PROCEEDINGS OF SCIENCE

HI Science with MeerKAT

W.J.G. de Blok[*]
Department of Astronomy
University of Cape Town
Rondebosch 7700
South Africa
E-mail: edeblok@ast.uct.ac.za

Roy Booth
Hartebeesthoek Radio Astronomy Observatory
PO Box 443
Krugersdorp 1740
South Africa
E-mail: roy@hartrao.ac.za

Bradley Frank
Department of Astronomy
University of Cape Town
Rondebosch 7700
South Africa E-mail: frank.brad@gmail.com

We give a brief description of the technical and scientific capabilities of the South African SKA precursor instrument, the Karoo Array Telescope MeerKAT. We describe the proposed configuration as well as some science applications, with emphasis on neutral hydrogen studies.

Panoramic Radio Astronomy: Wide-field 1-2 GHz research on galaxy evolution - PRA2009
June 02 - 05 2009
Groningen, the Netherlands

[*]Speaker.

1. Introduction

As possible hosts of the Square Kilometre Array (SKA), South Africa and Australia are building SKA Pathfinder arrays: MeerKAT and ASKAP, respectively. The two telescopes will complement each other well: ASKAP will have a wider field of view, while MeerKAT have a larger frequency and a larger frequency range, but with a smaller field of view. MeerKAT will have additional shorter and longer baselines, giving it enhanced surface brightness sensitivity as well as astrometric capability. It is also envisaged that MeerKAT will have the capability of phasing-up individual array elements and will, from time to time, participate in the European and Australian VLBI networks.

The Karoo Array Telescope MeerKAT will be the most sensitive centimetre wavelength instrument in the Southern Hemisphere; it will provide high-dynamic range and high-fidelity imaging over almost an order of magnitude in resolution (1 arcsec to 1 arcmin at 1420 MHz). The array will be optimized for deep and high fidelity imaging of extended low surface brightness emission, the detection of micro-Jansky radio sources, the measurement of polarization, and the monitoring of radio transient sources. It will be ideal for HI science, with the possibility of detecting extremely low column density gas, but highly resolved observations of individual galaxies are also possible. Its sensitivity combined with excellent polarisation purity will also make it well suited for studies of magnetic fields and their evolution, while its time domain capability will be ideal for studying transient events.

MeerKAT is being built in the Karoo, a part of South Africa's Northern Cape region, which has a particularly low population density and which, through an Act of Parliament, has been declared a Radio Astronomy Reserve. The approximate geographical coordinates of the array are longitude 21.3°E and latitude 30.8°S. MeerKAT will be an array of 80 antennas of 12 m diameter, mostly in a compact two-dimensional configuration with 70% of the dishes within a diameter of 1 km and the rest in a more extended two-dimensional distribution out to baselines of 8 km. An additional seven antennas will be placed further out, giving E-W baselines out to about 60 km. These will give a sub-arcsecond astrometric capability for position measurements of detected sources and enable their cross-identification with other instruments. The extra resolution will also drive down the confusion limit for surveys. Finally, it will be possible to phase the central core as a single dish for VLBI observations with the European and Australian networks. The initial frequency range of the instrument, in 2013, will be from 580 MHz to approximately 2 GHz and that range will be extended with a high frequency mode from 8-15 GHz in 2014.

2. HI Science with MeerKAT

We envisage a range of scientific projects for which MeerKAT will have unique capabilities. These include extremely sensitive studies of neutral hydrogen in emission – possibly out to $z = 1.4$ using gravitational lensing amplification – and highly sensitive continuum surveys to micro-Jansky levels, at frequencies as low as 580 MHz. The good polarisation properties will also enable sensitive studies of magnetic fields and Faraday rotation to be conducted. MeerKAT will be capable of sensitive measurements of pulsars and transient sources. The high frequency capability will facilitate such measurements even towards the centre of the Galaxy. MeerKAT will be sensitive enough

Number of dishes	80
Dish diameter	12 m
Aperture efficiency	0.7
System temperature	30 K
Low frequency range	0.58 - 2.0 GHz
High frequency range	8.5 - 15 GHz
Field of view	1 deg^2 at 1.4 GHz
	6 deg^2 at 580 MHz
	0.5 deg^2 at 2 GHz
$A_e/T_{\rm sys}$	200 m^2/K
Imaging dynamic range	1:10^5
Spectral dynamic range	1:10^6
Polarisation purity	-25 dB
Instantaneous bandwidth	1 024 MHz (4 096 MHz)
Maximum number of channels	32 768
Minimum sample time	0.1 ms
Minimum baseline	20 m
Maximum baseline	8 km (core array)
	$\sim$ 60 km (spur)

Table 1: MeerKAT properties

to conduct molecular line surveys over a wide frequency range: not only will Galactic Surveys of hydroxyl and methanol masers be possible, but at longer wavelengths (pre-biotic) molecules can also be detected. At the highest frequencies, CO will be detectable in its J=1-0 ground state transition at high redshifts.

A full in-depth discussion of the scientific capabilities of MeerKAT is beyond the scope (and page-limit) of this contribution. Below we therefore limit ourselves to some of the possibilities of doing HI science with MeerKAT.

2.1 Extragalactic HI science and the evolution of galaxies.

Deep HI observations are a prime science objective for MeerKAT. In the general SKA precursor environment, initial indications are that in the southern hemipshere MeerKAT will be the pre-eminent HI observation facility for regions $\sim$ 10 deg^2 or less and for individually significant HI detections out $z \sim 0.4$. For surveys of 30 deg^2 or more, ASKAP will likely remain the instrument of choice. Where exactly the ideal balance point lies between these facilities will continue to evolve as our understanding of both telescopes and their survey capabilities improve. Together, these facilities offer the opportunity to create a comprehensive tiered HI program covering all epochs to redshift unity and beyond.

2.1.1 Deep HI surveys

The formation of stars and galaxies since the epoch of re-ionisation is one of today's fundamental astrophysical problems. Determining the evolution of the baryons and the dark matter

PoS(PRA2009)007

therefore forms one of the basic motivations for the SKA and MeerKAT. A one-year deep HI survey with MeerKAT would give direct detections of HI in emission out to $z \sim 0.4$, and using the stacking technique and gravitational lensing would enable statistical measurements of the total amount of HI out to even higher redshifts up to $z \sim 1.4$. The advantage of the stacking technique is that high signal-to-noise detections of individual galaxies are not necessarily required. Using previously obtained (optical) redshifts, one can shift even very low signal-to-noise spectra (which would not on their own constitute a reasonable detection) such that all the spectral lines fall into a common channel and then stack the spectra to produce an average spectrum. Since spectroscopic redshifts are required, the HI survey will need to overlap with an existing or near-future redshift survey field. A further sensitivity enhancement involving gravitational lens amplification can be exploited in appropriate fields.

2.1.2 Studies of the Low Column Density Universe

Galaxies are believed to be embedded in a "cosmic web", a three-dimensional large scale structure of filaments containing the galaxy groups and clusters. It is now reasonably certain that most of the baryons do not, in fact, reside in galaxies, but are found outside galaxies spread along this "web". The material is, however, tenuous and the neutral fraction is small. It has possibly been seen in a few lines of sight as absorption features against background sources but a direct detection of the cosmic web would significantly improve our understanding of the baryon content of the universe. The cosmic web may be the source of the HI seen around galaxies taking part in the so-called cold accretion process. The material is expected to have column densities around 10^{17-18} cm^{-2}. Surveys for this low column density HI would likely be conducted by targeting a number of nearby galaxies. Assuming a 20 km s^{-1} channel spacing (the expected FWHM line-width of an HI line), one would need to integrate with MeerKAT for about 150 hours for a 5σ detection of a 10^{18} cm^{-2} signal at a resolution of $\sim 90''$. Assuming only night-time observing, this means that a direct detection of the low column density gas around galaxies can be done for a different galaxy every two weeks, thus rapidly enabling comparisons of morphology and properties of the low column density gas for a wide range in Hubble type. Depending on the flexibility of the correlator and the presence of background sources these observations could also be used to probe the low column density universe at higher redshifts using HI absorption.

2.1.3 A high-resolution survey of the HI distribution in 1000 nearby galaxies

Detailed, high-resolution (sub-kpc) observations of the interstellar medium in nearby galaxies are crucial for understanding the internal dynamics of galaxies as well as the conversion from gas into stars. Recent high-resolution HI surveys clearly showed the power of obtaining detailed 21-cm observations and combining them with multi-wavelength (particularly infrared and UV) data to probe galaxy evolution and physical processes in the interstellar medium. A more extensive sensitive high-resolution survey in the southern hemisphere will provide important data on star formation and dark matter in a large range of galaxy types in a wide range of environments; clusters, mergers, etc. This is particularly relevant with the advent of future surveys in the optical and IR and provides the local calibration point against which higher redshift HI studies can be gauged. The presence of major optical, IR and sub-mm telescopes in the southern hemisphere also make

PoS(PRA2009)007

MeerKAT an ideal instrument to produce a catalogue of detailed HI observations. A single 8-hour observation with MeerKAT already rivals standard multi-array VLA observations of nearby galaxies in terms of resolution and column density sensitivity.

2.1.4 An HI absorption line survey (and OH mega-masers)

Most HI absorption measurements have been made at optical wavelengths in damped Lyman-α systems. Such observations are prone to biases, as from the ground it is only possible to observe the line red-shifted to $z \simeq 1.7$. Furthermore, dust obscuration probably causes the observations to be biased against systems with a high metallicity. Such biases are not a problem for the HI line. As radio continuum sources span a large range of redshift, MeerKAT observations should detect absorption over the low frequency band to $z = 1.4$. The VLBI capability of the array should enable high-resolution follow up with either the EVN or the Australian array, depending on the redshift. A judicious choice of frequency bands for the HI absorption line survey will also pick up narrow band emission from hydroxyl, OH. The extragalactic OH emission, especially at 1667 MHz, will delineate mega-masers, maser emission associated mainly with interacting or starburst galaxies, some of which will show polarisation (Zeeman-)patterns from which line of sight magnetic fields may be inferred.

3. MeerKAT Specifications and Configuration

MeerKAT will consist of 80 dishes of 12 m each, capable of high-resolution and high fidelity imaging over a wide range in frequency. Initially it is intended that the array will have 2 frequency ranges with goals 0.58–2.0 GHz and 8.5–15.0 GHz. The precise frequency ranges will depend on the availability/development of wide-band feeds. The scientific priorities demand that the low frequency goal of 580 MHz and the high frequency goal of 15 GHz will be achieved, even if the full specified bandwidths may not be available at the beginning of operations.

MeerKAT commissioning will take place in 2012 with the array coming online for science operations in 2013. Table 1 summarizes some of the MeerKAT specifications.The MeerKAT array will be preceded by a smaller prototype array of seven antennas, called KAT-7. The commissioning of this science and engineering prototype will start in 2010, with shared-risk and test science observations expected later that year. KAT-7 will be used as a technology testbed for MeerKAT and is therefore more limited in its science scope with a smaller frequency coverage and a longest baseline of 200m.

The MeerKAT array will consist of three components:

- A dense inner core containing 70% or 56 of the dishes. These are distributed in a two-dimensional fashion with a Gaussian *uv*-distribution with a dispersion of 300 m, a shortest baseline of 20 m and a longest baseline of 1 km.

- An outer component containing 30% or 24 of the dishes. These are also distributed resulting in a two-dimensional Gaussian *uv*-distribution with a dispersion of 2500 m and a longest baseline of 8 km.

PoS(PRA2009)007

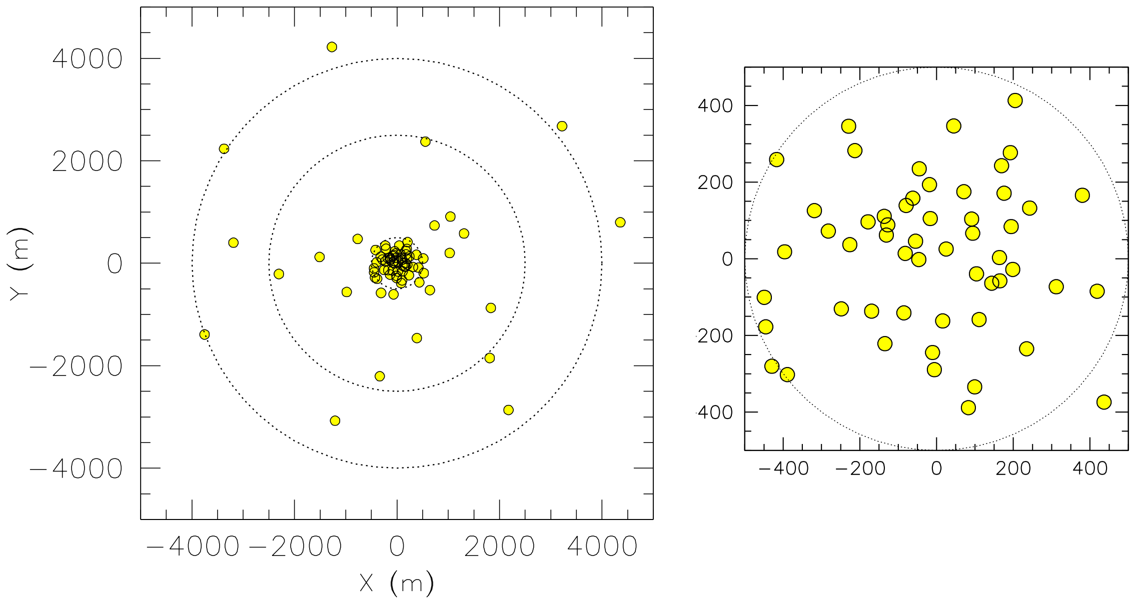

Figure 1: Overview of the MeerKAT configuration. The inner core contains 70% of the dishes, using a two-dimensional Gaussian *uv*-distribution with a dispersion of 300 m and a longest baseline of 1 km. The outer component contains 30% of the dishes, and is distributed as a two-dimensional Gaussian *uv*-distribution with a dispersion of 2.5 km and a longest baseline of 8 km. The shortest baseline is 20 m. The left panel shows an overview of the configuration. The three circles have diameters of 1, 5 and 8 km. The panel on the right shows a more detailed view of the inner core. The circle has a diameter of 1 km.

- A spur of an additional 7 antennas will be distributed along the road from the MeerKAT site to the Klerefontein support base, approximately 90 km SE from the site. This will result in E-W baselines of up to 60 km. The exact positions of these 7 antennas have yet to be decided.

It is likely that construction of the array will proceed roughly in the order listed above. Figure 1 shows a concept configuration of the two central array components listed above. Positions of individual antennas may still change pending completion of geophysical measurements, but will remain consistent with the concept of a 70/30 division between a 1 km maximum baseline core and an 8 km maximum baseline outer component. Some example *uv*-distributions for observations of different duration towards a declination of –30° are given in Fig. 2. It is clear that this choice of array design necessitates a degree of tapering in order to produce images at a desired resolution. The advantage of the design is however the large range of resolutions that can be sampled.

Figure 3 illustrates the sensitivities of the MeerKAT array over a range of resolutions, after tapering to that resolution. A comparison to other, existing, facilities is also made. For an 8 hr spectral line observation, assuming a channel width of 5 km s^{-1}, a system temperature of 30K, two polarizations, and a system efficiency of 0.7, the expected noise level is $\sim$ 0.6 mJy/beam.

4. Concluding Remarks

In conclusion, MeerKAT will be a fantastic instrument capable of interesting and exciting

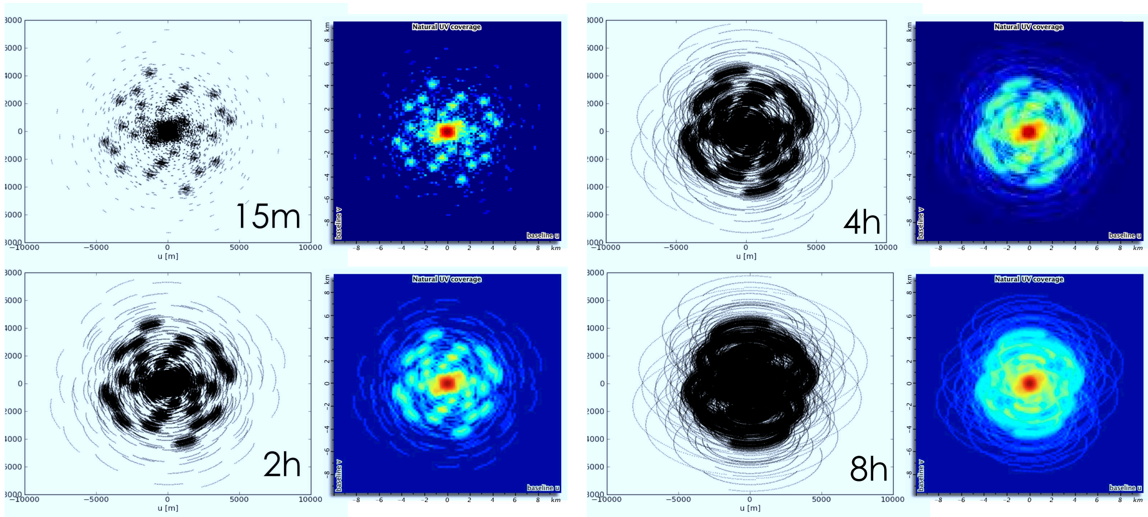

Figure 2: Black-and-white panels: uv distribution of the MeerKAT array for observations towards declination -30° with the observing time indicated in the sub-panels. Colour panels: density of *uv*-samples for the corresponding observation in the black-and-white panels.

scientific measurements. It will be a major pathfinder to the SKA, giving insights into many of the technical challenges of the SKA, but also giving a glimpse of the new fundamental studies that the SKA will facilitate. A call for proposals for MeerKAT is expected to be issued before the end of 2009, and this will enable the international community to fully participate in this new instrument. See `http://www.ska.ac.za/meerkat` for the latest developments.

We acknowledge the help and stimulation given by the MeerKAT International Scientific Advisory Group: Mike Garrett, Michael Kramer, Robert Laing, Scott Ransom, Steve Rawlings and Lister Staveley-Smith, aided by Bruce Bassett, Erwin de Blok, Roy Booth, Bernie Fanaroff, and Justin Jonas.

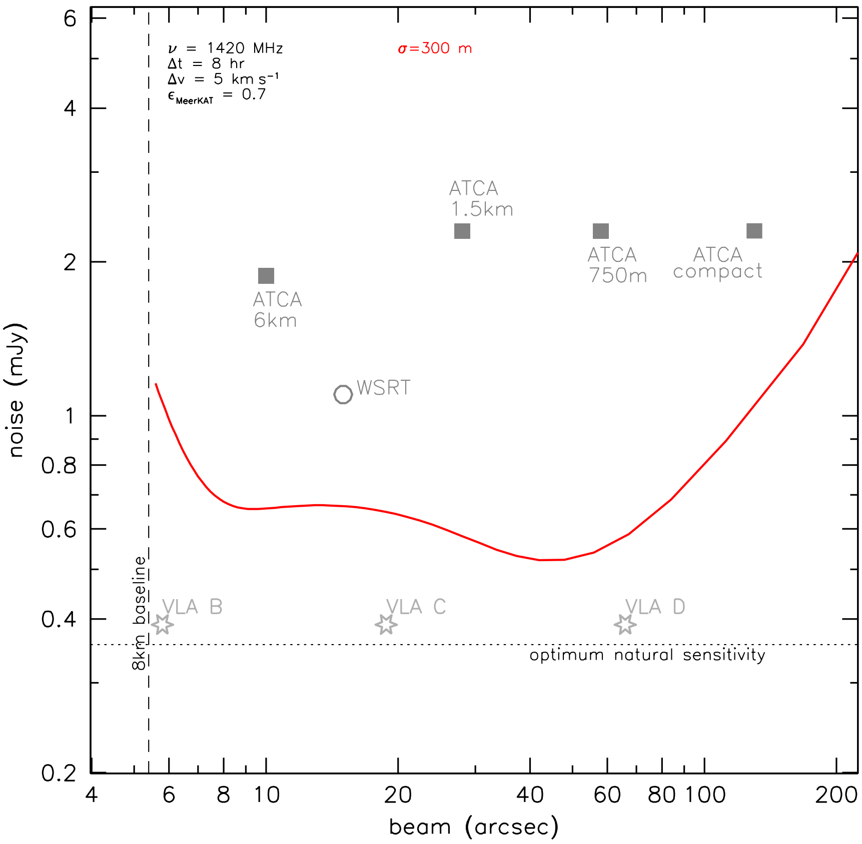

Figure 3: Expected point source sensitivity of the MeerKAT array after tapering to the desired resolution. The 1σ sensitivity is given by the red curve. The observation assumes a frequency of 1420 MHz, a channel width of 5 km s^{-1}, an observing time of 8h and a system efficiency of 0.7. The horizontal dotted line indicates the sensitivity for a similar 80-dish array, but optimized to only a single resolution. The vertical line indicates the approximate resolution limit imposed by an 8 km baseline. Sensitivities of the other, existing facilities have all been computed using their respective online sensitivity calculators.