THE SQUARE KILOMETRE ARRAY: AN INTERNATIONAL ENGINEERING PERSPECTIVE

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Abstract. The pace of the international Square Kilometre Array (SKA) project is accelerating, with major concept reviews recently completed and a number of technology demonstrators well underway. First-round submissions to host the telescope have been lodged by six countries. The SKA timeline currently shows a site decision in 2006, and one or more technology concepts chosen in 2008. The telescope is expected to be operational, in various phases, in the period 2015 – 2020. This paper gives a status review of the project, and outlines engineering concept development and demonstration projects.

Key words: Radio telescopes, next-generation telescopes, international science projects, novel antennas, interferometry, aperture synthesis.

1. Introduction

The SKA radio telescope project is an international endeavour to build an aperture synthesis radio telescope with one million square metres of effective collecting area, operating the range 100 MHz to 25 GHz (Schilizzi, 2004). A major target of the project is to achieve a sensitivity gain of 100 relative to present-day radio interferometers. This is expressed in a key specification (Jones, 2004): over a wide frequency range the sensitivity metric, A_{eff}/T_{sys}, should be of order 20,000. Here, A_{eff} is the effective collecting area (m^2) and T_{sys} is the system equivalent noise temperature (kelvin). With a canonical 50 K system temperature, the required A_{eff} is 10^6 m^2, or 1 km^2. While half the collecting area will be located in a central region of ~ 5 km diameter, the full array will extend across trans-continental distances (Figure 1).

The SKA project rose to prominence in the late 1990s with the formation of the International SKA Steering Committee, an overseeing body currently consisting of representatives from 17 countries. The estimated construction budget is USD 1B (2004 dollars), a figure demanding many new technology developments in order to yield a cost per unit collecting area of one-tenth that of existing radio telescopes. An International SKA Project Office (ISPO) is now functional and the first international Director and Project Engineer commenced appointments in 2003 and 2004, respectively.

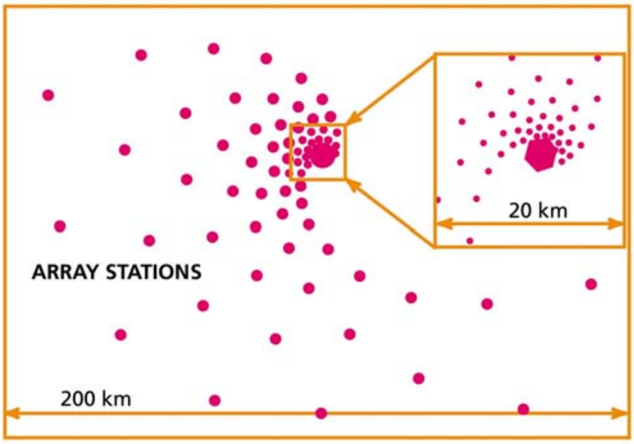

Figure 1. Example of a possible SKA configuration. In this model, patches of collecting area (stations) extend from a dense core in a log-spiral arrangement. The pattern continues to baselines of ~ 3000 km, with about 10% of the total collecting area being outside the scale depicted.

A recent series of whitepapers (ISPO Concept Whitepapers, 2003), or end-to-end descriptions of potential SKA designs, have proved invaluable in promoting science and engineering discussion, identifying areas in which there are deficiencies in knowledge or specification clarity, and stimulating new studies – including simulation of performance and cost tradeoffs. In effect, the whitepapers are slices through a complex problem and solution space, the sample solutions being used to illuminate critical issues and provoke still more imaginative designs. An updated science case for the SKA (Carilli and Rawlings, 2004) identifies five key areas of astronomy and cosmology, with the original driver – the evolution of structure in the primordial Universe – still figuring prominently.

As well as the many technology development projects underway, an important additional aspect of SKA engineering deals with site infrastructure design and costing. Initial siting proposals have been received from Argentina, Australia, Brazil, China, South Africa and the USA (ISPO Site Whitepapers, 2003). A first costing study (Hall, 2003a) puts the infrastructure value of the project at around USD 250M, including a custom optical fibre communications network for at least the central array. Regardless of the site chosen there will be significant infrastructure challenges in areas such as remote power provision, active and passive environmental conditioning, and low-cost access road construction.

A decision on SKA siting is scheduled for 2006, with preceding measurements of radio-frequency (RF) interference at candidate locations being made both by site proponents and the ISPO, the latter via a contract with ASTRON, the Dutch national radio astronomy organization. These technical efforts provide a snapshot of the current RF environments and a parallel part of the site proposal process involves proponents examining the feasibility of establishing a radio-quiet zone for the central part of the SKA; such a zone would provide long-term interference protection, especially for the SKA's lower-frequency operations. It is expected that tropospheric attenuation and stability measurements will be made at sites short-listed on the basis of the RF environment data. This will ensure that acceptable performance is also possible at the highest operating frequencies of the SKA.

2. Whitepapers and convergence

One of the main outcomes of the whitepaper preparation and subsequent review processes has been the recognition that no one concept meets all the SKA performance goals. In particular, cost-effective designs meeting the high-frequency sensitivity requirements optimize T_{sys} at the expense of A_{eff}, giving inadequate sensitivity at low frequencies, where T_{sys} is dominated not by receiver contributions but by cosmic radiation from the Milky Way galaxy. Furthermore, the high frequency designs do not provide the independent multi-fielding (or area re-use) capability which is now established as an SKA target, at least at the low frequency end of the Telescope's operating band.

Despite the realization that different low and high frequency solutions may be required, the whitepapers did establish the commonality of a large amount of the SKA system design, independent of the selected antenna or associated RF technology. A design convergence process is therefore underway, involving astronomers and engineers working iteratively to explore the assumption that a hybrid – or composite – telescope will give a better match to the science goals. In this model, at least two antenna solutions might share common sites, signal transport and back-end infrastructure. In the end though, the costs incurred in designing, implementing and operating a composite instrument will need to be weighed against scientific gains. The choice of either a hybrid, or a "best fit" single concept, will involve intense astronomy and engineering interaction, and much debate centered on prioritizing key science goals.

While the hybrid model looks promising, its elements will most likely come from technologies described in the whitepapers. In parallel with the convergence work, a number of engineering groups are therefore working to validate pivotal technologies by means of demonstrators, of various scales. The intention is to have critical technology reviews of these demonstrators form the basis of a 2008 concept selection process.

The SKA concept whitepapers have been successful in setting out possible implementations of the Telescope but the diverse origins of the documents means that a variety of design and costing assumptions currently exist, making it difficult to directly compare designs. A cost/performance estimation project now underway builds on an emerging

SKA system definition which recognizes the commonality in all concepts. The estimation tools will help compare concepts on the basis of agreed cost and performance assumptions, and via common assessment metrics.

3. SKA concepts and demonstrators

Figure 2 is a diagrammatic view of the SKA, with typical data rates shown for the outer and inner parts of the array. It is obviously possible to divide the 10^6 m^2 of collecting area in many ways but the idea of a station, representing a geographically localized (patch) of collecting area, is basic to most designs. The number of stations, N, is a useful design classifier: large-N (N>300) and small-N (N<50) concepts may offer relatively high-fidelity imaging and low infrastructure costs, respectively. However, a series of simulations to investigate the trade-offs in large- and small-N designs is still in progress. With the SKA imaging specification set at 60 dB dynamic range over a wide field of view, the simulations themselves are non-trivial, requiring significant algorithm development and super-computing resources.

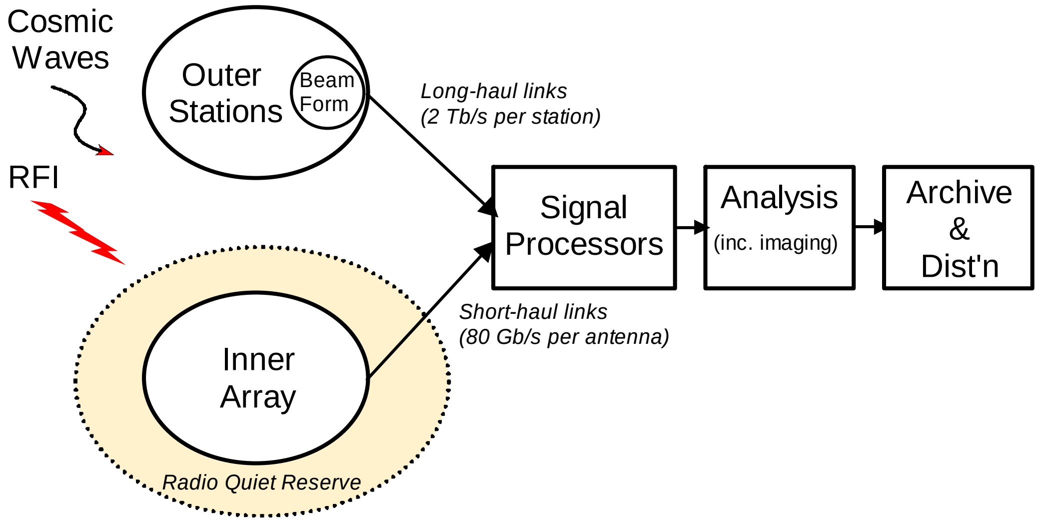

Figure 2. Simplified schematic view of the SKA. About half the total collecting area is contained within the inner array (< 5 km diameter). Actual data rates from outer stations depend on available (or affordable) bandwidths on custom and/or commercial networks. The amount of signal aggregation (beam-forming) can be adjusted as transmission capacity evolves.

There are currently seven antenna concepts for the SKA being considered. Table I aggregates these by form and summarizes some key features, while Figure 3 is a visualization of various instruments. The descriptions of area division given in the table are representative of those so far investigated by proponents of the various concepts. It is important to realize that the SKA is much more than antennas, requiring as it does major developments in fields such as low-noise integrated RF systems, long distance data transmission at Tb/s rates, real-time signal processing at peta operation per second speeds, and highly complex computing systems spanning a number of software engineering fields. Still, apart from being the most visible part of the telescope, antennas will account for 40 – 50% of the cost, despite intentions to make a “software telescope” by exploiting, as far as possible, the convergence of radio and computing technologies.

In the end, all ideas for realizing the SKA result in the transmission and processing of data from a given field-of-view, at given bandwidths and quantizing accuracies, across various distance regimes. Not surprisingly, one arrives fairly naturally at a system definition which views a large part of the SKA design process as simply an exercise in optimizing the transport and processing of very large volumes of data: an perspective likely to appeal to industry and other associates operating outside the astronomy arena. While this view is useful, there is still a large, specialized, design task involving antennas, RF systems, analog-digital conversion and, in most concepts, station-level signal processing. Nevertheless, with the exception of some antenna-specific descriptors, these more specialized sections of the SKA are also amenable to definition in terms of standard sub-systems and components. Apart from the engineering imperatives in this area, a first exercise in standardized system design has underlined that a continuing definition process is essential to refining the science goals of the Telescope, and to ensuring that stakeholders have a clear idea of what the instrument will actually be able to do.

Turning to concept selection, practical technology demonstration is the basis of the SKA process. Aggressive project timescales mean that "blind alleys" need to be avoided and the general philosophy is to succeed or fail early in proof-of-concept demonstrators. SKA concept proponents have been encouraged to tackle critical issues early in their programs and to establish that the cost reduction factors necessary to make the SKA viable can, in fact, be achieved.

A practical example of this approach is the decision not to proceed further, at this point, with development of the Luneburg Lens antenna in the SKA context. Despite notable achievements, including the patenting of a new dielectric material (Section 4), the Australian proponents used a highly-directed prototyping effort to conclude that the antenna is unlikely to be viable on SKA timescales. This decision was also bound to an evolving SKA science case favouring wide fields-of-view (FOVs) below 1 GHz over multiple, independent, FOVs at higher frequencies.

Two large-scale instruments currently being built will be especially important in the path to the SKA. The US Allen Telescope Array (ATA) will be central to verifying the feasibility of small reflector solutions incorporating new-generation cryogenic cooling techniques for broadband receivers. The LOFAR telescope, a geographically-distributed aperture array (30 – 240 MHz) being built in the Netherlands, will be the first software radio telescope and will address critical SKA concepts, including RF interference mitigation and area re-use via widely-separated multi-fielding. Apart from the ATA and LOFAR, planned extensions to the US Very Large Array (VLA) and Deep Space Network (DSN), and to the European MERLIN and EVN telescopes (via the EVLA, e-MERLIN and e-EVN projects) also have much to contribute to SKA demonstration, principally in the fields of data transport and software development. Similarly, many international project management and equipment production guidelines will undoubtedly be gleaned from the USD 0.5B Atacama Large Millimetre Array (ALMA) radio telescope now being constructed.

Large-scale SKA-specific technology proposals (USD 30M each) have recently been submitted to funding agencies in the USA and Europe. The US Technical Development Program seeks to demonstrate the viability of mass-production techniques for 12 m dish antennas and associated systems. In Europe, the Framework 6 proposal for SKA Design Studies aims to produce new insights into the economical manufacture of phased arrays, principally via the EMBRACE ("Electronic Multibeam Radio Astronomy Concept") 500 m^2 aperture array demonstrator, but also via the development of focal plane arrays for large reflectors, an activity being pursued in collaboration with the Australian and Canadian SKA consortia. Regardless of the ultimate applicability to the SKA of particular antenna solutions, consortia in Australia, Canada, China, and India have framed further plans to construct large-scale pathfinder science instruments based on many of the concepts outlined in Table I. In the case of China, the hope is that a current bridging project to optimize engineering for the 500 m FAST demonstrator could lead into construction of FAST itself on a timescale of perhaps six years.

TABLE I
Summary of SKA concepts

Concept Class	**Concept Name**	**Attributes**	**Challenges or Issues**	**Initial Demonstrators**
Large diameter (> 100 m) reflecting flux concentrators (N= 30-100 antennas; 1 antenna per station)	Large Adaptive Reflector (LAR) *(Canada).* --------------------- Kilometre-area Radio Synthesis Telescope (KARST) *(China).* --------------------- Cylindrical Reflector (CR) *(Australia).*	Filled station (high sensitivity to spatially extended radio emission). Small N may lower infrastructure costs. Potentially wide frequency coverage.	Large focal plane arrays for acceptable field-of-view. High-fidelity imaging with small N.	Scaled aerostat and control system *(Canada).* ---------------------- Scaled version of Five hundred metre Aperture Spherical Telescope (FAST) *(China).* ---------------------- SKA Molonglo Prototype (SKAMP) *(Australia).*
Small diameter (~12 m) reflecting flux concentrators (4500 – 8000 antennas, N=600 stations)	Large N – Small D array (LNSD) *(USA).* ---------------------- Pre-loaded Parabolic Dish (PPD) *(India).*	Large N may yield very good imaging. Good high-frequency sensitivity. Highly versatile array. Wide frequency coverage.	No multi-fielding. Poor low-frequency sensitivity.	Allen Telescope Array (ATA) *(USA).* ---------------------- Raman Research Institute 12 m antenna *(India).*
Refracting flux concentrator (20 000 antennas, N=300 stations)	Luneburg Lens (LL) *(Australia).*	Multi-fielding (quasi-optical beamforming).	10 - 15 GHz upper frequency limit with 3.5 m lenses. New dielectric material required.	1 m Luneburg Lens with new artificial dielectric *(Australia).*
Aperture Phased Array (Typically 200 000 elemental antennas for a constituent array operating at 500 MHz, N=100 stations)	Aperture Array Tile (AAT) *(Europe).*	Multi-fielding (electronic beamforming). Highly agile field translation.	1.5 GHz upper frequency limit. <3:1 bandwidth limitation – 3 constituent arrays needed to cover 100 MHz – 1.5 GHz Low-cost realization needed.	Thousand Element Array (THEA); *(Europe).*

Figure 3. SKA concept visualizations. The left panel shows two large adaptive reflector ideas, one based on a 200 m diameter Arecibo-like spherical reflector (upper), the other using a much flatter reflector and an aerostat-mounted focus cabin. The middle panel (upper) shows offset paraboloids, the proposed 12 m versions being similar to the 6 m Allen Telescope Array antennas shown; the lower illustration shows an SKA station using aperture arrays. The right panel (upper) shows a station based on 64 x 7 m diameter Luneburg Lenses; the lower visualization is of a station employing a single 110 m x 15 m cylindrical reflector. The concepts originate in China, Canada, the USA, Europe and Australia (both right hand panels). Not shown is a 12 m symmetrical paraboloid concept proposed by the Indian SKA group.

4. Pivotal technology and software

A recent review (Hall, 2003b) of updated SKA whitepapers produced a series of critiques for the various concepts and identified the major engineering challenges to be addressed in demonstrators. This list includes items such as:

- Low-cost manufacturing methods for both concentrators and dense aperture arrays;
- Sensitive, cheap, highly-integrated, uncooled receivers (Aperture Array, Luneburg Lens, Cylindrical Reflector);
- Efficient, broadband, feeds with optical arrangements yielding minimum spillover (concentrators);
- Low cost, reliable, cryogenics (concentrators other than Luneburg Lens and Cylindrical Reflector);
- Large, cheap, focal plane arrays with accurate, low-loss, beamforming networks operating to beyond 10 GHz (large concentrators);
- Economical, high bandwidth (Tb/s), fibre optic signal transmission links (compatibility with commercial standards and maximum bandwidth efficiency are dominant issues in distant and central SKA distance regimes, respectively); and
- Scaleable signal processors – including correlators – demonstrating processing power, flexibility and connectivity issues.

While much remains to be done, there have been some notable engineering achievements already. A sampling of the 2002-2003 engineering highlights noted in the report cited includes items such as:

- Broadband log-pyramidal feeds covering the range 0.5 – 11 GHz;
- New methods of accurately hydroforming aluminium paraboloids in the 6-12 m diameter range;
- Development and test of new pulse-tube cryogenic coolers operating at 70 K;
- Decade-band, low-noise, RF amplifier development, both cooled and uncooled, using technologies ranging from indium-phosphide to CMOS;
- Refinement of cost-effective, light-weight, dense focal plane arrays using Vivaldi end-fire elements;

- Active panel controls and new manufacturing methods for large reflectors (> 100 m diameter);
- Accurate, low-cost, feed positioning systems for large reflectors; and
- New low-loss artificial dielectric material (tan $\delta < 10^{-4}$) for Luneburg Lenses and other e.m. applications, together with an associated feed translation system for lenses.

Figure 4 shows some examples of recent SKA antenna-related prototyping.

Recent studies of SKA computing and software engineering requirements (e.g. Cornwell, 2004a,b) have highlighted the substantial challenges facing the project in these areas. Simply scaling up existing imaging techniques and using general-purpose computers (with projected computing powers adjusted for Moore's Law gains) appears unlikely to solve the SKA problem. In the worst-case estimate the cost of post-processing scales as the inverse eighth power of the concentrator diameter and the cube of the maximum baseline which, for geographically extended large-N concepts, implies 2015 costs well in excess of the entire SKA budget of USD 1B. At the same time, first simulations of imaging with large concentrators (small-N SKA) raise doubts about whether the required imaging quality can be achieved. Clearly, extension of the simulation program is essential if key SKA design questions are to be answered. In response to this imperative an international simulations working group has recently been established. The development of new imaging algorithms and methodologies, perhaps invoking a combination of dedicated hardware and general-purpose computers, will also be linked closely to the SKA simulation tools and facilities now being established.

Figure 4. SKA technology prototypes. At left are components for large reflectors. The upper panel shows a prototype deformable surface for the FAST demonstrator while the lower panel illustrates a test aerostat for the suspended-feed LAR concept . The middle panel shows three 6 m dishes of the Allen Telescope Array (upper), together with a patch of an aperture array demonstrator based on Vivaldi-notch end-fire elements (lower). At upper right is a 0.9 m Luneburg Lens with a two-arm feed translator. The lower right panel shows a prototype 12 m dish constructed using a mesh surface and pre-loaded radial members.

5. Industry collaboration

As a matter of principle the international SKA project, and its associated national programs, welcome interest from potential industry partners. In general terms any joint research and development is viewed as a shared-risk endeavour, with SKA consortia and industry each contributing to defined activities. In some countries industry is able to offset or recoup its contribution via government funding programs or the tax system. The SKA has an agreed policy on intellectual property (IP) developed under its aegis. Broadly, industry partners exploit their own IP contributions in arenas outside the SKA project but innovations are available to the SKA project free of any licensing charge. Advantages for industry participants include:

- The opportunity to hone the creative energies of their best professionals in a highly imaginative project;
- The ability to perfect leading-edge techniques and products in a demanding application, with technologically sophisticated users;
- The ability to generate and share information with R&D partners in a benign and commercially non-threatening environment;
- High visibility flowing from association with an innovative international mega-science project; and
- Potential for early involvement and favourable positioning in a USD1B project spanning a range of engineering and computing disciplines.

An outline timescale for industry involvement is shown in Table II, and a summary of SKA consortia interests and expertise is also available (Hall, 2004). Internationally, the first industry input may be via the ISPO and its interests in complex decision making formalisms and risk management strategies.

TABLE II
SKA key dates and industry opportunities

Year	**SKA Project Milestone**	**Industry Opportunities**
2003	Initial siting proposals received from four countries	Scope for continuing industry involvement in national site characterization
2004	Plans for national SKA demonstrators submitted	Possible links to national SKA technology development programs
2005	Final SKA site submissions	Possible involvement in compiling national proposals
2006	SKA site decision Critical review of technology demonstrator programs	Possible links in development of objective international methodology for site and technology selection, and for risk management
2008	Choice of SKA technology	
2009	Start construction of on-site SKA demonstrator (5-10% SKA area)	Likely participation in infrastructure provision, and instrument design and construction
2012	Start construction of SKA	Maximum involvement at levels of final design, project management, and construction contracts and sub-contracts
2015	Stage 1 SKA complete and operational	Opportunities in commissioning, operations and maintenance
2020	SKA complete	Continuing operations and maintenance role

6. Conclusions

With many innovative concepts proposed for the SKA the selection process relies heavily on demonstration of key systems and components. While not uniform in scale, demonstrators currently being built will give insight into the feasibility of various approaches. Additional engineering development programs valued at more than USD 60M may soon be available, paving the way to a large-scale, on-site, demonstrator using selected technologies. This will most likely be built in the period 2009 – 2012, minimizing the “leap of faith” required to build the full SKA. At 5-10% of the SKA area, this telescope will be a formidable instrument in its own right, allowing a huge expansion of, for example, the database of galaxy red-shift measurements. This data could conceivably reveal the equation of state (pressure/density relationship) of the Universe, giving insight into the birth, and eventual death, of the Cosmos.

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