PROCEEDINGS OF SCIENCE

The MeerKAT Karoo Array Telescope

W.J.G. de Blok[*],[a] **R.S. Booth**[b], **J.L. Jonas**[c] **and B. Fanaroff**[d]

[a] *Department of Astronomy, ACGC, University of Cape Town*
Rondebosch 7700, South Africa
[b] *Hartebeesthoek Radio Astronomy Observatory*
P.O.Box 443, Krugersdorp 1740, South Africa
[c] *Rhodes University, Dept. Physics & Electronics*
PO Box 94, Grahamstown 6410, South Africa
[d] *SKA South Africa Project Office, 17 Baker St*
Rosebank, Johannesburg, South Africa
Email: edeblok@ast.uct.ac.za, roy@hartrao.ac.za, j.jonas@ru.ac.za, bfanaroff@fanaroff.co.za

This contribution gives a short overview of the MeerKAT Karoo Array Telescope, the South African Square Kilometre Array Precursor. Some of the key specification and science for MeerKAT are described.

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[*]Speaker.

1. Introduction

As possible hosts of the Square Kilometre Array (SKA), South Africa and Australia are building SKA Precursor arrays: MeerKAT and ASKAP, respectively. The two telescopes will complement each other well: ASKAP will have a wider field of view but a smaller frequency range and lower sensitivity, while MeerKAT will be more sensitive, have 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 array elements and will, from time to time, participate in the European, Australian and global VLBI networks. This contribution gives a short overview of the expected scientific capabilities as well as the technical specifications of the MeerKAT telescope.

2. MeerKAT

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-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 extragalactic HI science, with the possibility of detecting extremely low column density gas, but high resolution 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. Planned high frequency capabilities will give access to Galactic Centre pulsars, and make possible measurements of CO in the early Universe at redshifts $z \sim 7$ or more.

MeerKAT is being built in the Karoo, a part of South Africa's Northern Cape region which has a particularly low population density. Part of the Northern Cape, through an Act of Parliament, is being declared a Radio Astronomy Reserve. The approximate geographical coordinates of the array are longitude $21^\circ 23'$E and latitude $30^\circ 42'$S. MeerKAT will have the equivalent sensitivity of 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 900 MHz to approximately 1.75 GHz. The lower frequency limit will be further extended to 580 MHz GHz in 2015. Finally, the available range will be extended with a 8–15 GHz high frequency mode in 2016.

3. 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 stacking and gravitational lens amplification — and highly sensitive continuum surveys to μJy 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 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 at $z > 7$ may be detectable in its $J = 1-0$ ground state transition.

Many of the applications of the Precursor instruments are driven by the SKA scientific programme. We do not intend to repeat the full scientific motivation here, but present a brief outline of the particular scientific programmes in which we believe MeerKAT will excel, and which we hope will excite collaborations from among astronomers world-wide. The location and science goals of MeerKAT lend themselves to intensive collaborations and joint projects with the many facilities at other wavelengths available in the southern hemisphere. Combinations with large mm-arrays like ALMA, but also SALT, VISTA, VST, APEX, VLT and Gemini South, to name but a few of the many instruments available, should prove to be fruitful.

3.1 Low frequency bands (580 MHz - 2.5 GHz)

3.1.1 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 MeerKAT will be the pre-eminent southern hemisphere HI observation facility for regions ~ 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 be 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.

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 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 and near-IR) 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 may be exploited in appropriate fields.

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.

A high-resolution survey of the HI distribution in 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 (such as The HI Nearby Galaxy Survey THINGS performed at the VLA) 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. A single 8-hour observation with MeerKAT rivals the THINGS VLA observations in terms of resolution and column density sensitivity. This is particularly relevant with the advent of sensitive surveys and observations of the molecular and dust component of the ISM by Herschel and, in the future, ALMA. These combined studies will provide the local calibration point against which higher redshift studies can be gauged. The presence of major optical, IR and sub-mm telescopes in the southern hemisphere make such a multi-wavelength approach desirable.

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 systems 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 declination and 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.

3.1.2 Continuum measurements

Ultra-deep, narrow-field continuum surveys with full polarisation measurements The MeerKAT-ASKAP complementarity discussed in relation to deep HI surveys applies also to surveys in radio continuum and polarisation. ASKAP will survey the entire southern sky to an rms noise limit of 50 μJy per beam in 1 year of observing time, while we envisage that MeerKAT will, in the first instance, make a number of deep pointings in fields that are already being studied at other wavelengths (e.g., Herschel ATLAS, Herschel HerMES, SXDS, GOODS and COSMOS). Within the 1 deg^2 MeerKAT field at 1400 MHz, a conservative (5σ) estimate of the sensitivity is 7 μJy per beam in 24 hours with 500 MHz bandwidth. This scales to 0.7 μJy in 100 days. Dealing with confusion at this level will require judicious use of the long baselines (using the 60 km E–W spur). This exciting work will study radio-galaxy evolution, the AGN-starburst galaxy populations and their relationship, perhaps through AGN feedback, in unprecedented detail, so addressing the evolution of black holes with cosmic time. It may even reveal a new population of radio sources and address the enigmatic far-IR-radio correlation at high redshifts.

Magnetic Fields Polarisation studies will, in the first instance, use the full low frequency band in determining rotation measures for the fraction of stronger sources. The intra-cluster medium has been shown to be magnetised and it would seem that magnetic fields play a critical role in the formation and evolution of clusters. A rotation measure survey of several clusters would be feasible with MeerKAT through observations, in several low frequency bands, of sources within and behind the cluster.

Galactic studies and the Magellanic Clouds As well as important extragalactic science, we envisage much interest in Galactic and Magellanic surveys with MeerKAT, both in HI, for measurements of dynamics, together with measurements of the Zeeman effect and determinations of the line of sight component of the magnetic field. Similar measurements may be made in the 4 ground state OH lines. There are relatively few measurements of all 4 ground state OH lines. MeerKAT's wide band and high spectral resolution will enable such measurements, which give valuable information on the excitation temperature and the column density of the cold gas component. Very few know interstellar molecules have lines in bands below L-band. An interesting exception is methanol whose transition at 830 MHz was the first to be measured and so identify the species. While a Galactic survey in this line would be interesting, it will also be exciting to perform a census of low frequency transitions in directions towards the Galactic Centre and Sgr B. Molecules with transitions at the lower frequencies tend to be bigger and could be more important as pre-biological molecules and their potential importance for the origin of life.

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3.2 High frequency science (8 - 15 GHz)

3.2.1 Pulsars and transients

The high-frequency capability of MeerKAT will be particularly useful for studies of the inner Galaxy. We expect the population of pulsars in the Galactic Centre to be large, but it is being obscured by interstellar scattering, which cannot be removed by instrumental means. Observing at sufficiently high frequencies ($\sim$ 10 GHz or higher) the pulsar population can be revealed. A number of these pulsars will be orbiting the central supermassive black hole. The orbital motion of these pulsars will be affected by the spin and quadrupole moment of the black hole. By measuring the effects of classical and relativistic spin-orbit coupling on the pulsar's orbital motion in terms of precession, traced with pulsar timing, we can test the cosmic censorship conjecture and the no-hair theorem. The technical requirements in terms of data acquisition and software involved in this application are, however, challenging and a large community effort will be needed to be successful in this challenging but exciting science goal.

3.2.2 High-z CO

While HI emission has been difficult to detect at even moderate redshifts, CO has been detected with the VLA in the $J = 3-2$ rotational transition at $z = 6.4$. The new large millimetre array, ALMA, will detect higher CO rotational transitions at $z > 6$, and it may be instructive to measure the ground state rotational transition for comparison. The new EVLA will open up CO$(1-0)$ surveying, particularly in the northern sky. In the southern sky, MeerKAT will be its counterpart, but with a larger field of view and sky coverage. MeerKAT at 15 GHz will facilitate the detection of CO$(1-0)$ emission at $z > 6.7$, and the ground state transition of HCO^+ at $z > 4.9$. It will be important to exploit such commensality with ALMA, and to compare the atomic and molecular content of galaxies as a function of redshift, since recent studies show that the molecular hydrogen proportion may increase with redshift.

3.3 VLBI science

The availability of the phased central MeerKAT antennas, as the equivalent of an $\sim$ 85 m diameter single-dish antenna, will have a profound effect on the highest resolution measurements, made with VLBI. A phased MeerKAT will both increase the uv-coverage available in the South, and provide great sensitivity on the longest baselines, where visibility amplitude is often low as sources are becoming resolved. This and the recently demonstrated e-VLBI capacity with the Hartebeesthoek Radio Telescope will create great demand for the phased MeerKAT in the VLBI networks. A particular application of significance with the European VLBI network will be wide field imaging VLBI of sources in Deep Fields. High sensitivity VLBI studies of the Hubble Deep Field revealed μJy sources, many of which were starburst galaxies. In one case a radio-loud AGN was detected in a dust obscured, $z = 4.4$ starburst system, suggesting that at least some fraction of the optically faint radio source population harbour hidden AGN.

Wide-field imaging developments with the EVN and MeerKAT will not only produce more interesting fine detail on galaxies in the early universe, they will also be a test bed for the SKA. Furthermore, the presence of the HESS high-energy telescope and its successor in close proximity

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to South Africa will enhance the importance of the southern VLBI arrays for studying the radio component of high-energy gamma ray sources.

Another field of interest for VLBI arrays including MeerKAT is that of (narrow band) masers. Trigonometric parallaxes of maser spots are refining distance measurements in the Milky Way and improving our knowledge of the structure and dynamics of the Galaxy. Both hydroxyl (1.6 GHz) and methanol (12 GHz lines) still reveal new and interesting properties, like alignments and discs, in regions of star formation. Studies of OH masers as well as the radio continuum in starburst galaxies like Arp 220 are revealing strings of supernovae and strange point sources whose spectra have high a frequency turnover, and might even be indicative of 'hypernovae'.

3.4 Other Science

We have described some of the exciting science that will be done with MeerKAT, but the new instrument will have the potential to do much more. All-sky surveys at 600 MHz and 8 GHz are possible, as well as Galactic polarisation measurements and deep studies of magnetic fields, and science requiring high brightness sensitivity at high frequency (e.g., of the Sunyaev-Zel'dovich effect). There are possibilities for pulsar surveys and much more, and we realise that this document has only given a flavour of the unique scientific capabilities of MeerKAT.

4. MeerKAT: specifications and configuration

MeerKAT will consist of the equivalent in sensitivity and resolution of 80 dishes of 12 m each, and it will be capable of high-resolution and high fidelity imaging over a wide range in frequency. The minimum baseline will be 27 m, the maximum 8 km. An additional spur of 7 dishes will be added later to provide longer (8–60 km) baselines. It is intended that the final array will have 2 frequency ranges: 0.58–1.75 GHz and 8–15 GHz, with the full frequency range gradually phased in during the first years of the array.

MeerKAT commissioning will take place in 2012 and 2013 with the full array coming online for science operations in 2014, but with the possibility of commissioning science observations already in 2013. Table 1 summarizes the final MeerKAT specifications. Table 2 gives an overview of the various phases of the MeerKAT construction and commissioning leading up to these final specifications.

MeerKAT will be preceded by a smaller prototype array of seven antennas, called KAT-7. The commissioning of this science and engineering prototype is underway, with the first single dish and interferometric observations already obtained. KAT-7 will be used as a test bed for MeerKAT, as well as for the data reduction pipelines etc. and is more limited in its science scope, with smaller frequency coverage (1.2-1.95 GHz), and longest and shortest baselines of 200m and 20m respectively, as also indicated in Table 2. The *maximum* processed bandwidth on MeerKAT will initially be 850 MHz per polarization. This will gradually be increased to 6 GHz.

4.1 Configuration

The MeerKAT array will be constructed in multiple phases (see Table 2) using the following configuration design.

Table 1: MeerKAT final system properties

Low frequency range[a]	0.58–1.75 GHz
High frequency range[a]	8–15 GHz
Field of view	1 deg^2 at 1.4 GHz
	6 deg^2 at 580 MHz
	0.5 deg^2 at 2 GHz
$A_e/T_{\rm sys}$	220 m^2/K (L-band)
$A_e/T_{\rm sys}$	200 m^2/K (X-band)
Continuum imaging dynamic range[b]	1:10^5
Spectral dynamic range[b]	1:10^5
Instrumental linear polarisation purity	−25 dB across field
Minimum and maximum bandwidth per polarization[a]	0.85–6 GHz/pol
Number of channels	32768 per band
Minimum baseline	27 m
Maximum baseline	8 km (without spur)
	60 km (with spur)

Notes: a: See Table 2 for roll-out schedule.
b: Dynamic range defined as rms/maximum.

Table 2: MeerKAT Phasing Schedule

	KAT-7 2010-2011	Phase 0 2012-2013	Phase 1 2014	Phase 2 2015	Phase 3 2016
Number of dishes	7	core (56) ++	80	87	87
Low freq. range (GHz)	1.2–1.95	0.9–1.75	0.9–1.75	0.58–1.75	0.58–1.75
High freq. range (GHz)	—	—	—	—	8–15
Maximum processed bandwidth/pol (GHz)	0.256	0.850	0.850	0.850	6
Min. baseline (m)	20	27	27	27	27
Max. baseline (km)	0.2	<8	8	60	60

- 1. A dense inner component containing 70% 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 27 m and a longest baseline of 1 km.

- 2. An outer component containing 30% 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.

This will be followed by a later phase which will involve the addition of a number of longer base-

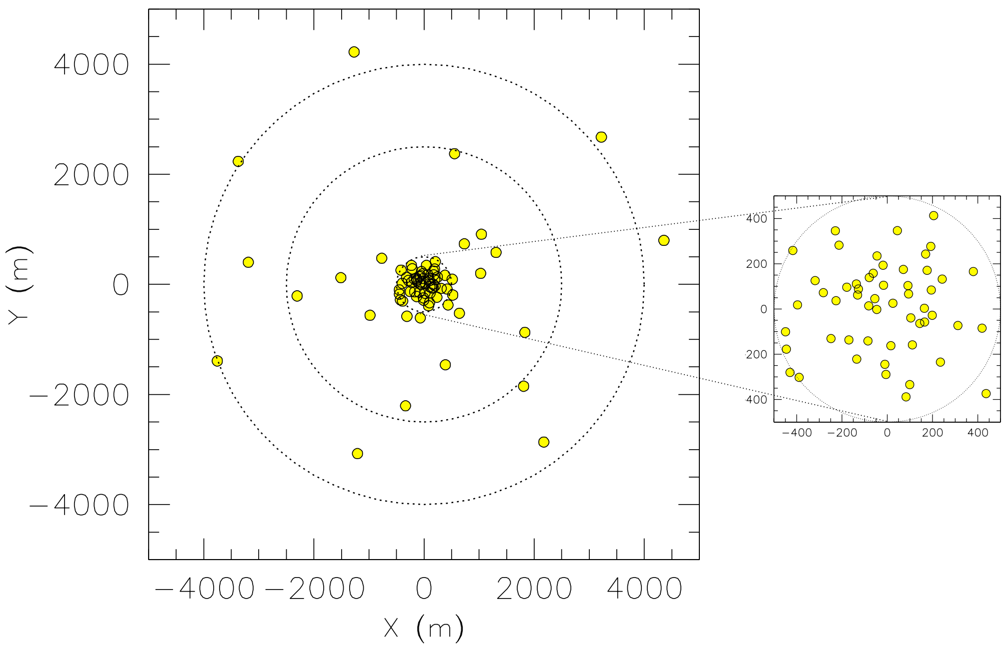

Figure 1: *Overview of a concept MeerKAT configuration. The inner component contains 70% of the dishes, using a two-dimensional Gaussian uv-distribution with a dispersion of 300 m and a longest baseline of 1 km. The outer component contains 30% of the dishes, and is distributed as a two-dimensional Gaussian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

lines.

- 3. 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 positions of these antennas will be chosen to optimize the high-resolution performance of the array to enable deep continuum imagine and source localisation.

Figure 1 shows a concept configuration of components 1 and 2 listed above. Positions of individual antennas may still change pending further optimization and completion of geological 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. Representative *uv*-distributions for observations of different duration towards a declination of -30° are given in Fig. 2. A histogram of the total baseline distribution for an 8h observation towards -30° is given in Fig. 3.

5. Concluding remarks

With this short discussion of the MeerKAT scientific goals and design, we hope to have shown that MeerKAT will be capable of very exciting science. It will be a major pathfinder to the SKA,

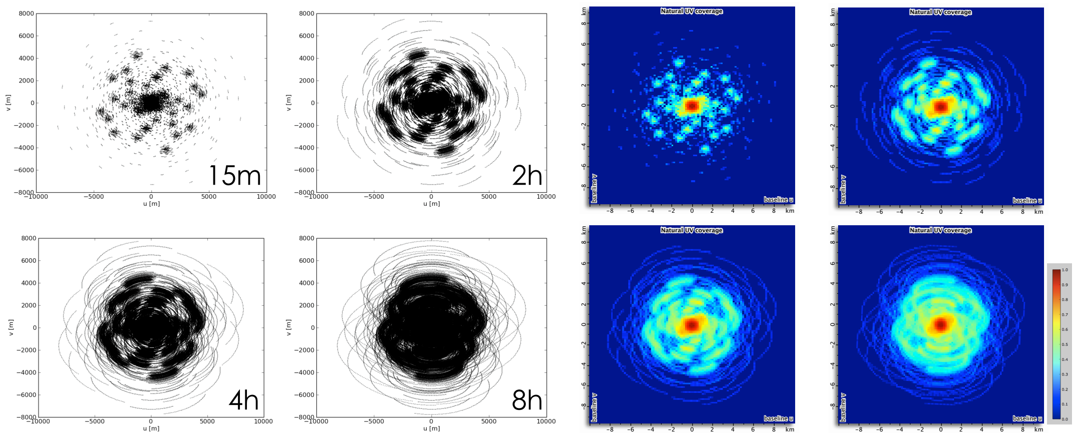

Figure 2: *Left panel: uv distribution of the MeerKAT array for observations towards declination* $-30°$*, with the observing time indicated in the sub-panels. Right panel: density of uv-samples for the corresponding observations in the left panel.*

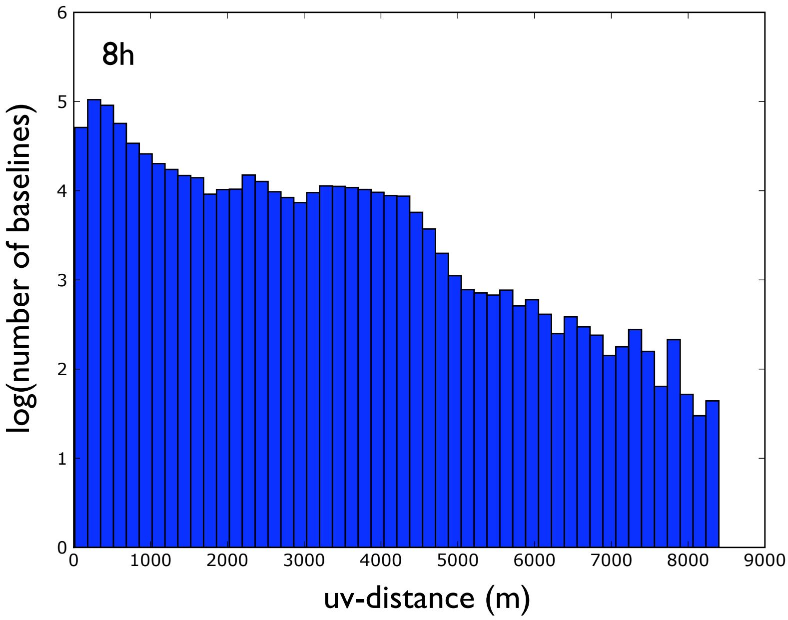

Figure 3: *Histogram of the uv-distance for an 8h observation towards -30°. The histogram numbers assume 5 min sample integration times.*

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.