An Overview of the MeerKAT Project

R.S. Booth[1], **J.L. Jonas**[2]

[1]*SKA South Africa, The Park, Park Road, Pinelands 7405, South Africa*
rbooth@ska.ac.za

[2]*Rhodes University, P.O. Box 94, Grahamstown 6140, South Africa*
J.Jonas@ru.ac.za

Abstract: The MeerKAT radio telescope is a precursor instrument for the SKA mid-frequency band. It will, in its own right, be the most sensitive centimetre-wavelength telescope in the southern hemisphere, and its scientific scope will cover a wide range of topics in both astronomy and physics, from understanding the evolution of galaxies to testing Einstein's theory of General Relativity. This article gives a brief overview of the technical aspects of the telescope, and outlines the large-scale surveys that will be performed within the first five years of operation.

Introduction

MeerKAT is the radio telescope array which is the precursor of the South African Square Kilometre Array (SKA). Its development began with a prototype 15 m diameter single antenna of innovative design, and a test interferometer array of seven antennae known as KAT-7, which is now fully operational and nearing the completion of its commissioning programme. The single dish antenna, known as XDM was built at Hartebeesthoek Radio Astronomy Observatory (HartRAO) in 2007.

The dish was cast in a single piece out of composite material (fibre-glass) on a mould constructed on site. The mould had been flame-sprayed with a thin layer of aluminium before the composite material was laid up, forming the reflecting surface.

The antenna performed well within specification, having a surface rms of better than 2 mm, a figure confirmed by photogrammetry, as well as by measurements of radio sources, thereby proving the concept of an accurately formed, easily erected antenna that could be manufactured on site. XDM is operational and currently being used by HartRAO for geodetic VLBI and pulsar timing observations .

The second component, the KAT-7 interferometer array, is up and running at the Karoo Radio Astronomy Reserve. Its 12 m antennae were all fabricated using a mould in a large building at the Losberg site complex and from there transported on a trailer to the KAT-7 site for erection on the telescope mounts. The KAT-7 antennae have a more easily formed reflecting surface of fine wire mesh, and an rms accuracy of 1 mm. The L-band receivers have cryogenically cooled frontends (70 K), and data processing is conducted using another innovative development, to which KAT engineers have made important contributions. This is the ROACH ("reconfigurable open architecture computing hardware") board, which is the primary building block for digital signal processing in several next generation radio telescopes.

The experience gained from these prototypes has been factored into the MeerKAT antenna, together with advice received during a 2010 Concept Design Review (CoDR). This review was performed by a strong international team of engineers and scientists, and chaired by Professor Wim Brouw. The resulting concept for the array design is that of 64 Gregorian offset antennae, each with a projected diameter of 13.5 m.

In October 2009, an open invitation was sent to the international astronomical community to propose Key Science Projects for MeerKAT. The result was an overwhelming response: 20 proposals from more than 500 scientists worldwide. (These will be discussed later in this paper.)

The MeerKAT Concept

The MeerKAT will be the most sensitive centimetre-wavelength radio telescope in the southern hemisphere, and will rank highly in the world. It will provide high dynamic range, high-fidelity imaging over almost an order of magnitude in resolution, with a maximum resolving power of 6 arcsec at 1420 MHz. It will be optimized for deep high-fidelity imaging of extended low brightness emissions, the detection of micro-Jansky radio sources, the measurement of polarization, and the detection and monitoring of transient radio sources. The frequency range will ultimately be 580 MHz to 14.5 GHz, but in the first phase (2016) we envisage a range of 1 to 1.75 GHz (although after a recent meeting of PIs we are attempting to decrease the lower end of the band to 900 MHz with, perhaps, a small penalty at the upper end which will probably be set at 1670 MHz). A high frequency receiver (8 to 14.5 GHz) will give access to Galactic Centre Pulsars and facilitate measurements of carbon monoxide and, by extension, studies of molecular hydrogen in the early Universe at red-shifts $z = 7$ or more.

MeerKAT Design Criteria

High sensitivity implies a large effective collecting area (A_e) and a low system temperature $T_{\rm sys}$, or maximization of the ratio $A_e/T_{\rm sys}$. High $A_e/T_{\rm sys}$, together with high dynamic range, are the hallmarks of a powerful interferometer array. $T_{\rm sys}$ must not be compromised, e.g. by using current ultra-wide band feed/receiver developments (until they match the noise performance of their more conventional narrower band units). Furthermore, A_e must be maximized through low antenna blockage and high aperture illumination, without introducing high or polarized antenna side-lobes.

Since MeerKAT is designed to be a multi-frequency instrument, the antennae should be capable of carrying several receivers simultaneously since changing receivers manually on 64 antennae would not be practical.

All of these factors point towards the final choice of Gregorian offset antennae, as recommended by the expert CoDR panel (see Fig. 1). Such antennae have lower side-lobes and better polarization characteristics than conventional centre-fed antennae, and have reduced spill-over and spurious polarization effects. This gives superior RFI rejection, and enhanced sensitivity and signal fidelity.

Furthermore, because receivers are not mounted at the prime focus but rather on the arm supporting the Gregorian subreflector, several (up to four) cryogenically cooled receivers may be supported without causing aperture blockage.

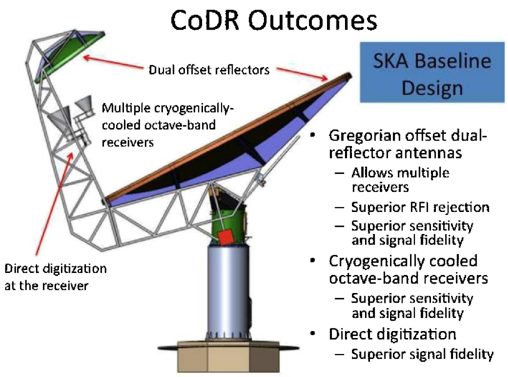

Figure 1: MeerKAT offset Gregorian antenna with its attributes listed.

In another bold move, the MeerKAT digital engineers are working to eliminate an intermediate frequency stage in the receivers by digitizing the entire RF frequency bandwidth after amplification in a low noise receiver. While this is currently feasible for the L-band receiver, it will be a significant challenge to digitize at 14.5 GHz, but the engineers involved are confident that by 2016 this will be possible.

MeerKAT Phasing

Being an array radio telescope, MeerKAT can and will be built in phases. Early science will be possible before the full 64 antennae are erected, and the receivers covering different parts of the operating frequency range will be deployed in a serial fashion. The initial and future phases are summarized below.

Phase 1

This will consist of 64 Gregorian offset antennae, each with a projected diameter of 13.5 m. The maximum baseline will be 8 km, and 70% of the collecting area will be within a 1 km diameter core to provide high brightness temperature sensitivity and reduce the computational load for transient data processing. There will be a receiver indexer at the secondary focal position, allowing up to four receivers. The single Phase 1 receiver is currently specified to cover 1.0-1.74 GHz, but this range may change to 0.9 - 1.67 GHz in order to allow the deep HI survey to probe deeper with respect to redshift. The specified sensitivity is 220 m^2/K, but this is expected to improve to $\approx$ 300 m^2/K with the use of cryogenic receiver systems that achieve $\approx$ 20 K physical temperature. Direct sampling of the radio frequency (RF) signal will be implemented, with all signal processing being performed in the digital domain using hardware and algorithms developed as part of the CASPER collaboration.

Future Phases

Future phases of MeerKAT will expand the capabilities of the telescope as funding allows. The frequency coverage of the instrument will be extended with the installation of up to three additional receivers:

1. 580 - 1000 MHz: This receiver will extend the redshift range of the deep HI survey and will be used to observe steep-spectrum continuum sources.
2. 8 - 14.5 GHz (goal: 4-16 GHz): This wide bandwidth receiver will allow the detection of highly redshifted CO emission, the detection and monitoring of pulsars in the Galactic centre, and the mapping of the emissions from a variety of molecules.
3. 1.5 - 3 GHz: The primary use of this receiver will be the precision timing of pulsars for the detection of gravitational waves.

If funding allows, an additional seven antennae will be added to the array, extending the maximum baseline out to 20 km. This will improve the resolution of the array so that the deep continuum survey will be able to probe to lower flux densities without being affected by source-confusion. Further expansion of the array to increase the collecting area (and perhaps resolution) will depend on the decisions relating to the construction of the SKA.

MeerKAT Science: The Large Survey Projects

MeerKAT is one of a number of new/re-scoped radio astronomy arrays under construction/test at the moment. These include the ALMA in Chile, EVLA in the USA, E-MERLIN in the UK, LOFAR and APERTIF in The Netherlands, and ASKAP in Australia. There is considerable synergy among these projects and at least four have chosen to allocate a large fraction of their observing time to large survey projects, which has generated considerable interest among members of the international astronomical community. In the case of MeerKAT, it was decided to allocate 70% of the observing time in this way, with the remaining 30% being reserved for PI projects ($\approx$ 20%) and the Director's discretionary/urgent observations ($\approx$ 10%).

The call for large survey project proposals returned 20 excellent and timely project ideas from a total of 700 astronomers world-wide (some 500 individuals, including 68 South African astronomers). The total time requested amounted to about 10 years of full-time observing and so a Time Allocation Committee (TAC) was set up to adjudicate and rank the proposals.

The TAC comprised 10 world-ranking astronomers, and was chaired by Joseph Lazio, the SKA Project Scientist. The other members were Frank Briggs, Simon Johnston, Athol Kemball, Robert Laing, Jay Lockman, Andrew Lyne, Roy Maartens and Thijs van der Hulst. The Committee rated ten of the proposals to be both of outstanding quality and feasible with MeetKAT, with a total observing time of about 5 years.

The two most highly rated proposals were a pulsar timing proposal (PI: Matthew Bailes) and a deep HI survey to detect HI at the highest possible redshift ($z = 1.4$) with MeerKAT (Acronym LADUMA) at 580 MHz. (PIs: Sarah Blythe, Andrew Baker and Benne Holweda). In addition to these ten highly ranked surveys, the TAC also felt that a proposal to measure polarization properties of some nearby galaxies using the technique of rotation measure synthesis had great merit, but suggested that only part of the observations should be conducted, as a bi-product of a proposal to study nearby galaxies. The committee also supported the use of MeerKAT for VLBI, a proposal led by Michael Bietenholz of HartRAO, even though this did not constitute a "large survey".

In this paper we can only summarise the scientific goals of the various projects, and we group the proposals in terms of Spectral Line, Continuum and Transient observations respectively.

HI (and OH) Galaxy Surveys

Galaxies form from gas that cools and condenses within dark matter halos. In the local Universe ($z < 0.5$) HI is the most easily detectable manifestation of this process (quoting Guinevere Kaufman in her summing up after an HI meeting in Perth, January 2011.)

LADUMA

PIs: Blythe (UCT), Baker (Rutgers) and Holweda (ESA)

This group will study HI and its properties at redshifts out to the maximum MeerKAT can reach ($z = 1.4$) towards the Hubble Deep Field (HDF) South. They will need to use the technique of "stacking" to detect the weak HI emission and this requires that the redshift from surveys at other wavelengths (e.g. optical and IR) is known. HDF-south is a well-studied region at many wavelengths and probably one of the best regions for this kind of work.

Galaxy Clustering

PI: Paolo Serra (ASTRON)

Fornax is the second most massive cluster within 20 Mpc of the Sun and the largest cluster in the southern hemisphere. Its low X-ray luminosity makes it representative of the environment where most galaxies exist. Furthermore, Fornax's ongoing growth makes it an excellent laboratory for the study of structure formation. Ideally located for MeerKAT observation, it provides an excellent opportunity to study the assembly of clusters, the physics of the accretion and stripping of gas in galaxies falling in the cluster, and to probe for the first time the connection between these processes and the neutral medium in the cosmic web.

MHONGOOSE

PI: de Blok (UCT)

This is essentially a continuation of an earlier study of HI (and OH) in nearby galaxies of several different types, with the VLA-THINGS. Among the large array of interesting studies in this proposal is the connection between star formation and HI dynamics and accretion (as implied by the above quotation). Of particular interest here is the study of the outer discs of galaxies and the Cosmic web, and galaxy halos and dark matter. The data will be compared with CO observations from ALMA and other millimetre arrays, as well as Spitzer (IR) data, building up a picture of the relative distribution and importance of atomic and molecular hydrogen (HI and H_2) in the evolution of galaxies.

Absorption Line Survey

PIs: Gupta (ATNF) and Srianand (IUCAA)

Since it is easier to detect small quantities of cool gas in absorption against a continuum radio source, than in emission, this is another way to detect HI and even the hydroxyl radical (OH) at high redshift. Given sufficient frequency-resolution, it is also an excellent way to detect the line splitting caused by the Zeeman effect. A further interesting study that will be conducted as part of this project is the constancy of Fundamental Constants as a function of z using OH lines and their different dependencies on the fine structure constant and the electron/proton mass ratio .

Spectroscopic Observations with the High-frequency Receiver (8-14.5 GHz)

MESMER

PI: Heywood (Oxford)

After molecular hydrogen (H_2) carbon monoxide (CO) is the next most abundant molecule. However, H_2 is difficult to observe in the ground state as it has no dipole moment and therefore has no rotational spectral lines. It is usually detected only in the IR or UV, when highly excited.

CO has been detected in a galaxy with a redshift of 6.4 (SDSS J1148+52), and is commonly detected at $z = 4$, or less, showing that molecular hydrogen, perhaps unexpectedly, had a relatively high abundance in the early Universe. Theoretical studies have shown that this could occur where galaxies may be more tightly wound, and the pressure and density may be relatively high. It is considered important to follow up on these discoveries and the highest frequency of MeerKAT was chosen for precisely this reason. The upper frequency of MeerKAT, 14.5 GHz, is equivalent to the CO line redshifted to $z \approx 7$.

MeerGAL

PIs: Thompson (Hertfordshire) and Goedhart (SKA SA Project)

MeerKAT and its high frequency receiver are unique in the southern hemisphere for studies of the southern Galaxy and the Magellanic Clouds. The MeerGAL study will measure the properties of the Galaxy, its stellar formation and evolution through continuum and line observations of HII regions, recombination lines and simple molecules. The recombination line work will give improved data on the Galactic rotation curve in the southern Galaxy. Interstellar methanol masers at 12 GHz are providing important data on Galactic astrometry (e.g. the distance to the Galactic centre). This project will enhance the existing data sets with important new data on those masers. Finally, the 8-14.5 GHz spectral region has not been studied in detail for new molecules, and especially astrobiologically important molecules.

Radio Continuum Studies

MIGHTEE

PIs: van der Heyden (UCT) and Jarvis (Hertfordshire)

Deep continuum studies require long integrations on selected regions: the deeper you want to search for radio sources, the narrower the field that can be searched in a given time. In this case the integrations will be performed on the same field as LADUMA but with the full bandwidth of MeerKAT. The goal is to reach flux levels of a few micro-Jansky. MIGHTEE will reach such low flux density levels that it is likely to detect a new generation of radio sources as earlier evolutionary phases in their development are exposed.

ThunderKAT

PIs: Woudt (UCT) and Fender (Southampton)

Slow radio transients (several seconds and longer in duration) are rare. Transient radio behaviour is recorded occasionally (e.g. Supernovae, Novae) and may accompany gamma ray bursts from AGN and other compact radio sources, but by its very nature, it has not been well studied. The ThunderKAT project aims to monitor a wide field with MeerKAT in the hope of finding transient events and calling upon a selection of other instruments to follow up on those events. The essence of the project is the high sensitivity of MeerKAT and the ability to marshal other instruments to follow through in the radio and other wavelengths.

Pulsars and Fast Transients

Pulsar Timing

PI: Bailes (Swinburne)

Using both the L-band and the high frequency receiver, this project will explore the Galactic Centre and the Galactic Plane to conduct precision pulsar timing. It will aim to detect the gravitational wave background using an array of millisecond pulsars, rigorously test General Relativity and alternative theories of gravity using the double pulsar and other relativistic binaries, determine the distribution of neutron star masses, precisely map the orbits of the binary pulsars to trace their origin and evolution, study pulsar planetary systems, determine the origin and evolution of the globular cluster pulsars, study the internal structure of neutron stars via glitch monitoring, explore the radio pulsar emission mechanism and its relation to gamma-ray and x-ray emission, understand magnetars, determine a large number of pulsar parallaxes and proper motions, rigorously map the interstellar medium, study the single pulses of a large ensemble of pulsars, determine the pulsar birthrate and population and determine the true nature of the rotating radio transients (RRATs).

TRAPUM

PIs: Stappers (Manchester) and Kramer (MPIfR)

Despite the enormous observing efforts since pulsars were discovered, it is only in the past few years that really unusual sources have been found. For instance, some pulsars switch on and off - why and how is unclear. The TRAPUM programme aims to increase the pulsar data base and in the process find and investigate the strange behaviour of such objects as RRATs, as well as discovering even stranger pulsating objects. Such a survey might discover pulsar black hole binaries, providing direct tests of gravity in the strong field limit.

All three timing/transient projects are data hungry and are anxious to sample all MeerKAT data streams from all other projects. While this may be a challenge for the engineers, it holds the promise of very exciting results.

The Way Forward

The MeerKAT organization is anxious to ensure that the Survey Teams will work with the project to ensure a coherent approach to issues like project development, special software, data format (we propose VO compatibility), team organization and dynamics (working groups), publication/data release policy and outreach.

We will hold regular (annual in the first instance) meetings of PIs (the first was in February 2011) and request that the project teams conduct annual meetings with our scientific/technical liaison personnel to report progress, problems in scientific priorities and possible changes as other projects progress. We are also encouraging projects to set up a coherent organization within their own structures.

The MeerKAT project will adapt its HR policy towards hiring special postdoctoral and PhD personnel in fields related to the accepted large survey programmes, and has requested that a reciprocal policy be adopted by the team leaders.