OSKAR Telescope Model

1 Introduction

This document describes the format of the telescope model used by OSKAR versions >= 2.7. 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 telescope centre position, 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 following section 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]
  - [file describing the centre position of 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]
  - [file describing the centre position of 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]
  - [file describing the centre position of 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]
  - [file describing the centre position of the interferometer]

2.2 Special Files

This section shows the names of files that may be present in the various directories of the telescope model.

position.txt

Centre reference position of telescope array.
See Position File
Required: Yes.
Allowed locations: Telescope model root directory.

2.2.1 Element Data

layout.txt

The layout (in horizontal East-North-Up coordinates) of stations or elements within stations.
See Layout Files
Required: Yes (but see below).
Allowed locations: All directories.

layout_ecef.txt

The layout of stations in Earth-centred-Earth-fixed coordinates.
Can be used instead of "layout.txt" or "layout_wgs84.txt" at top-level only, if required.
See Telescope Level Earth-centred Coordinates
Required: No, unless layout.txt and layout_wgs84.txt are omitted.
Allowed locations: Telescope model root directory.

layout_wgs84.txt

The layout of stations in WGS84 (longitude, latitude, altitude) coordinates.
Can be used instead of "layout.txt" or "layout_ecef.txt" at top-level only, if required.
See Telescope Level WGS84 Coordinates
Required: No, unless layout.txt and layout_ecef.txt are omitted.
Allowed locations: Telescope model root directory.

element_types.txt

Type index of each element in the station.
See Element Types
Required: No.
Allowed locations: Station directory.

gain_phase.txt

Per-element gain and phase offsets and errors.
See Element Gain & Phase Error Files
Required: No.
Allowed locations: Station directory.

apodisation.txt | **apodization.txt**

Per-element complex apodisation weight.
See Element Apodisation Files
Required: No.
Allowed locations: Station directory.

feed_angle.txt | **feed_angle_x.txt** | **feed_angle_y.txt**

Per-element and per-polarisation feed angles.
See Element Feed Angle Files
Required: No.
Allowed locations: Station directory.

2.2.2 Station Data

permitted_beams.txt

Permitted station beam directions relative to mounting platform.
See Permitted Beam Directions
Required: No.
Allowed locations: Station directory.

2.2.3 Element Type Data

element_pattern_fit_$*$.bin

Fitted element X-or Y-dipole responses for the station, as a function of frequency.
See Numerical Element Patterns
Required: No.
Allowed locations: Any. (Inherited.)

2.2.4 Noise Configuration Files

noise_frequencies.txt

Frequencies for which noise values are defined.
See System Noise Configuration Files
Required: No, unless another noise file is present.
Allowed locations: Telescope model root directory. (Inherited.)

rms.txt

Flux density RMS noise values, in Jy, as a function of frequency.
See System Noise Configuration Files
Required: No.
Allowed locations: Telescope model root directory, or top-level station directory. (Inherited.)

Fields in text files 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 Position File

The top-level "position.txt" file must specify the longitude and latitude of the telescope origin. It must contain one line with two or three numbers:

Column	Description	Comment
1	WGS84 longitude, in degrees	Required
2	WGS84 latitude, in degrees	Required
3	Altitude, in metres	Optional (default 0.0)

4 Layout Files

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

4.1 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 specified in the Position File. Each line contains up to six values, which correspond to positions represented as horizontal (x, y, z) coordinates in metres relative to a local tangent (horizon) plane, where x is towards geographic east, y is towards geographic north, and z is towards the local zenith.

Coordinate errors can also be specified using optional columns. The first three columns are the "measured" positions, while the "true" positions are obtained by adding the supplied offsets to the measured values. Coordinates are given in metres. In order, the parameter columns are:

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

4.1.1 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. Coordinates are given in metres. In order, the parameter columns are:

Column	Description	Comment
1	ECEF x coordinate (towards longitude 0, latitude 0)	Required
2	ECEF y coordinate (towards the east)	Required
3	ECEF z coordinate (towards the north pole)	Required
4	ECEF x coordinate error	Optional (default 0.0)
5	ECEF y coordinate error	Optional (default 0.0)
6	ECEF z coordinate error	Optional (default 0.0)

4.1.2 Telescope Level WGS84 Coordinates

As a final option, it is possible to specify station positions as WGS84 (longitude, latitude, altitude) values by using a file named "layout_wgs84.txt" instead of "layout.txt" in the top-level telescope directory. In order, the parameter columns are:

Column	Description	Comment
1	WGS84 longitude, in degrees	Required
2	WGS84 latitude, in degrees	Required
3	Altitude, in metres	Optional (default 0.0)

4.2 Station Level

In each station directory, there must 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.

The format of the element layout file is the same as that used for the telescope-level station coordinates in the horizon frame. It is not possible to use Earth-centred or WGS84 coordinates to specify element locations within a station.

5 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 element pattern data to select the correct file of fitted coefficients.

If the element types file is omitted, all elements have an implicit type of 0.

In order, the parameter columns are:

Column	Description
1	Element type index (must be an integer).

6 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.

Phases are given in degrees. In order, the parameter columns are:

Column	Description	Comment
1	Systematic gain factor, G_0	Optional (default 1.0)
2	Systematic phase offset, ϕ_0 [deg]	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) [deg]	Optional (default 0.0)

Gain (G_0, G_{std}) and phase (ϕ_0, ϕ_{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, z) and time t is given by:

$$W(\theta_b, \phi_b, x, y, z, t) = W_{\text{geometric}}(\theta_b, \phi_b, x, y, z, t)(G_0 + G_{\text{error}}) \exp\{i(\phi_0 + \phi_{\text{error}})\}$$

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.

7 Element Apodisation Files

In each station directory, there may be optionally an "apodisation.txt" (or "apodization.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	Description	Comment
1	Element multiplicative weight (real part)	Optional (default 1.0)
2	Element multiplicative weight (imaginary part)	Optional (default 0.0)

8 Element Feed Angle Files

In each station directory, there may be optionally "feed_angle.txt", "feed_angle_x.txt" and/or "feed_angle_y.txt" files to specify the Euler angles of the feeds of the nominal X and Y dipoles. If only a single "feed_angle.txt" file is present, the same data are used for both the X and Y polarisations. Note that all the angles represent differences from zero, which is the ideal case where both dipoles are orthogonal and in the plane of the station platform.

In order, the parameter columns are:

Column	Description
1	Euler angle alpha around z-axis [deg]

It will be possible to specify the remaining two Euler angles of individual elements in a future version of OSKAR.

9 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	Description
1	Azimuth coordinate of beam (local East from North) [deg]
2	Elevation coordinate of beam (relative to local horizon) [deg]

10 Element Pattern Files

10.1 Numerical Element Patterns

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. Since version 2.7.0, either the theta-phi or the Ludwig-3 polarisation system can be used to represent the data. These files must contain eight columns, in the following order:

1. Theta [deg]
2. Phi [deg]
3. Abs dir $*$
4. Abs theta (if theta-phi) / Abs horizontal (if Ludwig-3)
5. Phase theta [deg] (if theta-phi) / Phase horizontal [deg] (if Ludwig-3)
6. Abs phi (if theta-phi) / Abs vertical (if Ludwig-3)
7. Phase phi [deg] (if theta-phi) / Phase vertical [deg] (if Ludwig-3)
8. Ax. ratio $*$

(Columns marked $*$ are ignored during the load, but must still be present.)

Ludwig-3-format data are detected by the presence of the word "Horiz" on the first (header) line of the file; otherwise, the theta-phi system is assumed.

Since version 2.6.0, "unpolarised" (scalar) numerical element pattern data files can be supplied, and these will be used if OSKAR is running in a scalar or Stokes-I-only mode. Data files for scalar numerical element responses must contain three or four columns, in the following order:

1. Theta [deg]
2. Phi [deg]
3. Amplitude
4. Phase [deg] (optional)

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 use the following name pattern, which is created automatically by the fitting procedure:

`element_pattern_fit_[x|y|scalar]_<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 (as specified in the station's "element_types.txt"), and the frequency is the frequency in MHz for which the element pattern data are 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 element patterns for each station.

Attention

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 from a single-element station.

11 System Noise Configuration Files

11.1 Introduction

OSKAR telescope models optionally contain 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 the relevant section 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.

11.2 Noise Files

To allow for a different level of noise to be added to each station, telescope models can contain a number of plain text files which should be placed either in the station folders or top-level telescope model directory.

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.

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.

11.2.1 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
```

Revision 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.
7	2015-05-16	[2.6.0] Updated description of numerical element pattern data to allow for scalar-only element responses. Updated description of telescope layout files to allow for station position errors. Added section to describe element feed angles and removed old "orientation.txt" file description. Removed old "config.txt" file description, as these files have been deprecated since version 2.3, and can no longer be supported. Updated description of system noise files which are now greatly simplified.
8	2017-04-03	[2.7.0] Added description of required new "position.txt" file. Added description of optional "layout_wgs84.txt" file. Added description of Ludwig-3 format element data files.