Ionospheric Scintillation Impact Report: West Australian SKA Site

Prepared for the University of Manchester, Jodrell Bank Centre for Astrophysics

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If you should have questions regarding this report, please contact the report author, Mr. James Secan, at NWRA’s Tucson office (520-319-7773, jim@nwra.com).

System Synopsis

This Ionospheric Scintillation Impact Report (ISIR) provides a summary of the potential impact of ionospheric scintillation on a radio astronomy instrument, the Square Kilometer Array (SKA), proposed to be constructed in West Australia (Core site location 26.704° S, 116.659° E, 375m elevation). The summary is provided in the form of 72 day-of-year versus time (DVT) contour plots of the expected worst-case $S_4$ intensity-scintillation index for four frequencies of interest (100, 250, 600, and 1,000 MHz) at nine viewing geometries (overhead, and 30° and 60° elevation at 0°, 90°, 180°, and 270° azimuth from true north). Plots were generated for both solar minimum (defined as a sunspot number of 10) and solar maximum (150) conditions for all 36 frequency-geometry combinations.

General Scintillation Environment

The proposed location in West Australia is located in the ionospheric mid-latitudes, roughly halfway between two regions of potentially severe ionospheric scintillation: the southern equatorial anomaly to the north of the station and the high-latitude auroral region to the south. In general, the scintillation levels in this region show a diurnal variation and increases with the 11 year solar cycle (driven by increases in the solar output of extreme ultraviolet, or EUV, radiation). If the viewing geometry is such that the signal is passing through either the southern equatorial anomaly to the north of the station or the auroral region to the south, there will also be complex seasonal, temporal, and geomagnetic-activity variations which are different for the two regions.

Figures 1 through 3 illustrate the diverse scintillation environment within which the viewing geometry from this location covers. In all three figures, the color contours show the percent of time the $S_4$ intensity scintillation index (defined as the RMS variation of signal intensity) is expected to exceed 0.5 at a frequency of 100 MHz, which indicates a moderate scintillation level. The star indicates the Core location for the site. The dotted lines indicate geomagnetic latitude (the line passing just south of the Core location is 40° geomagnetic latitude, and the other lines are spaced 10° apart). The geometry used in generating these three figures is a vertical ray path from each latitude/longitude point in the figure to a transmitter located directly overhead above the ionosphere. (Note that these calculations were not for ray paths from the SKA location, but are all overhead ray paths for each point. These maps are to show the location of regions of strong irregularities with respect to the site location, not to indicate scintillation as would be seen from the site along any given ray path.)

The dark- and light-blue heavy lines around the Core location indicate the 5° horizon location for altitudes of 300km and 600km, respectively, and the red line indicates the 30° for an altitude of 350km. The height for the low-elevation lines were chosen as reasonable estimates for the lower and upper altitude boundaries of the strong ionospheric irregularities that could cause
scintillation impacts on SKA operations. Note that the WBMOD model uses an altitude of 350km as the centroid of the height distribution, also the height where the phase-screen used in the propagation model is located. Ionospheric irregularities will be seen above and below these altitudes, but these are not unreasonable values. The red line indicates the lowest elevation for which the diurnal-seasonal plots that make up the bulk of this report were generated. Note that this lies well within the mid-latitude ionosphere even during disturbed conditions.

The primary difference between these three figures are the geophysical conditions for which they were run, specifically the level of geomagnetic activity. Figure 1 is for low activity (geomagnetic $K_p$ index of 1), Figure 2 for high activity ($K_p$ of 8), and Figure 3 for a nominal average activity level ($K_p$ of 2+). Note also that Figure 1 and Figure 2 and 3 are at different UT times, selected to show the time of most likely impact from the equatorial ionosphere (Figure 1), which occurs near local sunset, and of the high-latitude ionosphere (Figures 2 and 3), which occurs near local midnight.

From these figures it is likely that, given caveats presented later in this document, there will be little problem from the very strong scintillation that is observed in the southern equatorial anomaly region except for low frequencies and very low elevation angles. The most likely incursion of scintillation-causing irregularities is likely to be on the southern horizon when the irregularities generated during strong geomagnetic activity are moved into the viewing area as the auroral region expands equatorward with increasing activity levels. Again, this is only for low elevation angles. One exception to this may be the point in the sky where the ray path passes nearly parallel to the local geomagnetic field direction within the altitude region where irregularities are found. This is described, and demonstrated, at the end of the Description of Model Results section of this report.

The diurnal variation of scintillation in the strictly mid-latitude ionosphere is modeled quite simply and shows a sinusoidal variation over the day with a maximum in scintillation during local night. This is the only variation that is seen in the contour plots of scintillation as a function of day-of-year and time-of-day.

**Geophysical Setting**

The parameters that specify the geophysical setting for the scintillation model are the sunspot number (SSN) and the planetary index of geomagnetic activity ($K_p$). The SSN index is used as a surrogate for the solar EUV radiation levels, and sets the general level of solar production of plasma in the ionosphere. The $K_p$ index provides a measure of the general level of geomagnetic activity and is used as an indicator of electrodynamics in the post-sunset equatorial ionosphere.

In the model runs used in this study, we have used a sunspot number of 10 for solar minimum conditions, and a sunspot number of 150 for solar maximum conditions. We have used a fixed value of 3.0 (3) for $K_p$ as a nominal typical level of geomagnetic activity.

**Description of Model Results**

The results of the 72 model runs are shown in Figures 4 through 39. The model was run to generate estimates of the 95th percentile in the expected $S_4$ scintillation distribution for the given
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date, time, and geophysical conditions. As such, these plots can be interpreted as the expected worst-case intensity scintillation levels in terms of the $S_4$ scintillation index. Each page shows two plots for a single frequency/geometry case: the upper plot for solar minimum conditions and the lower plot for solar maximum. The figures are grouped by frequency: Figures 4 through 12 for 100 MHz, 13 through 21 for 250 MHz, 22 through 30 for 600 MHz, and 31 through 39 for 1,000 MHz. Within each frequency, the overhead geometry is first, followed by the $60^\circ$ elevation case at $0^\circ$ azimuth, the $30^\circ$ elevation at $0^\circ$ azimuth, and so on around the other three azimuth headings.

Note that these plots are all uniformly unexciting, from a scintillation perspective. As pointed out in a previous section, all of these plots are generated for propagation paths that are well within the mid-latitude ionosphere.

A careful review of the results shown for 100 MHz will show an unintuitive result in the changes with elevation angle along the northern azimuth direction – the scintillation level increases from directly overhead ($90^\circ$ elevation) to $60^\circ$ elevation, as one would expect from purely geometrical considerations, but then it decreases from $60^\circ$ elevation to $30^\circ$ elevation (Figures 4 through 6). The cause of this can be seen in the four plots in Figure 40, which are sky maps (contour plots in elevation and azimuth angle from the site) of the percent of time $S_4$ exceeds 0.5 for the four frequencies used in this report. These were generated for the same, somewhat extreme, geophysical conditions as Figure 2 (solar maximum, high geomagnetic activity, local midnight). The enhancement seen to the north of overhead is due to a geometrical enhancement of scintillation which occurs when the propagation path is very nearly parallel to the local geomagnetic field direction within the irregularity layer. There is no increase in the strength of the irregularities in this particular part of the sky, it is purely due to propagation effects. It is this effect that causes the behavior noted in Figures 4 through 6.

**Caveats**

The general caveat for all products based on SCINTMOD or WBMOD is that these are climatological models designed to provide estimates of the expected levels of ionospheric scintillation for given geophysical conditions. Thus, scintillation maps generated from these models, such as that shown in Figures 1 through 3 of this report, should not be viewed as snapshots of the spatial distribution of scintillation on a given night, but rather as contours of the expected levels of scintillation, should it occur. These models provide expected levels of activity over a collection of observations, not individual realizations of the spatial coverage of scintillation for a specific day. A major weakness in the models is that they are based on a small number of stations, with barely adequate coverage of the latitude and longitude variations known to exist in ionospheric scintillation morphology.

A major source of uncertainty for the location of interest in this report is the lack of data from mid-latitude stations that was used in generating the WBMOD climatology. The only data available were three months of data collected during the mid-1970s from Menlo Park, CA, and two years of data from near Seattle, WA. Much of the data from the latter station was auroral or sub-auroral and not mid-latitude. It is generally agreed that mid-latitude scintillation is very weak, but it has not been systematically studied and it is likely that the WBMOD estimates for
mid-latitude scintillation at low frequencies (below 150 MHz or so) are quite likely the weakest link in the model.

Two other potential sources of uncertainty, but only at low elevations, are uncertainties in (1) the location of the southern equatorial anomaly and its transition into the mid-latitude ionosphere, and (2) the location of the high-latitude scintillation boundary at high levels of geomagnetic activity. These, however, should not effect the results shown in Figures 4-39 given the distance the 30° elevation horizon as shown in Figures 1-3 from both the equatorial and auroral regions.

Finally, the results at the lowest frequency, 100 MHz, are for a frequency range not sampled by any of the data sets used in producing the model climatology. The bulk of the data used in generating the climatology in the equatorial region was from GPS signals at frequencies of 1,227.60 and 1,575.42 MHz. Earlier climatology development used data from two stations (Kwajalein Island and Ancon, Peru) at frequencies as low as 137.67 MHz, and data from three other stations (Huancayo, Peru; Manila, Phillipines; and Ascension Island) at 250 MHz. The propagation model does explicitly scale with frequency, but care should be taken in interpreting the results below the 137.67 MHz lowest frequency in the data used in generating the climatology.
Figure 1. Scintillation coverage map for highest levels of scintillation in the equatorial region. The star indicates the location of the SKA West Australia Core site. The dark- and light-blue circles indicate the location of the 5° elevation horizon at altitudes of 300km and 600km, respectively. The red circle indicates the 30° elevation horizon at 350km altitude, which is the low-elevation bound of the calculations shown in Figures 4-39 of this report.
Figure 2. Scintillation coverage map for highest ($K_p = 8^\circ$) levels of scintillation in the high latitude region.
Figure 3. Scintillation coverage map for most-likely ($K_p = 2+$) levels of scintillation in the high-latitude region.
Figure 4. The 95th percentile $S_4$ as a function of GMT and day of the year for 100 MHz, overhead geometry. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 5. The 95th percentile $S_4$ as a function of GMT and day of the year for 100 MHz, 60° elevation angle, 0° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 6. The 95th percentile $S_4$ as a function of GMT and day of the year for 100 MHz, 30° elevation angle, 0° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 7. The 95\textsuperscript{th} percentile $S_4$ as a function of GMT and day of the year for 100 MHz, 60$^\circ$ elevation angle, 90$^\circ$ azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 8. The 95th percentile $S_4$ as a function of GMT and day of the year for 100 MHz, 30° elevation angle, 90° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 9. The 95th percentile $S_4$ as a function of GMT and day of the year for 100 MHz, 60° elevation angle, 180° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 10. The 95th percentile $S_4$ as a function of GMT and day of the year for 100 MHz, 30° elevation angle, 180° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 11. The 95$^{\text{th}}$ percentile S$_4$ as a function of GMT and day of the year for 100 MHz, 60° elevation angle, 270° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 12. The 95$^{th}$ percentile $S_4$ as a function of GMT and day of the year for 100 MHz, 30° elevation angle, 270° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 13. The 95th percentile $S_4$ as a function of GMT and day of the year for 250 MHz, overhead geometry. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 14. The 95th percentile $S_4$ as a function of GMT and day of the year for 250 MHz, 60° elevation angle, 0° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 15. The 95th percentile $S_4$ as a function of GMT and day of the year for 250 MHz, 30° elevation angle, 0° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 16. The 95th percentile $S_4$ as a function of GMT and day of the year for 250 MHz, 60° elevation angle, 90° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 17. The 95\textsuperscript{th} percentile $S_4$ as a function of GMT and day of the year for 250 MHz, 30° elevation angle, 90° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 18. The 95th percentile $S_4$ as a function of GMT and day of the year for 250 MHz, 60° elevation angle, 180° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 19. The 95\textsuperscript{th} percentile $S_4$ as a function of GMT and day of the year for 250 MHz, 30\degree elevation angle, 180\degree azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 20. The 95th percentile $S_4$ as a function of GMT and day of the year for 250 MHz, 60° elevation angle, 270° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 21. The 95th percentile $S_4$ as a function of GMT and day of the year for 250 MHz, 30° elevation angle, 270° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 22. The 95th percentile $S_4$ as a function of GMT and day of the year for 600 MHz, overhead geometry. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 23. The 95th percentile $S_4$ as a function of GMT and day of the year for 600 MHz, 60° elevation angle, 0° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 24. The 95th percentile $S_4$ as a function of GMT and day of the year for 600 MHz, 30° elevation angle, 0° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 25. The 95th percentile $S_4$ as a function of GMT and day of the year for 600 MHz, 60° elevation angle, 90° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 26. The 95th percentile $S_4$ as a function of GMT and day of the year for 600 MHz, 30° elevation angle, 90° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 27. The 95th percentile $S_4$ as a function of GMT and day of the year for 600 MHz, 60° elevation angle, 180° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 28. The 95th percentile S4 as a function of GMT and day of the year for 600 MHz, 30° elevation angle, 180° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 29. The $95^{\text{th}}$ percentile $S_4$ as a function of GMT and day of the year for 600 MHz, 60° elevation angle, 270° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 30. The 95th percentile $S_4$ as a function of GMT and day of the year for 600 MHz, 30° elevation angle, 270° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 31. The 95th percentile $S_4$ as a function of GMT and day of the year for 1,000 MHz, overhead geometry. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 32. The 95th percentile $S_4$ as a function of GMT and day of the year for 1,000 MHz, 60° elevation angle, 0° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 33. The 95\textsuperscript{th} percentile $S_4$ as a function of GMT and day of the year for 1,000 MHz, 30° elevation angle, 0° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 34. The 95th percentile S4 as a function of GMT and day of the year for 1,000 MHz, 60° elevation angle, 90° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 35. The 95th percentile $S_4$ as a function of GMT and day of the year for 1,000 MHz, 30° elevation angle, 90° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 36. The 95th percentile S₄ as a function of GMT and day of the year for 1,000 MHz, 60° elevation angle, 180° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 37. The 95th percentile $S_4$ as a function of GMT and day of the year for 1,000 MHz, 30° elevation angle, 180° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 38. The 95th percentile $S_4$ as a function of GMT and day of the year for 1,000 MHz, 60° elevation angle, 270° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 39. The 95th percentile $S_4$ as a function of GMT and day of the year for 1,000 MHz, 30° elevation angle, 270° azimuth angle. The top plot is for solar minimum conditions; the lower plot for solar maximum conditions.
Figure 40. The probability of $S_4$ exceeding 0.5 plotted as a function of elevation and azimuth angle from the Core site location for 100 MHz (upper left), 250 MHz (upper right), 600 MHz (lower left), and 1,000 MHz (lower right). The calculations were run for solar maximum (SSN = 150), high geomagnetic activity ($K_p = 8o$), 21 March 2011, at local midnight.