The Square Kilometre Array

This telescope, to be the largest in the world, will probe the evolution of black holes as well as the basic properties, birth and death of the Universe.

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ABSTRACT | The Square Kilometre Array (SKA) will be an ultrasensitive radio telescope, built to further the understanding of the most important phenomena in the Universe, including some pertaining to the birth and eventual death of the Universe itself. Over the next few years, the SKA will make the transition from an early formative to a well-defined design. This paper outlines how the scientific challenges are translated into technical challenges, how the application of recent technology offers the potential of affordably meeting these challenges, and how the choices of technology will ultimately be made. The SKA will be an array of coherently connected antennas spread over an area about 3000 km in extent, with an aggregate antenna collecting area of up to 106 m^2 at centimeter and meter wavelengths. A key scientific requirement is the ability to carry out sensitive observations of the sky over large areas (surveys). The "survey speed" of the SKA will be enabled by the application of the most up-to-date signal-processing technology available. The SKA science impact will be widely felt in astroparticle physics and cosmology, fundamental physics, galactic and extragalactic astronomy, solar system science, and astrobiology.

KEYWORDS | Aperture synthesis; digital correlator; digital data transmission; digital signal processing; Fourier imaging; low-noise amplifier; radio astronomy; radio telescope

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I. INTRODUCTION

Advances in astronomy over the past decades have brought the international community to the verge of charting a complete history of the Universe. In order to achieve this goal, the world community is pooling resources and expertise to design and construct powerful observatories that will probe the entire electromagnetic spectrum, from radio to gamma-rays, and even beyond the electromagnetic spectrum, studying gravitational waves, cosmic rays, and neutrinos.

The *Square Kilometre Array* (SKA) will be one of these telescopes, a radio telescope with an aperture of up to a million square meters. The SKA was formulated from the very beginning as an international, astronomer-led ("grass roots") initiative. The International Union for Radio Science (URSI) established a working group in 1993 to study the next-generation radio wavelength observatory. Since that time, the effort has grown to comprise 19 countries and 55 institutes. As many as seven different initial technical concepts for the SKA have been narrowed substantially. After a rigorous process, two sites, in the Karoo region of central South Africa and in the state of Western Australia, were identified as suitable for much of the SKA's intended wavelength range (see below). Fifteen funding agencies now regularly discuss SKA development and funding options. The project timeline has the telescope operational below 10 GHz by 2022.

At the highest level of generalization all telescopes are designed to tackle, in the wavebands at which they operate, the most important problems in astronomy, especially those for which technology can provide new opportunities for advancement. The U.S. Decadal Review Panel for 2000–2010 expressed these goals succinctly in their report, *Astronomy and Astrophysics in the New Millennium* [1], as follows.

- Determine the large-scale properties of the universe: the amount, distribution, and nature of its matter and energy, its age, and the history of its expansion.
- Study the dawn of the modern universe, when the first stars and galaxies formed.

- Understand the formation and evolution of black holes of all sizes.
- Study the formation of stars and their planetary systems, and the birth and evolution of giant and terrestrial planets.
- Understand how the astronomical environment affects Earth.

Similar goals are identified in similar reports from other countries and regions, such as the recent European AstroNet process.

Radio-wave observations address these goals in a way that is both unique and complementary to that provided in other wavebands. Observations and technical developments in radio astronomy have led to several Nobel prizes in physics. These successes were largely serendipitous but flowed from novel applications of technology; they are also attributable to the penetrating power of centimeter and meter waves to reveal phenomena and objects in the Universe that would otherwise be hidden, and to Nature's propensity to generate radio waves almost everywhere. Moreover, telescopes in these bands can be designed with extraordinary capabilities—large imaging fields of view, polarization measurement, high spatial and spectral resolutions, and high sensitivity. Using recent and emerging technology, all of these attributes may be achieved simultaneously. Although the precise range of wavelengths has not yet been determined, the SKA will eventually produce images and other data over wavelengths from ∼4.3 m (70 MHz) to ∼1 cm (30 GHz).

Of exceptional scientific significance in radio astronomy are: the ability to utilize optically thin spectral lines as tracers of many non stellar components of the universe, especially the fundamentally important 21-cm spectral line of hydrogen, the most abundant element; the ability to probe physics in extreme environments, such as by high-precision timing of the arrival times of pulses from radio pulsars; the exploitation of astrophysical masers found in the spectral lines of molecules; the sensing of magnetic fields in the Universe; and the tracing of almost ubiquitous interaction of high-energy electrons with magnetic fields to produce synchrotron radiation in stars, galaxies, and clusters of galaxies.

In order to make progress in modern astronomy, the SKA must be designed to observe these phenomena throughout the Universe. The expansion of the Universe both weakens the radiation and causes the wavelength of observation to be lengthened. The red-shift z is defined by $1 + z = \lambda_{\mathrm{observed}} / \lambda_{\mathrm{emitted}}$, where $\lambda_{\mathrm{observed}}$ is the wavelength measured by the observer and $\lambda_{\mathrm{emitted}}$ is the wavelength emitted by a distant object in the Universe. In the nearby Universe, the red-shift ("doppler") is given approximately by the Hubble law $z = v/c$, where v is the velocity of recession as the Universe expands and c is the speed of light. In the distant Universe, a similar but more complex relation takes into account the General Theory of Relativity.

The enormous capabilities of radio telescopes come at a price: radio emission in astrophysical situations is weak, and very sensitive telescopes are needed to carry out observations of the phenomena described above, particularly in the early Universe. To achieve the main science goals related to early Universe studies, the SKA will have to be much more sensitive than the current generation of radio telescopes in the centimeter and meter wave bands. These goals are fully described in the SKA science case [2]. What follows is a section on what new science is anticipated and how that translates into technical requirements; a section on potential design solutions; a section on important technical and cost challenges that must be met; and a section on how the project may proceed to make technology and design decisions. At this stage of the project, there is no direct route to a simple solution. Many different aspects must be considered in parallel and even iteratively.

II. DESIGN REQUIREMENTS AND MOTIVATION FOR NEW TECHNOLOGIES

The SKA will utilize radio-telescope design techniques developed over the past four to five decades. The most sophisticated concept, aperture synthesis [3], is an application of the Van Cittert–Zernike theorem [3, Ch. 14] and amounts to spatial, spectral, and temporal sampling of the incoming radio-radiation field so as to match the expected structure of the field in those three domains. In addition, careful attention must be paid to rejecting extraneous, man-made signals [radio-frequency interference (RFI)]. The manifestation of these concepts as a ground-based radio telescope requires an array of antennas and receivers covering a large area on the ground and configured so as to provide the required spatial sampling or telescope resolution. The signals from the antennas, including appropriately represented amplitude and phase, are cross-correlated in pairs and integrated to reduce noise. These data can be used to reconstruct the original brightness distribution, spectra at each point in the sky, and sometimes spectral and spatial variations with time.

For several decades, radio telescopes and telescope arrays have been limited to apertures of about 10^4 m² (with the exception of the Arecibo radio telescope, a large special-purpose radio telescope consisting of a single aperture whose resolution is very limited), constraining, for instance, studies of the 21-cm hydrogen emission from galaxies to the nearby universe ($z \approx 0.2$ [2]). Contemporaneous with the astronomical discoveries in the second half of the twentieth century have been technological developments that offer a path to substantial improvements in future radio astronomical measurements. Among the range of improvements are mass production of large centimeter-wavelength antennas, fiber optics for the transmission of large volumes of data, high-speed digital signal processing hardware for the analysis of the signals, and computational improvements leading to massive processing and storage.

These new technologies, enabling dramatically improved survey speeds and other advances, can open up an enormous volume of discovery space, providing access to many new celestial phenomena and structures, including three-dimensional mapping of the web of hydrogen gas through much of cosmic history ($z \sim 2$).

The detailed technical design requirements for the SKA must be derived from its science goals but constrained by other aspects of design, such as feasibility and cost. This is a complex problem with no unique solution. Indispensible to the overall science case [2] are five key science projects (KSPs); each KSP represents an unanswered question in fundamental physics or astrophysics and is either science unique to the SKA or for which the SKA plays a key role. The SKA approach is to distill the science case into a design reference mission (DRM) [4], including the KSPs. In a formal engineering sense, this is part of system validation. (Are we building the right system?) It is impossible to specify scientific performance succinctly as a model or formula; thus it must be done as a series of carefully selected, minimum set of case studies. The case studies must be constructed so as to yield actual numbers for key system performance indicators (e.g., system noise, dynamic range, spatial frequency coverage, etc.), cover the entire range of parameter space needed for the SKA and take into account science priorities. This process does not imply that the telescope is designed or optimized to carry out these observations alone.

The utilization of new technologies is the enabling factor needed to realize the science specifications embodied by the DRM (i.e., to build a more capable telescope at much lower cost). But clearly there are still cost/performance tradeoffs. The DRM cannot be regarded as immutable—science priorities will have to be adjusted in the face of evolving astronomy knowledge and cost pressures, and the DRM modified accordingly. Cost is a major factor forcing the SKA project towards new technologies and architectures. The overall target budget is 1500 million euros (2007). Reaching this target will require aggressive manufacturing optimization and, most importantly, pushing the system design to capture functionality/cost gains in data transmission, signal processing, computing, power consumption, and related technologies.

Coverage of observation parameter space in the DRM is critical. If there are gaps in the coverage of the DRM, those gaps are likely to show up in the actual design. The case studies are a series of mock surveys and observations sufficient to define the "envelope" of technical specifications. These envelope specifications jointly represent what has to be built to accomplish the most difficult key science. Two important case studies from the DRM are described below as examples of the input to the detailed specification process.

1) Wide-Area Survey: Survey a large fraction of the sky ($> 50\%$) available to the SKA with the goals of 1) detecting the HI-line from galaxies out to a red-shift of at least unity (half the age of the Universe) and using them to trace galaxy evolution and as a cosmological probe; 2) detecting a large fraction of observable pulsars in the Milky Way, in particular millisecond pulsars, with the objective of using them to study gravitational waves; and 3) constructing a large-scale Faraday rotation-measure grid in order to trace magnetic fields in regions of thermal and non-thermal emission.

2) Galactic Center: Detect radio pulsars near the central supermassive black hole in the Milky Way Galaxy and measure the arrival times of their pulses in order to probe the space–time environment of this supermassive black hole.

There is a danger that any set of case studies will cause loss of generality in the design of the telescope. The overall goals of the SKA are based on a philosophy, which has proven effective for current large radio facilities, to provide astronomers with powerful and flexible instruments for research into all astrophysical phenomena that emit radio waves. This statement of generality has been described as a particular science goal, "exploration of the unknown." This aspect of the design process counteracts the tendency to assume that the telescope is being designed only to carry out the DRM case studies. At the same time, the flexibility inherent in the marriage of radio engineering and new signal-processing techniques offers unprecedented opportunities in making "experiment-like" system configurations available, often to multiple simultaneous users. History shows that discovery science often flows from such instruments. The final choice of major design parameters will balance flexibility with the need to accomplish key science goals, constrained by cost and feasibility.

A. Technical Performance

The translation of the DRM into technical requirements yields a small number of performance indicators, which guide the design and motivates the development of new technologies. Table 1, adapted from [5], contains the list of KSPs alongside the performance indicators required for each one. Table 1 contains desirable specifications and will eventually be refined in a confrontation with feasibility and cost.

1) Wavelength Coverage: As shown in Table 1, the SKA must cover wavelengths from about 1 cm (30 GHz) to 4.3 m (70 MHz), more than two orders of magnitude. This cannot be managed with a single antenna technology when the sensitivity and efficiency requirements of the SKA are also considered. Moreover, as discussed further in Section IV-B and H, the site requirements at the extremes of this frequency range, combined with antenna cost considerations, indicate that an additional site for wavelengths shorter than $\sim$3 cm (10 GHz) may be needed.

2) Staring Sensitivity: This is the sensitivity of the telescope when pointed at a single direction on the sky. It is the best measure of sensitivity when the angular extent of

Table 1 Science-Based Specifications for the SKA

Description of Key Science Project		Frequency Range (GHz)	FoV	Sensitivity	Survey Speed	Resn.	Baseline	Dyn. Range Driver	Poln. Driver
		.1 0.3 1.0 3.0 10 30	deg²	m²/K	deg²m⁴K⁻²	mas*	Km		
1	**The Dark Ages**								
1a	EoR				$>\sim 3 \times 10^7$		10	√	√
1b	First Metals		0.003	15,000		50	125		
1c	First Galaxies & BHs			20,000		10	4500	√	√
2	**Galaxy Evolution, Cosmology & Dark Energy**								
2a	Dark Energy				6×10^9		5		
2b	Galaxy Evolution			20,000	1×10^9		10		
2c	Local Cosmic Web				2×10^7		0.5		
3	**Cosmic Magnetism**								
3a	Rotation Measure Sky				2×10^8		10-30		√
3b	Cosmic Web				1×10^8		5		√
4	**GR using Pulsars & Black Holes**								
	Search				1×10^8		< 1		
4a	Gravitational Waves		-	>15,000		1	200		√
4b	BH Spin		1	10,000			-		√
4c	Theories of Gravity			>15,000		1	200		√
5	**Cradle of Life**								
5a	Proto-planetary Disks		0.003	10,000		2	1000		
5b	Prebiotic Molecules		0.5-1	10,000		100	60		
5c	SETI		1						
6	**Exploration of the Unknown**		Large	Large	Large				

*milli-arcseconds of angular resolution

the radio emitting region is smaller than the instantaneous field of view (FoV) of the telescope, typically defined by the solid angle Ω over which the sensitivity of the antennas is greater than 0.5 of the maximum sensitivity. The strength of the weakest, unresolved (point-like) source that can be detected in a given observing time is proportional to T_{sys}/A_e, where T_{sys} is the system noise temperature at the terminals of each antenna and A_e is the sum of the effective areas of all antennas [3]. Telescope sensitivity is proportional to the inverse of this quantity A_e/T_{sys}. For the SKA, this must be at least 10^4 m²/K to meet the science objectives. The observing time required to detect such a source within the telescope's FoV is proportional to $(T_{sys}/A_e)^2$. The effective area is the physical area multiplied by an efficiency factor less than one. For a parabolic reflector antenna, the theoretically achievable area is the physical area. As a comparison, the staring sensitivity of the Expanded Very Large Array (EVLA) will be ~ 270 m²/K.

3) Survey Speed: The rate at which an area of sky much larger than the FoV can be surveyed for unresolved sources stronger than a specified limit is proportional to the ratio of Ω to the time required to detect a point-source of specified strength $(A_e/T_{sys})^2 \Omega$. This is called the survey speed figure of merit (SSFoM) [5], and for the SKA this must be at least 3×10^9 deg² m⁴ K⁻² at wavelengths longer than about 20 cm. In practice, the FoV may also be limited by the rate at which data from a large area of sky can be transmitted and processed (Section IV). Survey speed has not historically been a design requirement for most radio telescopes.

4) Array Configuration: This is the pattern of antennas on the ground, which in turn determines the range of spatial frequencies that the array can sample (see the Van Cittert–Zernike theorem). Pairs of antennas are used in interferometer mode: close pairs sample low spatial frequencies or coarse structure; distant pairs sample high spatial

frequencies or fine structure. Some of the science targets, such as the study of radio emission from the first galaxies, require very high angular resolution (potentially as high as several milliarcseconds). Simple Fourier analysis indicates sampling with a two-dimensional configuration of antennas spanning $> 10^7$ wavelengths or distances of 2000–3000 km are required at a wavelength of 20 cm. In contrast, there are other science targets, such as galaxies containing atomic hydrogen, that require the highest sensitivity to objects that are 10 arcsec in size; thus it is also important to locate the antennas within a 10 km radius. In these latter observations, antennas located at thousands of kilometers from the center are not only insensitive to these spatial frequencies; if included, they add unnecessary noise to the images. The Very Large Array [6] addresses this problem on a smaller scale (35 km) by using transportable antennas. However, the SKA, which will need thousands of antennas to achieve the sensitivity requirements, is unlikely to be able to use this method, though a restricted version of this solution has not yet been ruled out. A provisional distribution of collecting area in the array configuration [5] is the following: 50% 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. Fig. 1 shows a schematic configuration with a
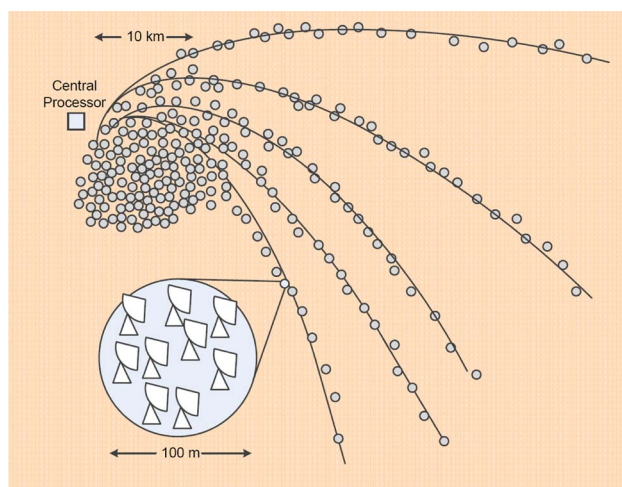

Fig. 1. *A schematic representation of an SKA array configuration. Each dot represents a cluster of antennas, shown clustered for local access to communications infrastructure, which will run along the lines shown. The full array configuration will continue a quasi self-similar pattern out to ~1000 km. Beyond that scale the number of antennas will be very small. The dense group of antennas (the core) at the upper left provides for a very dense pattern of baselines between pairs of antennas, an important aspect of the configuration needed obtain sensitivity to extended radio emission. Although not shown, a similar array of low and high frequency Aperture Arrays (Section III) would be placed next to the dish core. At large distances from the centers the placement of both dishes and AAs would overlap to facilitate data transport.*

condensed central core and with the density of antennas progressively reduced with distance from the core.

5) Bandwidth: The bandwidth affects two aspects of the telescope's performance. First, for continuum (broadband) sources, the instantaneous bandwidth that can be accessed and processed affects the final sensitivity as $B^{1/2}$, where B is the processed bandwidth [3]. Secondly, for spectral-line observations, such as of the HI line, the band must be broken into narrow spectral channels, and the sensitivity is determined by how narrow the channels must be to characterize the shape of the spectral lines. In this case, the overall bandwidth affects how large a range in red-shift can be observed instantaneously. The required number of spectral channels is the ratio of the overall bandwidth to the channel bandwidth. For other spectral-line observations, such as of the transitions of complex organic molecules, the instantaneous bandwidth affects how many lines can be studied and the efficiency of searching for new lines. As an example of this possibility, at the lower end of its tuning range, the EVLA will soon deliver octave bandwidths at center frequencies from 1.5–6 GHz with at least 16 000 channels across the band in each of two polarizations.

6) Imaging and Spectral Dynamic Range: Imaging dynamic range is the ratio of the brightest point in an image to the root mean square fluctuations in a region of the image devoid of real emission. These fluctuations could be from a combination of system noise, instrumental artifacts, scattered radiation, or systematic errors that limit the detection of weak emission. The SKA not only will require high sensitivity to detect weak radio sources; it must do so in the presence of relatively strong sources, which will also be present in the FoV. A statistical analysis of radio sources at a wavelength of 20 cm indicates that, in each square degree of sky, there will be, on average, one 80 mJy source, while the target imaging noise level, random fluctuations in the image, for long integrations (staring times) will be at least 106 times smaller. Calibration errors in the instrument are one mechanism by which the signal from a strong source can obscure a weak source, so achieving high dynamic range corresponds to achieving accurate calibration (see Section IV-E). Thus the imaging dynamic range requirements can be translated into a specification for postimaging calibration accuracy.

Measuring the polarized component of the received emission, important for tracing magnetic fields, is especially challenging because that component is typically a small fraction of the total intensity and because accurate calibration of instrumental polarization is difficult. Table 1 (Poln. Driver) shows the KSPs that require highly accurate polarization measurements.

A related specification concerns spectral imaging dynamic range in which the spectral-lines of atoms or molecules are observed across the FoV. In this case, strong

sources in the sidelobes of the antennas, which change shape slightly with wavelength, can contaminate the image. However, this effect will be much smaller than those described above.

High dynamic range is also needed in the frequency domain (spectral dynamic range) in order to detect weak emission in the presence of a strong but narrow-bandwidth signal, often RFI, elsewhere in the processed band. The achievable spectroscopic dynamic range is usually limited by nonlinearities in the signal processing.

7) Pulsar Capabilities: The SKA science case also has a high priority on using radio pulsars to probe fundamental physics, such as theories of gravity. For these observations, the spatial frequency coverage of the array is unimportant because pulsars are small enough and remote enough that they appear as point sources. However, what is required is to collect the voltages from the individual antennas, put in the appropriate delays, and add them to produce an effective aperture equivalent to their total collecting area. Time-gated averaging and removal of dispersion can be provided by postprocessing the array data.

8) Time Resolution: Until recently, it has been thought that the Universe is fairly static or at least predictable on human time-scales. But in the last few years, various irregular radio transients have been observed. These include stellar flares, giant pulses from the Crab Nebula, variations in flux density due to "multipath interference" as radio emission from unresolved objects transits the magnetoionic medium between the stars, and pulses of unknown origin [7]. With its high instantaneous sensitivity, the SKA is uniquely placed to investigate the radio transient parameter space. There is no numerical specification for this, since the parameter space is mostly open for exploration over many orders of magnitude.

III. DESIGN SOLUTIONS

The technical performance described above requires not only a telescope with a far larger number of antennas than today's most powerful radio telescopes but also solutions that were not available to the designers of these telescopes. The improvement derives largely from advances in the computing industry, the availability of advanced semiconductor processes for analog circuits, and the transportation of large volumes of data over optical fibers. These advances may enable the use of known but previously impractical designs for antennas, such as arrays of huge numbers of small antennas.

Fig. 2 shows the design solutions being considered for each wavelength range from 3 m to 3 cm. Fig. 3 is a system
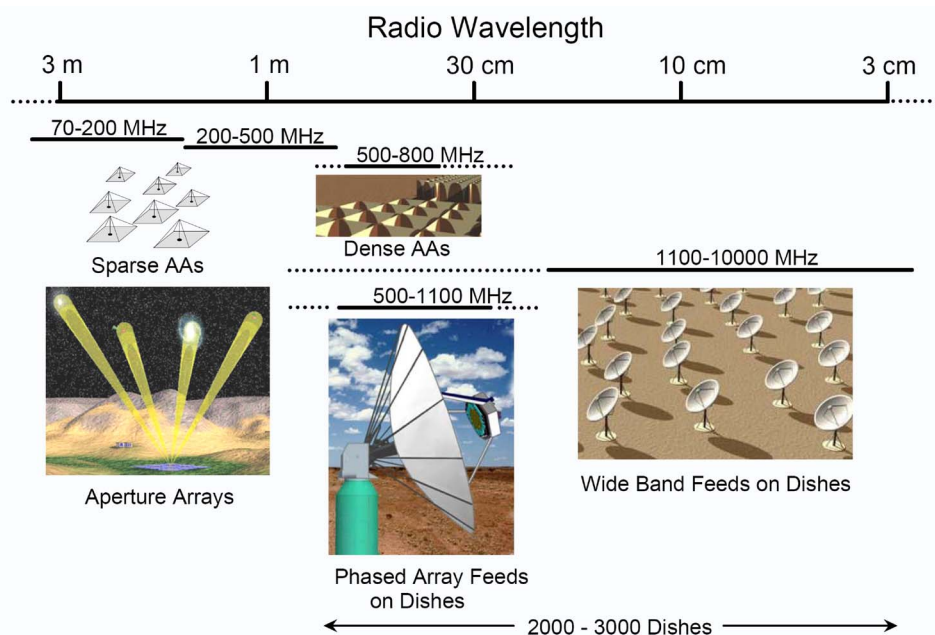

Fig. 2. *Design solutions being considered for the SKA in wavelength ranges from 3 m to 3 cm. The bars under the wavelength axis denote ranges over which four sensor technologies will be used. In order of decreasing wavelength, the design solutions are: sparse Aperture Arrays (AAs), dense AAs, parabolic reflectors with Phased Array Feeds (PAFs), and reflectors with Single Pixel Feeds (SPFs). The dotted lines indicate where technology choices may have to be made, or could co-exist. The graphic at the lower left shows the capability of AAs to form multiple simultaneous beams; above this graphic, sparse AAs are depicted on the left and dense AAs on the right, composed in this case of Vivaldi antennas. The middle diagram shows a parabolic reflector with a PAF at its focus. The right diagram shows an array of parabolic reflectors with SPFs at their foci. The reflectors could have both SPFs and PAFs, each covering a different frequency range.*
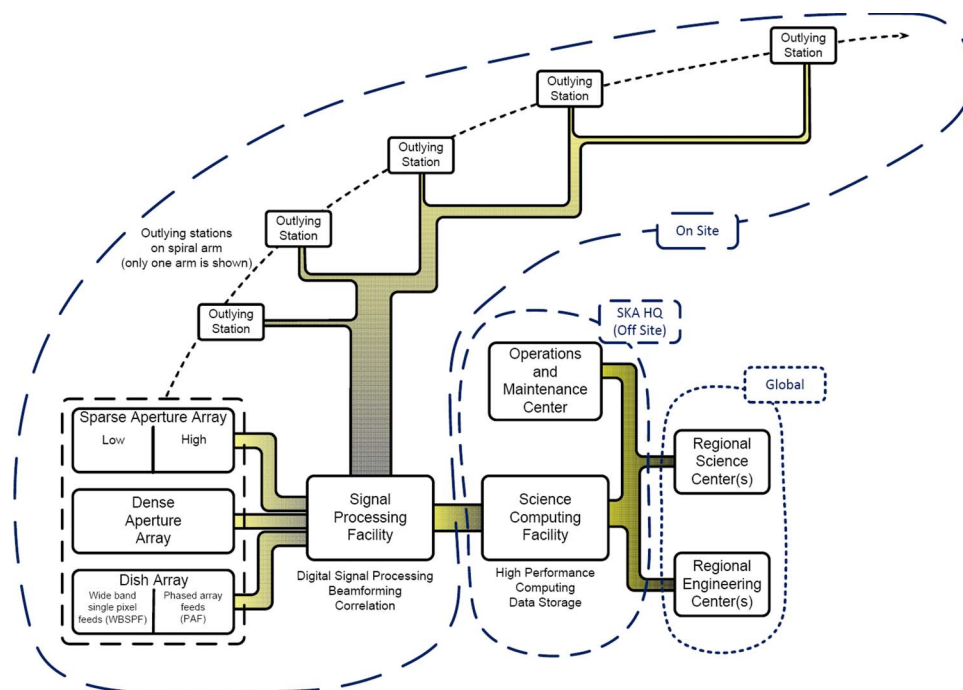
Fig. 3. *A conceptual block diagram for the SKA, showing the interconnection of major components, the location of major parts and the flow of data from the antennas (top and left) to the signal processing facility, and off-site to a computer facility. Control interconnections between the Operations and Maintenance Center and the on-site components are not shown.*

block diagram showing the interconnections and major components of the SKA. The base design solution includes large parabolic reflectors many wavelengths across (electrically large), with a dual polarization feed at the prime or secondary focus of each reflector. In SKA parlance, these are called "single-pixel feeds" (SPFs) because the field of view is determined by the (3 dB) primary power pattern set by the antenna diameter. Such antenna systems are very well developed for radio astronomy and industry [6]. In the SKA, they will be used at wavelengths shorter than 20 cm, where a high survey speed has not been shown to be scientifically compelling.

At wavelengths longer than ∼20 cm, a key specification is the survey speed and favors antenna designs with large instantaneous FoVs. Most radio telescopes for decimeter wavelengths have used parabolic reflectors with SPFs and thus have small fields-of-view, in proportion to $(\lambda/d)^2$, where d is the diameter of the antenna and λ is the wavelength. Electrically small antennas (a fractional wavelength in size) have small collecting area but very large fields-of-view (i.e., their antenna patterns are very broad). These can be used as elements of phased arrays [8], known as aperture arrays (AAs). In AAs, electronic beamformers perform the function of compensating for the geometrical delays of the signals from the array of elements and summing the signals to form a single output. The geometrical delay compensates for the delay between when the wave front strikes the first element of the array

and when it strikes a given element. It also determines the direction of maximum sensitivity (beam direction). Beam sizes formed by AAs and dishes of the same diameters are approximately the same. However, multiple beams can be formed simultaneously from all or a subset of elements in an aperture array using a beamformer for each beam. In this way aggregate fields-of-view of hundreds of degrees squared are potentially accessible [5]. In SKA design parlance, the phased arrays are known as dense aperture arrays (dense AAs) if the spacing of the elements within the AA is no more than one-half a wavelength at the shortest wavelength of operation; the area of dense AA used to form a single beam is known as an AA-patch. Dense AAs fully sample the spatial structure of the incoming wave front. However, to achieve a useful sensitivity with subwavelength-size elements, a large number may be needed. For example, at 30 cm wavelength and with a system noise temperature of 50 K, more than 22×10^6 elements are needed for each polarization to reach 10 000 m^2/K (Table 1).

Another means of expanding the FoV with multiple beams is to use phased arrays at the foci of parabolic reflectors to expand the single-pixel FoV. This FoV will be smaller than can be produced by an AA. In this concept, the weighted sums of electrically small antennas within a dense phased array at the focus forms a cluster of overlapping, off-axis beams to feed the reflector. With currently practical hardware, a 10×10 array of overlapping beams can be formed, increasing the field-of-view by a

factor of about 30 relative to an SPF. In SKA design parlance, this type of focal plane array is known as a phased-array feed (PAF) [9]. A second technique for expanding the FoV is also available—a cluster of standard feeds at the focus instead of a PAF. The disadvantages of this method for the SKA are discussed in [9]. It can be shown that within limits the total FoV can be set by the size of the PAF independently from the antenna diameter. The radius of the PAF from the axis of symmetry of the paraboloid determines the radius of the FoV. This is entirely geometric and independent of wavelength, in contrast to dishes with SPFs and AAs, where the radius of the FoV increases with λ for a given dish or AA diameter. Thus the total FoV and the number of dishes, which would otherwise be linked to dish diameter, can be chosen separately in the design of a synthesis telescope of given collecting area. One attraction of this approach is that a wide FoV, and high survey speed, may be obtainable with relatively few dishes, simplifying cross-correlation and postprocessing. With correlation load scaling as the square of the number of antennas, the PAF approach in which the correlator complexity scales only linearly with total FoV is conceptually attractive (Section IV-D). This is an example of the need to consider carefully the way receiver chains—the total number of which define the telescope FoV almost independently of SKA receptor concept—are interconnected and processed; see, for example, [10] and [30].

At wavelengths longer than ~1 m, it becomes possible to utilize sparse aperture arrays—electrically small antennas spaced much more widely than a half-wavelength. Again, the outputs of individual antennas are summed after correction for geometrical delay. At these wavelengths, even electrically small antennas have significant collecting area ($A_e \approx 0.12\lambda^2$), which is important because T_{sys} is dominated by irreducible noise emanating from the sky itself at long wavelengths; thus the principal route to improving A_e/T_{sys} is through larger A_e. In contrast to the shorter wavelengths at which dense AAs are proposed, a much smaller array of such antennas can provide sufficient sensitivity. This concept is being implemented in the Low-Frequency Array (LOFAR) being constructed in Europe; the Murchison Wide-Field Array (MWA), which is being constructed in Australia; and the Long Wavelength Array (LWA), which is in the prototype phase in New Mexico. Sparse aperture arrays made from elemental antennas fundamentally undersample the spatial structure of the incoming radiation field, resulting in a complex but predictable pattern of sidelobes at significant distances from the main beam. Knowledge of the positions and intensities of bright sources over the whole sky can be used to mitigate the effects of undersampling at the cost of additional data processing.

As noted above, a characteristic of AAs is that the elements have very broad antenna beams (i.e., sensitive to signals from most directions). Very strong signals, such as RFI, must be propagated through the amplifiers and the beamformer without significant distortion before finally being summed where these signals will be suppressed by destructive interference. This is a substantial challenge for very low-cost low-power receiver chains.

In summary, Fig. 2 shows the suite of design solutions available to the SKA as a function of frequency. At the lowest frequencies, sparse AAs are the most practical solution. It is likely that two different arrays of antennas will be needed to cover the frequency range up to ~500 MHz. From ~500 to ~1000 MHz, there are three possibilities: dense AAs, parabolic antennas with PAFs, and parabolic antennas with SPFs. From ~1000 MHz to 10 GHz, parabolic antennas with SPFs are chosen. The range of wavelengths shown for each potential design solution is unclear because at the time of writing, sufficient evidence for making a final technology selection has still to emerge from SKA development work. For example, SPFs could even be used as low as ~300 MHz. Thus a set of possible design solutions is suggested that will be increasingly powerful but take on successively increased allocation of technical risk. These risks and other design challenges will be elucidated in the next section and will lead to the outline of a plan on how the SKA design will proceed.

IV. TECHNICAL CHALLENGES

A. System Noise

As noted above, both the staring sensitivity and the survey speed are proportional to (A_e/T_{sys}) and $(A_e/T_{sys})^2$, respectively. Since the birth of radio astronomy, the capabilities of radio telescopes have increased dramatically, with a factor of ten improvement every ten years [11]. This is almost entirely due to improvements in system noise made in existing telescopes, particularly the noise component generated in the first amplifier connected to each antenna in the telescope, the low-noise amplifier (LNA). To achieve this performance, LNAs are cryogenically cooled to 10–20 K. Because receiver systems using this technology are large, complex, and expensive, it makes sense to use as few as possible per unit collecting area, consistent with other constraints in the design of a telescope. At wavelengths around 30 cm, LNAs operating at 300K (room temperature) are showing sufficient promise that they might in future tip the balance in favor of uncooled amplifiers at the longer wavelength end of the SKA frequency range.

The successful utilization of the AA design solutions instead of SPFs clearly implies that the increased Ω factor in the SSFoM $(A_e/T_{sys})^2\Omega$ is sufficient to compensate for the potentially higher T_{sys} that will result because AAs cannot use cryogenically cooled receivers at frequencies where the LNA noise dominates system noise. This assumes similar costs of aperture in both cases. A similar argument applies to PAFs. Thus a threshold of performance/cost ratio (SSFoM/unit cost) must be crossed before it makes sense to

use either FoV expansion technology. Because the actual cost per unit area of AAs and PAFs is potentially higher than for SPFs, improving T_{sys} for room-temperature receivers appears to be the most likely means of successfully utilizing AAs and PAFs.

Because in AA designs the LNAs are evenly distributed over the entire aperture, there is only one LNA design option available: the development of room-temperature LNAs with sufficiently low noise. At room temperatures in a band from 700–1400 MHz, it is now possible to reach noise temperatures < 20 K at the input connector of LNAs "on the bench" [12]. There is more design flexibility for PAF designs—the more limited number of spatially concentrated LNAs (i.e., in the focal region of reflectors) opens the possibility of practical cryocooling. Thus there are two LNA design options available: a) room-temperature LNAs and b) LNAs that are sufficiently cooled to cross the noise threshold noted above. For option b), note also that LNA noise improves monotonically with decreasing ambient physical temperature—significant improvement can be obtained at physical temperatures of $\sim10^2$ K [13].

A limiting factor in the current best LNA-feed combinations is their wavelength coverage—the best receivers cover a ratio of $\sim2:1$ between the shortest and longest wavelengths. For the SKA, this implies a need for about five LNA/feed combinations on each reflector. Very wide-band feeds are being adapted for the SKA, and a feed for Allen Telescope Array antennas has been developed that covers a wavelength ratio of $15:1$ [14]. If the wide-band designs are able to maintain very low noise over similar bandwidth ratios, it will represent a major improvement in the cost of reflector-based solutions for the SKA.

A common design theme for achieving low noise and high bandwidth ratio is the need to design the LNA and the antenna as an optimized integrated unit. This applies to SPFs for reflectors as well as to AAs and PAFs. This is a practical design and measurement challenge. Typically, LNAs are designed for standardized input impedances by people with different skills from those who design antennas and feeds. For AAs and PAFs, another design parameter is the noise coupled between adjacent antenna elements. Also, special measurement techniques, such as that depicted in Fig. 4, must be adopted to measure and compare the noise performance of integrated units that are difficult to measure separately [15].

At wavelengths longer than ~1 m, noise from the "sky" begins to dominate system noise increasingly with wavelength. At these wavelengths, LNAs operating at room temperature (~300 K) are suitable for the SKA. Although they may be needed in large numbers, they are very inexpensive to fabricate.

B. Antennas and Collecting Area

The design of the SKA will be strongly influenced by the reduction of LNA noise in radio telescopes, to the point where further (dramatic) reduction seems unlikely. The

Fig. 4. *A device constructed by ASTRON [15] for measuring noise from an antenna/LNA combination, which is placed at the bottom of the inverted pyramid (right). The metallic sides reflect all radiation towards the "cold" sky, which is used as a low-temperature reference. The cover (left) can be slid over the top of the device. It contains absorber at ambient temperature to act as a high temperature reference. Using these known reference radiation temperatures, noise properties of the antenna/LNA combination can be derived.*

SKA science goals require orders of magnitude more sensitivity than existing telescopes will be able to deliver. Thus the only way to increase the sensitivity is to increase the total A_e (ηA), where η is the aperture efficiency. Since efficiencies of existing telescopes are typically greater than 0.5, there is little scope for large efficiency improvements, but efficiency must be maintained in new designs. In the case of AAs, the efficiency subsumes a factor for average "foreshortening loss," a $\cos(Z)$ factor, where Z is the zenith angle of the pointing direction. Greater AA collecting area must be built to compensate for this factor.

Electrically large parabolic reflectors are the only design solutions available for wavelengths shorter than ~20 cm, although they also work at much longer wavelengths. Prime-focus versions of these antennas can maintain high efficiency at diameters greater than $\sim10\lambda$. The FoV of a reflector antenna is proportional to $(\lambda/d)^2$ steradians (increasing with wavelength).

The design of the appropriate SKA reflector antennas is a complex, constrained cost balance. The constraints are as follows.

a) The total collecting area must be sufficient to meet the sensitivity specification of 10^4 m^2/K (using the lower end of the sensitivities listed in Table 1). Using an estimate for T_{sys} of 40 K and an aperture efficiency of 0.7 yields a total collecting area of $\sim5.7 \times 10^5$ m^2.

b) The diameter cannot be smaller than $\sim10\lambda_{max}$, where λ_{max} is the maximum wavelength at which we think reflector technology will be useful. This wavelength will be determined by the relative success of AA technology but is unlikely to be larger than 1 m.

c) The shortest wavelength of operation is < 3 cm (> 10 GHz).

With cost pressures extreme, and much of the SKA key science achievable below 10 GHz, this judgment has been made after several years of engineering and astronomy

interchange. A contributing factor in the judgment is that, although the overall goals of the SKA are to reach wavelengths of less than 1 cm, it is not clear that telescope sites chosen to emphasize minimum RFI for long wavelengths have sufficiently benign troposphere, especially in terms of system noise loading, to use at shorter wavelengths [16]. Taking all constraints into account, a preliminary investigation of this optimization problem has led to an estimate of 2000–3000 15-m-diameter antennas [5].

One of the largest challenges for the SKA will be to build these antennas at an affordable cost. The current small market for large reflector antennas provides little incentive to emphasize production techniques for thousands of antennas. The traditional design of large radio reflectors utilizes a steel or aluminum space-frame structure that supports numerous adjustable reflector panels. While this can deliver the required SKA performance, the production, installation, and maintenance costs are a high barrier. Developments exploiting new materials and mold-based production technologies offer substantial cost reductions for volume fabrication of reflectors. The mold-based methods permit the repeatable fabrication of reflectors. The cost of a large accurate mold is amortized over many pieces. In addition, a reflector can consist of one or a few large pieces that can be field-installed with no adjustments. Mold-based reflectors can be made of metal or composite materials. Some composite materials offer weight and stiffness advantages as well as near-zero coefficient of thermal expansion. There is almost no dependence on the desired shape—offset or shaped reflectors are similar to symmetrical shapes [17]. Molded metal antennas offer the advantage that little care is needed to protect them from sunlight, whereas composite materials must be protected by a ultraviolet resistant layer. Although the comparative costs of these two new technologies have not yet been fully assessed, it is clear that either fabrication method offers an almost flat cost-wavelength curve for the reflector to 3-cm wavelength. It must be noted that reflectors are only one part of reflector antenna design. Volume production techniques will have to be adopted for mounts, towers, and foundations as well.

A similar challenge applies to the production of AAs, where there is also great scope for volume production techniques of the millions of elemental antennas and receiver chains. For example, techniques for "printing" rows of antennas are being developed [18], and presumably robotic assembly techniques will be used for the distributed active components in the AAs.

Because there are many exposed active components in AAs, a unique challenge is protection against destructive electromagnetic pulses induced by nearby lightning. This will require designing and testing a lightning protection system for the entire array area.

As noted in the previous section, a particular challenge for AAs and PAFs is to actually realize an improvement in survey speed at a competitive cost.

C. Data Transmission

The design of the SKA as envisaged in any of its forms would be impossible without the advances in data transmission brought about by optical fiber transmission technology. Nevertheless, data transmission will limit SKA performance, in particular the usable FoV of antennas at long distances from the array center (long baselines). Fortunately, it is not a high scientific priority to image a large instantaneous FoV (e.g., tens of degrees squared) with high resolution (e.g., < 1 arcsec). The data rate R entering the central correlator and the distances of transmission are the driving cost factors. In the simplest case where identical antennas are correlated throughout the SKA, $R \propto BNn_{\text{beam}}$, where B is the total instantaneous bandwidth from each correlated antenna in the same units as R, N is the number of antennas and n_{beam} is the number of beams within the FoV. Noting that the solid angle of the beam of an individual antenna or dense phased array collecting area is proportional to λ^2/A_e and $n_{\text{beam}} \propto (A_{\text{tot}}/N\lambda^2)\Omega$, then $R \propto BA_{\text{tot}}\Omega/\lambda^2$, where A_e is the effective collecting area of an antenna, A_{tot} is the total effective collecting area of the telescope, and Ω is the instantaneous FoV. This proportionality does not depend on the aperture technology (i.e., SPFs, AAs, or PAFs). For AAs and PAFs, Ω is an independent design parameter and can be limited to less than the available FoV defined by the antenna design, should that be necessary to reduce cost. For SPFs, $\Omega \propto (\lambda/d)^2$ and R is invariant with λ.

The distances of transmission depend on the configuration of antennas on the ground. From a practical perspective, different distance regimes will require different data transmission technology and have different associated costs. The range of distances will be from ~ 30 to at least 3×10^6 m. For distances up to a few kilometers, analog optical transmission will be less expensive than digital, but the performance of analog systems remains to be fully established. The data transmitted over distances longer than a few kilometers will be in digital form. Clearly, the cost will also depend directly on the number of bits used to encode each sample. In the complete absence of interfering signals, radio astronomy can be done with 2 bits per sample with only a small impact on performance. However, even in the radio-quiet sites selected for the SKA, at least 4 bits per sample will likely be needed because of RFI from air and space-borne sources.

Data rates for maximum bandwidth, FoV, and collecting area are: SPFs with 8 GHz of bandwidth in each of two polarizations will produce 160 Gbits/s from each dish (assuming 25% encoding overhead) or, for an array of 3000 dishes [5], a total of 480 Tbits/s entering the correlator. PAFs with 700 MHz bandwidth per polarization in each of 30 beams will produce a total of 840 Tbits/s for an array 2000 dishes [5]. An array of 250 AA-patches covering an FoV of 250 deg^2 with 700 MHz bandwidth will produce a total of ~ 4.1 Pbits/s of data. The cost of these very high

data rates is likely to limit bandwidth, FoV, or collecting area in practice.

D. Digital Signal Processing

Digital signal processing traditionally encompasses operations on the data from digitization to the point where correlated results (or in the case of pulsar observations, summed data; see Section II-A7) are written on general-purpose computer storage devices. For an SKA design consisting of SPFs, the correlator is the main data processing unit. Although this will be a very large data processor, it may not cost more than a small fraction of the total cost of the SKA [19].

AAs and PAFs require a beamforming operation, a weighted sum of the signals from individual or small groups of elemental antennas, resulting in a single data stream. AAs also require the insertion of delays in the signal path from each input to compensate for geometrical delay. In the case of AAs, the weights are used to form and steer the telescope beam, whereas for PAFs, the weights are used to form beams that are displaced from the optical axis of the dish. For PAFs, the weights will be a function of frequency within the observing band [20]. Thus it will be necessary to use digital filtering techniques to split these signals into a number of frequency channels before summing them. The filtering is efficiently done using a fast Fourier transform like operation called polyphase filtering [21]. Because the presummed data rate is very large, it is important to minimize the number of channels needed at this stage.

An aperture synthesis correlator cross-correlates the streams of data from pairs of antennas in the array. Each correlation consists of a multiply–accumulate (MAC) operation in which the accumulation component averages the product for a predetermined time. Before correlation, the data streams must also be corrected for geometrical delay and are digitally filtered into frequency channels. As explained in Section II-A5, the width of the channels is determined by the science program.

The size of a large correlator is approximately proportional to the rate of MAC operations N_{op}. $N_{op} \propto N_{apt}^2 N_{beam} N_{chan} B_{chan}$, where N_{apt} is the number of apertures (dishes or AA patches) in the array, N_{beam} is the number of beams required for each aperture to cover the required total FoV, N_{chan} is the number of frequency channels required, and B_{chan} is the bandwidth of each channel in samples per second.

It is useful to understand how the size of the correlator depends on the total collecting area A_{tot} and the total FoV Ω, which are factors appearing in the basic SKA parameters required by the science. For SPFs, $N_{beam} = 1$ because each dish can have only one beam. $N_{apt} \propto A_{tot}/d^2$ and $\Omega \propto (\lambda/d)^2$, where d is the diameter of the dish. Combining these two proportionalities yields $N_{apt} \propto \Omega(A_{tot}/\lambda^2)$, where Ω is the FoV of a dish, the total possible FoV using dishes with SPFs. The only way of increasing Ω for a fixed

A_{tot} is to decrease the dish size, which increases number of dishes and the size of the correlator. Note that the apparent λ^2 dependence disappears in the expression for N_{op} since $\Omega \propto \lambda^2$.

For AAs and PAFs, the total FoV Ω can be made up of a number of beams. $N_{beam} \propto \Omega/\Omega_{beam}$, where Ω_{beam} is the size of each beam. $\Omega_{beam} \propto (\lambda/d)^2 \propto \lambda^2 N_{apt}/A_{tot}$. For AAs, d is the diameter of an AA-patch and N_{apt} the number of patches. For PAFs, d is the diameter of the dish and N_{apt} is the number of dishes. Combining the two proportionalities, $N_{beam} \propto \Omega(A_{tot}/N_{apt}\lambda^2)$. Thus $N_{op} \propto N_{apt}\Omega(A_{tot}/\lambda^2)N_{chan}B_{chan}$. The number of AA-patches or PAF-equipped dishes can be chosen independently from the size of the specified total FoV. For example, by choosing large apertures, the size of the correlator can be reduced at the expense of requiring more beamforming equipment to supply data streams to the correlator. It is not yet apparent whether this trade is a good one. It depends on the relative cost of antennas, beamformers, and correlators.

The very high correlator-input data rates, arising from thousands of antennas potentially with enhanced fields-of-view and several gigahertz of input bandwidth, will require a large operations rate. Thus all of the digital signal processing described above will likely be carried out using special-purpose hardware. This will be needed to minimize power consumption, which could become a cost driver for the design or even a limiting factor in the size of the digital signal-processing systems.

E. Calibration, Image Formation, and Nonimaging Processing

Image formation and calibration operations are carried out using software running on general-purpose computers or supercomputers on data emanating from the correlator, from which the output data rate is significantly reduced compared with the input.

1) Image Formation and Calibration: The algorithms for image formation are a combination of 2-D gridding of data, Fourier transformation, deconvolution, and self-calibration. Wide-field imaging may require more steps or that these steps be carried out on subfields. These operations are carried out in a large iterative loop to reach an acceptable image, where the sidelobes of the synthesized beam and artifacts from inaccurate calibration are lower than the thermal noise level [22].

Self-calibration operates under the assumption that all system errors can be represented as complex gain changes in the signal path from the outer atmosphere to the correlator. This includes net amplifier gains, phases, polarization responses, and antenna response patterns, all of which will be functions of frequency and time, and some of which may be functions of direction on the sky. The radio telescope measurement equation parameterizes the perturbations of the signal as it traverses the path through the system [23]. The correlation measurements typically

contain enough information to solve for both the image and the parameters of the measurement equation simultaneously, assisted because the parameters change slowly. However, if the numbers of unknowns becomes too large, if variations in the unknowns are too rapid, or if the calibration measurements are too noisy, there will not be enough information in the measurements to yield robust estimates of the images. The SKA with very wide-field images will be more susceptible to these problems than present-day telescopes. Careful design will be required to ensure that as few system-wide parameters need be calibrated as possible.

The imaging task becomes enormous if the FoV to be processed is very large. Imaging a field much larger than the science FoV may be necessary if the antenna or beam-forming system cannot filter out signals, either from radio sources or radio interference, at large angular distances from the field center. Moreover, the interferometer data from sources that are outside this field may be undersampled. These problems can be solved if the system is linear and sufficiently stable, and the number of such signals is not large. A particular issue arises when the beam pattern rotates on the sky, as happens with AAs and with most designs of dishes. This imposes a quasi-predicable but rapid variation in the signals presented to the correlator from each antenna. Even if this effect is removed by post-processing, there will be residual errors that cannot be corrected. The SKA will have to cope with sources within the FoV that are $\sim 10^6$ times stronger than the thermal noise in images. This dynamic range specification will require care in specifying the accuracy of beamforming and control of antenna sidelobes. In fact this requirement will affect the specification of many of the subsystems directly in the signal path. The calibration techniques noted above will also have to recover direction-dependent gains due to uncalibrated changes in antenna beam patterns.

2) Nonimaging Processing: Searching for pulsars, especially millisecond pulsars, and carrying out sensitive timing analysis of pulsar signals is a key nonimaging SKA science requirement. Since neutron stars, the sources of pulsar signals, are point-like, making images is not the main scientific requirement. Currently, most pulsar observations are made with very large single reflectors rather than arrays of antennas. The SKA is attractive for pulsar observations because of its very large total collecting area, all of which can be pointed over most of the sky. The SKA will use beamforming techniques to form a number of dual polarized data-streams from weighted sums of the signals from antennas in the core of the array, after compensating for geometrical delays of the signals. These beams can be directed anywhere within the primary patterns of the antennas or just clustered together. Each beam is similar to what would be obtained with a single reflector of the same area as the antennas, except that the beam area is smaller in proportion to FF, where FF is the areal filling factor or the ratio of the total collecting area to the area occupied by the array. A small beam area is a disadvantage when searching the sky; thus it is advantageous to form a number of beams to increase the total area of sky being observed at one time. This is a relatively small cost compared to the total system cost. For pulsar timing observations, it may be possible to "time" more than one pulsar simultaneously using the electronically formed beams if the pulsars being timed are close enough to each other, as they might be in a globular cluster. Otherwise the array must be split into subarrays, each with its own beam.

The data-streams formed in the way described above are recorded on disks in most present-day pulsar observations and analyzed later using software running on super-computers, arrays of computers, or special-purpose hardware. Because of the very large data volumes attainable with the SKA, it will probably be necessary to build hardware that can do the computation in real time [24].

F. Scalability of Solutions

The SKA will be considerably larger than the largest radio astronomy project to date. Although such scaling is often proposed, many of the technologies and designs used in smaller radio telescope projects cannot be scaled to the SKA. Non-optimum use of resources is of little consequence in such projects, but they become major obstacles when scaled up. The most obvious examples are power, space, interconnection in signal-processing equipment and long-distance data transmission; the required computational performance, and the development and maintenance of software. The final SKA design will have to attain very high utilization of resources to reach fruition. This will require efficient architectures supported by the very latest electronics packaging, cooling, and interconnection technology.

G. Cost

The target budget for the SKA project, based on preliminary cost estimates, is 1500 million euros (2007). Of this, 1000 million euros are set aside for system, or hardware, costs. Software costs are estimated at a further 200 million, infrastructure at 200 million, and project delivery costs at 100 million euros. The latter includes larger scale nonrecoverable engineering costs (e.g., antenna manufacturing plant) and cost-loading for remote-area construction. The costing process is being refined continuously, with verifiable cost estimates being an aim of the PrepSKA program (Section V). Other radio telescopes have been designed with yet-to-mature technology and risk mitigation in the form of fallback options. However, the SKA is probably unique in scientific instrumentation in managing substantial risk across nearly all functional blocks. To derive cost estimates in such an environment requires both bottom-up estimates from better defined areas and top-down (parameterized) estimates, where the best information comes from initial demonstrators or industry trends. To distinguish as early as possible between competing technology implementations, a top-down

estimation tool *(SKAcost)* has been developed to investigate tradeoffs and design boundaries [25]. As detailed designs of subsystems emerge, bottom-up cost estimates will also be carried out, in parallel with improved system and infrastructure costs.

Over even a fraction of the lifetime of the SKA, operations cost as much as capital cost could limit its scope. Power costs are the most prominent example (Section IV-I), but there are too many other operational costs to list here. In general, careful planning will be required to maintain a system that is geographically distributed and is composed of a variety of new technologies.

H. Site and Infrastructure

The search for an SKA site began in 2003 with initial proposals from a number of countries to host the instrument. Following a detailed request for proposals in 2004, and consideration of comprehensive submissions from Argentina and Brazil, Australia, China, and South Africa, two candidate central sites were short-listed in 2006. One is in the Murchison area of Western Australia; the other in the Karoo region of South Africa. Representative SKA configurations are shown in [18] and [26]. Radio quietness was a prime selection criterion for site short-listing, and a one-year RFI monitoring program by site proponents was augmented by independent measurements by the ASTRON institute, acting under contract to, and in collaboration with, the SKA Program Development Office (SPDO, formerly the IPSO). Both wide-band (80 MHz–25 GHz) and sensitive (noise floor around -200 dBW m^{-2} Hz^{-1}) measurements were made, with broadcast signal peak levels being below about -150 dBW m^{-2} Hz^{-1}, and frequently much lower, in both short-listed locations. Both candidate central sites are very remote Southern Hemisphere places with low population densities, now and for the foreseeable future. Both are situated in areas of high ionospheric stability and have climatic water vapor characteristics supporting radio interferometer operation to at least 10 GHz [16]. Over the next two years more detailed site characterizations will be carried out, with a final site recommendation likely in 2011 and a decision in 2012.

Initial studies of SKA infrastructure requirements suggest that, while the isolation of the candidate sites poses major challenges, considerable experience exists in development of such locations, often in the context of natural resource exploitation. Challenges for the SKA include the provision of affordable power (Section IV-I), installation of a massive telescope optical fiber data network, access to national and international fiber backbones, and location of technical and staff facilities in remote areas. It is likely that the SKA will own all optical fibers within a few hundred kilometers of the central site, with more distant circuits being leased from telecommunications companies. Dedicated access to a number of telco fibers will be needed, but it is expected that the longest transnational and international links will be via commercial switched circuits. Both candidate sites support major SKA precursor telescopes and exemplar infrastructure development models, accounting for the growth in site needs [27]. It is expected that SKA infrastructure investment, including power provision and optical fiber trenching (but excluding terminal equipment), will be around 200 million euros in present-day currency. Studies by specialist engineering consultants over the next two years will look in more detail at costs, with more emphasis being placed on differentiating the two sites.

I. Power

Present estimates place the SKA power demand at 30–50 MW for the array proper, with a further 20–30 MW for supercomputing and associated facilities. While still quite uncertain, numbers such as these make it clear that power provision is a major challenge for the project. First, the isolated nature of the candidate sites means that over 100 million euros of capital expenditure will be needed to feed power to the central and remote parts of the array. Secondly, consumptions of this order mean that power will be a large factor in the total cost of ownership, with charges of tens of millions of euros per year being unavoidable. In capital terms, it is likely that the optimal infrastructure differs between South Africa and Australia, with grid-connection and self-generation options, respectively, being favored at this point. Part of the project investigation over the next few years will be to examine the suitability and possible use of renewable energy solutions in an effort to reduce supply costs and, perhaps, to break the nexus between SKA power costs and rising world-parity prices. Regardless of the solutions chosen for the central site, it is certain that renewable power will be required for remote, isolated array stations; a present estimate puts individual station requirements at > 100 kW. While normally prosaic considerations, available and affordable energy solutions will define, in large measure, the capability of the SKA.

On the demand side, the SKA system design will emphasize the use of low-power technology, passive environmental conditioning, and other energy reduction initiatives. Nevertheless, large digital systems consume a great amount of power. AAs and PAFs require power for the extensive digital processing in the beamformers to be delivered to antennas across the site. This is more expensive than a system that dissipates power centrally.

V. PROCEEDING WITH THE DESIGN OF THE SKA

The global network of institutions supporting the SKA, represented by the SKA Science and Engineering Committee, put together a plan in 2007 to, among other things, refine the technical design and carry out the work needed to obtain a cost for the SKA design. This new engineering phase, a four-year Preparatory Phase of the Square

Kilometre Array (PrepSKA) [28], began in April 2008 with funding by the European Community's Seventh Framework Program. The work is being carried out by the SPDO, with substantial in-kind contributions from the network of supporting institutions. This effort will lead at the end of the preparatory phase to a funding application to enable detailed design and construction of the SKA to proceed.

Part of the work will be to decide which technologies will be adopted and what modifications to the science plan must be made. This process began in 2006, when the SKA program adopted a reference design, consisting of a large number of small dishes at high and midfrequencies plus AAs at lower frequencies as the basis for continued technical development—several earlier options were set aside, although many goals and features outlined in preliminary concepts figure prominently in current SKA thinking [29], [31]. In 2007, preliminary specifications, derived from a balance of scientific requirements and technical capability, have been provided for the small number of implementation options described herein and depicted in Fig. 2 [5]. A baseline system design was defined, consisting of sparse AAs for frequencies from 70 to 500 MHz in two separate arrays for different frequency ranges and 15-m parabolic reflectors (dishes) equipped with SPFs for frequencies from < 500 MHz to 10 GHz. Two other possible designs contain alternatives for the 500–1500 MHz range: 1) parabolic reflectors equipped with PAFs for frequencies from 500 to 1500 MHz and SPFs for 1.5–10 GHz; or 2) dense AAs for 500–800 MHz and SPFs for 800 MHz– 10 GHz. In both of these options, fewer dishes would be constructed, so as to keep the total cost fixed.

Cost will play a major role in the adoption of options 1 or 2 above. Dishes are a component of all options, as are sparse AAs at frequencies < 500 MHz: the design and factory setup overheads will be fully absorbed for these technologies. Moreover, the additional cost of equipping dishes with feeds for frequencies down to 300 MHz to implement the base design is likely to be incremental.

However, if some key challenges to PAF and AA technology (Section IV-A and B) can be met, the PAFs or dense AAs could provide a sufficient improvement in survey speed that adopting them will be justified. The basis of this justification would be additional unique science capability from AAs or PAFs, i.e., capability that could not be obtained by using the same funds to expand the size and frequency range of the baseline design. In this case, the additional science capability will have to be sufficiently compelling to warrant fewer dishes in the array, given that this also leads to lower sensitivity at frequencies higher

than ∼1.5 GHz. Alternatively, one of these technologies could be sufficiently promising (i.e., successfully demonstrated but not yet mature) that an upgrade path can be incorporated into the original design, the cost of which would be judged in a similar way.

The following are examples of challenges that will probably have to be met to reach this threshold. (At this stage of development, only rough comparisons or numerical estimates can be provided).

- Integrated LNA/antenna element designs with room temperature LNAs with $T_{element} < 25$ K at frequencies from 300 to 1500 MHz, where $T_{element}$ is the noise contributed to the system noise from the integrated LNA/element. This development would enable both AAs and PAFs to operate in a similar noise regime to SPFs at these frequencies. An alternative for PAFs is to develop an inexpensive cryocooling system.
- The annual power consumption of large AAs is kept sufficiently low that the operating cost will not be a significant fraction of capital cost.
- The cost of AAs and associated beamformer electronics per unit area is not much more than the cost of dishes in unit area terms.
- The cost of a PAF is not much more than the cost of the associated reflector antenna equipped with a SPF. Otherwise, it may make sense to use the funds to construct more reflector antennas. Of course this is not the whole picture; the relative performance of the two systems for doing the science must also be a factor.
- AAs, both dense and sparse, can be sufficiently well calibrated to meet the spectral and imaging dynamic range requirements for large area surveys.

In order to reach a design whose cost can be estimated, decisions on whether, or when, to adopt these new technologies will have to be made during the PrepSKA program. Pathfinder and Design Study instruments and programs, described in overview in [18] and selectively in this paper, are central to informing these decisions and in mitigating risk within the complex SKA engineering development exercise. ∎

REFERENCES

[1] *Astronomy and Astrophysics in the New Millennium.* Washington, D.C.: National Academy Press, 2001.

[2] C. Carilli and S. Rawlings, Eds., "Science with the square kilometre array," *New Astron. Rev.*, vol. 48, Dec. 2004.

[3] A. R. Thompson, J. M. Moran, and G. W. Swenson, *Interferometry and Aperture Synthesis in Radio Astronomy,* 2nd ed. New York: Wiley, 1986.

[4] T. J. W. Lazio *et al.,* "The SKA design reference mission," unpublished.

[5] R. T. Schilizzi, P. Alexander, J. M. Cordes, P. E. Dewdney, R. D. Ekers, A. J. Faulkner,

B. M. Gaensler, P. J. Hall, J. L. Jonas, and K. I. Kellermann, "Preliminary specifications for the Square Kilometre Array," SKA Memo 100, Dec. 2007. [Online]. Available: http://www.skatelescope.org

[6] P. J. Napier, A. R. Thompson, and R. D. Ekers, "The very large array: Design and performance of a modern synthesis

radio telescope," *Proc. IEEE*, vol. 71, pp. 1295–1320, 1983.

[7] J. M. Cordes, "Radio transients and the SKA as a synoptic survey facility," *Bull. Amer. Astron. Soc.*, vol. 38, 2007.

[8] European SKA Consortium, "European concept for the SKA: Aperture array tiles," SKA Memo 19, Jul. 2002. [Online]. Available: http://www.skatelescope.org

[9] B. Veidt, "Focal plane array architectures: Horn clusters versus phased array techniques," SKA Memo 71, Feb. 2006. [Online]. Available: http://www.skatelescope.org

[10] J. D. Bregman, "System optimization of multi-beam aperture synthesis arrays for survey performance," in *The Square Kilometre Array: An Engineering Perspective*, P. J. Hall, Ed. Dordrecht, The Netherlands: Springer, 2005.

[11] R. D. Ekers, "Future radio telescopes," in *Proc. URSI Large Telescope Working Group 1 kT Tech. Workshop*, Sydney, Dec. 15, 1997.

[12] L. Belostotski and J. W. Haslett, *IEEE J. Solid-State Circuits*, vol. 42, Nov. 2007.

[13] M. W. Pospieszalski, S. Weinreb, R. D. Norrod, and R. Harris, "FET's and HEMT's at cryogenic temperatures—Their properties and use in low-noise amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. 36, no. 3, 1988.

[14] G. Engargiola, "Non-planar log-periodic antenna feed for integration with a cryogenic microwave amplifier," in *IEEE Symp. Dig. New Frontiers Antennas Propag. Wireless World*, San Antonio, TX, 2002.

[15] B. C. Enthoven and R. Maaskant, "Design of a hot-cold test facility," Apr. 2008, unpublished.

[16] SKA siting proposals, Internal SKA Project Documentation, Dec. 2005.

[17] "Composite applications for radio telescopes (CART): The MK2 reflector results," SKA Memo 106. [Online]. Available: http://www.skatelescope.org

[18] P. J. Hall, R. T. Schilizzi, P. E. F. Dewdney, and T. J. W. Lazio, "The Square Kilometre Array (SKA) radio telescope—Progress and technical directions," *Radio Sci. Bull.*, no. 326, pp. 4–19, Sep. 2008.

[19] L. D'Addario and C. Timoc, "Digital signal processing for the SKA: A strawman design," SKA Memo 25, Aug. 2002. [Online]. Available: http://www.skatelescope.org

[20] B. Veidt and P. E. Dewdney, "Bandwidth limits of beamforming networks for low-noise focal-plane arrays," *IEEE Trans. Antennas Propag.*, vol. 53, Jan. 2005.

[21] R. E. Crochiere and T. R. Rabiner, *Multirate Digital Signal Processing*. Englewood Cliffs, NJ: Prentice-Hall, 1983.

[22] T. Cornwell, "Wide field imaging III," in *Synthesis Imaging in Radio Astronomy: A Collection of Lectures From the Third NRAO Synthesis Imaging Summer School*, vol. 6, R. A. Perley, F. R. Schwab, and A. H. Bridle, Eds. San Francisco, CA: Astronomical Society of the Pacific, 1989.

[23] J. P. Hamaker, J. D. Bregman, and R. J. Sault, "Understanding radio polarimetry: I. Mathematical foundations," *Astron. Astrophys. Suppl.*, vol. 117, 1996.

[24] R. Smits, M. Kramer, B. Stappers, D. R. Lorimer, J. Cordes, and A. Faulkner, "Pulsar searches and timing with the SKA," *Astron. Astrophys.*, vol. 493, no. 3, 2009.

[25] A. P. Chippendale, T. M. Colegate, and J. D. O'Sullivan, "SKAcost: A tool for SKA cost and performance estimation," SKA Memo 92, Jun. 2007. [Online]. Available: http://www.skatelescope.org

[26] R. T. Schilizzi, P. E. F. Dewdney, and T. J. W. Lazio, "The square kilometre array," in *Proc. SPIE*, Jul. 2008, vol. 7012.

[27] ISPO Infrastructure Team, "SKA infrastructure development," SKA Memo 96, Sep. 2007. [Online]. Available: http://www.skatelescope.org

[28] "A preparatory phase proposal for the Square Kilometre Array (PrepSKA)," *Grant Agreement for Combination of Collaborative Project and Coordination and Support Actions, Seventh Framework Programme, Grant Agreement Number 212243. Annex I—Description of Work*, Feb. 2008. [Online]. Available: http://www.skatelescope.org

[29] P. J. Hall, "The square kilometre array: An international engineering perspective," in *The Square Kilometre Array: An Engineering Perspective*, P. J. Hall, Ed. Dordrecht, The Netherlands: Springer, 2005.

[30] J. D. Bregman, "System optimization of multi-beam aperture synthesis arrays for survey performance," *Exper. Astron.*, vol. 17, 2004.

[31] P. J. Hall, "The square kilometre array: An international engineering perspective," *Exper. Astron.*, vol. 17, 2004.