The Square Kilometre Array

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ABSTRACT

The Square Kilometre Array (SKA) is a global project to design and build a new generation radio telescope at metre to centimetre wavelengths. It will have a collecting area of order one million square metres, a sensitivity 50 times higher than the EVLA, an instantaneous field of view (FOV) of at least 1 square degree and, in some designs, more than one FOV allowing multiple simultaneous use. It will be an extremely powerful survey telescope with the capability to follow up individual objects with high angular and time resolution. The SKA will reach a point source sensitivity of 10 nano-Jy in 8 hours of integration, and a maximum resolution of 1 milli arcsec at 20 GHz with excellent imaging capability at all resolutions and frequencies. The SKA science impact will be felt in astro-particle physics and cosmology, fundamental physics, galactic and extragalactic astronomy, and solar system science. Technological innovation, closely paralleling commercial IT developments, is key to the design concepts under investigation and to the cost goal of € 1000/m^2. The final selection of technologies for the SKA is scheduled in early 2009. Proposals for siting the telescope will be submitted by four countries at the end of 2005, and ranked during the course of 2006; the final decision is expected in 2008. Construction of the first phase of the array is planned to start in 2010 with the full array completed in 2020.

INTRODUCTION

Radio astronomy has played a leading discovery role in astrophysics and cosmology over the last 50 years. Central to these discoveries have been innovations in technology pushing the observational frontiers of sensitivity and spatial, temporal and spectral coverage and resolution. The next generation radio telescope - the Square Kilometre Array - will carry on this tradition of innovation. The goal is to construct a network of antennas working at centimetre to metre wavelengths with 50 times the sensitivity of the Expanded VLA. This telescope will play a major role in the following decades, alongside other next generation facilities in the millimetre, optical/IR, X-ray, etc, in further exploring the content and evolution of the universe.

KEY SCIENCE PROJECTS FOR THE SKA

The science case for the SKA was published by Elsevier in December 2004 in the form of a book [1] "Science with the Square Kilometre Array", edited by C. Carilli and S. Rawlings. Five key science projects were identified (see Gaensler et al, SKA Memo 43, www.skatelescope.org):

The Evolution of Galaxies and Large Scale Structure

The original motivation for building the SKA was to detect HI in normal galaxies at high redshift. Such an experiment promises a particularly exciting result, in that the vast volume of space probed by an SKA HI galaxy survey will provide an exquisite matter power spectrum, with which we can compute the Universe's Equation of State, and map out the strength of Dark Energy as a function of cosmic epoch. At the same time, the SKA's unique capability to observe the neutral atomic component of gas in galaxies will allow us to chart the kinematics, merger history and environment of ordinary galaxies as they evolve from redshifts z~5 to the present.

Probing the Dark Ages

The epoch at which the first luminous objects in the Universe formed, and then reionized the neutral IGM, can only be studied at near-IR through radio wavelengths. In the redshifted HI line the SKA can map out the complicated processes occurring during the Epoch of Reionization; through redshifted CO, the SKA can detect star-forming galaxies at these redshifts; and with deep continuum observations, the SKA can detect the first AGNs. The ensemble of these data can provide unique information on how the first galaxies and black holes assembled themselves, and how they influenced their environment.

Strong Field Tests of Gravity Using Pulsars and Black Holes

Pulsar surveys with the SKA can discover tens of thousands of pulsars, amongst which one expects to find a pulsar in orbit around a stellar-mass black hole, thousands of millisecond pulsars which can form an immense pulsar timing array, and pulsars in close orbit around the supermassive black hole at the Galactic Centre. These data can be used to provide fundamental and detailed tests of our understanding of gravity, in regimes that cannot be probed by any other experiment.

The Origin and Evolution of Cosmic Magnetism

Radio astronomy is uniquely placed in its capability to study magnetic fields at large distances, through studies of Faraday rotation, polarized synchrotron emission and the Zeeman effect. Through an all-sky continuum survey, the SKA could measure rotation measures for 10^8 polarized extragalactic sources, with an average spacing between sightlines of 90". The sheer weight of statistics in these data, combined with deep polarimetric observations of nearby galaxies and clusters, would allow us to completely characterize the evolution of magnetic fields in galaxies and clusters from redshifts $z>3$ to the present, to measure the strength and structure of the magnetic field in the IGM, to determine whether there is a connection between the formation of magnetic fields and the formation of structure in the early Universe, and to provide solid constraints on when and how the first magnetic fields in the Universe were generated.

The Cradle of Life

Astrobiology and the search for Earth-like planets hold great fascination for the layman and astronomer alike. The SKA has enormous potential for finding evidence of extra-solar terrestrial planets and of other life like us. At 20 GHz, the SKA will provide thermal imaging at 0.15-AU resolution of stars out to a distance of 150 pc, encompassing many of the best-studied Galactic star-forming regions. Such observations will allow us to study the process of terrestrial planet formation; such systems will evolve on timescales of months. For the first time with the SKA, we will have the capability of detecting leakage radiation from ETI transmitters out to a few hundred parsecs, involving of order a million solar type stars.

Other top-level science areas

The impact of the SKA will be felt in many other areas of astronomy and astrophysics (see reference [1]). These include: the variable radio sky, gravitational lensing, masers, evolution of star formation in galaxies, relativistic jets, radio stars, the scintillating universe, and astrometry.

Exploration of the unknown

Finally, if history is any guide, the two orders of magnitude increase in sensitivity provided by the SKA will lead to the discovery of new phenomena in the cosmos.

DESIGN REQUIREMENTS

Analysis of the science goals, particularly the key science projects, and the types of measurements needed to carry them out yielded a set of requirements on the telescope design (D. Jones 2004, SKA Memo 45, www.skatelescope.org). These form the basis of the system design specifications.

TELESCOPE DESIGN

The SKA will be the most advanced synthesis array ever built. A simple sketch of its major elements is given in Fig. 1. High-quality imaging of both low brightness emission and compact structure on milli-arcsecond scales dictates a hierarchical configuration for the SKA including a centrally condensed core, an intermediate baseline array, and a very long baseline array of many thousands of km. It will therefore be a sparsely-sampled aperture synthesis array with individual antennas or clusters of antennas ("stations") positioned across the aperture in a 2-dimensional distribution and connected to a central signal processor by a high-capacity optical fibre network. The number of remote stations will be of order 100.

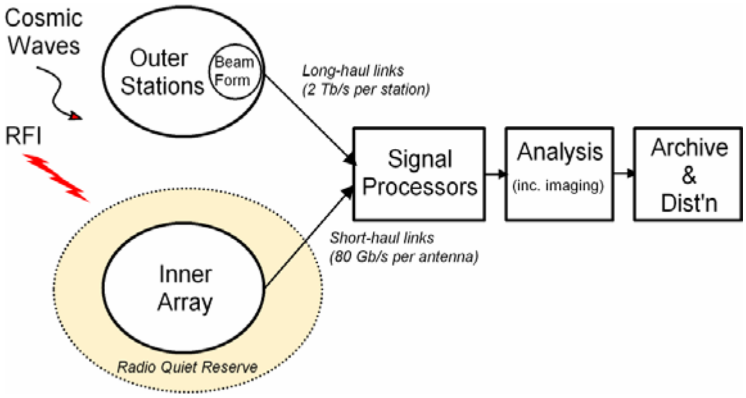

Fig. 1: The main elements of the SKA (credit: P. Hall).

The primary specifications for the telescope are those of sensitivity, defined as the ratio of the effective area of the aperture to system temperature, frequency range, field of view, and array configuration. The major technological challenges are to *reduce the cost per unit area by a factor of about ten compared to current and past radio telescopes*, and to cover the complete frequency range required by the key science projects. At the same time as reducing the unit cost to of order € 1000 /m^2, the design must be flexible, and minimise maintenance and running costs.

An innovative programme of R&D and demonstrator development is under way at a number of radio astronomy institutes around the world to allow selection of the implementation that maximises performance while minimising cost. These designs take advantage of the massive levels of R&D in the fibre optics and electronics industries for transport and handling of SKA data. The final design may incorporate features from more than one concept in order to satisfy the science goals, in particular the full frequency range. Leading contenders for the antenna technology are:

Parabolic Dishes with "Smart Feeds"
Reflector technology has traditionally been used for radio telescopes due to the availability of constant collecting area over a wide bandwidth. Traditional large single parabolic reflectors can, however, be replaced by clusters of small mass-produced parabolic antennas each of which is equipped with a feed and receiver system. Reflector diameters of order 10m are under consideration in a number of institutes around the world. More than 4000 of these antennas would be needed to meet the sensitivity specification, half of which would be in the central 5km core and the rest grouped into stations spread out over the full extent of the array. In addition, there are innovative designs for low-cost large diameter reflectors also under study.

At the low- and mid-band frequencies of the SKA (0.1-5 GHz), feed design efforts are concentrating on phased arrays in the focal plane of the individual dishes which provide fields-of-view of up to a few tens of square degrees for fast all-sky surveying. These phased arrays are closely related to the Aperture Arrays described in the next paragraph. At the high-band frequencies (5-25 GHz) where all-sky surveying does not have as high a priority, the feeds are likely to be broadband single-pixel elements.

Aperture Arrays
Aperture arrays are an unfamiliar concept in radio astronomy, but well known in radar circles in more narrow bandwidth applications. For the SKA, parabolic flux concentrators would be replaced by flat tiles comprising many all-sky broad-

band antenna+receiver chains designed for mass production. The signals from the individual antennas in a tile are combined electronically and in software to form a number of primary beams on the sky, and the signals from groups of tiles can also be combined to form narrower pencil beams within the primary beam. All beams can be steered on the sky as required without there being any moving parts. As with the small parabolas, the tiles outside the central core would be grouped in stations to reduce the connectivity costs over the large distances involved to the central signal processor.

This concept allows a number of full-sensitivity primary beams to be used for independent scientific programs, effectively creating a multi-telescope facility sharing a common aperture and signal transport infrastructure. Aperture arrays are most effective in the SKA context in the frequency range 100 MHz to 2 GHz.

LOCATION

Four countries are leading efforts to secure the location of the SKA: Argentina, Australia, China, and South Africa. Proposals are due at the end of 2005. Radio Frequency Interference measurements are being carried out at the proposed core sites, both by the individual site proposers themselves and by an internationally–financed team under contract to the SKA Project Office.

INTERNATIONAL ORGANISATION

The SKA is the first radio telescope to be born global. More than 50 institutes in 17 countries have committed themselves to share research and development for the telescope. The institutes have organised themselves into country-wide or regional consortia that nominate delegates to the International SKA Steering Committee (ISSC). The ISSC has established an International SKA Project Office, funded by subscription of the member institutions, to manage the detailed coordination of the project.

TIMELINE

The ISSC has adopted a timeline that calls for a decision on the ranking of the sites for the SKA by the ISSC in 2006, and a final decision on the location in 2008. An intensive period of technology verification via prototypes, demonstrators, and pathfinders has been underway for the last 5 years. Convergence on the design is planned in 2007, to be followed by the system design for Phase 1 in the period 2008-2010. Construction of Phase 1 (10% of the full array) is planned on the site chosen for the telescope from 2010-2014, with initial science expected in 2013. The full array should be completed and in operation in 2020.

COST

The cost goal for the SKA is € 1000M. An initial breakdown of costs suggests the following:
60% antennas/feeds/receivers/electronics, 20% software, 15% data transport infrastructure, and 5% data correlator. Operating costs are provisionally estimated to be of the order of € 75-100M/year.

FURTHER INFORMATION

Further information, copies of SKA memos, and links to the different aspects of the project can be found at www.skatelescope.org.

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REFERENCES

[1] C. Carilli, S. Rawlings (Eds) *Science with the SKA*, New Astronomy Reviews (Elsevier), Vol. 48, pp. 979-1563, 2004