The Square Kilometre Array

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ABSTRACT

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 Very Large Array, 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. In this paper, we describe 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.

Keywords: radio astronomy, Square Kilometre Array

1. INTRODUCTION

From its inception, development of the Square Kilometre Array Program has been a global endeavour. In the early 1990s, there were multiple, independent suggestions for a “large hydrogen telescope”. It was recognized that probing the fundamental baryonic component of the Universe much beyond the local Universe would require a substantial increase in collecting area. The SKA has evolved over the intervening years from a simple “hydrogen array” observing at frequencies near 1.4 GHz, to a multi-facetted science facility covering a frequency range from 70 MHz to at least 25 GHz (a wavelength range of at least 1 cm to 4 m) and capable of answering many of the major questions in modern astrophysics and cosmology, physics, and astrobiology.

The International Union for Radio Science (URSI) first established a working group in 1993 to begin a worldwide study of the next generation radio wavelength observatory. Since that time, the effort has grown to comprise 19 countries and 55 institutes, including about 200 scientists and engineers. Significant milestones in the SKA Program have included the establishment of an international program office, development of scientific specifications and a reference design, and identification of a short-list of suitable sites. The SKA Program Development Office (SPDO, initially called the International SKA Project Office) was established in the Netherlands (and has since moved to England) to coordinate development work. Five key science areas have been defined by the astronomy community as driving the specifications of the SKA [1, 2]. As many as 7 different technical concepts for the SKA have been narrowed to a reference design. Finally, after a worldwide effort, two sites—one in the Karoo region of central South Africa and one in the state of Western Australia—have been identified as suitable for the site. This organized SKA effort has been a key factor in the allocation of about €150M in funding worldwide to R&D in recent years. Fifteen funding agencies now regularly discuss SKA development and funding options.

In this article, we summarize the science and the technical effort, before going on to discuss siting issues and the project timeline.

2. KEY SCIENCE PROGRAMS

The SKA Key Science Programs were identified over a year-long process in 2004 by an international group of astronomers and physicists. The objective was to identify a select set of investigations in which centimetre- and metre-wavelength observations were required to make fundamental progress in outstanding questions of modern astronomy, physics, or astrobiology [1]. The five Key Science Programs are the following.

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2.1 Probing the Dark Ages: As the first stars and galaxies formed, their ionizing UV radiation produced a fundamental change in the surrounding intergalactic medium, from a nearly completely neutral state to the nearly completely ionized Universe in which we live today. The most direct probe of this era, the Epoch of Re-ionization (EoR), and of the first large-scale structure formation, will be obtained by imaging neutral hydrogen and tracking the transition of the intergalactic medium from a neutral to ionized state. Moreover, as the first galaxies and AGN form, the SKA will provide an unobscured view of their gas content and dynamics via observations of highly redshifted, low-order molecular transitions (e.g., CO).

2.2 Galaxy Evolution, Cosmology and Dark Energy: Hydrogen is the fundamental baryonic component of the Universe. With a sensitivity to the 21-cm hyperfine transition of H I allowing detection out to redshifts $z > 1$, the SKA will both follow the assembly of galaxies as well as use their H I emission as a scale tracer for cosmological probes. One of the key questions for 21st Century astronomy is the assembly of galaxies; the SKA will probe how galaxies convert their gas to stars over a significant fraction of cosmic time and how the environment affects galactic properties. Simultaneously, baryon acoustic oscillations (BAOs), remnants of early density fluctuations in the Universe, serve as a tracer of the early expansion of the Universe. The SKA will assemble a large enough sample of galaxies to measure BAOs as a function of redshift to constrain the equation of state of dark energy.

2.3 The Origin and Evolution of Cosmic Magnetism: Magnetic fields likely play an important role throughout astrophysics, including in particle acceleration, cosmic ray propagation, and star formation. Unlike gravity, which has been present since the earliest times in the Universe, magnetic fields may have been generated essentially *ab initio* in galaxies and clusters of galaxies. By measuring the Faraday rotation toward large numbers of background sources, the SKA will track the evolution of magnetic fields in galaxies and clusters of galaxies over a large fraction of cosmic time. In addition to elucidating the role of magnetic fields in galaxies and clusters of galaxies, the SKA observations will seek to address whether magnetic fields are primordial and dating from the earliest times in the Universe or generated much later by dynamo activity.

2.4 Strong Field Tests of Gravity Using Pulsars and Black Holes: With magnetic field strengths as large as 10^{14} G, rotation rates approaching 1000 Hz, central densities exceeding 10^{14} g cm^{-3}, and normalized gravitational strengths of order 0.4, neutron stars represent one of the most extreme laboratories in the Universe. Their utility as fundamental laboratories has already been demonstrated through results from observations of a number of objects, resulting in two Nobel Prizes. The SKA will find many new milli-second pulsars and engage in high precision timing of them in order to construct a Pulsar Timing Array for the detection of nanoHertz gravitational waves, probing the spacetime environment around black holes via both ultra-relativistic binaries (e.g., pulsar-black hole binaries) and pulsars orbiting the central supermassive black hole in the center of the Milky Way, and probe the equation of state of nuclear matter.

2.5 The Cradle of Life: The existence of life elsewhere in the Universe has been a topic of speculation for millennia. In the latter half of the 20th Century, these speculations began to be informed by observational data, including organic molecules in interstellar space, and proto-planetary disks and planets themselves orbiting nearby stars. With its sensitivity and resolution, the SKA will be able to observe the centimetre-wavelength thermal radiation from dust in the inner regions of nearby proto-planetary disks and monitor changes as planets form, thereby probing a key regime in the planetary formation process. On larger scales in molecular clouds, the SKA will search for complex prebiotic molecules. Finally, detection of transmissions from another civilization would provide immediate and direct evidence of life elsewhere in the Universe, and the SKA will provide sufficient sensitivity to enable, for the first time, searches for unintentional emissions or “leakage.”

In addition, recognizing the long history of discovery at radio wavelengths (pulsars, cosmic microwave background, quasars, masers, the first extrasolar planets, etc.), the international science community also recommended that the design and development of the SKA have **“Exploration of the Unknown”** as a philosophy. Wherever possible, the design of the telescope is being developed in a manner to allow maximum flexibility and evolution of its capabilities in new directions and to probe new parameter space (e.g., time-variable phenomena that current telescopes are not equipped to detect – radio transients). This philosophy is essential as many of the outstanding questions of the 2020–2050 era—when the SKA will be in its most productive years—are likely not even known today.

More recently, in an effort to guide the development of the telescope, a Reference Science Mission is being assembled. The Reference Science Mission is designed to identify the key scientific requirements required to conduct the Key Science Programs and how they then lead to the specification of instrumental requirements. While still under development, the Reference Science Mission is likely to have at least four components:

Deep H I Field: to trace galaxy evolution via the HI-line as part of the "Galaxy Evolution, Cosmology, and Dark Energy" Key Science Program.

Wide Area Survey: to address at least three Key Science Programs simultaneously by surveying a large fraction of the sky (> 50%) available to the SKA. These are "Galaxy Evolution, Cosmology, and Dark Energy" by detecting the H I line from galaxies out to a redshift of one (half the age of the Universe); "Strong-field Tests of Gravity using Pulsars and Black Holes" by constructing a millisecond pulsar gravitational wave observatory; and "Origin and Evolution of Cosmic Magnetism" by constructing a Faraday rotation-measure grid.

Galactic Plane: to probe gravity utilizing relativistic binaries (neutron star-neutron star or neutron star-black hole binaries) as part of the "Strong-field Tests of Gravity using Pulsars and Black Holes."

Galactic Centre: to probe gravity via radio pulsars in or near the spacetime environment of Sgr A*, the central supermassive black hole in the Galaxy.

A common theme for all components of the Reference Science Mission is exploration of the unknown, primarily through the search for radio transients.

3. TOP-LEVEL SPECIFICATIONS

The Square Kilometre Array will be an aperture synthesis radio telescope that employs the sophisticated concepts of radio imaging developed over the past four to five decades. In their most general form, these concepts amount to spatial, spectral and temporal sampling of the incoming radio-radiation field so as to match the expected structure of the field in those three domains. In addition, careful attention will be paid to rejecting extraneous, man-made signals (radio frequency interference). The manifestation of these concepts as a ground-based radio telescope requires an array of antennas and receivers (more generally radio "sensors") covering a large area on the ground, and configured so as to provide the required spatial sampling or telescope resolution. The Very Large Array is an example of an aperture synthesis telescope that employs many of these concepts (Figure 1). The signals from the sensors, including appropriately represented amplitude and phase, are cross-correlated in pairs and integrated to reduce noise. These data are used to reconstruct the original brightness distribution, and is typically provided to the astronomer as images of the sky in angular dimensions, spectra at each point in the sky, and sometimes spectral and spatial variations with time. The extremely weak astronomical radio signals require high sensitivity and low system noise. This is achieved mainly by the very large total collecting area of the sensors, and by receiver systems that contribute the minimum possible noise.

Preliminary top-level specifications for the SKA have been developed [2] following science-engineering trade-offs that have taken into account current knowledge of key technologies (§4) and their likely evolution, and cost at the time of construction. A number of possible implementations are proposed (§5) which are estimated to cost 300 M€ for the first stage (Phase 1) of the array and 1200 M€ for the second stage (Phase 2). Phases 1 and 2 will cover frequencies from ~70 MHz to 10 GHz. The Phases 1 and 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. (All costs are expressed as 2007 currency). 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.

Figure 1: The VLA antennas in one of its array configurations. The antennas can be transported to provide either more compact or more spread-out configurations. (Image from NRAO / AUI / NSF).

The science goals outlined above require the SKA to 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. The gain of the telescope measured by effective area/system temperature (A_e/T_{sys}) will be ~10000 m^2 K^{-1} (peak), a sensitivity ~50 times that of the Expanded VLA.

- A *wide frequency range* to enable the range of science in the Key Science Programs:
  - 70 – 300 MHz (low-band)
  - 0.3 – 10 GHz (mid-band)
  - 10 – >25 GHz (high-band)

  These bands are defined partly by the way that science maps into frequency space, but more importantly because different approaches to the technology will be needed for the three frequency ranges (§4). Note that the wavelength ratio is about two orders of magnitude.
- A fast surveying capability over the whole sky. This will be accomplished by means of a *very large angular field of view* (FoV), 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 (§4). A Survey Speed Figure-of-Merit (FoM) has been developed, $[(A_e/T_{sys})^2 \bullet \mathrm{FoV}]$. This FoM will be up to $3\mathrm{x}10^9\ \mathrm{deg}^2\ \mathrm{m}^4\ \mathrm{K}^{-2}$ [3]. Above 1 GHz, a field of view of 1 square degree, scaling with frequency squared, matches the high-frequency science goals sufficiently well.
- *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 an array with a *large physical extent,* up to at least 3000 km.

4. DESIGN TECHNOLOGIES

The SKA comprises five major systems: sensors, signal transport, signal processing, computing and software. Much of the R&D and design effort so far has gone into sensor technologies, and in this section we illustrate progress from around the world in this area. Details of the technologies can be found in [4, 5].

4.1 Sensors

The goals of the new work on sensors has been directed towards expanding their fields of view, increasing their instantaneous bandwidth and/or tuning range, and maintaining the standards of low system noise set by previous generations of telescopes. Part of the continuing development work is also devoted to a detailed understanding of the system-wide behaviour of the different sensors, particularly the impact of errors on image and spectral quality.

As illustrated in Figure 2, the sensor technologies under development for the SKA are, proceeding from high frequencies to low:

1. An array of reflector antennas (dishes), each equipped with single, wide-band, dual polarization feeds for the mid and high bands. In the SKA context, reflectors equipped with these feeds are known as "single-pixel" because their field of view consists of one "beam" whose properties are mainly determined by the optics of the reflector.
2. The array of dishes may also be equipped with phased array feeds (PAF's) at their foci, to be used at the mid-band frequencies. The purpose of PAF's is to provide multiple, overlapped beams in a close-packed array on the sky, thus expanding the field of view of each reflector without decreasing its diameter. Each beam produces an output signal, and as in the case of the single-pixel beam their properties are determined mainly by the optics of the reflector.
3. Aperture arrays. Aperture arrays consist of many wavelength-scale (elemental) antennas, whose output signals are summed. The elemental antennas have very broad beams, which are sensitive to emissions from almost the entire sky, but the summed array creates a beam whose angular dimensions in radians is approximately equal to the inverse of the physical dimensions of the array in units of wavelengths. The summed beam can be steered electronically to very large angles from the Zenith (Z), although a loss of sensitivity proportional to tan(Z) is suffered, due to projection of the collecting area in the steering direction. Note that there are no mechanically moving parts. In principle, many beams can be produced simultaneously, each steered in a different direction. Also the beams can be re-directed almost simultaneously. In the aperture synthesis telescope system, each of these arrays performs the same function as a multi-beam dish system.

a) Dense Aperture Arrays: In a dense array the elemental antennas are packed at half-wavelength intervals (the shortest useful wavelength), so as to guarantee that the wavefront is always fully sampled in the spatial sense. In a close-packed square lattice, there is oversampling of the spatial information because there are many repeated instances of the same spacing between elements. The advantages of dense aperture arrays are the high degree of control over the shape of the beam on the sky and the ability to eliminate distant subsidiary beams (sidelobes). The redundancy inherent in dense aperture arrays increases the initial cost

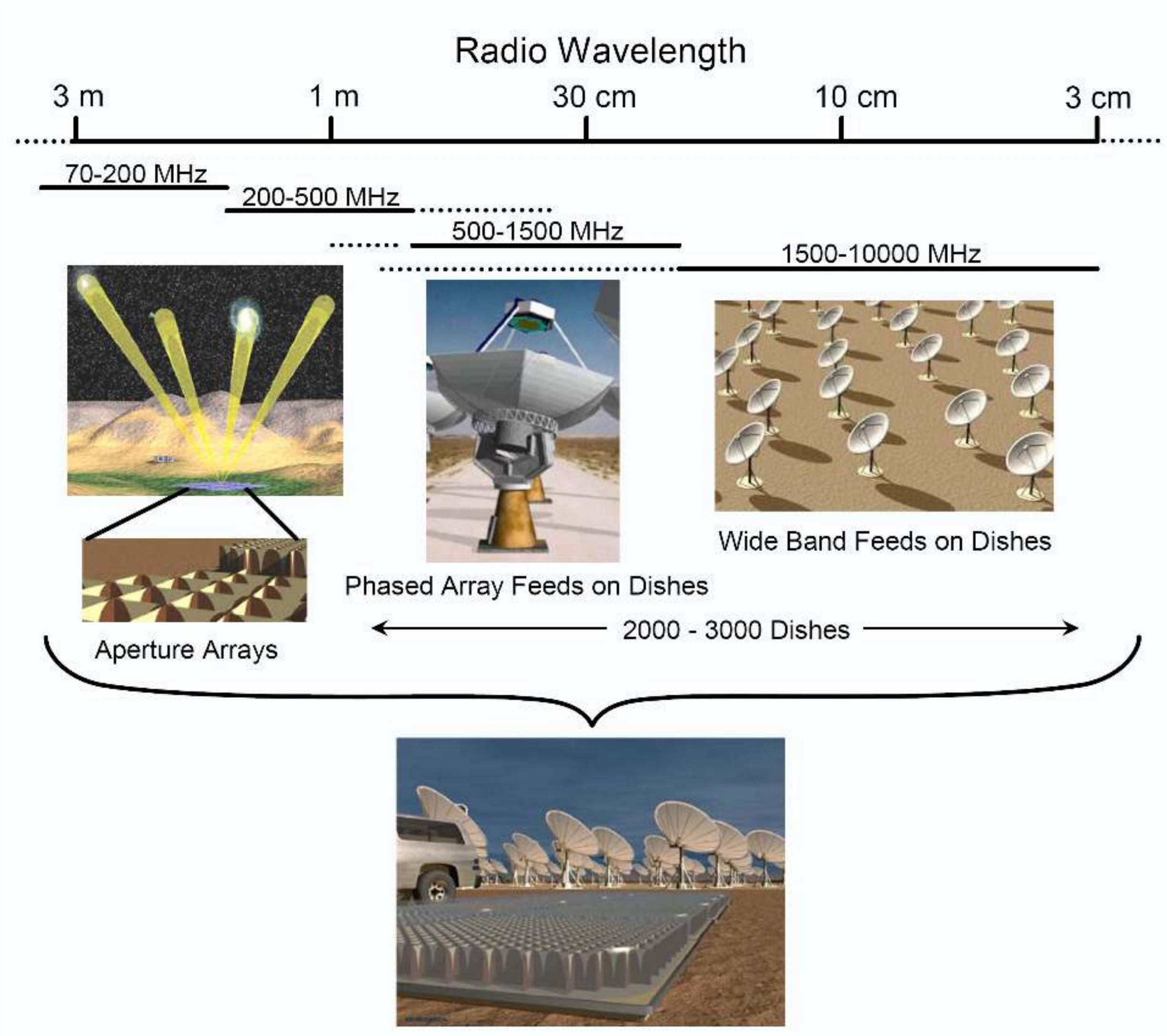


Figure 2: A schematic of the sensor technologies likely to be used over the range of SKA wavelengths. The bars under the wavelength axis denote ranges over which four sensor technologies will be used. At the longest wavelengths (leftmost bar), sparse aperture arrays are the most practical solution. At intermediate wavelengths, potentially both dense aperture arrays (leftmost middle bar) and reflectors with phased-array feeds (rightmost middle bar) are possible. At the shortest wavelengths (rightmost bar), only reflectors with single-pixel, wideband feeds are practical. The dotted lines indicate where technology choices may have to be made, or could co-exist. The upper left diagram shows an aperture array as a flat sensor system on the ground "illuminating" the sky with multiple beams. The exploded view shows the elements of the aperture array, in this case Vivaldi antennas. The middle diagram at the top shows a standard parabolic reflector with a phased-array feed at its focus. The upper right diagram shows an array of parabolic reflectors with ultra-wideband feeds at their foci. In practice the reflectors will likely have both feeds available. All the sensor technologies will share wideband communication/interconnection as well as signal processing and data processing infrastructure. The bottom picture is an artist's rendition of the core of the sensor configuration, showing both aperture arrays and dishes.

and the cost of powering more elemental sensors, but it also reduces sensitivity to errors. Dense aperture arrays can be used to form "tiles", which can themselves be combined further in either a dense or sparse configuration.

b) Sparse aperture arrays: These are similar to dense ones, except that the spacing between elements is larger. This enables more efficient spatial sampling and has a lower cost. By careful design of the spatial configuration it is possible to ameliorate under-sampling defects. Whether this is sufficient for the SKA and over what range of wavelengths is a subject being investigated. The use of a priori knowledge of the gross structure of the sky will be an important factor in making these arrays perform well.

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), USA (TDP) and Canada. (see §4.1.1 to §4.1.4) 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.

4.1.1 Dishes

Dishes and wide-band single pixel feeds (§4.1.2) are a lower-risk "reference design" for the mid-band SKA. Dishes will represent a very significant fraction of the cost for the entire SKA, and much effort is being devoted to finding a reflector fabrication technology that will ultimately yield a good cost/performance ratio when manufactured and field-installed in relatively large numbers. The eventual upper frequency limit of the mid-band SKA will depend on the outcomes of these cost-effectiveness studies. The two large pathfinder projects in South Africa and Australia will demonstrate antenna construction technology in medium numbers, although they may not be able to take full advantage of on-going R&D and design refinements. The up-front cost of testing a new design/fabrication technology is a challenge. A fabrication technology that requires expensive jigs or machinery, costing a great deal to build, could ultimately yield the best results for manufacturing in large numbers of antennas, but may be too risky to test as prototypes.

Reflector development itself is following two main approaches – fabrication with aluminum (either hydroformed or panels) and composite (with several different approaches to materials). Figure 3 shows examples of work around the world. Although both approaches have potential advantages, this paper cannot explore this level of detail.

4.1.2 Wide-band single pixel feeds

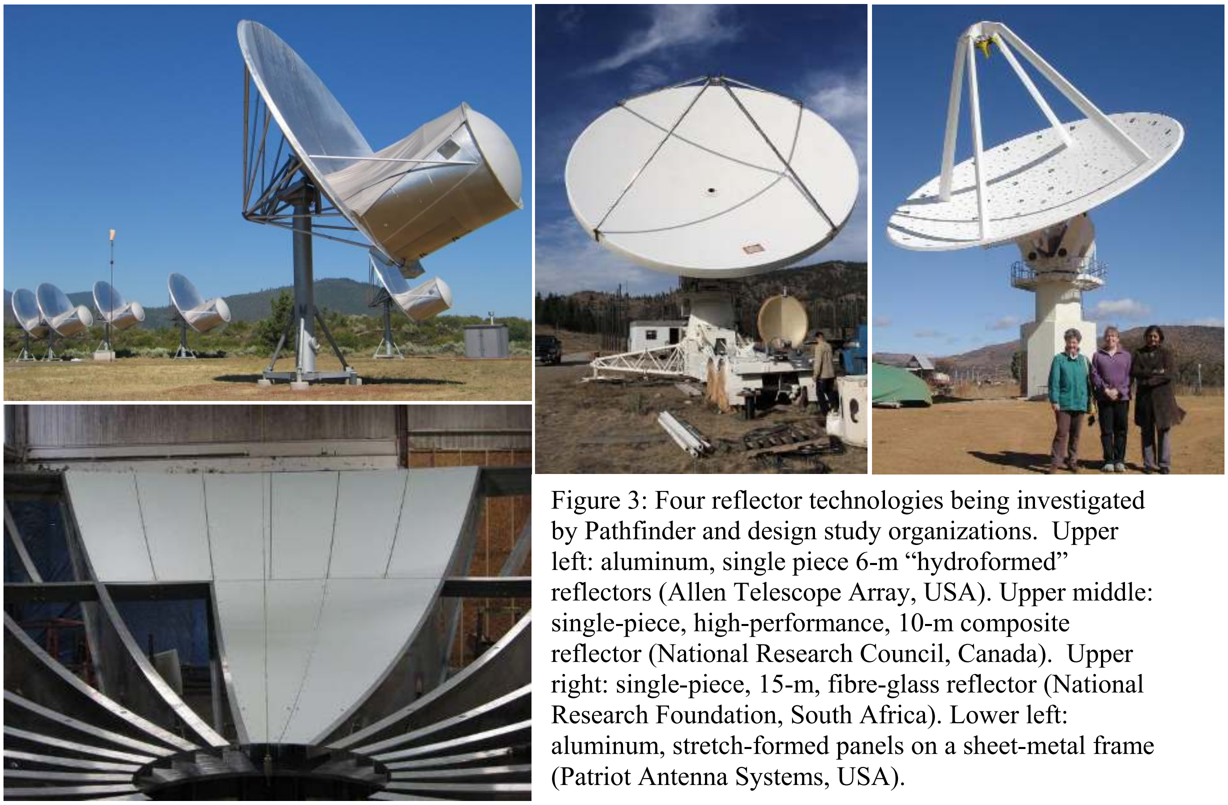


Figure 3: Four reflector technologies being investigated by Pathfinder and design study organizations. Upper left: aluminum, single piece 6-m "hydroformed" reflectors (Allen Telescope Array, USA). Upper middle: single-piece, high-performance, 10-m composite reflector (National Research Council, Canada). Upper right: single-piece, 15-m, fibre-glass reflector (National Research Foundation, South Africa). Lower left: aluminum, stretch-formed panels on a sheet-metal frame (Patriot Antenna Systems, USA).

Several concepts are under development around the world. Figure 4 shows photographs or diagrams of four different types of feeds. Three of them (a, b, d) share a common principle on which their wide bandwidth depends – they contain a series of closely spaced resonant structures from which a corresponding wavelength will be launched into free space. The Quad-ridge horn (d) is a continuously variable transmission line, which launches a free-space wave when the spacing of the line is about half a wavelength. The best design will have almost constant impedance at the output terminals, will not contain concentrated currents that could lead to resistive losses, will contain minimum dielectric material, will have almost constant beam width across the wavelength band, and will be sufficiently compact that all or part of the feed could be cryogenically cooled. (The overall physical size, of course, is determined by the longest wavelength of operation).

All of these feeds can achieve bandwidth ratios of more than 10:1. However, such ratios also tend to degrade efficiency, although adequate attention to details of the structure at the shortest wavelengths and to the structure that supports the terminal points may alleviate this issue.

Some of these feeds are quite low gain and thus most suitable for operation from the prime focus of a "deep" dish (f/D ≈ 0.3). The ATA feed, however, is higher gain and is used at a secondary focus. Most likely these feeds will have to co-exist with phased array feeds, which are most efficient for reflectors with f/D ≈ 0.5. This tradeoff space is still under investigation.

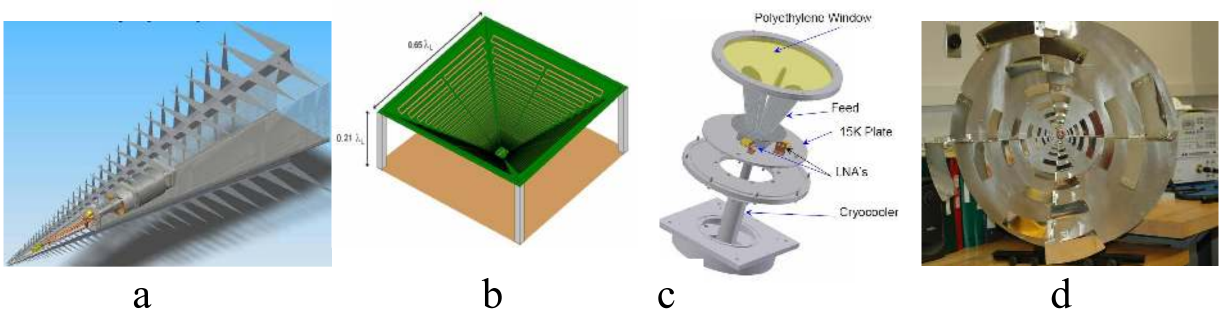


Figure 4: Examples of new single-pixel, wideband feeds for reflector antennas. a) Feed from the Allan Telescope Array; b) Chalmers feed [6]; c) quad-ridge Lindgren horn [7]; d) Quasi Self-Complementary Antenna [8]. All of these feeds are being evaluated for use with the SKA (illustrations courtesy of G. Cortes Medellin). All are dual polarization.

4.1.3 Phased Array Feeds in the focal plane

Phased array feeds (PAF's) 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. PAF's are a highly flexible means of controlling the illumination pattern of a reflector, both on the optical axis of the reflector and off-axis. These feeds are of similar construction to aperture arrays, in the sense that they are made up of small, elemental antennas. The elemental antennas must be designed so as to permit close packing (approximately half-wave spacing) at the shortest wavelength of operation. The signals from patches of elements are electronically combined in a weighted sum. The weights are adjusted to provide an optimum illumination of the reflector in the signal-to-noise sense. For off-axis illumination the weights can be adjusted to compensate for aberrations introduced by the reflector. Each illumination pattern is transformed to a beam on the sky by the reflector. The aggregated, overlapping beams can be designed so as to effectively form a flat response (equal sensitivity) in a circular area on the sky ("pillbox"). Thus after processing it is

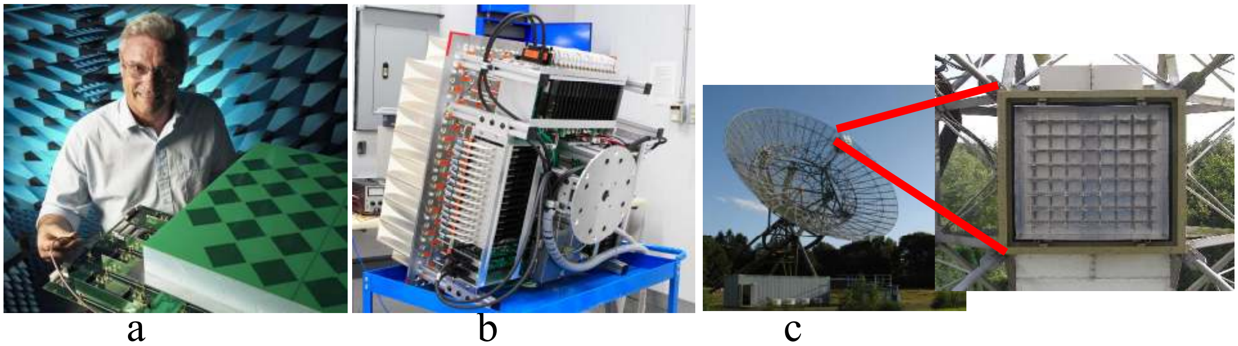


Figure 5: Three prototype phased array feed systems, which are being used to evaluate the technology for expanding the field of view of reflector antennas. a. The Chequer Board Array (CSIRO/ATNF Australia); b. Phased Array Demonstrator (National Research Council, DRAO Canada); c. APERTIF (ASTRON, The Netherlands).

possible to produce an image of this region of sky “instantaneously”.

As noted above, each summed patch produces an output signal, which must be sent to a common point and cross-correlated with like signals from other dishes. This could be a large amount of data, although fundamentally a large field of view will produce a proportionately large amount of data. Nevertheless, processing data from fields of view that are greatly expanded will represent a substantial design and cost challenge (see below).

Achieving low noise with PAF feeds will be an important goal. It is unlikely that such large devices will be easy to immerse in a cryostat, although this cannot be ruled out. Thus great emphasis is being place in the SKA R&D on low noise amplifiers that operate at ambient temperatures.

In summary PAF’s represent a compromise between the aperture arrays (see §4.1.4) and the single pixel feeds since they still get the concentrator cost advantage of the reflector antenna, with a greatly decreased number of phased array elements per square metre of collecting area.

4.1.4 Aperture arrays

As noted in §4.1, aperture arrays provide ultimate flexibility in providing many beams on the sky, rapid pointing, variable beam shaping, etc. The general idea is depicted as part of Figure 2. The signals from the individual antennas in a tile are combined electronically to simultaneously 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 very rapidly on the sky without any moving parts.

Figure 6: An example of elements of sparse aperture arrays, the LOFAR antennas (ASTRON, The Netherlands). On the left is a polarization pair of “droopy dipoles” that operate from 30-80 MHz. The inset shows the low noise amplifier hub. On the right is a “tile” of LOFAR high-band antennas, with the individual elements shown in the inset.

Figure 7: Two other low frequency arrays under development. On the left is the Murchison Wide Field Array (MWA) under construction by a consortium of US and Australian institutions. On the right is the Long Wavelength Array (LWA) under construction by a consortium of institutions in the USA.

This contrasts with other types of antennas (e.g. reflectors or electrically large antennas) in which there is a "passive pre-filter" that limits the direction from which emission can be detected (i.e. forms the beam). The root of aperture array flexibility is minimum spatial pre-filtering – the active components and the signal processing system have access to signals from all directions in a hemisphere. This flexibility exacts a price – the final throughput of the system is entirely dependent on carrying capacity and information processing power downstream from the antennas. In a wide-band telescope a tremendous amount of information must be processed. Thus most of the SKA R&D effort on aperture arrays is on developing efficient implementations of the required information processing systems.

Figure 8: Left – Prototype aperture array elements for EMBRACE. Right – experimentation with highly manufacturable elements for aperture arrays, in this instance utilizing a printing process for depositing the metallic elements on thin plastic film.

The SKA Design Studies (SKADS) program in Europe, with demonstrators EMBRACE and 2-PAD, is specifically working on aperture arrays for the SKA. Also using variations on this technology are LOFAR, a large operational telescope being constructed in Europe (The Netherlands, Germany, France, Sweden, UK), the Murchison Wide Field Array (MWA), a telescope being constructed in Western Australia, and the Long Wavelength Array (LWA), a telescope under development in the USA. All of these telescopes will operate at meter and decameter wavelengths. Figures 6 and 7 show these telescopes. Figure 8 shows examples of EMBRACE elements.

4.2 High speed data transport

An array of sensors that spans distances from tens of metres in the core to thousands of km for the outmost spacings will require a variety of technologies. Contributing to the requirements for communication capacity will be the instantaneous bandwidths, the number of bits of digital representation of samples, and the total field of view of the multi-beamed sensors. These are all functions of wavelength of operation. In general the bandwidth will be lower, the number of bits higher, and the field of view higher at the long wavelength end of the SKA spectrum. The field of view at longer spacings will be smaller than at short spacings. 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 optical fibre research networks.

4.3 Signal processing

Signal processing will occur at various levels in the SKA. Except for aperture arrays, in which analogue beam-forming is proposed for the first level of processing, all will be digital. Both aperture arrays and PAF's will utilize digital beamforming, which will be combined spectral processing. This processing will be done in the field, near the sensors. Although field processing is necessary to reduce the bandwidth of signals transmitted to the central processing system, it is more expensive to handle a large number of small processors than a few large ones. Aggregation of processing systems will be one of the practical tradeoffs needed in the final SKA design. A very large correlation system will be needed in a central location, where cross-correlation and final spectral decomposition will be done. The scale of the SKA will require a purpose-built processing machine, and will likely also require purpose-built integrated circuits as well. There are already precedents for this, such as the correlator system being built for the EVLA, although lower bandwidth telescopes, such as LOFAR, have been able to utilize a general-purpose supercomputer for the task. Most challenging will be the need to adopt highly scaleable solutions that take advantage of IT developments over the course of the 8-year long construction and deployment of Phases 1 and 2 of the telescope.

Both the signal processing systems and the computing systems for imaging and post-processing (see §4.4) will consume prodigious amounts of power. In fact power consumption is likely to be a limiting design factor – the SKA may have to be "designed for power". Delivering high power to a central location will be much less expensive than delivering an equivalent amount of power to a number of distributed locations. This factor could also play a role in design choices for SKA signal processing.

4.4 Post-processing, information management

Almost all projections of the SKA computing needs point to exa-flop (10^{18} floating point operations) computing requirements. At present the most powerful computers are in the 1 peta-flop range. This may require special-purpose hardware, new supercomputer architectures, and algorithms that are well matched to the hardware platforms [9]. A major challenge for the SKA will be to develop sufficient software. Although not an ideal solution, this challenge has been overcome on previous generations of radio telescopes by continuing to develop software over the lifetime of the telescope.

4.5 Infrastructure

Civil works, power delivery and communications infrastructure are estimated to be about one third of the total cost of the SKA. P. J. Hall et al [10] have set out initial thoughts on infrastructure in SKA Memorandum 96. One of the SKA challenges will be how to build out the SKA and associated infrastructure over a 7-8 year period while also carrying out observations. This is a particularly acute issue for control of RFI that may be generated during the installation of infrastructure.

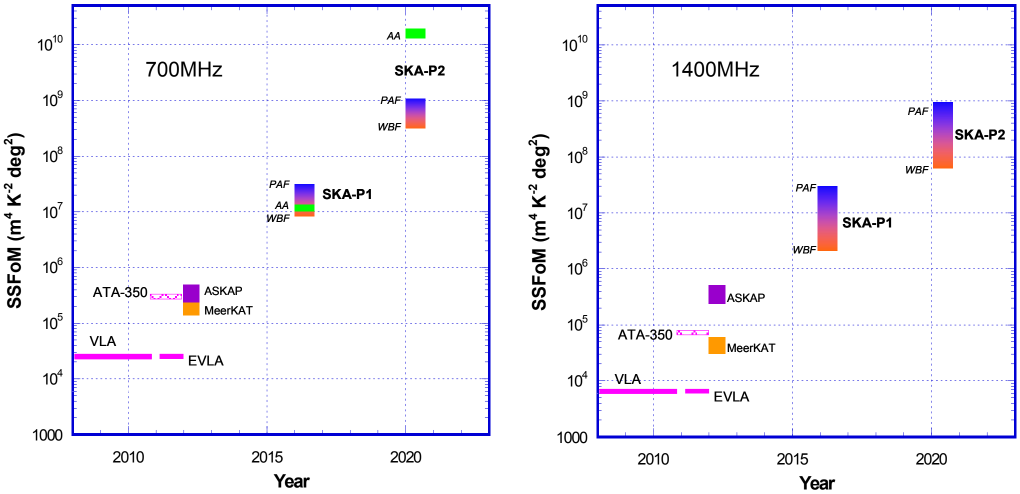
4.6 Operations and support

The top-level criteria for operations and support for the SKA have been examined in SKA Memorandum 84 by Kellermann et al [11].

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

Three potential implementations of Phase 2 SKA (mid and low bands) are currently receiving attention following analyses of their performance and cost in meeting the top-level specifications (see also Figure 2):

1) Sparse aperture arrays in the range 70-500 MHz + 3000 15m diameter dishes with wide-band single pixel feeds (SPF's) 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 (PAF's) in the range 0.5-1.5 GHz and single pixel feeds in the range 1.5-10 GHz.



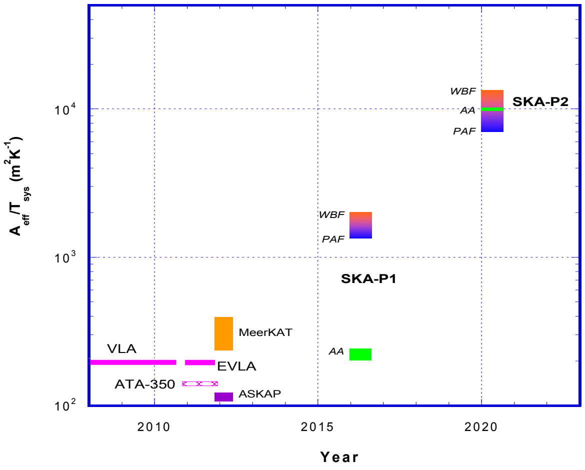


Figure 9: The progression of Survey Speed FoM and Sensitivity between 2008 and 2020, when the mid-band SKA is expected to be complete. The top two plots are Survey Speed at two important frequencies for HI and other surveys. The bottom left is SKA sensitivity when the telescope is used to integrate deeply at a single pointing. For reference, these values have also been provided for the VLA, EVLA, ATA and the SKA Pathfinders. The ranges shown by vertical bars delineate the impact on sensitivity of SKA technology assumptions.

3) Sparse aperture arrays in the range 70-500 MHz + a dense aperture array in the range 0.5-0.8 GHz + 2400 15m diameter dishes equipped with single pixel feeds 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 the PrepSKA program, using refined estimates from the Pathfinders and Design Studies, with a view to selecting an implementation by 2011.

The expected development of sensitivity (A_{eff}/T_{sys}) and the Survey Speed FoM for Phase 1 and the full SKA at mid and low band (Phase 2) are compared with various pathfinders in Figure 9 (see [2] for more details). In Figure 9, AA denotes Aperture Arrays; WBF, wide band single pixel feed; PAF, phased array feed. The actual sensitivity and Survey Speed FoM will depend on which technologies are adopted.

6. Sites

Following a comprehensive short-listing process in 2006 by the International SKA Steering Committee, sites in 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 §7).

Before then, further site characterisation and development 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 the construction of their respective SKA Pathfinder telescopes. Deep RFI measurements at the core sites and at selected remote sites will be carried out in 2009-10 as part of the PrepSKA program. And the optimum configuration for the array is under study by the SKA Simulations Working Group and the Science Working Group.

7. Timeline

Figure 10 shows the period from 2006 to 2025, which can be divided into five main stages:

2006-2007: concept design development in parallel with Pathfinder construction and SKADS design study work in Europe

2008-2012: 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.

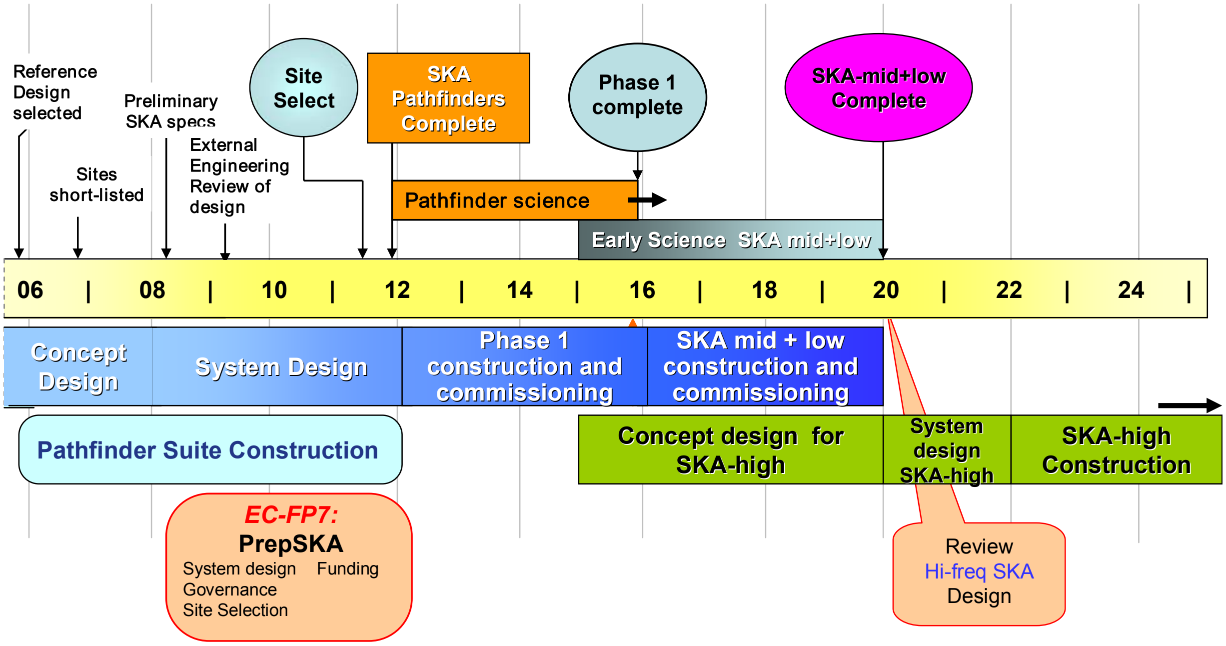


Figure 10: The SKA development and construction time line. The diagram shows the major milestones on the path to the full implementation of the low and mid-band SKA, and a parallel path to the development of the high-band SKA. The PrepSKA program, designed to produce a costed system design, will occupy the next four years. In parallel various SKA Pathfinder projects will be constructed and begin operations. The detailed design and roll-out of the SKA will begin at the end of the PrepSKA phase.

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