OSKAR Station Simulator: Coordinate System Specification

1 Overview

The Station Simulator will have the capability to work with a simple sky model to generate simulated antenna signals. Users will need to specify locations and properties of antennas within a station, a source distribution on the sky, and the beam directions of interest.

For a realistic simulation, the model SKA station should be located on the surface of a model Earth. Sources in the sky (and the beams that follow them) are specified in celestial coordinates, which are fixed to a suitable celestial reference frame for the duration of the simulation. The station is fixed at a point on the rotating Earth, where the location is specified in longitude and latitude. At any given time, an appropriate transformation must be applied to the celestial and geodetic coordinates to obtain the apparent source positions relative to the station horizon. The station processors will need to work with local (horizontal) coordinates internally, and be aware of the locations of all antennas that are part of the station. The rest of this document outlines the coordinate systems used by the Simulator, and discusses the implications of choosing these coordinate systems to allow the user to specify source, beam and antenna positions.

2 Celestial and geodetic coordinate systems

2.1 Specification

- The Earth is spherical, and the coordinates of the station phase centre are specified in conventional (geodetic) longitude and latitude.
- Observations are specified for a given sidereal time, but otherwise occur at the same point in the Earth's sidereal year and epoch, i.e. users supply sidereal time, but no date.
- The celestial reference frame is thus a generic equatorial system, defined by the projection of the Earth's equator onto the celestial sphere as shown in Figure 1. In this case, geodetic longitude and latitude map precisely to celestial longitude and latitude.

2.2 Justification

The real Earth is not spherical. Its axis of rotation is also inclined at an angle to the plane of the ecliptic, and exhibits a long-period precession due to tidal forces within the solar system. If the Simulator has to generate real sky data, these effects must be considered. However, the primary purpose of the Simulator is to investigate efficient ways to form and track station beams using the aperture array, not to provide an accurate celestial model: thus, timing information need only be specified over one sidereal day. Realistic data may still be simulated using this simplified celestial reference frame, which only includes the necessary features to evaluate the performance of the beamformer. Using a fixed, generic equatorial system will make the transformation to local coordinates much easier, since the effects of precession, the shape of the Earth and its orbital characteristics may be neglected completely. If the beamforming module of the Simulator is required to work with real data from a future instrument (e.g. 2-PAD), the simplified coordinate conversion routines will need to be replaced with those from a standard library that can process data from the actual epoch of the observation.

2.3 Implications

In a generic equatorial system the observation epoch is unspecified, so we cannot use currently defined standard equatorial coordinates (e.g. J2000, B1950). Coupled with a spherical Earth model, this means that the Simulator will be unable to cope accurately with real data from real instruments. If such functionality is required, the Simulator could use a third-party library (such as the SLALIB package, written by P.T. Wallace and originally part of the Starlink software collection) to convert to local horizon coordinates. The interface with the sky database may also be able to provide the necessary conversion routines.

Fixing the date of all observations should not limit the capabilities of the Simulator if sidereal time is used, rather than solar time. Objects are visible at different times of the solar day at different times of year, but radio telescopes can observe continuously, not just at night.

Source positions and beam directions are both specified in the celestial reference frame. This means that the user will not specify how the system tracks sources as the station moves under them, since all source positions and beam directions will undergo the same transformation to local horizon coordinates. The disadvantage of this is that the Simulator will not be able to track arbitrary objects that are not fixed to the celestial (or local) reference frame, such as Earth-orbiting satellites, or aircraft.

3 Local (horizontal) coordinate system

3.1 Specification

- The station processors use a conventional horizontal system (i.e. with respect to the horizon), where azimuth is the angle of the source (or beam) from geographic North measured through geographic East, and the elevation angle is measured from the horizon to the source, towards the zenith. See Figure 1.

3.2 Justification

Source positions and beam directions must be converted from the celestial frame to local coordinates (relative to the station's horizon), at every time-sample. The user may also supply direction-dependent corruptions in amplitude and phase using local coordinates, which provides the possibility of including terrestrial interferers in the Simulator. The local-coordinate frame is necessary to (a.) simulate the antenna signals from all sources, and (b.) compute the required complex weights to apply to the antenna signals for the current beam of interest.

3.3 Implications

Some users with an engineering background may be more familiar with using a polar coordinate system which defines the zenith angle, rather than the elevation. This has also has the advantage of mapping nicely to the commonly used spherical polar coordinate system in mathematics. However, it should not matter if all horizontal coordinates are used consistently throughout.

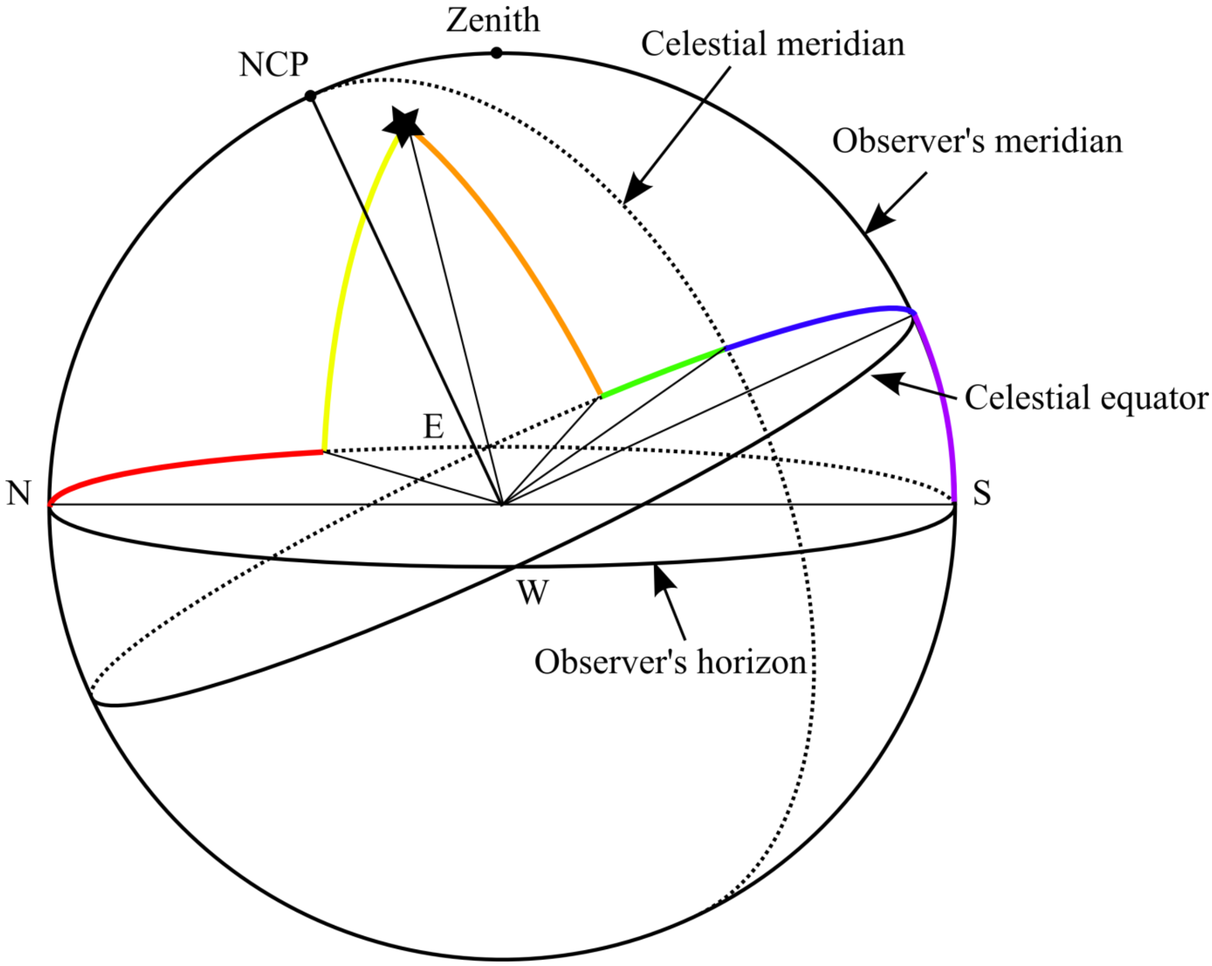

Figure 1: The celestial and local horizontal coordinate systems. The cardinal points (N, E, S, W), the North Celestial Pole (NCP), celestial equator, celestial meridian, and the observer's horizon, observer's meridian, and zenith are all indicated. Red: the instantaneous azimuth angle of the source, as viewed by the observer. Yellow: the instantaneous elevation angle of the source, as viewed by the observer. Orange: the celestial latitude of the source. Green: the celestial longitude of the source (East-positive convention). Blue: the **negative** *hour angle of the celestial meridian (as drawn in the figure). Purple: the geodetic* **co-latitude** *of the observer.*

4 Antenna coordinate system

4.1 Specification

- All antennas in a station are specified in two dimensions on an *x*-*y*-plane.
- The *x*-*y*-plane is drawn in the conventional sense, so that the *x*-axis points towards geographic East and the *y*-axis towards geographic North, when viewed looking towards the Earth. (Note that this is in the opposite sense to the orientation used by the astronomical community, where East and West are defined using the same directions, but viewed towards the sky, not the Earth.) See Figure 2.
- Antenna coordinates are specified in metres along the *x* and *y* axes, where the origin is the (arbitrary) phase centre for the station.

- Tile phase-centres are specified on the same *x*-*y*-plane. Each antenna may (in general) belong to an arbitrary number of tiles: in such cases the antenna locations are also expressed in the local coordinate system of each tile, so that each tile can form its own beam.

4.2 Justification

The user must be able to specify the locations of antennas relative to the station phase-centre, and (optionally) group arbitrary collections of antennas together into 'tiles' (which may overlap, in the case where some antennas are part of more than one tile). This is necessary to (a.) simulate the antenna signals from all sources, and (b.) compute the required complex weights to apply to the antenna signals for the current beam of interest. Specifying arbitrary locations of all antennas (and, optionally, tiles) in the station on a single *x*-*y*-plane maintains a flexible, hierarchical and extensible framework for the beamformer.

4.3 Implications

The requirement that all antennas in the station lie on a single plane means that non-coplanar baselines are not modelled by the Simulator. If required, a *z*-offset (defaulted to zero) could be specified for each antenna and modelled as a phase error, to include non-coplanar effects.

The choice of East-West convention is somewhat arbitrary – however, in this case it is used to specify locations of antennas on the ground, rather than objects in the sky. Since it is usual to work with a plan view when describing features on Earth, we adopt the usual geographic meaning rather than the astronomical one to specify the antenna positions on the ground.

Each antenna in a station is fixed in a position relative to the station phase centre. Keeping all antennas at fixed positions during each simulation is a realistic constraint, and should not cause problems. If the user opts to define tiles (or sub-stations) for hierarchical beamforming or local correlation, specifying an arbitrary position for the phase centre of each tile will maintain maximum flexibility in the beamformer. Each antenna is then assigned to (possibly more than) one tile.

5 Conclusion

This document outlines the coordinate systems in use at various stages for the planned Station Simulator: a simplified celestial and geodetic coordinate system, a local horizon coordinate system, and a means to specify the spatial and logical configuration of antennas within a SKA station.

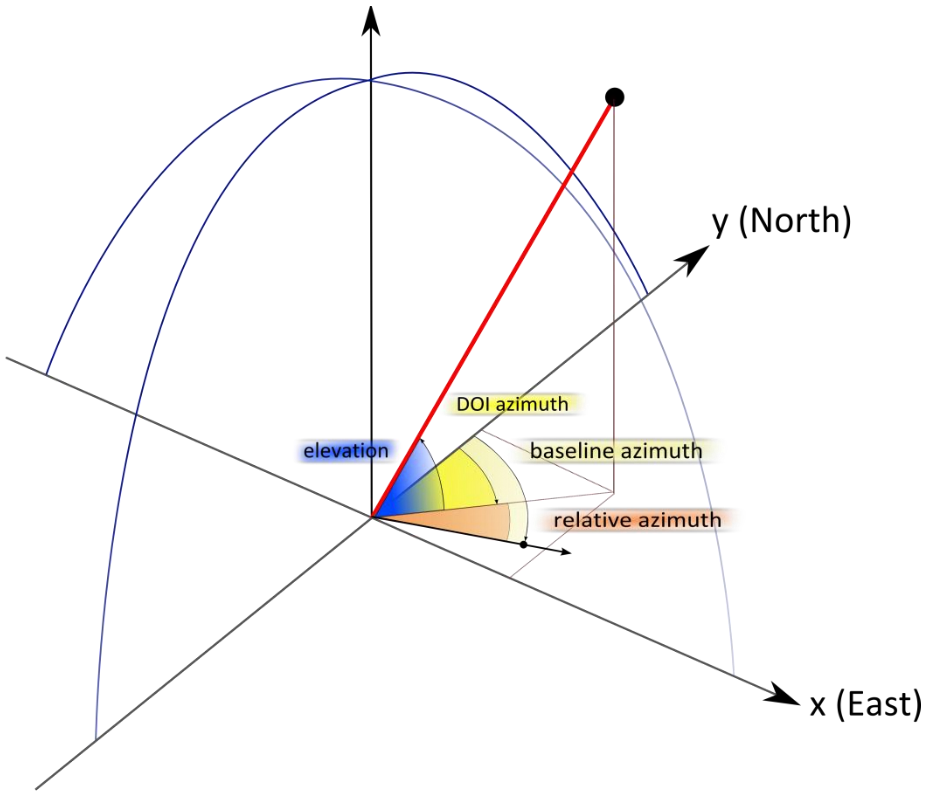

Figure 2: The relationship between local horizon coordinates (North, East), and antenna coordinates (x, y). The station (or tile) phase centre is at the origin; the source or beam (DOI) position is marked by the red line; and the antenna location is marked by the black dot in the x-y-*plane.*