The Square Kilometer Array (SKA) Radio Telescope: Progress and Technical Directions

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Abstract

The international SKA project will deliver the most sensitive and flexible radio telescope yet built. This paper outlines the significant recent progress in the project, discusses briefly key technology components, and describes some of the suite of Pathfinder instruments and design studies now being pursued.

1. Introduction

The SKA was "born global," and arose out of suggestions in the early 1990s for a very large "hydrogen telescope" operating at 1.4 GHz and below (see, for example, [1-3). Since then, the SKA mandate has grown to include a range of astronomy applications that, taken together, demand an instrument with frequency coverage extending from 70 MHz to at least 25 GHz, and an array of antennas spread over at least 3000 km.

In 1993, URSI established a Large Telescope Working Group to begin an international study of the next-generation radio observatory. In the period since then, the SKA project has grown to include 19 countries, 55 institutes, and over 200 scientists and engineers. This global effort is steered by the SKA Science and Engineering Committee, a 22-member body with representatives from Europe, USA, and the rest of the world. After being coordinated on a day-to-day basis for five years by the International SKA Project Office, hosted at the ASTRON institute in the Netherlands, the project is now run by the SKA Program Development Office (SPDO), located at the Jodrell Bank Centre for Astrophysics in Manchester (UK).

The SKA global engineering development effort includes an expanding team at the SPDO in Manchester, together with large regional ventures associated with Pathfinders and design studies. In the period 2008 to 2011, the SKA Preparatory Phase Study (PrepSKA), an international effort operating under the aegis of the European FP7 initiative, will see delivery of an SKA design and completion of a number of policy initiatives designed to advance funding and construction. In effect, the PrepSKA program will take the SKA to the point of construction readiness, at least for the first phase of the instrument. The goal is then to have a full-capacity telescope operating at frequencies less than 10 GHz by 2020.

Since 2004, five key science areas have been identified as prime drivers for SKA specifications and three antenna technologies have been selected as the basis of a reference design. After an intensive characterization process, two possible sites for the core of the telescope have been identified. One site is in the Karoo wilderness of South Africa, while the other is in the Murchison region of Western Australia. Worldwide, over €150M has been allocated to SKA-related research and development in recent years, with at least a similar amount being devoted to the roll-out of Pathfinder instruments. A highlight of the past two years has been the engagement of national funding agencies with the project. Some 15 agencies now meet regularly to discuss SKA realization strategies.

2. Key Science Programs

The SKA Key Science Programs (KSPs) have been selected by an international Science Working Group as observations enabling fundamental progress in modern astronomy, physics, or astrobiology [4]. The five Key Science Programs are listed below.

2.1 Probing the Dark Ages and the Epoch of Re-Ionization

The ionizing ultraviolet radiation from the first stars and galaxies 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 Epoch of

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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 an ionized state. Moreover, as the first galaxies and active galactic nuclei (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. The SKA will have sufficient sensitivity to the 21-cm hyperfine transition of H I to detect galaxies to redshifts $z > 1$. One of the key questions for 21st century astronomy is how galaxies were first assembled. 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 collect a large enough sample of galaxies to measure baryon acoustic oscillations 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. The SKA observations also will seek to address whether magnetic fields are primordial and dating from the earliest times in the universe, or were 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 gravitational fields about 10^{11} times stronger than that of the Earth, neutron stars represent extreme laboratories. 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 millisecond 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 space-time environment around black holes via both ultra- relativistic binaries (e.g., pulsar/black-hole binaries) and pulsars orbiting the central super massive 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 high sensitivity and resolution, the SKA will be able to observe the centimeter-wavelength thermal radiation from dust in the inner regions of nearby proto-planetary disks and will be able to 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. The SKA will provide sufficient sensitivity to enable, for the first time, searches for unintentional emissions or “leakage.”

In addition to the Key Science Programs listed, and recognizing the long history of discovery at radio wavelengths (pulsars, cosmic microwave background, quasars, masers, the first extra-solar 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 to probe new parameter space (e.g., time-variable phenomena that current telescopes are not well equipped to detect). 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.

In an effort to guide the development of the telescope, a Reference Science Mission is now being assembled. The Reference Science Mission is designed to identify the main scientific requirements needed to conduct the Key Science Programs and to codify in more detail how they these requirements lead to the SKA engineering specifications. A common theme for all components of the Reference Science Mission is “Exploration of the Unknown,” including the search for cosmic radio transients.

3. SKA Technical Overview

The Square Kilometer Array will be an aperture-synthesis radio telescope that employs the concepts of radio imaging developed over the past four to five decades. These

Figure 1. The VLA in one of its more compact antenna array configurations. The 27 antennas are moveable on rail tracks, and different configurations are used to obtain different spatial samplings of incoming cosmic radiation (image from NRAO/AUI/NSF).

concepts amount to spatial, spectral, and temporal sampling of the incoming radio-radiation field to match the expected structure of the field in these three domains. In addition, careful attention will be paid to rejecting extraneous, manmade signals (radio-frequency interference).

Synthesis radio telescopes require an array of antennas and receivers (more generally, radio "sensors") covering a large area on the ground, and configured to provide the required spatial sampling. The Very Large Array (VLA), currently undergoing a major upgrade, is an example of an aperture-synthesis telescope that employs many of these concepts (Figure 1). The complex voltages from the sensors are cross-correlated in pairs, then integrated to reduce noise. These data are used to reconstruct the original brightness distribution, typically giving images of the sky, radio-frequency 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 principally by virtue of 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 [5] following science-engineering trade-offs that have taken into account current knowledge of key technologies (Section 4), and their likely evolution path and cost at the time of construction. A number of possible implementations are proposed (Section 5), which are estimated to cost 300M Euro for the first stage (Phase 1) of the array and 1200M Euro for the second stage (Phase 2). Phases 1 and 2 will cover frequencies from ~70 MHz to 10 GHz. The Phase 1 and 2 costs include 100M Euro and 500M Euro, respectively, for infrastructure, software, labor, 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.

The science goals outlined in Section 2 require the SKA to be a radio telescope with the attributes set out below.

- The *sensitivity* to detect and image hydrogen in the early universe. This is to be accomplished by deploying a *very large collecting area*, up to several km^2 at the lowest frequencies. The sensitivity of the telescope at frequencies around 1.4 GHz, described in terms of the ratio of effective area to system temperature (A_e/T_{sys}), will be ~10 000 m^2 K^{-1} (peak), about 50 times that of the Expanded VLA. (In communications-engineering sensitivity units, the G/T specification of the SKA is about 65 dB K^{-1}).
- A *wide frequency range* to enable the range of science in the Key Science Programs:
  70 to 300 MHz (low band)
  0.3 to 10 GHz (mid-band)
  10 to $>$ 25 GHz (high band)
  These bands are defined principally by the way that science maps into frequency space, but also by technology, and possibly site, considerations. Note that the operating range spans more than two decades in frequency.
- A *fast surveying capability* over the whole sky. This is to be accomplished by means of the high sensitivity, together with a *large angular field of view* (FoV), possibly several tens of square degrees at frequencies near 1 GHz, and up to 250 square degrees at the lowest frequencies. Above 1 GHz, an FoV of one square degree, scaling with wavelength squared (the scaling obtained with many conventional antennas), matches the 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 center of the array, a further 25% within 180 km of the center, and the remaining 25% out to the maximum extent of the array. The details of the array configuration are still being investigated, but Figure 2 depicts one possible layout and core-array arrangement.

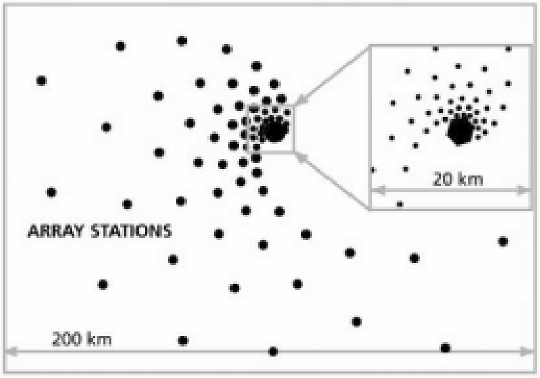

Figure 2a. An example of a possible SKA configuration. In this model, patches of collecting area (stations) extend from a dense core in a log-spiral arrangement. The pattern continues to baselines of ~3000 km. The huge number of SKA sensors gives excellent spatial sampling characteristics without the need to periodically relocate antennas.

Figure 2b. An artist's impression of the SKA core region, with planar-aperture arrays and dishes visible. All the sensor technologies will share wideband communication as well as signal-processing and data-processing infrastructures

- 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. SKA Sensor Concepts

An earlier review [6], in 2005, outlined six SKA concepts based on various sensor technologies. These were described originally in a series of 2002-2003 white papers (available via http://www.skatelescope.org). They were divided equally between "large-*N*, small-*D*" and "small-*N*, large-*D*" concepts, with *N* being the number of correlated entities (antennas or stations) and *D* being the antenna diameter. All concepts had signals from sensors in the central region of the array being directly cross-correlated; some arrangements grouped outer antennas into stations, thereby aggregating the corresponding signals prior to correlation. The 2005 review noted a high degree of post-sensor commonality among all concepts, unsurprising when the telescope is viewed as an information technology machine, transporting and processing defined data rates and volumes over given distance regimes. In 2005, it was already clear that performance and cost considerations would most likely dictate a mix of sensors (Figure 3).

Over the past three years, guided interaction between astronomers and engineers has clarified a number of points, which has allowed engineers to advance the conceptual design of the telescope. These include the following considerations.

- High survey speed is a preeminent specification, ranking alongside the high point-source sensitivity, which has always been a key SKA requirement; for many (but not all) SKA science applications point-source sensitivity can be exchanged for survey speed. The sensitivity metric is taken as A_{eff}/T_{sys} (Section 3), while a common survey speed figure-of-merit is $\left(A_{eff}/T_{sys}\right)^2$ FoV .
- Most SKA science is well addressed by an instrument with an upper frequency limit of about 10 GHz. However, important observations – some likely to be linked to emerging ALMA (Atacama Large Millimeter Array) and EVLA (Expanded VLA) science – require a new-generation telescope operating to > 25 GHz; the 10 GHz breakpoint separates SKA Phases 2 and 3 (Section 3).

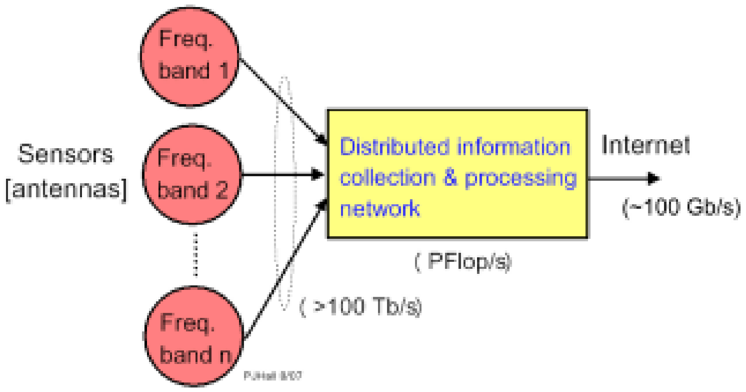

Figure 3. A view of the SKA as an information and communications technology (ICT) machine. Signals from a variety of different types of electromagnetic-field sensors (antennas and receivers) are transported and processed via common machinery. Sensors are chosen largely on the basis of their performance-to-cost ratio within particular frequency bands.

- The requirement of an SKA continuum imaging dynamic range of $>10^6$ is only likely to be achievable with the excellent interferometer baseline density (u,v-plane coverage) of large-N solutions, and then only with substantial development of current imaging techniques.
- Computing performance and cost are integral to the overall SKA system design, with the pace of change in this and related areas dictating the need for an evolutionary, or at least staged, instrument specification and implementation.
- With computing and signal-processing considerations in mind, and accounting for an N^2 (or number of baselines) dependence of correlation and first-level post-processing demands, technology offering high survey speed via wide FoV should do so without increasing the antenna count. This can be achieved by the production of multiple FoVs, each with an extent commensurate with the FoV of a primary element (e.g., a dish). Baseline-dependent processing then scales, to the first order, only linearly with total FoV.

Noting these points, and weighing additional issues such as operational flexibility and technology maturation timescales, the SKA project has adopted a Reference Design (RD), based on a mix of three sensor types in a large-N, small-D arrangement [7]. Two of these – aperture-plane phased arrays (AA) and small (~12m) dishes with single-pixel feeds (SD+SPF) – were included in the six concepts examined in [6]. The "new" sensor type in the Reference Design is a mid-frequency sensor based on small dishes equipped with focal-plane phased-array feeds (SD+PAF). This arrangement – which is, of course, an intermediate arrangement between "pure" AA and SD+SPF solutions – uses both optical and electronic beamforming to generate wide FoVs and high survey speeds in the region near 1 GHz. It is potentially a cost-effective SKA solution. Figure 4 shows the application of the sensor suite across the operating frequency range of the SKA.

An international Engineering Working Group, and many associated specialist task forces, have been active in mapping out the SKA system design as well as key elements of major subsystems [8, 9]. Interestingly, all the original concepts [6] for SKA sensors have proved to be important vehicles for exploration of scientific possibilities and system-design ideas. For example, the Large Adaptive Reflector contributed the "hybrid" dish plus phased-array feed; the Cylindrical Reflector underlined the value of wide FoV in enabling practical all-sky surveys; and the Luneburg Lens provided the basis of wide-field, large-N system architecture. The remaining concept, KARST, inspired the now-funded Chinese Five-hundred metre Aperture Spherical Telescope (FAST), is itself likely to be an important scientific precursor to the SKA.

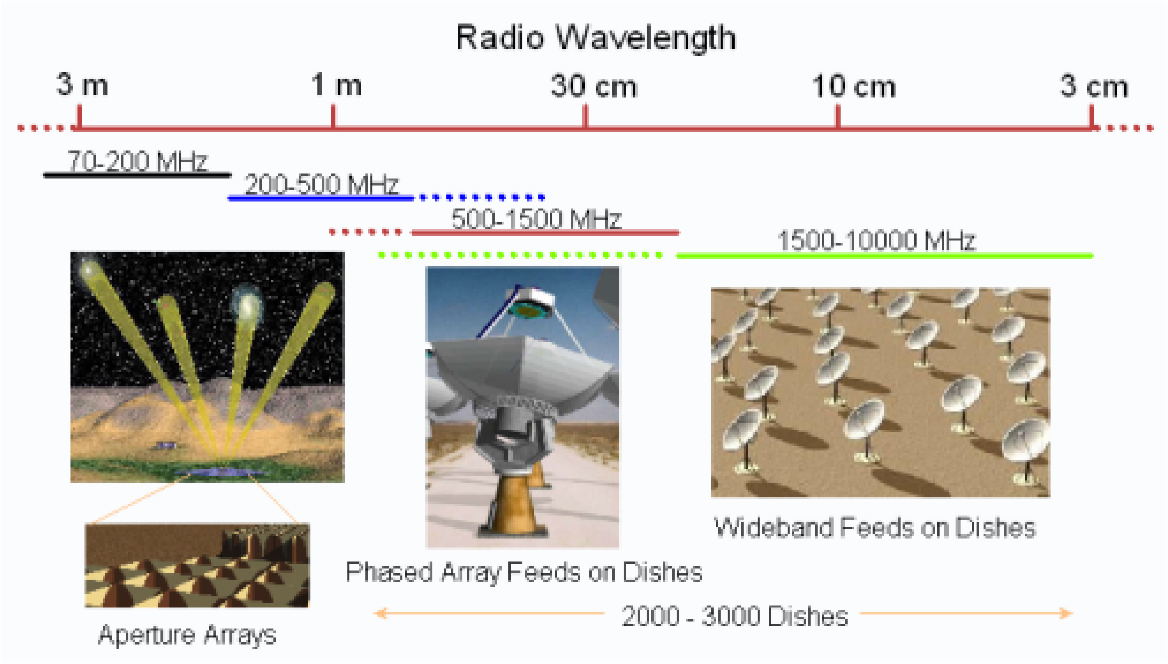

Figure 4. A schematic diagram of the Reference Design sensor technologies over the range of SKA wavelengths. The bars under the wavelength axis denote ranges over which four sensor technologies will be used. At the longest wavelengths (leftmost bar), sparse aperture arrays are the most practical solution. At intermediate wavelengths, potentially both dense aperture arrays (left-most middle bar) and reflectors with phased-array feeds (right-most middle bar) are possible. At the shortest wavelengths (right-most bar), only reflectors with single-pixel feeds are practical. The dotted lines indicate where technology choices may have to be made, or could coexist. 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, each covering a different frequency range.

5. SKA Specifications and Technology Implementations

Within the Reference Design, the numbers of each sensor type and the exact operating frequency band of each type are yet to be determined on the basis of refined science goals and demonstrated performance/ cost achievements. Recognizing this, the initial SKA specifications have been framed with several possible development outcomes in mind. All, or only some, of the Reference Design constituent technologies may prove successful, and the initial specifications reflect various technology mixes enabling high-impact science. While major science drivers are reflected in each mix, different technology-development outcomes will certainly give rise to different SKA optimizations.

Some Reference Design technologies are more mature than others, and are already being applied in astronomical observations. For example, LOFAR and several other telescopes are proving the merits of sparse aperture arrays (inter-element spacing $> \lambda/2$), and the Allen Telescope Array is demonstrating the effectiveness of small dishes equipped with wideband, single-pixel feeds (Section 8). There is therefore a "low-risk" SKA technology path. However, at the same time, the adopted specification and system design processes allow for the augmentation of this path with highly-attractive dense phased-array technology, having both aperture and focal-plane application. As described in Section 8, significant demonstrations are underway to bring Reference Design technologies to maturation within the four-year timescale of the SKA system design.

Detailed SKA specification considerations were discussed in [5], and a range of possible array implementations was given on the basis of various technology research and development outcomes. Three scenarios are currently being investigated in some detail.

- Sparse aperture arrays (AAs) in the range of 70 MHz to 500 MHz, plus 3000 × 15 m diameter dishes equipped with wideband single-pixel feeds (SPFs) covering 0.5 GHz to 10 GHz.
- Sparse aperture arrays in the frequency range of 70 MHz to 500 MHz, plus 2000 × 15 m diameter dishes equipped with both phased-array feeds (PAFs), covering 0.5 GHz to 1.5 GHz, and single-pixel feeds, operating from 1.5 GHz to 10 GHz.
- Sparse aperture arrays in the range of 70 MHz to 500 MHz, plus a dense aperture array in the range of 0.5 GHz to 0.8 GHz, plus 2400 × 15 m diameter dishes equipped with single-pixel feeds covering 1 GHz to 10 GHz.

Figure 5 shows the two key SKA specifications, point-source sensitivity and survey speed, plotted as a function of epoch, with the spread in values representing the range of technology choices. Note that the large SKA Pathfinders (ASKAP and meerKAT) are powerful telescopes in their own right, and that SKA Phase 1 provides order-of-magnitude improvements over the largest existing synthesis array. The final values of the SKA specifications depend on the adopted technologies and, by implication, the outcomes of the various research and development programs over the next few years.

In itself, the specification process has been an interesting one, requiring a global consensus in the face of incomplete engineering information. While recognizing the impracticality of a purely serial demonstration and design process, the SKA project has nevertheless sought to retire risk as early as possible by using many demonstrators with a succeed or fail-early approach, especially for base technology options, such as sparse arrays and small dishes.

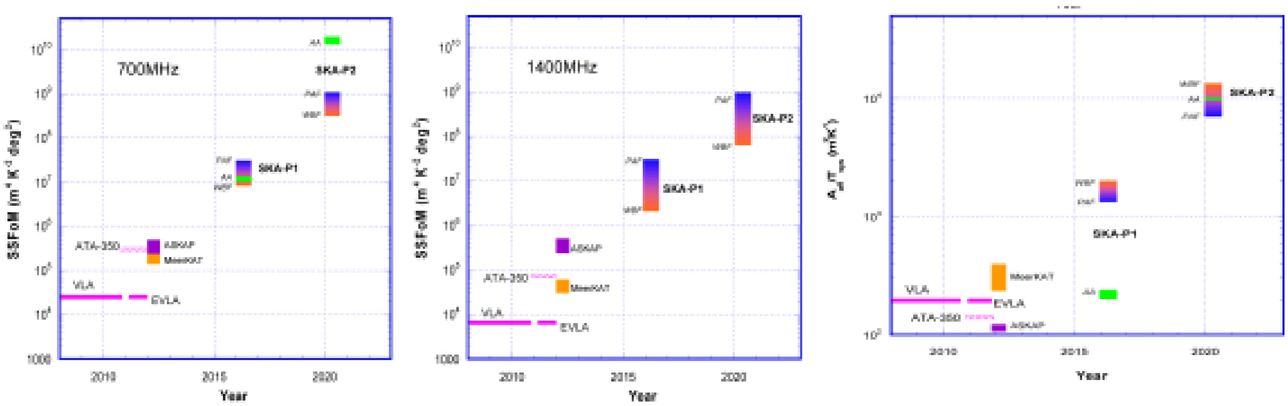

Figure 5. The progression of survey speed figure-of-merit and sensitivity between 2008 and 2020, when the mid-band SKA is expected to be complete. The top two plots are survey speed at two important frequencies for HI (hydrogen) and other surveys. The bottom plot is SKA sensitivity when the telescope 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.

The project is also using an evolving performance and cost-estimation tool, providing a framework for iterative science and engineering discussions. The tool, like the underlying system-design approach, is hierarchical in nature, allowing a boot-strapped design process as more complete information becomes available from SKA Pathfinders, design studies, and other sources. While much remains to be done, the inclusion of key system elements in the estimation environment has led to many insights, and has been important in bounding the design space to that summarized above.

6. SKA Sensor Technologies in More Detail

As far as possible, the Reference Design sensors have been chosen to capitalize on cost and flexibility gains provided by advances in technology, especially in the information and communications technology (ICT) area. Many potential SKA gains flow from the increasingly-feasible "software telescope" approach, in which analog components are replaced by programmable digital-signal-processing (DSP) engines, or even by general-purpose computers. While the radio/ICT marriage is currently most attractive at frequencies below ~1 GHz, the SKA system design will allow integration of "smart" high-frequency sensors as they become available. In this context, "smart" refers to antennas with associated (or embedded) DSP solutions. Even first-generation high-frequency SKA sensors will feature innovative solutions, many of which are based on gains in commercial off-the-shelf items, or at least in allied manufacturing processes (e.g., the use of low-noise highly-integrated receivers).

Some relevant general considerations and examples relating to each Reference Design technology are set out below, beginning with the more developed technologies employing "pure" beamforming solutions, either electronic or optical.

6.1 Aperture Array (AA)

At frequencies below ~300 MHz, where the system noise is dominated by galactic noise (with a $\lambda^{2.6}$ spectrum), sparse aperture arrays are an attractive technology. With broadband receiving elements spaced by more than $\lambda/2$, the mutual coupling is relatively small. The effective collecting area grows as λ^2, partially compensating for the rapid increase in galactic noise. In practice, the elements may be variants of "fat" dipoles or bowtie antennas (Figure 6), and, in present designs, arrays feature at least one stage of analog beamforming prior to digital processing. Even with beamforming, the field of view of a sparse-array station is very large: up to 250 deg^2 at hundreds of MHz. Furthermore, replicating the beamforming allows the collecting area to be reused, giving multiple independent fields of view, and increasing greatly the operational flexibility of the instrument (e.g., by supporting several users observing different parts of the sky).

While potentially excellent survey telescopes, the wide field of view and inescapable grating-lobe response of sparse arrays mean that strong cosmic sources and terrestrial radio-frequency interference (RFI) often intrude on the desired field. Much of the work of Pathfinders, such as LOFAR (Section 8) and the Murchison Widefield Array [10], is aimed at establishing the ability to calibrate sparse aperture arrays, bearing in mind the required imaging dynamic range and practical limits on computing.

Dense aperture arrays, in which the elemental broadband radiators are packed closer than $\lambda/2$ over much of the operating band, are a potentially attractive replacement for dish antennas below ~1 GHz. Like sparse arrays, the all-electronic realization allows completely independent fields of view, contributing greatly to operational flexibility, and enabling the time-intensive surveys effectively precluded on single-user telescopes. Unlike sparse arrays, the high

Figure 6a. An example of sparse aperture array technology from the LOFAR telescope (ASTRON): A polarization pair of "droopy dipoles" that operate from 30-80 MHz. The inset shows the low-noise amplifier hub.

Figure 6b. An example of sparse aperture array technology from the LOFAR telescope (ASTRON): A "tile" of LOFAR high-band antennas, with the individual elements shown in the inset.

Figure 7a. Prototype dense aperture array elements for the EMBRACE demonstrator (section 8). The elements are Vivaldi end-fire types.

Figure 7b. An assembly of experimental printed versions of the Vivaldi elements.

mutual coupling of the dense arrangement leads to essentially constant effective area over the operating band, similar to a dish antenna.

In the SKA context, most of the dense aperture array work has so far been based on Vivaldi end-fire radiators (Figure 7) offering >2.5:1 bandwidth. The work of Pathfinders and design studies centers on establishing (i) whether new-generation dense arrays are competitive in a performance/cost sense with dish antennas, (ii) whether the expected superior control of sidelobes translates in practice into easier calibration than is the case in sparse aperture arrays, and (iii) whether other characteristics of highly-coupled arrays, including scan blindness, materially affect their application to radio astronomy.

6.2 Small Dish + Single-Pixel Feed (SD+SPF)

At frequencies above ~1 GHz, tiling a large collecting area with elemental sensors becomes prohibitively expensive, given the approximate λ^{-2} dependence of the number of elements and associated electronics. Furthermore, it becomes progressively more difficult at higher frequencies to maintain low-noise performance with economical receiving systems and a myriad of lossy RF interconnects operating at ambient temperature. Conventional "optical" beamforming therefore becomes more attractive, with a single feed element being placed at the focus of a parabolic dish. While one could contemplate using multiple feeds in a focal-region cluster to increase the field of view, the SKA science community has determined that more scientific

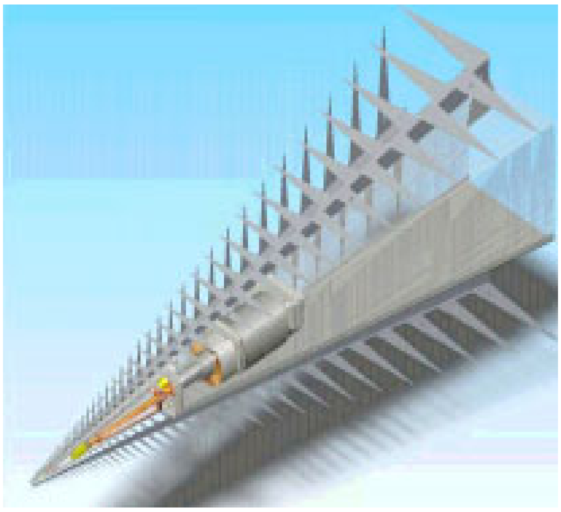

Figure 8a. An example of a new single-pixel, wideband feed for reflector antennas: A feed from the Allan Telescope Array.

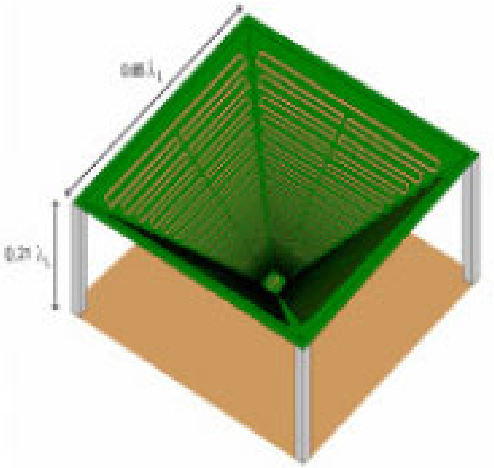

Figure 8b. An example of a new single-pixel, wideband feed for reflector antennas: A Chalmers feed [11].

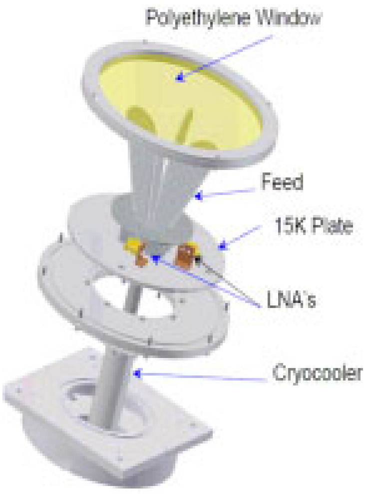

Figure 8c. An example of a new single-pixel, wideband feed for reflector antennas: A quad-ridge Lindgren horn [12].

Figure 8d. An example of a new single-pixel, wideband feed for reflector antennas: A quasi self-complementary antenna [13]. All of these dual-polarization feeds shown in Figure 8 are being evaluated for use with the SKA (illustrations courtesy of G. Cortes Medellin).

benefit accrues above 1 GHz from the use of a single, very wideband feed. (Close-packed feeds would inevitably exhibit restricted bandwidth).

A number of efficient single-pixel feed designs have been proposed. While demonstrations so far have been based on a logarithmic pyramid arrangement, other designs are being developed (Figure 8). The thrust of SKA work in the SD+SPF area is (i) to demonstrate dish-manufacturing technologies resulting in a cost reduction factor of at least two relative to current 6 m to 15 m antennas; (ii) to demonstrate high-sensitivity-optics arrangements, including efficient decade-bandwidth feeds; and (iii) to establish the merits or otherwise of cooled receiving systems based on new-generation cryo-coolers.

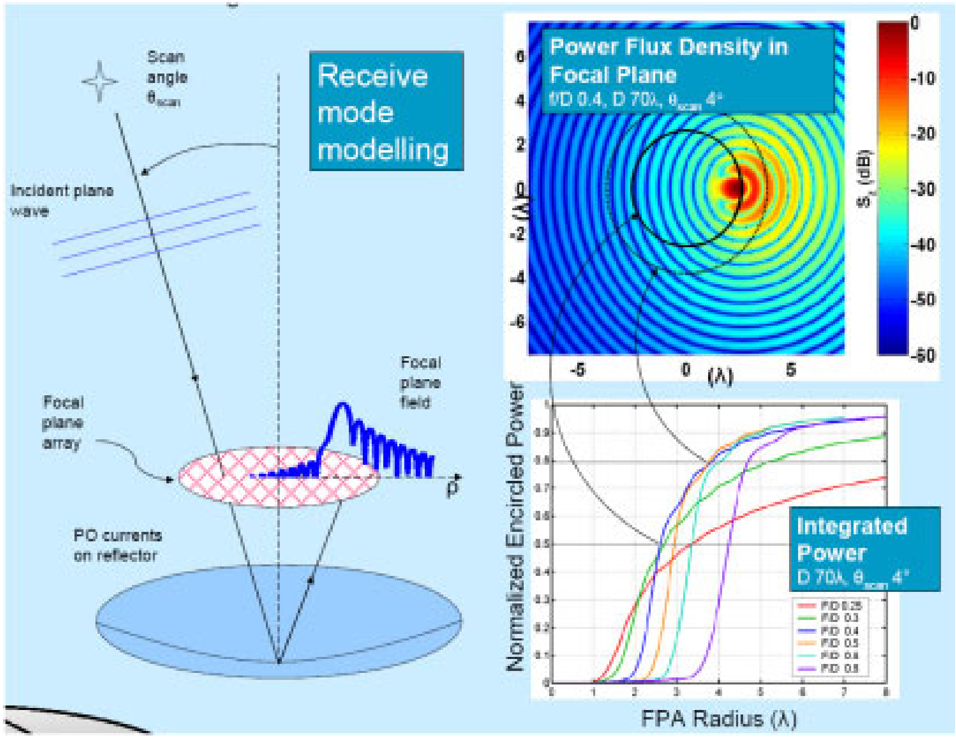

Figure 9. An illustration of the focal-plane field for a parabolic dish with f/D = 0.4 and the off-axis ("scan") parameters shown. The aberrations can be corrected with a phased-array feed and beamforming, but, as shown, badly distorted fields require sizeable arrays and concomitantly complex beamforming (courtesy D. Hayman et al. [14]).

6.3 Small Dish + Phased Array Feed (SD+PAF)

The SD+PAF concept uses a conventional metal beamformer (the dish), in combination with dense-phased-array field-of-view expansion technology. At radio frequencies, energy is concentrated by the dish into a focal zone of appreciable extent. In the on-axis case the field distribution is symmetrical, but off-axis distributions become progressively more distorted (Figure 9). By sampling the field pattern with a dense phased array of appropriate size and then using an electronic beamformer, it is possible to form clean off-axis beams exhibiting high efficiency, good polarization purity, and other desirable characteristics.

Each beam has an angular extent similar to the natural field of view of the dish, and, with tractably complex digital beamformers (< 100 inputs), one may generate perhaps 30 independent beams. A 15 m diameter dish has a natural field of view of ~1deg^2 at 1 GHz, so a typical SD+PAF sensor gives a total field of view of ~30deg^2. If the field-of-view expansion does not come at the expense of system temperature, the survey speed also increases by a factor of ~30 relative to a single-pixel-feed arrangement. Importantly, the field of view and survey speed increases come without increasing the SKA dish count, so the required increase in correlator and subsequent processing power grows only by a factor of about 30, rather than 30^2 (Section 4).

With a beamformer of given complexity, it is easy to adjust the field-of-view expansion factor across the operating band, and constant total fields of view across frequency ratios of at least 2.5:1 are possible. While still being refined, phased-array-feed technology offers, via a range of programmable beamforming solutions, much greater flexibility and survey efficiency than more conventional multiple-feed cluster arrangements [15]. SD+PAF prototyping is underway in both Australia and The Netherlands; Figure 10 shows some examples of test systems.

One of the practical challenges for SKA antenna designers involves accommodating both phased-array feeds and single-pixel feeds on the one dish to give an upper frequency range extending to 10 GHz (Section 5). A number of options are currently being investigated, ranging from simple offset arrangements to folded optical paths.

7. Beyond the Sensors: Other SKA Design Challenges

While antennas are the visible face of the SKA, there are many other challenges associated with signal transport, processing, scientific post-processing, and data archiving and retrieval. Here, we discuss a few key points in each area.

7.1 Signal Transport

Challenges exist over a range of distance regimes, from intra-chip and inter-chip switching and routing through to trans-oceanic data connections. Low-cost, short-haul (<~50m) signal transport, either digital or analog, is an enabling technology for wide-field-of-view sensors, such as aperture arrays. Typical data rates from individual dish antennas may be of the order of 100 Gbs^{-1} and, at the next level, aggregate data rates of several Tbs^{-1} will be required from each SKA station. Following centralized data processing near the SKA core region, transcontinental and transoceanic data rates of at least 100 Gbs^{-1} will be needed. While a large part of the telescope's internal data network will be owned by the SKA project, telescope data will at some point flow via other links, including those of national research networks and telecommunications carriers. Achieving the desired data rates at a tractable cost involves both technical and policy issues, and will undoubtedly figure prominently in final SKA site-selection discussions.

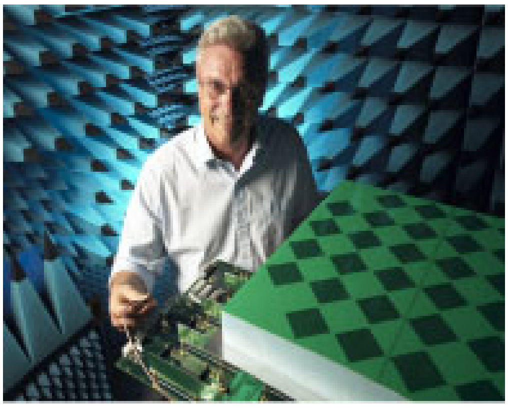

Figure 10a. A prototype phased-array feed system that is are being used to evaluate the technology for expanding the field of view of reflector antennas: The Chequer Board Array (CSIRO/ATNF Australia).

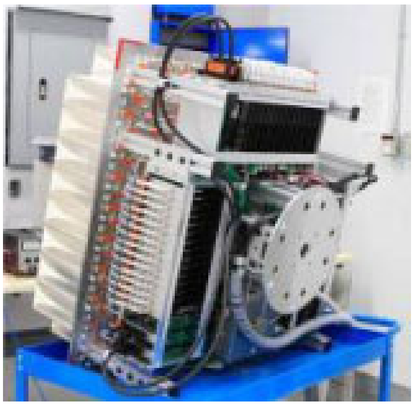

Figure 10b. A prototype phased-array feed system that is are being used to evaluate the technology for expanding the field of view of reflector antennas: The Phased Array Demonstrator (National Research Council, Dominion Radio Astronomy Observatory, Canada).

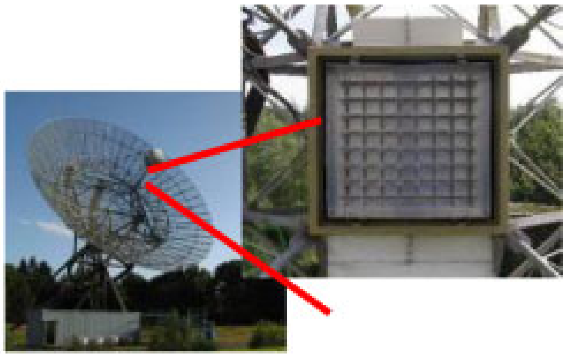

Figure 10c. A prototype phased-array feed system that is are being used to evaluate the technology for expanding the field of view of reflector antennas: The APERTIF at the Westerbork Synthesis Radio Telescope (ASTRON, The Netherlands).

7.2 Signal Processing

The great majority of SKA signal processing will be digital, with the only likely exception being first-stage beamforming in first-generation aperture arrays. In a synthesis telescope of the scale of the SKA, the most cost-effective approach to cross-correlation involves an "FX" architecture, in which signal bands are split into channels prior to being cross-multiplied and integrated. This architecture, with the frequency-channelization done at the antennas or stations, also lends itself well to efficiently supporting other operations, including beamforming (at various hierarchical levels in the system) and RFI excision. The amount of station-based DSP will depend on sensor arrangements. In some cases, station-level beamforming can be used to reduce data rates from the station to the central-processing site, particularly if a reduction in processed field of view is acceptable in a given experiment.

The SKA correlator – or, perhaps more likely, correlator suite – could be constituted from a number of approaches being demonstrated in various Pathfinder instruments. These range from purpose-built machines based on field-programmable gate arrays (FPGAs) or application-specific integrated circuits (ASICs), through to high-performance computing solutions. Early indications are that with a total processing load of peta-operations per second, and constraints on available power (Section 7.4), purpose-built correlators are most attractive. There is no doubt, though, that flexibility and "time-to-market" demands will push SKA designers to consider wide-spread application of programmable DSP engines and high-performance computing (HPC) subsystems, where possible.

Apart from the synthesis imaging application, the SKA will need to support other operational modes, most notably time-domain and radio-transient observations. This imposes additional requirements on the telescope architecture, particularly in terms of preserving data-stream coherence and continuity across the huge number of signal paths, and in the provision of machinery to produce and process summed-array modes across the entire SKA, or within subarrays. Part of the PrepSKA task is to ensure non-imaging modes are well-integrated into the SKA design, perhaps via the use of data spigots to which an evolving suite of backend instrumentation can be attached.

7.3 Post-Processing

With correlation rates of 10^{15} operations per second, and each correlator output data point (or u, v plane sample) requiring thousands of accurate operations upon it if existing imaging algorithms are used, post-correlation solutions capable of more than 10^{18} floating-point operations per second (FLOPS) are needed. While leading-edge peak computing capacities of this order are in fact forecast on 2015-2020 timescales, keeping the SKA computation load affordable will require developments on several fronts, including new and more efficient algorithms, new super-computing architectures (possibly departing from full floating-point implementations), and the use of special-purpose hardware and high-performance computing in close concert.

Software for the SKA is also a major challenge. The push towards a "software telescope" reduces hardware costs, but with a natural desire to fully exploit the new paradigm – and a concomitant increase in complexity – the magnitude of the software-development task increases, perhaps disproportionately. One early estimate, derived by scaling costs in a recent large telescope project, put the SKA software task at about ~2000 person-years [16]. Likely mechanisms for controlling costs are based on capping complexity at each stage of SKA development. This requires system designers to consider not only progressive gains in DSP and computing hardware performance, but also to account for the evolution of software capacity. Making the best use of this capacity forces a shift towards the use of commercial software (where possible), and an emphasis on reuse of software components.

7.4 Infrastructure

Both candidate SKA sites have been chosen to be remote from human settlement, principally in order to minimize external RFI. Providing the infrastructure to construct and operate the telescope will therefore be a logistical challenge, and a challenge magnified by the need to support a progressive "build-out" of the array whilst scientific observations are taking place. Fortunately, both candidate sites will have Pathfinder instruments nearby, and the infrastructure plans for these telescopes provide for at least SKA Phase 1 requirements [17].

Power provision represents a major part of the SKA infrastructure project. Core requirements may be of order 30 MW (excluding any high-performance computing), and remote stations may need ~0.5MW each. If a high-performance computing facility is added, requirements in the range 50 to 100 MW are likely, resulting in energy costs of 50M Euro to 100M Euro annually, even with the relatively favorable unit costs foreseen by the candidate host nations. Apart from the need to keep overall consumption as low as possible, designers face a further challenge in powering remote stations: in Australia, at least many of these will require renewable energy solutions, together with appropriate storage technology. Provision of power, while normally considered a prosaic engineering activity, may well determine the capability of the installed SKA systems, and thus the ultimate scientific performance of the instrument.

7.5 Operations

The SKA Operations Working Group has produced two studies [18, 19] outlining operational considerations. First analyses have relied on resource scaling from existing radio arrays, and have also set down key lessons to be learned from facilities in both astronomy and other branches of science. In general terms, operational costs of the order of 10% of capital investment per year are foreseen, amounting to about 100M Euro per annum in 2007 dollars. Of this figure, 2% to 3% of capital is foreseen as being set aside for renewal and upgrades, while a similar fraction is expected to cover user support. With the SKA project confronting high energy costs (Section 7.4), constraining operations costs to 100M Euro per annum without compromising scientific utility will be challenging. Regardless of the exact figure, it is clear that total operational costs over a 30 to 50 year lifetime will far exceed initial capital investment. Life-cycle and support modeling is therefore a central activity of the PrepSKA design initiative.

First operational models see the SKA as part of a global e-science network, with Tier-1 science centers – each supporting base science and one or more specializations – spread around the world. The SKA will effectively supplant some national facilities, and the need to fund engineering innovation, education, and public outreach as part of the international program is specifically recognized.

8. SKA Pathfinders and Design Studies

Since the early days of the project, technology demonstration has been the basis of SKA engineering decision making. In the sensor area, some technologies are inherently more mature than others, and the challenge is to balance implementation risk against scientific promise. Not all technology demonstrations are of equivalent scale, if only because of regional research and development funding variations. However, the general approach adopted requires demonstration of pivotal technologies, on a 2010-11 timescale, by the SKA Design Studies and Pathfinders (or significant parts thereof). This will allow key results to flow into the PrepSKA system design, which, in its early years, tackles generic issues common to all Reference Design sensor technologies. For more information on programmatic aspects of the SKA see Schilizzi et al. [20].

The summaries below outline the larger Pathfinder and design study projects now underway. Specifications given are only indicative. We have listed only projects born in the SKA milieu, but we note that other new radio telescopes, such as the Atacama Large Millimetre Array (ALMA), and major upgrades of existing instruments, are all contributing substantially to the SKA knowledge base. Two significant upgrades are the previously-mentioned EVLA project in the USA, and the eMERLIN (enhanced MERLIN) program in the UK. In addition, we record the key role of the APERTIF (Aperture Tile in Focus) upgrade project at the Netherlands Westerbork Synthesis Radio Telescope in advancing the development of phased-array feed technology (see Figure 10). Canadian SKA design and prototyping activities are also associated with phased-array-feed development, together with the construction of light-weight carbon-fiber dish antennas.

8.1 LOFAR (Low-Frequency Array)

- *Brief description:* Synthesis imaging telescope using sparse aperture phased arrays, 36 800 m2 total effective collecting area at 150 MHz; see Figure 6.

- *Site:* Central site near Exloo (NL), with stations placed around The Netherlands and Europe.

- *Main proponent:* LOFAR Consortium, led by ASTRON (NL).

- *Investment:* 83M Euro cash + 83M Euro in-kind from Consortium partners.

- *Operating band:* 30-80 MHz, 110-250 MHz.

- *SKA Reference Design technology demonstration:* Sparse aperture array (AA).

- *Scale:* Operational astronomical instrument; sensitivity 70 m^2K^{-1}; angular resolution 4 arcsec (Dutch component); 7 deg^2 remote station field of view (150 MHz specifications).

- *Key technologies and techniques:* Sparse aperture arrays; tile-level RF beamforming; direct RF-digital conversion; digital band separation and station beamforming; RFI mitigation algorithms; long-distance data transport and real-time processing; correlation based on high-

Figure 11. Part of the ATA-42 array that is now operational at Hat Creek Radio Observatory in Northern California. The hydro-formed 6.1 m diameter dishes use a Gregorian-optics configuration (with ground shield), incorporating the wideband pyramidal feed shown in Figure 8.

performance computing; new calibration algorithms including aperture array beam-level calibration; transient detection algorithms; multiple, independent field of view observing; structured software engineering; design for manufacture and significant industry involvement; generalized wide-area sensor network, including, e.g., geophysical and agricultural sensors.

- *Date commenced:* 2001 (R&D); 2004 (final design); 2006 (rollout).

- *Projected completion date:* 2010.

- *Status:* First central stations operational and producing astronomical data; 20 stations (13 in central core region) to be complete by end of 2008. Web site: http://www.lofar.org

8.2 Allen Telescope Array

- *Brief description:* 350 × 6.1 m dish synthesis array; see Figure 11.

- *Site:* Hat Creek Radio Observatory, northern California, USA
- *Main proponents*: University of California (Berkeley), SETI Institute, Allen Foundation.
- *Investment*: USD100M = 67M Euro.

- *Operating band*: 0.5-11 GHz.

- *SKA Reference Design technology demonstration*: Small dish + single-pixel feed (SD+SPF).

- *Scale*: Operational astronomical instrument; sensitivity 160 m^2K^{-1}; angular resolution 72 arcsec; 2.5 deg^2 field of view (1.4 GHz specifications)

- *Key technologies and techniques*: Hydro-formed dishes with Gregorian optics; wideband single-pixel feed (20:1 bandwidth); cooled low-noise amplifiers with new topologies; low-cost cryogenic cooling based on commercial Stirling-cycle coolers; wideband analog (RF on fiber) signal transport; DSP design based on modular programmable-engine approach; RFI mitigation algorithms; wideband amplification of sky signal, allowing multiple experiments within wide field of view.

- *Date commenced:* 2001 (R&D); 2004 (construction).

- *Projected completion date:* 2011.

- *Status (August 2008):* 42-dish array operational and producing astronomical data. Web site: http://ral.berkeley.edu/ata/.

8.3 meerKAT (extended Karoo Array Telescope)

- *Brief description:* >50 dish × ~12 m dish synthesis array.

- *Site:* Karoo wilderness, Republic of South Africa.

- *Main proponent:* National Research Foundation, RSA.

- *Investment:* ZAR 860M = 72M Euro.

- *Operating band:* Approximately 0.5-2 GHz (initially).

- *SKA Reference Design technology demonstration:* Small dish + single-pixel feed (SD+SPF).

- *Scale:* Operational astronomical instrument; sensitivity >160 m^2K^{-1} ; angular resolution ~10 arcsec; field of view 1.1 deg^2 (1.4 GHz specifications).

- *Key technologies and techniques:* Dishes optimized for low-cost, high-volume production; wideband single-pixel feeds; scalable signal-processing solutions; data-transport solutions; formalized system-engineering approach to design (including software) and operations; remote-area construction and operation; radio-quiet-zone establishment and operation; SKA infrastructure studies.

- *Date commenced:* 2006.

- *Projected completion date:* 2012.

- *Status:* Experimental 15 m dish constructed from composite material constructed and tested; seven-dish array scheduled for end of 2009; see Figure 12a. Web site: http://www.ska.ac.za/meerkat/index.shtml.

8.4 ASKAP (Australian SKA Pathfinder)

- *Brief description:* 30-45 × 12 m dish synthesis array.

- *Site:* Murchison Radioastronomy Observatory, outback Western Australia. One remote station at 3000 km for transcontinental data-transport demonstration.

- *Main proponent:* CSIRO Australia Telescope National Facility.

- *Investment:* AUD110M = 66M Euro.

- *Operating band:* 0.7-1.8 GHz.

- *SKA Reference Design technology demonstration:* Small dish + phased array feed (SD+PAF).

- *Scale:* Operational astronomical instrument; sensitivity >85 m^2K^{-1}; angular resolution 8 arcsec; field of view 30 deg^2 (1.4 GHz specifications).

- *Key technologies and techniques:* Dishes optimized for low-cost, high-volume production; phased-array feeds (PAFs) with digital beamformers; low-cost receiver solutions, including system-on-chip; calibration and imaging using phased-array feeds; data-transport solutions; remote-area construction and operation; radio-quiet-zone establishment and operation; SKA infrastructure studies.

- *Date commenced:* 2006.

- *Projected completion date:* 2012.

- *Status:* Two-element interferometer phased-array feed test-bed completed and operational; new phased-array feed design ("Chequer Board") developed and being tested (Figure 10 and Figure 12b); Parkes 12 m antenna test-bed facility completed. Web site: http://www.atnf.csiro.au/projects/askap/.

8.5 SKADS (SKA Design Studies)

- *Brief description:* European-led R&D program to produce end-to-end SKA designs and prototypes based principally on dense aperture phased arrays, together with generic SKA technology studies and simulations to verify SKA performance.

- *Site:* EMBRACE (Electronic Multibeam Radio Astronomy Concept) demonstrator elements at Westerbork (NL) and Nancay (FR); 2-PAD (two polarization, all digital) demonstrator in UK; BEST (Basic Element for SKA Training) development platform using Northern Cross radio telescope near Bologna (IT).

- *Main proponents:* European FP6 initiative; 26-institute consortium, including international collaborators.

Figure 12a. An experimental dish antenna. The meerKAT 15 m diameter dish constructed with low-cost fiberglass material and flame-sprayed aluminum reflective layer. The 2 mm rms surface accuracy allows effective operation to about 10 GHz. This is a platform designed to test various design concepts, but is unlikely to be the actual design used in SKA Pathfinders

Figure 12b. An experimental dish antenna. The ASKAP 12 m test antenna at Parkes. The Chequer Board feed shown in Figure 10a is mounted at the prime focus of the dish. The antenna uses a stretch-formed panel construction and operates to beyond 20 GHz; it is supplied by Patriot Antenna Systems, Inc. This is a platform designed to test various design concepts, but is unlikely to be the actual design used in SKA Pathfinders.

- *Investment:* 38M Euro, including 10.4M Euro funding from EC FP6 program.

- *Operating band:* 0.5-1.5 GHz (EMBRACE); 0.3-1.0 GHz (2-PAD); 0.4-0.414 GHz (BEST).

- *SKA Reference Design technology demonstration:* Dense aperture array (AA).

- *Scale:* Astronomically-capable, single-polarization dense aperture array demonstrator, 200 m^2 collecting area (EMBRACE). Technical demonstration of dual-polarization, dense array tile with all element signals digitized, ~10m^2 (2-PAD). Astronomically-capable development platform using part of Northern Cross telescope (BEST).

- *Key technologies and techniques:* Dense aperture phased arrays (Figure 7); highly-integrated RF and beamforming solutions; low-cost analog and digital signal transport; array phase-transfer technologies and techniques; multiple independent field of views; astronomical characterization of dense phased array telescope; simulation catalogues of the radio sky as seen by SKA; simulations of ionospheric and instrumental effects on SKA observations; SKA science and operations with aperture-array telescopes; low-cost aperture-array realization via design for manufacture and industry engagement; SKA infrastructure studies.

- *Date commenced:* July 2005.

- *Projected completion date:* June 2009.

- *Status:* Successful midterm review with first-round prototypes delivered. Construction and test of demonstrators underway. Web site: http://www.skads-eu.org/.

8.6 TDP (Technology Development Project)

- *Brief description:* US-led design and prototyping program to develop technology options for SKA; strong working links with PrepSKA.

- *Site:* Various US institutes.

- *Main proponents:* US SKA Consortium, with international collaborators.

- *Operating band:* Emphasis on mid- and high-frequency (>1 GHz) SKA technology and technology choices.

- *Investment:* USD 12M = 7M Euro.

- *SKA Reference Design technology demonstration:* Small dish + single-pixel feed (SD+SPF).

- *Scale:* Astronomically capable dish demonstrators; selected signal transport and processing prototypes; delivery of prototype optimized SKA antenna.

- *Key technologies and techniques:* Antennas, feeds (Figure 8), and receivers focusing on low-cost single-dish optimization; system analysis and design, including choice of antenna diameter; determination of antenna cost versus frequency function; calibration and data processing.

- *Date commenced:* 2007.

- *Projected completion date:* 2011.

- *Status:* Work packages commenced, with first of annual top-level project reviews in September 2008.

9. Conclusion

The gestation time of mega-science projects is invariably long, with 20-30 years being typical. In the case of the SKA, much of the conceptual design and scientific positioning of the instrument is complete, and the project is entering the exciting phase in which the details of the telescope are being mapped out. With continued momentum, the SKA could be undertaking its transformational astronomy mission by 2020. Part of the excitement of the SKA journey comes from the highly innovative precursor radio telescopes spawned around the world, each of which is opening up new areas of radio science and astronomy.

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