC: Compressional attenuation	dB/Λ	AC≥ 0
.	AS: Shear attenuation	dB/Λ	AS≥ 0
	RO: Density	g/cm^3	RO≥ 0
	RG: RMS value of interface roughness	m	-
	CL: Correlation length of roughness	m	CL> 0
NL, SECL	Sector 2: No. layers, length	-, km	NL≥ 2
D,CC,CS,AC,AS,RO,RG,CL			-
.			
.			
BLOCK V: SOURCES			
SD,NS,DS,AN,IA,FD,DA	SD: Source depth (mean for array)	m	-
	NS: Number of sources in array	-	NS> 0
	DS: Vertical source spacing	m	DS> 0
	AN: Grazing angle of beam	deg	-
	IA: Array type	-	$1 \leq$IA≤ 5
	FD: Focal depth of beam	m	FD$\neq$SD
	DA: Dip angle. (Source type 4).	deg	-
BLOCK VI: RECEIVERS			
RD1,RD2,NR	RD1: Depth of first receiver	m	-
	RD2: Depth of last receiver	m	RD2>RD1
	NR: Number of receivers	-	NR> 0
D1,D2,ND:	Depth sampling opt I, T etc.		
BLOCK VII: WAVENUMBER SAMPLING			
CMIN,CMAX	CMIN: Minimum phase velocity	m/s	CMIN> 0
	CMAX: Maximum phase velocity	m/s	-
NW,IC1,IC2	NW: Number of wavenumber samples	-	NW$= 2^M, -1(auto)$
	IC1: First sampling point	-	IC1≥ 1
	IC2: Last sampling point	-	IC2$\leq$NW

Table 5: Layout of RDOAST input files: I. Computational parameters.

Input parameter	Description	Units	Limits
BLOCK VIII: RANGE AXES			
RMIN,RMAX,RLEN,RINC	RMIN: Minimum range on plots	km	-
	RMAX: Maximum range on plots	km	-
	RLEN: Length of x-axis for all plots	cm	RLEN> 0
	RINC: Distance between tick marks	km	RINC> 0
BLOCK IX: TRANSMISSION LOSS AXES (Only for Options A,D,T)			
TMIN,TMAX,TLEN,TINC	TMIN: Minimum transmission loss	dB	-
	TMAX: Maximum transmission loss	dB	-
	TLEN: Length of vertical TL axes	cm	TLEN> 0
	TINC: Distance between tick marks	dB	TINC> 0
BLOCK X: DEPTH AXES (Only for Options C,D)			
DUP,DLO,DLN,DIN	DUP: Min. depth for plots	m	-
	DLO: Max. depth for plots	m	-
	DLN: Length of depth axes	cm	DCLN> 0
	DIN: Distance between tick marks	m	DCIN> 0
BLOCK XI: CONTOUR LEVELS (Only for Option C,f)			
ZMIN,ZMAX,ZINC	ZMIN: Minimum contour level	dB	-
(	ZMAX: Maximum contour level	dB	-
	ZINC: Contour level increment	dB	ZINC> 0
BLOCK XII: SVP AXES (Only for Option Z)			
VLEF,VRIG,VLEN,VINC	VLEF: Wave speed at left border	m/s	-
DVUP,DVLO,DVLN,DVIN	VRIG: Wave speed at right border	m/s	-
	VLEN: Length of wave speed axis	cm	VLEN> 0
	VINC: Wave speed tick mark distance	m/s	VINC> 0
	DVUP: Depth at upper border	m	-
	DVLO: Depth at lower border	m	-
	DVLN: Length of depth axis	cm	DVLN> 0
	DVIN: Depth axis tick mark distance	m	DVIN> 0

Table 6: Layout of RDOAST input files: II. Plot parameters.

H Horizontal velocity calculated.

I Hankel transform integrands are plotted for each of the selected field parameters.

J Complex integration contour. The contour is shifted into the upper halfpane by an offset controlled by the input parameter COFF (Block III).

K Computes the bulk pressure. In elastic media the bulk pressure only has contributions from the compressional potential. In fluid media the bulk pressure is equal to the acoustic pressure. Therefore for fluids this option yields the negative of the result produced by option N or R.

L Linear vertical source array.

N Normal stress σ_{zz} ($= -p$ in fluids) calculated.

P Plane geometry. The sources will be line-sources instead of point-sources as used in the default cylindrical geometry.

R Computes the radial normal stress σ_{rr} (or σ_{xx} for plane geometry).

S Computes the stress equivalent of the shear potential in elastic media. This is an angle-independent measure, proportional to the shear potential, with no contribution from the compressional potential (in contrast to shear stress on a particular plane). For fluids this option yields zero.

T Transmission loss plotted as function of range for each of the selected field parameters.

V Vertical velocity calculated.

Z Plot of velocity profile.

a Angular spectra of the integration kernels are plotted. A $0 - 90°$ axis is automatically selected representing the grazing angle ($0°$ corresponds to horizontal propagation). NOTE: The same wavenumber corresponds to different grazing angles in different media!. The vertical axis is selected automatically, representing the angular density (as opposed to the wavenumber density for integrand plots (option I).

b Solves the depth-separated wave equation with the lowermost interface condition expressed in terms of a complex reflection coefficient. The reflection coefficient must be tabulated in a input file `input.trc` which may either be produced from experimental data or by the reflection coefficient module OASR as described on Page 30. See also there for the file format. The lower halfspace must be specified as vacuum and the last layer as an isovelocity fluid without sources for this option. Add dummy layer if necessary. Further, the frequency sampling must be consistent. Therefore, if this option is combined with option `f` , the input file must have cosistent logarithmic sampling. Using

`OASR` this is optained by using option `C` with the same minimum and maximum frequencies, and number of frequencies. Note: Care should be taken using this option with a complex integration contour, option `J` . The tabulated reflection coefficient must clearly correspond to the same imaginary wavenumber components for `OAST` to yield proper results. `OASR` calculates the reflection coefficient for real horizontal wavenumbers.

c Contours of integration kernels as function of horizontal wavenumber (abcissa) and receiver depth (ordinate). The horizontal wavenumber axis is selected automatically, whereas the depth axis is plotted according to the parameters given for option C. The contour levels are determined automatically.

d Source/receiver dynamics. OAST v 1.7 handles the problem of source and receiver moving through the waveguide at the same speed and direction. The velocity projection V onto the line connecting source and receiver must be specified in Block III, as shown in table 3. Since source and receiver are moving at identical speeds there is no Doppler shift, but the Green's function is different from the static one, as described by Schmidt and Kuperman[9].

f Contours of transmission loss plotted vs frequency and range. Requires NFREQ > 0 (see below). A logarithmic frequency axis is assumed for this option. Requires ZMIN, ZMAX and ZINC to be specified in Block XII (same contour levels as for option **C** which may be specified simultaneously).

g Rough interfaces are assumed to be characterized by a Goff-Jordan power spectrum rather than the default Gaussian (Same as G).

l User defined source array. This new option is similar to option **L** in the sense that that it introduces a vertical source array of time delayed sources of identical type. However, this option allows the depth, amplitude and delay time to be be specified individually for each source in the array. The source data should be provided in a separate file, **input.src**, in the format described below in Section 7.1.5.

s Outputs the mean field discontinuity at a rough interface to the file 'input'.rhs for input to the reverberation model OASS.

t Solves the depth-separated wave equation with the top interface condition expressed in terms of a complex reflection coefficient. The reflection coefficient must be tabulated in a input file `input.trc` which may either be produced from experimental data or by the reflection coefficient module `OASR` as described on Page 30. See also there for the file format. The upper halfspace must be specified as vacuum and the first layer as an isovelocity fluid without sources for this option. Add dummy layer if necessary. Further, the frequency sampling must be consistent. Therefore, if this option is combined with option `f` , the input file must have cosistent logarithmic sampling. Using `OASR` this is optained by using option `C` with the same minimum and maximum frequencies, and number of frequencies. Note: Care should be taken using this option with a complex integration contour, option `J`. The tabulated reflection coefficient must clearly correspond to the same imaginary wavenumber components for `OAST` to yield proper results. `OASR` calculates the reflection coefficient for real horizontal wavenumbers.

Number $(1-4)$ specifying the source type (explosive, forces, moment) as described in Section 7.1.5

7.1.3 Block III: Frequencies

A frequency loop has been incorporated in OAST to allow for computation of transmission loss over a wide frequency band in one run. The frequency specification (Block III in SAFARI Manual) has therefore been changed to:

```
FR1 FR2 NF COFF [V]
```

where FR1 and FR2 are the minimum and maximum frequencies, respectively. NF is the number of frequencies, spaced equidistantly between FR1 and FR2, except if option **f** was specified; then the frequencies will be spaced logarithmically. COFF is the complex wavenumber integration contour offset. To be specified in dB/λ, where λ is the wavelength at the source depth SD. As only the horizontal part of the integration contour is considered, this parameter should not be chosen so large, that the amplitudes at the ends of the integration interval become significant. In lossless cases too small values will give sampling problems at the normal modes and other singularities. For intermediate values, the result is independent of the choice of COFF, but a good value to choose is one that gives 60 dB at the longest range considered in the FFT, i.e.

$$\mathrm{COFF} = \frac{60 * \mathrm{CC(SD)}}{(\mathrm{FREQ} * \mathrm{R}_{max})}$$

where the maximum FFT range is

$$\mathrm{R}_{max} = \frac{\mathrm{NP}}{\mathrm{FREQ} * (1/\mathrm{CMIN} - 1/\mathrm{CMAX})}$$

This value is the default which is applied if COFF is specified to 0.0.

The optional parameter V is the identical speed of source and receiver relative to the medium, projected onto the radial vector connecting them. This parameter is only used for option **d**.

7.1.4 Block IV: Environmental Model

RDOAST supports all the environmental models allowed for SAFARI as well as the ones described above in Section 4.1. The stepwise range-independent environment is specified by a standard OAST environment block for eac sector, with the length of the sector added to the line containing the number of layers. The sector length is given in kilometers. The significance of the environmental parameters is as follows

NSEC: Number of sectors, each of which should have a block with layer data in input file.

NL: Number of layers, including the upper and lower half-spaces. These should Always be included, even in cases where they are vacuum.

SECL: Length of sector in kilometers.

D: Depth in m of upper boundary of layer or halfspace. The reference depth can be choosen arbitrarily, and D() is allowed to be negative. For layer no. 1, i.e. the upper half-space, this parameter is dummy.

CC: Velocity of compressional waves in m/s. If specified to 0.0, the layer or half-space is vacuum.

CS: Velocity of shear waves in m/s. If specified to 0.0, the layer or half-space is fluid. If CS()< 0, it is the compressional velocity at bottom of layer, which is treated as fluid with $1/c(z)^2$ linear.

AC: Attennuation of compressional waves in dB/λ. If the layer is fluid, and AC() is specified to 0.0, then an imperical water attenuation is used (Skretting & Leroy).

AS: Attenuation of shear waves in dB/λ

RO: Density in g/cm^3.

RG: RMS roughness of interface in m. RG(1) is dummy. If RG< 0 it represents the negative of the RMS roughness, and the associated correlation length CL should follow. If RG> 0 the correlation length is assumed to be infinite.

CL: Roughness correlation length in m.

7.1.5 Block V: Sources

RDOAST supports the same sources as OAST. Multible sources in a vertical array are supported. The significance of the source parameters are as follows

SD: Source depth in m. If option 'L' has been specified, then SD defines the mid-point of the vertical source array.

NS: Number of sources in the array.

DS: Source spacing in m.

AN: Specifies the nominal grazing ANG of the generated beam in degrees. $ANG > 0$ corresponds to downward propagation.

IA: Array type

1. Rectangular weighted array
2. Hanning weighted array
3. Hanning weighted focusing array
4. Gaussian weighted array
5. Gaussian weighted focusing array

FD: Focal depth in m for an array of type 3 and 5.

DA: Dip angle in degrees for dip-slip sources (type 4).

Source Types

As in SAFARI the default source type in OAST is an explosive type compressional source. In addition to the optional vertical point force, and axisymmetric seismic moment source has been added to OAST. The source type is specified by a number $(1-5)$ in the option field (line 2). The translation is as follows:

1. Explosive source (default) normalized to unit pressure at 1 m distance.
2. Vertical point force with amplitude 1 N.
3. Horizontal (in-plane) point force with amplitude 1 N.
4. Dip-slip source with seismic moment 1 Nm. Dip angle specified in degrees in block V, following the other parameters.
5. Omnidirectional seismic moment source representing explosive source. Same as type 1, but all three force dipoles have seismic moment 1 Nm.

Source Normalization

In SAFARI, the source strength was normalized to yield unit pressure (in Pa) at a distance of 1 m from the source (for solids the negative of the normal stress 1 m below the source).

In OASES, the same source normalization has been maintained for point sources (explosive sources) in fluid media. For solid media, however, the sources are normalized to unit volume (1 m^3) injection for explosive sources and unit force 1 N for point sources or 1 N/m for line sources.

User defined Source Arrays

Version 1.6 of OAST has been upgraded to allow a user-defined source array through option **l**.

Option **l** is intended for general physical arrays with uneven spacing or special shadings, As for the built-in arrays, such user-defined arrays may be present in fluid as well as elastic media. The array definition should be given in the file **input.src** in the following format

```
LS
SDC(1)   SDELAY(1)  SSTREN(1)     # Depth (m), Delay (s), Amplitude
SDC(2)   SDELAY(2)  SSTREN(2)
SDC(3)   SDELAY(3)  SSTREN(3)
  :         :          :
  :         :          :
SDC(LS) SDELAY(LS) SSTREN(LS)
```

7.1.6 Block VI: Receivers

The specification of the receiver depths is slightly different than for OAST, with two records instead of one. The significance of the parameters is

RD1 Depth of uppermost source/receiver in vertical field matching arrays in meters.

RD2 Depth of lowermost source/receiver in vertical field matching arrays in meters.

NR Number of source/receiver depths.

D1 Depth of uppermost receiver for which integrands and/or TL plots should be generated . Will be modified to closest depth in receiver array specified by RD1, RD2, and NR.

D2 Depth of lowermost receiver for which integrands and/or TL plots should be generated. Will be modified to closest depth in receiver array specified by RD1, RD2, and NR.

ND Number of equidistant depths for which integrands and/or TL will be plotted.

By default, the NR and ND receivers are placed equidistantly in the vertical. Note that the vertical source/receiver arrays provide the only mechaanism for the field to propagate. Therefore, RD1 and RD2 must be chosen carefully. E.g. RD2 must be deep enough into the lower halfspace to include all significant upward radiating field. NR must be large enough to sample the vertical field distribution, i.e. denser than half the shortest vertical wavelength.

Non-equidistant Receiver Depths

In RDOASES the source/receiver depths can optionally be specified individually. The parameter NR is used as a flag for this option. Thus, if NR $<$ 0 the number of receivers is interpreted as –NR, with the individual depths following immidiately following Block VI.

7.1.7 Block VII: Wavenumber Integration

This block specifies the wavenumber sampling in the standard SAFARI format. The critical issues involved in selecting the wavenumber sampling is described in the SAFARI manual [4], but even more detailed in *Computational Ocean Acoustics* [3]. The structure of this input block is as follows:

CMIN: Minimum phase velocity in m/s. Determines the upper limit of the truncated horizontal wave- number space:

$$k_{max} = \frac{2\pi * \text{FREQ}}{\text{CMIN}}$$

CMAX: Maximum phase velocity in m/s. Determines the lower limit of the truncated horizontal wave- number space:

$$k_{min} = \frac{2\pi * \text{FREQ}}{\text{CMAX}}$$

In plane geometry (option P) CMAX may be specified as negative. In this case, the negative wavenumber spectrum will be included with $k_{min} = -k_{max}$, yielding correct solution also at zero range. In contrast to SAFARI, OAST allows for complex contour integration (option J) in this case.

NW: Number of sampling points in wavenumber space. Should be an integer power of 2, i.e. NWN= 2^m. The sampling points are placed equidistantly in the truncated wavenumber space determined by CMIN and CMAX.

IC1: Number of the first sampling point, where the calculation is to be performed. If IC1$>$ 1, then the Hankel transform is zeroed for sampling points 1,2. . .IC1-1, and the discontinuity is smoothed.

IC2: Number of the last sampling point where the calculation is to be performed. If IC2$<$NWN, then the Hankel transform is zeroed for sampling points IC2+1,. . .NW, and the discontinuity is smoothed by Hermite polynomial extrapolation.

Automatic wavenumber sampling

RDOAST supports the standard OAST auto sampling option. The automatic sampling is activated by specifying the parameter NW = -1 and it automatically activates the complex wavenumber integration contour even though option J may not have been specified. The parameters IC1 and IC2 have no effect if the automatic sampling is selected.

7.2 Execution of RDOAST

As for OAST, filenames are passed to the code via environmental parameters. In Unix systems a typical command file **rdoast** (in $HOME/oases/bin) is:

```
#!/bin/csh
setenv FOR001 $1.dat
setenv FOR002 $1.src
setenv FOR023 $1.trc
setenv FOR016 $1.vss
setenv FOR019 $1.plp
setenv FOR020 $1.plt
setenv FOR022 $1.bot
setenv FOR028 $1.cdr
setenv FOR029 $1.bdr
setenv FOR045 $1.rhs
rdoast2
```

After preparing a data file with the name **input.dat**, RDOAST is executed by the command:

> **rdoast input**

7.3 Graphics

Command files are provided in a path directory for generating the graphics.

To generate curve plots, issue the command:

> **mplot input**

To generate contour plots, issue the command:

> **cplot input**

7.4 RDOAST - Examples

7.4.1 Reverberation Benchmark problem

The following RDOAST data file represents the test case 3a from the NORDA Reverberation and Scattering Workshop. The resulting contour plots of the forward propagated and backscattered fields are shoown in Fig. 3.

RSWT3a.dat

```
R&S Workshop Test Case 3a
P N T J B C
30. 30. 1 0.0 # FREQ_1,FREQ_2,NFREQ,OFFDB
5 # NCUT = No. of sectors

4 3.00 # NUML, KNUML
0 0 0 0 0 0 0                              # LAYER 1 ; SECTOR 1
0.0   1500 0 0.0 0 1.0 0 #       2
50.0  1500 0 0.0 0 1.0 0 # 4
150.0 1800 0 0.5 0 1.5 0 #       7

4 0.12 # NUML, KNUML
0 0 0 0 0 0 0                              # LAYER 1 ; SECTOR 2
0.0   1500 0 0.0 0 1.0 0 #       2
50.0  1800 0 0.5 0 1.5 0 # 4
150.0 1800 0 0.5 0 1.5 0 #       7

4 0.10 # NUML, KNUML
0 0 0 0 0 0 0                              # LAYER 1 ; SECTOR 3
0.0   1500 0 0.0 0 1.0 0 #       2
50.0  1500 0 0.0 0 1.0 0 # 4
150.0 1800 0 0.5 0 1.5 0 #       7

4 0.12 # NUML, KNUML
0 0 0 0 0 0 0                              # LAYER 1 ; SECTOR 4
0.0   1500 0 0.0 0 1.0 0 #       2
50.0  1800 0 0.5 0 1.5 0 # 4
150.0 1800 0 0.5 0 1.5 0 #       7

4 0.66 # NUML, KNUML
0 0 0 0 0 0 0                              # LAYER 1 ; SECTOR 5
0.0   1500 0 0.0 0 1.0 0 #       2
```

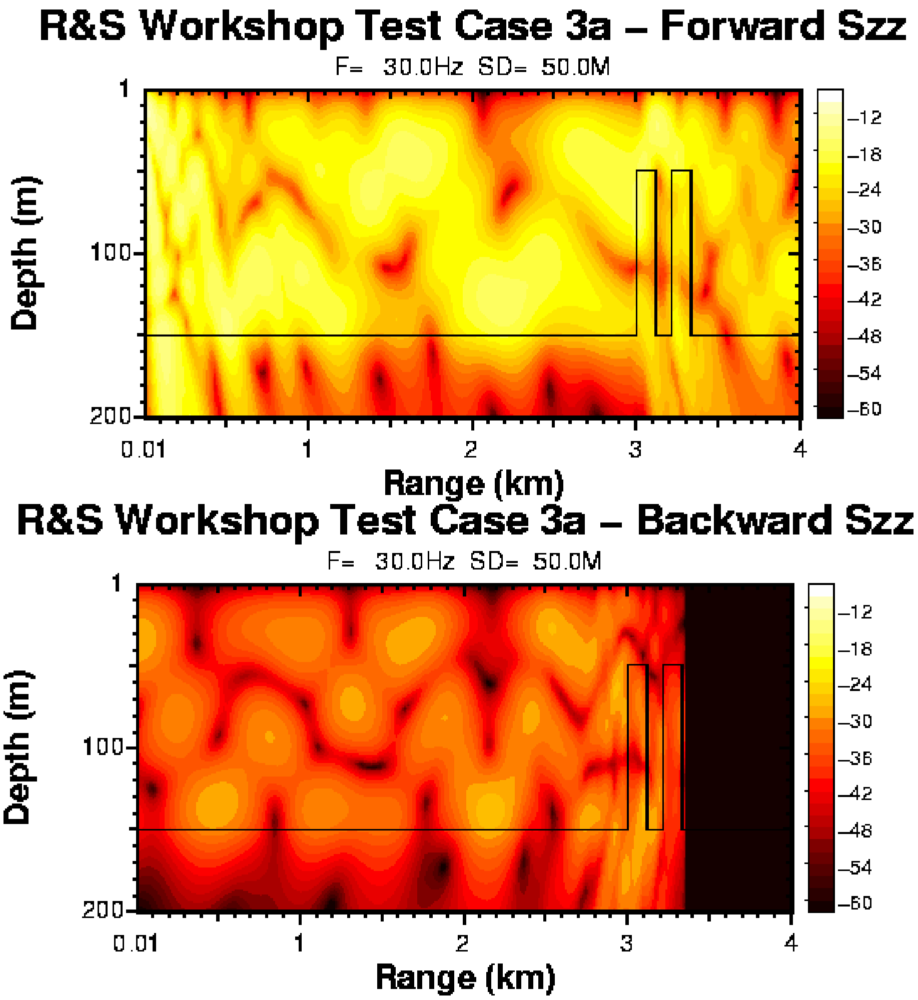

Figure 3: Transmission loss contours produced by RDOAST for Test case 3b of the Reverberation and scattering Workshop. a) Forward propagating field. b) Backscattered field

```
50.0  1500 0 0.0 0 1.0 0 # 3
150.0 1800 0 0.5 0 1.5 0 #       4

50. # SOURCE DEPTH
1 201. 101 1 # RECEIVER DEPTH
45 45 1
800  -800         # CMIN CMAX
-1 1 1
0 4. 20. 5.      # XLEFT XRIGHT XAXIS XINC
20 80 12. 10.  # LOSS LEVELS IN DB
0 200 10 50
20 80 5
```

8 OASP: 2-D Wideband Transfer Functions

The OASES-OASP module calculates the depth-dependent Green's function for a selected number of frequencies and determines the transfer function at any receiver position by evaluating the wavenumber integral. The frequency integral is evaluated in the Post-processor PP. As is the case for OASES-OAST, both stresses and particle velocities can be determined, and the field may be produced by either point or line sources. By arranging the sources in a vertical phased array, pulsed beam propagation can be analyzed.

8.1 Two-Step Execution

Whereas its predecessor SAFARI-FIPP was always run in a one-step mode, directly generating the time responses on the receiver array corresponding to the chosen source function, OASES-OASP is always run in a two-step mode in conjunction with the PP Pulse Post-processor. OASP generates the transfer functions for the selected environment and source- receiver geometry. The interactive postprocessor is then used to select time windows, source pulses, stacking format etc.

Since the computation of the transfer functions is by far the most computationally intensive part of synthetic seismogram computation, the 2-step mode will be most user friendly and efficient, except for cases where large batches of synthetic seismograms have to be generated. The transfer function file will have the same name as the input file, but extension **.trf**, i.e. for an input file **input.dat**, the transfer function file will be

input.trf.

8.2 Transfer Functions

In addition to generating timeseries through the two-step procedure, OASP may be used for generating the complex CW field over a rectangular grid in range and depth. Here it is important to note that when OASP is used with option 'O' or with automatic sampling enabled, the transfer functions are computed for complex frequencies. Complex frequency corresponds to applying a *time-domain damping* which cannot be directly compensated for in the transfer functions. However, real frequencies can be forced in automatic sampling mode by using option 'J' (Version 2.1 and later).

Also, in version 2.1 and later, the postprocessor PP has been expanded with a transmission loss option which converts the transfer function to transmission losses plotted in the standard OAST forms of TL vs range or depth-range contours. Here it is obviously important to use option 'J' together with the automatic sampling. Otherwize the losses will be overestimated.

Also note that the automatic sampling works differently from OAST's. Thus, OASP will use the selected time window to select a wavenumber sampling which eliminates time-domain wrap-around. This feature may actually be used for convergence tests, by systematically increasing the time window $(NX \times DT)$ to allow reduced wavenumber sampling.

8.3 Input Files for OASP

The input files for OASP is structured in 8 blocks, as outlined in Tables 7. In the following we describe the significance of the various blocks, with particular emphasis on differences between SAFARI-FIPP and OASP.

8.4 Block I: Title

The title printed on all graphic output generated by OASP.

8.5 Block II: OASP options

OASP is downward compatible with SAFARI Version 3.0 and higher, and therefore supports all options and features described in the SAFARI manual, except for those affecting the generation of time-series, i.e. the following SAFARI options are not supported by OASP:

D Depth stacked seismograms

S Range stacked seismograms

R Plot of source pulse

n Source pulse type

In addition to improved speed and stability, OASP offers several new options. The currently supported options are:

C Creates an $\omega - k$ representation of the field in the form of contours of integration kernels as function of horizontal wavenumber (slowness if option **B** is selected) and frequency (logarithmic y-axis). All axis parameters are determined automatically.

H Horizontal (radial) particle velocity calculated.

Input parameter	Description	Units	Limits
BLOCK I: TITLE			
TITLE	Title of run	-	$\leq$ 80 ch.
BLOCK II: OPTIONS			
A B C $\cdots$	Output options	-	$\leq$ 40 ch.
BLOCK III: SOURCE FREQUENCY			
FRC,COFF,IT,VS,VR	FRC: Center frequency of source	Hz	> 0
	COFF: Integration contour offset	dB/Λ	COFF≥ 0
	IT: Source pulse type (only for option d)		
	VS,VR: Sou./Rec. velocity (only for option d)	m/s	
BLOCK IV: ENVIRONMENT			
NL	Number of layers, incl. halfspaces	-	NL≥ 2
D,CC,CS,AC,AS,RO,RG,CL	D: Depth of interface.	m	-
.	CC: Compressional speed	m/s	CC≥ 0
.	CS: Shear speed	m/s	-
.	AC: Compressional attenuation	dB/Λ	AC≥ 0
.	AS: Shear attenuation	dB/Λ	AS≥ 0
	RO: Density	g/cm^3	RO≥ 0
	RG: RMS value of interface roughness	m	-
	CL: Correlation length of roughness	m	CL> 0
	M: Spectral exponent		¿ 1.5
BLOCK V: SOURCES			
SD,NS,DS,AN,IA,FD,DA	SD: Source depth (mean for array)	m	-
	NS: Number of sources in array	-	NS> 0
	DS: Vertical source spacing	m	DS> 0
	AN: Grazing angle of beam	deg	-
	IA: Array type	-	$1 \leq$IA≤ 5
	FD: Focal depth of beam	m	FD$\neq$SD
	DA: Dip angle. (Source type 4).	deg	-
BLOCK VI: RECEIVER DEPTHS			
RD1,RD2,NRD	RD1: Depth of first receiver	m	-
	RD2: Depth of last receiver	m	RD2$>$RD1
	NRD: Number of receiver depths	-	NR> 0
BLOCK VII: WAVENUMBER SAMPLING			
CMIN,CMAX	CMIN: Minimum phase velocity	m/s	CMIN> 0
	CMAX: Maximum phase velocity	m/s	-
NW,IC1,IC2,IF	NW: Number of wavenumber samples	-	> 0, -1 (auto)
	IC1: First sampling point	-	IC1≥ 1
	IC2: Last sampling point	-	IC2$\leq$NW
	IF: Freq. sample increment for kernels		≥ 0
BLOCK VIII: FREQUENCY AND RANGE SAMPLING			
NT,FR1,FR2,DT,R1,DR,NR	NT: Number of time samples		NT$= 2^M$
	FR1: lower limit of frequency band	Hz	≥ 0
	FR2: upper limit of frequency band	Hz	$\geq$FR1
	DT: Time sampling increment	s	> 0
	R1: First range	km	
	DR: Range increment	km	
	NR: Number of ranges		> 0

Table 7: Layout of OASP input files: Computational parameters.

J Complex wavenumber contour. The contour is shifted into the upper halfpane by an offset controlled by the input parameter COFF (Block III). NOTE: If this option is used together with automatic sampling, the complex frequency integration (option **O**) is disabled, allowing for computation of complex CW fields or transmission losses (plotted using PP).

K Computes the bulk pressure. In elastic media the bulk pressure only has contributions from the compressional potential. In fluid media the bulk pressure is equal to the acoustic pressure. Therefore for fluids this option yields the negative of the result produced by option N or R.

L Linear vertical source array.

N Normal stress σ_{zz} ($= -p$ in fluids) calculated.

O Complex frequency integration contour. This new option is the frequency equivalent of the complex wavenumber integration (**J** option in OAST). It moves the frequency contour away from the real axis by an amount reducing the time domain wrap-around by a factor 50 [3]. This option can yield significant computational savings in cases where the received signal has a long time duration, and only the initial part is of interest, since it allows for selection of a time window shorter than the actual signal duration. Note that only wrap around from later times is reduced; therefore the time window should always be selected to contain the beginning of the signal!

P Plane geometry. The sources will be line-sources instead of point-sources as used in the default cylindrical geometry.

R Computes the radial normal stress σ_{rr} (or σ_{xx} for plane geometry).

S Computes the stress equivalent of the shear potential in elastic media. This is an angle-independent measure, proportional to the shear potential, with no contribution from the compressional potential (incontrast to shear stress on a particular plane). For fluids this option yields zero.

T The new option 'T' allows for specification of an array tilt in the vertical plane containing the source and the receivers. See below for specification of array tilt parameters.

U Decomposed seismograms. This option generates 5 transfer function files to be processed by PP:

File name	Contents
input.trf	Complete transfer functions
input.trfdc	Downgoing compressional waves
input.trfuc	Upgoing compressional waves
input.trfds	Downgoing shear waves alone
input.trfus	Upgoing shear waves

V Vertical particle velocity calculated.

Z Plot of SVP will be generated.

d Radial *Doppler shift* is accounted for by specifying this option, using the theory developed by Schmidt and Kuperman [9]. The source pulse and the radial projections of the source and receiver velocities must be specified in the input file following the specification of the centre frequency and the contour offset (Block II). Since this option requires incorporation of the source function in the wavenumber integral, the PP post-processor must be used with source pulse -1 (impulse response).

f A full Hankel transform integration scheme is used for low values of kr and tapered into the FFP integration used for large kr. The compensation is achieved at insignificant additional computational cost and is recommended highly for cases where the near field is needed.

g Rough interfaces are assumed to be characterized by a Goff-Jordan power spectrum rather than the default Gaussian (Same as G).

l User defined source array. This new option is similar to option **L** in the sense that that it introduces a vertical source array of time delayed sources of identical type. However, this option allows the depth, amplitude and delay time to be be specified individually for each source in the array. The source data should be provided in a separate file, **input.src**, in the format described below in Section 8.5.3.

s Outputs the mean field discontinuity at a rough interface to the file 'input'.rhs for input to the time domain reverberation model OASSP.

t Eliminates the wavenumber integration and computes transfer functions for individual slowness components (or plane wave components). The Fourier transform performed in PP will then directly compute the slowness/intercept-time or $\tau - p$ response for each of the selected depths. When option **t** is selected, the range parameters in the data file are insignificant.

v As option **l** this option allows for specifying a non-standard source array. However, it is more general in the sense that different types of sources can be applied in the same array, and the sources can have different signatures. The array geometry and the complex amplitudes are specified in a file **input.strf** which should be of **trf** format as described in Section 8.5.3.

Number $(1 - 5)$ specifying the source type (explosive, forces, seismic moment) as described in Section 8.5.3

8.5.1 Block III: Source Frequency

FRC is the source center frequency. As the source convolution is performed in PP, FRC is not used in OASP, but will be written to the transfer function file and become the default for PP.

COFF is the complex wavenumber integration contour offset. To be specified in dB/λ, where λ is the wavelength at the source depth SD. As only the horizontal part of the integration contour is considered, this parameter should not be chosen so large, that the amplitudes at the ends of the integration interval become significant. In lossless cases too small values will give sampling problems at the normal modes and other singularities. For intermediate values, the result is independent of the choice of COFF, but a good value to choose is one that gives 60 dB attenuation at the longest range considered in the FFT, i.e.

$$\mathrm{COFF} = \frac{60 * \mathrm{CC(SD)}}{(\mathrm{FREQ} * \mathrm{R}_{max})}$$

where the maximum FFT range is

$$\mathrm{R}_{max} = \frac{\mathrm{NP}}{\mathrm{FREQ} * (1/\mathrm{CMIN} - 1/\mathrm{CMAX})}$$

This value is the default which is applied if COFF is specified to 0.0.

Doppler shift

By specifying option **d** in OASP V.1.7 and higher, radial *Doppler shift* is accounted for using the theory developed by Schmidt and Kuperman [9]. The source pulse and the radial projections of the source and receiver velocities must be specified in the input file following the specification of the centre frequency and the contour offset (Block II), i.e.

Standard	For option **d**
FRC COFF	IT VS VR

`IT` is a number identifying the source pulse as described in Sec. 16. `VS` and `VR` are the projected radial velocities in m/s of the source and receiver, respectively, both being positive in the direction from source to receiver. Since this option requires incorporation of the source function in the wavenumber integral, the PP post-processor must subsequently be used with source pulse -1 (impulse response).

8.5.2 Block IV: Environmental Model

OASP supports all the environmental models allowed for SAFARI as well as the ones described above in Section 4.1. The significance of the standard environmental parameters is as follows

NL: Number of layers, including the upper and lower half-spaces. These should always be included, even in cases where they are vacuum.

D: Depth in m of upper boundary of layer or halfspace. The reference depth can be choosen arbitrarily, and D() is allowed to be negative. For layer no. 1, i.e. the upper half-space, this parameter is dummy.

CC: Velocity of compressional waves in m/s. If specified to 0.0, the layer or half-space is vacuum.

CS: Velocity of shear waves in m/s. If specified to 0.0, the layer or half-space is fluid. If CS()< 0, it is the compressional velocity at bottom of layer, which is treated as fluid with $1/c(z)^2$ linear.

AC: Attenuation of compressional waves in dB/λ. If the layer is fluid, and AC() is specified to 0.0, then an imperical water attenuation is used (Skretting & Leroy).

AS: Attenuation of shear waves in dB/λ

RO: Density in g/cm^3.

RG: RMS roughness of interface in m. RG(1) is dummy. If RG< 0 it represents the negative of the RMS roughness, and the associated correlation length CL and the spectral exponent M should follow. If RG> 0 the correlation length is assumed to be infinite.

CL: Roughness correlation length in m.

M: Spectral exponent of the power spectrum as defined by Turgut [25], with $1.5 <$ M ≤ 2.5 for realistic surfaces, with M $= 1.5$ corresponding to the highest roughness, and M $= 2.5$ being a very smooth variation. For 2-D Goff-Jordan surfaces, the fractal dimension is D $= 4.5 -$ M Insignificant for Gaussian spectrum (option **g** not specified) but a value must be given.

8.5.3 Block V: Sources

OASP supports the same sources as SAFARI-FIPP, i.e explosive sources in fluids or solids or vertical point forces in solids (option X). Multible sources in a vertical array are supported. If sources with horizontal directionality are desired, the 3-dimensional version OASP3D must be used.

Source Types

As in SAFARI the default source type in OASP is an explosive type compressional source. In addition to the optional vertical and horizontal point forces, various seismic moment sources have been added to OASP. The source type is specified by a number $(1 - 5)$ in the option field (line 2). The translation is as follows:

1. Explosive source (default) normalized to unit pressure at 1 m distance.
2. Vertical point force with amplitude 1 N.
3. Horizontal (in-plane) point force with amplitude 1 N.
4. Dip-slip source with seismic moment 1 Nm. Dip angle specified in degrees in block V, following the other parameters.
5. Omnidirectional seismic moment source representing explosive source. Same as type 1, but all three force dipoles have seismic moment 1 Nm.

Source Normalization

In SAFARI-FIPP, the source pulse shape was defined as the pressure pulse produced at a distance of 1 m from the source (for solids the negative of the normal stress 1 m below the source).

In OASP, the same source normalization has been maintained for point sources (explosive sources) in fluid media. For solid media, however, the sources are normalized to unit volume (1 m^3) injection for explosive sources and unit force 1 N for point sources or 1 N/m for line sources.

User defined Source Arrays

Version 1.6 of OASP has been upgraded to allow a user-defined source array through options **l** and **v**.

Option **l** is intended for general physical arrays with uneven spacing or special shadings, As for the built-in arrays, such user-defined arrays may be present in fluid as well as elastic media. The source type is specified as described above, and the array geometry and shading should be given in the file **input.src** in the following format

```
LS
SDC(1)  SDELAY(1)  SSTREN(1)    # Depth (m), Delay (s), Amplitude
SDC(2)  SDELAY(2)  SSTREN(2)
SDC(3)  SDELAY(3)  SSTREN(3)
  :         :          :
  :         :          :
SDC(LS) SDELAY(LS) SSTREN(LS)
```

Option **v** is more general in the sense that it allows for different source types to be mixed in the array, and the pure time delay is replaced by a specification of the complex amplitudes in the frequency domain, allowing for representation of multibles etc. This option is used for *virtual arrays* such as those imposed by coupling of wave systems. For example, this option is used for coupling tube wave phenomenae to propagation in a stratified formation when modeling borehole seismics. Option **v** is only allowed for source arrays in elastic media (including transversily isotropic layers). The complex amplitudes of the source array is specified in the file **input.strf**. This should be an ASCII **trf** file, and the frequency sampling should be consistent with the frequency sampling selected in the input file **input.dat**. There are 3 source types available. All are omnidirectional in the horizontal. The source type is identified by a type number in the file header, and each depth can have one of each source type present. The possible source types are:

10 Seismic monopole, i.e. 3 perpendicular and identical force dipoles. The unit is seismic moment (Nm).

11 Vertical force dipole. The unit is seismic moment (Nm).

12 Vertical force, positive downwards. The unit is force (N).

The source types are regognized by PP which can therefore be used to check your source timeseries by simply specifying **input.strf** in Field 1 of the PP main menu. An example of an **strf**-file for 21 source depths, with a monopole and a dipole source at each depth, is

```
PULSETRF                                # TRF file identification
OASP16                                  # Calculating program
          2                             # No. sources per depth NSIN
         10          11                 # Source types
tube wave simulation                    # Title
+                                       # Sign if time factor exponent
400.0                                   # Center frequency
  6.0                                   # Depth of primary source
 -0.5  19.5  21                         # SD-min, SD-max, LS
  0.0   0.0   1                         # Range (fixed).
 1024   2   104  0.0001                 # Time/frequency parameters
          1                             # Dummy
 -38.20335                              # Imag. part of frequencies
          1                             # One Fourier order (fixed)
          1                             # Fixed
          0                             # Dummy
          0                             # Dummy
          0                             # Dummy
 0.0                                    # Dummy
 0.0                                    # Dummy
 0.0                                    # Dummy
 0.0                                    # Dummy
```

```
 0.0                                   # Dummy
 -24.15950 82.01517 -24.15950 82.01517 # Data
 -28.20251 83.04697 -28.20251 83.04697 # Data
 -32.38960 83.93490 -32.38960 83.93490 # Data
 -36.71837 84.66933 -36.71837 84.66933 # Data
 -41.18590 85.24049 -41.18590 85.24049 # Data
      :        :         :        :        :
```

Note: All lines should start with an empty space!. The time/frequency parameters are given in the form

```
 NT  LX  MX  DT
```

where

NT is the number of time samples

DT is the time sampling interval in seconds

LX is the index of the first frequency, LX = INT(FR1*DT)

MX is the index of the last frequency, MX = INT(FR2*DT)

The complex data must be written in the following loop structure

```
      DO 10 K = LX,MX
       DO 10 L = 1,LS
        WRITE(15,*) (REAL(TRF(K,L,M)),AIMAG(TRF(K,L,M)), M=1,NSIN)
 10   CONTINUE
```

8.5.4 Block VI: Receivers

The default specification of the receiver depths is the same as for SAFARI, i.e. through the parameters RD1, RD2 and NRD in Block VI, with

RD1 Depth of uppermost receiver in meters

RD2 Depth of lowermost receiver in meters

NRD Number of receiver depths

The NRD receivers are placed equidistantly in the vertical.

Non-equidistant Receiver Depths

In OASES the receiver depths can optionally be specified individually. The parameter NRD is used as a flag for this option. Thus, if NRD < 0 the number of receivers is interpreted as –NRD, with the individual depths following immidiately following Block VI. As an example, SAFARI FIPP case 2 with receivers at 100, 105 and 120 m is run with the following data file:

```
SAFARI-FIPP case 2.
V H F O        # Complex frequency integration.
5 0
4
  0    0      0 0   0   0   0
  0 1500      0 0   0   1   0
100 1600    400 0.2 0.5 1.8 0
120 1800    600 0.1 0.2 2.0 0
95
100 100 -3                     # 3 receivers
100.0 105.0 120.0              # Receiver depths in meters
300 1E8
1024 1 950 0
2048 0.0 12.5 0.006 0.5 0.5 5
```

The PP Post-processor is compatible and will depth-stack the traces at the correct depths.

Tilted Receiver Arrays

The new option ‘T’ allows for specification of an array tilt in the vertical plane containing the source and the receivers.

The tilt angle and rotation origin is specified in the receiver depth line (Block VI):

Standard	For option T
RD1 RD2 NR	ZREF ANGLE

The vertical arrays are rotated by an angle ‘ANGLE’ in deg relative to the vertical. The rotation is performed with origin at depth ‘ZREF’.

The parameters RD1, RD2 and NR always refer to the untilted case. In the tilted case these parameters do therefore define the array geometry and not the actual depths of the receivers in the tilted array. The same is the case for the graphics output produced by the post-processor PP.

The source(s) is always at the origin and is therefore not rotated. Thus, for zero-offset tilted VSP-s, the reference depth ZREF should be set equal to the source depth SD!

8.5.5 Block VII: Wavenumber integration

This block specifies the wavenumber sampling in the standard SAFARI format, with the significance of the parameters being as follows:

CMIN: Minimum phase velocity in m/s. Determines the upper limit of the truncated horizontal wavenumber space:

$$k_{max} = \frac{2\pi * \text{FREQ}}{\text{CMIN}}$$

CMAX: Maximum phase velocity in m/s. Determines the lower limit of the truncated horizontal wave- number space:

$$k_{min} = \frac{2\pi * \text{FREQ}}{\text{CMAX}}$$

In plane geometry (option P) CMAX may be specified as negative. In this case, the negative wavenumber spectrum will be included with $k_{min} = -k_{max}$, yielding correct solution also at zero range. In contrast to SAFARI, OASP allows for complex contour integration (option J) in this case.

NW: Number of sampling points in wavenumber space. In contrast to what is the case for OAST, NW does here not have to be an integer power of 2. The sampling points are placed equidistantly in the truncated wavenumber space determined by CMIN and CMAX. If CMAX< 0, i.e. the inclusion of the negative spectrum is enabled, then the NW sample points will be distributed along the positive wavenumber axis only, with the negative components obtained by symmetry.

IC1: Number of the first sampling point where the calculation is to be performed. If IC1$>$ 1, then the Hankel transform is Hanning-windowed in the interval 1,2. . .IC1-1 before integration.

IC2: Number of the last sampling point where the calculation is to be performed. If IC2$<$NWN, then the Hankel transform is Hanning windowed in the interval IC2+1,. . .NW before integration.

IF: Frequency increment for plotting of integration kernels. A value of 0 disables the plotting.

Automatic wavenumber sampling

OASP Version 1.4 and higher have been supplied with an automatic sampling feature, making it possible for inexperienced users to obtain correct answers in the first attempt without the usual convergence testing. The automatic sampling is activated by specifying the parameter NW to -1 and it automatically activates the complex frequency integration contour even though option **O** may not have been specified. The parameters IC1 and IC2 have no effect if the automatic sampling is selected.

As an example, to run the SAFARI-FIPP case 2 problem with automatic sampling, change the data file as follows:

```
SAFARI-FIPP case 2. Auto sampling.
V H f                        # Bessel integration.
5 0
4
  0    0     0 0   0   0   0
  0 1500     0 0   0   1   0
100 1600   400 0.2 0.5 1.8 0
120 1800   600 0.1 0.2 2.0 0
95
100 100 1
 300 1E8
-1 0 0                        # NW   =   -1
2048 0.0 12.5 0.006 0.5 0.5 5
```

8.6 Execution of OASP

As for SAFARI, filenames are passed to the code via environmental parameters. In Unix systems a typical command file **oasp** (in $HOME/oases/bin) is:

```
#                              the number sign invokes the C-shell
setenv FOR001 $1.dat        # input file
setenv FOR002 $1.src        # Source array input file
setenv FOR015 $1.strf       # Source array trf file
setenv FOR019 $1.plp        # plot parameter file
setenv FOR020 $1.plt        # plot data file
setenv FOR028 $1.cdr        # contour plot parameter file
setenv FOR029 $1.bdr        # contour plot data file
setenv FOR045 $1.rhs        # mean field amplitudes at rough interface
setenv FOR046 $1.vol        # mean field in volume scattering layer
oasp2                       # executable
```

After preparing a data file with the name **input.dat**, OASP is executed by the command:

> **oasp input**

8.7 Graphics

Command files are provided in a path directory for generating the graphics.

To generate curve plots, issue the command:

> **mplot input**

To generate contour plots, issue the command:

> **cplot input**

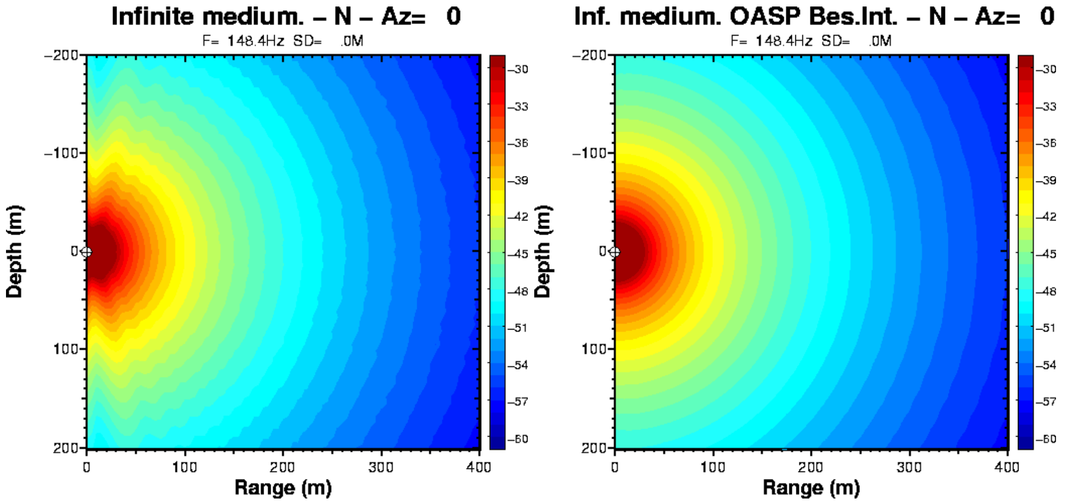

Figure 4: Transmission loss contours produced by OASP and PP for a point source in an infinite fluid medium. a) Default trapezoidal rule integration with fast-field Hankel function approximation. b) Same problem, but full bessel function integration (Option f)

8.8 OASP - Examples

8.8.1 OASP Transmission loss calculation

As an example of the use of OASP for computing transmission losses, and for demonstrating the difference between the full Bessel function integration and the default fast-field Hankel function approximation, the following data files computes the transfer function for a 150 Hz simple point source in a lossless, infinite fluid medium.

```
free.dat                                 |   free_f.dat
---------------------------------------------------------------------------
Infinite medium.                         |   Inf. medium. OASP Bes.Int.
N J                                      |   N J f
150 0                                    |   150 0
2                                        |   2
0 1500 0 0.1 0 1 0                       |   0 1500 0 0.1 0 1 0
0 1500 0 0.1 0 1 0                       |   0 1500 0 0.1 0 1 0
0                                        |   0
-200 200 61 30                           |   -200 200 61 30
1000 1E8                                 |   1000 1E8
-1 1 1 1                                 |   -1 1 1 1
1024 150 150 0.0005 0 0.005 81           |   1024 150 150 0.0005 0 0.005 81
```

The execution of OASP with these input files generates the transfer function files, which are then converted to transmission loss by PP. Figure 4 shows the transmission loss contours in depth and range, plotted from PP using `plotmtv`. `The near field differences between the 'exact' and the fast-field Hankel transforms are evident.`

9 RDOASP: 2-D Range-dependent Transfer Functions

`RDOASP` is the **range-dependent** version of `OASP`. `RDOASP` uses a Virtual Source Approach for coupling the field between range-independent sectors, basically using a *vertical source/receiver array*, and a *single-scatter*, *local plane wave* handling of vertical discontinuities [21]. In contrast to the similar approach of the elastic PE, VISA properly handles seismic conversion at the vertical boundaries. The solutions compare extremely well with PE solutions for week contrast problems, and with full boundary integral approaches for several canonical elastic benchmark problems [20, 21].

The frequency integral is evaluated in the Post-processor PP.

9.1 Transfer Functions

In addition to generating timeseries through the two-step procedure, RDOASP may be used for generating the complex CW field over a rectangular grid in range and depth. Here it is important to note that when RDOASP is used with option 'O' or with automatic sampling enabled, the transfer functions are computed for complex frequencies. Complex frequency corresponds to applying a *time-domain damping* which cannot be directly compensated for in the transfer functions. However, real frequencies can be forced in automatic sampling mode by using option 'J' (Version 2.1 and later).

Also, in version 2.1 and later, the postprocessor PP has been expanded with a transmission loss option which converts the transfer function to transmission losses plotted in the standard RDOAST forms of TL vs range or depth-range contours. Here it is obviously important to use option 'J' together with the automatic sampling. Otherwize the losses will be overestimated. Also note that the automatic sampling works differently from RDOAST's. Thus, OASP will use the selected time window to select a wavenumber sampling which eliminates time-domain wrap-around. This feature may actually be used for convergence tests, by systematically increasing the time window $(NX \times DT)$ to allow reduced wavenumber sampling.

9.2 Input Files for RDOASP

The input files for RDOASP is structured in 8 blocks, as outlined in Tables 8. In the following we describe the significance of the various blocks.

9.3 Block I: Title

The title printed on all graphic output generated by OASP.

Input parameter	Description	Units	Limits
BLOCK I: TITLE			
TITLE	Title of run	-	$\leq$ 80 ch.
BLOCK II: OPTIONS			
A B C $\cdots$	Output options	-	$\leq$ 40 ch.
BLOCK III: SOURCE FREQUENCY			
FRC,COFF,IT,VS,VR	FRC: Center frequency of source	Hz	> 0
	COFF: Integration contour offset	dB/Λ	COFF≥ 0
	IT: Source pulse type (only for option d)		
	VS,VR: Sou./Rec. velocity (only for option d)	m/s	
BLOCK IV: ENVIRONMENT			
NSEC	Number of sectors	-	NSEC≥ 1
NL, SECL	Sector 1: No. layers, length	-, km	NL≥ 2
D,CC,CS,AC,AS,RO,RG,CL	D: Depth of interface.	m	-
.	CC: Compressional speed	m/s	CC≥ 0
.	CS: Shear speed	m/s	-
.	AC: Compressional attenuation	dB/Λ	AC≥ 0
.	AS: Shear attenuation	dB/Λ	AS≥ 0
	RO: Density	g/cm^3	RO≥ 0
	RG: RMS value of interface roughness	m	-
	CL: Correlation length of roughness	m	CL> 0
NL, SECL	Sector 2: No. layers, length	-, km	NL≥ 2
D,CC,CS,AC,AS,RO,RG,CL			-
.			
.			
BLOCK V: PHYSICAL SOURCES			
SD,NS,DS,AN,IA,FD,DA	SD: Source depth (mean for array)	m	-
	NS: Number of sources in array	-	NS> 0
	DS: Vertical source spacing	m	DS> 0
	AN: Grazing angle of beam	deg	-
	IA: Array type	-	$1 \leq$IA≤ 5
	FD: Focal depth of beam	m	FD$\neq$SD
	DA: Dip angle. (Source type 4).	deg	-
BLOCK VI: RECEIVER DEPTHS			
RD1,RD2,NRD	RD1: Depth of first virtual receiver	m	-
	RD2: Depth of last virtual receiver	m	RD2>RD1
	NRD: Number of virtual receivers	-	NRD> 0
D1,D2,ND	D1: Depth of first physical receiver	m	-
	D2: Depth of last physical receiver	m	D2>D1
	ND: Number of physical receivers	-	ND> 0
BLOCK VII: WAVENUMBER SAMPLING			
CMIN,CMAX	CMIN: Minimum phase velocity	m/s	CMIN> 0
	CMAX: Maximum phase velocity	m/s	-
NW,IC1,IC2,IF	NW: Number of wavenumber samples	-	> 0, -1 (auto)
	IC1: First sampling point	-	IC1≥ 1
	IC2: Last sampling point	-	IC2$\leq$NW
	IF: Freq. sample increment for kernels		≥ 0
BLOCK VIII: FREQUENCY AND RANGE SAMPLING			
NT,FR1,FR2,DT,R1,DR,NR	NT: Number of time samples		NT$= 2^M$
	FR1: lower limit of frequency band	Hz	≥ 0
	FR2: upper limit of frequency band	Hz	$\geq$FR1
	DT: Time sampling increment	s	> 0
	R1: First range	km	
	DR: Range increment	km	
	NR: Number of ranges		> 0

9.4 Block II: RDOASP options

RDOASP Version 2.0 supports all OASP options:

- **C** Creates an $\omega - k$ representation of the field in the form of contours of integration kernels as function of horizontal wavenumber (slowness if option **B** is selected) and frequency (logarithmic y-axis). All axis parameters are determined automatically.
- **G** Rough interfaces are assumed to be characterized by a Goff-Jordan power spectrum rather than the default Gaussian.
- **H** Horizontal (radial) particle velocity calculated.
- **J** Complex integration contour. The contour is shifted into the upper halfpane by an offset controlled by the input parameter COFF (Block III). NOTE: If this option is used together with automatic sampling, the complex frequency integration (option **O**) is disabled, allowing for computation of complex CW fields or transmission losses (plotted using PP).
- **K** Computes the bulk pressure. In elastic media the bulk pressure only has contributions from the compressional potential. In fluid media the bulk pressure is equal to the acoustic pressure. Therefore for fluids this option yields the negative of the result produced by option N or R.
- **L** Linear vertical source array.
- **N** Normal stress σ_{zz} $(= -p$ in fluids) calculated.
- **O** Complex frequency integration contour. This new option is the frequency equivalent of the complex wavenumber integration (**J** option in OAST). It moves the frequency contour away from the real axis by an amount reducing the time domain wrap-around by a factor 50 [3]. This option can yield significant computational savings in cases where the received signal has a long time duration, and only the initial part is of interest, since it allows for selection of a time window shorter than the actual signal duration. Note that only wrap around from later times is reduced; therefore the time window should always be selected to contain the beginning of the signal!
- **P** Plane geometry. The sources will be line-sources instead of point-sources as used in the default cylindrical geometry.
- **R** Computes the radial normal stress σ_{rr} (or σ_{xx} for plane geometry).
- **S** Computes the stress equivalent of the shear potential in elastic media. This is an angle-independent measure, proportional to the shear potential, with no contribution from the compressional potential (incontrast to shear stress on a particular plane). For fluids this option yields zero.

T The new option 'T' allows for specification of an array tilt in the vertical plane containing the source and the receivers. See below for specification of array tilt parameters.

U Decomposed seismograms. This option generates 5 transfer function files to be processed by PP:

File name	Contents
input.trf	Complete transfer functions
input.trfdc	Downgoing compressional waves
input.trfuc	Upgoing compressional waves
input.trfds	Downgoing shear waves alone
input.trfus	Upgoing shear waves

V Vertical particle velocity calculated.

Z Plot of SVP will be generated.

d Radial *Doppler shift* is accounted for by specifying this option, using the theory developed by Schmidt and Kuperman [9]. The source pulse and the radial projections of the source and receiver velocities must be specified in the input file following the specification of the centre frequency and the contour offset (Block II). Since this option requires incorporation of the source function in the wavenumber integral, the PP post-processor <u>must</u> be used with source pulse -1 (impulse response).

f Full Bessel function integration. This new option does not apply the asymptotic representation of the Bessel function in the evaluation of the inverse Hankel transforms. The implementation is very efficient, and the integral evaluation is performed just as fast as the asymptotic evaluations. It is more sensitive to truncation, however, and therefore usually requires a much larger wavenumber interval to avoid truncation arrivals. Further, the Bessel function represents both outgoing and incoming waves, such that the periodicity of the discrete integral transforms introduces false arrivals from the periodic sources. It is therefore recommended to solely apply this option for cases where very steep propagation angles are important, e.g. short offset VSP computations. For all other cases the asymptotic Filon (option F) is highly recommended.

g Rough interfaces are assumed to be characterized by a Goff-Jordan power spectrum rather than the default Gaussian (Same as G).

l User defined source array. This new option is similar to option **L** in the sense that that it introduces a vertical source array of time delayed sources of identical type. However, this option allows the depth, amplitude and delay time to be be specified individually for each source in the array. The source data should be provided in a separate file, **input.src**, in the format described in Section 8.5.3.

t Eliminates the wavenumber integration and computes transfer functions for individual slowness components (or plane wave components). The Fourier transform performed in

PP will then directly compute the slowness/intercept-time or $\tau - p$ response for each of the selected depths. When option **t** is selected, the range parameters in the data file are insignificant.

v As option **l** this option allows for specifying a non-standard source array. However, it is more general in the sense that different types of sources can be applied in the same array, and the sources can have different signatures. The array geometry and the complex amplitudes are specified in a file **input.strf** which should be of **trf** format as described in Section 8.5.3.

Number $(1 - 5)$ specifying the source type (explosive, forces, seismic moment) as described in Section 8.5.3

9.4.1 Block III: Source Frequency

FRC is the source center frequency. As the source convolution is performed in PP, FRC is not used in RDOASP, but will be written to the transfer function file and become the default for PP.

COFF is the complex wavenumber integration contour offset. To be specified in dB/λ, where λ is the wavelength at the source depth SD. As only the horizontal part of the integration contour is considered, this parameter should not be chosen so large, that the amplitudes at the ends of the integration interval become significant. In lossless cases too small values will give sampling problems at the normal modes and other singularities. For intermediate values, the result is independent of the choice of COFF, but a good value to choose is one that gives 60 dB attenuation at the longest range considered in the FFT, i.e.

$$\mathrm{COFF} = \frac{60 * \mathrm{CC(SD)}}{(\mathrm{FREQ} * \mathrm{R}_{max})}$$

where the maximum FFT range is

$$\mathrm{R}_{max} = \frac{\mathrm{NP}}{\mathrm{FREQ} * (1/\mathrm{CMIN} - 1/\mathrm{CMAX})}$$

This value is the default which is applied if COFF is specified to 0.0.

Doppler shift

By specifying option **d** in RDOASP V.2.0 and higher, radial *Doppler shift* is accounted for using the theory developed by Schmidt and Kuperman [9]. The source pulse and the radial projections of the source and receiver velocities must be specified in the input file following the specification of the centre frequency and the contour offset (Block II), i.e.

Standard	For option **d**
FRC COFF	IT VS VR

`IT` is a number identifying the source pulse as described in Sec. 16. `VS` and `VR` are the projected radial velocities in m/s of the source and receiver, respectively, both being positive in the direction from source to receiver. Since this option requires incorporation of the source function in the wavenumber integral, the PP post-processor must subsequently be used with source pulse -1 (impulse response).

9.4.2 Block IV: Environmental Model

RDOASP supports all the environmental models allowed for SAFARI as well as the ones described above in Section 4.1. The stepwise range-independent environment is specified by a standard OASP environment block for each sector, with the length of the sector added to the line containing the number of layers. The sector length is given in kilometers. The significance of the environmental parameters is as follows

NSEC: Number of sectors, each of which should have a block with layer data in input file.

NL: Number of layers, including the upper and lower half-spaces. These should Always be included, even in cases where they are vacuum.

SECL: Length of sector in kilometers.

D: Depth in m of upper boundary of layer or halfspace. The reference depth can be choosen arbitrarily, and D() is allowed to be negative. For layer no. 1, i.e. the upper half-space, this parameter is dummy.

CC: Velocity of compressional waves in m/s. If specified to 0.0, the layer or half-space is vacuum.

CS: Velocity of shear waves in m/s. If specified to 0.0, the layer or half-space is fluid. If CS()$<$ 0, it is the compressional velocity at bottom of layer, which is treated as fluid with $1/c(z)^2$ linear.

AC: Attennuation of compressional waves in dB/λ. If the layer is fluid, and AC() is specified to 0.0, then an imperical water attenuation is used (Skretting & Leroy).

AS: Attenuation of shear waves in dB/λ

RO: Density in g/cm^3.

RG: RMS roughness of interface in m. RG(1) is dummy. If RG<0 it represents the negative of the RMS roughness, and the associated correlation length CL should follow. If RG>0 the correlation length is assumed to be infinite.

CL: Roughness correlation length in m.

9.4.3 Block V: Sources

RDOASP supports the same sources as OASP, i.e explosive sources in fluids or solids or vertical point forces in solids (option X). Multible sources in a vertical array are supported.

Source Types

As in SAFARI the default source type in RDOASP is an explosive type compressional source. In addition to the optional point forces, and some seismic moment sources have been added to RDOASP. The source type is specified by a number $(1-5)$ in the option field (line 2). The translation is as follows:

1. Explosive source (default) normalized to unit pressure at 1 m distance.
2. Vertical point force with amplitude 1 N.
3. Horizontal (in-plane) point force with amplitude 1 N.
4. Dip-slip source with seismic moment 1 Nm. Dip angle specified in degrees in block V, following the other parameters.
5. Omnidirectional seismic moment source representing explosive source. Same as type 1, but all three force dipoles have seismic moment 1 Nm.

Source Normalization

In SAFARI-FIPP, the source pulse shape was defined as the pressure pulse produced at a distance of 1 m from the source (for solids the negative of the normal stress 1 m below the source).

In RDOASP, the same source normalization has been maintained for point sources (explosive sources) in fluid media. For solid media, however, the sources are normalized to unit volume (1 m^3) injection for explosive sources and unit force 1 N for point sources or 1 N/m for line sources.

User defined Source Arrays

RDOASP allows allow a user-defined source array through options **l** and **v**, as described in Section 8.5.3.

9.4.4 Block VI: Receivers

The default specification of the virtual source/receiver arrays used for coupling the field between the sectors is the same as for RDOAST, i.e. through the parameters RD1, RD2 and NRD in Block VI, with

RD1 Depth of uppermost virtual source/receiver in meters

RD2 Depth of lowermost virtual source/receiver in meters

NRD Number of virtual source/receivers

The NRD receivers are placed equidistantly in the vertical.

The physical receiver depths are specified similarly on a separate line. It should be noted that for each depth, the code will compute the field at the closest virtual receiver depth.

D1 Depth of uppermost physical receiver in meters

D2 Depth of lowermost physical receiver in meters

ND Number of physical receiver depths

9.4.5 Block VII: Wavenumber integration

This block specifies the wavenumber sampling in the standard SAFARI format, with the significance of the parameters being as follows:

CMIN: Minimum phase velocity in m/s. Determines the upper limit of the truncated horizontal wavenumber space:

$$k_{max} = \frac{2\pi * \text{FREQ}}{\text{CMIN}}$$

CMAX: Maximum phase velocity in m/s. Determines the lower limit of the truncated horizontal wave- number space:

$$k_{min} = \frac{2\pi * \text{FREQ}}{\text{CMAX}}$$

In plane geometry (option P) CMAX may be specified as negative. In this case, the negative wavenumber spectrum will be included with $k_{min} = -k_{max}$, yielding correct solution also at zero range. To properly handle the coupling at the vertical interfaces, negative wavenumbers are highly recommended, as is the automatic sampling option, `NW = -1` .

NW: Number of sampling points in wavenumber space. In contrast to what is the case for OAST, NW does here not have to be an integer power of 2. The sampling points are placed equidistantly in the truncated wavenumber space determined by CMIN and CMAX. If CMAX<0, i.e. the inclusion of the negative spectrum is enabled, then the NW sample points will be distributed along the positive wavenumber axis only, with the negative components obtained by symmetry. `NW = -1` activates the automatic sampling algorithms.

IC1: Number of the first sampling point where the calculation is to be performed. If IC1> 1, then the Hankel transform is Hanning-windowed in the interval 1,2. . .IC1-1 before integration.

IC2: Number of the last sampling point where the calculation is to be performed. If IC2<NWN, then the Hankel transform is Hanning windowed in the interval IC2+1,. . .NW before integration.

IF: Frequency increment for plotting of integration kernels. A value of 0 disables the plotting.

Automatic wavenumber sampling

RDOASP supports automatic sampling, making it possible for inexperienced users to obtain correct answers in the first attempt without the usual convergence testing. The automatic sampling is activated by specifying the parameter NW to -1 and it automatically activates the complex frequency integration contour even though option **O** may not have been specified. The parameters IC1 and IC2 have no effect if the automatic sampling is selected.

9.5 Execution of RDOASP

As for OASP, filenames are passed to the code via environmental parameters. In Unix systems a typical command file **rdoasp** (in $HOME/oases/bin) is:

```
#                              the number sign invokes the C-shell
setenv FOR001 $1.dat         # input file
setenv FOR002 $1.src         # Source array input file
setenv FOR015 $1.strf        # Source array trf file
setenv FOR019 $1.plp         # plot parameter file
setenv FOR020 $1.plt         # plot data file
setenv FOR028 $1.cdr         # contour plot parameter file
setenv FOR029 $1.bdr         # contour plot data file
rdoasp2                        # executable
```

After preparing a data file with the name **input.dat**, OASP is executed by the command:

> **rdoasp input**

To create timeseries, run the post-processor `pp`

9.6 Graphics

Command files are provided in a path directory for generating the graphics.

To generate curve plots, issue the command:

> **mplot input**

To generate contour plots, issue the command:

> **cplot input**

10 OASP3D: 3-D Wideband Transfer Functions

The OASES-OASP3D module calculates the depth-dependent Green's function for a selected number of frequencies and determines the transfer function at any receiver position by evaluating the wavenumber integral. The frequency integral is evaluated in the Post-processor PP. As is the case for OASES-OASP, both stresses and particle velocities can be computed, but the field may be produced by point or line sources with *horizontal directionality* (forces of arbitrary direction, seismic moment sources) as described in [10]. The solution technique is the 3-dimensional extension of the global matrix approach described in Ref. [11]. Otherwise, OASP3D and OASP are identical in terms of environmental models, receiver arrays, wavenumber sampling etc.

10.1 Two-Step Execution

As is the case for OASP, OASP3D is always executed in the 2-step mode. OASP3D will generate the transfer functions for the selected environment and source-receiver geometry and for all Fourier orders of the source directionality. The interactive postprocessor is then used to select time windows, source pulses, stacking format etc. and azimuth for the receivers.

10.2 OASP3D Options

Except for the specification of source type, OASP3D Version 3.6 is compatible with OASP Version 1.6 in terms of options supported:

C Creates an $\omega - k$ representation of the field in the form of contours of integration kernels as function of horizontal wavenumber (slowness if option **B** is selected) and frequency (logarithmic y-axis). All axis parameters are determined automatically.

K Computes the bulk stress. In elastic media the bulk stress only has contributions from the compressional potential. In fluid media the bulk stress is equal to the negative of the pressure. Therefore for fluids this option yields the same result as option N or R.

O Complex frequency integration contour. This new option is the frequency equivalent of the complex wavenumber integration (**J** option in OAST). It moves the frequency contour away from the real axis by an amount reducing the time domain wrap-around by a factor 50 [3]. This option can yield significant computational savings in cases where the received signal has a long time duration, and only the initial part is of interest, since it allows for selection of a time window shorter than the actual signal duration. Note that only wrap around from later times is reduced; therefore the time window should always be selected to contain the beginning of the signal!

R Computes the radial normal stress σ_{rr} (or σ_{xx} for plane geometry).

S Computes the shear stresses σ_{rz} and $\sigma_{\theta z}$. In PP these components are selected for display by 'X' and 'Y', respectively, under the "Parameter" selection options.

U Decomposed seismograms. This option generates 7 transfer function files to be processed by PP:

File name	Contents
input.trf	Complete transfer functions
input.trfdc	Downgoing P waves
input.trfuc	Upgoing P waves
input.trfds	Downgoing SV waves
input.trfus	Upgoing SV waves
input.trfdh	Downgoing SH waves
input.trfuh	Upgoing SH waves

f A full Hankel transform integration scheme is used for low values of kr and tapered into the FFP integration used for large kr. The compensation is achieved at very low additional computational cost and is recommended highly for cases where the near field is needed.

l User defined source array. This new option is similar to option **L** in the sense that that it introduces a vertical source array of time delayed sources of identical type. However, this option allows the depth, amplitude and delay time to be specified individually for each source in the array. The source data should be provided in a separate file, **input.src**, in the format described below in Section 10.3.2.

v As option **l** this option allows for specifying a non-standard source array. However, it is more general in the sense that different types of sources can be applied in the same array, and the sources can have different signatures. The array geometry and the complex amplitudes are specified in a file **input.strf** which should be of **trf** format as described in Section 10.3.2.

t Eliminates the wavenumber integration and computes transfer functions for individual slowness components (or plane wave components). The Fourier transform performed in PP will then directly compute the slowness/intercept-time or $\tau - p$ response for each of the selected depths. When option **t** is selected, the range parameters in the data file are insignificant.

10.3 Sources

The source specification is the only difference between data files prepared for OASP and OASP3D.

10.3.1 Source Types

OASP3D Version 3.5 supports the 5 types of sources (either point or line sources, controlled by option P), corresponding to those defined in [10]:

1. Explosive (omnidirectional) sources.
2. Force of arbitrary vertical and horizontal direction.
3. Dip-slip seismic source of arbitrary dip angle.
4. Strike-slip seismic source of arbitrary dip angle.
5. Tensile crack source in elastic media.
6. Normal seismic moment source with arbitrary moment amplitudes M_{11}, M_{22}, and M_{33}
7. General seismic moment source with arbitrary components M_{ij}.

The source type and parameters are specified in a separate line right after the environmental block in the data file, before the source depth line. The format of this data line depends on the source type:

ITYP							(Type 1)
ITYP	FMAG	HANG	VANG				(Type 2)
ITYP	SMOM	DANG					(Type 3-4)
ITYP	M11	M22	M33	DANG			(Type 5,6)
ITYP	M11	M12	M13	M22	M23	M33	(Type 7)

where

ITYP:	Source type
FMAG:	Magnitude of force in N (N/m for line source).
HANG:	Horizontal angle of force relative to x-axis in deg.
VANG:	Vertical angle in degg of force relative to horizontal plane. Positive downwards.
SMOM:	Seismic moment of slip sources in Nm
DANG:	Dip angle in deg. Positive rotation around x-axis 0° : crack in $x - y$ plane 90°: crack in $x - z$ plane
M11:	Moment of force dipole in x'-direction, M_{11}.
M22:	Moment of force dipole in y'-direction, M_{22}.
M33:	Moment of force dipole in z'-direction M_{33}.
Mii:	Seismic moment component.

The pulse response output produced by PP is available as either individual pulse plots for each single receiver or as stacked plots, where the stacking can be performed in either range, depth or azimuth. For the individual plots the time series are produced in true units, i.e. Pa for stresses and m/s for particle velocities.

As an example, to run the SAFARI-FIPP case 2 problem with automatic sampling, and a point force within the sea bed at $45°$ angle with the sea bed, and $30°$ horizontal angle relative to the x-axis, change the data file as follows:

```
SAFARI-FIPP case 2. Auto sampling. Force 30/45 deg
V H f                          # Bessel integration.
5 0
4
  0    0      0 0   0   0   0
  0 1500      0 0   0   1   0
100 1600    400 0.2 0.5 1.8 0
120 1800    600 0.1 0.2 2.0 0
2 1.0 30.0 45.0                 # ITYP, FMAG, HANG, VANG
101                             # SD = 101 m
100 100 1
 300 1E8
-1 0 0                          # NW   =   -1
2048 0.0 12.5 0.006 0.5 0.5 5
```

10.3.2 User defined Source Arrays

Version 3.6 of OASP3D has been upgraded to allow a user-defined source array through options **l** and **v**.

Option **l** is intended for general physical arrays with uneven spacing or special shadings, As for the built-in arrays, such user-defined arrays may be present in fluid as well as elastic media. The source type is specified as described above, and the array geometry and shading should be given in the file **input.src** in the following format

```
LS
SDC(1)  SDELAY(1)  SSTREN(1)    # Depth (m), Delay (s), Amplitude
SDC(2)  SDELAY(2)  SSTREN(2)
SDC(3)  SDELAY(3)  SSTREN(3)
  :         :          :
  :         :          :
SDC(LS) SDELAY(LS) SSTREN(LS)
```

Option **v** is more general in the sense that it allows for different source types to be mixed in the array, and the pure time delay is replaced by a specification of the complex amplitudes in the frequency domain, allowing for representation of multibles etc. This option is used for *indirect arrays* such as those imposed by coupling of wave systems. For example, this option is used for coupling tube wave phenomenae to propagation in a stratified formation when modeling borehole seismics. Option **v** is only allowed for source arrays in elastic media (including transversily isotropic layers). The complex amplitudes of the source array are specified in the file **input.strf**. This should be an ASCII **trf** file, and the frequency sampling should be consistent with the frequency sampling selected in the input file **input.dat**. There are 3 source types available. All are omnidirectional in the horizontal. The source type is identified by a type number in the file header, and each depth can have one of each source type present. The possible source types are:

10 Seismic monopole, i.e. 3 perpendicular and identical force dipoles. The unit is seismic moment (Nm).

11 Vertical force dipole. The unit is seismic moment (Nm).

12 Vertical force, positive downwards. The unit is force (N).

The source types are recognized by PP which can therefore be used to check your source timeseries by simply specifying **input.strf** in Field 1 of the PP main menu. An example of an **strf**-file for 2 source depth, with a monopole and a dipole source at each depth, is

```
PULSETRF                                # TRF file identification
OASP16                                  # Calculating program
          2                             # No. sources per depth NSIN
         10          11                 # Source types
tube wave simulation                    # Title
+                                       # Sign if time factor exponent
400.0                                   # Center frequency
  6.0                                   # Depth of primary source
 -0.5  19.5  21                         # SD-min, SD-max, LS
  0.0   0.0   1                         # Range (fixed).
 1024   2   104  0.0001                 # Time/frequency parameters
          1                             # Dummy
 -38.20335                              # Imag. part of frequencies
          1                             # One Fourier order (fixed)
          1                             # Fixed
          0                             # Dummy
          0                             # Dummy
          0                             # Dummy
 0.0                                    # Dummy
 0.0                                    # Dummy
 0.0                                    # Dummy
 0.0                                    # Dummy
```

```
 0.0                                     # Dummy
 -24.15950 82.01517 -24.15950 82.01517 # Data
 -28.20251 83.04697 -28.20251 83.04697 # Data
 -32.38960 83.93490 -32.38960 83.93490 # Data
 -36.71837 84.66933 -36.71837 84.66933 # Data
 -41.18590 85.24049 -41.18590 85.24049 # Data
      :        :         :        :        :
```

Note: All lines should start with an empty space!. The time/frequency parameters are given in the form

```
 NT   LX   MX   DT
```

where

NT is the number of time samples

DT is the time sampling interval in seconds

LX is the index of the first frequency, LX = INT(Fmin*DT)

MX is the index of the last frequency, MX = INT(Fmax*DT)

The complex data must be written in the following loop structure

```
      DO 10 K = LX,MX
       DO 10 L = 1,LS
        WRITE(15,*) (REAL(TRF(K,L,M)),AIMAG(TRF(K,L,M)), M=1,NSIN)
 10   CONTINUE
```

10.4 Receivers

The default specification of the receiver depths is the same as for SAFARI-FIPP, i.e. through the parameters RD1, RD2 and NR in Block VI, with

Parameter	Description
RD1	Depth of uppermost receiver in m
RD2	Depth of lowermost receiver in m
NR	Number of receiver depths

The NR receivers are placed equidistantly in the vertical.

10.4.1 Non-equidistant Receiver Depths

In OASP3D the receiver depths can optionally be specified individually. The parameter NR is used as a flag for this option. Thus, if NR < 0 the number of receivers is interpreted as –NR, with the individual depths following immidiately following Block VI. As an example, to run the SAFARI-FIPP case 2 problem with automatic sampling, and a point force within the sea bed at $45°$ angle with the sea bed, and $30°$ horizontal angle relative to the x-axis, and with receivers at depths 100, 105 and 120 m, change the data file as follows:

```
SAFARI-FIPP case 2. Auto sampling. Force 30/45 deg
V H f                        # Bessel integration.
5 0
4
  0    0      0 0   0   0   0
  0 1500      0 0   0   1   0
100 1600   400 0.2 0.5 1.8 0
120 1800   600 0.1 0.2 2.0 0
2 1.0 30.0 45.0               # ITYP, FMAG, HANG, VANG
101                           # SD = 101 m
100 100 -3                    # 3 receivers
100.0 105.0 120.0             # Receiver depths in meters
300 1E8
-1 0 0                        # NW   =   -1
2048 0.0 12.5 0.006 0.5 0.5 5
```

The PP Post-processor is compatible and will depth-stack the traces at the correct depths.

10.4.2 Tilted Receiver Arrays

The new option 'T' allows for specification of an array tilt in the vertical plane containing the source and the receivers.

The tilt angle and rotation origin is specified in the receiver depth line (Block VI in SAFARI manual):

Standard	For option T
RD1 RD2 NR	ZREF ANGLE

The vertical arrays are rotated by an angle 'ANGLE' in deg relative to the vertical. The rotation is performed with origin at depth 'ZREF'.

The parameters RD1, RD2 and NR always refer to the untilted case. In the tilted case these parameters do therefore define the array geometry and not the actual depths of the receivers in the tilted array. The same is the case for the graphics output produced by the post-processor PP.

The source(s) is always at the origin and is therefore not rotated. Thus, for zero-offset tilted VSP-s, the reference depth ZREF should be set equal to the source depth SD!

10.5 Execution of OASP3D

As for SAFARI, filenames are passed to the code via environmental parameters. In Unix systems a typical command file **oasp3** (in $HOME/oases/bin) is:

```
#                               the number sign invokes the C-shell
setenv FOR001 $1.dat          # input file
setenv FOR002 $1.src          # Source array input file
setenv FOR019 $1.plp          # plot parameter file
setenv FOR020 $1.plt          # plot data file
setenv FOR028 $1.cdr          # contour plot parameter file
setenv FOR029 $1.bdr          # contour plot data file
oasp3d                        # executable
```

After preparing a data file with the name **input.dat**, OAST is executed by the command:

oasp3 input

10.6 Graphics

Command files are provided in a path directory for generating the graphics.

To generate curve plots, issue the command:

mplot input

To generate contour plots, issue the command:

cplot input

11 OASN: Noise, Covariance Matrices and Signal Replicas

The OASES-OASN module models the seismo-acoustic field on arbitrary 3-dimensional arrays of hydrophones and geophones in the presence of surface noise sources and discrete signal sources. This module is used to model the propagation of surface-generated ambient noise and for providing simulated array responses as well as signal replicas to the array processing module OASES-MFP described later. The SAFARI predecessor of OASN was used for the noise propagation study in Ref. [12] and for computing covariance matrices and replicas for the matched field processing study in Ref. [13].

11.1 Input Files for OASN

The input file for oasn is structured in 10 blocks, the first 6 of which, shown in Table 9 contain data which must always be given, such as the frequency selection, the environment and receiver array. The last 4 blocks should only be included for certain options and parameter settings, as indicated in Table 10. The various blocks and the significance of the data is described in the following.

11.1.1 Block I: Title of Run

Arbitrary title to appear on graphics output.

11.1.2 Block II: Computational options

Similarly to the other modules, the output is controlled by a number of one-letter options:

- C Produces a contour plot of the spatial spectrum of the surface generated ambient noise vs. frequency and horizontal slowness. This option overrides option **K**.
- F Produces a curve plot of the noise level in dB vs frequency for each sensor in the receiving array.
- J Applies a complex integration contour with offset given in Block III for all wavenumber integrations.
- K Creates a plot of the wavenumber spectrum of the surface generated ambient noise for each individual frequency.
- N Outputs the noise covariance matrices to a direct access file with extension `.xsm` . The file format is described below.

Input parameter	Description	Units	Limits
Block I: TITLE			
TITLE	Title of run	-	$\leq$ 80 ch.
Block II: OPTIONS			
A B C $\cdots$	Output and computational options	-	$\leq$ 40 ch.
Block III: FREQUENCIES			
FREQ1, FREQ2, NFREQ, COFF	FREQ1: Minimum frequency	Hz	> 0
	FREQ2: Maximum frequency	Hz	> 0
	NFREQ: Number of frequencies		> 0
	COFF: Integration contour offset	dB/Λ	≥ 0
Block IV: ENVIRONMENT			
NL	Number of layers, incl. halfspaces	-	≥ 2
D,CC,CS,AC,AS,RO,RG,CL	D: Depth of interface.	m	
.	CC: Compressional speed	m/s	≥ 0
.	CS: Shear speed	m/s	
.	AC: Compressional attenuation	dB/Λ	≥ 0
.	AS: Shear attenuation	dB/Λ	≥ 0
	RO: Density	g/cm^3	≥ 0
	RG: RMS of interface roughness	m	
	CL: Correlation length of roughness	m	> 0
Block V: RECEIVER ARRAY			
NRCV	NRCV: Number of receivers in array	-	> 0
Z,X,Y,ITYP,GAIN	Z: Receiver depth	m	
.	X: x-offset of receiver	m	
.	Y: y-offset of receiver	m	
.	ITYP: Receiver type	-	> 0
	GAIN: Receiver signal gain	dB	
Block VI: SOURCES			
SSLEV,WNLEV,DSLEV,NDNS	SSLEV: Surface noise source strength	dB	
	WNLEV: White noise level	dB	
	DSLEV: Deep source level	dB	
	NDNS: Number of discrete sources		

Table 9: OASN input file structure, mandatory components: Environment, Array geometry and Sources.

Input parameter	Description	Units	Limits
Block VII: SEA SURFACE NOISE (SSLEV $\neq$ 0)			
CMINS,CMAXS	Phase velocity interval, *surface noise*		
	CMINS: Minimum phase velocity	m/s	> 0
	CMAXS: Maximum phase velocity	m/s	> 0
NWSC,NWSD,NWSE	Wavenumber sampling, *surface noise*		
	NWSC: Samples in *continuous* spectrum		
	NWSD: Samples in *discrete* spectrum		
	NWSE: Samples in *evanescent* spectrum		
Block VIII: DEEP NOISE SOURCES (DSLEV $\neq$ 0)			
DPSD	DPSD: Depth of *deep* source sheet		
CMIND,CMAXD	Phase velocity interval, *deep* sources		
	CMIND: Minimum phase velocity	m/s	> 0
	CMAXD: Maximum phase velocity	m/s	> 0
NWDC,NWDD,NWDE	Wavenumber sampling, *deep* sources		
	NWDC: Samples in *continuous* spectrum		
	NWDD: Samples in *discrete* spectrum		
	NWDE: Samples in *evanescent* spectrum		
Block IX: DISCRETE SOURCES (NDNS $>$ 0)			
ZDN,XDN,YDN,DNLEV	ZDN: Depth of *discrete* source	m	
:	XDN: x-offset of discrete source	km	
:	YDN: y-offset of discrete source	km	
	DNLEV: Source level of discrete source	dB	
CMIN,CMAX	Phase velocity interval, *discrete* sources		
	CMIN: Minimum phase velocity	m/s	> 0
	CMAX: Maximum phase velocity	m/s	> 0
NW,IC1,IC2	NW: Wavenumber sampling, *discrete* sources	-	
	IC1: First sampling point	-	≥ 1
	IC2: Last sampling point	-	$\leq$NW
Block X: SIGNAL REPLICAS (Option R)			
ZMINR,ZMAXR,NZR	Depth sampling of *replicas*	m	
XMINR,XMAXR,NXR	x-offset sampling of *replicas*	km	
YMINR,YMAXR,NYR	y-offset sampling of *replicas*	km	
CMINR,CMAXR	Phase velocity interval, *replicas*		
	CMINR: Minimum phase velocity	m/s	> 0
	CMAXR: Maximum phase velocity	m/s	> 0
NWR,ICR1,ICR2	NWR: Wavenumber sampling, *replicas*	-	
	ICR1: First sampling point	-	≥ 1
	ICR2: Last sampling point	-	$\leq$NWR

Table 10: OASN input file structure, optional components: Computational parameters.

P Produces plots of noise intensity vs. receiver number for each selected frequency.

R Outputs the array replicas to a file with extension `.rpo` . The file format is described below.

T Produces a transfer function file with extension `.trf` for the selected array and one discrete source. Only allowed for `NDNS = 1` . For file format see `OASP` . The ranges for the receivers in the `.trf` file are not the true ones, but simply the receiver numbers. To plot all traces together use *range stacking* in `PP` .

Z Produces a plot of the sound speed profiles in the standard format.

b Solves the depth-separated wave equation with the lowermost interface condition expressed in terms of a complex reflection coefficient. The reflection coefficient must be tabulated in a input file `input.trc` which may either be produced from experimental data or by the reflection coefficient module OASR as described on Page 30. See also there for the file format. The lower halfspace must be specified as vacuum and the last layer as an isovelocity fluid without sources for this option. Add dummy layer if necessary. Further, the frequency sampling must be consistent. Using `OASR` this is optained by using the same minimum and maximum frequencies, and number of frequencies, but without option `C` . Note: Care should be taken using this option with a complex integration contour, option `J` . The tabulated reflection coefficient must clearly correspond to the same imaginary wavenumber components for `OASN` to yield proper results. `OASR` calculates the reflection coefficient for real horizontal wavenumbers.

t Solves the depth-separated wave equation with the top interface condition expressed in terms of a complex reflection coefficient. The reflection coefficient must be tabulated in a input file `input.trc` which may either be produced from experimental data or by the reflection coefficient module `OASR` as described on Page 30. See also there for the file format. The upper halfspace must be specified as vacuum and the first layer as an isovelocity fluid without sources for this option. Add dummy layer if necessary. Further, the frequency sampling must be consistent. Using `OASR` this is optained by using the same minimum and maximum frequencies, and number of frequencies, but without option `C` . Note: Care should be taken using this option with a complex integration contour, option `J` . The tabulated reflection coefficient must clearly correspond to the same imaginary wavenumber components for `OASN` to yield proper results. `OASR` calculates the reflection coefficient for real horizontal wavenumbers.

A digit (1–9) identifying the order of the surface source correllation. The default is totally uncorrelated sources. Higher numbers yield more vertical directionality.

11.1.3 Block III: Frequency Selection

This block controls the frequency sampling. Covariance matrices, replicas and graphics will be produced for `NFREQ` frequencies equidistantly sampled between `FREQ1` and `FREQ2`. `COFF` is the wavenumber integration offset in DB/λ and only has significance for option **J**. Option **J** and `COFF = 0` will invoke the default integartion offset.

11.1.4 Block IV: Environmental Data

The environmental data are specified in the standard SAFARI format.

11.1.5 Block V: Receiver Array

OASN will compute the noise and signal field on arbitrary three dimensional arrays. The first line of this block specifies the number of sensors. Then follows the position, type and gain for each sensor in the array. The the sensor positions are specified in cartesian coordinates in meters. The types currently implemented are as follows

1. Hydrophone. Normal stress σ_{zz} (negative of pressure in water) in Pa for source level 1 Pa (or μPa for source level 1 μPa).
2. Geophone. Particle velocity $\dot{u}$ in x-direction (horizontal). Unit is m/s for source level 1 Pa (or μm/s for source level 1 μPa).
3. Geophone. Particle velocity $\dot{v}$ in y-direction (horizontal). Unit is m/s for source level 1 Pa (or μm/s for source level 1 μPa).
4. Geophone. Particle velocity $\dot{w}$ in z-direction (vertical, positive downwards). Unit is m/s for source level 1 Pa (or μm/s for source level 1 μPa).

The gain is a calibration factor in dB which is applied to ambient noise and signal on all sensors. *Note that the gain is not applied to the white noise!* When combining hydrophones and geophones in array processing it is important to note that there is a difference in order of magnitude of pressure and particle velocity of the order of the acoustic impedance. Therefore the geophone sensors should usually have a gain which is of the order 120 dB higher than the gain applied to the hydrophone sensors.

11.1.6 Block VI: Noise and Signal Sources

OASN treats 4 types of noise and signal sources simultaneously, depending on the value of the parameters in this block:

SSLEV Strength in dB of sea surface noise sources. Per definition the source strength corresponds to the acoustic pressure the same source distribution would yield in an infinitely deep ocean [3, 12]. The value of `SSLEV` is interpreted in two different ways, depending on its sign:

SSLEV≥ 0: Level in dB of white surface source spectrum.

SSLEV< 0: A negative value identifies a logical unit for a file containing the frequency dependence of the surface source level. The format of the source level files is described in Section 11.1.11.

WNLEV Level of white noise on sensor in dB. Note that the white noise is added after the sensor gain.

DSLEV To allow for more horizontal directionality of the noise field than predicted by the surface noise model, an additional, deeper sheet of sources can be introduced.

NDNS This parameter specifies the number of discrete sources present (targets or interferers).

11.1.7 Block VII: Surface Noise Parameters

This block contains the wavenumber sampling parameters for computing the noise covariance matrix. The parameters `CMINS` and `CMAXS` are the phase phase velocities defining the wavenumber integration interval. Note here that the continuous spectrum is always important for surface noise. Therefore `CMAXS` must be specified to a large number (e.g. 10^8) to include the steep propagation angles. `CMINS` should be chosen small enough to include all important evanescent components.

The wavenumber sampling parameters `NWSC, NWSD` and `NWSE` are interpreted in two different ways by `oasn`, depending of the value specified for `NWSD` :

NWSD < 10 The wavenumber sampling parameters are given in the standard SAFARI format, with the parameters interpreted as follows:

NWSC Total number of wavenumber samples, distributed equidistantly between $k_{min} = \omega/c_{max}$ and $k_{max} = \omega/c_{min}$.

NWSD Sampling point where the kernel computation starts. The kernel will be Hermite extrapolated. In this format NWSD will usually be set to 1 since the steep angles are always important.

NWSE Sampling point where the kernel computation ends. The kernel will be Hermite extrapolated.

NOTE: The sampling parameters must be specified in this format for options **K** and **C**, which require equidistant sampling.

NWSD ≥ 10 The wavenumber sampling parameters are given individually for each of the three spectral regimes. This allows for a much denser sampling in the discrete spectrum without forcing a dense sampling of the smooth kernel in the other regimes.

NWSC Number of wavenumber wavenumber samples distributed equidistantly over the *continuous spectrum* between $k_{min} = \omega / c_{max}$ and the critical wavenumber k_c corresponding to the compressional speed in the sub-bottom.

NWSD Number of wavenumber wavenumber samples distributed equidistantly over the *discrete spectrum* between the critical wavenumber k_c corresponding to the compressional speed in the sub-bottom and the wavenumber k_w corresponding to the minimum sound speed in the water column.

NWSE Number of wavenumber wavenumber samples distributed equidistantly over the *evanescent spectrum* between the wavenumber k_w corresponding to the minimum sound speed in the water column and $k_{max} = \omega / c_{min}$.

11.1.8 Block VIII: Deep Noise Source Parameters

The parameter `DPSD` is the depth of the deep noise source sheet. The other parameters in this block are specified in a format identical to that described above for the surface sources.

11.1.9 Block IX: Discrete Noise and Signal Sources

If `NDNS`>0, then this block should first contain the coordinates and source level for each discrete source. Note that the depth is specified first in *meters*, followed by the x- and y-ranges in *kilometer* (in contrast to the array element coordinates which were all given in meters).

The source levels `DNLEV` are interpreted in two different ways, dependent on whether specified value is positive or negative:

DNLEV≥ 0**:** Level in dB of white source spectrum.

DNLEV< 0**:** A negative value identifies a logical unit of a file containing the frequency dependence of the source level. The format of the source level files is described in Section 11.1.11.

The wavenumber sampling parameters for the discrete sources should follow in the standard OASES format. In Version 2.2 automatic sampling is supported, and activated by NW=-1. In this case Ic1 and IC2 are insignificant. As is the case for automatic sampling in all OASES modules, the desired phase velocity interval must be specified manually. The kernel tapering invoked by the automatic sampling will be initiated at the specified phase velocities.

11.1.10 Block X: Signal Replica Parameters

The first three lines of this block defines the computational grid over which the replica sources will be placed. The sampling is equidistant in all 3 coordinate directions. Note the the depths Z should be specified in *meters* whereas the ranges x and y should be specified in *kilometers*.

The wavenumber sampling parameters for the replica sources should follow in the standard OASES format. In Version 2.2 automatic sampling is supported, and activated by NW=-1. In this case IC1 and IC2 are insignificant. As is the case for automatic sampling in all OASES modules, the desired phase velocity interval must be specified manually. The kernel tapering invoked by the automatic sampling will be initiated at the specified phase velocities.

11.1.11 Source Level Input Files

The source level for surface generated noise and discrete sources is by default assumed to be constant in frequency. Although this is a reasonable assumption for surface generated noise over reasonably wide frequency bands, it is usually unrealistic for discrete sources which will be characterized by distinct frequency lines in their source spectrum. Therefore the source spectra can optionally be specified in ASCII files which will be read by OASN if the source levels are specified as negative, in which case the value is interpreted as the negative of the logical unit corresponding to the file. Therefore, the file should either be assigned to the environmental variable `FORxxx` or the file should have the name `fort.xxx`, where `xxx` is the absolute value of the number specified for `SNLEV` or `DNLEV` .

A particular source file (and logical unit) can be shared by any number of sources.

The format of the file is a follows:

```
NFREQ   FREQ1   FREQ2
dB(FREQ1)
```

```
dB(FREQ1+DELFRQ)
 :
 :
 :
dB(FREQ2)
```

The first line specifies the frequency sampling of the source levels, and it must be consistent with the sampling specified in Block III of the input file. The following lines simply states the source level in dB at each frequency value.

11.1.12 Examples

The following OASN input file `fram4.dat` produces the covariance matrix and replicas used for the arctic matched field study reported in Ref. [14]:

```
                # >>> Block I: Title
FRAM IV environment.
                # >>> Block II: Options
R N J 3             # Covariance, replicas, cos^3 sources
                # >>> Block III: Frequency sampling
20 20 1 0           # 20 Hz

                # >>> Block IV: Environment
12
0 0 0 0 0 0 0
0 1431 -1443 0 0 1 0
85 1443 -1460 0 0 1 0
200 1460 -1462 0 0 1 0
330 1462 -1466 0 0 1 0
1225 1466 -1508 0 0 1 0
3800 1508 0 1.0 0 2.2 0
4200 1508 -2506 0.5 0 2.9 0
4433 2506 -3503 0.5 0 2.9 0
4667 3503 -4500 0.5 0 2.9 0
4900 4500 -6000 0.4 0 2.9 0
5900 6000 0 0.2 0 2.9 0

                # >>> Block V: Receiver Array
18                      # 18 elements
30 0 0 1 -1             # Hydrophone at z = 30 m. Gain -1 dB
60 0 0 1 -1
90 0 0 1 -1
140 0 0 1 -1
180 0 0 1 -7
```

```
210 0 0 1 -7            # Hydrophone at z =210 m. Gain -7 dB
270 0 0 1 -1
330 0 0 1 -1
350 0 0 1 -1
390 0 0 1 -1
450 0 0 1 -1
510 0 0 1 -1
570 0 0 1 -1
630 0 0 1 -1
690 0 0 1 -1
782 0 0 1 -1
860 0 0 1 -1
960 0 0 1 -1            # Hydrophone at z =960 m. Gain -1 dB

                # >>> Block VI: Noise and Signal Sources
70 50 0 1               # 70 dB surface noise. 50 dB white noise
                        # 1 discrete source

                # >>> Block VII: Surface noise
1400 1E8                # CMINS, CMAXS
400 400 100             # Samples in cont., discr., evanes. spec.

                # >>> Block IX: Discrete source parameters
91 250 0 180            # Source at depth 91 m, 250 km x-range,
                        #       strength 180 dB.
1425 1570               # CMIN, CMAX. Only waterborne important.
512 25 490              # 512 samples. (-1 0 0 for auto sampling)

                # >>> Block X: Replica parameters
10 1000 23              # 23 source depth, 10 - 1000 m
150 300 76              # 76 source ranges, 150 - 300 km
0 0 1                   # 1 y-range (omnidirectional response)

1425 1570               # CMINR, CMAXR. Only waterborne important.
512 25 490              # 512 samples. (-1 0 0 for auto sampling)
```

11.2 Execution of OASN

As for the other OASES modules, filenames are passed to OASN via environmental parameters. In Unix systems a typical command file **oasn** (in $HOME/oases/bin) is:

```
#                              the number sign invokes the C-shell
setenv FOR001 $1.dat         # input file
setenv FOR019 $1.plp         # plot parameter file
setenv FOR020 $1.plt         # plot data file
```

```
setenv FOR023 $1.trc       # reflection coefficient table (input)
setenv FOR028 $1.cdr       # contour plot parameter file
setenv FOR029 $1.bdr       # contour plot data file
setenv FOR014 $1.rpo       # signal replicas
setenv FOR016 $1.xsm       # covariance matrices
oasn2_bin                  # executable
```

After preparing a data file with the name **input.dat**, OASN is executed by the command:

oasn input

11.3 Graphics

Command files are provided in a path directory for generating the graphics produced by oasn.

To generate curve plots, issue the command:

mplot input

To generate contour plots, issue the command:

cplot input

11.4 Output Files

In addition to the graphics output files, OASN optionally produces files containing the computed covariance matrices and replica fields for use by the array processing module OASES-MFP, or by other processing software. Note that OASN assumes a time factor $\exp(i\omega t)$.

11.4.1 Covariance Matrices

The covariance matrix is written to a binary, direct access file with a fixed record length of 8 bytes. The file will have the name `input.xsm` . The file is opened with the following statements:

```
C         *****  OPEN XSM FILE...Note that the logical unit 16 must
C         be assigned a filename external to the program,
C         in Unix: setenv FOR016 input.xsm
          LUN=16
          call getenv('FOR016',XSMFILE)
          OPEN  ( UNIT       = LUN
```

```
     -,          FILE       = XSMFILE
     -,          STATUS     = 'UNKNOWN'
     -,          FORM       = 'UNFORMATTED'
     -,          ACCESS     = 'DIRECT'
     -,          RECL       = 8         )
```

Note: This `OPEN` statement is used for machines where the fixed record length for unformatted files is given in *bytes* (e.g. Alliant FX-40). Some machines (e.g. DEC 5000 workstations) require the record lenth in words; in that case specify `RECL = 2` .

The first 10 records of the `xsm` file contains the header, identifying the file in terms of title, number of sensors and frequency sampling. The header has been written with the following statements, with the parameters defined in Table 9:

```
C *** WRITE HEADER
         WRITE (LUN,REC=1) TITLE(1:8)
         WRITE (LUN,REC=2) TITLE(9:16)
         WRITE (LUN,REC=3) TITLE(17:24)
         WRITE (LUN,REC=4) TITLE(25:32)
         WRITE (LUN,REC=5) NRCV, NFREQ
c >>> Dummy integers IZERO
         WRITE (LUN,REC=6) IZERO, IZERO
         WRITE (LUN,REC=7) FREQ1, FREQ2
c >>> DELFRQ is the frequency increment (FREQ2 - FREQ1)/(NFREQ-1)
         WRITE (LUN,REC=8) DELFRQ, ZERO
c >>> The surface and white noise levels for info
         WRITE (LUN,REC=9) SSLEV,WNLEV
c >>> BLANK FILL NEXT RECORD FOR FUTURE USE
         WRITE (LUN,REC=10) ZERO,ZERO
```

OASN writes the covariance matrix columnwise using the following loop structure

```
         :
      COMPLEX COVMAT(NRCV,NRCV,NFREQ)
         :
         :
C >>> WRITE XSM
      DO 20 IFREQ=1,NFREQ
       DO 20 JRCV=1,NRCV
        DO 20 IRCV=1,NRCV
         IREC = 10 + IRCV + (JRCV-1)*NRCV + (IFREQ-1)*NRCV*NRCV
         WRITE (LUN,REC=IREC) COVMAT(IRCV,JRCV,IFREQ)
20    CONTINUE
```

11.4.2 Replica Fields

If option **R** is chosen, OASN writes the replica field toa binary, sequential file with the name `input.rpo` . The file is opened using the following statements

```
C        *****  OPEN RPO FILE...Note that the logical unit 14 must
C        be assigned a filename external to the program
C        In Unix: setenv FOR014 input.rpo.
C
         LUN=14
         CALL GETENV('FOR014',RPOFILE)
         OPEN  (UNIT       =  LUN        ,
     -          FILE       =  RPOFILE    ,
     -          STATUS     = 'UNKNOWN'   ,
     -          FORM       = 'UNFORMATTED')
```

The `rpo` file will first have a header for identification in terms of title, frequency sampling, array geometry and replica scanning space. The header is written by the following code, and should clearly be read accordingly. The parameters are defined in Tables 9 and 10.

```
        :
      CHARACTER*80  TITLE
        :
        :
c *** WRITE HEADER
       WRITE (LUN) TITLE
       WRITE (LUN) NRCV, NFREQ
c >>> DELFRQ is the frequency increment (FREQ2 - FREQ1)/(NFREQ-1)
       WRITE (LUN) FREQ1, FREQ2, DELFRQ
c >>> Replica sampling
       WRITE (LUN) ZMINR, ZMAXR, NZR
       WRITE (LUN) XMINR, XMAXR, NXR
       WRITE (LUN) YMINR, YMAXR, NYR
c >>> Array element data
       DO 10 IRCV=1,NRCV
        WRITE(LUN) X(IRCV),Y(IRCV),Z(IRCV),ITYP(IRCV),GAIN(IRCV)
 10    CONTINUE
```

The complex replicas follow frequency by frequency, written with the following loop structure

```
        :
      COMPLEX REPLIC(NRCV,NYR,NXR,NZR,NFREQ)
```

```
         :
         :
       DO 20 IFREQ=1,NFREQ
        DO 20 IZR=1,NZR
         DO 20 IXR=1,NXR
          DO 20 IYR=1,NYR
           DO 20 IRCV=1,NRCV
            WRITE (LUN) REPLIC(IRCV,IYR,IXR,IZR,IFREQ)
20     CONTINUE
```

12 OASI: Environmental Inversion

The OASES-OASI module is very similar to OASN, modeling the seismo-acoustic field on arbitrary 3-dimensional arrays of hydrophones and geophones in the presence of surface noise sources and discrete signal sources. This module is used to model the propagation of surface-generated ambient noise and for providing simulated array responses as well as signal replicas for matched field environmental inversion using OASES-MFP. OASI and MFP were used to generate the inversion and resolution results shown in Fig. 4 of Ref.[23].

12.1 Input Files for OASI

The input file for oasi is structured in 10 blocks, of which most are identical to the format for OASN. The first 6 blocks, shown in Table 11,contain data which must always be given, such as the frequency selection, the environment and receiver array. The last 4 blocks should only be included for certain options and parameter settings, as indicated in Table 12. The various blocks and the significance of the data is described in the following.

12.1.1 Block I: Title of Run

Title to appear on graphics output.

12.1.2 Block II: Computational options

Similarly to the other modules, the output is controlled by a number of one-letter options:

C Produces a contour plot of the spatial spectrum of the surface generated ambient noise vs. frequency and horizontal slowness. This option overrides option **K**.

F Produces a curve plot of the noise level in dB vs frequency for each sensor in the receiving array.

J Applies a complex integration contour with offset given in Block III for all wavenumber integrations.

K Creates a plot of the wavenumber spectrum of the surface generated ambient noise for each individual frequency.

N Outputs the noise covariance matrices to a direct access file with extension `.xsm` . The file format is described below. Note that a discrete source must be specified corresponding to the replica source.

Input parameter	Description	Units	Limits
Block I: TITLE			
TITLE	Title of run	-	$\leq$ 80 ch.
Block II: OPTIONS			
A B C $\cdots$	Output and computational options	-	$\leq$ 40 ch.
Block III: FREQUENCIES			
FREQ1, FREQ2, NFREQ, COFF	FREQ1: Minimum frequency	Hz	> 0
	FREQ2: Maximum frequency	Hz	> 0
	NFREQ: Number of frequencies		> 0
	COFF: Integration contour offset	dB/Λ	≥ 0
Block IV: ENVIRONMENT			
NL	Number of layers, incl. halfspaces	-	≥ 2
D,CC,CS,AC,AS,RO,RG,CL	D: Depth of interface.	m	
.	CC: Compressional speed	m/s	≥ 0
.	CS: Shear speed	m/s	
.	AC: Compressional attenuation	dB/Λ	≥ 0
.	AS: Shear attenuation	dB/Λ	≥ 0
	RO: Density	g/cm^3	≥ 0
	RG: RMS of interface roughness	m	
	CL: Correlation length of roughness	m	> 0
Block V: RECEIVER ARRAY			
NRCV	NRCV: Number of receivers in array	-	> 0
Z,X,Y,ITYP,GAIN	Z: Receiver depth	m	
.	X: x-offset of receiver	m	
.	Y: y-offset of receiver	m	
.	ITYP: Receiver type	-	> 0
	GAIN: Receiver signal gain	dB	
Block VI: NOISE SOURCES			
SSLEV,WNLEV,DSLEV,NDNS	SSLEV: Surface noise source strength	dB	
	WNLEV: White noise level	dB	
	DSLEV: Deep source level	dB	
	NDNS: Number of discrete sources		

Table 11: OASI input file structure, mandatory components: Environment, Array geometry and Sources.

Input parameter	Description	Units	Limits
Block VII: SEA SURFACE NOISE (SSLEV $\neq$ 0)			
CMINS,CMAXS	Phase velocity interval, *surface noise*		
	CMINS: Minimum phase velocity	m/s	> 0
	CMAXS: Maximum phase velocity	m/s	> 0
NWSC,NWSD,NWSE	Wavenumber sampling, *surface noise*		
	NWSC: Samples in *continuous* spectrum		
	NWSD: Samples in *discrete* spectrum		
	NWSE: Samples in *evanescent* spectrum		
Block VIII: DEEP NOISE SOURCES (DSLEV $\neq$ 0)			
DPSD	DPSD: Depth of *deep* source sheet		
CMIND,CMAXD	Phase velocity interval, *deep* sources		
	CMIND: Minimum phase velocity	m/s	> 0
	CMAXD: Maximum phase velocity	m/s	> 0
NWDC,NWDD,NWDE	Wavenumber sampling, *deep* sources		
	NWDC: Samples in *continuous* spectrum		
	NWDD: Samples in *discrete* spectrum		
	NWDE: Samples in *evanescent* spectrum		
Block IX: DISCRETE SOURCES (NDNS $>$ 0)			
ZDN,XDN,YDN,DNLEV	ZDN: Depth of *discrete* source	m	
:	XDN: x-offset of discrete source	km	
:	YDN: y-offset of discrete source	km	
	DNLEV: Source level of discrete source	dB	
CMIN,CMAX	Phase velocity interval, *discrete* sources		
	CMIN: Minimum phase velocity	m/s	> 0
	CMAX: Maximum phase velocity	m/s	> 0
NW,IC1,IC2	NW: Wavenumber sampling, *discrete* sources	-	
	IC1: First sampling point	-	≥ 1
	IC2: Last sampling point	-	$\leq$NW
Block X: SIGNAL REPLICAS (Option R)			
ZSR,XSR,YSR,SRLEV	ZSR: Depth of replica source	m	
	XSR: x-offset of replica source	km	
	YSR: y-offset of replica source	km	
	SRLEV: Source level of replicasource	dB	
LY1,PA1,VMIN1,VMAX1,NV1	Replica parameter 1		
LY2,PA2,VMIN2,VMAX2,NV2	Replica parameter 2		
CMINR,CMAXR	Phase velocity interval, *replicas*		
	CMINR: Minimum phase velocity	m/s	> 0
	CMAXR: Maximum phase velocity	m/s	> 0
NWR,ICR1,ICR2	NWR: Wavenumber sampling, *replicas*	-	
	ICR1: First sampling point	-	≥ 1
	ICR2: Last sampling point	-	$\leq$NWR

Table 12: OASI input file structure, optional components: Computational parameters.

P Produces plots of noise intensity vs. receiver number for each selected frequency.

R Outputs the array replicas to a file with extension `.rpo`. The file format is described below.

T Produces a transfer function file with extension `.trf` for the selected array and one discrete source. Only allowed for `NDNS = 1`. For file format see `OASP`. The ranges for the receivers in the `.trf` file are not the true ones, but simply the receiver numbers. To plot all traces together use *range stacking* in `PP`.

Z Produces a plot of the sound speed profiles in the standard format.

b Solves the depth-separated wave equation with the lowermost interface condition expressed in terms of a complex reflection coefficient. The reflection coefficient must be tabulated in a input file `input.trc` which may either be produced from experimental data or by the reflection coefficient module OASR as described on Page 30. See also there for the file format. The lower halfspace must be specified as vacuum and the last layer as an isovelocity fluid without sources for this option. Add dummy layer if necessary. Further, the frequency sampling must be consistent. Using `OASR` this is optained by using the same minimum and maximum frequencies, and number of frequencies, but without option `C`. Note: Care should be taken using this option with a complex integration contour, option `J`. The tabulated reflection coefficient must clearly correspond to the same imaginary wavenumber components for `OASI` to yield proper results. `OASR` calculates the reflection coefficient for real horizontal wavenumbers.

c This option - unique to OASI - generates plots of the eigenvectors of the Cramer-Rao bounds over the selected replica space, to be plotted by mplot. If multiple frequencies are specified, option 'c' will generate bounds for both coherent and incoherent wideband processing.

t Solves the depth-separated wave equation with the top interface condition expressed in terms of a complex reflection coefficient. The reflection coefficient must be tabulated in a input file `input.trc` which may either be produced from experimental data or by the reflection coefficient module `OASR` as described on Page 30. See also there for the file format. The upper halfspace must be specified as vacuum and the first layer as an isovelocity fluid without sources for this option. Add dummy layer if necessary. Further, the frequency sampling must be consistent. Using `OASR` this is optained by using the same minimum and maximum frequencies, and number of frequencies, but without option `C`. Note: Care should be taken using this option with a complex integration contour, option `J`. The tabulated reflection coefficient must clearly correspond to the same imaginary wavenumber components for `OASI` to yield proper results. `OASR` calculates the reflection coefficient for real horizontal wavenumbers.

A digit (1–9) identifying the order of the surface source correlation. The default is totally uncorrelated sources. Higher numbers yield more vertical directionality.

12.1.3 Block III: Frequency Selection

This block controls the frequency sampling. Covariance matrices, replicas and graphics will be produced for `NFREQ` frequencies equidistantly sampled between `FREQ1` and `FREQ2` . `COFF` is the wavenumber integration offset in DB/λ and only has significance for option **J**. Option **J** and `COFF = 0` will invoke the default integartion offset.

12.1.4 Block IV: Environmental Data

The environmental data are specified in the standard SAFARI format.

12.1.5 Block V: Receiver Array

OASI will compute the noise and signal field on arbitrary three dimensional arrays. The first line of this block specifies the number of sensors. Then follows the position, type and gain for each sensor in the array. The the sensor positions are specified in cartesian coordinates <u>in meters</u>. The types currently implemented are as follows

1. Hydrophone. Normal stress σ_{zz} (negative of pressure in water) in Pa for source level 1 Pa (or μPa for source level 1 μPa).
2. Geophone. Particle velocity $\dot{u}$ in x-direction (horizontal). Unit is m/s for source level 1 Pa (or μm/s for source level 1 μPa).
3. Geophone. Particle velocity $\dot{v}$ in y-direction (horizontal). Unit is m/s for source level 1 Pa (or μm/s for source level 1 μPa).
4. Geophone. Particle velocity $\dot{w}$ in z-direction (vertical, positive downwards). Unit is m/s for source level 1 Pa (or μm/s for source level 1 μPa).

The gain is a calibration factor in dB which is applied to ambient noise and signal on all sensors. *Note that the gain is not applied to the white noise!* When combining hydrophones and geophones in array processing it is important to note that there is a difference in order of magnitude of pressure and particle velocity of the order of the acoustic impedance. Therefore the geophone sensors should usually have a gain which is of the order 120 dB higher than the gain applied to the hydrophone sensors.

12.1.6 Block VI: Noise and Signal Sources

OASI treats 4 types of noise and signal sources simultaneously, depending on the value of the parameters in this block:

SSLEV Strength in dB of sea surface noise sources. Per definition the source strength corresponds to the acoustic pressure the same source distribution would yield in an infinitely deep ocean [3, 12]. The value of `SSLEV` is interpreted in two different ways, depending on its sign:

SSLEV≥ 0: Level in dB of white surface source spectrum.

SSLEV< 0: A negative value identifies a logical unit for a file containing the frequency dependence of the surface source level. The format of the source level files is described in Section 11.1.11.

WNLEV Level of white noise on sensor in dB. Note that the white noise is added after the sensor gain.

DSLEV To allow for more horizontal directionality of the noise field than predicted by the surface noise model, an additional, deeper sheet of sources can be introduced.

NDNS This parameter specifies the number of discrete sources present (targets or interferers).

12.1.7 Block VII: Surface Noise Parameters

This block contains the wavenumber sampling parameters for computing the noise covariance matrix. The parameters `CMINS` and `CMAXS` are the phase phase velocities defining the wavenumber integration interval. Note here that the continuous spectrum is always important for surface noise. Therefore `CMAXS` must be specified to a large number (e.g. 10^8) to include the steep propagation angles. `CMINS` should be chosen small enough to include all important evanescent components.

Similar to OASN, the wavenumber sampling parameters `NWSC, NWSD` and `NWSE` are interpreted in two different ways by OASI, depending of the value specified for `NWSD` :

NWSD < 10 The wavenumber sampling parameters are given in the standard SAFARI format, with the parameters interpreted as follows:

NWSC Total number of wavenumber samples, distributed equidistantly between $k_{min} = \omega/c_{max}$ and $k_{max} = \omega/c_{min}$.

NWSD Sampling point where the kernel computation starts. The kernel will be Hermite extrapolated. In this format NWSD will usually be set to 1 since the steep angles are always important.

NWSE Sampling point where the kernel computation ends. The kernel will be Hermite extrapolated.

NOTE: The sampling parameters must be specified in this format for options **K** and **C**, which require equidistant sampling.

NWSD ≥ 10 The wavenumber sampling parameters are given individually for each of the three spectral regimes. This allows for a much denser sampling in the discrete spectrum without forcing a dense sampling of the smooth kernel in the other regimes.

NWSC Number of wavenumber wavenumber samples distributed equidistantly over the *continuous spectrum* between $k_{min} = \omega/c_{max}$ and the critical wavenumber k_c corresponding to the compressional speed in the sub-bottom.

NWSD Number of wavenumber wavenumber samples distributed equidistantly over the *discrete spectrum* between the critical wavenumber k_c corresponding to the compressional speed in the sub-bottom and the wavenumber k_w corresponding to the minimum sound speed in the water column.

NWSE Number of wavenumber wavenumber samples distributed equidistantly over the *evanescent spectrum* between the wavenumber k_w corresponding to the minimum sound speed in the water column and $k_{max} = \omega/c_{min}$.

12.1.8 Block VIII: Deep Noise Source Parameters

The parameter DPSD is the depth of the deep noise source sheet. The other parameters in this block are specified in a format identical to that described above for the surface sources.

12.1.9 Block IX: Discrete Noise and Signal Sources

If NDNS>0, then this block should first contain the coordinates and source level for each discrete source. Note that the depth is specified first in *meters*, followed by the x- and y-ranges in *kilometer* (in contrast to the array element coordinates which were all given in meters).

The source levels DNLEV are interpreted in two different ways, dependent on whether specified value is positive or negative:

DNLEV≥ 0**:** Level in dB of white source spectrum.

DNLEV< 0: A negative value identifies a logical unit of a file containing the frequency dependence of the source level. The format of the source level files is described in Section 11.1.11.

The wavenumber sampling parameters for the discrete sources should follow in the standard OASES format. In Version 2.2 automatic sampling is supported, and activated by NW=-1. In this case Ic1 and IC2 are insignificant. As is the case for automatic sampling in all OASES modules, the desired phase velocity interval must be specified manually. The kernel tapering invoked by the automatic sampling will be initiated at the specified phase velocities.

12.1.10 Block X: Signal Replica Parameters

The first three lines of this block defines the sampling of the environmental parameters for replicas and resolution bounds. This block is the only one that differs from the OASN format. The first line specifies the source coordinates and level used for generating the environmental replicas, in the same format used for the discrete sources in Block IX.

The next two lines identifies the environmental parameters searched, and specifies the sampling:

LY1: Layer number for parameter 1.

PA1: Parameter number (1: depth, 2: Cp, 3: Cs, 4: Ap, 5: As, 6: Rho)

VMIN1: Minimum value of parameter 1

VMAX1: Minimum value of parameter 1

NV1: Number of samples in parameter 1

The wavenumber sampling parameters for the replica sources should follow in the standard OASES format. In Version 2.2 automatic sampling is supported, and activated by NW=-1. In this case IC1 and IC2 are insignificant. As is the case for automatic sampling in all OASES modules, the desired phase velocity interval must be specified manually. The kernel tapering invoked by the automatic sampling will be initiated at the specified phase velocities.

12.1.11 Examples

The following OASI input file `nrlcr.dat` produces the covariance matrix and replicas, and Cramer-rao bounds shown in Ref. [23].

```
Workshop case. nl=50 dB, sl=120 dB.
N J 1 R c
100 100 1 0
4
0 0 0 0 0 0 0
0 1500 0 0 0 1 0
102.5 1600 -1750 0.35 0. 1.75 0
200 1750 0 0.35 0. 1.75 0

15
10 0 0 1 0
15 0 0 1 0
20 0 0 1 0
25 0 0 1 0
30 0 0 1 0
35 0 0 1 0
40 0 0 1 0
45 0 0 1 0
50 0 0 1 0
55 0 0 1 0
60 0 0 1 0
65 0 0 1 0
70 0 0 1 0
75 0 0 1 0
80 0 0 1 0

0 50 0 1
50 1 0 120
1400 1e8
-1 1 480                        # Automatic sampling


50 1 0 120               # source coordinates
3 2 1550 1650 11 # seabed speed
4 2 1700 1800 11          # subbottom speed

1400 1e8
-1 1 480
```

12.2 Execution of OASI

As for the other OASES modules, filenames are passed to OASI via environmental parameters. In Unix systems a typical command file **oasi** (in $HOME/Oases/bin) is:

```
#                           the number sign invokes the C-shell
setenv FOR001 $1.dat       # input file
setenv FOR019 $1.plp       # plot parameter file
setenv FOR020 $1.plt       # plot data file
setenv FOR023 $1.trc       # reflection coefficient table (input)
setenv FOR028 $1.cdr       # contour plot parameter file
setenv FOR029 $1.bdr       # contour plot data file
setenv FOR014 $1.rpo       # signal replicas
setenv FOR016 $1.xsm       # covariance matrices
oasi2_bin                  # executable
```

After preparing a data file with the name **input.dat**, OASI is executed by the command:

oasi input

12.3 Graphics

Command files are provided in a path directory for generating the graphics produced by oasi.

To generate curve plots, issue the command:

mplot input

To generate contour plots, issue the command:

cplot input

12.4 Output Files

In addition to the graphics output files, OASI optionally produces files containing the computed covariance matrices and replica fields for use by the array processing module OASES-MFP, similar to those produced by OASN, and described in Sec. 11.4.1 (Page 103), and 11.4.2 (Page 105).

13 OASM: Matched Field Processing Module

The OASES-MFP module is a post-processor used in connection with OASN or OASI to perform traditional or advanced signal processing on either real or synthetic fields on arbitrary 3-dimensional arrays of hydrophones and/or geophones.

MFP has built-in traditional plane wave replicas, but will accept any precomputed replicas in the file format described in Section 11.4.2, including Green's function replicas for matched field processing.

In terms of beamformers, OASES-MFP is modular and currently includes 4 built-in algorithms, including the conventional Bartlett, and adaptive beamformers such as MLM and MCM.

The ambiguity functions are output as curve plots (displayed by `mplot`) vs angle for the plane wave replicas, or for 2-dimensional plane wave beamforming (bearing and pitch) in the form of contour plots (displayed by `cplot`). For matched field replicas MFP produces contour plots of the ambiguty function in vertical or horizontal planes. The SAFARI-PEST predecessor of OASES-MFP was used for generating all ambiguity functions in Refs. [13, 14], and OASES-MFP was used in combination with OASN to produce those in Chap. 10 of Ref. [3].

13.1 Input Files for OASM

The input file for OASM is structured in 7 blocks, the first 5 of which, shown in Table 13 contain data which must always be given, such as the frequency selection, receiver array and replica sampling. The last 3 blocks should only be included for certain options as indicated. The various blocks and the significance of the data is described in the following.

13.1.1 Block I: Title of Run

Arbitrary title to appear on graphics output.

13.1.2 Block II: Computational options

Similarly to the other modules, the output is controlled by a number of one-letter options:

B Bartlett Beamformer [13].

M Maximum Likelihood Method (MLM) Beamformer [13].

Input parameter	Description	Units	Limits
Block I: TITLE			
TITLE	Title of run	-	$\leq$ 80 ch.
Block II: OPTIONS			
A B C $\cdots$	Output and computational options	-	$\leq$ 40 ch.
Block III: FREQUENCIES			
FREQ1, FREQ2, NFREQ, COFF	FREQ1: Minimum frequency	Hz	> 0
	FREQ2: Maximum frequency	Hz	> 0
	NFREQ: Number of frequencies		> 0
	COFF: Integration contour offset	dB/Λ	≥ 0
Block IV: RECEIVER ARRAY			
NRCV	NRCV: Number of receivers in array	-	> 0
Z,X,Y,ITYP,GAIN	Z: Receiver depth	m	
.	X: x-offset of receiver	m	
.	Y: y-offset of receiver	m	
.	ITYP: Receiver type	-	> 0
	GAIN: Receiver signal gain	dB	
Block V: REPLICA SPACE			
ZMINR,ZMAXR,NZR	Depth (grazing angle) interval	m (°)	(-90–90)
XMINR,XMAXR,NXR	x (bearing) interval	km (°)	(-360–360)
YMINR,YMAXR,NYR	y (dummy)	km	
Block VI: REFERENCE SOUND SPEED (Option W)			
CBEAM	Reference speed for plane wave replicas	m/s	
Block VII: TOLERANT BEAMFORMER (Option T)			
CLRMIN,CLRMAX,NCLR	Coherence lengths for *replicas*	m	
TOLR	Tolerance		
Block VII: SIGNAL BLURRING (Option K)			
CLS	Coherence length for *signals*	m	

Table 13: OASM input file structure. Terms in bracket in Block V are for plane wave beamforming (option W).

Q Multible Constraint Method (MCM) Beamformer [14].

T Tolerant beamformer. One of ABB's inventions, not yet published. The estimated spatial coherence and the tolerance must be specified in Block VII.

W Plane wave replicas. Used in combination with any of the beamformers.

K Blurring of covariance matrix corresponding to the coherence length specified in Block VIII.

D Produces a contour plot of the ambiguity function vs depth and range (for matched field processing) for each of the selected beamformers. The plot axes are determined automatically to fit the replica space. If option **W** (plane wave beamforming) is also specified, the ambiguity function will be contoured vs azimuth (bearing) and vertical angle (grazing, positive downward).

R Produces a contour plot of the ambiguity function vs x-range and y-range (for matched field processing) for each of the selected beamformers. The plot axes are determined automatically to fit the replica space. This option has no effect for option **W** (plane wave beamforming)

X Produces an expanded printout of beamformer results.

13.1.3 Block III: Frequency Selection

This block controls the frequency sampling. Covariance matrices, and replicas read from external files must be consistent with the specified sampling. OASM is usually run for a single frequency. If multible frequencies are specified, the ambiguity functions will be geometrically averaged as described in Ref. [13]. COFF is the wavenumber integration offset in DB/λ which is a dummy parameter for OASM.

13.1.4 Block V: Receiver Array

For option **W** OASM will compute the plane wave replicas for the specified array. Matched field and other replicas are read from an external file of the format described in Sec. 11.4.2, and here the array geometry in Block IV is just used for consistency check. Note that such a consistency is not required for the covariance matrix file, which allows for simulation of array mismatch. The first line of this block specifies the number of sensors. Then follows the position, type and gain for each sensor in the array. The the sensor positions are specified in cartesian coordinates <u>in meters</u>. The types currently implemented are as follows

1. Hydrophone. Normal stress σ_{zz} (negative of pressure in water) in Pa for source level 1 Pa (or μPa for source level 1 μPa).
2. Geophone. Particle velocity $\dot{u}$ in x-direction (horizontal). Unit is m/s for source level 1 Pa (or μm/s for source level 1 μPa).
3. Geophone. Particle velocity $\dot{v}$ in y-direction (horizontal). Unit is m/s for source level 1 Pa (or μm/s for source level 1 μPa).
4. Geophone. Particle velocity $\dot{w}$ in z-direction (vertical, positive downwards). Unit is m/s for source level 1 Pa (or μm/s for source level 1 μPa).

The gain is a calibration factor in dB which is applied to the replica on all sensors. When combining hydrophones and geophones in array processing it is important to note that there is a difference in order of magnitude of pressure and particle velocity of the order of the acoustic impedance. Therefore the geophone sensors should usually have a gain which is of the order 120 dB higher than the gain applied to the hydrophone sensors.

13.1.5 Block V: Signal Replica Parameters

For non-plane wave beamforming (matched field processing), the replicas are read from an external file, and in this case this block serves only as a consistency check. The sampling in the three coordinate directions must be identical to that used for OASN in computing the replicas. Note the the depths z should be specified in *meters* whereas the ranges x and y should be specified in *kilometers*.

For plane wave beamforming (option **W**), the first line defines the grazing angle interval and number of sampling points. Usually this interval ranges from $-90°$ (upward) to $90°$ (downward). The second line similarly selects the bearing interval and number of samples. The third line is dummy (but must be included) for plane wave beamforming.

13.1.6 Block VI: Reference Sound Speed

This block should only be included for option **W**. It defines the reference sound speed used for plane wave beamforming.

13.1.7 Block VII: Tolerant Beamformer

The tolerant beamformer (option **T**) incorporates knowledge (or expectation) of the spatial signal correlation in the beamforming. This block, which should only be included for option

T, specifies the coherence length scanning interval; ambiguity functions will be generated for all values of the coherence length. The tolerance `TOLR` is a tuning parameter (usually set to 0.1).

13.1.8 Block VIII: Signal Blurring

The signal component of the covariance matrix produced by OASN is characterized by a perfect spatial coherence. To account for a more realistic, limited spatial coherence, the covariance matrix can be blurred by specifying option **K**. This block defines the coherence length `CLS` to which the blurring should correspond.

13.1.9 Examples

The following OASM input file `frammfp.dat` produces the contour plots of the ambiguity functions shown in Fig. 8 in Ref. [14], using the covariance matrix and replicas computed by OASN from the corresponding data file `fram4.dat` shown in Sec. 11.1.12.

```
                # >>> Block I: Title
FRAM IV environment.
                # >>> Block II: Options
M Q D               # MLM and MCM. Depth-range contours
                # >>> Block III: Frequency sampling
20 20 1 0           # 20 Hz

                # >>> Block IV: Receiver Array
18                  # 18 elements
30 0 0 1 -1         # Hydrophone at z = 30 m. Gain -1 dB
60 0 0 1 -1
90 0 0 1 -1
140 0 0 1 -1
180 0 0 1 -7
210 0 0 1 -7        # Hydrophone at z =210 m. Gain -7 dB
270 0 0 1 -1
330 0 0 1 -1
350 0 0 1 -1
390 0 0 1 -1
450 0 0 1 -1
510 0 0 1 -1
570 0 0 1 -1
630 0 0 1 -1
690 0 0 1 -1
782 0 0 1 -1
```

```
860 0 0 1 -1
960 0 0 1 -1        # Hydrophone at z =960 m. Gain -1 dB

                # >>> Block V: Replica parameters
10 1000 23              # 23 source depth, 10 - 1000 m
150 300 76              # 76 source ranges, 150 - 300 km
0 0 1                   # 1 y-range (omnidirectional response)
```

13.2 Execution of OASM

As for the other OASES modules, filenames are passed to OASM via environmental parameters. In Unix systems a typical command file **mfp** (in $HOME/oases/bin) is:

```
#                             the number sign invokes the C-shell
setenv FOR001 $1.dat        # input file
setenv FOR013 $2.rpo        # signal replicas
setenv FOR015 $3.xsm        # covariance matrices
setenv FOR019 $3.plp        # plot parameter file
setenv FOR020 $3.plt        # plot data file
setenv FOR028 $3.cdr        # contour plot parameter file
setenv FOR029 $3.bdr        # contour plot data file
mfp2_bin
```

After preparing a data file with the name **input.dat**, `mfp` is executed by the command:

mfp input repinput covinput

The files `repinput` and `covinput` are the input *replica* and *covariance matrix* files, respectively. These files must be written in the formats described in Sec. 11.4.2 and Sec. 11.4.1, respectively. The file headers are checked for consistency with the input file in terms of frequencies, replica space and number of sensors in the array. The element positions in the array do not have to be consistent, allowing for simulation of array geometry mismatch.

13.3 Graphics

Command files are provided in a path directory for generating the graphics produced by `mfp` . Note that the plotfiles get the name of the input covariance matrix file.

To generate curve plots, issue the command:

mplot covinput

To generate contour plots, issue the command:

cplot covinput

14 OASS: OASES Scattering and Reverberation Module

OASS is a modfied version of OAST which computes the spatial statistics of the reverberant field in 2-D waveguides with 1-D rough interfaces. The input file and output features are very similar to the ones for OAST. OASS also includes several components of OASN, both interms of specification of 3-D array geometries and the option of generating covariance matrices. The covariance matrices may be added to the covariance matrices computed for the mean field using OASN. The addition is performed offline using the `addcov` utility included in the oases package. Two other utilities are provided for computing from the generated `.xsm` files the normalized spatial correlation (`nrmcov`) or the coherence (`coher`).

The theoretical background for OASS as well as several applications are described in Ref. [15].

OASS is always used in conjunction with OAST or OASR. These are used first to compute the mean field and generate a file (`.rhs`) containing the mean field boundary operators at the rough interfaces (option **s**). OASS then uses these to comp[ute the scattered or reverberant field using the expressions in Ref. [15].

OASS has two rather indepemdent brances:

- **Scattering kernels:** This branch is activated by options **I, S, c**. Computes the expectation of the scattering kernal amplitude for a single incident plane wave component. In general used together with OASR.
- **Reverberation:** This branch is activated by the options **C,D,R,a,r**. Computes the expectation of the spatial correlation or coherence of the reverberant field in stratified waveguides. Always used together with OAST since wavenumber sampling is adopted from mean field calculation.

14.1 Input Files for OASS

The input file for OASS is structured in 9 blocks, the first 7 of which must always be given. The last 2 blocks should only be included for certain options and parameter settings, as indicated in Table 14. The various blocks and the significance of the data is described in the following.

14.1.1 Block I: Title of Run

Arbitrary title to appear on graphics output.

Input parameter	Description	Units	Limits
Block I: TITLE			
TITLE	Title of run	-	$\leq$ 80 ch.
Block II: OPTIONS			
A B C $\cdots$	Output and computational options	-	$\leq$ 40 ch.
Block III: FREQUENCY			
FREQ1, COFF	FREQ: Frequency	Hz	> 0
	COFF: Integration contour offset	dB/Λ	≥ 0
Block IV: ENVIRONMENT			
NL	Number of layers, incl. halfspaces	-	≥ 2
D,CC,CS,AC,AS,RO,RG,CL	D: Depth of interface.	m	
.	CC: Compressional speed	m/s	≥ 0
.	CS: Shear speed	m/s	
.	AC: Compressional attenuation	dB/Λ	≥ 0
.	AS: Shear attenuation	dB/Λ	≥ 0
	RO: Density	g/cm^3	≥ 0
	RG: RMS of interface roughness	m	
	CL: Correlation length of roughness	m	> 0
	M: Spectral exponent		¿ 1.5
Block V: SCATTERING DATA			
CPH, INTFC	CPH: Phase vel. incident plane wave	m/s	
	INTFC: Interface no. for which to compute reverb.		≥ 2
Block VI: RECEIVER ARRAY			
NRCV	NRCV: Number of receivers in array	-	> 0
Z,X,Y,ITYP,GAIN	Z: Receiver depth	m	
.	X: x-offset of receiver	m	
.	Y: y-offset of receiver	m	
.	ITYP: Receiver type	-	> 0
	GAIN: Receiver signal gain	dB	
Block VII: WAVENUMBER SAMPLING			
CMIN,CMAX	Phase velocity interval, *scattered field*		
	CMIN: Minimum phase velocity	m/s	> 0
	CMAX: Maximum phase velocity	m/s	
NW,IC1,IC2	NW: Wavenumber sampling	-	
	IC1: First sampling point	-	≥ 1
	IC2: Last sampling point	-	$\leq$NW
Block VIII: RANGE OFFSETS (Options C,D,R,a,r)			
RMIN,RMAX,NR	RMIN: Minimum range	km	
	RMAX: Maximum range	km	
	NR: Number of ranges		> 0
Block IX: RANGE INCREMENT (Option C)			
DR,NDR	DR: Range increment for horizontal correlation	m	> 0
	NDR: Number of range increments		> 0

Table 14: OASS input file structure.

14.1.2 Block II: Computational options

Similarly to the other modules, the output is controlled by a number of one-letter options:

C Produces a contour plot of the horizontal spatial correlation vs range. The horizontal axis, defined in Block VIII, represents the range separating the source and the array origin, while the vertical axis represents the horizontal separation (in radial direction) between two receivers. The separation and the number of separations must be given in Block IX.

D Produces a contour plot of the intensity expectation of the scattered field vs. range and depth. The depths are defined as the depths of the sensors specified for the array in block VI, while the ranges are the ones given in Block VIII.

G Uses a Goff-Jordan roughness spectrum as opposed to the default gaussian spectrum.

I Creates a plot of the wavenumber spectrum of the scattered field at all depths of the receivers in the array, for a single incident plane wave with phase velocity CPH (Block V). Note that this option cannot be applied together with the reverb options `C,D,R,a,r` !

P Computes scattered field assuming plane geometry. The default is an axisymmetric environment.

R Computation of reverberant field in spatial domain. Automatically set by options **C,D,a,r**. Cancels options `I, S, c.`

S Creates a plot of the angular spectrum of the scattered field at all depths of the receivers in the array, for a single incident plane wave with phase velocity CPH (Block V). Note that this option cannot be applied together with the reverb options `C,D,R,a,r` !

a Outputs the covariance matrix for the scattered field to a direct access file with extension `.xsm` . The file format is described below.

c Produces a contour plot of the scattering kernels (wavenumber spectrum of scattered field) vs. wavenumber and depth, for a single incident plane wave with phase velocity CPH (Block V). Similar to option **c** in OAST for mean field. Note that this option cannot be applied together with the reverb options `C,D,R,a,r` !

g Same as **G**.

p Uses the perturbed boundary operator for the reverberant field, i.e. the effect of loss through re-scattering is included. Yields lower bound for reverb levels. The default ignores re-scattering and therefore yields upper bound.

r Produces plot vs. range of expectation value of reverberant field in dB for all depths of the receivers in the array.

14.1.3 Block III: Frequency Selection

In contrast to OAST, OASS works only for single frequency, FREQ. The input `.rhs` file is checked for consistency. `COFF` is a leftover from OAST and has no effect since OASS will use the same wavenumber sampling and offset used for generating the `.rhs` file.

14.1.4 Block IV: Environmental Data

The environmental data are specified in the standard SAFARI format. Just note that the interface rms roughness, correlation and spectral exponent must be specified. These are not adopted from OASR or OAST, and may therefore be different than the ones used for computing the mean field. This allows you to use a Born approoximation where the mean field is computed without roughness. Note also that OASS will only compute reverb from one interface at a time, as specified in Block V. However, several rough interfaces may be specified in the environment block. The additional rough interfaces only have effect for secondary scattering, option **p**.

14.1.5 Block V: Scattering parameters

These parameters control the reverberation computation. `CPH` is the phase velocity of the incident field component for which the scattering kernel should be computed. Only has significance for options `I, S and c,` otherwize it is dummy.

INTFC is the number of the rough interface for which the scattered field or reverberation has to be computed. The roughness for that interface must be specified in the corresponding line in block IV. Note that the uppermost interface (lower boundary of upper halfspace) is interface number 2!

14.1.6 Block VI: Receiver Array

OASS will compute the reverberant field on arbitrary three dimensional arrays. The first line of this block specifies the number of sensors. Then follows the position, type and gain for each sensor in the array. The sensor positions are specified in cartesian coordinates in meters. The types currently implemented are as follows

1. Hydrophone. Normal stress σ_{zz} (negative of pressure in water) in Pa for source level 1 Pa (or μPa for source level 1 μPa).
2. Geophone. Particle velocity $\dot{u}$ in x-direction (horizontal). Unit is m/s for source level 1 Pa (or μm/s for source level 1 μPa).

3. Geophone. Particle velocity $\dot{v}$ in y-direction (horizontal). Unit is m/s for source level 1 Pa (or μm/s for source level 1 μPa).
4. Geophone. Particle velocity $\dot{w}$ in z-direction (vertical, positive downwards). Unit is m/s for source level 1 Pa (or μm/s for source level 1 μPa).

The gain is a calibration factor in dB which is applied to ambient noise and signal on all sensors. *Note: OASS v 1.7 does not currently allow for mixed arrays.*

14.1.7 Block VII: Wavenumber Sampling

The wavenumber sampling block is of the standard SAFARI/OASES format. The phase velocities control the wavenumber interval included in the computation of both scattering kernels (options `I,S,c`), and the reverberant field (options `C,D,R,a,r`). The sampling data `NW,IC1,IC2` are only used for kernel computations. For computation of reverberation (options `C,D,R,a,r`) the sampling, including the complex offset, is automatically chosen to be identical to the one used for the mean field in OAST.

14.1.8 Block VIII: Range Offsets

OASS will compute the reverberation for multible range offsets between the source (at origin in OAST) and the receiver array origin in OASS. This allows for efficient computation of the range-dependence of the reverberant field. The range offsets are specified as a minimum and maximum value, `RMIN, RMAX` in km, and the number of offsets considered `NR.`

Note that the offset does not apply to option `a.` The covariance matrix is computed for zero offset. For bistatic scenarios the range must therefore be specified directly in the receiver coordinates.

On the other hand the other reverb options `C,D,r` do not use the horizontal coordinates of the array, i.e they basically compute the reverb for a VLA at different horizontal offsets. In other words, only the receiver depths are used for these options.

14.1.9 Block VIII: Range Increments

Used to define a local horizontal array with spacing `DR` in meter and `NDR` sensors, for which option `C` will compute the horizontal correlation vs offset.

14.1.10 Examples

The following OASR input file `dacol-rhs.dat` produces the plot of the reflection coefficient shown in Fig. 3 of Ref. [16], and generates the file `dacol-rhs.rhs` with the boundary operators used subsequently by OASS to compute the scattering kernels.

`dacol-rhs.dat:`

```
Dacol and Berman. l= 7.07.
N s
3
0 1500 0 0 0 1 0
0 1500 0 0 0 1 0
0 5000 2000 0.00 0.00 3.0 -1. 7.07
100 100 1 1
0.01 89.99 91 0
90 0 12 15                          # Grazing angle axes
0. 10 12 1                          # Loss axes
```

The input file used subsequently by OASS to generate the plots in Figs. 4 and 5 of Ref. [16], is

`dacol-sca.dat:`

```
Dacol and Berman. l= 7.07.
P N I S                              # Plane geometry
100
3
0 1500 0 0 0 1 0
0 1500 0 0 0 1 0
0 5000 2000 0.00 0.00 3.0 -1. 7.07
2121.32 3                            # cph=2121 ~ 45 deg.
2                                    # two depths
-60 0 0 1 0
-10 0 0 1 0

1000 -1000                           # pos+neg spectrum
1024 1 1024
```

The following OAST input file `arsrp-mean.dat` produces the contour plot of the mean field for the ARSRP scenari, shown in Fig. 1 of Ref. [15]:

`arsrp-mean.dat:`

```
ARSRP J218. 6 deg. Basalt.      # >>> Block I: Title
```

```
N J C I T L P G s               # >>> Block II: Options
250 250 1 0                     # >>> Block III: Frequency sampling
16                              # >>> Block IV: Environment
0 0 0 0 0 0 0
0 1544 -1524 0 0 1 0
175.0 1524. -1521 0 0 1 0
350   1521. -1510 0 0 1 0
650 1510 -1497 0 0 1 0
950 1497 -1495 0 0 1 0
1250 1495 -1497 0 0 1 0
1500 1497 -1498 0 0 1 0
1750 1498 -1500 0 0 1 0
2125 1500 -1504 0 0 1 0
2500 1504 -1510 0 0 1 0
2875 1510 -1516 0 0 1 0
3250 1516 -1523 0 0 1 0
3625 1523 -1530 0 0 1 0
3990 1530 0 0 0 1 0             # Note iso layer at rough bottom!
4000 5200 2500 .2 .5 2.4 -2 6   # 2 m RMS, L=6 m


175 10 3.66 6.0 1 4000          # Block V: Source array
1 4000 41 40                    # Block VI:Receiver depths

1520 1545                       # Block VII: Phase velocities
-1 1 1                          #            Auto sampling

0 40 20 10                      # Block VIII: Range axis
0 80 12 10                      # Block IX: TL axes.
0 4000 12 500                   # Block X: Depth axis
40 70 3                         # Block XI: Contour intervals

1450 1550 15 25                 # Block XII: Velocity axis
0 4000 15 1000                  #            Depth axis
```

To create the expectation of the scattered field intensity in Fig. 2b of Ref.[15], use the following input file with OASS.

```
arsrp.dat:

ARSRP J218. 6 deg. Basalt. L=6m # Block I: Title
P D G                           # Block II: Options
250 0                           # Block III: Frequency
16                              # Block IV: Environment
0 0 0 0 0 0 0
0 1544 -1524 0 0 1 0
175.0 1524. -1521 0 0 1 0
```

```
350   1521. -1510 0 0 1 0
650 1510 -1497 0 0 1 0
950 1497 -1495 0 0 1 0
1250 1495 -1497 0 0 1 0
1500 1497 -1498 0 0 1 0
1750 1498 -1500 0 0 1 0
2125 1500 -1504 0 0 1 0
2500 1504 -1510 0 0 1 0
2875 1510 -1516 0 0 1 0
3250 1516 -1523 0 0 1 0
3625 1523 -1530 0 0 1 0
3990 1530 0 0 0 1 0           # Note iso layer at rough bottom!
4000 5200 2500 .2 .5 2.4 -2 6   # 2 m RMS, L=6 m

1500 16                         # Block V: dummy, Interface #.

21                              # Block VI: 4 km long VLA
1 0 0 1 0
200 0 0 1 0
400 0 0 1 0
600 0 0 1 0
800 0 0 1 0
1000 0 0 1 0
1200 0 0 1 0
1400 0 0 1 0
1600 0 0 1 0
1800 0 0 1 0
2000 0 0 1 0
2200 0 0 1 0
2400 0 0 1 0
2600 0 0 1 0
2800 0 0 1 0
3000 0 0 1 0
3200 0 0 1 0
3400 0 0 1 0
3600 0 0 1 0
3800 0 0 1 0
3999 0 0 1 0

1450 -1450                      # Block VII: CMIN, CMAX
2048 1 2048 #            dummy

0 40 101                        # Block VIII: 101 ranges, 0<r<40 km
```

14.2 Execution of OASS

As for the other OASES modules, filenames are passed to OASS via environmental parameters. In Unix systems a typical script file **oass** (in $HOME/oases/bin) is:

```
#                              the number sign invokes the C-shell
setenv FOR001 $1.dat       # input file
setenv FOR019 $1.plp       # plot parameter file
setenv FOR020 $1.plt       # plot data file
setenv FOR028 $1.cdr       # contour plot parameter file
setenv FOR029 $1.bdr       # contour plot data file
setenv FOR045 $2.rhs       # rough boundary operator input file
setenv FOR016 $1.xsm       # covariance matrices
oass2                  # executable
```

To compute the coherent reflection coefficient and the scattering kernels for the rough granite halspace problem above, use the commands:

> **oasr dacol-rhs**

> **oass dacol-sca dacol-rhs**

To run the ARSRP cases described above, use the following commands:

> **oast arsrp-mean**

> **oass arsrp arsrp-mean**

14.3 Graphics

Command files are provided in a path directory for generating the graphics produced by oass.

To generate curve plots, issue the command:

> **mplot input**

To generate contour plots, issue the command:

> **cplot input**

14.4 Output Files

In addition to the graphics output files, OASS optionally (option **a**) produces a file containing the computed covariance matrix, e.g. for use by the array processing module OASES-MFP, or by other processing software. Note that OASS assumes a time factor $\exp(i\omega t)$.

14.4.1 Covariance Matrices

The covariance matrix is written to a binary, direct access file with a fixed record length of 8 bytes, identical to the format generated by OASN. The covariance matrices for the total field may be obtained by adding the ones generated for OASN and OASS using the utility `addcov`. The file will have the name `input.xsm` . The file is opened with the following statements:

```
C        *****  OPEN XSM FILE...Note that the logical unit 16 must
C        be assigned a filename external to the program,
C        in Unix: setenv FOR016 input.xsm
         LUN=16
         call getenv('FOR016',XSMFILE)
         OPEN  ( UNIT      = LUN
     -,          FILE      = XSMFILE
     -,          STATUS    = 'UNKNOWN'
     -,          FORM      = 'UNFORMATTED'
     -,          ACCESS    = 'DIRECT'
     -,          RECL      = 8         )
```

Note: This `OPEN` statement is used for machines where the fixed record length for unformatted files is given in *bytes* (e.g. Alliant FX-40). Some machines (e.g. DEC 5000 workstations) require the record lenth in words; in that case specify `RECL = 2` .

The first 10 records of the `xsm` file contains the header, identifying the file in terms of title, number of sensors and frequency sampling. The header has been written with the following statements, with the parameters defined in Table 9:

```
C *** WRITE HEADER
         WRITE (LUN,REC=1) TITLE(1:8)
         WRITE (LUN,REC=2) TITLE(9:16)
         WRITE (LUN,REC=3) TITLE(17:24)
         WRITE (LUN,REC=4) TITLE(25:32)
         WRITE (LUN,REC=5) NRCV, NFREQ
c >>> Dummy integers IZERO
         WRITE (LUN,REC=6) IZERO, IZERO
         WRITE (LUN,REC=7) FREQ1, FREQ2
c >>> DELFRQ is the frequency increment (FREQ2 - FREQ1)/(NFREQ-1)
         WRITE (LUN,REC=8) DELFRQ, ZERO
c >>> The surface and white noise levels for info
         WRITE (LUN,REC=9) SSLEV,WNLEV
c >>> BLANK FILL NEXT RECORD FOR FUTURE USE
         WRITE (LUN,REC=10) ZERO,ZERO
```

OASS writes the covariance matrix columnwise using the following loop structure

```
         :
      COMPLEX COVMAT(NRCV,NRCV,NFREQ)
         :
         :
C >>> WRITE XSM
      DO 20 IFREQ=1,NFREQ
       DO 20 JRCV=1,NRCV
        DO 20 IRCV=1,NRCV
         IREC = 10 + IRCV + (JRCV-1)*NRCV + (IFREQ-1)*NRCV*NRCV
         WRITE (LUN,REC=IREC) COVMAT(IRCV,JRCV,IFREQ)
20    CONTINUE
```

15 OASSP: 2-D Waveguide Reverberation Realizations

The OASES-OASSP module is the time domain equivalent of the OASS reverberation model. However, in contrast to OASS which directly generates expectation values for the scattered field correlation, OASSP generates timeseries using realizations of the environmental perturbations. Earlier versions of OASSP allowed for rough interfaces with Gaussian or power law power spectra. Version 2.2 and later in addition allows for generating field realizations for scattering from volume inhomogeneities in fluid layers with or without sound speed gradients, based on the theoretical developments of LePage and Schmidt [24]. OASSP is used in conjunction with OASP, which is used for computing the mean, coherent field, which is driving the scattering. The data files for OASSP are very similar to those of OASP, and OASSP generates a transfer function file in the same format, which is post-processed and plotted using PP. As is the case for all the other modules, both stresses and particle velocities can be computed.

15.1 Transfer Functions

Similar to OASP, in addition to generating timeseries, OASSP may be used for generating the complex CW reverberant field over a rectangular grid in range and depth. Here again it should be noted that when OASSP is used with option 'O' or with automatic sampling enabled, the transfer functions are computed for complex frequencies. Complex frequency corresponds to applying a *time-domain damping* which cannot be directly compensated for in the transfer functions. However, real frequencies can be forced in automatic sampling mode by using option 'J' (Version 2.1 and later). In any case the frequency sampling must be consistent for the computation of the mean and scattered fields.

15.2 Input Files for OASSP

The input files for OASSP are virtually identical to the ones used for computing the mean field using OASP. A few of the options have different significance (**s**), and the option **p** is unique to OASSP. In addition, OASSP is unique in terms of allowing for computation of the reverberation from sound speed inhomogeneities in fluid layers. The spatial statistics of the volume inhomogeneities is controlled by the interface roughness parameters for such layers. The input files for OASSP are structured in 8 blocks, as outlined in Table 15.

15.3 Block I: Title

The title printed on all graphic output generated by OASSP.

Input parameter	Description	Units	Limits
BLOCK I: TITLE			
TITLE	Title of run	-	$\leq$ 80 ch.
BLOCK II: OPTIONS			
A B C $\cdots$	Output options	-	$\leq$ 40 ch.
BLOCK III: SOURCE FREQUENCY			
FRC,COFF,IT,VS,VR	FRC: Center frequency of source	Hz	> 0
	COFF: Integration contour offset	dB/Λ	COFF≥ 0
	IT: Source pulse type (only for option d)		
	VS,VR: Sou./Rec. velocity (only for option d)	m/s	
BLOCK IV: ENVIRONMENT			
NL	Number of layers, incl. halfspaces	-	NL≥ 2
D,CC,CS,AC,AS,RO,RG,CL	D: Depth of interface.	m	-
.	CC: Compressional speed	m/s	CC≥ 0
.	CS: Shear speed	m/s	-
.	AC: Compressional attenuation	dB/Λ	AC≥ 0
.	AS: Shear attenuation	dB/Λ	AS≥ 0
	RO: Density	g/cm^3	RO≥ 0
	RG: RMS value of interface roughness	m	-
	CL: Correlation length of roughness	m	-
	M: Spectral exponent		¿ 1.5
BLOCK V: SOURCES			
SD,NS,DS,AN,IA,FD,DA	SD: Source depth (mean for array)	m	-
	NS: Number of sources in array	-	NS> 0
	DS: Vertical source spacing	m	DS> 0
	AN: Grazing angle of beam	deg	-
	IA: Array type	-	$1 \leq$IA≤ 5
	FD: Focal depth of beam	m	FD$\neq$SD
	DA: Dip angle. (Source type 4).	deg	-
BLOCK VI: RECEIVER DEPTHS			
RD1,RD2,NRD	RD1: Depth of first receiver	m	-
	RD2: Depth of last receiver	m	RD2$>$RD1
	NRD: Number of receiver depths	-	NR> 0
BLOCK VII: WAVENUMBER SAMPLING			
CMIN,CMAX	CMIN: Minimum phase velocity	m/s	CMIN> 0
	CMAX: Maximum phase velocity	m/s	-
NW,IC1,IC2,IF	NW: Number of wavenumber samples	-	> 0, -1 (auto)
	IC1: First sampling point	-	IC1≥ 1
	IC2: Last sampling point	-	IC2$\leq$NW
	IF: Freq. sample increment for kernels		≥ 0
BLOCK VIII: FREQUENCY AND RANGE SAMPLING			
NT,FR1,FR2,DT,R1,DR,NR	NT: Number of time samples		NT$= 2^M$
	FR1: lower limit of frequency band	Hz	≥ 0
	FR2: upper limit of frequency band	Hz	$\geq$FR1
	DT: Time sampling increment	s	> 0
	R1: First range	km	
	DR: Range increment	km	
	NR: Number of ranges		> 0

Table 15: Layout of OASSP input files: Computational parameters.

15.4 Block II: OASSP options

The significance of the single-letter OASSP options are:

C Creates an $\omega - k$ representation of the field in the form of contours of integration kernels as function of horizontal wavenumber (slowness if option **B** is selected) and frequency (logarithmic y-axis). All axis parameters are determined automatically.

G Rough interfaces are assumed to be characterized by a Goff-Jordan power spectrum rather than the default Gaussian.

H Horizontal (radial) particle velocity calculated.

J Complex wavenumber contour. The contour is shifted into the upper halfpane by an offset controlled by the input parameter COFF (Block III). NOTE: If this option is used together with automatic sampling, the complex frequency integration (option **O**) is disabled, allowing for computation of complex CW fields or transmission losses (plotted using PP).

K Computes the bulk stress. In elastic media the bulk stress only has contributions from the compressional potential. In fluid media the bulk stress is equal to the negative of the pressure. Therefore for fluids this option yields the same result as option N or R.

L Linear vertical source array.

N Normal stress σ_{zz} ($= -p$ in fluids) calculated.

O Complex frequency integration contour. This new option is the frequency equivalent of the complex wavenumber integration (**J** option in OAST). It moves the frequency contour away from the real axis by an amount reducing the time domain wrap-around by a factor 50 [3]. This option can yield significant computational savings in cases where the received signal has a long time duration, and only the initial part is of interest, since it allows for selection of a time window shorter than the actual signal duration. Note that only wrap around from later times is reduced; therefore the time window should always be selected to contain the beginning of the signal!

P Plane geometry. The sources will be line-sources instead of point-sources as used in the default cylindrical geometry.

R Computes the radial normal stress σ_{rr} (or σ_{xx} for plane geometry).

S Computes the stress equivalent of the shear potential in elastic media. This is an angle-independent measure, proportional to the shear potential, with no contribution from the compressional potential (incontrast to shear stress on a particular plane). For fluids this option yields zero.

T The new option 'T' allows for specification of an array tilt in the vertical plane containing the source and the receivers. See below for specification of array tilt parameters.

U Decomposed seismograms. This option generates 5 transfer function files to be processed by PP:

File name	Contents
input.trf	Complete transfer functions
input.trfdc	Downgoing compressional waves
input.trfuc	Upgoing compressional waves
input.trfds	Downgoing shear waves alone
input.trfus	Upgoing shear waves

V Vertical particle velocity calculated.

Z Plot of SVP will be generated.

d Radial *Doppler shift* is accounted for by specifying this option, using the theory developed by Schmidt and Kuperman [9]. The source pulse and the radial projections of the source and receiver velocities must be specified in the input file following the specification of the centre frequency and the contour offset (Block II). Since this option requires incorporation of the source function in the wavenumber integral, the PP post-processor must be used with source pulse -1 (impulse response).

f Full Bessel function integration. This new option does not apply the asymptotic representation of the Bessel function in the evaluation of the inverse Hankel transforms. The implementation is very efficient, and the integral evaluation is performed just as fast as the asymptotic evaluations.

g Rough interfaces and volume inhomogeneities are assumed to be characterized by a Goff-Jordan power spectrum rather than the default Gaussian (Same as G).

l User defined source array. This new option is similar to option **L** in the sense that that it introduces a vertical source array of time delayed sources of identical type. However, this option allows the depth, amplitude and delay time to be be specified individually for each source in the array. The source data should be provided in a separate file, **input.src**, in the format described in Section 8.5.3.

p The perturbed Green's functions will be used for the waveguide propagation of the scattered field. This corresponds to applying scattering loss to the propagation and therefore constitutes a higher order scattering term, representing multiple scattering. In general **p** will yield a lower bound for the scattered field, while the default yields an upper bound. Option **p** has no effect for volume scattering, which is always computed in the Born approximation.

s OASSP will compute the scattered field perturbation alone. By default the total field will be calculated.

t Eliminates the wavenumber integration and computes transfer functions for individual slowness components (or plane wave components). The Fourier transform performed in PP will then directly compute the slowness/intercept-time or $\tau - p$ response for each of the selected depths. When option **t** is selected, the range parameters in the data file are insignificant.

v As option **l** this option allows for specifying a non-standard source array. However, it is more general in the sense that different types of sources can be applied in the same array, and the sources can have different signatures. The array geometry and the complex amplitudes are specified in a file **input.strf** which should be of **trf** format as described in Section 8.5.3.

Number $(1 - 5)$ specifying the source type (explosive, forces, seismic moment) as described in Section 8.5.3

15.4.1 Block III: Source Frequency

FRC is the source center frequency. As the source convolution is performed in PP, FRC is not used in OASSP, except for cases involving moving sources (option **d**), but will be written to the transfer function file and become the default for PP.

COFF is the complex wavenumber integration contour offset. To be specified in dB/λ, where λ is the wavelength at the source depth SD. As only the horizontal part of the integration contour is considered, this parameter should not be chosen so large, that the amplitudes at the ends of the integration interval become significant. In lossless cases too small values will give sampling problems at the normal modes and other singularities. For intermediate values, the result is independent of the choice of COFF, but a good value to choose is one that gives 60 dB attenuation at the longest range considered in the FFT, i.e.

$$\mathrm{COFF} = \frac{60 * \mathrm{CC(SD)}}{(\mathrm{FREQ} * \mathrm{R}_{max})}$$

where the maximum FFT range is

$$\mathrm{R}_{max} = \frac{\mathrm{NP}}{\mathrm{FREQ} * (1/\mathrm{CMIN} - 1/\mathrm{CMAX})}$$

This value is the default which is applied if COFF is specified to 0.0.

Doppler shift

By specifying option **d** in OASP V.1.7 and higher, radial *Doppler shift* is accounted for using the theory developed by Schmidt and Kuperman [9]. The source pulse and the radial projections of the source and receiver velocities must be specified in the input file following the specification of the centre frequency and the contour offset (Block II), i.e.

Standard	For option **d**
FRC COFF	IT VS VR

`IT` is a number identifying the source pulse as described in Sec. 16. `VS` and `VR` are the projected radial velocities in m/s of the source and receiver, respectively, both being positive in the direction from source to receiver. Since this option requires incorporation of the source function in the wavenumber integral, the PP post-processor <u>must</u> subsequently be used with source pulse -1 (impulse response).

15.4.2 Block IV: Environmental Model

OASSP supports all the environmental models allowed for SAFARI as well as the ones described above in Section 4.1. The significance of the standard environmental parameters is as follows

NL: Number of layers, including the upper and lower half-spaces. These should always be included, even in cases where they are vacuum.

D: Depth in m of upper boundary of layer or halfspace. The reference depth can be choosen arbitrarily, and D() is allowed to be negative. For layer no. 1, i.e. the upper half-space, this parameter is dummy.

CC: Velocity of compressional waves in m/s. If specified to 0.0, the layer or half-space is vacuum.

CS: Velocity of shear waves in m/s. If specified to 0.0, the layer or half-space is fluid. If CS()$<$ 0, it is the compressional velocity at bottom of layer, which is treated as fluid with $1/c(z)^2$ linear.

AC: Attenuation of compressional waves in dB/λ. If the layer is fluid, and AC() is specified to 0.0, then an imperical water attenuation is used (Skretting & Leroy).

AS: Attenuation of shear waves in dB/λ

RO: Density in g/cm^3.

RG: RMS roughness of interface in m. RG(1) is dummy. If RG$<$ 0 it represents the negative of the RMS roughness, and the associated correlation length CL and the spectral exponent should follow. If RG$>$ 0 the correlation length is assumed to be infinite.

CL: Roughness correlation length in m. If RG and CL are both negative, the interface is assumed to be smooth, but the layer below will contain volume inhomogeneities with vertical and horizontal correlation lengths -RG and -CL, respectively.

M: Spectral exponent of the power spectrum as defined by Turgut [25], with $1.5 < \text{M} \leq 2.5$ for realistic surfaces, with $\text{M} = 1.5$ corresponding to the highest roughness, and $\text{M} = 2.5$ being a very smooth variation. For 2-D Goff-Jordan surfaces, the fractal dimension is $\text{D} = 4.5 - \text{M}$ Insignificant for Gaussian spectrum (option **g** not specified) but a value must be given.

15.4.3 Volume Scattering Layer

If a volume scattering layer is flagged by RG and CL both being negative, these parameters will be interpreted as the negative of the vertical and horizontal correlation lengths of the volume inhomogeneities. In this case 4 more parameters should be added on the same line to completely describe the spatial statistics:

```
D CC CS AC AS RO RG CL SKW M RMS GAM
```

with the significance:

SKW Skewness angle of the correlation ellipse in degrees. 0.0 represents no skewness. Angle measured positive downwards.

M Volume spectral exponent as defined by Turgut [25] for power-law spectra. $\text{M} > 1.5$ is required for the power spectrum to be integrable, independent on the dimension of the problem. Insignificant unless option **g** was specified.

RMS RMS of relative sound speed perturbation $\Delta c/c$ for volume inhomogeneities.

GAM Ratio γ of relative density perturbation to sound speed perturbation, $\Delta\rho/\rho = 2.0\gamma\ \Delta c/c$.

15.4.4 Block V: Sources

When computing the total field (option **s** not specified), OASSP supports the same sources as OASP, as described in Sec. 8.5.3, including source arrays. However, the source specification must be consistent with the one used for the associated OASP run, since the scattered field is controlled by the latter. If option **s** is specified in OASSP, the source type is insignificant.

15.4.5 Block VI: Receivers

The default specification of the receiver depths is the same as for SAFARI, i.e. through the parameters RD1, RD2 and NRD in Block VI, with

RD1 Depth of uppermost receiver in meters

RD2 Depth of lowermost receiver in meters

NRD Number of receiver depths

The NRD receivers are placed equidistantly in the vertical.

Non-equidistant Receiver Depths

In OASES the receiver depths can optionally be specified individually. The parameter NRD is used as a flag for this option. Thus, if NRD < 0 the number of receivers is interpreted as –NRD, with the individual depths following immidiately following Block VI.

The PP Post-processor is compatible and will depth-stack the traces at the correct depths.

Tilted Receiver Arrays

Option ‘T’ allows for specification of an array tilt in the vertical plane containing the source and the receivers.

The tilt angle and rotation origin is specified in the receiver depth line (Block VI):

Standard	For option T
RD1 RD2 NR	ZREF ANGLE

The vertical arrays are rotated by an angle ‘ANGLE’ in deg relative to the vertical. The rotation is performed with origin at depth ‘ZREF’.

The parameters RD1, RD2 and NR always refer to the untilted case. In the tilted case these parameters do therefore define the array geometry and not the actual depths of the receivers in the tilted array. The same is the case for the graphics output produced by the post-processor PP.

The source(s) is always at the origin and is therefore not rotated. Thus, for zero-offset tilted VSP-s, the reference depth ZREF should be set equal to the source depth SD!

15.4.6 Block VII: Wavenumber integration

This block specifies the wavenumber sampling in the standard OASES format, with the significance of the parameters being as follows:

CMIN: Minimum phase velocity in m/s. Determines the upper limit of the truncated horizontal wavenumber space:

$$k_{max} = \frac{2\pi * \text{FREQ}}{\text{CMIN}}$$

CMAX: Maximum phase velocity in m/s. Determines the lower limit of the truncated horizontal wave- number space:

$$k_{min} = \frac{2\pi * \text{FREQ}}{\text{CMAX}}$$

In plane geometry (option P) CMAX may be specified as negative. In this case, the negative wavenumber spectrum will be included with $k_{min} = -k_{max}$, yielding correct solution also at zero range.

NW: Number of sampling points in wavenumber space. In contrast to what is the case for OAST, NW does here not have to be an integer power of 2. The sampling points are placed equidistantly in the truncated wavenumber space determined by CMIN and CMAX. If CMAX< 0, i.e. the inclusion of the negative spectrum is enabled, then the NW sample points will be distributed along the positive wavenumber axis only, with the negative components obtained by symmetry. NW=-1 activates automatic wavenumeber sampling.

IC1: Number of the first sampling point where the calculation is to be performed. If IC1$>$ 1, then the Hankel transform is Hanning-windowed in the interval 1,2. . .IC1-1 before integration. Insignificant for automatic sampling (NW = -1).

IC2: Number of the last sampling point where the calculation is to be performed. If IC2$<$NWN, then the Hankel transform is Hanning windowed in the interval IC2+1,. . .NW before integration. Insignificant for automatic sampling (NW = -1).

IF: Frequency increment for plotting of integration kernels. A value of 0 disables the plotting.

Automatic wavenumber sampling

As foor the other OASES modules the automatic sampling is activated by specifying the parameter NW to -1 and it automatically activates the complex frequency integration contour even though option **O** may not have been specified. The parameters IC1 and IC2 have no effect if the automatic sampling is selected.

15.5 Execution of OASSP

As for the other modules filenames are passed to the code via environmental parameters. In Unix systems a typical command file **oassp** (in $HOME/oases/bin) is:

```
#!/bin/csh
    setenv FOR001 $1.dat       # input file
    setenv FOR002 $1.src       # Source array input file
    setenv FOR015 $1.strf      # Source array trf file
    setenv FOR019 $1.plp       # plot parameter file
    setenv FOR020 $1.plt       # plot data file
    setenv FOR028 $1.cdr       # contour plot parameter file
    setenv FOR029 $1.bdr       # contour plot data file
    setenv FOR045 $2.rhs       # mean field amplitudes at rough interface
    setenv FOR046 $2.vol       # mean field in volume scattering layer
    oassp2                      # executable
```

After preparing an OASP data file with the name `input-rhs.dat` , OASP is executed by the command:

> **oasp input-rhs**

To generate the associated scattered field transfer functions, OASSP is then executed,

> **oassp input-scat input-rhs**

where `input-scat.dat` is the input file for OASSP.

15.6 OASSP - Examples

15.6.1 Rough Seabed Reverberation

This example computes the reverberation in a 200 Hz band around 500 Hz from a rough stratified seabed in shallow water. The source is assumed to be a line source (option P). The field is computed for vertical arrays at range 0 m (monostatic) and 500 m (bistatic). The data file `wg-rhs.dat` for computing the mean field using automatic sampling is:

```
Line source. Mean field. Goff. auto.
P B N s g O
500 0
4
0          0      0     0     0     0     0
0       1500      0     0     0     1     0
128.    1470   0000.00  0.01  0.00  1.650  0.5  0
228.00  2300   0000.00  0.50  0.00  2.650  0.0000

100.
52. 127. 51

1200 -1200
-1 1 1 0
2048 400 600 0.0004 0 .5 2
```

Figure 5 shows the depth-stacked plots of the the mean field envelopes for the monostatic receiver array, generated using PP.

The associated input file `wg-scat.dat` for OASSP is:

```
Seabed scat. Line source. Goff-J. auto.
P B N O s g
500 0
4
  0.       0      0     0     0     1     0      0
  0.    1500      0     0     0     1     0      0
128.    1470   0000.00  0.01  0.00  1.650  -0.5   5.0
228.00  2300   0000.00  0.50  0.00  2.650  0.0000 0.0

128.
77. 127. 51
```

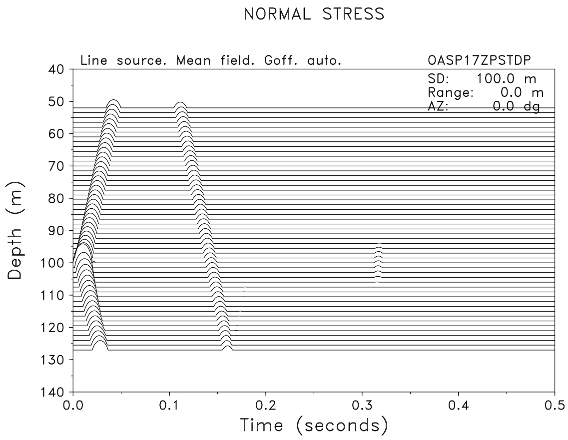

Figure 5: Mean field envelope in shallow water example

```
1200 -1200
2048 1 2048 0
2048 400 600 0.0004 0 0.5 2
```

The main difference is that the wavenumber sampling was chosen manually here, and a finite roughness correlation length was specified. The field envelopes for the monostatic vertical array are shown in Fig. 6.

15.6.2 Seabed Volume Scattering

The use of OASSP for computing realizations of scattering and reverberation produced by random distributions of volume inhomogeneities in the seabed is illustrated by the following example. The environment is similar to the above, but the seasurface is eliminated. The data file `vol-rhs.dat` for the OASP mean field is

```
Halfsp. Line source. Mean field. Goff. auto.
P B N s g O
500 0
3
128.    1500      0      0    0    1      0      0
128.    1470  -2270.10  0.01  0.00  1.650  1.0000  0
```

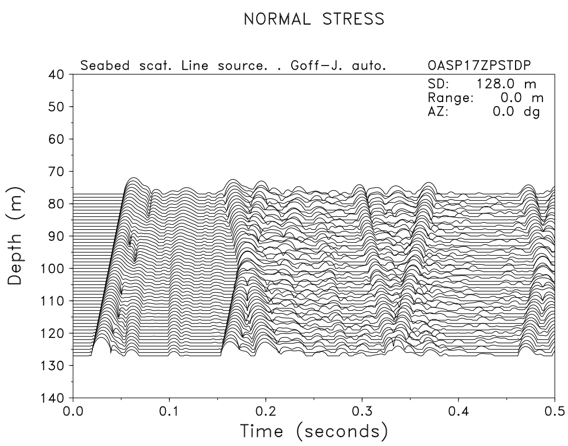

Figure 6: Reverberant field envelope in shallow water seabed roughness scattering example

```
228.00  2300   0000.00  0.50  0.00  2.650  0.0000  0

100.
77. 127. 51

1200 -1200
-1 1 1 0
2048 400 600 0.0004 0 .5 2
```

The resulting depth-stacked envelope plot is shown in Fig. 7.

The associated OASSP data file `vol-scat.dat` for calculating the field scattered is

```
Volume scat. Line source. . Goff-J. auto.
P N s O g
500 0
3
128.    1500       0     0     0     1       0    0.0
128.    1470  -2270.10  0.01  0.00  1.650  -2.0 -5.0 0 2.5 1.0 0.0
228.00  2300   0000.00  0.50  0.00  2.650  0.0000 0.0

128.
77. 127. 51
```

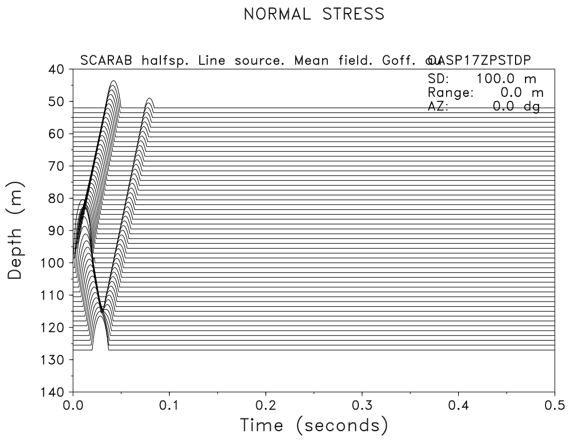

Figure 7: Monostatic mean field envelope in shallow water environment with sediment layer having a strong sound speed gradient and volume inhomogeneities

```
1200 -1200
2048 1 2048 0
2048 400 600 0.0004 0 0.5 2
```

With the skewness set to 0 deg the main axes of the correlation function are alligned with the stratification, and the horizontal correlation length is specified to 5 m, with the vertical correlation length being 2 m. The fractal dimension of the power law spectrum (option 'g') is 2.5. The RMS relative sound speed perturbation is set to unity, while the relative density is set to 0.

The resulting depth-stacked scattered field envelopes are shown in Fig. 8. The fundamental differences between the scattering from seabed roughness and volume inhomogeneities is didcussed in Ref. [24].

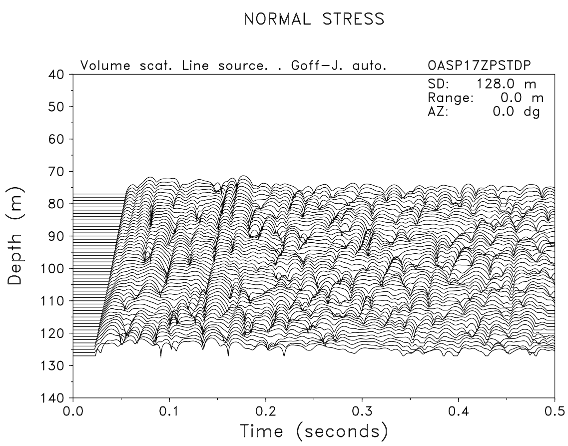

Figure 8: Monostatic backscattering envelope in shallow water environment with sediment layer having a strong sound speed gradient and volume inhomogeneities

16 PP - The OASES Pulse Post-processor

The post-processor PP convolves the transfer functions produced by OASP, RDOASP, OASP3D or SUPERSNAP with an interactively selected source spectrum and performs the inverse Fourier transform yielding the synthetics.

The synthetics are plotted directly using MINDIS or PLOTMTV, and a hardcopy can be requested after each plot Alternatively, a trace file can be created in a user specified format, containing the computed timeseries.

16.1 Executing PP

PP is menu-driven, with the menus being machine-independent. The program is executed directly without any parameters or switches by issuing the command **pp**, prompting with the menu:

```
**************************************************************
*                     OASES PULSE POST-PROCESSOR             *
**************************************************************
*   1. File name:      temmllra.trf                          *
*   2. Source type:          2     (    -1 -    6 )          *
*   3. Source file:    tria.sou                              *
```

```
 *  4. Min frequency:         0.000  Hz                            *
 *  5. Max frequency:         0.000  Hz                            *
 *  6. Cen frequency:         0.000  Hz                            *
 *  7. Plot options:   SHD,POS                                     *
 *  8. Contour options:CPX                                         *
 *  9. Depth stacked:                                              *
 * 10. Range stacked:                                              *
 * 11. Azimuth stacked:                                            *
 * 12. Individual:                                                 *
 * 13. Transmission Los                                            *
 * 14. Snap shots:                                                 *
 * 15. Source pulses:                                              *
 * 16. Demodulation:          N     ( Y/N )                        *
 * 17. Log Traces:            N     ( Y/N )                        *
 * 18. Save plot files:       N     ( Y/N )                        *
 * 19. Trace format:          A     ( Asc/Cfs/Gld/Mat/Sdr )        *
 * 20. Add TRF files:                                              *
 * 21. Multiply TRF fil                                            *
 * 22. Exit PP:                                                    *
 *******************************************************************
     SELECT OPTION: 1
File name:      ?   input.trf
```

The first option selected is 1 to specify the file name, here a file **input.trf** containing transfer functions produced by OASP or another compatible code. PP now reads the header of the file and displays the frequency interval, the default source type (the source types 1-5 are those given in the SAFARI manual [4]) and the center frequency specified in the OASP data file. Any of these parameters may now be changed if desired. The plot options (field 7) can be specified in the format described in Sec. 17.1, and similarly for the contour options (field 8) in Sec. 17.2.

16.2 Source Pulses

PP has a set of built-in source pulses, selected in Field 2 of the PP main menu. Types 1 to 5 are those available in SAFARI [4].

Type 6 is a new pulse type. It is generated as a Hanning windowed sine wave with a duration corresponding to the bandwidth of the transfer function in the **trf**-file. This source pulse minimizes artificial ringing of the response due to the truncation of the transfer function and is the recommended pulse type for narrow band propagation problems.

Type -1 yields the band-limited impulse response by simply eliminating the source pulse convolution. To reduce truncation ringing the transfer function is Hermite-extrapolated before being Fourier transformed.

Type 0 lets the user input his own pulse shape. The source pulse should be defined in an ASCII file in the following format:

$$\begin{array}{ll} t_0 & p_0 \\ t_1 & p_1 \\ t_2 & p_2 \\ t_3 & p_3 \\ : & : \\ : & : \\ t_n & p_n \end{array}$$

where t_i is the time in seconds and p_i is the corresponding source pulse amplitude. The time sampling does not have to be equidistant, and the file needs only contain the actual length of the source pulse. PP will use interpolation and zero-padding to conform with the time window and sampling defined by the **trf**-file. The name of the source file is specified in Field 3 of the main menu.

16.3 Trace file format

All timeseries submenues include the option of creating trace files, rather than the scaled plot files, for post-processing. A generic ASCII file format is the default, while the other formats represent site-specific costumizations. Thus, for example (**G** chooses the GLD format used extensively in the past by MIT/WHOI. As the latest addition (Version 2.2 and higher) the trace files may be generated directly in MATLAB-5©format (**M**). The *matlab_util* sub-directory contains a sample MATLAB script, `pp_matreader.m` , for reading the files.

All file formats include a header identifying the traces. Thus, for example, the ASCII file has a master header with information etc., and a sub-header for each trace with depth, range etc. The data for each trace then follow sequencially:

```
TEMME-MULLER. Auto f.
           V          # Parameter
           1          # Number of planes
          23          # Number of traces
        1001          # Number of samples/trace
    1000.00           # Sampling frequency in Hz

    600.000           # Range (m)
    50.0000           # Depth (m)
   0.000000E+00       # Bearing (deg)
   0.000000E+00       # Starting time (sec)
  -0.366703E-08  -0.292363E-08  -0.200186E-08  -0.977132E-09   0.445733E-10
   0.947549E-09   0.163239E-08   0.203979E-08   0.216378E-08   0.205015E-08
```

```
 .
 .
0.253403E-06   0.303194E-06   0.327134E-06   0.318899E-06   0.278182E-06
0.211619E-06

 600.000           # Range (m)
 75.0000           # Depth (m)
0.000000E+00       # Bearing (deg)
0.000000E+00       # Starting time (sec)
0.371295E-08   0.323503E-08   0.249180E-08   0.154489E-08   0.474728E-09
 .
 .
```

Field 16 and 17 control the plot format for all timeseries plots and trace outputs. IF 'Y' is selected in field 16, all timeseries will be demodulated by the centre frequency to generate the magnitude complex signal envelope. If in addition 'Log traces' is chosen in field 17, the magnitude envelopes will be plotted or output in dB. This option is particularly useful when large dynamic range is needed, such as for reverberation simulations using OASSP.

16.4 Depth-Stacked Time Series

If the synthetics should be depth-stacked, Field 9 is selected in the main menu, showing the sub-menu:

```
*********************************************************************
*                         DEPTH STACKED PLOTS                       *
*********************************************************************
*  1. Plot title:     TEMME-MULLER. Auto f.                         *
*  2. Min time:              0.000 s                                *
*  3. Max time:              1.000 s                                *
*  4. Time tick inc:         0.200 s                                *
*  5. t-axis length:        20.000 cm                               *
*  6. Depth down:          700.000 m                                *
*  7. Depth up:              0.000 m                                *
*  8. Depth tick inc:      100.000 m                                *
*  9. d-axis length:        15.000 cm                               *
* 10. d-axis label:   Depth (m)                                     *
* 11. Red. velocity:         0.000 m/s                              *
* 12. Range:                 0.600 km                               *
* 13. Azimuth:               0.000 deg                              *
* 14. Scale factor:          1.000                                  *
* 15. Parameter:             V     ( V H )                          *
* 16. Generate plot:                                                *
* 17. Trace file:                                                   *
* 18. Return:                      ( PP main menu )                 *
*********************************************************************
    SELECT OPTION:
```

The menu should be self explanatory for users familiar with SAFARI, with only the following being particular to PP:

Field 12 selects the receiver range.

Field 13 specifies the azimuth of the receiver plane. This parameter is only significant for transfer functions with horizontal directionality, produced by OASP3D.

Field 14 represents a scaling factor which will be applied to all traces. The default is 1.0, i.e. no scaling, but may be changes as desired.

Field 15 represents the parameter to be plotted, consistent with the options specified in the OASP data file, i.e. with N representing the normal stress or negative pressure in fluids, V the vertical particle velocity and H the horizontal particle velocity etc. The bracket indicates that only V and H transfer functions are available in the file, and the program will therefore not allow any other choice.

Field 16 produces the plot with the specified parameters.

Field 17 produces a trace file containing the time series, in file format specified in main menu (default ASCII). The trace file include all the timeseries which would be included in the stacked plot.

Field 18 Returns to main menu for change of e.g. source data, plot format etc.

16.5 Range-Stacked Time Series

If instead the range stacking was selected the following menu appears:

```
*********************************************************************
*                         RANGE STACKED PLOTS                       *
*********************************************************************
*  1. Plot title:     TEMME-MULLER. Auto f.                         *
*  2. Min time:              0.000 s                                *
*  3. Max time:              1.000 s                                *
*  4. Time tick inc:         0.200 s                                *
*  5. T-axis length:        20.000 cm                               *
*  6. Range down:           -0.500 km                               *
*  7. Range up:              1.000 km                               *
*  8. Range tick inc:        0.500 km                               *
*  9. R-axis length:        15.000 cm                               *
* 10. R-axis label:   Range (km)                                    *
* 11. Red. velocity:         0.000 m/s                              *
* 12. Depth:               600.000 m                                *
* 13. Azimuth:               0.000 deg                              *
* 14. Scale factor:          1.000                                  *
* 15. Range scaling?         N     ( Y/N )                          *
* 16. Parameter:             V     ( V H )                          *
* 17. Generate plot:                                                *
* 18. Trace file:                                                   *
* 19. Return:                      ( PP main menu )                 *
*********************************************************************
      SELECT OPTION:
```

The menu should be self explanatory for users familiar with SAFARI, with only the following being particular to PP:

Field 12 selcts the depth of the receivers to be stacked.

Field 13 specifies the azimuth of the receiver plane. This parameter is only significant for transfer functions with horizontal directionality, produced by OASP3D.

Field 14 represents a scaling factor which will be applied to all traces. The default is 1.0, i.e. no scaling, but may be changes as desired.

Field 15 enables/disables the range scaling (amplitudes multiplied by range). By defaults range scaling is enabled.

Field 16 represents the parameter to be plotted, with N representing the normal stress or negative pressure in fluids, V the vertical particle velocity and H the horizontal particle velocity. The bracket indicates that only V and H transfer functions are available in the file, and the program will therefore not allow any other choice.

Field 17 produces the plot with the specified parameters.

Field 18 produces a trace file containing the time series, in file format specified in main menu (default ASCII). The trace file include all the timeseries which would be included in the stacked plot.

Field 19 Returns to main menu for change of e.g. source data, plot format etc.

16.6 Azimuth-Stacked Time Series

If the azimuth stacking was selected the following menu appears:

```
********************************************************************
*                        AZIMUTH STACKED PLOTS                     *
********************************************************************
*  1. Plot title:     TEMME-MULLER. Auto f.                        *
*  2. Min time:              0.000 s                               *
*  3. Max time:              1.000 s                               *
*  4. Time tick inc:         0.200 s                               *
*  5. t-axis length:        20.000 cm                              *
*  6. Azimuth down:        -50.000 deg                             *
*  7. Azimuth up:          400.000 deg                             *
*  8. Azim. tick inc:       50.000 deg                             *
*  9. a-axis length:        15.000 cm                              *
* 10. Red. velocity:         0.000 m/s                             *
* 11. Range:                 0.600 km                              *
* 12. Depth:               600.000 m                               *
* 13. No. of traces:        18     (     1 -  999 )                *
* 14. Scale factor:          1.000                                 *
* 15. Parameter:             V     ( V H )                         *
* 16. Generate plot:                                               *
* 17. Trace file:                                                  *
* 18. Return:                      ( PP main menu )                *
********************************************************************
     SELECT OPTION:
```

The menu should be self explanatory for users familiar with SAFARI, with only the following being particular to PP:

Field 11 specifies the range of the receivers in km.

Field 12 specifies the depth of the receivers in meters.

Field 13 specifies the number of azimuths of the receiver plane for which the response should be computed and stacked.

Field 14 represents a scaling factor which will be applied to all traces. The default is 1.0, i.e. no scaling, but may be changes as desired.

Field 15 represents the parameter to be plotted, with N representing the normal stress or negative pressure in fluids, V the vertical particle velocity and H the horizontal particle velocity. The bracket indicates that only V and H functions are available in the file, and the program will therefore not allow for any other choice.

Field 16 produces the plot with the specified parameters.

Field 17 produces a trace file containing the time series, in file format specified in main menu (default ASCII). The trace file include all the timeseries which would be included in the stacked plot.

Field 19 Returns to main menu for change of e.g. source data, plot format etc.

16.7 Transmission Loss Plots

Version 2.1 of PP has been modified to allow for plotting of transmission losses, derived from the OASP transfer functions. This also allows for extreme near-field transmission loss computations with the full exact Bessel function integration (OASP option **f**).

Choosing field 13 brings up the transmission loss submenu,, allowing selction of plot formats, currently supporting TL vs range, depth or frequency, depth-averaged TL, or depth-range contours:

```
********************************************************************
*                          TRANSMISSION LOSS                       *
********************************************************************
*  1. TL vs Freq:                                                  *
*  2. TL vs Range:                                                 *
*  3. TL vs Depth:                                                 *
*  4. Depth Average:                                               *
*  5. Depth-Range Cont                                             *
*  6. Return:                      ( PP main menu )                *
********************************************************************
     SELECT OPTION: 5
                            --------------------
********************************************************************
*                      DEPTH-RANGE TL CONTOURS                     *
********************************************************************
*  1. Plot title:     TEMME-MULLER. Auto f.                        *
*  2. Range left:            0.000 km                              *
*  3. Range right:           0.600 km                              *
*  4. Range tick inc:        0.100 km                              *
*  5. R-axis length:        20.000 cm                              *
*  6. Depth down:          600.000 m                               *
*  7. Depth up:              0.000 m                               *
*  8. Depth tick inc:      100.000 m                               *
*  9. D-axis length:        12.000 cm                              *
* 10. Azimuth:               0.000 deg                             *
* 11. Frequency:            50.000 Hz                              *
* 12. Min. loss:            30.000 dB                              *
* 13. Max. loss:            90.000 dB                              *
* 14. Increment:             3.000 dB                              *
* 15. Undef. file:                                                 *
* 16. Shade file:                                                  *
* 17. Parameter:             V     ( V H )                         *
* 18. Generate plot:                                               *
* 19. Return:                      ( PP main menu )                *
********************************************************************
```

16.8 Snap Shots

This option (Field 14) produces snap shots of the field in the form of contours vs range and depth.

```
*******************************************************************
*                        PULSE SNAP SHOTS                         *
*******************************************************************
*  1. Plot title:     TEMME-MULLER. Auto f.                       *
*  2. Range left:           0.000 km                              *
*  3. Range right:          0.600 km                              *
*  4. Range tick inc:       0.100 km                              *
*  5. R-axis length:       20.000 cm                              *
*  6. Depth down:         600.000 m                               *
*  7. Depth up:             0.000 m                               *
*  8. Depth tick inc:     100.000 m                               *
*  9. D-axis length:       12.000 cm                              *
* 10. Time,frst frame:      0.000 s                               *
* 11. Time,last frame:      0.000 s                               *
* 12. Number of frames      0      (     1 -   99 )               *
* 13. Max. level:         -99.000                                 *
* 14. Norm. exp.:         -99      (   -99 -   99 )               *
* 15. No. contours:         0      (     1 -   21 )               *
* 16. Undef. file:                                                *
* 17. Shade file:                                                 *
* 18. Parameter:            V      ( V H )                        *
* 19. Range scaling?        N      ( Y/N )                        *
* 20. Generate plot:                                              *
* 21. return:                      ( PP main menu )               *
*******************************************************************


    SELECT OPTION:
```

The menu should be self explanatory for users familiar with SAFARI, with only the following being particular to PP:

Field 10 specifies the time in seconds of the first snapshot produced. This will also be the trace used for the automatic scaling invoked by fields 13 and 14.

Field 11 specifies the time in seconds of the last snapshot.

Field 12 specifies the number of snapshots produced equidistantly for the selected time interval.

Field 13 Is used to set the maximum level $A_{\max}$ for the contours. The interval $[-A_{\max}, A_{\max}]$ will be equidistantly covered by the number of contours specified in Field 13.

Field 14 Here the logarithm of the scaling factor is specified. If -99 is specified the exponent will be selected automatically based on the snap-shot data. Usually the first snap-shot is made with automatic scaling, whereas the rest are produced with the so determined exponent. The automatic scaling will also suggest a value of $A_{\max}$ in Field 11, which may of course be changed by the user if desired.

Field 15 Number of contour levels applied for snapshots. For UNIRAS colour plots this number should not be more that 12. UNIRAS is selected by specifying the contour options `UNI,X11,COL` in Field 8 of the main menu (X11 selects X-windows as device).

Field 16 Name of a file containing a binary map of undefined points.

Field 17 Name of file containing the coordinates of an optional shaded polygon superimposed to the snap-shot. Used for shading bottom or objects. The file format is the standard shading specification used in the **cdr** files providing plot parameters to **cplot**.

Field 18 represents the parameter to be plotted, consistent with the options specified in the OASP data file, i.e. with N representing the normal stress or negative pressure in fluids, V the vertical particle velocity and H the horizontal particle velocity etc.

Field 19 a 'Y' here applies a linear scaling of the snapshots with horizontal range, similar to the range scaling in the range-stacked plots. This is useful for animations of near-field problems with significant geometric spreading.

Field 20 produces the contour plots with the specified parameters.

Field 21 Returns to main menu for change of e.g. source data, plot format etc.

17 Graphics Post-Processors

17.1 mplot

`mplot` is one of the graphics post-processors used in connection with OASES and other compatible acoustic propagation models. It produces publication quality line-style graphics using the `MINDIS` graphics library.

Alternatively, `plotmtv` may be chosen as the default line plot package by setting an environment variable:

```
setenv PLP_PACKGE MTV
```

It should be noted that some of the `mplot` options described below may not be fully supported by `plotmtv`.

17.1.1 Input files

`mplot` requires two input files, with extensions `plp` and `plt` .

The file with extension `plp` contains plot parameters such as axis lengths, titles, labels etc, whereas the other file, with extension `plt` , contains the actual data values to be plotted. Both files are formatted ASCII files, and it is therefore possible to change the layout of the plots by editing the `plp` file.

A typical `plp` file is:

```
     1024                              MODULO
_FIPP__STLDAV,CPX,IYA
_DEPTH AVERAGED LOSS
_SAFARI-FIP case 3.
_        2                             NUMBER OF LABELS
_Freq:    30.0 Hz$
_SD:      50.0 m$
_       20.000000                      XLEN
_       12.000000                      YLEN
_        0                             GRID TYPE
_     0.000000                         XLEFT
_      5.00000                         XRIGHT
_      1.00000                         XINC
_      1.00000                         XDIV
_Range (km)$
```

```
_LIN
_     80.0000                                 YDOWN
_     20.0000                                 YUP
_     10.0000                                 YINC
_     1.00000                                 YDIV
_Normal stress (dB//1Pa)$
_LIN
_        1                                    NC
_      112                                    N
_        0.044957                             XMIN
_    0.449567-001                             DX
_    0.000000                                 YMIN
_        0.000000                             DY
_FIP___PLTEND
```

The underscore denotes a space which is necessary for `mplot` to correctly read the file. The `plp` file will always start with a block size MODULO, with which the corresponding data file was written. This parameter is a leftover from the versions using binary data files, but for the present version of `mplot` this parameter is dummy. The file ends with the `PLTEND` flag signalling the end-of-file.

Between these two records the blocks of actual plot parameters are specified, in the present case for a single plot only. Any number of blocks could, however, be included, each generating one plot.

The plot parameter block starts with a record specifying a 12-character plot identification (FIPP STLDAV) followed by a series of 3-character options separated by commas. The files generated by the acoustic propagation models will in general not have any options specified, but these are important tools for generating final plots. The following options are currently available:

DUP A **DUPLEX** character generator will be used in stead of the default **SIMPLEX**.

CPX The **COMPLEX** character generator is selected.

ITA The **ITALIC** character generator is used.

IXA Integer format will be used for plotting the x-axis tick mark numbers instead of the default decimal format.

IYA Integer format will be used for plotting the y-axis tick mark numbers instead of the default decimal format.

DSD If the plot contains more than one curve (NC$>$ 1), then the first curve will be plotted with a solid line, the second with a dashed and the third with a dotted. If more than three curves are plotted, this sequence will be repeated.

COL This option will plot individual curves in different colour, using the repeatable sequence: red - green - blue - cyan - magenta - yellow. Also affects the shading option `SHD` .

MRK A marker will be plotted for each 10th data point on the curves. In the case of more curves, different markers will be used for each.

TCT This option is used in connection with the stacked time series plots in order to truncate the amplitude of each trace at an amplitude corresponding to half the distance between traces.

SHD Produces shaded wiggles on timeseries plots. If specified alone both positive and negative wiggles will be shaded. If specified together with options `POS` or `NEG` only the positive or negative wiggles will be shaded, respectively. If specified together with `COL` the shading is color coded depending on the amplitude. Currently the shading will only appear on the hardcopy devices.

POS Shading only applied to positive wiggles.

NEG Shading only applied to negative wiggles.

NWR Disables plotting of the option at the upper right corner of the plot. Used when generating final figures for documents.

NOP This option will read both the parameters from the `plp` file and the data from the `plt` file but no plot is produced. It is therefore used for time saving when only selected plots are required.

The next record specifies the main title of the plot, followed by a record containing the title specified in the data file for the propagation models. This title will be plotted just above the plot frame.

There is then a sub-block containing the labels to be plotted in the upper right corner of the plot frame. The number of labels (≥ 0) is given first, followed by the label texts, each of which should be on separate lines and terminated by a $.

The parameters XLEN and YLEN specify the length in cm of the x- and y-axis, respectively. The parameter labelled `GRID TYPE` indicates whether a grid should be plotted. A value of 1 will produce a dotted grid.

The next 6 records contain the parameters for the x-axis of the plot. `XLEFT` and `XRIGHT` are the data values at the left and right borders of the plot frame, respectively, whereas `XINC` is the distance in the same units between the tick marks. `XDIV` is a multiplication factor which will be applied to both the axis parameters and the data values. After `XDIV` the x-axis label is specified, terminated by a $, and finally `LIN` indicates that the x-axis should be linear.

Another possibility is a logarithmic axis, which has not yet been implemented however. The parameters for the y-axis are given in the same way in the next 6 records.

The parameter `NC` specifies the number of curves to be plotted. For each curve a sub-block of 5 records has to be specified. The first parameter `N` indicates the number of points in the curve. If `N` is negative, no curve will be plotted; instead a marker will be plotted at the position of each data point. The parameter `XMIN` is the x-coordinate (range) of the first data point, whereas `DX` is the equidistant spacing. If `DX` had been specified as 0, then the `N` x-coordinates of the data points would be read from the `plt` file. In that case `XMIN` would be interpreted as an x-offset to be applied to the curve. The same rules apply to `YMIN` and `DY` . In the above example the y-values will therefore be read from the PLT file, and no y-offset will be applied. The offsets are mainly used for the stacked time series plots If both `DX` and `DY` are specified as 0, then `mplot` will first read all `N` x-values and then all y-values.

17.1.2 Executing mplot

To execute `mplot` , prepare the input files, e.g. `input.plp` and `input.plt` as described above. Then execute the script

```
mplot input
```

17.2 cplot

`cplot` is the standard script for producing contour plots generated by SAFARI, OASES or SNAP. However, `cplot` is available for more general use, provided the data to be contoured and the plot lay-out parameters are file-structured as described below.

The plot lay-out parameters are transferred to `cplot` in a file with extension `.cdr` , whereas the actual contour data are transferred in a file with extension `.bdr` . The data file is allowed to be in both ASCII or binary format, but in computational environments with different types of hardware platforms, it is most convenient to use ASCII format.

The `cdr` file can be edited for changing the layout of the contour plot. As a typical example, the `cdr` file used to create the contour plot in Fig. 14b of the *SAFARI User's Guide* is as follows:

```
CONDR,FIP,FMT,CPX,UNI,TEK
SAFARI-FIP case 5.
saffip5.bdr
Range (m)
          0.0000    RMIN
```

```
        299.8535    RMAX
          0.0000    XLEFT
        300.0000    XRIGHT
         15.0000    XSCALE
         50.0000    XINC
Depth (m)
         50.0000    YUP
        125.0000    YDOWN
          6.2500    YSCALE
         25.0000    YINC
        141.0000    DATA POINTS ALONG X AXIS
         51.0000    DATA POINTS ALONG Y AXIS
          1.0000    DIVX
          1.0000    DIVY
          0.0000    FLAGRC
         50.0000    RDUP
        125.0000    RDLO
         50.0000    SOURCE DEPTH (M)
        141.0000    GRID POINTS ALONG X AXIS
         51.0000    GRID POINTS ALONG Y AXIS
       1000.0000    FREQUENCY (HZ)
          0.0000    DUMMY
          5.0000    CAY
          5.0000    NRNG
         21.0000    ZMIN
         54.0000    ZMAX
          3.0000    ZINC
          2.0000    X ORIGIN OF PLOT IN INCHES
          0.0000    DUMMY
          2.0000    Y ORIGIN OF PLOT IN INCHES
          0.0000    NSM
          0.1000    HGTPT
          0.1400    HGTC
         -3.0000    LABPT
          1.0000    NDIV
          5.0000    NARC
         -1.0000    LABC
         -1.0000    LWGT
BOTTOM  1
  0.0 100.0
300.0 100.0
300.0 120.0
  0.0 120.0
BOTTOM  3
  0.0 120.0
300.0 120.0
300.0 125.0
```

```
0.0 125.0
```

The first record specifies one 5-character option (CONDR) followed by a series of 3-letter options. The CONDR option indicates that the actual contour plot is of the depth-range type and `cplot` will interpret the parameters accordingly. *This option should therefore never be changed*. The first 3-letter option (FIP) is purely for identification and has no further effect. The FMT option indicates that the `bdr` data file is ASCII formatted (BIN for binary format). These first 3 options should always be present in the specified order, but the options following are optional and can be given in any order. The implemented options are as follows:

DUP The **DUPLEX** character generator will be used for MINDIS plots instead of the default **SIMPLEX**.

CPX The **COMPLEX** character generator is selected for MINDIS plots.

ITA The **ITALIC** character generator will be used by MINDIS.

MIN The MINDIS plot package will be used to produce line contour plots.

MTV The PLOTMTV plot package will be used to generate a colour or greytone contour plot. MINDIS is the default plot package.

UNI The UNIRAS plot package will be used to generate a colour or greytone contour plot. MINDIS is the default plot package.

X11 The raster plot will be produced on the X-windows display defined by the current setting of the `DISPLAY` environmental variable. (UNIRAS only).

TEK The raster plot will be produced on the Tektronix 4691 ink jet plotter (UNIRAS only).

LAS The raster plot will be produced on the default laser printer (UNIRAS only).

CLA A Colour-Postscript file is created which may be printed on a colour laser printer (UNIRAS only).

PSP A Grey-tone Postscript file in portrait mode is created for later printing or inclusion in LaTeX documents.

PSL A Grey-tone Postscript file in landscape mode is created for later printing or inclusion in LaTeX documents.

COL If the options MTV or UNI has been selected, a colour raster plot using an inbuilt colour scale will be generated. By default greytone scale is applied (UNIRAS and PLOTMTV).

REV Reverses the default colour or grey-tone scales (UNIRAS only).

ROT UNIRAS plots will be rotated 90 degrees. On most graphics devices the default is landscape mode.

NCL By default the raster plots will have the contour lines separating the levels plotted as well. This option disables this feature.

NCS By default a colour scale will be produced to the right of the contour map. This option disables this feature.

If you are using `cplot` through X-Windows, UNIRAS or PLOTMTV plots may alternatively be generated interactively after the default MINDIS plot is produced. The default graphics package may be changed by setting environmental parameters. Thus, to change the default to PLOTMTV color in X-windows, use the following definitions in your `.login` file:

```
setenv CON_BWCOL COL
setenv CON_PACKGE MTV
setenv CON_DEVICE X11
```

PLOTMTV is available in public domain, and is easily installed, as described inSection 2.3.

After the option record there is a record containing the title of the plot and a record containing the name of the file containing the data, i.e. the `bdr` file. Except for 2 records containing the x-axis and y-axis labels, the rest of the records contain numerical parameters, all supplied with a descriptive label. In general only a few of these parameters should be changed. The most important ones are described below.

The lengths of the x- and y-axes are controlled by the parameters XSCALE and YSCALE, respectively. `cplot` requires these parameters to be specified in coordinate units per cm. ZMIN and ZMAX specify the limits of the contouring interval, whereas ZINC is the associated increment. If UNIRAS is selected, areas with small data values will be filled with magenta colour or black in the greytone mode. The colour scale then moves through different red tones into blue (white in the greytone mode). If the default MINDIS package is selected, only contour lines with identifying numbers are plotted.

Another important parameter is NSM, which controls the amount of smoothing applied to the calculated contours. This parameter can be set to any value between 0 and 10, with 0 corresponding to no smoothing. It is obvious that this parameter should be used with extreme care.

At the end of the file, any number of blocks – identified by the keyword `BOTTOM` – can be specified, creating a shaded polygon in one of 4 grey-tones as specified by the number following the keyword `BOTTOM` (1 is light grey and 4 black). Each line following states the x- and y-coordinates of the corners of the polygon.

The top of the corresponding `bdr` file looks as follows:

```
 141.00    51.00  0.0E+00   1.0000  0.0E+00  0.0E+00
0.0E+00  0.0E+00  0.0E+00  0.0E+00  0.0E+00  0.0E+00
0.0E+00  0.0E+00  0.0E+00  0.0E+00  0.0E+00  0.0E+00
0.0E+00  0.0E+00  0.0E+00  0.0E+00  0.0E+00  0.0E+00
0.0E+00  0.0E+00  0.0E+00  0.0E+00
 25.866   22.212   20.700   20.726   21.781   23.280
 24.908   26.937   29.723   33.102   36.234   38.500
 40.540   43.220   45.981   47.238   48.749   52.225
 55.318   56.159   59.268   64.670   65.453   67.815
 75.660   77.704   79.630   90.666   109.52   91.888
 89.072   87.422   83.239   85.975   85.229   81.266
 84.744   85.196   81.190   84.615   86.690   82.392
   :        :        :        :        :        :
   :        :        :        :        :        :
```

The `bdr` file must have a header with 28 real numbers. Only the first 4 numbers are of significance. The first is the number of columns (or x-values) in the data matrix, with the second similarly giving the number of rows (or y-values). These numbers must be identical to the corresponding number of data points specified in the `cdr` file. The third and fourth numbers must be specified as 0.0 and 1.0, respectively. After the header the data to be contoured follow row by row in free format. Alternatively, the data may be specified column-wise, provided the parameter FLAGRC is set to 1.0 in the `cdr` file.

17.2.1 Executing cplot

To execute `cplot` , prepare the input files, e.g. `input.cdr` and `input.bdr` as described above. Then execute the `cplot` script

```
cplot input
```

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A Porous Media Model

The Model

The equations of motion for a porous sediment layer may be written in the form[5]

$$\begin{aligned}\mu\nabla^2\mathbf{u} + (H-\mu)\nabla e - C\nabla\zeta &= \rho\ddot{\mathbf{u}} - \rho_f\ddot{\mathbf{w}} \\ C\nabla e - M\nabla\zeta &= \rho_f\ddot{\mathbf{u}} - \frac{c_m\rho_f}{\phi}\ddot{\mathbf{w}} - \frac{F\eta}{\kappa}\dot{\mathbf{w}}\end{aligned}$$

where $\mathbf{u}$ is the displacement vector associated with the frame and $\mathbf{w} = \phi(\mathbf{u} - \mathbf{u_f})$ is the weighted (by porosity) relative displacement of the frame with respect to the pore fluid. Also $e = \operatorname{div}\mathbf{u}$ and $\zeta = \operatorname{div}\mathbf{w}$; $\rho = \phi\rho_f + (1-\phi)\rho_s$ is the average density of the saturated sediment and H, C, and M are (complex) elastic moduli calculated from the prescribed moduli as

$$\begin{aligned}M &= \frac{K_r}{1 - \frac{K}{K_r} + \phi(\frac{K_r}{K_f} - 1)} \\ C &= \frac{1 - \frac{K}{K_r}}{M} \\ H &= (1 - \frac{K}{K_r})C + K + \frac{4}{3}\mu\end{aligned}$$

Finally, F is a frequency dependent drag coefficient which is taken as[8]

$$F = \frac{\xi T(\xi)}{4[1 + 2i\frac{T(\xi)}{\xi}]}$$

where

$$\xi = a\sqrt{\frac{\omega\rho_f}{\eta}} \quad \text{and} \quad T(\xi) = \frac{\mathrm{ber}'(\xi) + i\mathrm{bei}'(\xi)}{\mathrm{ber}(\xi) + i\mathrm{bei}(\xi)}$$

The constitutive equations describing the Biot porous sediment model on which the above equations of motion are based may be written as

$$\begin{aligned}\boldsymbol{\sigma} &= \mu[\nabla\mathbf{u} + (\nabla\mathbf{u})^{\mathrm{T}}] + [(H-2\mu)e - c\zeta]\mathbf{I} \\ p &= M\zeta - Ce\end{aligned}$$

where $\boldsymbol{\sigma}$ is the total stress in the saturated sediment and p is the pore fluid pressure.

Implementation

¿From this point the development follows the lines given in the SAFARI Users Guide[4] and subsequent updates. Scalar and vector potentials are introduced so that

$$\mathbf{u} = \nabla\Phi + \operatorname{curl}\boldsymbol{\Psi} \qquad \mathbf{w} = \nabla\Phi^f + \operatorname{curl}\boldsymbol{\Psi}^f$$

In terms of these potentials, and in the absence of sources, the equations of motion become

$$\begin{aligned}
H\nabla^2\Phi - C\nabla^2\Phi^f - \rho\frac{\partial^2\Phi}{\partial t^2} - \rho_f\frac{\partial^2\Phi^f}{\partial t^2} &= 0\\
C\nabla^2\Phi - M\nabla^2\Phi^f - \rho_f\frac{\partial^2\Phi}{\partial t^2} + \frac{c_m\rho_f}{\phi}\frac{\partial^2\Phi^f}{\partial t^2} - \frac{F\eta}{\kappa}\frac{\partial\Phi^f}{\partial t} &= 0\\
\mu\nabla^2\mathbf{\Psi} - \rho\frac{\partial^2\mathbf{\Psi}}{\partial t^2} + \rho_f\frac{\partial^2\mathbf{\Psi}^f}{\partial t^2} &= \mathbf{0}\\
\rho_f\frac{\partial^2\mathbf{\Psi}}{\partial t^2} + \frac{c_m\rho_f}{\phi}\frac{\partial^2\mathbf{\Psi}^f}{\partial t^2} - \frac{F\eta}{\kappa}\frac{\partial\mathbf{\Psi}^f}{\partial t} &= \mathbf{0}
\end{aligned}$$

These equations are first subjected to Fourier transform in time and either Fourier transform (for plane strain) or Hankel transform (for axial symmetry) in the plane perpendicular to the depth coordinate z. We show details assuming plane strain with motion restricted to the xz-plane (the axial symmetry case is similar and follows the outline in the SAFARI Users Guide). In this event the vector potentials have only a single nontrivial component, $\mathbf{\Psi} = \Psi\mathbf{j}$, so the displacement components take the form

$$\begin{aligned}
u &= \Phi_{,x} - \Psi_{,z} & w &= \Phi_{,z} + \Psi_{,x}\\
u^f &= \Phi^f{}_{,x} - \Psi^f{}_{,z} & w^f &= \Phi^f{}_{,z} + \Psi^f{}_{,x}
\end{aligned}$$

Furthermore, the constitutive equations, in terms of the potentials, become

$$\begin{aligned}
\sigma_{xx} &= H\Phi_{,xx} + (H-2\mu)\Phi_{,zz} - 2\mu\Psi_{,xz} - C(\Phi^f{}_{,xx} + \Phi^f{}_{,zz})\\
\sigma_{zz} &= H\Phi_{,zz} + (H-2\mu)\Phi_{,xx} - 2\mu\Psi_{,xz} - C(\Phi^f{}_{,xx} + \Phi^f{}_{,zz})\\
\sigma_{xz} &= \mu[2\Phi_{,xz} + \Psi_{,xx} - \Psi_{,zz}]\\
p &= M[\Phi^f{}_{,xx} + \Phi^f{}_{,zz}] - C[\Phi_{,xx} + \Phi_{,zz}]
\end{aligned}$$

The solution of the transformed equations take the form

$$\begin{aligned}
\varphi &= A^- e^{-\alpha z} + A^+ e^{\alpha z} + B^- e^{-\beta z} + B^+ e^{\beta z}\\
\varphi^f &= \delta_1[A^- e^{-\alpha z} + A^+ e^{\alpha z}] + \delta_2[B^- e^{-\beta z} + B^+ e^{\beta z}]\\
\psi &= i[C^- e^{-\gamma z} + C^+ e^{\gamma z}]\\
\psi^f &= \Gamma\psi
\end{aligned}$$

where φ and ψ are the transformed potentials and $A^\pm$, $B^\pm$, and $C^\pm$ are functions of angular frequency ω and wave number s. Also

$$\Gamma = \frac{\rho_f}{\frac{c\rho_f}{\phi} - i\frac{F\eta}{\kappa\omega}}$$

$$\delta_1 = \frac{H(\alpha^2 - s^2) + \rho\omega^2}{C(\alpha^2 - s^2) + \rho_f\omega^2} \qquad \delta_2 = \frac{H(\beta^2 - s^2) + \rho\omega^2}{C(\beta^2 - s^2) + \rho_f\omega^2}$$

and

$$\alpha^2 = s^2 - {h_f}^2 \qquad \beta^2 = s^2 - {h_s}^2 \qquad \gamma^2 = s^2 - k^2$$

where h_f, h_s, and k are respectively the complex wavenumbers associated with fast, slow and shear waves in the Biot medium at angular frequency ω. For the shear wave we have

$$k^2 = \frac{\rho - \Gamma\rho_f}{\mu}\omega^2$$

while the wave numbers associated with the fast and slow waves are given by

$$h^2 = b \pm \sqrt{b^2 - g}$$

where

$$\begin{aligned} b &= \frac{M\rho + H[\frac{c_m\rho_f}{\phi} - i\frac{F\eta}{\kappa\omega}] - 2C\rho_f}{2(HM - C^2)}\omega^2 \\ g &= \frac{\rho[\frac{c_m\rho_f}{\phi} - i\frac{F\eta}{\kappa\omega}] - {\rho_f}^2}{HM - C^2}\omega^4 \end{aligned}$$

and the two compression wave numbers are ordered so that $\Re(1/h_f) > \Re(1/h_s)$.

In terms of the six degrees of freedom $A^\pm$, $B^\pm$, and $C^\pm$ for a porous sediment layer, the transformed displacement and stress components are

$$\begin{aligned}
\hat{u} &= is[A^- e^{-\alpha z} + A^+ e^{\alpha z} + B^- e^{-\beta z} + B^+ e^{\beta z}] + i\gamma[C^- e^{-\gamma z} - C^+ e^{\gamma z}] \\
\hat{w} &= \alpha[-A^- e^{-\alpha z} + A^+ e^{\alpha z}] + \beta[-B^- e^{-\beta z} + B^+ e^{\beta z}] + s[C^- e^{-\gamma z} + C^+ e^{\gamma z}] \\
\hat{w}^f &= \alpha\delta_1[-A^- e^{-\alpha z} + A^+ e^{\alpha z}] + \beta\delta_2[-B^- e^{-\beta z} + B^+ e^{\beta z}] + s\Gamma[C^- e^{-\gamma z} + C^+ e^{\gamma z}] \\
\hat{\sigma}_{xx} &= [(C\delta_1 - H)(s^2 - \alpha^2) - 2\mu\alpha^2][A^- e^{-\alpha z} + A^+ e^{\alpha z}] \\
&\quad + [(C\delta_2 - H)(s^2 - \beta^2) - 2\mu\beta^2][B^- e^{-\beta z} + B^+ e^{\beta z}] + 2\mu\gamma s[C^- e^{-\gamma z} - C^+ e^{\gamma z}] \\
\hat{\sigma}_{zz} &= [(C\delta_1 - H)(s^2 - \alpha^2) + 2\mu s^2][A^- e^{-\alpha z} + A^+ e^{\alpha z}] \\
&\quad + [(C\delta_2 - H)(s^2 - \beta^2) + 2\mu s^2][B^- e^{-\beta z} + B^+ e^{\beta z}] - 2\mu\gamma s[C^- e^{-\gamma z} - C^+ e^{\gamma z}] \\
\hat{\sigma}_{xz} &= i\mu\Big[2\alpha s[-A^- e^{-\alpha z} - A^+ e^{\alpha z}] + 2\beta s[B^- e^{-\beta z} + B^+ e^{\beta z}] \\
&\quad - (s^2 + \gamma^2)[C^- e^{-\gamma z} + C^+ e^{\gamma z}]\Big] \\
\hat{p} &= [(C - M\delta_1)(s^2 - \alpha^2)][A^- e^{-\alpha z} + A^+ e^{\alpha z}] \\
&\quad + [(C - M\delta_2)(s^2 - \beta^2)][B^- e^{-\beta z} + B^+ e^{\beta z}]
\end{aligned}$$

Boundary conditions to be satisfied at each interface involve continuity of pore fluid normal displacement and pressure, and continuity of displacement and traction components for the frame. To complete table 1 of the SAFARI Users guide we add the following table entries where the symbol $\sim$ means the parameter is not involved, 0 means it should be set to zero, and

= means continuity is enforced at the interface. In the following table the first four columns correspond to the same entries in the Users Guide table, while the last column corresponds to the negative of the traction component σ_{zz} in adjacent fluid layers.

Type	Field parameter					
	$w - w^f$	u	σ_{zz}	σ_{xz}	w^f	p
Biot/vacuum	$\sim$	$\sim$	0	0	$\sim$	0
Biot/fluid	=	$\sim$	=	0	$\sim$	=
Biot/solid	=	=	=	=	0	$\sim$
Biot/Biot	=	=	=	=	=	=