PROCEEDINGS OF SCIENCE

The Square Kilometre Array

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The SKA will have a collecting area of up to one million square metres spread over at least 3000 km, providing a sensitivity 50 times higher than the Expanded VLA, and an instantaneous field of view (FOV) of at least several tens of square degrees and possibly 250 square degrees. The SKA science impact will be widely felt in astro-particle physics and cosmology, fundamental physics, galactic and extragalactic astronomy, solar system science and astrobiology. I will outline the main features of the SKA, paying attention to the design activities around the world, and outline plans for the final design and phased implementation of the telescope. Other papers in these Proceedings go into greater detail on SKA science.

From planets to dark energy: the modern radio universe
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1. Introduction

The Square Kilometre Array has evolved over the years from a purely “hydrogen array” observing at frequencies of 1.4 GHz and below, to a multi-facetted science facility covering a frequency range from 70 MHz to at least 25 GHz and capable of answering many of the major questions in modern astrophysics and cosmology. Five key science areas have been defined by the astronomy community as driving the specifications of the SKA [1, 2], and major R&D work is underway around the world to develop the required technology to meet these specifications. In this article, I summarize the science and the technical effort before going on to discuss siting issues and the project timeline.

2. Key Science Programs

2.1.1 Probing the Dark Ages: The formation of the first structures, as the Universe made the transition from largely neutral to its largely ionized state today, will be studied in redshifted neutral hydrogen and carbon monoxide.

2.1.2 Galaxy Evolution, Cosmology and Dark Energy: The structure of the Universe and its fundamental constituent, galaxies, will be studied by carrying out all-sky surveys of continuum emission and of HI to a redshift $z \sim 2$. HI surveys can probe both cosmology (including dark energy) and the properties of galaxy assembly and evolution.

2.1.3 The Origin and Evolution of Cosmic Magnetism: Magnetic fields are an essential part of many astrophysical phenomena, but fundamental questions remain about their evolution, structure, and origin. The goal of this KSP is to trace magnetic field evolution and structure across cosmic time.

2.1.4 Strong Field Tests of Gravity Using Pulsars and Black Holes: The nature of space and time in the context of strong gravitational fields will be probed using high precision timing measurements on pulsars.

2.1.5 The Cradle of Life: This KSP aims to probe the full range of astrobiology, from the formation of prebiotic molecules in the interstellar medium to the emergence of technological civilisations on habitable planets.

2.1.6 Exploration of the Unknown: The scientific challenges outlined above are currently top priority. However, from the very earliest days of the project, it has been recognized that the telescope must be highly flexible, able to evolve its capabilities into new parameter space, in order to allow it to answer the new problems confronting astronomers in the period 2020-2050 and beyond, when the SKA will be in its most productive years.

3. Top-level specifications

Preliminary top-level specifications of the Square Kilometre Array have been developed [2] following science-engineering trade-offs that have taken into account current knowledge of likely key technologies (see section 4 below) and their likely evolution, and cost at the time of construction. A number of possible implementations are proposed (see section 5) which are estimated to cost 300 M€ (2007) for the first stage (Phase 1) of the array and 1500 M€ (2007)

for the full array at frequencies from ~70 MHz to 10 GHz (Phase 2). The Phase 1 and Phase 2 costs include 100 M€ and 500 M€ respectively for infrastructure, software, labour, management costs, and delivery; the remaining two-thirds in both cases is for hardware components. The third phase of the SKA Program, the extension to at least 25 GHz, is less well-defined at this stage, and the technical outlines and costs of its implementation are left to future studies.

The SKA will be a radio telescope with

- The sensitivity to detect and image hydrogen in the early universe.
  This will be accomplished by deploying a *very large collecting area,* up to several km^2 at the lowest frequencies, in an interferometer array. The gain of the telescope measured by effective area/system temperature will be ~ 10000 (peak) which provides a sensitivity approximately 50 times the Expanded VLA.

- A *wide frequency range* to enable the range of science in the Key Science Programs
  - 70 – 200 MHz (low-band)
  - 0.2 – 10 GHz (mid-band)
  - 10 – >25 GHz (high-band)

- A fast surveying capability over the whole sky. This will be accomplished by means of a *very large angle field of view* of up to several tens of square degrees at frequencies below 1 GHz using focal plane arrays in dishes, and up to 250 square degrees using aperture arrays (see section 4). The Survey Speed Figure of Merit will be up to 3×10^9 deg^{2}m^{4}K^{-2} [3]. Above 1 GHz, a field of view of 1 square degree scaling with frequency squared will be sufficient.

- *A central concentration of the collecting area* for optimal detection of hydrogen, pulsars, and magnetic fields. Fifty percent of the collecting area will be located within a radius of 2.5 km of the centre of the array, a further 25% within 180 km of the centre and the remaining 25% out to the maximum extent of the array.

- The capability for detailed imaging of compact objects and astrometry. This requires a *large physical extent,* up to at least 3000 km.

4. Design Technologies

The SKA is an interferometer comprised of five major systems: sensors, signal transport, signal processing, computing and software. Much of the detailed design effort so far has gone into the possible sensor technologies, and in this section I show photographs of progress around the world in this area. Details of the technologies can be found in [4, 5].

The sensor technologies under development for the SKA are:

1. multiple dishes each equipped with single pixel wide-band feeds for the mid and high bands,
2. multiple dishes equipped with phased array feeds at their foci for the mid-band, and
3. aperture arrays, both dense and sparse, for the mid and low bands respectively.

The primary work on sensors is being carried out in the Pathfinder projects (ASKAP, Australia; ATA, USA; LOFAR, Netherlands and other European countries; LWA, USA; MWA, USA/Australia; meerKAT, South Africa), and design studies in Europe (SKADS) and USA (TDP). From 2008 to 2012, the R&D effort around the world will be integrated into a final costed system design by the SKA Program Development Office with support from the PrepSKA program. PrepSKA is a global preparatory program funded by the European Commission to coordinate all the technical, site characterisation, governance, procurement and financial activities required before formal construction proposals for the SKA are submitted.

4.1 Dishes

Dishes and wide-band single pixel feeds (see next section) are a low-risk reference scenario for the mid-band SKA. The eventual upper frequency limit will depend on the outcomes of cost-effectiveness studies undertaken by the regional SKA projects, specifically the US TDP. Dish development itself is following two main directions – metal (either hydroformed or panels) and composite.

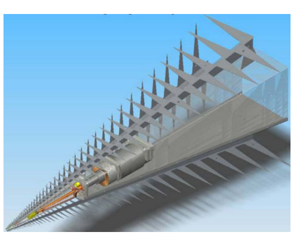
Allen Telescope Array, USA, 6m hydroformed aluminium dish.

MeerKAT, South Africa 15 m fibreglass+foam dish (<2 mm rms).

CART, Canada, 10 m composite dish (1 mm rms)

4.2 Wide-band single pixel feeds

A number of concepts are under development around the world. Some of them are shown below, courtesy of G. Cortes Medellin.



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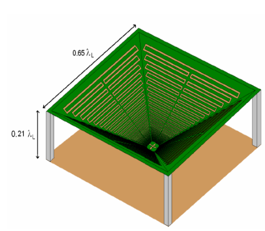

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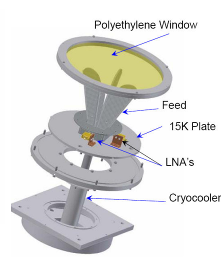

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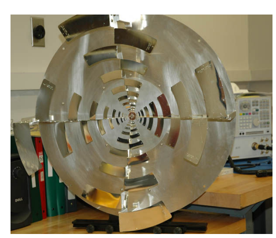


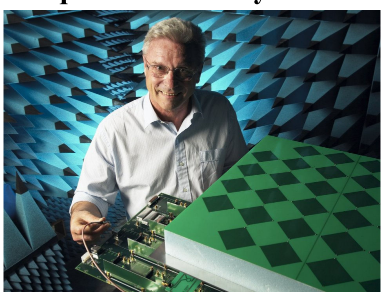
d)

a) ATA feed (www.seti.org); b) Chalmers feed (R. Olson, P.S. Kildal, and S. Weinreb. *IEEE Transactions on Ant and Prop*, vol 54, no 2, part 1, Feb 2006, pp. 368–375); c) quad-ridge Lindgren horn (W. A. Imbriale, S. Weinreb and H. Mani. IEEE 2007 Aerospace Conference, Big Sky, Montana); d) Quasi Self-Complementary Antenna, Germán Cortés Medellin. IEEE AP-S International Symposium, Honolulu, Hawaii, June, 2007

4.3 Phased Array Feeds in the focal plane

Phased array feeds at (or near) the focus of a dish are a cost effective way to increase the FoV - up to several tens of square degrees - and hence survey speed of a single dish. They represent a compromise between the aperture arrays and the single pixel feeds since they still get the concentrator cost advantage of the single dish, with decreased number of phased array elements per square metre of collecting area.

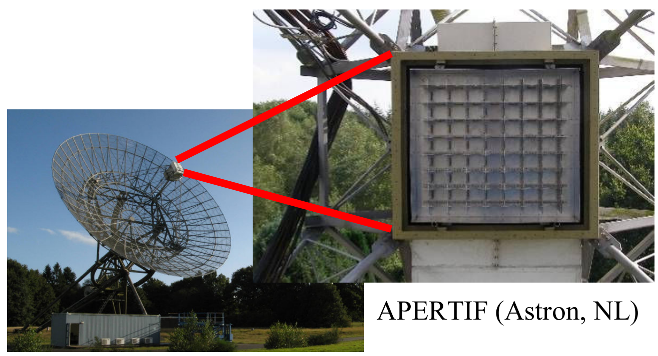
Chequerboard array



CSIRO-ATNF, Australia

Vivaldi array

DRAO, Canada



APERTIF (Astron, NL)

4.4 Aperture arrays

Parabolic flux concentrators can be replaced by 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 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.

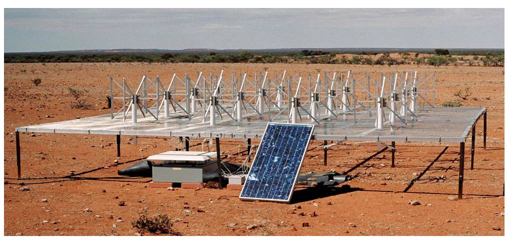
4.1.1 Sparse aperture arrays

In a sparse array, the elements are spaced further apart than $\lambda/2$; it is the preferred solution at frequencies below 500 MHz.

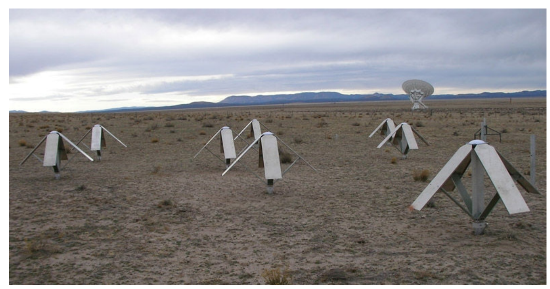
LOFAR (Netherlands, Germany, France, Sweden, UK)

Low band antenna: 30 – 80 MHz

High band antenna: 120 – 240 MHz



Murchison Wide-field Array (USA, Australia)

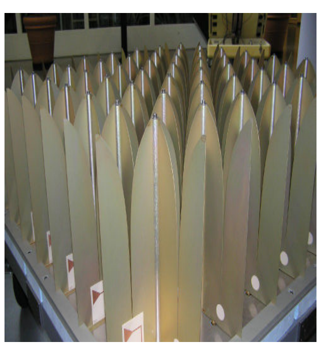


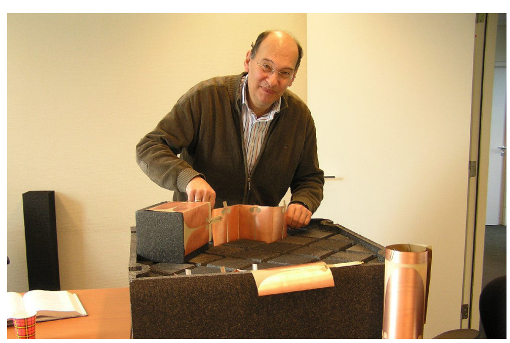
Long Wavelength Array (USA)

4.4.2 Dense aperture arrays

In a dense aperture array, the incoming wavefront is sampled at the Nyquist rate or better, allowing tight control on the beams produced.

SKA Design Study (Europe), EMBRACE using Vivaldi elements





4.5 High speed data transport

Speeds of Tb/s from each station will be required on scales out to hundreds of km, while for the trans-continental and trans-oceanic links, a more modest requirement of 100 Gb/s is specified. These longer links will rely on telecommunication companies and research networks

4.6 Signal processing: Substantial processing power of peta-operations per second will be required. Highly scaleable solutions will be needed to take advantage of IT developments over the course of the 8-year long construction and deployment of Phases 1 and 2 of the telescope.

4.7 Post-processing, information management: New super-computer architectures may be required. Archive and sharing of data will be a major challenge, as will algorithm development

4.8 Infrastructure: Civil, electrical (power, …), and communications infrastructures are a major element of the design and cost of the telescope. Initial thoughts on infrastructure have been set out in SKA Memorandum 96 by P. J. Hall et al [6].

4.9 Operations and support: The top-level criteria for operations and support for the SKA have been examined in SKA Memorandum 84 by Kellermann et al [7].

5. Representative Implementations for the SKA at mid and low band

Three potential implementations of the full SKA for the mid and low bands are currently receiving attention following analyses of their performance and cost in meeting the top-level specifications:

1) Sparse aperture arrays in the range 70-500 MHz + 3000 15m diameter dishes with wide-band single pixel feeds (SPFs) in the range 0.5–10 GHz

2) Sparse aperture arrays in the frequency range 70 - 500 MHz + 2000 15m diameter dishes equipped with phased array feeds (PAFs) in the range 0.5-1.5 GHz and SPFs in the range 1.5-10 GHz

3) Sparse aperture arrays in the range 70-500 MHz + a dense aperture array in the range 0.5-1 GHz + 2400 15m diameter dishes equipped with SPF in the range 1-10 GHz

For Phase 1 of the SKA, the two implementations under consideration are (obviously) subsets of the full SKA implementation:

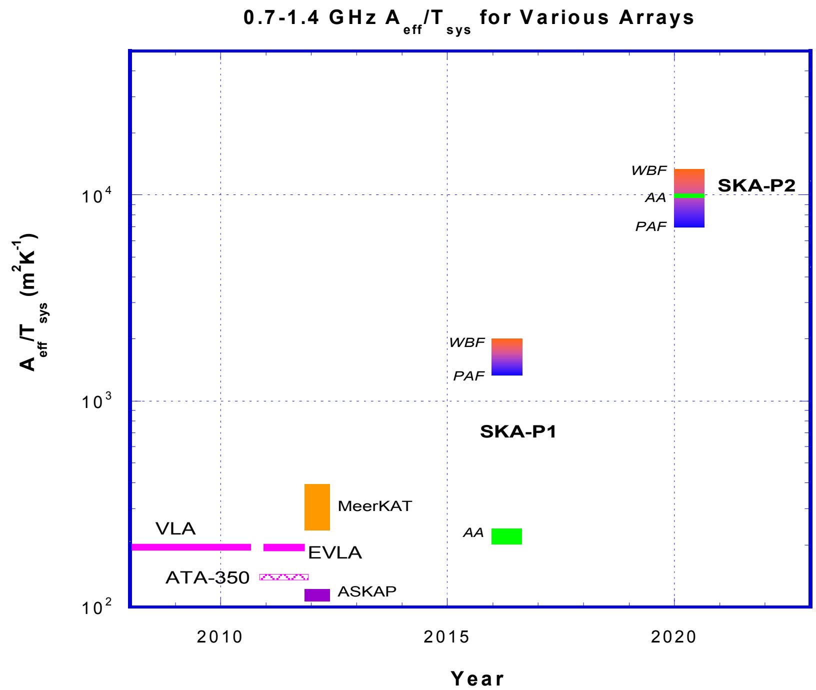
1) Dense aperture array in the frequency range 500-800 MHz + 490 15m dishes equipped with PAFs in the range 0.5-1.5 GHz and SPFs in the range 1.5-10 GHz

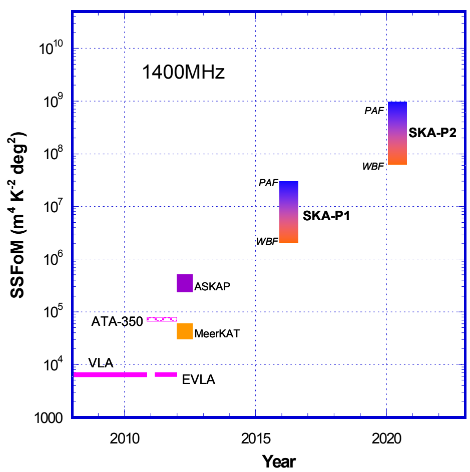
2) Dense aperture array in the range 500-800 MHz + 620 15m dishes with SPFs in the range 0.5-10 GHz

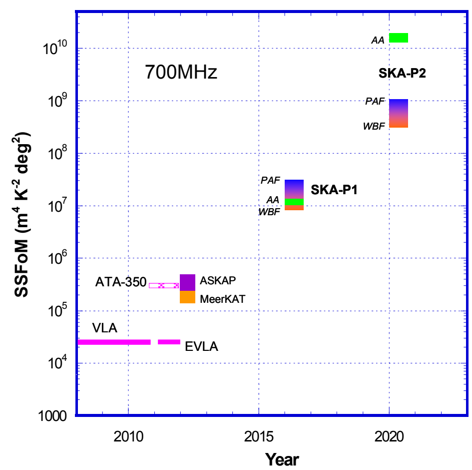
The dense aperture array could be replaced by sparse aperture arrays in the frequency range 100-500 MHz if science and technical considerations so dictate.

Further analysis of the performance and cost of the implementations will be carried out during PrepSKA using refined estimates from the Pathfinders and Design Studies, with a view to selecting an implementation by 2011.

The sensitivity (A_{eff}/T_{sys}) and survey speed figure of merit for Phase 1 and the full SKA at mid and low band (Phase 2) are compared to various pathfinders in the figures below (see [2] for more details). AA = Aperture Arrays; WBF = wide band single pixel feed; PAF = phased array feed.





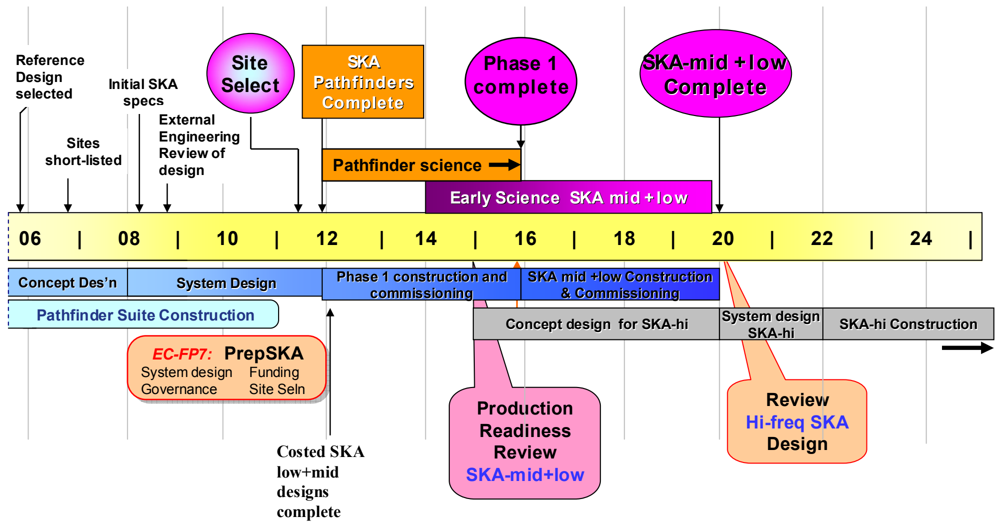


6. Sites

Following a comprehensive short-listing process in 2006 by the International SKA Steering Committee, Australia and Southern Africa were selected as candidate locations for the SKA. The final decision on the site is likely to be made during the discussions on construction funding planned in 2011 (see next section).

In the meantime, further site characterisation and development is being, and will be, undertaken. Infrastructure suitable for expansion into the SKA core site is already under development in both Western Australia and in the Northern Cape Province of South Africa as part of ASKAP and meerKAT construction respectively. Deep RFI measurements at the core sites and at selected remote sites are to be carried out in 2009 as part of the PrepSKA Work Program. And the optimum configuration for the array is under study by the Simulations Working Group and the Science Working Group.

7. Timeline



The period from 2006 to 2025 can be roughly divided into five main stages as shown by the blue and gray bars under the timeline

2006-2007: concept design development in parallel with Pathfinder construction and SKADS design study work in Europe
2008-2011: final system design and costing for SKA Phases 1 and 2 coordinated by the SKA Program development Office supported by PrepSKA and in parallel with completion of the Pathfinders, SKADS and TDP. At the end of this period, it is expected that a proposal for construction funding will be under consideration by the funding agencies and government departments, and that the site selection will have been made.
2012-2015: Phase 1 (15-20% SKA) construction in parallel with scientific exploitation of the Pathfinders. As Phase 1 is built out, early science observations will be done with the array.
2016-2020: Continuation of construction from Phase 1 to the full SKA at mid and low band frequencies, and use for early science. The concept design for SKA-high will run in parallel.
2020-2025+: final system design for SKA-high, and start of construction.

Acknowledgements
Many people around the world are part of the international project, and I would like to acknowledge their contributions, direct and indirect, to the contents of this paper. In particular, I want to acknowledge the work by Peter Hall (International Project Engineer) and Chris Carilli, Steve Rawlings and Bryan Gaensler (International Project Scientists) over the past few years in leading the development of the engineering design and the science case.

References

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