A Giant Step: from Milli- to Micro-arcsecond Astrometry
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The Square Kilometre Array

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Abstract. The SKA is a global project to plan and construct the next-generation international radio telescope operating at metre to cm wavelengths. More than 50 institutes in 19 countries are involved in its development. The SKA will be an interferometric array with a collecting area of up to one million square metres and maximum baseline of at least 3000 km. The SKA reference design includes field-of-view expansion technology that will allow instantaneous imaging of up to several tens of degrees. The SKA is being designed to address fundamental questions in cosmology, physics and astronomy. The key science goals range from the epoch or re-ionization, dark energy, the formation and evolution of galaxies and large-scale structure, the origin and evolution of cosmic magnetism, strong-field tests of gravity and gravity wave detection, the cradle of life, and the search for extraterrestrial intelligence. The sensitivity, field-of-view and angular resolution of the SKA will make possible a program to create a multi-epoch data base of wide-angle relative astrometry to a few μas precision for $\sim$10,000,000 radio sources with $S > 10$ μJy.

Keywords. instrumentation: interferometers, techniques: high angular resolution, surveys

1. Introduction

The Square Kilometre Array (SKA) is a next-generation radio telescope being planned and developed by a consortium of institutions in 19 countries, including Argentina, Australia, Brazil, Canada, China, France, Germany, India, Italy, The Netherlands, New Zealand, Poland, Portugal, Russia, South Africa, Sweden, United Kingdom and the United States. It will be an interferometric array with collecting area of order one million square metres, providing a sensitivity about 50 times higher than the largest currently existing radio telescopes. Taking advantage of technology developments in radio frequency devices and digital processing it will achieve an sky imaging capacity 10,000 times faster than our best imaging radio telescopes.

The science case for the SKA has been under development for over a decade, e.g. Taylor (1999), Carilli & Rawlings (2004). The major leap in our ability to observe the universe enabled by the SKA will advance a broad range of modern astrophysics. The SKA science community has identified five key science areas where the SKA is targeted to make transformational advances in questions of fundamental importance in physics and astrophysics.

- *Strong-field tests of gravity using pulsars and black holes:* Surveys will detect tens of thousands of new pulsars including binary systems and potentially black hole companions. Thousands of milli-second pulsars will form a pulsar timing array for detection of gravity waves.
- *The origin and evolution of cosmic magnetism.* Surveys of polarization properties of the sky will yield measures of polarized synchrotron radiation arising from relativistic

particles interacting with magnetic fields. Faraday rotation for $\sim 10^8$ polarized extragalactic radio sources to cosmological distances.

- *Galaxy evolution and cosmology.* Atomic hydrogen emission will be detectable in normal galaxies to high redshift, providing measure of the cosmic evolution of HI and star formation. The large-scale distribution of galaxies out to high z will allow precise studies and determination of the equation of state of of dark energy.
- Probing the Dark Ages: At its lowest frequencies the SKA will probe the structure of the neutral IGM before and during the epoch of reionization.
- *The cradle of life:* Sub-AU imaging of thermal emission will trace the process of terrestrial planet formation. The raw sensitivity of the SKA will allow "leakage" radiation to be detected from potential civilizations in planetary systems around millions of solar-type stars.

Complete and current information in the SKA can be found at the project web site http://www.skatelescope.org.

2. The Square Kilometre Array

2.1. *SKA technology*

The technical specifications of the SKA are listed in Table 1, and Fig. 1 shows an artists conception of the SKA. The telescope will consist of an inner core region about 5 km across. Outside of the inner core arrays of "stations" will be distributed out to the

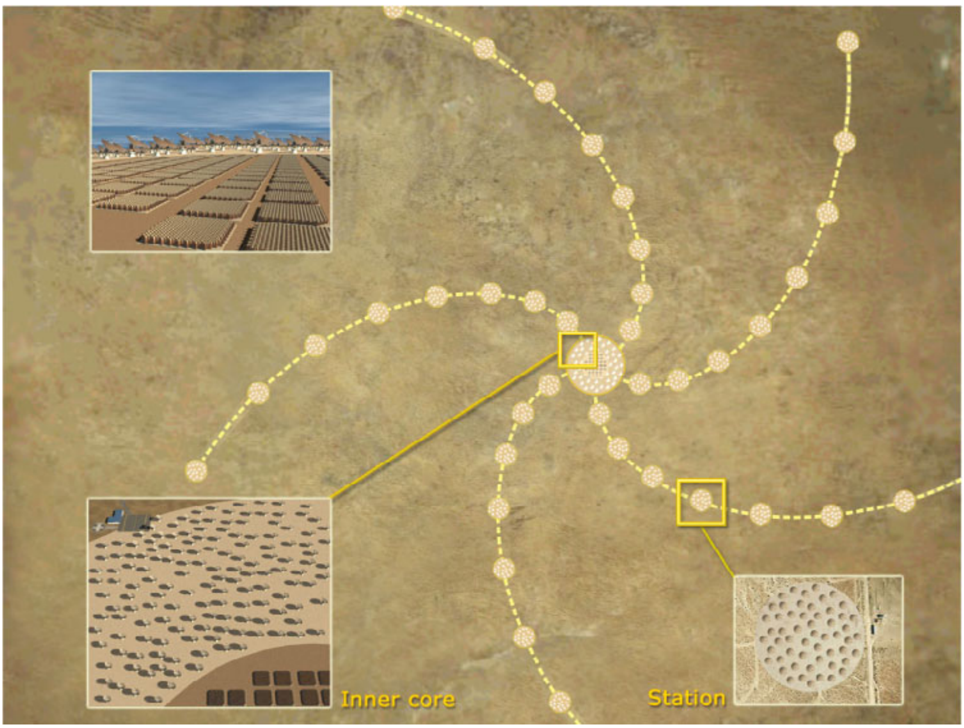

Figure 1. Artists conception of an arial view of the inner parts of the SKA. An inner core of about 5 km in diamter will contain about 50% of the collection area (see Table 3). Outside this area the SKA will be comprised of "stations", each made up of many antenna elements, extending to baselines of at least 3000 km.

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maximum baseline. Both the inner core and the stations will be comprised of many antenna elements.

The lowest frequencies (below about 500 MHz) will be detected with arrays of tiles of aperture-plane phased-array feed systems, providing instantaneous field-of-view of hundreds of square degrees. At higher frequencies, large numbers of 10-15m class parabolic antennas will be equipped with new technology feed systems: focal-plane, phased-array feeds at GHz frequencies, and very wide-band, single-pixel feeds at higher frequencies. Focal-plane phased array feeds are critical technology for field-of-view expansion in the GHz regime. This technology is under rapid development. Figure 2 shows a prototype phase-array feed with 180 antenna element that has been constructed at the Dominion Radio Astrophysical Observatory of the Herzberg Institute of Astrophysics. This system will be installed and tested on a new-technology parabolic antenna at DRAO.

The SKA antenna technology thus separates in three frequency regimes, low, mid and high. This frequency-dependence of the SKA technology is summarized in Table 2. In the low- and mid-range, field-of-view expansion technology based on aperture-or focal-plane phased array feeds combined with the large leap in sensitivity makes the SKA a prodigious synoptic survey imaging telescope.

Table 1. SKA Specifications

Parameter	**Specification**
Frequency Range	70 MHz – 25 GHz
Sensitivity	$\frac{A_{\rm eff}}{T_{\rm sys}}$ = 5,000 to 10,0000, depending on frequency
Field-of-view	200 to 1 square degree, depending on frequency
Angular Resolution	0.1 arcsecond at 1.4 GHz
Instantaneous bandwidth	25% of band centre, maximum 4 GHz
Calibrated polarization purity	10,000 : 1
Imaging dynamic range	1,000,000 : 1 at 1.4 GHz
Output data rate	1 Terrabyte per minute

Figure 2. A focal-plane phase array demonstrator system (PHAD) at the Herzberg Institute of Astrophysics, Dominion Radio Astrophysical Observatory. This system will be tested on a new-technology 10-metre parabolic antenna as part of the technology development for the SKA and the Australian SKA Pathfinder.

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Table 2. SKA Technology Dependent Frequency Ranges

SKA	Frequency Range	$\frac{A_{\mathrm{eff}}}{T_{\mathrm{sys}}}$	Field of View
low	$200 - 500$ MHz	$4,000 - 10,000$	200 sq degrees
mid	$0.5 - x$ GHz	10,000	10's of square degrees
high	$x - 25$ GHz	5,000	$\left(\frac{1.4}{\nu}\right)^2$ square degrees

Notes:
[1] The value of x, which is the frequency where the sensor technology changes from mid to high, will be determined by studies and the technology demonstrators planned for the 2008-2012 time frame (see discussion in text). Initial studies suggest that x will be $\sim$10 GHz

2.2. *SKA development*

The SKA will be built in a staged program. The development timeline is shown in Fig. 3. Construction of SKA technology pathfinder telescopes have begun at radio-quiet sites in Western Australia and South Africa, and will be completed by 2012. These pathfinder will have $\sim$1% of the collecting area of the complete SKA and will demonstrate the low-mid band SKA technologies. The demonstration of field-of-view expansion technology on the pathfinders will provide them with significant scientific potential as synoptic survey instruments. Early, pre-SKA, survey science with the pathfinders will be carried out between 2012 and 2015.

Following further technical studies of the properties of the proposed sites, a selection will be made in 2011. Construction of the low-mid technology of the SKA will begin around 2015 at the selected sites, and the low-mid SKA will be rolled-out over five years leading to completion of the low-mid SKA by around 2020.

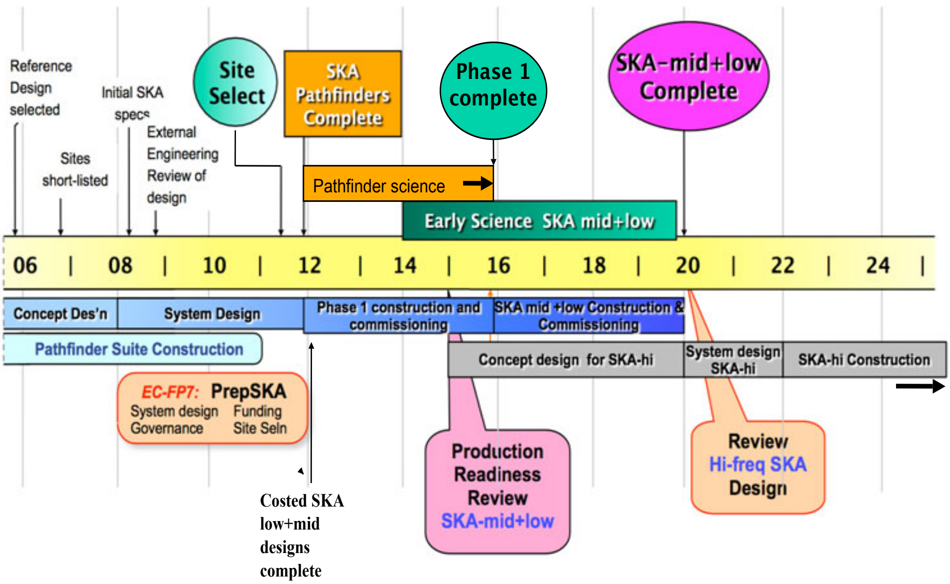

Figure 3. Timeline for SKA Development and Science. Pathfinder instruments at 1% scale of the the SKA collecting will be completed in Western Australia and South Africa by 2012. The rollout of the SKA will begin a few years later with construction start for SKA mid-low around 2015.

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3. Astrometry with the SKA

With a maximum baseline of 3000 km, the highest angular resolution of the SKA will be similar to that currently achieved with global VLBI arrays. However, the main limitation to astrometric precision with current VLBI comes not from the angular resolution but from the need to have nearby, strong compact sources as phase references for differential astrometry. This is limited by the sensitivity of existing telescopes and their limited field-of-view. The SKA will have a significant fraction of its aperture out to the largest baselines (see Table 3), ensuring good sensitivity at the highest resolution. The combination of wide field-of-view and sensitivity of the SKA will instantaneously provide a large number of reference sources.

Table 3. Distribution of the SKA Aperture

Region	Distance	Cumulative Fraction of Aperture
core	< 1 km	20%
inner	< 5 km	50%
mid	< 150 km	75%
outer	at least 3000 km	100%

For a 3000 km maximum baseline the angular resolution is

$$\theta = \frac{20}{\nu_{\mathrm{GHz}}} \text{ mas} = 2 \text{ mas at } 10 \text{ GHz}. \tag{3.1}$$

At 10 GHz the SKA will achieve a minimum detectable flux density of 0.3 μJy (5σ) in one hour. The SKA will be designed for high dynamic range imaging (see Table 1). At this frequency the imaging dynamic range will be less challenging than lower frequency so noise-limited images over the full field-of-view will be routine. The angular precision of phase-referenced astrometry is given approximately by

$$\Delta\theta = \frac{\theta}{\mathrm{SNR}}, \tag{3.2}$$

where SNR is the signal-to-noise ratio on the radio source. In a deep VLA integration at 8.4 GHz by Fomalont et. al. (2002), 0.64 sources per arcmin^2 were detected above 7.5 μJy. From fits to the number of sources versus flux density they derive an expression for the integral source counts,

$$N(>S) = 0.099\left(\frac{S}{40}\right)^{-1.11}. \tag{3.3}$$

The SKA will achieve SNR $>$ 2000 in one hour at 10 GHz on sources with flux density above 200 μJy. Within one square degree there will be on average 105 sources above this flux limit. The astrometric precision for these source will be $\sim$1 μas. In the same area there will be more than 1000 source above 12 μJy which will have differential astrometry to $\sim$10 μas. The SKA could therefore very quickly establish a dense grid of more than 10,000,000 sources with astrometric accuracy of a few μas that can be re-observed at multiple epochs.

In combination with the next-generation space VLBI mission, VSOP2, even higher precision astrometry will be possible. Assuming Earth-space baselines of about 30,000 km, angular resolution of 2 μas will be achieved at 8 GHz and 5-σ detection limit of 1.0 μJy. Sub-μas astrometry will be possible to sources with flux densities down to 0.4. mJy.

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The astrometric capabilities of the SKA will be used for a range of science goals. In the most recent SKA science case Fomalont & Reid (2004) list a number of areas where SKA astrometry at the μarc-second level will enable significant advance

- distance, proper motions and orbital motions of many thousands of radio stars
- planetary detections
- masses of degenerate stars
- calibration of the universal distance scale from 10 to 10^7 pc,
- AGN core-jet interactions
- fundamental frame tie to <10 μarc-second
- terrestrial dynamics
- fundamental physics via solar and Jovian deflections
- pulsar array geometry for gravity wave detection

4. Conclusion

The combination of sensitivity and imaging field-of-view of the SKA will allow μas precision astrometry to 10's of millions of compact radio sources, including AGN and thousands or radio stars. In combination with VSOP2, astrometry on mJy sources will be possible to well below a μas. This capability will both provide a dense, μas astrometric grid of radio sources and will underpin a range of fundamental astronomy based on ultra-precise astrometry.

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