Report of the
Expert Panel on Tropospheric Turbulence (EPTT)

R.Blundell, L.D'Addario, G.Elgered, R.Neri (chair), J.Richer

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PRELIMINARY

1. Preamble

The terms of reference described the EPTT work as reviewing the SPDO report [1] to characterize tropospheric turbulence at the candidate sites and identify possible limitations to performance of the SKA design.

The EPTT reviewed the SPDO report. The report outlines the experimental setups and provides a statistical analysis of the atmospheric phase stability observed during austral winter and spring time at the Karoo (South Africa, KSA) and Murchison (West Australia, MWA) sites. The SPDO report provides technical details of the instruments and calibration procedures, includes information on the locations, period of coverage of observations, and is supported by numerous figures, tables and references.

The EPTT examined the data reduction procedure and the results obtained to assess the quality of the phase data obtained at the KSA and MWA sites, and verify that results can be compared with data from other sites according to a common evaluation grid.

Given the generality of the terms of reference and the absence of a clear set of SKA specifications and operating criteria against which to conduct the evaluation, the EPTT has come up with its own assumptions to see what would be the connection between the results presented in the SPDO report and the array capabilities for different configurations and operating frequencies.

2. Executive Summary

The EPTT summary conclusions on the KSA and MWA sites are as follows:

- The site test interferometer (STI) data obtained at both sites are robust, of good quality and of comparable accuracy to phase stability data obtained at other sites.
- The data are of insufficient duration to allow firm conclusions about the long-term viability of the sites for observations requiring high dynamic range imaging. We have less than one year of data, so not all seasons are covered, and multi-year data is needed for a good statistical analysis. Consequently, all of the following results are tentative.
- The STI data from the candidate SKA sites were compared with data from similar instruments at other sites. The data suggest that neither SKA site is as good as the ALMA, VLA, or Goldstone (DSN) site, all of which are at higher altitudes and in desert climates, and that both are slightly better than the Canberra DSN station at night time.

- After adjusting for small differences in the observing geometry, the median RMS delay fluctuations were about 17% larger at the Murchison, Western Australia (MWA) site than at the Karoo, South Africa (KSA) site during the overlapping monitoring period, June through October 2011 (mostly winter).
    - The difference was 3% for nighttime measurements, and 28% for daytime measurements.
    - It is not known whether these differences would persist, become larger, or be reversed if the monitoring covered a full year or multiple years.
    - In any case, these differences are small and the EPTT considers them insignificant for determining the suitability of the sites for high dynamic range imaging.
- The STIs at the candidate SKA sites are of identical design and similarly installed, but they necessarily used different geostationary satellites as their signal sources. Their antenna separations were close to the same (199.1 m at MWA and 205.9 m at KSA). Because the vertical distribution of turbulence is not measured, an accurate adjustment for the geometrical differences is not possible, so a reasonable model was used. The ratio of the adjustment factors (MWA/KSA) was 0.79.
    - An alternative model (see section 3) gives an adjustment factor ratio of 0.94, which would increase the median difference during the overlap period from 17% to 38%.
    - The geometries were sufficiently similar that the adjustment (for either model) is insignificant for determining the suitability of the sites for high dynamic range imaging.

The EPTT attempted to estimate the imaging dynamic range available at each site due to tropospheric turbulence in the absence of any other errors. This is difficult because it depends on calibration strategy and other imaging techniques. However, in the opinion of the EPTT, if the SKA had been operating at either of the subject sites during the period of monitoring, the tropospheric turbulence would not have been a significant limitation on high-dynamic-range imaging for nighttime observations at 3 GHz. At 30 GHz and in the daytime, it would have made such observations more difficult.

3. SPDO report assessment

The SPDO report shows that phase data from both sites were filtered by removing a mean, slope and best-fit 24 hrs sinusoid over sliding intervals of 10 min. The phase delay data were then reduced to statistical quantities (cumulative phase RMS distributions) over sample intervals of 5 min, and these were adjusted to a common baseline length and air mass.

To evaluate the performance of the filtering procedure, verify the robustness of the statistical results and trends presented in the SPDO report, and enable comparisons between statistical results obtained at the KSA and MWA site and existing results obtained with sample intervals of 10 min at other sites, the EPTT requested statistical results computed over intervals of 5 min and 10 min for one month of data from both sites. The result of the analysis is that results obtained are consistent within the systematic uncertainties and that differences between the 5 min and 10 min data samples are negligible for both sites i.e. smaller than 0.1 ps over 24 hrs at the 50^{th} percentiles.

The EPTT addressed questions about the validity of the adjustments of the phase data for differences in baseline and air mass. The formula used in the SPDO report ([1], p 8) is

$$d = \frac{P}{2\pi f} \sin e \left(\frac{b_0}{b} \right)^{\beta}$$

where d is the normalized delay difference, P is the filtered interferometer phase, f is the observing frequency, e the satellite elevation, b is the antenna separation distance, b_0 = 200 m is the reference or normalization baseline, and β = 5/6 is the thick-screen exponent derived from Kolmogorov turbulence theory [2].

Regarding the baseline dependence, the question was whether the effective baseline of the observations might be different from the antenna separation b. If the turbulence in the refractive index is confined to a layer of thickness $h \ll b$, then the separation of the paths is very nearly b while they are in the layer, regardless of the observation direction. But if $h \gg b$, then, when the paths are within the turbulent layer, their separation at most points is equal to the projected baseline b', or the spacing in the (u,v) plane. At the zenith and at the azimuth normal to the antenna separation, $b' = b$, but otherwise $b' < b$. In general, the variance of the phase difference seen at two antennas is a complicated integral of the 3-dimensional structure function of the refractive index along the two paths [2]. In our case, h is variable and not accurately known, but it is believed to range from ~100 m to ~2 km; and $b \approx 200$ m. Thus, we are at neither of the two extremes where an effective baseline is determined by a simple argument. Fortunately, the instruments at the two subject sites, as well as those at comparison sites considered below, used satellites at azimuths not too far from normal to the antenna separation, so we have $b' \approx b$. Furthermore, the two antenna separations were nearly the same. Specifically, we have (from [1]):

	MWA	KSA
Satellite azimuth relative to baseline	-68.03^o	-94.74^o
Satellite elevation	36.72^o	50.82^o
Antenna separation, b	199.1 m	205.9 m
Projected separation, b'	189.9 m	205.6 m
$(b'/b)^{5/6}$	0.9615	0.9989

Table 1: Configuration geometry of the site testing interferometers

We therefore conclude that the use of antenna separation b in the normalization, as was done in the SPDO report [1], is sufficiently accurate for our purposes.

Regarding the reliability of the air mass adjustment factor, the EPTT considered whether it would be more appropriate to scale phase delays with air mass $1/\sin(e)$, as in [1], or with square root of air mass. The EPTT concluded (based on the analysis in [2]) that 1) the true dependence on air mass is somewhere between these two; 2) the effective scaling may change with time and is a function of the thickness of the turbulent layer; and 3) whereas the satellite elevations used for the STI observations were reasonably large (>36°) at the subject sites and at other sites used for comparison, the scaling differences are not large enough to affect the overall conclusions about the KSA and MWA sites and their comparison to other sites. The EPTT also notes that the dependence of phase fluctuations on air mass has never been extensively explored in tropospheric site stability campaigns and that other factors like the site topography are likely to affect the structural geometry of the turbulence layer and so the tropospheric phase dependence on elevation.

The EPTT considered that it would have been helpful to include in the SPDO report measurements of the temporal structure functions for the purpose of measuring the speed of the tropospheric phase screen and of estimating the Kolmogorov exponent. This information would have helped to extrapolate some of the conclusions to longer baselines but it was understood that it would not be possible for the EPTT to receive it before the reporting deadline. The EPTT recommends that this information be considered for inclusion in a possible amendment to the SPDO report and in future site testing reports.

The EPTT concluded that the troposphere phase fluctuation data obtained at both sites are robust, of good quality and of comparable accuracy to phase data obtained at other sites.

4. Sites Evaluation

According to the standard Kolmogorov model of atmospheric turbulence, delay fluctuations scale according to b^{β}, where b is the separation between the columns of turbulence probed by two antennas and β a power law exponent. The model suggests $\beta=0.83$ for antenna spacings much smaller than the thickness of the turbulence layer, $\beta=0.33$ for much larger spacings up to the largest turbulence structures, and $\beta=0$ beyond. Since these exponents hold true on a statistical basis for a number of sites, the EPTT considered it reasonable to assume the same for the KSA and MWA sites.

Using the available statistics for the common monitoring period (June through October 2011), Table 2 summarizes 1) the estimated phase noise at KSA and MWA extrapolated to baselines of 1 and 10 km and scaled to 3, 10 and 30 GHz, and 2) the expected amplitude correlation losses resulting from the estimated phase noise. The table assumes for both sites a constant value of 1 km for the height of the turbulence layer (about half the scale height of the vertical water vapor distribution) and of 6 km for the largest turbulence structures. Results are given for the median (50th percentile) conditions over the 5-month interval[1]. Much of this phase error can be removed by calibration, as discussed below.

One of the main concerns for SKA is the imaging quality possible to achieve. While a large phase RMS might be acceptable for detection projects, it would be not for high dynamic range imaging. In order to evaluate the impact of the atmospheric phase fluctuations on the imaging capabilities of the array, the EPTT has attempted to estimate the dynamic range performance achievable in median winter conditions at

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[1] The median values over the 5-month period were not readily available, but instead we had the cumulative distributions for each month separately. The 5-month medians were estimated as the mean of the medians for the separate months.

Karoo South Africa (KSA), 0.99 ps RMS									
Frequency	3 GHz			10 GHz			30 GHz		
Baseline	200 m	1 km	10 km	200 m	1 km	10 km	200 m	1 km	10 km
Phase RMS, deg	1.07	4.09	6.99	3.56	13.63	23.30	10.69	40.88	69.91
Decorrelation	0.02%	0.25%	0.74%	0.19%	2.79%	7.94%	1.73%	22.47%	52.50%
Murchison West Australia (MWA), 1.16 ps RMS									
Frequency	3 GHz			10 GHz			30 GHz		
Baseline	200 m	1 km	10 km	200 m	1 km	10 km	200 m	1 km	10 km
Phase RMS, deg	1.25	4.78	8.18	4.17	15.94	27.26	12.51	47.82	81.77
Decorrelation	0.02%	0.35%	1.01%	0.26%	3.80%	10.70%	2.35%	29.41%	63.88%

Table 2: Median estimated tropospheric phase noise and coherence losses at KSA and MWA in the zenith direction on baselines of 200 m, 1 km and 10 km, and at 3, 10 and 30 GHz over the common monitoring period, June through October 2011. Results are derived from the median RMS delay measured by the STI instruments over that period (0.99 ps at KSA and 1.16 ps at MWA, normalized to zenith and 200 m).

the MWA and KSA sites if the tropospheric turbulence were the only source of error (everything else being perfect). The panel assumed for the evaluation that the astronomical target is strong enough to be mapped with high dynamic range but either too weak or structurally too complex that visibility phases cannot be corrected for tropospheric fluctuations using self-calibration techniques. It is also assumed that no attempt is made to correct visibility phases for tropospheric fluctuations using external measurements but that antennas have motion capabilities that allow fast switching between astronomical targets and nearby phase calibration sources.

Tests at the VLA [8][9] have shown that periodic observation of a calibration within a few degrees of a target reduces the phase fluctuations on long baselines to that of a shorter baseline whose dominant fluctuation time is comparable to the calibration cycle time. This is because the larger fluctuations at long baselines are due to large-spatial-scale turbulence whose effect is more slowly varying. The residual RMS phase on *all* baselines after calibration can then be estimated from the STI measurements [6] as

$$\phi_{\text{res}} = 2\pi f \frac{d}{\sin e}\left(\frac{t_{\text{cycle}}}{2\,t_{\text{corn}}}\right)^{\beta}$$

where f is the observing frequency, d the zenith RMS delay measured by the STI, e the elevation of the target source, and t_{corn} the corner time of the temporal phase structure function measured by the STI. The corner time is the time when the power-law function saturates at an approximately constant value, and is about the time for a parcel of turbulent troposphere to blow across the STI baseline. In the absence of measurements of the temporal structure function, the EPTT used for both sites, as an approximation to the corner time, a typical baseline crossing time of 40 s, corresponding to a mean wind speed in the turbulent layer of 5 m/s. It is worth noting that according to [5] the monthly average wind speed at ground level is lower at KSA than at MWA, but we have no data on the wind speeds aloft.

Following Perley ([3], eqn 13-9), we estimate the image dynamic range as

$$D = \frac{N\sqrt{M}}{\phi_{\rm res}}$$

where N is the number of antennas and M is the number of intervals with independent phase errors during the entire observation. For a "snapshot" observation, $M = 1$. This equation applies regardless of the cause of the phase errors, but it assumes that all antennas have independent errors with zero mean and the same standard deviation. Here we consider the case where the tropospheric turbulence is the only cause of errors (everything else is perfect), even though this is hardly realistic. We take $\phi_{\rm res}$ to be the residual error on each baseline after calibration, as estimated above. In general, the phase errors caused by the turbulence are not independent; they are correlated on nearby antennas. But the *residual* errors after calibration can be reasonably assumed to be due to small-scale turbulence that produces independent fluctuations on all but the shortest baselines.

Using N=3000 for the full SKA-mid, e=45°, t_{corn}=40 s, t_{cyc}=10 s, and β=5/6, we obtain the results in Table 3, under several conditions. Results are given for M=1 (snapshot) and M=144. The latter corresponds to an 8 hour observation if the residual phase fluctuations (after calibration) are independent in each 200 s interval.

	Median Dynamic Range, Full SKA (N=3000)					
	Single Snapshot (M=1)			8 hrs Track (M=144)		
Frequency	3 GHz	10 GHz	30 GHz	3 GHz	10 GHz	30 GHz
Nighttime, best month, either site	60 dB	55 dB	50 dB	71 dB	66 dB	61 dB
Daytime, KSA Jun-Oct 2011	56 dB	51 dB	46 dB	67 dB	62 dB	57 dB
Daytime, MWA Jun-Oct 2011	55 dB	50 dB	45 dB	66 dB	60 dB	56 dB

Table 3: Dynamic range figures of merit that would have been achieved at either of the candidate sites during median nighttime conditions for the best month of the common monitoring period (0.61 ps RMS at zenith and 200 m baseline, June at MWA and July at KSA), and for median daytime conditions at each site over the full common monitoring period (1.6 ps rms at KSA and 2.1 ps rms at MWA). Results are given for a single snapshot and for an 8-hour observation.

The EPTT comes to the conclusion that if the full SKA had been operating at either of the subject sites during the period of monitoring, the tropospheric turbulence would not have been a significant limitation on high-resolution and high-dynamic-range imaging at 3 GHz; other errors are likely to dominate. At higher frequencies, the tropospheric turbulence would likely have been the limiting factor, but high quality imaging would still have been possible. For nighttime observations, the troposphere sometimes permits dynamic range of several times 10^7 at low frequencies. Nevertheless, some of the science goals and the associated dynamic range requirements (up to 74 dB) outlined in the Design Reference Mission document [4] are extremely challenging and may be precluded at these sites by tropospheric turbulence, except on rare occasions.

It is emphasized that these conclusions are based on various assumptions, as stated here, including the use of aggressive (10 s cycle time) fast-switching calibration, and are subject to error[2]. They apply only to the five-month common monitoring period, which was mostly in winter. Summer will almost certainly be worse, but we do not know by how much. Other years may be better or worse for the same months.

5. Site Comparison and Data Representativeness

The tropospheric phase measurements consisted of a near complete set of 5 months duration for the MWA site with a number of unexpected interruptions, a rather complete period of 8 months for the KSA site, and provide a complete overlap for the June to October period, 2011.

To compare the troposphere stability at the candidate sites to other radio telescope sites, the EPTT obtained STI data from the VLA, ALMA, and two DSN stations. Many other radiotelescope sites have been equipped with STI instruments but the EPTT was not able to obtain such data in time for this report. The VLA and ALMA data were taken from published reports [10][11], and each gives statistics covering one full year. The DSN stations have recently-installed STI instruments identical to those at the candidate SKA sites; the one at Goldstone, California has been in operation since mid-2010, and the one at Canberra, ACT has been in operation since May 2011.

In all cases, the raw STI phase measurements are first filtered to remove satellite motion and instrumental drift, and then reduced to RMS fluctuations over intervals of 5 min or 10 min. Cumulative distributions are then calculated from time series of the RMS values, typically for each month. For this report, the distributions were converted to delay units and scaled to a common baseline (200 m) and air mass (zenith). Table 4 shows the monthly 50th-percentile and 90th-percentile RMS delays for each of the 5 sites for those months where data are available. The data are generally from different years, but are organized by calendar month, with northern hemisphere and southern hemisphere stations offset by 6 months so that results on the same line correspond to the same season. Where available, the 50th percentile RMS delays from distributions of only nighttime data and only daytime data are also listed.

The data suggest that 1) neither SKA site is as good as the ALMA, VLA, or Goldstone (DSN) site, all of which are at higher altitudes and in desert climates, and 2) both candidate sites are potentially slightly better than the Canberra DSN station at night time.

To evaluate the representativeness of the time period for which there are STI data from the candidate SKA sites, the EPTT was provided with a document on the meteorological conditions observed at the two sites over the years 1985-2011 [5]. The data were compared with temperature and precipitation data ([7], Australian Bureau of Meteorology) of the Murchison weather station 70 km south-west of the MWA site. They suggest the June through October conditions were marginally less favorable than normal i.e. the region experienced precipitation on average +1.2 days more than normal per month and the lowest and highest temperatures were on average +1.4° C and +0.2° C higher. It has not been possible to do the same

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[2] Using the same methodology to predict the dynamic range available at the VLA (N=27) with the median nighttime STI results from that site for Feb 1998 [10] gives a dynamic range of 51 dB, underestimating the 55 dB that has actually been achieved there [3].

analysis for the KSA site. Anyhow, the period over which the atmospheric turbulence was monitored is considered statistically insignificant, possibly biased towards weather conditions which are not necessarily representative, and eventually not adequate to characterize site specific effects.

The EPTT recommends assessing the tropospheric representativeness of the area covered by SKA in addition to assessing the representativeness of the sites. This could be achieved by contacting one of the large meteorological analysis centers (NCAR or ECMWF or JMA) to compare the monthly mean profiles of humidity, temperature and wind for the two candidate areas and the monitoring period with the corresponding monthly means based on 30 year averages as well as the corresponding spread in these profiles over the same 30 years.

6. Acknowledgments

The EPTT would like to acknowledge the very valuable contribution of Rob Millenaar (SPDO) to this report and hopes that conclusions drawn will assist the SPDO/SSAC in the site selection process.

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[8] VLA Test Memo 212 http://www.vla.nrao.edu/memos/test/213/213.pdf (see Fig 4 on p 12).
[9] ALMA Memo 262 http://www.alma.nrao.edu/memos/html-memos/alma262/memo262.pdf (see Fig 7 on p 33).
[10] B. Butler and K. Desai, "Phase fluctuations at the VLA derived from one year of site testing interferometer data." VLA Test Memo 222, 1999.
[11] B. Butler *et al.*, "Atmospheric phase stability at Chajnantor and Pampa la Bola." ALMA Memo 365, June 2006.

Table 4: Cumulative phase RMS statistics at Goldstone (DGA, 900 m altitude), Canberra (DCB, 650 m), Socorro (VLA, 2100 m), Chajnantor (ALMA, 5000 m), Murchison (MWA, 370 m) and Karoo (KSA, 1080 m)

Comparison of Troposphere Stability At Various Sites Zenith rms delay, scaled to 200m baseline, ps

Month	DGA-10	DCB-11	VLA-98	ALM-97	MWA-11	KSA-11	DGA-10	DCB-11	VLA-98	ALM-97	MWA-11	KSA-11
N/S	[1]	[1]	[2]	[3]	[4]	[4]	[1]	[1]	[2]	[3]	[4]	[4]
	All Hours, 50th Percentile						All Hours, 90th Percentile					
May/Nov	1.094			0.76			2.750					
Jun/Dec	1.327			0.80			**3.518**					
Jul/Jan	1.512			**1.38**			3.864					
Aug/Feb	1.320			0.90			3.353					
Sep/Mar	1.327			0.87		1.94	3.407					4.93
Oct/Apr	1.191			0.62		1.66	2.835					4.57
Nov/May	0.701	0.835		0.53		1.27	1.729	2.100				3.71
Dec/Jun	0.666	1.324		1.06	**0.91**	0.94	1.612	3.093			**2.83**	2.45
Jan/Jul	0.609	1.307		**0.51**	1.18	**0.77**	1.258	3.443			2.67	**1.86**
Feb/Aug	**0.575**	1.038		0.55	1.26	0.93	**1.148**	2.657			3.23	2.21
Mar/Sep	1.036	1.466		0.57	1.09	1.07	2.455	3.298			3.40	2.93
Apr/Oct	1.080	1.218		0.99	1.35	1.24	2.747	3.589			3.66	3.13
	Day (8h) 50th Percentile						Day (8h) 90th Percentile					
May/Nov	1.504		1.10				1.923		2.79			
Jun/Dec	1.730		1.33				2.668		3.40			
Jul/Jan	**2.001**		1.75				**3.212**		4.40			
Aug/Feb	1.599		2.09				2.360		4.87			
Sep/Mar	1.561		**2.38**			3.08	2.797		**4.98**			6.30
Oct/Apr	1.100		1.42			2.77	2.401		2.82			6.63
Nov/May	0.610	1.184	0.96			1.99	1.537	2.755	2.82			5.04
Dec/Jun	0.600	1.615	0.60		1.80	1.54	1.597	3.584	1.21		3.44	3.20
Jan/Jul	0.557	1.600	0.67		**1.64**	**1.15**	1.086	3.762	1.56		**4.18**	**2.46**
Feb/Aug	**0.491**	1.365	**0.65**		2.13	1.48	**0.968**	3.304	**1.39**		4.76	2.85
Mar/Sep	0.912	1.982	0.91		2.28	1.77	1.765	3.914	2.31		4.61	4.57
Apr/Oct	1.013	1.834	1.17		2.40	2.06	2.089	4.561	2.44		4.88	4.20
	Night (8h) 50th Percentile						Night (8h) 90th Percentile					
May/Nov	1.249		0.53				3.094		1.70			
Jun/Dec	1.436		0.60				3.700		1.21			
Jul/Jan	1.662		0.96				4.242		2.16			
Aug/Feb	**1.328**		**1.09**				**3.684**		**2.47**			
Sep/Mar	1.296		1.07			**1.52**	3.403		2.33			2.91
Oct/Apr	1.181		0.75			1.27	2.803		1.74			2.85
Nov/May	0.675	0.727	0.67			0.97	1.600	1.631	1.54			2.68
Dec/Jun	0.661	1.145	0.39		**0.61**	0.72	1.548	2.727	0.88		2.08	1.85
Jan/Jul	0.604	1.111	0.44		0.94	**0.61**	1.255	3.101	1.12		1.86	**1.41**
Feb/Aug	**0.604**	**0.860**	**0.37**		0.91	0.76	**1.120**	**2.204**	**0.98**		1.99	1.64
Mar/Sep	1.106	1.237	0.47		0.62	0.81	2.592	2.788	1.00		**1.66**	1.96
Apr/Oct	1.131	0.938	0.54		0.91	0.96	2.832	2.577	1.23		2.10	2.01

[1] JPL, unpublished data from 2010--2011. All scaled to zenith and 200m baseline. 191--250m, 5min, sliding sinusoid.

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[3] A44 Data from July 1996 -- March 1999. 300m, 35d, 11.198GHz, 10min, poly2. Scaled to zenith and 200m.

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