SKA Science Requirements: Version 2

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The system-level performance requirements[1] for the SKA have been slowly evolving for several years, largely in response to additional science drivers. Ron Ekers published a summary of technical specifications as SKA Memo 4 in 2002; this document has been regarded as version 1 of the SKA science requirements. However, it was recognized that the specifications were not complete or sufficiently detailed in some areas. For example, one of the primary SKA specifications for many years has been an A/T of 20000 m^2/K. This value is well justified by the requirements of deep HI surveys. But this one number cannot plausibly apply to all possible observing frequencies and elevations. To guide concept design work, we need an expanded set of requirements that take into account variations in parameter values and that provide as much internal consistency as possible.

Following the 2003 international SKA workshop in Geraldton, a small working group was formed by the ISSC and charged with developing a revised and expanded set of requirements for the SKA. The members of this group were Richard Schilizzi, Ron Ekers, Chris Carilli, Steve Reynolds, Bryan Gaensler, Russ Taylor, Ken Kellermann, Jill Tarter, and Dayton Jones. After several iterations by this group, a revised set of requirements was distributed to the ISSC, ISAC, IEMT, and others for comments. After some additional revisions the expanded requirements were presented and discussed at the Leiden meeting in Nov 2003.

In parallel with the requirement revision effort, a working group of the ISAC led by Bryan Gaensler has developed a set of "level 0", or highest priority, science goals for the SKA. The definition of level 0 science, now called Key Science Projects, and the process used to determine what science topics should be included are described in SKA Memo 35, published by B. Gaensler in 2003. Five key science topics were presented and discussed at the Leiden meeting (see Memo 44 by Gaensler and the ISAC):

- Gravity – probing strong field gravity via timing of pulsars in very compact binaries
- Probing the Dark Ages – epochs of reionization, star formation, black hole formation
- Cosmic Magnetism – origin and evolution of magnetic fields in galaxies and clusters
- The Cradle of Life – terrestrial planet formation, SETI, astrochemistry
- Evolution of Galaxies and Large Scale Structure – observations of HI in galaxies at high redshifts leading to the strength of dark energy as a function of cosmic epoch

The SKA requirements are intended, above all, to allow the Key Science Project goals to be achieved. They should also allow a wide range of "level 1" science areas to be addressed, and as much flexibility as practical.

The most recent version of the science-based SKA requirements, incorporating results from Leiden, are listed in Table 1. The values in this table have not yet been approved by the full ISSC, and further revisions are likely that will be published in subsequent versions of the

[1] The term "requirement" indicates something that the SKA must do to achieve a key science goal. Other documents have sometimes used "specification" in the same way. The term "goal" is used to indicate an area of expanded capability that would significantly enhance the SKA's scientific productivity, but which may not be feasible for technical or financial reasons. The terms "level 0 science" and "key science" are synonymous.

Table 1 – Expanded SKA Science Requirements (version 9)

1.	**Frequency range**	100 MHz - 25 GHz Goal: 60 MHz - 35 GHz
2.	**Simultaneous independent observing bands**[2]	2 pairs (2 polarizations at each of two independent frequencies, with same FoV centers)
3.	**Max. freq. separation of observing bands**	Factor of 3 between observing band center frequencies (same FoV centers)
4.	**Instantaneous bandwidth of each observing band**	Full width = 25% of observing band center frequency, up to a maximum of 4 GHz BW for all frequencies above 16 GHz
5.	**Sensitivity at 45 degrees elevation (A/T)**	Goal: 2500 at 60 MHz 5000 at 200 MHz, 20000 between 0.5 and 5 GHz, 15000 at 15 GHz, and 10000 at 25 GHz Goal: 5000 at 35 GHz
6.	**Configuration**	Minimum baselines 20 meters, 20% of total collecting area within 1 km diameter, 50% of total collecting area within 5 km diameter, 75% of total collecting area within 150 km diameter, maximum baselines at least 3000 km from array core (angular resolution < 0.02 / f_{GHz} arcsec)
7.	**Image quality**	Dynamic range > 10^6 and image fidelity > 10^4 between 0.5 and 25 GHz, over a range of 90 degrees in declination and 100 in angular resolution
8.	**Contiguous imaging field of view (FoV)**	1 square degree within half power points at 1.4 GHz, scaling as λ^2, 200 sq. deg. within half power points at 0.7 GHz, scaling as λ^2 between 0.5-1.0 GHz
9.	**Number of separated fields of view**	1 with full sensitivity Goal: 4 with full sensitivity 10 simultaneous sub-arrays
10.	**Correlator and post-correlation processing**	Input bandwidth 25% of center frequency for frequencies below 16 GHz and 4 GHz for frequencies above 16 GHz (per observing band) Imaging of 1 square degree at 1.4 GHz with 0.1 arcsec angular resolution Imaging of 200 sq. degrees at 0.7 GHz with 0.2 arcsec angular resolution Imaging of 10^4 separate regions within the FoV, each covering at least 10^5 beam areas at full (maximum baseline) angular resolution Spectral resolution of 10^4 channels per observing band per baseline Minimum sampling interval 0.1 ms for wide-field pulsar searches
11.	**Beamformer capability**	50 simultaneous summed (phased array) beams within FoV, inner 5 km diameter of array. No time averaging, 8 bits/sample.
12.	**Survey speed**	FoV x $(A/T)^2$ x BW = 3 x 10^{17} $deg^2\, m^4\, K^{-2}\, Hz^{-1}$ at 1.5 GHz FoV x $(A/T)^2$ x BW = 1.5 x 10^{19} $deg^2\, m^4\, K^{-2}\, Hz^{-1}$ at 0.7 GHz
13.	**Antenna pointing and slewing**	Blind pointing < 0.1 HPBW, move between adjacent sky positions separated by 0.5 HPBW in 3 sec, move between sky positions sep. by 90 deg. in < 60 s
14.	**Instrumental polarization**	Polarization error / total intensity –40 dB at FoV center, -30 dB out to FoV edge (after routine calibration)
15.	**Spectral dynamic range**	10^4 (flatness of bandpass response after calibration)
16.	**Total power calibration**	Total power (zero-spacing) flux density measured with 5% error within 1 hr.

[2] An "observing band" is a contiguous set of frequencies that pass through all processing steps simultaneously.

science requirements document.

Key Science Drivers for Each Requirement

A discussion of the science drivers for each item and a summary of how these requirements differ from previous versions now follows. For brevity, the strong-field gravity key science project will be referred to below as "pulsars", and probing the dark ages will be referred to as either "EoR" for observations of HI at very high redshifts and as "galaxy origins" for continuum and CO line observations. Also, the "cradle of life" key science project will be defined by high resolution imaging of proto-planetary disks and SETI observations. Finally, the evolution of galaxies and large-scale structure key science project will be referred to as "dark energy".

1. The low frequency limit of 100 MHz is a compromise between what is needed to study the epoch of reionization (EoR) over its full redshift range and what is needed for all other key science projects (200-300 MHz). 100 MHz corresponds to a redshift of 13 for HI. The low frequency goal of 60 MHz corresponds to a redshift of 23 for HI. The final low frequency requirement may be changed when results from LOFAR are available.

   The high frequency limit is required by the galaxy origins and cradle of life key science projects. The limit is increased from 20 to 25 GHz to cover the H20 and NH3 lines. The goal of 35 GHz allows observation of CO over a wider redshift range, higher resolution imaging and astrometry of AGN/jets and both higher resolution and higher SNR imaging of protoplanetary disks, stars, solar system objects and other thermal sources. Spacecraft tracking in the 32-GHz band would also be possible.

2. No explicit key science requirement, but needed for plasma delay calibration and desired for general observational flexibility.

3. Not explicitly required, but desired for both pulsars and dark energy (to cover 0.5-1.0 GHz frequency range simultaneously, for example), for spectra of fast transients, and for absolute astrometry.

4. Wide bandwidths are required by the pulsars, galaxy origins, cradle of life, and dark energy key science projects. It is desired in general to take full advantage of the SKA collecting area for continuum observations.

5. The sensitivity at low frequencies is required by EoR and (above 200 MHz) the galaxy origins key science projects. Between 0.5 and 5 GHz the requirement is set by the pulsars, galaxy origins, magnetic universe, and dark energy projects. At 10 GHz the requirement is set by the galaxy origins, magnetic universe, and cradle of life projects. At 25 GHz the requirement is set by galaxy origins and cradle of life projects, and also H2O and NH3 observations, AGN/jet imaging, astrometry, and thermal imaging. At the highest frequencies the specification is set by the cradle of life project, and also spacecraft tracking, AGN/jet imaging, astrometry, and thermal imaging.

6. The minimum baseline requirement is set at allow wide-field imaging. The 20% collecting area within 1 km diameter specification is needed for high surface brightness sensitivity in general. The 50% collecting area within 5 km diameter is

needed for pulsars, EoR, and cradle of life (SETI). It is also desired for transients and spacecraft tracking. The 75% collecting area within 150 km diameter specification is needed for pulsars, EoR, galaxy origins, magnetic universe, and dark energy. The maximum baseline length is required by the galaxy origins and cradle of life projects. It is also desired for astrometry, AGN/jets, pulsars, and spacecraft tracking. The detailed breakdown of collecting area vs. diameter is taken from the recommendations of the configuration working group at the Groningen SKA workshop. An approximately scale-free configuration giving a smooth decrease in surface brightness sensitivity from minimum to maximum angular resolution is desired for maximum imaging flexibility.

7. High dynamic range and high fidelity imaging are required by all key science projects.

8. The 1 square degree FoV is required by all key science projects. In addition, the 200 square degree FoV for 0.5-1.0 GHz is required by the dark energy key science project.

9. One FoV is required for all projects (obviously). None require more than a single FoV, but most would benefit from this (especially the large surveys) and it would dramatically increase the general observational flexibility of the SKA. Sub-arraying is needed for pulsars and desired for astrometry.

10. The correlator and post-correlation processing bandwidth requirement is identical to the observing bandwidths in item 4. The full field (but not full resolution) imaging requirements are needed for pulsars, galaxy origins, magnetic universe, and dark energy. The high angular resolution requirement is needed for pulsars, galaxy origins, and cradle of life. It is also desired for AGN/jets, astrometry, and imaging of stars, solar system objects, and maser sources. The requirement for 10^4 spectral channels is needed for adequate velocity resolution over wide bandwidths for the dark energy project. (Note that the full-field imaging requirement for the dark energy project implies higher spectral resolution to avoid bandwidth decorrelation.) The 0.1 ms sampling interval is needed for the wide-field search phase of the pulsars project.

11. A large number of beamformers is required by pulsars and the cradle of life, and also desired for transients and spacecraft tracking. The exact number is somewhat flexible. Detection equipment for the beamformer signals is expected to be experiment specific and is not considered here.

12. The survey speed specification is required by all key science projects except the cradle of life. The 0.7 GHz requirement is needed by the dark energy project.

13. Accurate blind antenna pointing is required by all projects. The small and wide angle slew requirements are not explicitly needed by key science projects, but the small-angle slew requirement is desired for mosaicing and the large-angle slew requirement is desired for transient source observations and absolute astrometry.

14. The polarization requirement is needed for the pulsars and magnetic universe projects.

15. High spectral dynamic range is required for the galaxy origins, cradle of life, and dark energy projects.

16. Total power calibration is required for the galaxy origins, cradle of life, and dark energy projects. It is desired for all imaging observations.

Differences from Previous SKA Requirements

1. Frequency range was 0.03 - 20 GHz in SKA Memo 4, and 0.15 - 20 GHz in several other documents and presentations.

2. The requirement of two simultaneous observing bands is not new, but was not included in SKA Memo 4.

3. The maximum frequency separation of observing band pairs is a new requirement. It is intended mainly to allow simultaneous observations at widely separated frequencies for plasma delay calibration in astrometry. In effect, it sets a lower limit for the width of individual front ends.

4. The bandwidth requirement was $0.5 + \nu/5$ GHz in SKA Memo 4. However, at the lowest frequencies a bandwidth of 500 MHz is probably not useful. The revised requirement sets a fixed bandwidth within a given RF band, and retains a large fractional bandwidth to make efficient use of the SKA's collecting area. It also imposes an upper limit of 4 GHz per observing band to give designers something specific to plan for. Note that with two pairs of observing bands (item 2), up to 8 GHz per polarization will be possible at high frequencies.

5. The basic sensitivity requirement of A/T = 20000 m^2/K remains unchanged, but now applies only to the 0.5-5 GHz frequency range. This is the critical range for many of the key science projects. At low frequencies, we need to recognize the unavoidable increase in Tsys caused by the galactic background. At high frequencies, the cost per unit of collecting area will increase due to the tighter mechanical tolerances needed. Tsys will also increase with frequency due to both atmospheric emission and receiver temperature. The current sensitivity requirement is an attempt to balance these factors in a self-consistent way. In all cases A is the effective (not physical) aperture and T is the total system noise including sky and quantization.

6. In SKA Memo 4, the array configuration is specified indirectly through an angular resolution requirement (0.1 arcsec at 1.4 GHz) and a surface brightness requirement (1K at 0.1 arcsec, continuum). In the revised requirement the configuration is defined explicitly in terms of minimum and maximum baseline lengths, and a series of constraints on the concentration of collecting area within regions of different size. This is based on the recommendations of the configuration working group at the Groningen SKA meeting in 2002.

7. Image quality was specified as a clean beam dynamic range of 10^6 at 1.4 GHz in SKA Memo 4. The revised requirement define values for both dynamic range (the ratio of peak image brightness to the rms noise level) and image fidelity (ratio of peak image brightness to the brightest artifact). Image dynamic range is easier to measure, but image fidelity is often the more important quantity. Three important additions to this requirement are the frequency range, declination range, and angular resolution

range over which high quality imaging must be achieved. The motivation for these additions is to insure that the SKA is designed for flexible, general purpose imaging rather than being optimized for any one specific type of observation.

8. The primary field of view (FoV) specification remains 1 square degree at 1.4 GHz. This is now defined as the area within half-power points. A new requirement for a much larger FoV in the 0.5-1.0 GHz frequency range has been added to allow rapid, wide area HI surveys to z ~ 2 for the dark energy key science project.

9. The number of separate fields of view was not previously specified. This item refers to widely separated imaging FoVs, not separate phased-array beams within a single FoV. The goal of 4 full-sensitivity FoVs is not required be any specific key science project, but would enhance observing flexibility and the speed of all large-scale surveys. Some observing modes such as pulsar timing and absolute (wide angle) astrometry require observations in multiple widely-separated directions, but do not require the full SKA sensitivity. For these cases sub-arraying (dividing the total collecting area) is sufficient.

10. The required correlator capabilities were not previously specified, other than imaging with 10^8 pixels (SKA Memo 4) and 10^4 spectral channels. The revised requirements call for a combined correlation and post-processing system capable of imaging 1 square degree at 1.4 GHz with 0.1 arcsec angular resolution, and a new requirement to image 200 square degrees at 0.7 GHz with 0.2 arcsec angular resolution. The angular resolution is needed to avoid confusion in deep images. The imaging areas given here are equal to the half-power FoV sizes specified in item 8.

    There is also a need to image a large number of small areas within the FoV at an angular resolution at least ten times higher than specified for the full-FoV imaging (corresponding to the maximum baseline length of at least 3000 km). By limiting full resolution imaging to the regions immediately surrounding reasonably strong sources in the field, we can reduce the correlator output data rate significantly.

    There is another new requirement of 0.1 ms for the sampling interval needed for wide-field (but low angular resolution) pulsar searches.

11. SKA Memo 4 specified 100 "pencil beams" within the FoV. The revised requirement for beamforming calls for 50 simultaneous phased-array (vector summed) beams, and clarifies that only the inner 5 km diameter of the array (containing half of the total collecting area) needs to be summed by the beamformers. For pulsar timing, SETI, and spacecraft tracking it is required that the beamforming be done without any time averaging and with at least 8 bits/sample.

12. The survey speed requirement is new. The value given for 1.5 GHz applies to most of the key science projects, while the value for 0.7 GHz is for the dark energy project. In all cases FoV is the sum of all simultaneous fields of view if multiple fields are available, and A/T is the sensitivity of each separate field of view in the case of sub-arraying. Full FoV imaging is assumed. The dependence of survey speed on band-width (BW) can be complex if the total frequency range to be surveyed is divided into multiple bands. SKA Memo 40 published by John Bunton in 2003 considers this issue in detail. For the purpose of these specifications a straightforward linear dependence on total bandwidth has been used for simplicity.

13. The antenna pointing and slewing requirement is new. The specification for motion between adjacent sky areas is needed for mosaicing observations and desirable for phase-referenced astrometry at high frequencies. The specification for large-angle slewing is desirable for transient source observations and absolute astrometry.

14 SKA Memo 4 includes a specification of –40 dB for polarization purity, the residual polarization error as a fraction of total intensity after all normal calibration has been applied. This value has been retained for on-axis observations, but an additional specification for polarization error across the FoV edge has been added in recognition of the fact that polarization measurements will need to be made over the full FoV.

15. There was no previous requirement for spectral dynamic range, which is relevant for the detection of very weak or very broad spectral features. The new requirement of 10^4 is the ratio of the maximum amplitude within the bandpass to the maximum amplitude error within the bandpass. This is determined by the flatness of the bandpass response after calibration.

16. There was no previous requirement for total power measurements, which are needed for wide-field mapping of extended sources and desired for all imaging observations.