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The Mid-frequency Telescope for the Square Kilometre Array (SKA-mid)

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Abstract

The Square Kilometre Array (SKA) is an ambitious project to build a radio telescope that will enable breakthrough science and discoveries not possible with current facilities.

Initially, two telescopes are planned, SKA1-mid and SKA1-low, built over two sites in southern Africa and Western Australia, respectively. Constructed in two phases: SKA1 is being designed now; SKA2 is planned to follow. This paper describes the science capabilities and overall design of SKA1-mid – given the present stage, a transition from preliminary design to detailed design.

1. Scientific Motivation

The motivation for the technical design of the SKA1 telescopes cannot be too narrow. While it is essential to have specific scientific goals (and commensurate telescope implementations), the history of astronomy is replete with unexpected discoveries. Astronomy is not a laboratory science; it is an observational science in which the most general possible designs will always win out. Where choices can reasonably be made, they tend toward generality of purpose and maximisation of discovery space.

This telescope will primarily address observations of radio pulsars and observations of the 21-cm hyperfine line of neutral hydrogen from the local Universe, to moderate redshifts, as well as high sensitivity observations of continuum emitting objects at all frequencies, including proto-planetary disks at high frequencies. It will also be well suited for conducting observations of various spectral lines in addition to the 21-cm hydrogen line (e.g. OH-lines), many classes of radio transients, magnetized plasmas both in the Galaxy and intergalactic space.

2. General Description of SKA1-mid

The SKA1-mid telescope will consist of a 150-km diameter array of reflector antennas (‘dishes’). It will be a mixed array of 133 15-m SKA1 dishes and 64 13.5-m diameter dishes from the MeerKAT telescope.

Scientific performance is determined mainly by seven characteristics.

- *Frequency Range*: The range of frequencies or wavelengths over which the telescope has significant sensitivity (0.35 to ~20 GHz).
- *Sensitivity*: The sensitivity can be defined in a variety of ways. A customary way to specify sensitivity is A_e/T_{sys}, where A_e is the effective collecting area, taking into account inefficiencies and losses, and T_{sys} is the total system noise, including sky noise and instrumental noise. This normally does not include systematic effects, which limit sensitivity through noise-like errors that cannot be removed. A second measure of sensitivity is ‘survey speed’, a measure of the time taken to reach a specified noise level on an image over a large area of sky. The customary parameterisation of this is $(Ae/T_{sys})^2\Omega$, where Ω is the instantaneous field-of-view of the telescope. Neither of these measures takes into account bandwidth. Sensitivity is shown in figures below.
- *Bandwidth*: The RF bandwidth that is available to the telescope at any one time. Sensitivity for wide-band (continuum) observations is proportional to $\sqrt{B}$, where B is the bandwidth. Bandwidth does not confer additional sensitivity for spectral line observations, but does assist searches for spectral-line emission at unknown frequencies. SKA1-mid will offer typical fractional bandwidths 0.6 and spectral resolution of a few hundred Hz over restricted frequency ranges.
- *Polarisation capability*: The capability to measure and image polarisation characteristics of radio emission with high fidelity over large fields.
- *Distribution of Collecting Area*: At a given frequency, the sensitivity of the telescope to components of the spatial spectrum. This is determined by the array configuration, which is shown in the figures below.
- *Maximum Baseline*: This determines the ultimate resolution of the telescope, although the detailed distribution of collecting area determines the sensitivity at maximum resolution. The resolution is given approximately by the inverse of the maximum baseline, measured in wavelengths (nominally 0.2 arcsec scaled by 1.4/f [GHz]).
- Processing capability of the telescope along three dimensions:
    - *Spatial processing*: the capability to make images of the sky in a given frequency band in all four Stokes parameters (IQUV).

- *Spectral processing*: the capability to measure spectra over a defined area of sky.
- *Temporal processing*: the capability to determine changes in the flux of emission from a defined (localized) area of sky over a given frequency band.

- *Very Long Baseline Interferometry (VLBI)*: A capability to participate in observations with VLBI networks for which there is mutual sky visibility and frequency range compatibility. The geographic location of SKA-mid in southern Africa provides valuable baselines at high sensitivity.

3. The Telescope System

Because it is difficult to design very high-efficiency feeds over bandwidths greater than 2:1 (upper-to-lower frequency ratio), the frequency range is covered by a series of feeds, in most cases a version of corrugated horns, except for Band 1, which is a quadridge feed. Their distribution in frequency is shown in Figure 1. Bands 3, 4, and 5c will not be deployed initially.

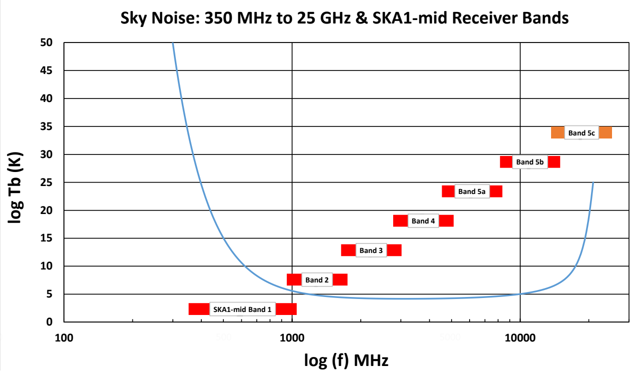

Figure 1: The positioning of receiver bands, superimposed on a plot of sky brightness temperature on a linear scale over the SKA1-mid range of frequencies.

Figure 2 is a diagram showing the major physical and functional blocks in the system. The blocks outlined in red have been assigned to 'design consortia' whose expertise covers the technologies shown in blue. The design does not include computing facilities for actually doing the science, but it does include calibration, imaging pipelines, time-domain transient capture, RFI flagging and preliminary sifting of pulsar candidates. With a few individual exceptions, retention of raw visibility data is not expected to be affordable.

The entire system is synchronised by distributing phase-locked reference signals to each antenna, as well as 'time-stamped' pulses. The time-stamps can be traced to atomic time through time-scale transfer using GNSS satellite receivers. This is required in order to maintain a long-term timescale for pulsar timing observations. The transfer accuracy required over a 10-yr period is ~10 ns.

Figure 3 shows the configuration of the SKA and MeerKAT antennas. At medium-to-long baselines (vector distances between antennas) this configuration efficiently provides a uniform distribution of baseline angles as well as an exponential fall-off of baseline lengths. This yields well-behaved point response function (PSF), the Fourier transform of the aperture distribution. Pulsar observations are best done with very short baselines so as to simulate as closely as possible a large 'single dish'. For this reason the configuration additionally contains a strong central 'core'. This also provides very high brightness temperature sensitivity when required.

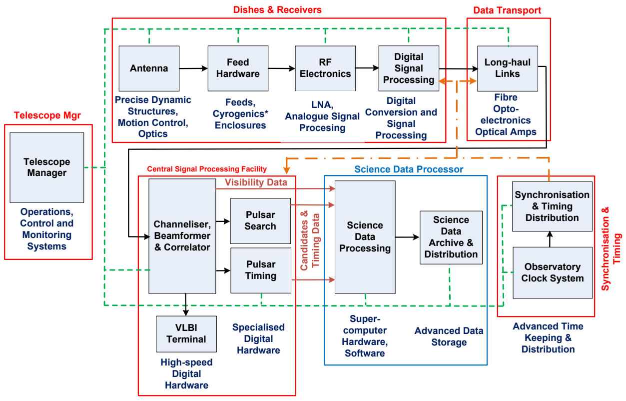

Figure 2: Major components of SKA1-mid following the signal flow, showing also the areas of consortia responsibility (red boxes) and the key technologies needed to implement the components. The green dashed line shows the bi-directional flow of monitor, control and operational data, and the dot-dashed line shows the distribution of synchronisation and timing signals.

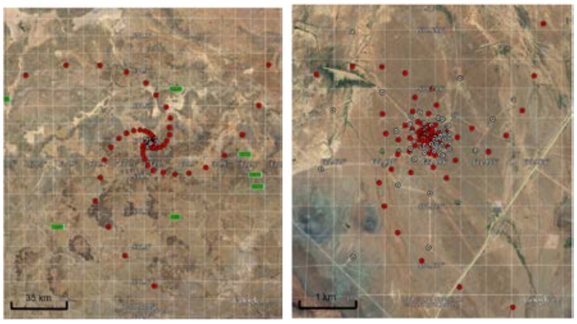

Figure 3: Location of SKA1-mid dishes (red dots) on the Karoo SKA site at two different scales (lower left). The black and white circles show the locations of the MeerKAT antennas. The background is from Google Earth.

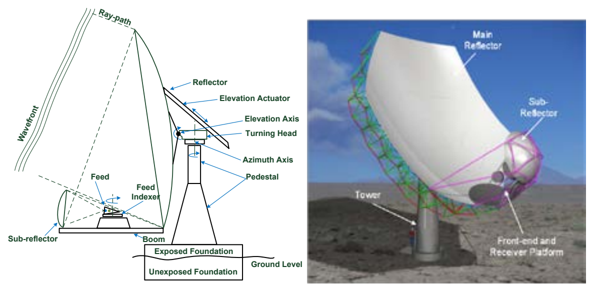

Figure 4: The offset Gregorian reflector design. Left: Schematic showing locations of major components. Right: An artist's rendition of the physical design.

Figure 4 illustrates the design of the SKA antennas. For the most part these are the performance-determining components of the telescope. The selection of offset Gregorian optics was guided by the following properties: large frequency range covering low frequencies, minimal scattering, a large amount of space in the focal region, lowest possible instrumental noise (i.e. spillover noise), smooth spatial and spectral responses limited only by fundamental physics (e.g. edge diffraction). This design has all of these properties but also requires more physical collecting area than a similar symmetrical design. The optics design includes 'shaping'; parameter space in other respects has been highly optimized over the full field-of-view.

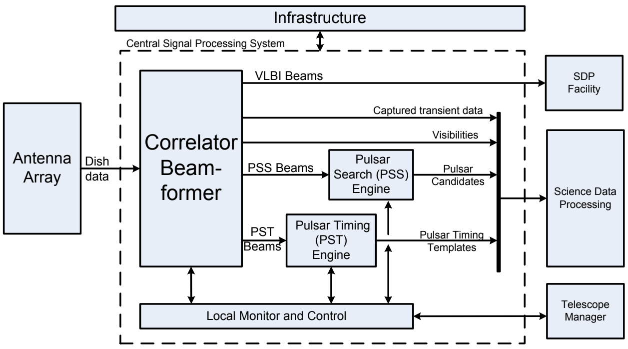

Figure 5: The functional context and flow diagram of Central Signal Processing (CSP) and Science Data Processing (SDP) systems.

Figure 5 shows the digital signal processing part of the system. The correlator beam-former (CBF) compensates for geometric and instrumental delays, divides the wide-band input data (up to 2 x 2.5 GHz) into narrow frequency channels ('channelises'), and correlates the signals (cross and auto) from each of the antenna pairs. Separately for pulsar search applications and for the inner 20 km of the array, the CBF provides channelized output data-streams for 1500 pulsar search beams each with 300 MHz of bandwidth, individually 'steerable' within the primary beam of the antenna. For pulsar timing applications, 16 'high-specification' beams can be formed so that polarization and time-domain artefacts are minimised. In addition, there is a beam-former that provides a data stream to a VLBI recording or e-VLBI interface.

Pulsar Search (PSS) consists of many processing steps that must be carried out on each beam. Time series lasting 100's of seconds are processed in sequence. An outline of basic steps is: de-dispersion (progressively delaying the signal with decreasing frequency to compensate for the dispersion of the interstellar medium), Fourier transform (FFT), folding and 'acceleration search'. The goal is to search a multi-dimensional space for weak repetitive signals with periods between a few ms and a few seconds, and with pulse widths from a few μs to a 10's of ms. In cases where a pulsar is orbiting a massive object, its period can change rapidly; hence the need for 'acceleration' as an extra search dimension.

The goal of pulsar timing is to monitor the 'arrival time' of pulsar signals over periods of up to 10 years. The means of doing this is described in the previous section.

Science data processing (Figure 5) is a major component of the telescope system. A summary of its functional requirements is:

1. Ingest of data from the CSP and the Telescope Manager.
2. Processing of input data into science data products:
   - Spectral data cube imaging and spectral extraction,
   - Continuum data cube imaging,
   - Final qualification of Pulsar Search candidates,
   - Transient detection,
   - Single-dish intensity mapping,
   - Rotation-Measure mapping.
3. Processing of input data into calibration products:
   - Telescope signature removal,
   - Removal of atmospheric and ionospheric effects.
4. Archiving of the science data products.
5. Access to the long-term science data archive.

The problem size and the amount of data to be generated by the correlator, and the pulsar search and timing engines requires high-performance-computing (HPC) infrastructure.

4. Performance

Telescope performance has so many dimensions that only a cursory treatment is within the scope of this paper. Figure 6 is a plot of the ratio of effective area to system temperature (A_e/T_{sys}) for an individual SKA antenna. For reflector antennas, effective area is the product of the physical area and an efficiency factor.

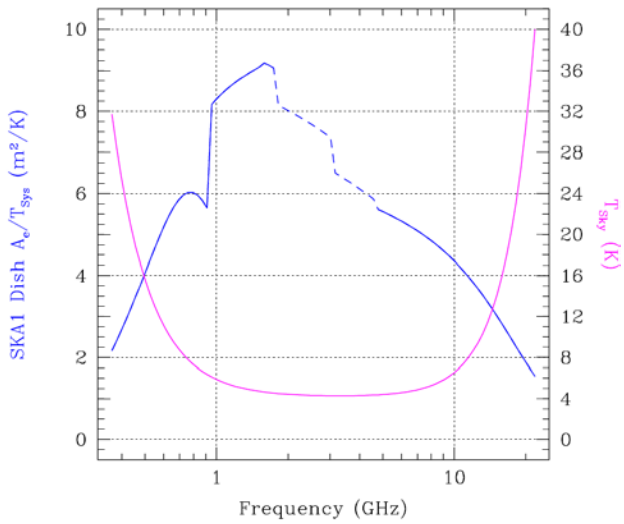

Figure 6: The A_e/T_{sys} sensitivity of an SKA1-mid antenna over its frequency range. SKA1-mid requires 5 receiver bands to cover from 0.35 to 13.8 GHz . The dashed part of the curve is for bands 3 and 4, which are not expected to be fitted initially.

For SKA antennas, the efficiency is 80-90% from ~1-15 GHz. It drops off at the low-frequency end because the sub-reflector becomes electrically small, and at the high end when reflector surface errors become larger than ~λ/30. Noise at the extreme ends of the frequency range arises mainly from sky background (see Figure 6). Between 1 and 20 GHz, noise arises from the front-end amplifiers and increases with frequency.

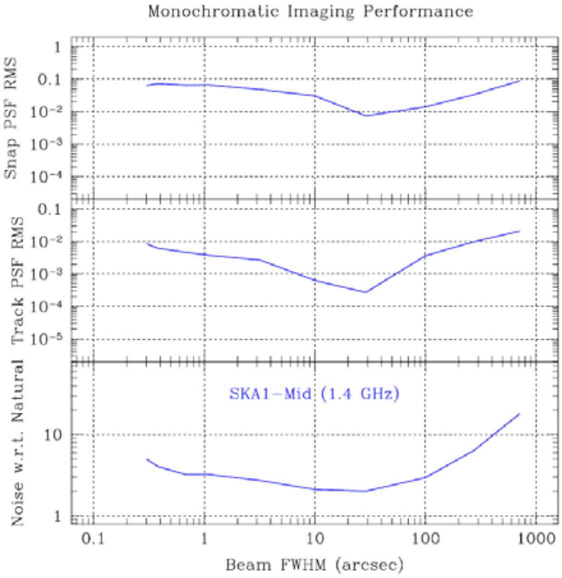

Figure 7: Beam performance at 1.4 GHz for a single frequency, equivalent to a typical spectral line observation. Bottom: The ratio of noise on an image to the minimum attainable (with natural weighting) as a function of beamsize. Middle: The ratio of rms sidelobe level to the peak of the beam for an 8-hr track. Top: The ratio of rms sidelobe level to the peak of the beam for a zenith snapshot observation.

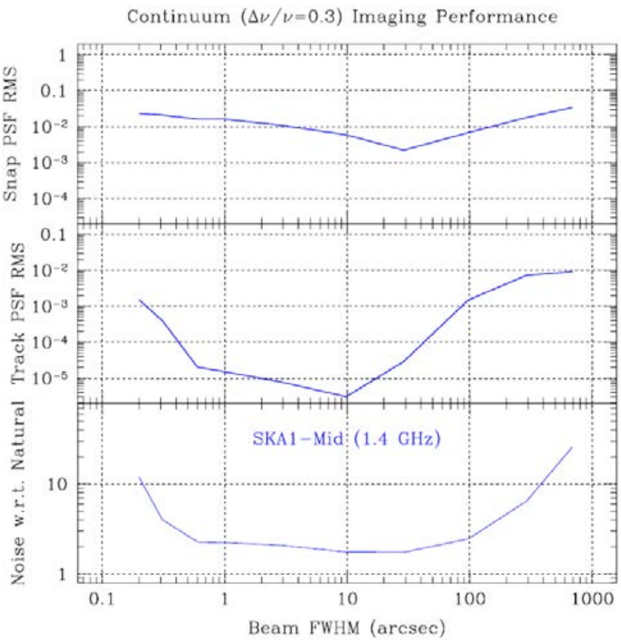

Figure 8: Similar to Figure 7, except that the bandwidth ratio is similar to that expected for a typical continuum observation.

Figure 7 and Figure 8 are plots of three measures of beam quality. The quality of the synthesised beam can be characterised by its rms sidelobe level for a given sensitivity (A_e/T_{sys}). The metric used here is the side-lobe level in the central 10x10 beam areas around the synthesised beam (PSF). The primary drivers are the distribution of collecting area (array configuration) and the duration of tracking. Almost as important is the fractional bandwidth being sampled, which for continuum observations can be very large, but cannot be considered for spectral line observations. In addition, the visibility weights used in forming the beam, which can be applied post-observation, are also important. However, there is always a trade-off between signal-to-noise ratio and beam-shape. Unweighted *u-v* samples (so-called natural weighting) produce the highest signal-to-noise, but a rather poorly shaped beam. The visibility data weighting method employed for the illustration is so-called "uniform" weighting, followed by a Gaussian visibility taper to yield the specified PSF diameter.

5. Systematic Errors

Many of the most challenging science programs will require very long integration times – a target of 1000 hr has been set. The essential test of this is whether fluctuations on images and in the spectral domain are reduced in amplitude as $\sqrt{\tau}$, where τ is the integration time (i.e., limited only by 'natural' sources of noise, not instrumental errors). For spectral-line and continuum imaging applications, this applies at the full resolution over the full field-of-view across the full range of frequencies. Similarly challenging requirements exist in the time domain.

In general the aperture synthesis technique is robust because correlation tends to suppress independent errors arising from different array elements. Also phase and amplitude 'closure' rules enhance robustness. Nevertheless errors that that add coherently over time tend to be those that are inherent in the design. Accordingly a significant part of the design effort is devoted to identifying sources of error and to providing 'budgets' to distribute allocations across the system. Antenna optics, pointing, path length, and 'design for calibration and modeling' and examples of this work.

6. Acknowledgements

The huge number of engineers, scientists and others working on the design of the SKA telescopes are acknowledged here. This paper is possibly the smallest possible description of one telescope, and cannot possibly do justice to all those contributions.