OSKAR Telescope Model

Version history:

Revision	Date	Modification
1	2012-04-20	Creation
2	2012-10-23	[2.1.0] Added description of files specifying uncorrelated system noise.
3	2013-03-01	[2.2.0] Added comment in overview to describe the format of telescope models containing hierarchical stations, and a description of an easier way to create models where all stations are identical. Updated examples.
4	2013-11-20	[2.3.0] Re-wrote initial sections and restructured document to describe revised telescope model files. The old configuration files are deprecated, but still supported.
5	2014-02-26	[2.4.0] Added section to describe file containing permitted beam directions.
6	2014-07-16	[2.5.0] Updated description of how numerically-defined element patterns should be used.

1 Introduction

This document describes the format of the telescope model used by OSKAR versions >= 2.5. The telescope model includes a description of the position of each station in the interferometer, the configuration of each station, and a custom element pattern for each station (if any).

2 Directory Structure

2.1 Overview

A telescope model is defined using a directory structure. The name of the top-level directory is arbitrary, but it must contain a special file to specify the position of each station, and a set of sub-directories (again, with arbitrary names), one for every station. Each of these sub-directories contains one or more special files to specify the configuration of that station.

The table in Section 2.2 shows the names of special files allowed at each level in the directory structure.

Station directories may themselves contain further directories to describe the configuration of sub-stations (or "tiles") that will be beamformed hierarchically. For a two-level hierarchical station, the top station level describes the layout of the tiles with respect to the station centre, and files in the sub-directories describe the layout of each tile with respect to its own centre.

The *alphabetical* order of the station directories corresponds to the order in which the station coordinates and element data appear in the layout and configuration files. (*Note that leading zeros must be used in directory names when necessary.*) With one exception, there must be the same number of directories as the number of rows in all configuration file(s) at that level. The exception is the case where all stations (or sub-stations) are identical, where it is sufficient to specify only one station directory: in this case, the configuration will be copied for all stations defined in the parent layout.

2.1.1 Example Telescope Model (single level beamforming; general case)

An example telescope model directory might contain the following:

- my_telescope_model/
    - station001/
        - [files describing the configuration of station 1]
    - station002/
        - [files describing the configuration of station 2]
    - station003/
        - [files describing the configuration of station 3]
    - … [other station directories]
    - [file describing the layout of stations in the interferometer]

2.1.2 Example Telescope Model (single level beamforming; all stations identical)

For stations that are all identical, it is sufficient to specify only one top-level station directory as follows:

- my_telescope_model/
    - station/
        - [files describing the configuration of all stations]
    - [file describing the layout of stations in the interferometer]

2.1.3 Example Telescope Model (two-level beamforming; general case)

An example telescope model directory where stations are composed of tiles could look like this:

- my_telescope_model/
    - station001/
        - tile001/
            - [files describing the configuration of tile 1 in station 1]
        - tile002/
            - [files describing the configuration of tile 2 in station 1]
        - … [other tile directories]
        - [file describing the layout of tiles in station 1]
    - station002/
        - tile001/
            - [files describing the configuration of tile 1 in station 2]
        - tile002/
            - [files describing the configuration of tile 2 in station 2]
        - … [other tile directories]
        - [file describing the layout of tiles in station 2]
    - … [other station directories]
    - [file describing the layout of stations in the interferometer]

2.1.4 Example Telescope Model (two-level beamforming; all tiles and stations identical)

For hierarchical stations that are all identical, and made of identical tiles, it is sufficient to specify only one station directory at each level:

- my_telescope_model/
    - station/
        - tile/
            - [files describing the configuration of each tile]
        - [file describing the layout of tiles in the station]
    - [file describing the layout of stations in the interferometer]

2.2 Locations of Special Files

The table below shows which files may be present in the various directories of the telescope model.

Filename	Brief description	Allowed locations	Required?
	Telescope & Station Configuration Files		
layout.txt	The layout (in horizontal East-North-Up coordinates) of stations or elements within stations. See Section 3.	All.	Yes (but see below).
layout_ecef.txt	The layout of stations in Earth-centred-Earth-fixed coordinates. Can be used instead of “layout.txt” at top-level only, if required. See Section 3.1.2.	Telescope model root.	No, unless layout.txt is omitted.
gain_phase.txt	Per-element gain and phase offsets and errors. See Section 4.	Station.	No.
apodisation.txt	Per-element complex apodisation weight. See Section 5.	Station.	No.
orientation.txt	Per-element X- and Y-dipole orientations. See Section 6.	Station.	No.
permitted_beams.txt	Permitted station beam directions in local horizon frame. See Section 7.	Station.	No.
element_types.txt	Type index of each element in the station. See Section 8.	Station.	No.
element_pattern_fit_*.bin	Element X-or Y-dipole responses for the station, as a function of frequency. See Section 10.	Any. (Inherited.)	No.
config.txt	Deprecated. See Section 9.	All, if layout.txt is omitted.	N/A
	Noise Configuration Files (See Section 11)		
noise_frequencies.txt	Frequencies for which noise values are defined.	Telescope model root. (Inherited.)	No, unless another noise file is present.
rms.txt	Flux density RMS noise values, in Jy, as a function of frequency.	Telescope model root or top-level station. (Inherited.)	No.
sensitivity.txt	System sensitivities, in Jy, as a function of frequency.	Telescope model root or top-level station. (Inherited.)	No.
t_sys.txt	System temperatures, in K, as a function of frequency.	Telescope model root or top-level station. (Inherited.)	No.

area.txt	Effective areas, in m^2, as a function of frequency.	Telescope model root or top-level station. (Inherited.)	No.
efficiency.txt	System efficiencies, as a function of frequency.	Telescope model root or top-level station. (Inherited.)	No.

These files contain tables of ASCII-formatted values. For telescope and station configuration files, each row contains data for one station or element, respectively, and each column is interpreted according to the file type. The file types are described in the following sections.

There must be a consistent number of rows in all configuration files within any given directory.

When the file is read, parameters are assigned according to their column position. In order to specify an optional parameter, all columns up the designated column must be specified.

The fields can be space-separated and/or comma-separated. Characters appearing after a hash ('#') symbol are treated as comments, and any further characters on that line are ignored. Empty lines are also ignored.

3 Layout Files

Layout files contain the coordinates of stations or elements at (respectively) the telescope or station level.

3.1 Telescope Level

The top-level "layout.txt" file contains a table of ASCII text to represent station positions relative to the centre of the interferometer array. Each line contains three numeric values, which correspond to positions represented as horizontal (*x, y, z*) coordinates in metres relative to a horizon plane, where *x* is towards geographic east, *y* is towards geographic north, and *z* is towards the local zenith. (The telescope centre position on Earth is specified using longitude and latitude values in the main OSKAR settings file, which is described in a separate document.)

In order, the parameter columns are:

Column	Parameter	Unit	Comment
1	Horizontal x (east) coordinate	Metres	Required
2	Horizontal y (north) coordinate	Metres	Required
3	Horizontal z (up) coordinate	Metres	Optional (default 0.0)

3.1.1 Example

```
# Example telescope "layout.txt" containing 5 stations, arranged randomly
# x (east), y (north), z (up)
   0.000,     0.000,  0.000
 225.027, -501.234,  0.000
 326.258,     8.812,  0.000
-200.205,  113.146,  0.000
 453.210, -152.415,  0.000
```

3.1.2 Telescope Level Earth-centred Coordinates

Many radio interferometers specify station positions in Earth-centred coordinates. It is possible to do the same in OSKAR by using a file named "layout_ecef.txt" instead of "layout.txt" in the top-level telescope directory.

In order, the parameter columns are:

Column	Parameter	Unit	Comment
1	ECEF x coordinate (towards longitude 0, latitude 0)	Metres	Required
2	ECEF y coordinate (towards the east)	Metres	Required
3	ECEF z coordinate (towards the north pole)	Metres	Required

3.2 Station Level

In each station directory, there should be a "layout.txt" file to specify the element position in horizontal (*x, y, z*) coordinates relative to the station centre, and (optionally) the (*x, y, z*) position errors.

In order, the parameter columns are:

Column	Parameter	Unit	Comment
1	Horizontal x (east) coordinate	Metres	Required
2	Horizontal y (north) coordinate	Metres	Required
3	Horizontal z (up) coordinate	Metres	Optional (default 0.0)
4	Horizontal x (east) coordinate error	Metres	Optional (default 0.0)
5	Horizontal y (north) coordinate error	Metres	Optional (default 0.0)
6	Horizontal z (up) coordinate error	Metres	Optional (default 0.0)

4 Element Gain & Phase Error Files

In each station directory, there may be optionally a “gain_phase.txt” file to specify the per-element systematic and time-variable gain and phase errors.

In order, the parameter columns are:

Column	Parameter	Unit	Comment
1	Systematic gain factor, G_0		Optional (default 1.0)
2	Systematic phase offset, ϕ_0	Degrees	Optional (default 0.0)
3	Time-variable gain factor, G_{std}, (std. deviation)		Optional (default 0.0)
4	Time-variable phase error, ϕ_{std}, (std. deviation)	Degrees	Optional (default 0.0)

Gain (G_0, G_{std}) and phase $(\phi_0, \phi_{\mathrm{std}})$ parameters define a complex multiplicative factor applied to each detector element. This complex factor is combined with the geometric beamforming weights (i.e. weights that define the Array Factor) to give a set of weights used to evaluate the station beam at each source direction.

As a result, the beamforming weight, W, for a given beam direction (θ_b, ϕ_b), detector position (x, y) and time t is given by:

$$W(\theta_b, \phi_b, x, y, t) = W_{\mathrm{geometric}}(\theta_b, \phi_b, x, y, t) \cdot (G_0 + G_{\mathrm{error}}) e^{i(\phi_0 + \phi_{\mathrm{error}})},$$

where G_{error} and ϕ_{error} are pseudo-random values picked, at each time-step, from Gaussian distributions with standard deviations G_{std} and ϕ_{std} respectively.

5 Element Apodisation Files

In each station directory, there may be optionally an “apodisation.txt” file to specify additional complex multiplicative beamforming weights to modify the shape of the station beam. If present, these weights are multiplied with the DFT weights calculated for the beam direction required at each time-step.

In order, the parameter columns are:

Column	Parameter	Unit	Comment
1	Element multiplicative beamforming weight (real part)		Optional (default 1.0)
2	Element multiplicative beamforming weight (imaginary part)		Optional (default 0.0)

6 Element Orientation Files

In each station directory, there may be optionally an “orientation.txt” file to specify north-through-east azimuth of the nominal X- and Y-dipole axes.

In order, the parameter columns are:

Column	Parameter	Unit	Comment
1	Nominal X dipole axis azimuth (East from North)	Degrees	Optional (default 90.0)
2	Nominal Y dipole axis azimuth (East from North)	Degrees	Optional (default 0.0)

7 Permitted Beam Directions

In each station directory, there may be optionally a "permitted_beams.txt" file to specify a list of azimuth and elevation coordinates for all local beam directions permitted at that station. If the file is omitted, it is assumed that the station can form a beam anywhere on the sky. If the file is present, then the nearest permitted direction to the computed phase centre will be selected for each time step.

In order, the parameter columns are:

Column	Parameter	Unit	Comment
1	Azimuth coordinate of beam (local East from North)	Degrees	
2	Elevation coordinate of beam (relative to local horizon)	Degrees	

8 Element Types

In each station directory, there may be optionally an "element_types.txt" file to specify the type of each element in the station. This type index is used in conjunction with numerically-defined element pattern data, to select the correct file of fitted coefficients. If the file is omitted, all elements have an implicit type of 0.

In order, the parameter columns are:

Column	Parameter	Unit	Comment
1	Element type index	N/A	Must be an integer

9 Configuration Files (Deprecated)

The "config.txt" file used for telescope models in OSKAR versions 2.0 to 2.2 is deprecated, but still supported. If any files named "config.txt" are present in a telescope model directory, they are loaded first. Any other parameter files present will override the contents of this file.

Please do not use "config.txt" when constructing new telescope models – this description is provided only for reference with old telescope models. (Note also that columns 7 to 9 are in a different order to those in the "gain_phase.txt" file.)

Column	Parameter	Unit	Comment
1	Horizontal x (east) coordinate	Metres	Required
2	Horizontal y (north) coordinate	Metres	Required
3	Horizontal z (up) coordinate	Metres	Optional (default 0.0)
4	Horizontal x (east) coordinate error	Metres	Optional (default 0.0)
5	Horizontal y (north) coordinate error	Metres	Optional (default 0.0)
6	Horizontal z (up) coordinate error	Metres	Optional (default 0.0)

7	Systematic gain factor, G_0		Optional (default 1.0)
8	Time-variable gain factor, G_{std}, (std. deviation)		Optional (default 0.0)
9	Systematic phase offset, ϕ_0	Degrees	Optional (default 0.0)
10	Time-variable phase error, ϕ_{std}, (std. deviation)	Degrees	Optional (default 0.0)
11	Element multiplicative beamforming weight (real part)		Optional (default 1.0)
12	Element multiplicative beamforming weight (imaginary part)		Optional (default 0.0)
13	Nominal X dipole axis azimuth (East from North)	Degrees	Optional (default 90.0)
14	Nominal Y dipole axis azimuth (East from North)	Degrees	Optional (default 0.0)

10 Embedded Element Pattern Files

Numerically-defined antenna element pattern data can be used for the simulation. OSKAR currently supports the loading of ASCII text files produced by the CST (Computer Simulation Technology) software package. These files must contain eight columns, in the following order:

1. Theta [deg]
2. Phi [deg]
3. Abs dir *
4. Abs theta
5. Phase theta [deg]
6. Abs phi
7. Phase phi [deg]
8. Ax. ratio *

* (these two columns are ignored during the load, but must still be present)

Before being used in the simulation, the element pattern data must be fitted with B-splines. The fitting procedure is performed using the 'oskar_fit_element_data' application which is built as part of the OSKAR package. Please see the settings file documentation for a description of the options used by this application.

To be recognised and loaded, the fitted element data must be supplied in files that adhere to the following name pattern, which is created automatically by the fitting procedure:

element_pattern_fit_[x|y]_<element type index>_<frequency in MHz> .bin

The element type index should be 0 unless there is more than one type of element in the station, and the frequency is the frequency in MHz for which the element pattern data is valid: so, for example, "element_pattern_fit_x_0_600.bin" would contain fitted coefficients to the data for the first type of X-dipole at 600 MHz. The frequency nearest to the current observing frequency is used when evaluating the response.

These files define the patterns used for the nominal X- and Y-dipoles. The location of these files defines their scope: if placed in the top-level directory, then they are used for all stations; if placed in a station directory, they are used only for that station. In this way, it is possible to specify different average embedded element patterns for each station.

10.1.1 Caution

Surfaces are fitted to the numerically-defined antenna data using bicubic B-splines. Since the quality of the fit depends critically on the fitting parameters (adjustable using the OSKAR settings file), **it is essential that each fitted surface is inspected graphically to ensure that there are no artefacts introduced by the fitting process**. This can be done by saving a FITS image of the element pattern (created by evaluating the fitted coefficients) by making an image of the station beam with the array factor disabled.

11 System Noise Configuration Files

11.1 Introduction

OSKAR telescope models optionally contain a number of files, which, if present, can be used to specify the addition of uncorrelated system noise to interferometry simulations.

For details of how uncorrelated noise is added to interferometry simulations, please refer to section 4 of the *OSKAR Theory of Operation* document. It should be noted that simulation settings files control the use and selection of noise files within a telescope model. A description of these settings can be found in the interferometry section of the *OSKAR Settings Files* documentation.

Uncorrelated system noise is added to the complex visibilities by drawing from a Gaussian distribution for each baseline, time integration, frequency channel and polarisation. The standard deviation of the Gaussian distributions can be specified three different ways:

1. Directly, as an RMS flux density (σ), in Jy.
2. As the system equivalent flux density, or system sensitivity (S_{sys}), in Jy.
3. As the system temperature (T_{sys}), in K, the station effective area ($A_{\mathrm{eff}}^{\mathrm{station}}$), in m^2, and the system efficiency η.

11.2 Noise files

To support the various noise specification modes, telescope models can contain a number of plain text files. The name and contents of each file type are described below.

- **`noise_frequencies.txt`**
  A list of frequencies, in Hz, for which noise values are defined. This file should be situated in the root of the telescope model directory structure.
- **`rms.txt`**
  A list of noise flux density RMS values, in Jy, as a function of frequency. The number of RMS values in the list should match the number of specified noise frequencies. Files can be situated in the root of the telescope model directory or in the top-level station folders. Files in station directories allow a different RMS values to be specified per station, and files in the root directory allow a quick way to specifying common RMS values for the entire array.

- **`sensitivity.txt`**
  A list of system sensitivities, in Jy, as a function of frequency. Sensitivity files should be placed in the root of the telescope directory or in the top-level station folders. As with other noise value files, this allows sensitivities to be specified per station or a common value to be shared by all stations.
- **`t_sys.txt`**
  A list of system temperatures, in K, as a function of frequency. System temperature files should be placed in the root of the telescope directory or in the top-level station folders. As with other noise value files, this allows system temperatures to be specified per station or a common value to be shared by all stations.
- **`area.txt`**
  A list of effective areas, in m^2, as a function of frequency. Effective area files should be placed in the root of the telescope directory or in the top-level station folders. As with other noise value files, this allows areas to be specified per station or a common value to be shared by all stations.
- **`efficiency.txt`**
  A list of system efficiencies, as a function of frequency. System efficiency files should be placed in the root of the telescope directory or in the top-level station folders. As with other noise value files, this allows efficiencies to be specified per station or a common value to be shared by all stations.

All of these files take the form of a plain text file list with successive values in the list separated by a new line. As with all of the other OSKAR plain text format configuration files, lines starting with a hash '#' character are treated as comments, and empty lines are ignored. See Section 11.2.2 for some examples.

11.2.1 Noise file load priority

In the case where more than one type of noise value specification file (RMS; sensitivity; or temperature, area and efficiency) is found in the telescope model directory, the values used for the simulation follow a simple priority system, with RMS files being favoured over sensitivity, and sensitivity files favoured over temperature, area and efficiency files. This is shown the following diagram where priority decreases from left to right.

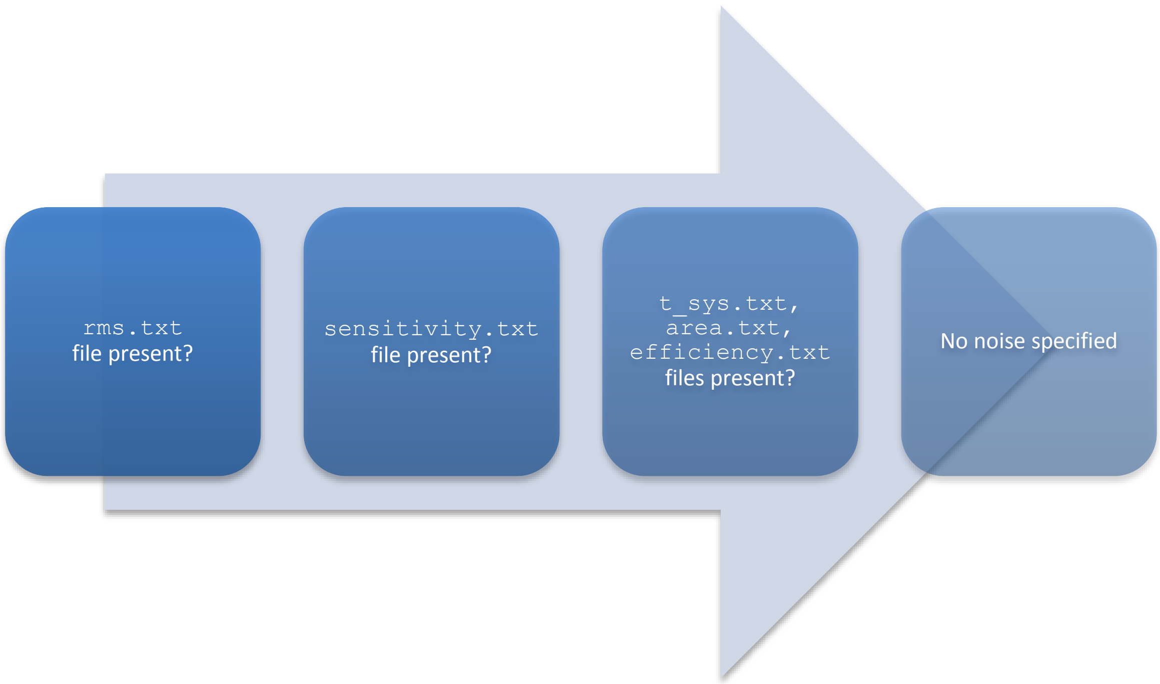

Figure 1: Priority of files used to specify interferometric uncorrelated system noise.

11.2.2 Examples

noise_frequencies.txt

```
# Example noise_frequencies.txt file
#
# This file contains a list of frequencies, in Hz, for which noise
# files are defined.
#

50.0e6
60.0e6
70.0e6
80.0e6
```

rms.txt

```
# Example rms.txt file
#
# This file contains a list of Gaussian RMS values, in Jy, from which noise
# amplitude values are evaluated. Entries in the list correspond to the noise RMS
# value at the frequency defined either by the corresponding line in the
# noise_frequencies.txt file or by the frequency specification in the noise
# settings.
#

0.7
0.5
0.3
0.2
```