The Square-Kilometre Array Radio Telescope

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Introduction

The square-kilometre array (SKA) is a major next-generation radio-telescope expected to be completed in the decade 2010 - 2020. As the name implies, it has an effective collecting area of a square-kilometre, or 1 million square metres: the equivalent of more than one hundred, 100 m diameter, dish antennas. This is two orders of magnitude as great as the biggest operational telescopes, giving astronomers the factor of 100 in sensitivity they require to do critical new observations. At present a seven-member international consortium is planning and promoting the new instrument; Australia is a major player in this group. With interest in the $A1 billion instrument growing, more formal international and national project management plans are about to be put in place. A number of deadlines have already been set, with the end of 2005 being an agreed point for deciding between competing technological realizations. The astronomical wish-list is so extensive that compromise is inevitable, and continuous iteration between science and technology groups will be necessary over the next few years to match the astronomical goals with feasible engineering. While a site for the SKA is still being sought, Australia has a good chance of hosting the instrument, giving substantial economic and other benefits. CSIRO has recently launched a seed program to co-ordinate Australian SKA research and is actively seeking links with industry and other partners.

The SKA - Background

Astronomy and technology have always been inextricably linked, with discoveries flowing as ever-more-capable instruments view the Universe. This ancient science is no mere consumer though; the demands on innovators are many and astronomy often proves a benign testing ground for advanced engineering - much of which is destined ultimately for far more lucrative military or consumer markets. Like other branches of the science, radio astronomy relies on new technology to probe hitherto unexplored volumes of the observational phase space, thereby maintaining its discovery rate. The start of the 21st century sees the convergence of radio and software and, while radio astronomy has for some years used what are now being called software-defined radios, the commercial products of this technology, turned back to the astronomy world, make possible radio telescopes of awesome potential. More regions of our observational phase space than ever before will be accessible, and multiple access - relying on only one set of expensive signal-gathering infrastructure - will be the norm. This concept of the software telescope is basic to the SKA.

While a full science case for the SKA now exists [1], there are two key drivers. The first, illustrated in Figure 1, is the pragmatic observation that radio telescope sensitivity needs to scale exponentially with time if the discovery rate is to be maintained. Just extrapolating from the best contemporary instruments means that a 100-fold increase by 2010 is necessary; in practice, this also allows the science done at radio wavelengths to complement that coming from new-generation ground and space-based telescopes operating at infra-red, optical, X-ray and gamma wavelengths.

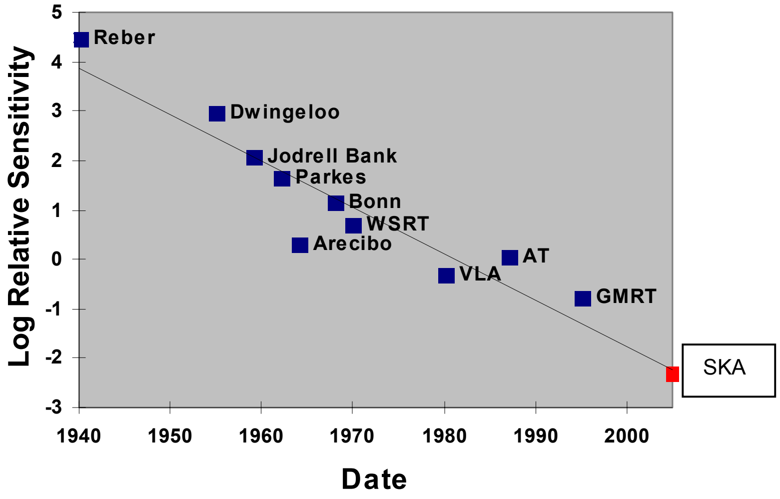

Figure 1 - Relative sensitivity of radio telescopes as a function of time

The second driver is more specific: astronomers want to look to the distant Universe to see the processes which first imposed structure and order, allowing galaxies and stars to form. It turns out that the best way of seeing into this "dark time" is to observe the quasi-CW microwave radiation from hydrogen atoms - the HI emission. The rest frequency for this emission is ~1420 MHz but, with the Doppler shift of an expanding Universe, observations down to 200 MHz are needed to reveal the weak, and presently undetectable, signature of early structures destined to become galaxies. While many other applications of the SKA have emerged since the first discussions in the late 1980s, these early Universe studies remain at the core of the science.

There are a couple of fundamental SKA design questions which are often asked, and which can be answered fairly quickly. First, why not gain the factor of 100 in sensitivity by equipping existing telescopes with more sensitive receivers? In fact, upgrades in this vein are in progress on major instruments such as the US Very Large Array (VLA) and the Australia Telescope Compact Array (ATCA). However, state-of-the art receivers on centimetre-wave (<10 GHz) telescopes have reached performance levels where the sensitivity is no longer limited solely by electronics - the background emission from our Galaxy is a sizeable fraction of total system noise levels. The only practical way to increase sensitivity is to collect more microwave photons from the sources being studied, and this means more antenna aperture.

The second question is why an "array"? Apart from the obvious difficulties of building a million square metre single aperture, it turns out that the extent of the aperture has to be of order hundreds of kilometres if the SKA is to have the ~100 μarcsec resolution needed to separate all the new radio sources it will see. This then leads to the notion of a synthesized aperture telescope, along the same broad lines as the VLA or ATCA. One caveat, though, is that obtaining good fidelity images of the new, weak, sources, will require an imaging dynamic range in excess of 10^6 (60 dB): far in excess of that obtained routinely with present-day aperture synthesis techniques.

Technology

The top-level design goals for the SKA are summarized in Table 1. The composite sensitivity specification recognizes different tradeoffs between collecting area, aperture efficiency and noise equivalent temperature inherent in various conceivable SKA realizations. To give an idea of an acceptable system, a 2 x 10^6 m^2 physical aperture with an efficiency of 50 % and system temperature of 50 K will meet the specification. In earth station design terms, the L-band SKA sensitivity might be quoted as ~ 68 dB K^{-1} . For further reference, a 14 m aperture just satisfies the field-of-view specification; array elements larger than this reduce the amount of sky viewed at a given time.

Table 1 - SKA Specifications

Parameter	**Design Goal**
Sensitivity	Effective Area/System Temperature = 2 x 10^4 m^2K^{-1}
Frequency range	f = 0.2 to ≥ 12 GHz
Number of simultaneous beams	~ 100
Field of view	1 degree square at 1.4 GHz
Angular resolution	0.1 arcsecond at 1.4 GHz
Instantaneous bandwidth	0.5 + (f/5) GHz
Number of spectral channels	10^4
Number of simultaneous bands	2
Polarization purity	≤ –40 dB coupling
Synthesized image dynamic range	≥ 10^6 at 1.4 GHz

The specification which really drives the choice of technology relates to the number and distribution of simultaneous beams. Everyone agrees that multi-beaming is a necessity for reasons of science, observing efficiency and effective mitigation of man-made interference; the real question is whether it is satisfactory to concentrate the beams within the 1° primary field-of-view. If so, SKA implementations using, e.g., reflector antennas may be feasible. If not, designs using arrays or 3-D lenses become attractive. An important point to evaluate when making this critical design decision concerns the end efficiency of the solution: one may in fact be better to position-switch, or configure sub-arrays of the 10^6 m^2, rather than implement an inefficient multi-beam solution. It remains true though that there are classes of science, including investigations of some transient phenomena, which can only be done with widely-separated beams. The merit of these drivers must obviously be weighed carefully by the science community. An interesting twist is that, with the SKA, the beams could be formed digitally, from buffered data, after a transient event has been detected. This does not, of course, affect the need to design multi-beaming solutions into the antenna and RF systems.

Related to the number of beams is the question of signal aggregation hierarchies. The most flexible SKA might have perhaps 1 million antennas of effective area 1 m^2, followed by an ultra-wide signal connection network leading into a digital signal processing engine which performs, among other operations, the cross correlations required for aperture synthesis. Ignoring RF complexities, and allowing for the continuation of Moore's Law in computing systems, astronomical correlators in 2010 may run at ~10^7 G ops/sec. Even for one imaging beam in our ultra-wide SKA, a capacity of ~10^{12} G ops/sec would be needed, assuming an unambitious variant of a present-day "FX" correlator. In a feasible SKA then, some RF (or similar) signal aggregation will be necessary to reduce the number of elements correlated and hence the signal processing demands. A design for 2010 might specify 5000 elements and meet the Moore's Law projection; a 2020 design might triple that number. With any aggregation though, versatility will be lost, and very careful thought is needed if the utility of the SKA across a range of science applications is to be preserved.

There have been a number of proposed SKA implementations, ranging from extensions of well-accepted technology (e.g. parabolic dishes) to the more exotic (large deformable reflectors with driven aerostat-mounted focal platforms). Reference [2] contains a summary of initial proposals. Several concepts are now quite old and do not meet updated specifications. My own choice of contenders for an SKA to be built around 2010, together with the major advantages and disadvantages of each, are summarized in Table 2. Of these, the Luneburg Lens (LL) proposal [3] is the most recent and is the only one offering full-sensitivity multi-beaming. Recent CSIRO analyses show that obtainable dielectric losses could allow operation to beyond 10 GHz, but that cost and manufacturing challenges require more investigation. Figure 2 shows what an SKA station using 400 x 5 m LLs (the equivalent of a ~100 m dish) might look like. An SKA using this approach may have 100 stations, and perhaps an aggregation of 10 x 40-element sub-arrays per station to make the signal processing requirements feasible.

Figure 2 - Artist's impression of an SKA station using 5m diameter Luneburg Lenses

Australia and the SKA

The decision of where to build the SKA will be made around 2005. Australia, with abundant unoccupied land, relative radio quietness, good scientific and engineering infrastructure, and a stable political environment, is clearly a possible host. Our southern location also helps: a telescope built at moderate southern latitudes gets an excellent view of the astronomically-rich centre of the Milky Way.

Table 2 - SKA Antenna Technology Summary

Technology	**Advantages**	**Disadvantages**	**Comments**
Parabolic reflector	Known technology	Traditionally expensive structures, drives and mounts	Prospects for advances in fabrication. Light-weight wire and mesh construction for larger dishes. Arrays of TV receiving dishes (~ 5 m) with simplified mounts at smaller end of scale.
	Inherently directional - good discrimination against unwanted signals	Restricted instantaneous sky coverage - can only have closely-spaced multiple beams	
	Optical beamforming - broadband, easy to get some level of multi-beaming at focus		
Planar array	Easy to manufacture and assemble	Little use outside high cost military and similar applications	Need design tools capable of handling mutual coupling effects in dense, active, broadband arrays
	Potentially cheap integrated construction	Area projection and scan blindness effects limit available sky coverage at good efficiency	
		Problems achieving required element bandwidth and spacing	
Luneburg Lens	Full-sensitivity, randomly placeable, multi-beaming over close to whole sky	Solid (3D) structure; 5 m foam lens weighs ~ 100 tonnes	Needs new work in materials design (artificial dielectrics) and manufacturing
	Optical beamforming - potentially broadband	Uses to date have been confined to small (<1 m) lenses	Feed arrays to capitalize on broadband multi-beaming are challenging
		Potentially lossy and expensive	

A consultant's study [4] commissioned by the Department of Industry, Science and Resources (DISR) outlined separately the benefits and costs of Australia (a) participating in and (b) participating in and hosting, the international SKA project. The study attempted to quantify outlays and returns such as R&D contributions, share of construction expenditure, and returns from tourism and the growth in human capital. However, it noted that there were, as yet, unquantifiable benefits, including the following partial list:

- telescope development contracts;
- access to new intellectual property from R&D contracts;
- access to new technological knowledge for Australian industry;
- site and additional construction contracts;
- national prestige;
- human resource and technology spin-offs to other industries.

The final estimate was that, in the case of participation only, the unquantifiable benefits needed to exceed ~$60 M for break-even. Given both hosting and participation, the corresponding break-even numbers are ~$40 M. These requirements seem modest when set against past experience. For example, an independent study of CSIRO earth station antenna research [5] found a two-fold return on national investment. The $50 M Australia Telescope was a contribution to this research and, while the AT was certainly "high tech", the SKA project offers far more potential for researchers and industry to capitalize on fundamental contributions in the antenna, RF systems and signal processing areas. A comparable recent Canadian study [6] showed a similar economic return on astronomy investment, noting that this is a respectable "real" return, not subject to the double-counting often inherent in figures used to promote some projects involving substantial public investment.

While the economic arguments are important, they should not necessarily be dominant. Basic science is a genuine cultural pursuit and, according to DISR reckoning, astronomy is consistently at, or near, the top of Australian science in its impact on the world scene (see, e.g., [7]). With support for the SKA and other projects at the limit of our capabilities, we play our part in humanity's quest for knowledge of itself and its place in the Universe.

References

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