PROCEEDINGS OF SCIENCE

MeerKAT Science and Technology

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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 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.
The reference design for MeerKAT is a connected array of 80 12-metre dishes equipped with single-pixel wide-band feeds covering 500 MHz to 3 GHz in a continuous band. The array configuration will support a compact core for imaging of low-brightness objects and detection of rapid transient events and pulsars, and a component extending out to 7 km and beyond for sub-arcminute continuum and line imaging.
The point-source sensitivity of 200 $m^2.K^{-1}$ 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. These performance metrics will allow new insight into the evolution of galaxies, cosmic magnetic fields, radio transients and pulsars. The instrument will provide information that will guide the specifications of the SKA Phase-1 and the full SKA.

Innovative technologies that are to be demonstrated by the MeerKAT include inexpensive dish fabrication using composite materials, novel wide-band feed antennas, and packet-switched correlator and array signal processing hardware based on reconfigurable logic. Formal systems engineering methodologies are being used to constrain integration risks and cost overruns, and the logistics of remotely operating a large facility are being studied to reduce operations costs.

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1. Introduction

The South African government, through the Department of Science & Technology (DST) and the National Research Foundation (NRF), has identified Astronomy as priority discipline in the natural sciences because of the advantages provided by the geographic location and topography of the country and its neighbours. Major existing astronomical instruments in the Southern Africa region include SALT (optical/UV) and HESS (γ-ray).

This prioritization of astronomy was the motivation for South Africa's participation in the international SKA project. One aspect of this involvement is the South African proposal to host the SKA, but from the outset the DST and the NRF indicated that the country's scientists and engineers should be embedded in the scientific and engineering aspects of the project, independent of the SKA site contest. This policy culminated in the proposal to construct an SKA pathfinder near to the proposed SKA core site in the Karoo region.

Initially the pathfinder project was dubbed the Karoo Array Telescope, or KAT, but was subsequently renamed MeerKAT when additional funding was secured from the Treasury. Currently the funding provided by the Treasury for MeerKAT development and construction stands at about 80 million Euros. This figure excludes supplementary funding for major infrastructure such as roads, and the provision of grid power and data transport. MeerKAT is scheduled for completion at the end of 2012.

The location and extent of the radio astronomy reserve in the Northern Cape province is shown in Figure 1. The national government have recently passed the Astronomy Geographic Advantage Act that provides stringent legislation to protect the reserve against transmissions that would interfere with the operation of radio telescopes in the reserve. Figure 2 illustrates the physical characteristics of the region.

2. MeerKAT Reference Design and Specifications

The scope of the project has evolved since the original KAT was proposed. This evolution has been driven by the funding scenario, the progress made in defining the science case and specifications of the SKA itself, and the technical advances being pioneered by SKA-related development programs around the world. The initial KAT was specified as 20 15-m dishes with phased array feeds (PAFs) located at the prime focus. The PAF concept was replaced by a multi-feed cluster (MFC) when the technology readiness of PAFs on the KAT time-scale became a concern. When additional funding was approved for MeerKAT the array expanded to 80 12-m dishes with single-pixel wide-band feeds, matching one of the proposed SKA scenarios for frequencies above 500 MHz.

Being an SKA pathfinder, it is imperative that the MeerKAT tracks the scientific and technology developments in the international project, but it is also important for there to be sufficient focus within the project in order for local timeline and funding constraints to be met. In this volatile environment the concept of a Reference Design has proved useful. This Reference Design defines the most probable realization of the MeerKAT at any given time. Changes to this nominal specification are made in response to new science opportunities, technology advances, changes in

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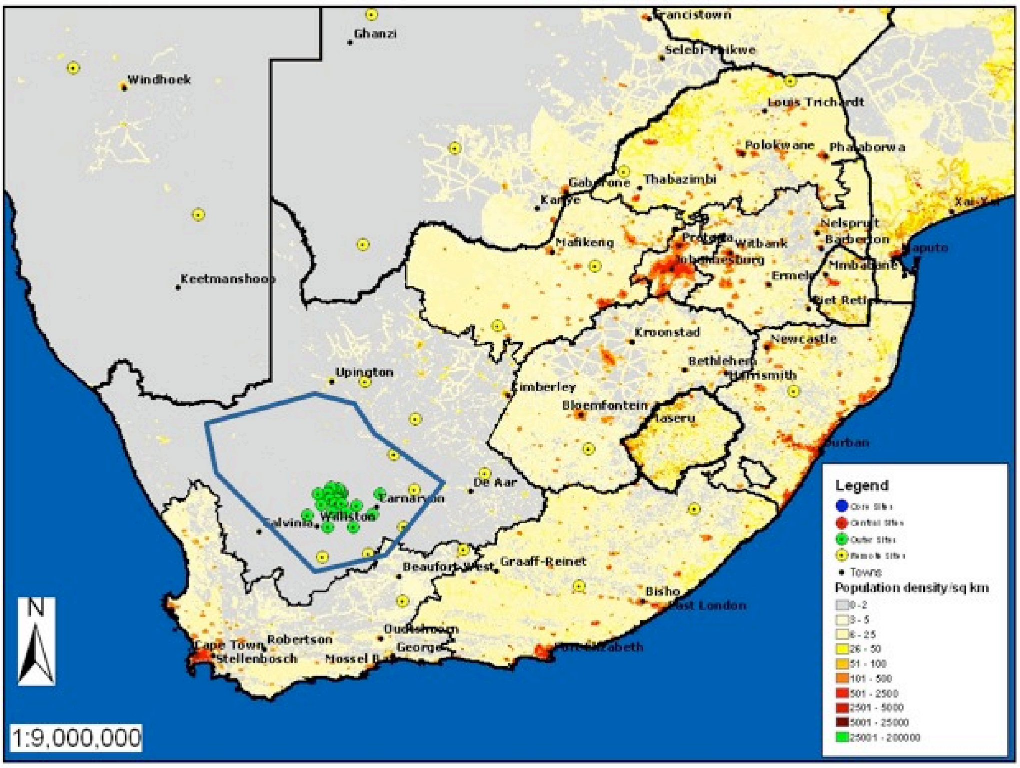

Figure 1: The location and extent of the Radio Astronomy Reserve established in the Northern Cape province in South Africa. The MeerKAT will be located within this reserve. Most of this Reserve overlaps with the semi-arid Karoo geographic region.

component costs, and changes within the SKA project itself. The changes to specifications and design are only made after careful review.

The middle column of Table 1 lists the top level specifications and technology choices for the current Reference Design for MeerKAT. The right-hand column of Table 1 is discussed in Section 5. Table 2 provides the sensitivity and survey speed metrics derived from these specifications. Figures 3, 4 and 5 compare the performance of MeerKAT against existing radio astronomy facilities in these metrics. Although the sensitivity of the MeerKAT is equivalent to existing 100 m single dishes and the eVLA, it exceeds these instruments in the various measures of survey speed because of the relatively large field of view provided by the primary beam of the 12 m dishes.

The size of the array (80 dishes) was determined from detailed costing exercises using realistic component and construction costs, and the expected funding scenario. This costing exercise indicated that the cost of dish antennas is a dominant component of the cost equation for such an array telescope. The 12 m dish diameter was determined from optimization exercises using the SKA costing tool, and a study conducted by a consulting engineering company. The centre-fed optical configuration was chosen for simplicity and expected low construction cost. The alt/az mount geometry was selected for similar reasons.

The Reference Design frequency range reflects early speculation on the band to be covered by the mid-frequency SKA. This band covers the HI, magnetism, pulsar and transient science

Figure 2: The Karoo landscape near to the proposed site for the MeerKAT array and the SKA core. Notice the extensive flat area in the foreground and the flat-topped hills in the distance that provide RFI shielding towards the south.

programmes that are appropriate to MeerKAT. The specified surface accuracy is more than adequate for the upper frequency of 2.5 GHz. The 12 m dish diameter corresponds to 20λ at 500 MHz, which is sufficiently large to avoid diffraction and spillover losses in the prime focus configuration.

A tradeoff study indicated that in order to achieve a competitive sensitivity (A_e/T_{sys}) it will be necessary to cryogenically cool the receiver, and possibly the feed antenna, to achieve an aggregate system temperature of 30 K. The instantaneous bandwidth and spectral resolution were matched to the requirements of the proposed HI and OH maser science, and moderated by cost implications.

The configuration of the MeerKAT array has not been finalized, and is the subject of various simulation studies. It is likely that about 70% of the collecting area will be located within a 700 m diameter region in order to achieve the high filling factor required for observing extended low surface brightness targets and transient sources. Baselines out to 10 km will be included to provide sufficient u-v coverage for source localization that will allow cross-identification with surveys at other wavelengths.

3. Technology Development

The funding of the MeerKAT by the South African government is provided on the understanding that it will be a world-class scientific facility, delivered on an ambitious time-scale. As an SKA pathfinder the MeerKAT project has the responsibility to develop and test technologies that are required by the larger project. These two requirements provide an interesting challenge,

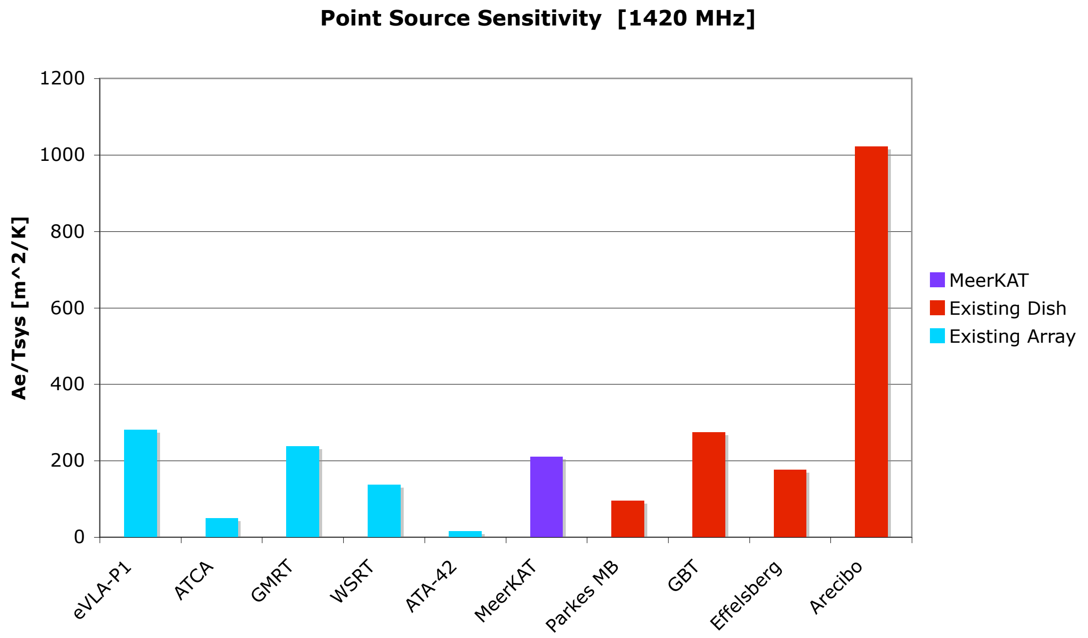

Figure 3: Comparison of the sensitivity (A_e/T_{sys}) of MeerKAT at 1420 MHz against various existing array and single dish facilities. The sensitivity metric for MeerKAT was derived from the specifications for the Reference Design in Table 1.

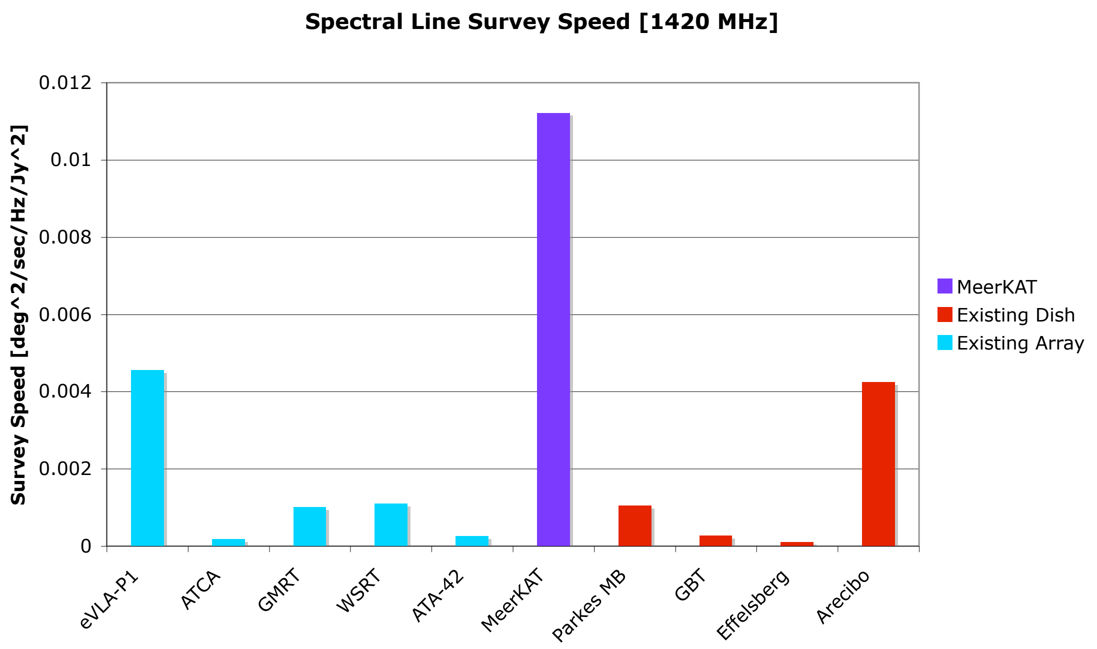

Figure 4: Comparison of the spectral line survey speed of MeerKAT at 1420 MHz against various existing array and single dish facilities. The survey speed metric for MeerKAT was derived from the specifications for the Reference Design in Table 1.

Table 1: Specifications and technology choices for the MeerKAT Reference Design. The right-hand column indicates the directions that the specifications might move towards in the next iteration of the Reference Design (see Section 5).

	Current Reference Design	Possible future scenario
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 Gregorian
Mount geometry	alt/az	alt/az
Number of dishes	80	80
Aperture efficiency $\varepsilon_{\rm ap}$	0.7	0.7
System temperature $T_{\rm sys}$	30 K	30 K
Polarization isolation	20 dB	25 dB
Instantaneous bandwidth	512 MHz	1024 MHz
Spectral channels	16 k	64 k
Minimum baseline	20 m	20 m
Maximum baseline	10 km (70% within 700 m)	10 km (70% within 700 m)
Correlator architecture	FX	FX

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

Metric	Value
$A_{\rm e}/T_{\rm sys}$	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}

requiring a careful trade between risk and reward (in the form of performance enhancement and cost reduction).

In order to achieve these somewhat contradictory objectives it has been necessary to ensure that the project includes processes that constrain budgetary and technology risks within acceptable bounds. Two such processes are:

- Well-defined prototyping phases that retire technology risks and advise technology choices as soon as possible.

- The use of formal systems engineering methodologies to reduce integration risks and budgetary overruns.

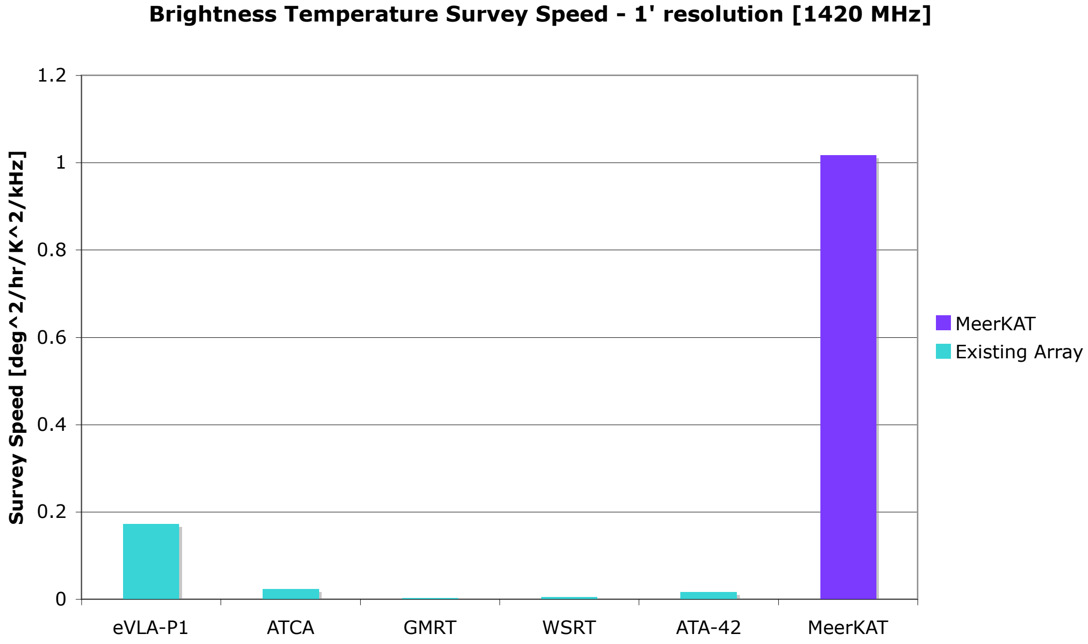

Figure 5: Comparison of the brightness temperature survey speed of MeerKAT at 1420 MHz against various existing array facilities for an imaging resolution of $1'$ (corresponding to a maximum baseline of 700 m at 1420 MHz). The survey speed metric for MeerKAT was derived from the specifications for the Reference Design in Table 1.

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 most prominent of these are discussed briefly below.

3.1 Novel dish 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, which saw "first light" in July 2007 just 7 months after the foundations were laid in December 2006, is shown in Figure 6. 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 $\approx$ 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.

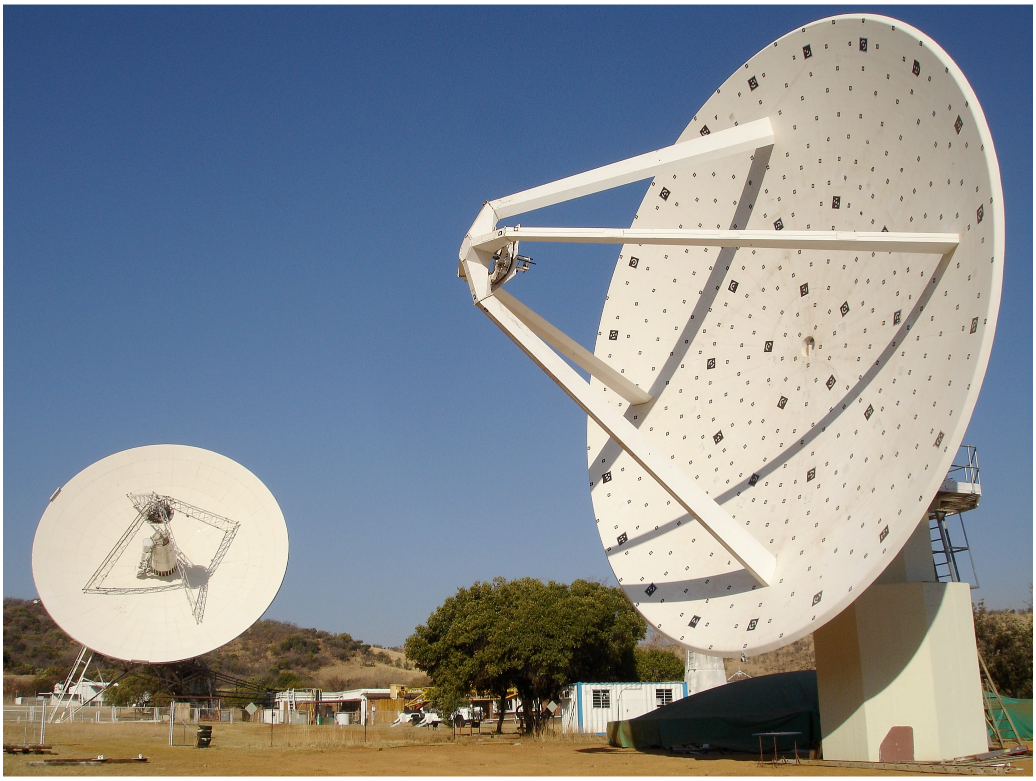

Figure 6: Prototype 15-m composite dish at HartRAO. Photogrammetry targets have been attached to the primary reflector for surface accuracy tests. The HartRAO 26-m dish is in the background.

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 for MeerKAT. Included in the options is the offset Gregorian optical path used by the ATA [3], but it is likely that the MeerKAT dishes will be larger than 6.1 m and the effective focal ratio will be shorter to match the illumination angle of the feeds discussed in the following section.

3.2 Wide-band feeds and receivers

The MeerKAT Reference Design call for a dual-polarization feed with a 5:1 frequency span. 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 [4], 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" [6] 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 [2] 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 [7]. 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 [5]. Current prototyping is being conducted on IBOB and BEE-2 hardware, with the ROACH board currently being produced for greater performance [1].

4. Science Objectives

A brief listing of the science objectives envisioned for the MeerKAT is given below. The MeerKAT science case is currently being drafted, and it is likely that the observing programme will be dominated by long-term blind and directed surveys, and temporal monitoring programmes.

- An all-sky HI emission survey to detect $\approx 10^6$ galaxies out to $Z = 0.2$ (a sensitivity and resolution extension to HIPASS).
- An all-sky HI absorption survey towards $\approx 10^7$ targets.
- Ultra-deep single-pointing HI emission surveys to study the HI mass function out to $Z = 0.6$.
- Shallow all-sky and deep restricted field surveys of rotation measures (RMs) towards point sources to (1) study the evolution of the magnetic structure in local clusters, (2) probe the magnetic fields in galaxies out to $Z \approx 2$, and (3) map the RM structure of local galaxies (including the Milky Way).
- All-sky continuum point source surveys to detect radio galaxies down to the confusion limit in order to study (1) the formation and evolution of large scale structure (LSS) and (2) active galactic nuclei (AGN).

- Wide-field continuum maps to conduct polarimetry of the extended synchrotron emission from local galaxies and the Milky Way.
- Serendipitous transient signal monitoring surveys to detect pulsars and other known and new classes of radio transient sources.
- Targeted pulsar monitoring surveys to study intrinsic and extrinsic variations in pulse profiles and timing.
- Detection and monitoring of Galactic and extra-galactic OH masers.
- Mapping of hydrogen, helium and carbon recombination lines from diffuse HII regions in the Milky Way and nearby galaxies.
- Continuum mapping of extended, low surface brightness Galactic radio sources, including diffuse HII regions and supernova remnants (SNR).
- Mapping the diffuse, low surface brightness HI and continuum emission associated with the "cosmic web" and galaxy clusters.

5. The Evolution of MeerKAT

The right-hand column of Table 1 indicates the direction in which the MeerKAT Reference Design specifications might move in the future. These changes in specification are being driven to a large extent by the recent changes in the SKA mid-band specifications, and the concern over dynamic range limitations imposed by time-varying image-plane effects. Although non-symmetric folded optical configurations will undoubtedly cost more than centre-fed symmetrical configurations, the cost premium might be outweighed by the expected improvements in sensitivity and beam sidelobe performance.

The raising of the lower operating frequency from 500 MHz to 700 MHz was made in recognition of the role that aperture arrays might play in this region of the spectrum. This shift also reduces the size of the wide-band feeds, easing the problem of cryogenic cooling of large antennas.

Raising the upper operating frequency from 2.5 GHz to 10 GHz was in response to the SKA scientific community's instance that the SKA mid-band implementation operate up to this frequency. This shift will significantly improve MeerKAT's continuum imaging capabilities.

Feasibility and costing studies will be undertaken before redefining the MeerKAT Reference Design to reflect some or all of these new specifications. Parallel technology development programmes will be undertaken to inform these studies.

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