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The Karoo Array Telescope

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Abstract. The Karoo Array Telescope (KAT) will be a "1% demonstrator" for the SKA, located in a radio quiet reserve in the Karoo region of the Northern Cape province of South Africa. Besides developing technologies for the SKA project, the KAT will perform wide-field surveys that will be precursors to the eventual SKA products. The nominal specification for the KAT are listed, and the proposed science themes for the facility are outlined.

1. Introduction

Progress in many of the major topics in astronomy, cosmology and fundamental physics requires astronomy survey data sets that probe large volumes of observational discovery space. The discovery space has dimensions of sky coverage, redshift (i.e. bandwidth in the radio context) and temporal coverage. The data from these massive surveys will constrain to high precision the parameters of cosmological models and fundamental physics, and also improve the opportunities for discovery of new phenomena.

New large-scale telescopes are being planned to perform these surveys, and the Square Kilometre Array (SKA) is will be the prime survey instrument in the radio regime. The SKA is being designed to have unprecedented sensitivity and survey speed, and will also probe a large volume of discovery space. It will produce vast quantities of data at enormous data rates.

The technical challenges provided by the ambitious SKA specifications require a phased approach to its development and implementation. An early and key phase is the construction and operation of "1% demonstrators". These demonstrators will develop and test novel technologies and observing modes that will make the SKA affordable and allow its ambitious specifications, and hence science goals, to be met.

The International SKA Steering Committee (ISSC) have settled on a reference design for the SKA which specifies that in the gigahertz frequency range the receptors will be "small dishes with smart feeds" (SKA Memo 69). Dish diameters in the range 6 to 20 metres appear to optimize the aperture cost equation, and one interpretation of smart feeds is the use of multi-pixel focal plane arrays. These multi-pixel feeds might be traditional horn feed clusters, or phased array devices that fully sample the Airy pattern in the focal plane.

2. The KAT as an SKA demonstrator

Besides optimizing aperture cost, the combination of small dishes and multi-pixel feeds naturally results in a large field of view (FoV) and hence survey speed. The Karoo Array Telescope (KAT) is intended to be a "1% demonstrator" for this receptor concept. Although it is primarily a South African project, there is a significant international component that is expected to grow as the project develops.

In addition to being a demonstrator for SKA technology and science, a prime goal for the KAT is to provide South Africa with a radio telescope that is capable of supporting world-class science programmes. Strictly speaking the KAT will have 0.35% of the SKA aperture, which is equivalent to a single 67-m dish. Despite this modest aperture, the wide FoV of the instrument boosts its survey speed to a competitive level. The surveys that the KAT will undertake will provide valuable early results and direction to the science teams working on the 10% and full SKA instruments.

The following items illustrate the key technical and operation issues for which the KAT will be a SKA pathfinder:

Focal Plane Arrays: The use of multi-pixel feeds on a reflector antenna allows the re-use of the receptor aperture, and hence increases the science return for each unit of aperture. A conservative technology choice is the use of multi-feed horn clusters, as used on existing single dish telescopes. Densely packed phased arrays have the potential to improve frequency coverage, aperture efficiency and FoV, but currently carry both cost and technology risks. Initially the KAT will employ 7-feed horn clusters to avoid these risks (referred to as Phase 1), but all telescope systems are being designed for eventual use of phased array focal plane packages (Phase 2).

COTS components: In order to drive down the cost of the SKA it will be necessary to use commodity-off-the-shelf (COTS) components, rather than the purpose built systems traditionally used on radio telescopes. The KAT will employ generic electronic, communication and computing technologies that can achieve the required cost/performance metric. Moore's Law and commodity market forces will improve this metric over time.

Multiplexed observing: Radio telescopes allow the unlimited re-use of the received signals, which in turn allows multiplexed observing. The KAT will use multiplexed observing and a dynamic scheduler to make optimal use of the large FoV of the telescope. This effectively enhances the survey speed of the instrument ("multiplex gain") because multiple surveys can be conducted simultaneously.

Data pipelining: Even the KAT as a modest SKA pathfinder will produce a prodigious data flow, which will require massive computing resources to provide pipelined data reduction. The use of cluster and reconfigurable computing platforms will be explored in the KAT project. In addition to the challenges provided by the large data volume and rate, new fast algorithms will have to be developed to perform pipelined high dynamic range wide-field imaging and fast transient detection.

Scalable architecture: The survey speed of the SKA will be limited by the digital backend processing capacity. The data rate is proportional to the product of FoV and instantaneous bandwidth, and therefore survey speed. The architecture of the backend therefore needs to be such that it is "scale free", i.e. does not have inflection points in its cost/throughput characteristic. The KAT will explore the use of commodity data switching platforms and fabrics to achieve this scalable architecture.

3. Technical specifications and observing modes

Table 1 lists the nominal technical specifications for the KAT. These specifications will be revised during 2006 in response to the requirements of the science programme currently being finalized. Boundary conditions on the specifications will also be set by technology readiness and cost. Phase 1 will employ clusters of 7 horn feeds in the focal package, while Phase 2 will replace these feeds with dense phased arrays if that technology proves to be viable. The outputs of the EU FP6 SKA Design Study (SKADS) and other international phased array research programmes will be monitored closely, and the KAT project plan includes a programme to investigate focal plane phased arrays.

The array processor for the KAT will support both correlation for imaging applications and beamforming for multiple independent pencil beam observations. These operations will be performed simultaneously to achieve the required multiplexed observing. The FX correlator will normally use narrow spectral channels so that HI, OH and continuum visibilities can be obtained simultaneously. Similarly, the array beamformer will operate on channelized data for pointed spectral line observation and pulsar de-dispersion. The narrow channels will also assist with RFI excision. The pencil beam data will either be captured as digital baseband signals, or as Stokes IQUV vectors. The data streaming out of the array processor will either be processed by a pipeline of "software instruments", or recorded for off-line processing (e.g. VLBI, pulsar searching).

Table 1. Nominal specification for the first and second phases of the KAT.

Parameter	Phase 1	Phase 2	Unit
$N_{\rm ant}$	20	20	dishes
$D_{\rm ant}$	15	15	m
$T_{\rm sys}$	< 50	< 30	K
$A_{\rm e}/T_{\rm sys}$	> 40	> 80	$\rm m^2.K^{-1}$
FoV	7	30	□°
$F_{\rm low}$	1.0[a]	0.7	GHz
$F_{\rm high}$	1.45[a]	1.75	GHz
BW[b]	256	256	MHz
Polarization[c]	IQUV	IQUV	
Spectral Chan.	$> 16\,384$[d]	$> 16\,384$[d]	
Baselines	TBD[e]	TBD[e]	

[a] Frequency range limited by feed horns. Alternative range might be 1.2–1.75 GHz to include OH lines.
[b] Not necessarily contiguous sub-bands.
[c] Feeds receive both orthogonal polarization modes.
[d] Not necessarily contiguous. Might extend to 65 536 channels.
[e] Reconfigurable array might be necessary.

In order to exploit the multiplexed observing capability, the KAT will employ a complex and adaptable queue scheduler. This scheduler will optimally manage a mix of survey and target of opportunity operations, and will attempt to maximize the discovery of transient phenomena.

4. Project plan and timeline

The KAT project is currently underway with committed funding streams from various South African government sources (primarily the Department of Science & Technology). A project team of around 26 engineers and scientists has been hired, most of whom are located at the KAT laboratory in Cape Town. Smaller groups of managers, engineers and scientists are located in Johannesburg and Pretoria, and the HartRAO science and engineering staff are also involved in the project.

Table 2 broadly summarizes the key milestones in the timeline for Phase 1 of the KAT project. The timelines of the various 1% demonstrators clearly have a direct influence on the timeline of the SKA project.

The site for the KAT will be in the Karoo region of South Africa, near to the proposed SKA core site. This area will be declared to be a radio astronomy reserve once the Astronomy Geographic Advantage Bill has been passed into law by parliament. This law will ensure that the RFI environment of the area remains conducive to radio astronomy.

5. Science programme

The KAT will primarily be a survey instrument, and its science goals reflect this bias. The KAT science pro-

Table 2. Broad overview of the timeline for Phase 1 of the KAT project.

2006	Establishment of the KAT project team. High-level architecture choice and system design. Commissioning of a commodity cluster high-performance computing facility. Construction of a small 4-element interferometer to be used as an early test-bed for operational software. Refinement of the science case.
2007	Construction of a 15-metre prototyping antenna at HartRAO for use as a development and test facility for feed systems, digital receivers and backend data processing systems. Construction of the correlator and other digital backend systems. Implementation of control and data pipelining software.
2008	Construction of infrastructure and first dishes at Karoo site. First correlator fringes from a subset of antennas.
2009	Completion of full array of 20 antennas.
2010	Full science operation.

gramme and survey protocols are currently being developed and refined. The wiki site www.kat.ac.za provides an on-line forum for the development of the science case. The list below outlines some of the survey work envisioned for the KAT during Phase 1. The increased survey speed provided by Phase 2 will allow deeper surveys that will probe to greater redshift.

Blind HI surveys: Although having less sensitivity than the Parkes multi-beam L-band feed system, the survey speed of the KAT will extend the all-sky galaxy catalogue produced by the HIPASS survey (Meyer et al. 2004), both numerically and in redshift. The KAT survey will also benefit from baselines in excess of 2 km that will provide positional precision necessary for optical identification and cross-correlation with other surveys. In addition to a shallow all-sky HI survey there will also be deeper surveys of smaller areas of sky that will map the HI mass distribution of the nearby universe and reveal the evolution of the gas associated with galaxies. A high resolution Galactic HI map will allow the study of the turbulent velocity fields in the ISM, and coupled with the Galactic continuum polarization survey data will provide clues to the mechanisms that generate the Galactic magnetic field.

Extra-galactic continuum source surveys: The continuum survey speed of the KAT will allow a southern hemisphere equivalent of the NVSS L-band survey (Condon et al. 1998) to be completed every week. Such serial surveys will provide variability time series data for more than a million sources. As with the HI surveys, deeper source surveys of smaller areas of sky will be conducted. The continuum surveys drive the array configuration to longer baselines, and simulation studies are underway to determine the optimal configuration that will defeat confusion and allow optical identification.

Galactic continuum and polarization mapping surveys: A by-product of the continuum source surveys will be a full-polarization map of the diffuse Galactic emission. This map will be useful for studying the Galactic magnetic field, and will contribute to the understanding of the polarized foreground that contaminates CMB measurements.

Rotation measure surveys: The wide instantaneous bandwidth, and ability to break this bandwidth into non-contiguous sub-bands, will allow the measurement of rotation measure (RM) towards a large number of galactic and extra-galactic sources. The grid of RMs obtained will allow a tomographic analysis (Beck & Gaensler 2004; Han et al. 2006) of the Galactic magnetic fields and the ISM.

Pulsar timing: The wide FoV of the KAT, and the ability to form arbitrary pencil beams within that FoV, make it an efficient instrument for monitoring known sources. The KAT will be able to perform timing measurements on a large fraction of the known pulsar population, and thus provide valuable data for the study of stochastic and periodic processes that affect the pulsar periods.

Transient detection: The wide FoV of the KAT suggests its use as a “transient patrol” instrument, and back-end instrumentation dedicated to transient detection is envisaged. Transient phenomena span a wide range of timescales, and different techniques are required to cover these timescale regimes. Fast transients, such as periodically active and bursting pulsars (Kramer et al. 2006; McLaughlin et al. 2006), provide a data processing challenge if the array antenna signals are summed coherently because of the large number of pixels per FoV. Real-time monitoring of correlator visibilities and incoherent summing techniques are being investigated to overcome the data flow problem.

Galactic Hα mapping: A by-product of the HI surveys will be a blind survey of diffuse hydrogen recombination lines associated with the Galactic warm ionized medium (Reynolds 2004; Heiles, Reach & Koo 1996). The instantaneous bandwidth of the KAT will allow the simultaneous detection of a “comb” of these lines, which will allow co-adding to improve detection sensitivity. The characterization of this gas will be useful for determining the thermal galactic foreground emission that contaminates CMB data (Odegard et al. 2001).

Many of these surveys will be conducted simultaneously because of the multiplex observing capability of the KAT. Continuum surveys will be natural by-products of imaging spectral line surveys.

6. Conclusion

The South African KAT project team is actively soliciting technical and scientific partnerships with international institutions. Interested parties are invited to register on the KAT wiki site (www.kat.ac.za). We are particularly interested in developing science themes that make use of the KAT, SALT and HESS telescopes.

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