MeerKAT as an SKA Pathfinder

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Abstract

The MeerKAT is a pathfinder for the “small dish plus single-pixel wideband feed” scenario for the SKA. The current reference design is a centrally condensed array of 80 12-meter dishes with baselines extending out to 10 km. The goal frequency coverage is 0.7-10 GHz, matching the SKA draft specification for mid-band dishes. The technologies and techniques that MeerKAT will develop and evaluate include: wide-bandwidth feeds, low-cost dish antennas, instrumentation for high dynamic range observations, packet-switched array processing architectures, shielding of component RFI, mitigation of external RFI, and low-cost and reliable remote telescope operation.

1. Introduction

The MeerKAT is a “Large-N Small-D” (LNSD) science and technology demonstrator for the SKA radio telescope. It will be located in the Karoo radio astronomy reserve, an RFI quiet environment protected by new legislation designed to ensure the maintenance and improvement of the current low RFI levels. This reserve is also the location for the SKA as proposed by South Africa, and the extensive reserve area will be available for other radio astronomy instruments requiring stringent RFI control.

2. Specifications and Performance

Table 1 lists the specifications for the current MeerKAT reference design, and also indicates the direction in which these parameters and technology choices might evolve as products from the associated technology development programme become available. The eventual operating frequency range will be directed by the needs of the SKA project. Currently it appears that the upper frequency limit for SKA Phase 1and Phase 2 will be 10 GHz, hence the goal upper frequency of this value. The 2.5 GHz value for the reference design reflects the SKA mid-band specification prior to November 2007. The lower frequency limit will be partially determined by the upper operating frequency of the aperture array component of the SKA.

Table 1: Specifications and technology choices for the MeerKAT Reference Design, and possible alternatives that might be realized.

Subsystem/specification	Current Reference Design	Possible Alternative
Feed	single-pixel wide-band	single-pixel wide-band
Lower frequency	500 MHz	700 MHz
Upper frequency	2.5 GHz	10 GHz
Dish diameter	12 m	12 m
Surface accuracy (RMS)	2 mm	1 mm
Optical configuration	symmetric prime focus	offset or symmetric Gregorian
Mount geometry	alt/az	equatorial
Number of dishes	80	80
Aperture efficiency	0.7	0.7
T_{sys}	30 K	25 K
Polarization isolation (antenna)	20 dB	25 dB
Instantaneous bandwidth	512 MHz	1024 MHz
Spectral channels	16 k	64 k
Minimum baseline	20 m	20 m
Maximum baseline	7 km (70% within 700 m)	10 km (70% within 700 m)
Correlator architecture	FX	FX

MeerKAT is scheduled for completion at the end of 2012 and it will be preceded by a series of prototyping phases and technology development programmes. The final specifications will be modulated by the need to build MeerKAT for a fixed capital and operational cost.

The centre and right-hand columns of Table 1 have entries that indicate that there are open design choices for MeerKAT. Two key specification decisions that depend on cost and performance requirements are the optical path and the mount geometry. Dynamic range has been identified as an important driver for the SKA design, and the stability and quality of the antenna primary beam are important factors that limit the achievable dynamic range in existing interferometer arrays. The MeerKAT project includes extensive studies of the effects of optical configurations and mount geometries on the performance of the primary beam.

The choice of 12 m for the dish diameter resulted from a number of tradeoff studies, including the use of various costing models. An implicit consequence of this choice is the restriction of the lower operating frequency to about 500 MHz. Because the antenna structure is a dominant cost component, even for relatively small dishes, it appears that cryogenic cooling of receivers is warranted for cost effectiveness above 700 MHz, hence the goal T_{sys} of 25 K.

Table 2 lists the performance metrics derived at 1420 MHz for the MeerKAT reference design, using the specifications from the middle column of Table 1. The point-source sensitivity of 211 $m^2.K^{-1}$ for the reference design is close to the L-band performance of the eVLA, but the mapping speed and brightness temperature sensitivity at 1' resolution outstrips the eVLA and other existing compact interferometer arrays because of the high filling factor within a diameter of 700 m. These performance metrics will allow new insight into the evolution of galaxies, the nature of cosmic magnetic fields, the mapping of extended low-brightness radio emission features, and the detection of radio transients and pulsars. The MeerKAT observing programme will consist largely of shallow wide-field and deep narrow-field surveys of radio continuum, HI emission and absorption, OH maser lines, recombination lines and radio transients (including pulsars). Full Stoke polarimetry will be available and the optical configuration will be designed to contribute low instrumental polarization.

Table 2: Performance metrics at 1420 MHz derived from the MeerKAT Reference Design specifications in Table 1.

Metric	Value
A_e/T_{sys}	211 $m^2.K^{-1}$
Spectral line survey speed	1.12×10^{-2} $deg^2.s^{-1}.Jy^{-2}.Hz^{-1}$
Continuum survey speed	5.75 $deg^2.s^{-1}.Jy^{-2}$
Brightness temperature survey speed (1' resolution)	1.02 $deg^2.hr^{-1}.K^{-2}.kHz^{-1}$

3. Technology Development

As an SKA pathfinder the MeerKAT project includes a technology development programme that will investigate novel technologies and techniques aimed at reducing the technical and cost risks associated with modern radio telescopes. Some of the entries in the right-hand column of Table 1 represent goal specifications that might be achieved if these development activities are successful. The technology development programme is underpinned by prototyping and early deployment phases, including extensive laboratory integration, a prototype 15-m composite material dish with feed, receiver and digital backend at the HartRAO observatory, and a seven antenna prototype array of 12-m dishes at the Karoo site. Formal systems engineering processes are employed to minimize risks associated with integration and commissioning, and cost overruns.

The MeerKAT project has identified a subset of the technology challenges that face the SKA that will be pursued by the project team in the development of MeerKAT. The three most prominent of these are briefly described below. In addition to these three areas of development the MeerKAT programme will also require investigation into other technical operational issues, such as reduction of RFI emission from all classes of electronic equipment, shielding of residual RFI emissions, RFI mitigation in the signal processing path, pipelined data processing and quality assessment, remote operation of a large scientific instrument, RFI silent provision of grid and backup power, and the use of renewable energy technologies for power and cooling.

3.1 Novel dish antenna design and fabrication

A prototype 15 m dish fabricated using composite materials (glass-fibre, foam and steel) was constructed at HartRAO during early 2007. The relatively large diameter and flat focal ratio (f/D = 0.5) seem inappropriate for the MeerKAT Reference Design, but this was because the dish specifications were frozen at a time that PAFs were being considered for MeerKAT. The dish saw "first light" in July 2007 just 7 months after the foundations were laid in December 2006. This prototype has shown that the use of composite materials is viable and financially competitive. The overall rms surface accuracy is 2 mm, with the inner 12 m section achieving better than 1.5 mm rms.

The next round of prototyping will involve the construction of 7 dishes at the MeerKAT site. These dishes will have a diameter of 12 m, and have a focal radio f/D = 0.38, which is more appropriate for the wide-band feeds being considered. The company that built the initial prototype has undertaken an extensive optimization study based on their experiences with the 15 m dish. This study has provided a new design that will be much lighter and cheaper than the original, and will provide a surface accuracy of 1 mm rms.

In the light of the concerns within the SKA community over imaging and spectral dynamic range, feasibility and design studies are underway to investigate alternative optical configurations and mount geometries for MeerKAT. Included in the options being considered are symmetric and offset Gregorian optical paths to reduce stray sidelobes and antenna crosstalk, and equatorial mounts to defeat primary beam rotation on the sky.

3.2 Wide-band feeds and receivers

The MeerKAT Reference Design calls for a dual-polarization feed with a 5:1 frequency span and the goal frequency range is more than double this. Conventional waveguide OMTs and feeds cannot operate optimally beyond octave frequency ranges, so a novel wide-band feed antenna will be required if a single feed/receiver package is to be employed. The ATA already uses a log-periodic feed that boasts an 11:1 frequency coverage with good impedance matching across the band [1], but this feed suffers from the drawback of a frequency-dependent phase centre.

Two groups are working on wide-band feed antennas for radio astronomy use that have fixed phase centres, both of which employ a structure based on dual parallel dipoles over a ground plane. The "Eleven Feed" [2] developed at Chalmers University produces a circular beam with an illumination angle that is constant with frequency. Current implementations of this feed show poor matching performance across the band, and resistive losses contribute significantly to system temperature. Further development of this feed will be conducted as a joint collaboration between the MeerKAT project and Chalmers. This development will include the optimization of the feed structure, and the investigation of how to cool the entire feed to counter ohmic contributions to system temperature.

A quasi self-complementary feed structure is being developed at Cornell University [3] that has been designed to overcome the mismatch and loss problems currently suffered by the Chalmers feed. The prototype of this feed is currently being fabricated and tested. This feed will also be considered as a solution for MeerKAT, with the possibility of cooling the entire feed antenna structure.

The cooling of either of these feeds to cryogenic temperatures provides a significant challenge because of their large diameter. A project within the MeerKAT programme is currently underway to determine the feasibility of developing a cryostat for these feeds. This study includes the electromagnetic effects caused by enclosing the feed in a metallic cylinder. The most likely cooling technology will be high-reliability Stirling cycle refrigeration devices, similar to those used by the ATA.

3.3 Packet-based signal processing

The CASPER collaboration on reconfigurable signal processing systems for radio astronomy grew out of the pioneering work done at Berkeley [4]. Signal digitization and front-end array processing for MeerKAT will be implemented using hardware and firmware developed within the CASPER development environment, and the MeerKAT DSP team are active members of the collaboration. A novel feature of the CASPER architecture is the use of a packet-switched network fabric for data routing. Current prototyping is being conducted on IBOB and BEE-2 hardware [5], with the ROACH board currently being produced for greater performance.

4. Conclusion

When operational from 2013 the MeerKAT will demonstrate novel technologies that will drive down the cost of construction and operation of large radio telescope facilities, and improve their reliability and performance. It will also demonstrate the benefits of operating a sensitive radio telescope in a controlled radio quiet environment, and highlight the challenges presented by remote operation of a large facility in an arid area. The science programme for MeerKAT will provide early results that will steer the future development of SKA Phases 1 and 2.

5. References

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