Wave Optics Propagator Package Description and User Guide

CONTRACT EUM/CO/10/460000812/CJA Order 4500005632

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Moscow and Copenhagen 2012

DOCUMENT SIGNATURE TABLE

	Name	Date	Signature
Prepared by:	Michael. E. Gorbunov	13.06.2011	
	Hans-Henrik Benzon	November 2011	
Approved by:	Hans-Henrik Benzon	March 2012	

DOCUMENT CHANGE RECORD

Issue / Revision	Date	Description
Version 1.0	19.05.2011	First draft – contains description of algorithms and user guide prepared by Michael E. Gorbunov at IAP during April and May 2011.
Version 1.1	13.06.2011	Detailed description of FIO algorithm, turbulence and ionospheric modeling is added.
Version 2.0	November 2011	A new Parabolic Equation (PE) based solver has been added to the package. A model for surface reflections can be called from the PE solver. A new option makes it possible to change the refractivity profiles along the screens.
Version 2.2.2	March 2012	New installation guide lines and updates

DOCUMENT DISTRIBUTION LIST

Issue / Revision	Date	Distributed to
Version 1.0	19.05.2011	DMI
Version 2.0	November 2011	EUMETSAT
Version 2.2.2	March 2012	EUMETSAT

Contents

List of Tables

List of Figures

1. Introduction

This report is prepared according to CONTRACT EUM/CO/10/460000812/CJA defining project "Optimization of tracking strategy for radio occultation".

This report describes the internal structure and user interface of the Wave Optics Propagator (further referred to as WOP).

1.1 Scope

The scope of this report is to document the WOP features listed below:

1. *The WOP package installation procedure.*
2. *The WOP user interface including command line options.*
3. *The WOP implementation of wave propagation algorithms including multiple phase screens and the asymptotic solution for the wave equation obtained in the framework of theory of Fourier Integral Operators (FIO).*
4. *Options for modeling satellite orbits including simple analytical models and the use of orbit data from radio occultation (RO) files from different missions.*
5. *Options for modeling atmosphere including analytical phantoms and interpolated gridded fields from European Centre for Medium-Range Weather Forecasts (ECMWF) and National Centers for Environmental Prediction (NCEP).*
6. *Options for modeling ionosphere, which currently only comprise International Reference Ionosphere (IRI) or the absence of the ionosphere.*
7. *Mathematical and physical description of algorithms implemented in WOP.*

1.2 Documents and References

References are found in chapter 8.

1.3 List of Acronyms

Acronyms used throughout this document are listed in Table 1.

Table 1. List of acronyms

Acronym	Meaning
ACE	Atmospheric Chemistry Experiment
ASCII	American Standard Code for Information Interchange
AtmPhs	Atmospheric excess phases and auxiliary data
BA	Bending angle
BP	Back Propagation
CHAMP	Challenging Minisatellite Payload

Acronym	Meaning
CL	Closed Loop
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
CT	Canonical Transform (of 1st type)
CT2	Canonical Transform of 2nd type
DMI	Danish Meteorological Institute
ECHAM	European Centre/Hamburg Model
ECEF	Earth-Centered Earth-Fixed Frame
ECI	Earth-Centered Inertial Coordinate Frame
ECMWF	European Centre for Medium-Range Weather Forecasts
FIO	Fourier Integral Operator
FSI	Full-Spectrum Inversion
GDS	Grid Description Section (of GRIB files)
GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GO	Geometrical Optics
GPS	Global Positioning System
GPS/MET	GPS/Meteorology
GRAS	The Global Navigation Satellite Systems Radio Occultation Receiver for Atmospheric Sounding
GRIB	Gridded Binary Format
IGW	Internal Gravity Waves
IRI	International Reference Ionosphere
JGM	Joint Geopotential Model
LEO	Low-Earth Orbiter
LZT	Linearized Zverev Transform
MetOp	Meteorological Operational Satellite
MSIS	Mass Spectrometer Incoherent Scatter Model
NB	Navigation Bits
NCEP	National Centers for Environmental Prediction
NCO	Numerically Controlled Oscillator
NetCDF	Network Common Data Form
NWP	Numerical Weather Prediction

Acronym	Meaning
O-B/B	Observation – Background over Background (relative deviation of observations from background)
OCC	Radio Occultation processing package developed by M. Gorbunov
OLC	Optimal Linear Combination
OSU	Ohio State University
PM	Phase Matching
QC	Quality Control
RAM	Random Access Memory
RH	Radio Holography
RINEX	Receiver Independent Exchange Format
RO	Radio Occultation
RS	Raw Sampling
SNR	Signal-to-Noise Ratio
UCAR	University Corporation for Atmospheric Research
UNIX	UNIplexed Information and Computing System
WGS84	World Geodetic System 1984
WO	Wave Optics
WOP	Wave Optics Propagator

2.   General Characterization of WOP

Wave Optics Propagator (WOP) is a package developed for modeling wave propagation in the Earth's atmosphere in order to generate realistic artificial radio occultation (RO) data. The package is delivered in the form of Fortran/C source code and can be installed under UNIX-like operating system. See reference 53. WOP is a command line utility that is invoked with options described in this document.

For modeling RO data WOP must be provided with orbit data for GPS satellite and Low-Earth Orbiter (LEO). The orbit data can be extracted from an existing RO file of one of the existing missions including GPS/MET, CHAMP, COSMIC, of GRAS. Another option is to provide an ASCII file with parameters describing the orbits. The format of orbit-description files is documented below. The model of the atmosphere includes the neutral and optional ionospheric components. The neutral atmosphere can be taken in the form of interpolated 3D gridded fields of atmospheric parameters or in the form of analytical phantoms. WOP can read and interpolate gridded fields atmospheric fields in GRIB format from European Centre for Medium-Range Weather Forecasts (ECMWF) or National Centers for Environmental Prediction (NCEP). Above the upper border of the gridded fields, an extrapolation is used. The extrapolation is based on the MSIS climatology. The analytical phantoms are provided in the form of ASCII files containing the identifier of the phantom and its parameters. The model of the ionosphere is based on the International Reference Ionosphere (IRI) from 2007.

A new solver has been added to the package. This solver is based on a solution to the wave equation. This equation is approximated by the *parabolic equation* which is solved using the split-step sine transformation. The earth surface is modelled with the use of an impedance model. The value of the earth impedance is given as a function of the range along the earth surface. This impedance concept gives an accurate lower boundary condition in the determination of the electromagnetic field. Another new feature added to the wave propagation simulation is the possibility of using both 1D and 2D refractivity fields. The 2D refractivity fields make it possible to simulate the effect of both vertical and horizontal atmospheric gradients.

WOP performs modeling of RO data in two modes: Wave Optics (WO) and Geometric Optics (GO). The output data of WO modeling are provided in two optional formats. The first one is the LEO-LEO format developed for LEO-LEO RO observations in X/K band (9–30 GHz). The LEO-LEO format is an extended version of RINEX format used for the distribution of CHAMP data. The difference is that the LEO-LEO format supports a variable number of frequency channels, where the frequencies are also specified. The second option is the NetCDF format identical to the AtmPhs format used for the distribution of COSMIC data. The AtmPhs format can only be used for simulated data at the conventional GPS frequencies. The output of GO modeling contains the bending angle profile. Additional optional files contain local profiles of the atmospheric variables such as temperature, humidity, specific absorption, refractivity and other one documented below.

3. Installation of WOP

3.1 Installation in UNIX Environment

The compilation of the package is performed in the following sequence:
First install the two external libraries fftw and netcdf. See the homepages www.fttw.org and http://www.unidata.ucar.edu/software/netcdf. Version 3.2.2 of the fftw library and version 4.0.1 of the netcdf library will work with the wave propagation software using the GNU compilers. There is an issue with version 4.0.1 of the netcdf library and the Intel version 11 Fortran compiler. Version 3.6.2 of the netcdf library has been tested to work with the Intel Fortran compiler version 11 and the wave propagation software package. The external libraries and include files must be installed in $HOME/local/lib and $HOME/local/include or in /usr/local/lib and /usr/local/include. The wave progation software can then be installed. The installation should be performed from $HOME/ Eumetsat-WOPLinux. This is the directory generated after 'untarring' the software package.

An example of running the `configure` script:

```
./configure
```

This will configure the parameters for compiling the package as follows. The GNU Fortran compiler `gfortran` and GNU C compiler `gcc` will be used to compile the program.

The following the configure script:

```
./configure FC=ifort
```

This will configure the parameters for compiling the package as follows. The Intel Fortran compiler ifort and GNU C compiler gcc will be used to compile the program. It is also possible to set compiler flags. If the netcdf library has been installed in $HOME/SpecialDir then the following script:

```
./configure FC=ifort FCFLAGS="-I../../SpecialDir/INCLUDE -
L../../SpecialDir/lib"
```

will configure the compilation process using the Intel Fortran compiler. The option FCFLAGS can also be used to give special code generation switches to the compilers.

The following command

```
make all
```

compiles the package and creates the executable in the subdirectory /Wave. When the Intel Fortran compiler is used it can be necessary to increase the memory stack reserve, in order for the program to run properly, this can be done with the following command

ulimit –s unlimited

To clean all the object libraries and executables invoke make utility as follows:

```
make clean
```

To install the program on linux systems invoke make utility as follows:

```
sudo make install
```

This assumes that user is administrator on the mashine. The software should always be run from the Wave directory. This is due to assumptions made on where the files are placed. To uninstall the program on linux systems invoke make utility as follows:

```
sudo make uninstall
```

Wave propagation calculations are time consuming. This is especially true in the case of wave propagation with a large number of modulation frequencies. An openMP version of another version of the wave propagator has therefore been constructed, working both in the Windows and Linux environment. In this multithreaded version the program splits up into a number of threads, each of these threads perform in parallel one modulation frequency wave propagation calculation. After the calculations has ended the threads are closed and the main thread writes the results to a file. The openMP version will significantly decrease the calculation time on multi core CPUs and on systems with many CPUs. This is one of a number of features that could also be included in the EUMETSAT wop software. For more information on these topics please contact DMI.

4. WOP User Interface

4.1 Running WOP

In the UNIX environment, WOP is started by the command:

```
./Wave/Wave.x <options>
```

or

```
<path>/Wave/Wave.x <options>
```

Here `<path>` stays for the full path to the package installation directory. An overview of the options is given in Subsection 4.2; their complete description can be found in Section 5.

In the Windows environment, WOP can be started from within Visual Studio by setting `Wave` as a startup project and choosing `Start with Debugging` or `Start without Debugging` from the menu. In this case, in the project properties the working directory can be specified. For more details, consult the Visual Studio User Guide.

Alternatively, WOP can be started from the Windows command line by the command:

```
.\Wave\<config>\Wave.exe <options>
```

or

```
<path>\Wave\<config>\Wave\Wave.x <options>
```

Here `<config>` refers to the configuration used for the package compilation, which can be `Debug` or `Release`.

One more possibility is to run WOP compiled under Visual Studio under Cygwin environment (http://www.cygwin.com). In this case, WOP is started by the command:

```
./Wave/<config>/Wave.exe <options>
```

or

```
<path>/Wave/<config>/Wave.exe <options>
```

4.2 WOP Options

WOP options and their brief explanations are listed in Table 2 below. A detailed description is given in Section 5. Square brackets `[]` are a meta-notation indicating optional elements that can be omitted. Curled brackets are a meta-notation denoting alternative elements. For example `` `{a|b}' `` refers to a value that can be a or b. Dots `` `...' `` are a meta-notation that refers to a repetition of the previous value. For example, `` `<file>[,...]' `` refers to a sequence of file-names delimited by commas.

12

Table 2. WOP options

Option	Explanation		
-atm=<*type*>,[<*hg*>],<*file*>[,...]	Atmospheric model specification:		
	<*type*>:		
		echam	ECHAM grib file
		ncep	NCEP grib file
		phantom	analytical model
	<*hg*> - horizontal gradients:		
		1d	no horizontal gradients
		3d	full horizontal gradients (default)
	<*file*>[,...] - pathname(s)		
-turb=<*file*>	Turbulence parameter file		
-earth=<*shape*>[,<*path*>]	<*shape*> specifies Earth shape:		
		sphere	spherical
		ellips	reference elliposid WGS 1984
		geoid	geoid
	<*path*> is optional path to coefficient file		
-iono=<*type*>,<*hg*>,<*hi*>[,<*path*>]	Ionospheric model specification:		
	<*type*>:		
		iri	International Reference Ionosphere
		none	no ionosphere (default)
	<*hg*> - horizontal gradients:		
		1d	no horizontal gradients
		3d	full horizontal gradients (default)
	<*hi*>- ionospheric height [km] (default = 150 km)		
	<*path*> - path to coefficient files (default auto)		
-gps=<*file*>	RO data file patname		
-orb=<*file*>	Orbit data file pathname		
-msis=<*path*>	Path to MSIS coefficient files		
-out=<*outname*>	Template for output names (default = Name of RO file or Name of orbit data file)		

Option	Explanation	
-chan=<*chan*>	Channels processing mode:	
	peo	The PE solver is used The different options for the solver is controlled using the RunOptionsE.wop setup file
	par	Parallel, one frequency calculation
	seq	sequential, many frequency calculation
-freq=<*freqs*>	Frequency channels specification:	
	gps	GPS frequencies, see table 14
	gal	GALILEO frequencies, see table 14
	glo	GLONASS frequencies, see table 14
	acestd	ACE+ standard frequencies
	aceopt	ACE+ optional frequencies
	acemax	ACE+ maximum frequencies
	<*f1*>[,<*f2*> ...]	user-specified frequencies [GHz]
-afreq=<*freqs*>	Frequency channels for absorption (similar to option –freq)	
-hmax=<*hmax*>	Maximum height for WO simulation [km] (default = 100 km)	
-hmin=<*hmin*>	Minimum height for WO simulation [km] (default = -999 km)	
-hgo=<*hgo*>	Maximum height for GO simulation [km] (default = 120 km)	
-dyn=<*dyn*>	Vertical resolution of refractivity field [km] (default = 0.025 km)	
-dx=<*dx*>	Step between phase screens [km] (default = 30 km)	
-xls=<*xls*>	Additional phase screen position [km] (default = 0 km)	
-ct={y|n}	Perform CT in last screen (default = yes)	
-fz=<*fz*>	Fresnel zone size for diffractive integral [π rad] (default = 10π rad)	
-sr=<*sr*>	Sampling rate for simulated data [Hz] (default = 50 Hz)	

Option	Explanation	
-ts={y|n}	Time scaling (default = no). If true the times found in the occultation files are kept	
-ecef={y|n}	All coordinates in ECEF (default = no, the coordinates are in J2000 frame)	
-wo={y|n}	Perform WO simulation (default = yes)	
-go={y|n}	Perform GO simulation (default = yes)	
-rh={y|n}	Output of ray heights (default = yes)	
-ab={y|n}	Modeling of absorption (default = no)	
-as={y|n}	Use asymptotic solution for WO simulation (default = no)	
-fio={y|n}	Use FIO solution for propagation from last screen to LEO orbit (default = yes)	
-sd=<*sd*>	Spatial dimension; can be 2 or 3 (default = 2)	
-ngo=<*ngo*>	Number of GO rays (default = 1500)	
-fwp=<*fwp*>	Filter width for computing $\dfrac{dp_{GPS}}{dp}$ [km] (default = -1)	
-v=<*vrb*>	Verbosity level:	
	-1	silent mode
	0	version and error info
	1	progress messages
	2	static messages
	3	dynamic messages (default)
-b	Batch mode (obsolete; equivalent to -v=1)	
-o=<*exts*>[,...]	Specification of output files extensions:	
	none	no output
	all	output of all extensions
	min	minimum output data set
	script	output data set for use some simulation script (default)

15

Option	Explanation

`<ext>[-],...`	`user-defined set of`
	`extensions:`
	`<ext> turns specific`
	`extension on`
	`<ext>- turns specific`
	`extension off`

	`List of extensions:`
	`    WOP, WCA, WCE, CAU, GOP, GRP, XBP,`
	`    GOZ, GON, GOT, MOT, MOQ, MON, MOA,`
	`    MTR, MTD, NC`

4.3 WOP Input Files

1. Atmospheric model files as required by option `-atm`. If the `echam` or `ncep` type is specified, the files are assumed to be ECMWF/NCEP files in the GRIB format containing global atmospheric gridded fields of temperature and humidity on model levels. If `phantom` type is specified, the files are assumed to an ASCII file containing the type of the phantom and its parameters. The structure of phantom files is specified in Section 5.

2. Atmospheric turbulence parameter file if required by option `-turb`. These files are ASCII file containing the type of the turbulence model and its parameters.

3. Geoid coefficient file if the Earth's shape defined by option `-earth = geoid`. Only path to the file can be specified; its name is fixed. The path can be omitted. If this is case and the geoid shape is requested, the program tries to locate the file at some pre-specified absolute and relative paths. If the program fails to locate the file, it exits with a corresponding error code.

4. Ionospheric coefficient files if required by option `-iono`. If IRI ionospheric model is requested, the program tries to located the IRI coefficient files at the path specified or, if the path is omitted, at some pre-specified absolute and relative paths. If the program fails to locate the files, it exits with a corresponding error code.

5. Orbit data files as required by one of the alternative options `-gps` and `-orb`. It is mandatory to specify one (and only one) of these options. Option `-gps` tells to extract the orbit data from a RO data file of one of the following missions: GPS/MET, CHAMP, COSMIC, GRAS/METOP. Option `-orb` tells to use an ASCII file containing parameters defining the GPS and LEO orbits. The structure of the orbit data file is specified in Section 5.

6. MSIS coefficient files. These files are mandatory. The path where they are located can be specified by option `-msis`. If the option is omitted, the program tries to locate the files at some pre-specified absolute and relative paths. If the program fails to locate them, it exits with a corresponding error code.

4.4 WOP Output Files

Extensions of WOP output files are listed in Table 3. Detailed explanations of the files are given in Section 7.

Table 3. Extensions of WOP output files.

Extension	Explanation
<wop>	Simulated occultation data file
wca*<c>*	CT amplitude for channel <c>
wce*<c>*	CT BA for channel <c>
cau	Caustic structure [km]
gop	GO BA profile [rad, km]
grp	GO reflected BA profile [rad, km]
xbp	Back propagation plane position [km]
goz	GO BA vs perigee height [rad, km]
gon	Refractivity profile from GO BA [N-units, km]
got	Dry temperature profile from GO BA [K, km]
mot	Local profile of temperature [K, km]
moq	Local profile of humidity [g/kg, km]
mon	Local profile of refractivity [N-units]
moa*<c>*	Local profile of specific absorption for channel <c>
moa*<c1c2>*	Differential specific absorption for channels <c1>,<c2>
mtr*<c>*	Transmission for channel <c>
mtr*<c1c2>*	Differential transmission for channels <c1>,<c2>
mtd	Local dry temperature [K]
nc	Occultation data in atmPhs-NetCDF format

5. Introduction to the Parabolic Equation solver

Electromagnetic wave propagation in the atmosphere can be described by the wave equation and this equation can be approximated by the *parabolic equation (PE)* in a rectangle containing the neutral atmosphere. The *parabolic equation* in our simulator is solved using the split-step sine transformation. The earth surface is modelled with the use of an impedance. The value of the earth impedance is given as a function of the range along the earth surface. This impedance concept gives an accurate lower boundary condition in the determination of the electromagnetic field.

Simulation of wave propagation through the atmosphere is based on the solutions to the Helmholtz wave equation. In this study these solutions are computed by solving the parabolic approximation to the Helmholtz wave equation. The electromagnetic field component, ψ can in a normal Cartesian coordinate system be expressed by the following 2-D scalar wave equation

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + k^2 n^2 \psi = 0 \tag{1}$$

where k and n represent wave number and index of refraction. It is now common practice to use the reduced function u given by

$$u(x, y) = e^{-ikx} \psi(x, y) \tag{2}$$

The reduced function will be slowly varying along the x-axis for propagation angles close to the paraxial direction (the horizontal direction), which gives it convenient numerical properties. The wave equation for the reduced function is given by

$$\frac{\partial^2 u}{\partial x^2} + 2ik \frac{\partial u}{\partial x} + \frac{\partial^2 u}{\partial y^2} + k^2 (n^2 - 1)u = 0 \tag{3}$$

This equation can be formally factored in to two equations. The solutions to the first of these equations correspond to waves travelling along the positive x-direction (forward propagation) while solutions to the last equation correspond to waves travelling along the negative x-direction (backward propagation). The two differential equations are therefore called the *outgoing* and *incoming* parabolic wave equations, respectively. The wide-angle parabolic equation (WPE) for the forward travelling wave is given by

$$\frac{\partial u}{\partial x} = ik \left(\sqrt{1 + \frac{1}{k^2} \frac{\partial^2}{\partial y^2}} - 1 \right)u + ik(n-1)u \tag{4}$$

The operator can in a wide angle approximation be approximated by

$$\sqrt{\frac{1}{k^2}\frac{\partial^2}{\partial y^2}+n^2(x,y)} \approx \sqrt{\frac{1}{k^2}\frac{\partial^2}{\partial y^2}+1}+n(x,y)-1 \tag{5}$$

This operator is valid for a wide span of propagation angles. The corresponding split-step/sine transform solution for this wider angle parabolic equation (WPE) is given by

$$u(x+\Delta x,y) = e^{ik(n-1)\Delta x}S^{-1}\{e^{ik\Delta x(\sqrt{1-\frac{\pi^2 p^2}{k^2}}-1)}S\{u(x,y)\}\} \tag{6}$$

$S\{\}$ represent the sine transformation. The split-step/sine transform solution can be thought of as a field propagating through a number of phase screens. The concept of phase screens comes from the solution of the equations. The distance between the screens is Δx. The field propagates along the positive x-axis and the screens are all orthogonal to the x-axis. The expression within the inverse sine transform operator propagates the field a distance Δx, while the first exponential in the equation (Eq. 5-6) give us the impact on the field of the phase screen. The equation above is not exact, it is however a good approximation provided the variations of n remain slow on the scale of a wavelength. The primary limitations of this technique are that the backscattered field is neglected, and that accurate calculations are restricted to an angular span around a preferred direction, in this case a near-horizontal direction. However, for the current study these limitations are not considered to have any measurable impact on the results. The equations above are correct under the assumption of a wave propagating along the x-axis in a Cartesian coordinate system. The Earth will in our simulations be modelled as an impedance giving a more accurate lower boundary condition for the electromagnetic field and making it possible to simulate reflections in different types of earth surfaces. The value of the Earth impedance can be given as a function of the range along the Earth surface making it possible to simulate reflections and the effect of transitions between different mediums. The diffraction effects caused by buildings and mountains can also be simulated with this method.

5.1 Reflection model

This section describes how surface reflection can be modelled in our wave propagator that models the Earth as an impedance. This gives a more accurate lower boundary condition for the
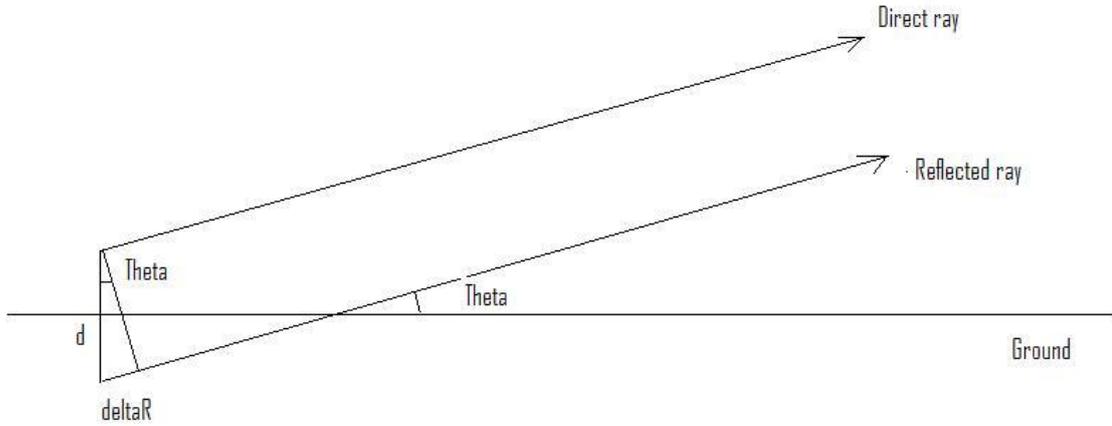
electromagnetic field.

Figure 5.1-1: Rays propagating from the source and the image source.

The transmitted electromagnetic wave from the GNSS satellites are right hand circular polarised. The following discussion on surface reflections assume linear vertical or horizontal polarisation. It is however possible to simulate circular polarisation from the linear polarisation cases but this is out of scoop for this project.

Initialisation of the propagated field is done by applying image theory on the source of the field, see the schematic drawing in Figure 5.1-1. The extra path ΔR the reflected ray needs to propagate compared to the direct ray is given by

$$\Delta R = d \sin(\Theta) \tag{7}$$

The total field is given by the equation below

$$E_{total} = E_{direct} + R E_{direct} e^{-ik\Delta R} \tag{8}$$

where ζ is the complex reflection coefficient and E_{direct} is the value of the direct field. The reflection coefficient is given by

$$\zeta(\varpi) = \frac{\sqrt{\sin(\Theta)^2 - \delta(i\varpi)}}{\sqrt{\sin(\Theta)^2 + \delta(i\varpi)}} \tag{9}$$

where Θ is the grazing angle of the field with respect to the ground and ω is the angular frequency of the wave. $\delta(i\,\omega)$ is the complex surface impedance which is a function of the wave frequency and the polarisation. An extra phase term must be added to the reflection coefficient in case of horizontal polarisation. The rules for phase shift are listed below:

vertical polarisation no phase shift
horizontal polarisation a phase shift of π

The rule for vertical polarisation is valid under the assumption that incidence angle is greater than the Brewster angle, this assumption is true for radio occultations where we in general have small grazing angles corresponding to large incidence angles.

5.2 Parameters for the Parabolic Equation solver

The Parabolic Equation (PE) solver is used as the wave propagator if the peo option for the chan switch is used. The solver can be controlled from the options found in the RunOptionsE.wop set-up file. The options that can be selected in this setup file are shown together with an explanation in the table below. An explanation of the option is also given in the setup file next to the chosen option value.

Possible option values	Swich name	Explanation
0 or 1	UseTheLowFreqYesNo	1 a set of low frequencies are used 0 the standard L1 and L2 frequencies are used. 0 is the normal setting for the option
0 or 1	UseL1L2OrAbsorptionFreq	1 the standard L1 and L2 frequencies are used. 0 two higher frequencies are used. 1 is the normal setting for the option
0 or 1	AbsorptionCalYesNo	1 absorption calculations are performed 0 no absorption calculations are performed. 0 is the normal setting for the option
0 to 90 degrees	Theta75	75% of maximum propagation angle in PE calculations, the value is in degrees. Normal values are between 3 and 6 degrees. This value is directly related to the number of calculation points on the screens.
A positive value	Dx	The distance between the screens. The unit for the distance is m
0 or 1	UseModulationCodesYesNo	1 the calculations are performed for a number of modulation frequencies around the carrier frequency. 0 no modulation frequencies are used. 0 is the normal setting for the option
A positive integer	NoOfFreqsInModulationBW	This is the number of frequencies used in the modulation band width. 5 or 8 is the normal setting for the option
A positive value	ModulationBW	This is the band width of the modu-

		lation. It is in MHz
0 or 1	SaveAFileForEachModFreqYesNo	1 a wave propagation file is saved for each modulation frequency 0 no wave propagation file is saved for each modulation frequency. 0 is the normal setting for the option
A string	'ModulationFile'	The start of the modulation file names
0 or 1	UseFioYesNo	1 use FIO from the last screen to the LEO orbit 0 use Fresnel diffraction integral from the last screen to the LEO orbit. 0 is the normal setting for the option
0 or 1	UseTurbulenceModelYesNo	1 use the turbulence model 0 no turbulence model is used. 0 is the normal setting for the option
0 or 1	UseIonosphereModelYesNo	1 use the IRI ionosphere model 0 no IRI ionosphere model model is used. 0 is the normal setting for the option
0 or 1	UseAntennaYesNo	1 use the surface reflection model 0 no surface reflection model is used. 0 is the normal setting for the option
A positive value	GrazingAngleTheta	The grazing angle used in surface reflections. 0 to 8 is the normal setting for the option depending on the size of the propagation area
Four numbers	ReSf1, ImSf1 ReSf2, ImSf2	The real and imaginary part of the surface impedance for the L1 and L2 frequencies
0 or 1	UseTwoDProfileYesNo	1 use 2D refrativity profiles, the refractivity profiles change with propagation range 0 use a 1D refrativity profile. 0 is the normal setting for the option
0 or 1	UseL1AndL2ModFreqsYesNo	1 use both L1 and L2 in the calculation 0 use only L1. 1 is the normal setting for the option
0 or 1	ReadFreqsFromFileYesNo	1 read the frequencies from file 0 do not read the frequencies from file. The modulation frequencies are calculated by the program from the values of ModulationBW and NoOfFreqsInModulationBW
A list of positive values	List of calculation frequencies	The number of frequencies should be equal to NoOfFreqsInModulationBW. The unit for the frequencies is Hz

Table 5. PE solver options selectable from the RunOptionsE.wop file.

The program will perform wave propagation for a number of modulation frequencies if the value 1 has been selected for the UseModulationCodesYesNo option. The result of the calculations can after the calculation be found in the file ALLModFreqFile.dat. If the value of the UseT-

woDProfileYesNo parameter is equal to 1 the PE solver will use 2D refractivity fields. The 2D refractivity fields are read from the EcmwfRefrProfiles.dat file. The data format for this file is simple because it assumes that the propagation range value is followed by two coloums representing the height and refractivity in SI units. The number of range values is 121 while the total range distance is 3000 km. The number of refractivity values in the profiles has been set to 10000. These are the default values.

6. Getting started

6.1 Examples and compilation verification

A number of batch files have been included in the package. Each of these files runs the wave propagator with a specific setting. For example Tnoiricase.bat performs wave propagation using the PE solver. The simulated amplitude and phases for the same wave propagation calculated in the Windows and Linux environment is shown below
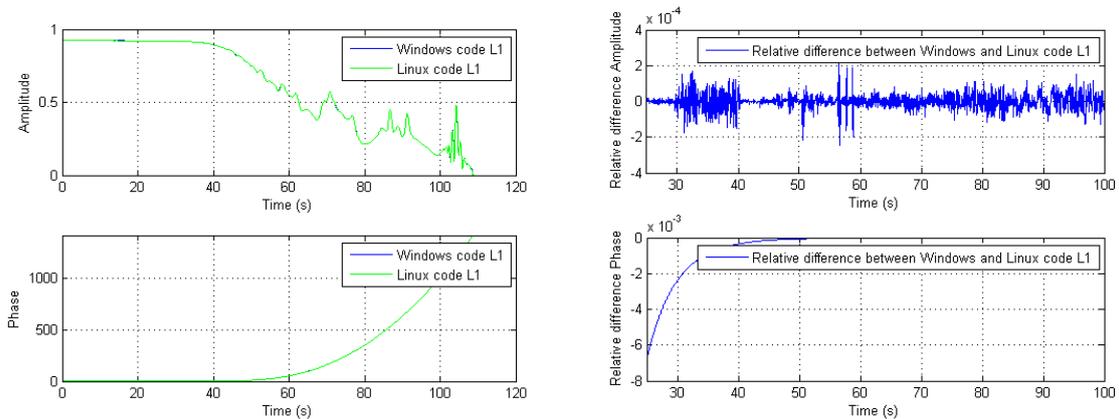

Figure 6.1-2: Left panel: The blue and green curves show the calculated amplitude and phase. These signals have been calculated using the Windows based respectively the Linux based wave propagator implementation. The corresponding relative differencies for amplitude and phase are shown in right panel.

It can be seen from the plots that the simulation results for the two implementations are practically indentical. The relative difference plots are shown in an interval where the amplitude and phases are not close to zero. This would lead to problems in the interpretation of the plots. The simulation above is the result of running the wave propagation contained in the Tnoiricase.bat file. Two example files Tnoiricase.bat and Tiricase.bat have been included in the software pakage, running these scripts will result in the generation of two output files. These output files can be compared to the results found in the same output files with the extension PriRun. A phantom refrativity profile has been used in these examples, see section 7.1.3. Phantom refractivity profiles have also been used in the Optimisation of tracking strategies for radio occultations study.

7. Detailed Description of WOP Options

All the WOP options are key parameters. This means that the options can be specified in an arbitrary order and their format determines which variables they affect. All the options have format `<key>=<value>[,<value>...]`. The options are interpreted in the order they appear in the command line. Options that appear later override ones previously specified.

7.1 Option `-atm=<type>,[<hg>],<file>[,...]`

Option `-atm` determines the model of the atmosphere to be used for the simulation. Its first sub-option `<type>` determines the type of the model and can take the following values: `echam`, `ncep`, `phantom`. The second sub-option `<hg>` determines the horizontal gradient mode and can take the following values: `3d`, `1d`. The third and optional following sub-options `<file>` determine the file(s) containing the specific information about the atmospheric model to be used.

7.1.1 Model type `echam`

If model type `echam` is specified, then the corresponding file(s) are assumed to contain model fields in the GRIB format produced by ECHAM general atmospheric circulation model and by ECWMF [1]. The file(s) must contain the set of model variables related to one time layer. The variables must include the following ones: surface geopotential ϕ_s, surface pressure P_s (or its logarithm), temperature T_i and specific humidity q_i at the full levels defined by index i. Here all the variables are implicitly assumed to also depend on the indices of the latitude-longitude grid. The program supports equidistant, Gaussian and icosahedral horizontal grids. The type of the grid is defined by the corresponding field in the grid description section (GDS) of the GRIB files Pressure at the full and half levels is defined by the surface pressure P_s and the vertical coordinates A_i and B_i:

$$P_{i+\frac{1}{2}} = A_i + B_i P_s,$$

$$P_i = \frac{1}{2}\left(P_{i-\frac{1}{2}} + P_{i+\frac{1}{2}} \right). \tag{10}$$

The levels are numbered from the highest one. The program attempts to read the vertical coordinates from the GDS. If it does not contain the vertical coordinates, two pre-defined sets of vertical coordinates for 19 levels and 31 levels are used. If the number of levels differs from these ones, the program will exit with a corresponding error message.

The geopotential at the full and half levels is determined from the discretized form of the hydrostatic equation [1].

$$\phi_{i+\frac{1}{2}} - \phi_{i-\frac{1}{2}} = -R_d T_{v,i} \ln\left(\frac{P_{i+\frac{1}{2}}}{P_{i-\frac{1}{2}}} \right),$$

$$\phi_{i_{\max}+\frac{1}{2}} = \phi_s, \tag{11}$$

where R_d is the gas constant for dry air, ϕ_s is the geopotential at the Earth's surface (orography), $T_{v,i}$ is the virtual temperature at the i-th full level defined by the following equation:

$$T_{v,i} = T_i \left(1 + \left(\frac{R_d}{R_v} - 1 \right) q_i \right),$$
(12)

where R_v is the water vapor gas constant. The full geopotential levels are defined as follows:

$$\phi_i = \phi_{i+\frac{1}{2}} + \ln \left(\frac{P_{i+\frac{1}{2}}}{P_i} \right) R_d T_{v,i}.$$
(13)

The altitudes of the full levels above the reference ellipsoid or geoid are defined by the following relation:

$$z_i = \frac{R_0 \phi_i}{g_s R_0 - \phi_i},$$
(14)

where g_s is the gravity acceleration at the Earth's surface, and R_0 is the effective radius of the Earth. Parameters g_s and R_0 are functions of the latitude depending on the setting of the Earth's shape described below in Section 7.3.

Real (non-dispersive) part of refractivity at the full levels is computed from full pressure P, water vapor pressure P_w, and temperature T using the Smith—Weintraub formula [2]:

$$\operatorname{Re} n_i \equiv 1 + \operatorname{Re} N_i = 1 + c_1 \frac{P_i}{T_i} + c_2 \frac{P_{w,i}}{T_i^2},$$
(15)

where $c_1 = 7.76 \times 10^{-5} \frac{\text{K}}{\text{hPa}}$, $c_2 = 0.37 \frac{\text{K}^2}{\text{hPa}}$, and water vapor pressure is linked to the full pressure and specific humidity by the following equation

$$P_{w,i} = \frac{P_i q_i}{a_q + b_q q_i},$$
(16)

The computation of the imaginary (dispersive) part of refractivity is affected by options $-ab$, $-freq$, and $-afreq$. If the absorption computation is requested by option $-ab$, then the imaginary part of refractivity $\operatorname{Im} N_{il}$ is computed for the frequencies f_l defined by options $-freq$ and $-afreq$ using the Liebe model [6]. Otherwise $\operatorname{Im} N_{il}$ is set to 0.

Above the upper border of the model gridded fields, we add supplementary half pressure levels such that $\lg \left(P_{i-1/2} / P_{i+1/2} \right) = 1/3$, $i = -N_M..0$, the uppermost level corresponding to the pressure of 10^{-5} hPa. Corresponding full levels are defined by equation (10). For the supplementary full levels we compute the altitudes and the refractivities using the MSIS climatology. In order to preserve the hydrostatic relation in the transfer area between the ECMWF gridded field and the MSIS refractivity profile, the latter is multiplied by the following correction coefficient:

$$\beta = \frac{P_{\frac{1}{2}}}{P_{1\frac{1}{2}}} \exp \left(-\frac{g}{R_d} \frac{\phi_1 - \phi_{1\frac{1}{2}}}{T_1} \right).$$
(17)

Finally, we arrive at the united ECMWF–MSIS gridded refractivity profile (z_i, N_i). We use the spline interpolation of $\ln \operatorname{Re} N$ and $\operatorname{Im} N$ to obtain $N(z)$ and its derivative $N'(z)$. These verti-

cally-interpolated values are related to specific nodes of the latitude-longitude grid (φ_j, λ_k). To obtain interpolated refractivity and its vertical gradient at an arbitrary point (z, φ, λ) we employ the bi-linear interpolation inside each cell of rectangular latitude longitude grids (equidistant and Gaussian) or linear interpolation inside each triangular simplex of the icosahedral grid.

Only vertical component of the refractivity gradient is evaluated, the horizontal component is set to 0. This approximation was found to give satisfactory results.

7.1.2   Model type `ncep`

If model type `ncep` is specified, then the corresponding file(s) are assumed to contain model fields in the GRIB format produced by NCEP. These files have the following basic variables: surface geopotential ϕ_s, geopotential ϕ_i, temperature T_i, and relative humidity Q_i at the isobaric levels P_i. The isobaric levels are the same for all the nodes of the latitude-longitude grid.

The water vapor pressure is found by using the following relation:

$$P_{w,i} = 0.0611\, Q_i \exp\left(\frac{17.27\left(T_i - 273.16\right)}{T_i - 35.86}\right), \tag{18}$$

where T has the units of K, and P_w has the units of hPa. The real part of refractivity is found by using equation (15), and the altitudes of the isobaric levels are defined by equation (14). The imaginary part of the refractivity in a way similar to that described above.

The levels are numbered from lowest. Above the uppermost isobaric level P_K we add supplementary half pressure levels such that $\lg\left(P_{i+1}/P_i\right) = 1/3$, $i = K..K + N_M$. For the supplementary isobaric levels we compute the altitudes and the refractivities using the MSIS climatology. In order to preserve the hydrostatic relation in the transfer area between the NCEP gridded field and the MSIS refractivity profile, we proceed as follows. For the united NCEP–MSIS refractivity profile we integrate the hydrostatic equation and find the corresponding temperature profile T_i'. Then we find the height level correction as follows:

$$\Delta z = \frac{T_K - T_K'}{g\left(z, \varphi\right)} R_d N_K \frac{\ln\left(\dfrac{N_{K+1}}{N_K}\right)}{N_{K+1} - N_K}, \tag{19}$$

where $g\left(z, \varphi\right)$ is the gravity acceleration for altitude z and latitude φ:

$$g\left(z, \varphi\right) = g_s\left(\varphi\right)\left(\frac{R_0\left(\varphi\right)}{R_0\left(\varphi\right) + z}\right)^2. \tag{20}$$

The heights of the MSIS levels are now defined as $z_i + \Delta z$, $i = K+1..K + N_M$. The interpolation of the resulting gridded field of refractivity follows the same guidelines as for ECMWF files.

7.1.3   Model type `phantom`

If model type `phantom` is specified, then the corresponding file is assumed to contain a phantom that can be defined a simple analytical formula or by a single gridded vertical profile. The file is an ASCII file in the following format.

The first line contains the number of the phantom. This line is followed by a NAMELIST block containing the phantom parameters. The NAMELIST block is followed by lines containing the

gridded if this is implied by the phantom number. Each line of the gridded profile represents data related to a single height level. The detailed format specifications can be found below.

Phantom #1

For this phantom, the real refractivity is defined by the following analytical formula:

$$\operatorname{Re} N_{ph}(z, \varphi) = N_0 \exp\left(-\frac{z}{H_0}\right) + N_0^\beta \exp\left(-\frac{\beta z}{H_0}\right) \times$$
$$\times \alpha \cos\left(2\pi \frac{z - H_p}{h}\right) \exp\left[-\left(\frac{z - H_p}{L}\right)^2\right]\left(1 + \gamma \frac{2}{\pi} \arctan\left(\frac{\pi R_e \varphi}{\Delta x}\right)\right), \tag{21}$$

where z is the altitude, φ is the longitude, and R_e is the Earth's curvature radius. The parameters defining the phantom are summarized in Table 4.

Imaginary part of refractivity will only differ from 0 if its computation is requested by option -ab. In this case it is computed by using the following formula:

$$\operatorname{Im} N_{ph}(z, \varphi) = \kappa \operatorname{Re} N(z, \varphi) \tag{22}$$

The phantom has the maximum height z_{max}, above which only MSIS refractivity is used and below which there is a smooth transfer to the MSIS refractivity of the real part of refractivity:

$$\operatorname{Re} N(z, \varphi) = \alpha(z, z_{max}, \Delta z) N_{MSIS}(z) + (1 - \alpha(z, z_{max}, \Delta z)) \operatorname{Re} N_{ph}(z, \varphi), \tag{23}$$

where the transition coefficient is defined as follows:

$$\alpha(z, z_{max}, \Delta z) = \begin{cases} \exp\left(-\left(\frac{z - z_{max}}{\Delta z}\right)^2\right), & z < z_{max} \\ 1, & z \geq z_{max} \end{cases} \tag{24}$$

For the real part of refractivity, $z_{max} = 15$ km and $\Delta z = 0.5$ km.

For the imaginary part we use the following formula:

$$\operatorname{Im} N(z, \varphi) = (1 - \alpha(z, z_{max}, \Delta z)) \operatorname{Im} N_{ph}(z, \varphi), \tag{25}$$

where $z_{max} = 15$ km and $\Delta z = 0.5$ km. The formulas for the transfer from the phantom to MSIS relate also to all the other phantom.

Table 4. Phantom #1 parameters

Phantom parameter	NAMELIST variable	Explanation
z_{max}	Zmax_01	Maximum height [km]
κ	K_01	Coefficient for imaginary part
N_0	N0_01	Refractive index amplitude [absolute]
H_0	H0_01	Exponential height of atmosphere [km]
β	beta_01	$\beta = 0$ – absolute perturbation $\beta = 1$ – relative perturbation
α	alpha_01	Perturbation amplitude

Phantom parameter	NAMELIST variable	Explanation
H_p	HP_01	Perturbation height [km]
h	h_01	Perturbation internal scale [km]
L	L_01	Perturbation external scale [km]
γ	gamma_01	Magnitude of horizontally inhomogeneous perturbation
Δx	DX_01	Scale of horizontal inhomogeneity [km]

An example of a phantom #1 file is given below:

```
1
&MODEL_01
N0_01 = 340e-6,
H0_01 = 7.5,
beta_01 = 1
alpha_01 = 0.001,
h_01  = 0.05,
HP_01 = 0.0
L_01  = 3.0
K_01  = 0.0
gamma_01 = 0.1
DX_01 = 300.0
/
```

Phantom #2

For this phantom, the refractivity profile is computed from the analytical profiles of temperature and specific humidity:

$$T(z) = T_0 + \Delta T \cos\left(\frac{2\pi z}{\Delta H_T}\right),$$

$$q(z) = q_0^V \exp\left(-\frac{z}{\Delta H_q^V}\right) + q_0^L \exp\left(-\left(\frac{z - H_0^L}{\Delta H_q^L}\right)^2\right). \tag{26}$$

The real part of refractivity is computed by using the Smith–Weintraub formula. The imaginary part of refractivity is computed by using the Liebe model if requested by option -ab for frequencies defined by option -afreq. The parameters of this phantom are summarized in Table 5.

Table 5. Phantom #2 parameters

Phantom parameter	NAMELIST variable	Explanation
z_{max}	Zmax_02	Maximum height [km]
T_0	T0_02	Mean temperature [K]

Phantom parameter	NAMELIST variable	Explanation
ΔT	`DT_02`	Temperature perturbation [K]
ΔH_T	`DHT_02`	Temperature perturbation scale [km]
q_0^V	`QV0_02`	Magnitude of exponential part of humidity profile [kg/kg]
ΔH_q^V	`HQV_02`	Vertical scale of exponential part of humidity profile [km]
q_0^L	`QL0_02`	Magnitude of humidity layer [kg]
H_0^L	`HQL_02`	Altitude of humidity layer [km]
ΔH_q^L	`DHQL_02`	Humidity layer thickness [km]

An example of a phantom #2 file is given below:

```
2
&MODEL_02
Zmax_02 = 30.0
T0_02 = 250.0
DT_02 = 20.0
DHT_02 = 30.0
QV0_02 = 0.015
HQV_02 = 3.0
QL0_02 = 0.010
HQL_02 = 3.0
DHQL_02 = 1.0
/
```

Phantom #3

This phantom represents an exponential atmosphere with an atmospheric front superimposed:

$$\mathrm{Re}\, N_{ph}(z,\varphi) = N_0 \exp\left(-\frac{z}{H_0}\right)\left(1 + \mu \sin\left\{\frac{\pi}{2}\min\left[1,\quad \max\left(-1,\quad \left(\frac{z}{\varepsilon} - R_e\varphi\right)\frac{1}{d}\right)\right]\right\}\right). \quad (27)$$

The computation of the imaginary part of refractivity (if requested by option `-ab`) is based on the computation of the temperature and pressure under the assumption of the dry atmosphere. The parameters of this phantom are summarized in Table 6.

Table 6. Phantom #3 parameters

Phantom parameter	NAMELIST variable	Explanation
z_{max}	`Zmax_03`	Maximum height [km]
N_0	`N0_03`	Unperturbed field magnitude
H_0	`H0_03`	Homogeneous atmosphere height

Phantom parameter	NAMELIST variable	Explanation
μ	mu_03	Relative magnitude of perturbation
ε	eps_03	Front inclination angle [rad]
d	dd_03	Front length [km]

An example of a phantom #3 file is given below:

```
3
&MODEL_03
Zmax_03 = 30.0
N0_03 = 300e-6,
H0_03 = 7.5,
mu_03 = 0.1,
eps_03 = 0.03,
dd_03 = 50.0
/
```

Phantom #101

This phantom uses a gridded profile of refractivity provided by the user. The profile is included into the phantom file and follows the NAMELIST format. The parameters of this phantom are summarized in Table 7.

Table 7. Phantom #101 parameters

NAMELIST variable	Explanation
NC_101	Number of columns
CZ_101	Column number of Z data
CN_101	Column number of N data
FZ_101	Conversion factor Z $\rightarrow$ [km]
FN_101	Conversion factor N $\rightarrow$ [abs]

The gridded profile is extracted from multicolumn data. The total number of columns and column number for height z and refractivity N are NAMELIST variables. The NAMELIST also contains factors conversion of height z to [km] and refractivity N to absolute units. If z in the file is given in meters, then the corresponding conversion factor equals 0.001. If N in the file is given in N-units, then the corresponding conversion factor equals 10^{-6}.

An example of Phantom #101 file is given below:

```
101
&GRIDDED_101
NC_101 = 2
CZ_101 = 1
CN_101 = 2
FZ_101 = 1e-3
FN_101 = 1e-6
```

```
/
 1.9000000e+002 3.6411834e+002
 2.1100000e+002 3.6301218e+002
 2.3000000e+002 3.6217394e+002
…
 1.1857000e+004 7.5814274e+001
 1.1875000e+004 7.5701902e+001
 1.1890000e+004 7.5521446e+001
```

The computation of the imaginary of refractivity follows the same guidelines as for phantom #3.

Phantom #102

This phantom uses gridded profiles of pressure, temperature, and relative humidity as functions of geopotential height. The profiles are included into the phantom file and follow the NAMELIST. The parameters of this phantom are summarized in Table 8.

Table 8. Phantom #102 parameters

NAMELIST variable	Explanation
NC_102	Number of columns
CGH_102	Column number of geopotential height data
CP_102	Column number of pressure data
CTC_102	Column of temperature data
CQR_102	Column of QR data
TC_102	T – use degree Celcius F – use degree Kelvin
FGH_102	Conversion factor GH $\rightarrow$ [gpkm]
FP_102	Conversion factor P $\rightarrow$ [hPa]
GDLat_102	Geodetic latitude [deg]

The gridded profiles are extracted from multicolumn data. The total number of columns and column number for geopotential height h, pressure P, temperature T, and relative humidity Q are NAMELIST variables. The NAMELIST contains a logical variable TC_102 that defines whether temperature T is measured in degree Celcuis or in Kelvin. The NAMELIST also contains factors conversion of geopotential height h to [gpkm] and pressure P to [hPa].

An example of phantom #102 file is given below.
```
102
&GRIDDED_102
 NC_102 = 6,    ! Number of columns
 CGH_102 = 1,   ! Column number of GH data
 CP_102 = 3,    ! Column number of P data
 CTC_102 = 4,   ! Column of TC data
 CQR_102 = 5,   ! Column of QR data
 TC_102 = F,    ! Use degree Celius
```

```
 FGH_102 = 1.0,   ! Conversion factor GH -> [gpkm]
 FP_102 = 1.0,    ! Conversion factor P -> [mb]
 GDLat_102 = 10   ! Geodetic latitude [deg]
/
  0.052  0.052 1000.000 297.400 14.000 278.807
  0.269  0.269  975.000 296.100 14.000 272.200
...
 26.296 26.441  20.000 226.200  0.000   6.861
 30.984 31.178  10.000 233.900  0.000   3.318
```

7.1.4   Horizontal gradients mode `1d`

If horizontal gradients mode `1d` is specified, then the model of the atmosphere will be spherically symmetrical. In every call of the routine for the interpolation of the refractivity the latitude and longitude will be substituted for by fixed values. The fixed latitude and longitude are determined as by the occultation point. The occultation point is defined as the perigee of the straight line between the GPS and LEO satellites nearest to the Earth's surface.

7.1.5   Horizontal gradients mode `3d`

For this horizontal gradients mode, a full 3D atmospheric model is used.

7.2   Option `-turb=<file>`

This option defines the turbulence model. For the simulation, one realization of turbulent perturbation of the refractive index field is generated. During a simulation the perturbation is added to the refractivity values computed for each model of the regular atmosphere defined by option `-atm`. The screen-to-screen distance defined by option `-dx` (Section 7.16) must comply with the characteristic internal scale of the requested turbulence.

The turbulence is determined by its energy spectrum. Currently 4 different spectrum models are implemented as described in the following sections. The file specified in the option is an ASCII file. In the first line it contains the model number. The following lines contain NAMELIST structure with the model parameter. If this is required by the specific model the NAMELIST may be followed by lines containing the profile of the relative perturbation magnitude.

Each model is formulated in the polar coordinates in the vertical occultation plane (z, θ). The spectrum density $F(\omega_z, \omega_\theta)$ is defined as a function of spatial frequencies ω_z and ω_θ. The spectrum is normalized in such a way that the corresponding random field $f(z, \theta)$ has a unit covariance $\langle f^2 \rangle$, which is achieved by defining for each spectrum a corresponding normalizing constant A'. The refractive index perturbation is then defined as $A(z) f(z, \theta)$, where $A(z)$ is the perturbation magnitude as a function of height.

For each model, a random sequence identifier is defined. This allows for multiply generating the same random realization by specifying the same identifier. If the identifier equals zero, then a default initialization of the random number generation is performed and the realization will randomly differ from run to run.

Turbulence model #1

The spectrum of this model has a Gaussian shape and a constant anisotropy and it is defined as follows:

$$F\left(\omega_z, \omega_\theta\right) = A' \exp\left[-\frac{1}{2}\Delta z^2\left(\omega_z^2 + \frac{\kappa^2}{R_e^2}\omega_\theta^2\right)\right]. \tag{28}$$

This model has a constant perturbation magnitude $A(z) \equiv A$ independent from the altitude. The other parameters are summarized in Table 9.

Table 9. Turbulence model #1 parameters

Turbulence parameter	NAMELIST variable	Explanation
	ID_01	Random sequence id
A	A_01	Magnitude of perturbation
Δz	DZC_01	Vertical correlation radius [km]
κ	Kap_01	Anisotropy coefficient

An example of turbulence model #1 file is given below:
```
1
&MODEL_01
A_01 = 0.01
DZC_01 = 0.2
Kap_01 = 100
/
```

Turbulence model #2

This model implements a power spectrum with a constant anisotropy.

$$F\left(\omega_z, \omega_\theta\right) = A' \max\left(\left(\frac{2\pi}{\Delta z_{\text{ext}}}\right)^{-\mu/2}, \left(\omega_z^2 + \omega_\theta^2\frac{\kappa^2}{R_e^2}\right)^{-\mu/2}\right) \times$$
$$\times \exp\left(-\left(\frac{4\max\left(0, \omega - 2\pi/\Delta z_{\text{int}}\right)}{2\pi/\Delta z_{\text{int}}}\right)^2\right) \tag{29}$$

This model has a constant perturbation magnitude $A(z) \equiv A$ independent from the altitude. The other parameters are summarized in Table 10.

Table 10. Turbulence model #2 parameters

Turbulence parameter	NAMELIST variable	Explanation
	ID_02	Random sequence id
A	A_02	Magnitude of perturbation
κ	Kap_02	Anisotropy coefficient

Turbulence parameter	NAMELIST variable	Explanation
Δz_{ext}	DZext_02	External scale
Δz_{int}	DZint_02	Internal scale
μ	Mu_02	Power of spectrum

An example of turbulence model #2 file is given below:

```
2
&MODEL_02
A_02  = 0.01
Kap_02 = 30
DZext_02 = 1.0
DZint_02 = 0.1
Mu_02 = -6
/
```

Turbulence model #3

This model has a spectrum identical to that of model #2 (29). The difference is that it allows for specifying the altitude profile of the magnitude perturbation. The NAMELIST parameters are summarized in Table 11.

Table 11. Turbulence model #3 parameters

Turbulence parameter	NAMELIST variable	Explanation
	ID_03	Random sequence id
κ	Kap_03	Anisotropy coefficient
Δz_{ext}	DZext_03	External scale
Δz_{int}	DZint_03	Internal scale
μ	Mu_03	Power of spectrum

An example of turbulence model #3 file is given below:

```
3
&MODEL_03
ID_03 = 100
Kap_03 = 20
DZext_03 = 0.1
DZint_03 = 0.015
Mu_03 = -4
/
2.0 0.005
8.0 0.0004
10.0 0.0004
12.0 0.0007
```

Turbulence model #4

This model is defined in [7], it implements the three-dimensional spectrum of anisotropic temperature irregularities generated by internal gravity waves (IGW) in a stably stratified atmosphere. The spectrum is defined as follows:

$$F\left(\omega_z, \omega_\theta\right) = \sqrt{\frac{\pi}{2}} \frac{T_0\, \Omega_{BV}^4\, N\left(\omega_z\right) \left|10^{-3}\omega_z\right|}{g^2\left(\left|10^{-3}\omega_z\right|^5 + \left(10^{-3}\kappa_*\right)^5\right)} \exp\left[-\frac{1}{2}\left(\frac{\omega_\theta}{R_e}\right)^2\left(\frac{N\left(\omega_z\right)}{\omega_z}\right)^2\right], \qquad (30)$$

where anisotropy factor $N\left(\omega_z\right)$ is defined as follows:

$$N\left(\omega_z\right) = \begin{cases} 9\left(1 + \kappa_\omega^2 / \omega_z^2\right), & \text{if } \left|\omega_z\right| > \kappa_m \\ \kappa = 409 & \text{otherwise} \end{cases}. \qquad (31)$$

The parameters of this model are summarized in Table 12.

Table 12. Turbulence model #4 parameters

Turbulence parameter	NAMELIST variable	Explanation
	ID_04	Random sequence id
A	A_04	Amplitude of perturbation
κ_m	Km_04	Vertical wave number
κ_ω	Kw_04	Vertical wave number for $\left|\omega_z\right| > \kappa_m$
Ω_{BV}	Wbv_04	Brunt-Väisälä frequency
g	G_04	Gravity acceleration
κ_*	Kstar_04	Vertical wave number for regularizing function
T	T0_04	Temperature

An example of turbulence model #4 file is given below:

```
4
&MODEL_04
ID_04   = 1000
DZext_04 = 7.5,
DZint_04 = 0.1,
Km_04   = 1.5,
Kw_04   = 10.0,
Wbv_04  = 0.02,
G_04    = 9.8,
Kstar_04 = 40.0,
T0_04   = 250.0
/
```

7.3 Option `-earth=<shape>[,<path>]`

This option defines the assumed shape of the Earth. This affects the transforms between the geodetic and Cartesian coordinates in the Earth-centered inertial (ECI) frame. It also affects the evaluation of the gravity acceleration at the surface g_s and the effective radius of the Earth R_0 defined as functions of the latitude [3, 4, 5].

Earth's shape `sphere`

This defines the spherical Earth with the radius of 6371 km.

Earth's shape `ellips`

This defines the elliptical Earth with the equatorial semiaxis of 6378.1370 km and the inverse flatness of 298.257223563 according to WGS84 reference ellipsoid.

Earth's shape `geoid`

This defines the geoid based on WGS84 reference ellipsoid with the addition of the geoid undulation based on JGM-3/OSU91A model [8].

7.4 Option `-iono=<type>,<hg>,<hi>[,<path>]`

This option defines the ionosphere. Possible types currently include `none` and `iri`. If the ionosphere type `none` is chosen, the ionosphere is not modeled. If the ionosphere type `iri` is chose, then the ionospheric model is based on International Reference Ionosphere (IRI).
The horizontal gradient mode has the same meaning and the same possible values (`1d` and `3d`) as for the model of the neutral regular atmosphere.
The positional sub-parameter `<hi>` specifies the upper height of the ionosphere. The optional positional sub-parameter `<path>` specifies the path to the IRI coefficient files.

7.5 Option `-gps=<file>`

Option `-gps` specifies the file with RO data, from which the orbit data for the simulation should be extracted. Currently, files from GPS/MET, CHAMP, COSMIC and GRAS/METOP missions are supported. This option is incompatible with the option `-orb`.

7.6 Option `-orb=<file>`

Option `-orb` specifies a file with orbit data. The file is organized in a way similar to phantom and turbulence files. It is an ASCII file. The first line contains the number of orbit model (currently, it can only take the value of 1). This information is presently not used. This line is followed by NAMELIST containing the orbit model parameters summarized in Table 13.

Table 13. Orbits description parameters

NAMELIST variable	Explanation
ID_01	Event identifier
Year_01	Event year
Month_01	Event month
Day_01	Event day of month
Hour_01	Event hour of day
Minute_01	Event minute
Second_01	Event second
GPS_H_01	Transmitter height above the Earth's surface
LEO_H_01	Receiver height above the Earth's surface
Lat_01	Occultation point latitude
Lon_01	Occultation point longitude
Theta_01	Occultation plane azimuth angle

This model implies circular orbits of the satellites with the velocities defined by the inverse square gravity acceleration. The orbits lie in the vertical plane defined by the geodetic coordinates of the occultation point and the azimuth angle (counted counterclockwise from the direction to the North).

An example of a file with orbit data is given below:

```
1
&ORBIT_01
ID_01   = 1
Year_01 = 2008
Month_01 = 1
Day_01 = 2
Hour_01 = 12
Minute_01 = 00
Second_01 = 00
GPS_H_01 = 26000
LEO_H_01 = 720
Lat_01 = 8
Lon_01 = 60
Theta_01 = 40
/
```

7.7 Option -msis=<path>

This option specifies the path to the MSIS coefficient files.

7.8   Option -out=<*outname*>

Option -out specifies the template for the output filenames. By default, the template will be defined by the orbit data filename (as specified by option -gps or -orb).
If the orbit data filename begins with 'occ', then this context is replaced with 'wop'.
If the orbit data filename begins with 'CH-', 'iCH-', 'atmPhs_', 'gras_', 'PS-', then any of these contexts is replaced with 'WO-'.
If the orbit data filename begins with 'wop', then template will coincide with it.
Otherwise the template will consist of prefix 'WO-' followed by the original orbit data filename.

7.9   Option -chan=<*chan*>

This option defines the channel processing mode. The mode can be parallel (par) or sequential (seq). In the parallel mode, all the frequency channels are simulated simultaneously. In the sequential mode, the frequency channels are simulated one by one. Both of these modes give identical simulation results. The parallel mode requires more random access memory (RAM).

7.10   Option -freq=<*freqs*>

This option allows the user to specify the frequency channels. There are a few predefined frequency sets that can be specified by the name. These are defined Table 14.

Table 14. Predefined frequency sets

Frequency set name	Frequencies [GHz]	Explanation
gps	1.57542, 1.22760	GPS(L1, L2)
gal	1.57542, 1.17645	Galileo
glo	1.602, 1.246	GLONASS
acestd	9.7, 17.25, 22.6	ACE+ standard
aceopt	9.7, 13.5, 17.25, 22.6	ACE+ optional
acemax	9.7, 13.5, 17.25, 20.2, 22.6	ACE+ maximum

The desired frequency set can be specified directly as a sequence of decimal numbers referring to frequencies in GHz separated by commas. For example, -freq=10,12,17.5,22.6.

7.11   Option -afreq=<*freqs*>

This option has the same format as option -freq. Option -afreq specifies the frequencies for the computation of absorption (if this is requested by option -ab). This option is convenient for the fast estimate of absorption effects. For example, if the user specifies options -freq=1.5,1.2 -afreq=17,22.6, then the wave propagation will be computed for lower frequencies of 1.5 and 1.2 GHz, which will require a lower resolution in the phase screens and can be performed faster. However, the absorption effects will be computed as if the frequencies were 17 and 22.6 GHz.

7.12 Option -hmax=<hmax>

This option specifies the maximum height H_{max} [km] for the wave propagation. This is illustrated for phase screens by **Fejl! Henvisningskilde ikke fundet.**.
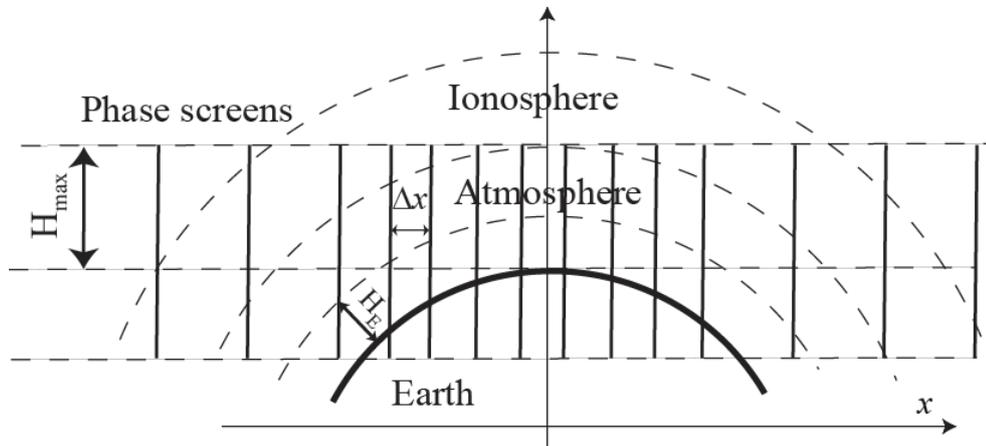

Figure 7.12-3: Phase screens geometry.

7.13 Option -hmin=<hmin>

This option is equivalent to the Earth's surface elevated by the height of <hmin> [km].

7.14 Option -hgo=<hgo>

This option defines the maximum height [km] for the GO propagation.

7.15 Option -dyn=<dyn>

This option is used to set the characteristic vertical scale Δy_N of the refractivity field. This setting affects the adaptive integration step size in the GO ray tracing. The step size is chose in such a way that below the height of 35 km the variation of the vertical coordinate of the current point of a ray within one integration step does not exceed Δy_N. Above 35 km, this scale is assumed to have a fixed value of 0.5 km. This scale is also used for the estimates of the optimal resolution in phase screens when performing WO simulation.
When performing simulations with ECMWF gridded fields, this parameter should be chosen to approximately correspond to the minimum step between the model levels. A typical choice would then be -dyn=0.05.

7.16 Option -dx=<dx>

This option defines the minimum step between the phase screens in the area where the estimated lowest ray perigee lies below the height of $H_E = 25\ \text{km}$. Outside this area the maximum step is

chosen to equal $\max\left(\Delta x,\ \min\left(20\ \mathrm{km}, 10\,\Delta x\right)\right)$. Therefore, if $\Delta x < 2\ \mathrm{km}$, the maximum step equals $10\Delta x$; if $\Delta x > 20\ \mathrm{km}$ the maximum step equals Δx; otherwise it equal 20 km.

7.17 Option $-\mathtt{xls}=<xls>$

If this option is specified it requests the propagation to an additional phase screen. The regular phase screens are positioned so as to cover the area where the estimated perigee of the lowest ray lies inside atmosphere or ionosphere (if ionospheric modeling is requested by option $-\mathtt{iono}$). The upper height of the neutral atmosphere is assumed to be 150 km. The height of the ionosphere is specified by option $-\mathtt{iono}$. An additional phase screen can be positioned outside this area at the horizontal coordinate $<\mathtt{xls}>\ [\mathtt{km}]$ counted from the straight line perigee located at the Earth's surface (**Fejl! Henvisningskilde ikke fundet.**). This option may be useful if the propagation of the wave field from the last phase screen to the LEO orbit is performed by the computation of Fresnel integrals if requested by option $-\mathtt{fio}$ (see Section 7.28). In this case, a typical setting will be
$-\mathtt{xls}=1000$. This option is not necessary if option $-\mathtt{fio}$ defines that the propagation from the last phase screen to the LEO orbit is performed by the Linearized Zverev Transform (LZT) [9].

7.18 Option $-\mathtt{ct}=\{\mathtt{y}|\mathtt{n}\}$

This option defines whether the wave field in the last phase screen (which can be either the regular of additional phase screen) is processed by Canonical Transform (CT) method [10]. If $-\mathtt{ct}=\mathtt{y}$ is specified, then files with extensions.$\mathtt{wca}<c>$ (CT amplitude) and.$\mathtt{wce}<c>$ (CT bending angles) are written out. This option is convenient for test purposes.

7.19 Option $-\mathtt{fz}=<fz>$

This option defines the numerical integration zone size for the computation of the Fresnel integrals if the propagation of the wave field from the last phase screen to the LEO orbit is performed by the computation of Fresnel integrals if requested by option $-\mathtt{fio}$ (see Section 7.28). The option defines the deviation of the phase [π rad] at the borders of the integration zone from the stationary phase. Outside the numerical integration zone, asymptotic formulas are used for the estimate of the residuals.

7.20 Option $-\mathtt{sr}=<sr>$

This option specifies the sampling rate [Hz] of the simulated data.

7.21 Option $-\mathtt{ts}=\{\mathtt{y}|\mathtt{n}\}$

This option specifies the time scaling. The original trajectory that is generated from the prescribed orbit data or extracted from RO data files may need extension or shrinking according to the specific wave propagation conditions. If $-\mathtt{ts}=\mathtt{y}$ is specified, the time of the output data is scaled in such a way that the start and finish time of the original trajectory are conserved. If $-\mathtt{ts}=\mathtt{n}$ is specified the time of the output data will correspond to time of the original trajectory,

where it covers the trajectory of the output data, and outside this area the time will be extrapolated.

7.22 Option `-ecef={y|n}`

This option specifies whether the input and output coordinates should be in the Earth-centered Earth-fixed (ECEF) frame (`-ecef=y`) or in the Earth-centered inertial (ECI) frame (`-ecef=n`).

7.23 Option `-wo={y|n}`

This option defines whether the WO propagation based on phase screens should be performed (`-wo=y`) or not (`-wo=n`).

7.24 Option `-go={y|n}`

This option defines whether the ray tracing GO propagation should be performed (`-go=y`) or not (`-go=n`).

7.25 Option `-rh={y|n}`

This option defines whether the output bending angle profiles should be output as functions of ray impact height counted from the Earth's radius (`-rh=y`) or the impact parameter counted from the Earth's curvature center (`-rh=n`).

7.26 Option `-ab={y|n}`

This option defines whether absorption should be computed (`-ab=y`) or not (`-ab=n`). If the computation of absorption is requested then for the regular atmosphere the imaginary part of refractivity for the frequencies defined by option `-freq` or `-afreq` will be computed. Otherwise the imaginary part of refractivity will be set to 0.

7.27 Option `-as={y|n}`

This option defines the use of the FIO-based asymptotic propagation method. The combination -wo=y -as=y corresponds to the propagation method described in [11]. In the method the wave field in the last phase screen is computed asymptotically and this is followed by the propagation to the LEO orbit.
The combination -wo=n -as=y corresponds to the full asymptotic solution described in [12]. In this method the wave field is computed along the LEO trajectory. In the standard phase screen propagation and the asymptotic solution [11], the GPS satellite is stationarized [10]. The asymptotic solution [12] can be used for modeling moving transmitter.

7.28 Option -fio={y|n}

This option defines whether the propagation of the wave field from the last phase screen to the LEO orbit is performed by the computation of Fresnel integrals (-fio=n) or by using the LZT FIO-based solution described in [9] (-fio=n).

7.29 Option -sd=<sd>

This option defines the spatial dimension used for the computation of the amplitude in the asymptotic solutions. The standard phase screen propagation uses the 2D solution and it corresponds to -sd=2. When using the asymptotic solutions, it is possible to specify both -sd=2, which is compatible with and can be compared to the phase screen simulation, and -sd=3, which is more realistic.

7.30 Option -ngo=<ngo>

This option defines the number of rays for the GO ray tracing.

7.31 Option -fwp=<fwp>

This option is used if the asymptotic solution described in [12] is employed. It defines the filter width [km] for the computation of the derivative of the impact parameter at the GPS p_{GPS} over the effective impact parameter p. If a negative value is specify (cf. the default value of -1), then the derivative is assumed to equal 1.

7.32 Option -v=<vrb>

This option defines the verbosity level. The value of -1 corresponds to the silent mode, which implies that no messages are output to the terminal. The value of 0 only implies the output of program version number and error messages. The value of 1 implies that also progress messages (messages about the simulation stages) are output. The value of 2 adds static messages including some variable parameters. The value of 3 adds also dynamic messages used for the output of rapidly changing dynamic values in the same terminal line.

7.33 Option -b

Option -b is an an obsolete abbreviation for the batch mode, which is equivalent to -v=1.

7.34 Option -o=<exts>[,...]

This options allows for the total control of the output files. The value consists of comma-delimited list of specification. Each specification can be the name of a predefined set of file extensions, an extension turn-on specification, of an extension turn-off specification.
The predefined extension sets are summarized in Table 15. For the explanation of extension see Section 4.4.

Table 15. Predefined extension sets

Extension set name	**Extensions**
none	no output
all	output of all extensions
min	WOP
script	WOP, GOP, GRP, GON, GOT, MOT, MOQ, MON, MOA, MTR,MTD

An extension turn-on specification has a form of extension name set in capital letters, for example GON. An extension turn-off specification has a form of extension name set in capital letters followed by the minus sign, for example GON-.

Extension set script is set by default. Specifications are interpreted in the order they appear in the command line. A later specification overrides an earlier one. Omitting this option would mean that the script extension set is activated. If it is required to use the default extensions with the exception of GRP, MOA, and MTR, the following option should be specified:

-o=GRP-,MOA-,MTR-

If it is only required to output WOP, GOP, and GON files, the following option should be specified:

-o=none,WOP,GOP,GON

Note, the specification none is used here to override the default specification script. If it is required to output all the extensions except MOT, MOQ, MON, MOA, and MTR, the following option should be specified:

-o=all,MOT-,MOQ-,MON-,MOA-,MTR-

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