



Memo 69
Reference design for the SKA
Discussion Document

International SKA Project Office
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Summary

The Reference Design for the SKA is a radio interferometer array capable of imaging the radio sky at frequencies from 100 MHz to 25 GHz, and providing an all-sky monitoring capability at frequencies below 1 GHz. Half of the total collecting area is concentrated in a core of 5 km diameter, with the remainder in array stations at distances up to at least 3000 km. These requirements will be implemented with three receptor components:

- 1) a Small Dish array with “smart feeds”. The dish diameter is of the order of 10m, and the feeds comprise phased arrays in the focal planes of the dishes for frequencies between 0.3 and 3 GHz, and wide-band feeds at higher frequencies up to 25 GHz. This “radio camera” is the basis of the Reference Design;
- 2) Aperture Array tiles in the core of the array. This innovative technology provides a “radio fish-eye lens” for all-sky monitoring in the frequency range 0.3 to 1 GHz, and multiple independent field observations; and
- 3) an Epoch of Reionisation array in the ≤ 0.1 to 0.3 GHz range, also in the core of the array. This array will make use of broad-band dipoles similar to those developed for LOFAR, MWA, and LWA, and will be constructed as part of the second phase of the SKA.

These three receptor components all make use of the same data transport, processing, and software infrastructure. Descriptions of the receptors and considerations on the risk factors involved in their implementation are given in this document.

1. Introduction

Defining a Reference Design for the SKA has five main aims:

- (i) to focus the engineering and science efforts around the world to develop the optimum receptor set in order that the project is in a position to start construction of the telescope in five years time in 2011,
- (ii) to provide the basis for detailed costing of the array
- (iii) to provide a recognizable image of the SKA for policy makers,
- (iv) to provide a basis for discussion of SKA science to our scientific peers who use other technologies (scientific outreach), and
- (v) to provide a visualization that will appeal to the public (public outreach)

Other considerations are that the Reference Design should contain a substantial component of known technology in order to minimise risk, yet should include an innovative component that enables access to new scientific parameter space, is challenging for the engineering community, and is attractive to policy-makers and industry. Furthermore, it is important to note that the Reference Design is being defined for the full array, not just Phase 1 (the first 10% of the array), and that it is a reference design and not necessarily the final design

A glossary of acronyms is given in Section 6.

2. Basic Parameters Influencing the Reference Design

2.1 Table

	SKA Science Specifications (Memo 45)	Reference Design for full SKA (see below and section 3)	Phase I (see below)
Frequency Range (GHz)	0.1-25	0.1-25	0.3-10
Aeff/Tsys			
0.1-0.3 GHz	5000 m ² K ⁻¹	5000 m ² K ⁻¹	Not applicable
0.3-1	20000	20000	2000 m ² K ⁻¹
1-3	20000	20000	2000
3-10	20000	20000	2000
10-25	10000	10000	Not applicable
Field of View			
0.1-0.3 GHz	Not defined	200 deg ²	Not applicable
0.3-1	200 deg ² (0.7/f) ²	50 deg ²	50 deg ²
1-3	1 deg ² (1.4/f) ²	1-10 deg ²	1-10 deg ²
3-10	1 deg ² (1.4/f) ²	0.33 deg ² (3/f) ²	1 deg ² (1.4/f) ²
10-25	1 deg ² (1.4/f) ²	0.33 deg ² (3/f) ²	Not applicable
No. of Fields of View	1 at full sensitivity; goal of 4 FoVs; 10 sub-arrays	Not defined	Not defined
Baseline length (km)	>3000 km	>3000 km	50 km

2.2 Notes on the Reference Design parameters for the full SKA

Frequency range: ~0.1 GHz – 25 GHz

The prime drivers of the Key Science Projects cover the full frequency range from 100 MHz to 25 GHz

Field-of-View:

- 0.1 – 0.3 GHz 200 square degrees. To be defined on the basis of experience with LOFAR and other first generation arrays investigating the EoR.
- 0.3 - 1 GHz 50 square degrees, ~constant with frequency for a phased array feed in the focus of a small dish. This has been reduced compared to Memo 45

based on considerations of the required survey speed for HI in high-z galaxies

1 - 3 GHz 1-10 square degrees; the upper limit of 10 square degrees would allow faster surveying to be done for pulsars and RMs, but is not strictly required by the science case. Trade-offs between FoV and effective collecting area for some of the science cases need further investigation

Baseline Length >3000 km

Long baselines of several 1000 km (as in Memo 45) are required at low, intermediate, and high frequencies (first AGN in the universe, pulsar astrometry, protoplanetary disks). Additional long baselines can be provided by other current or planned $\geq 70\text{m}$ -class telescopes such as FAST.

2.3 Phase 1 SKA (10% collecting area)

The construction of the SKA is assumed to commence in the core with most of the first 10% of the collecting area being concentrated in the inner 5 km diameter. In order that a relatively wide range of significant science can be carried out at the Phase 1 stage, some collecting area should be deployed on baselines up to 50 km. The SKA implementation at the Phase 1 stage will be a sub-set of the Reference Design in terms of collecting area, frequency range, and baseline, and possibly receptor type. Note that the details of the Phase 1 configuration need to be defined on the basis of the science to be done with 10%.

Frequency range: 0.3 - 10 GHz:

Between 0.3 and 10 GHz, the prime science drivers are extragalactic neutral hydrogen, pulsar surveys/timing, and the polarization rotation measure grid. The frequency range above 10 GHz is not included since the prime science driver at 20 GHz – detecting Earth-sized gaps in protoplanetary disks – requires the full angular resolution capacity which will not be provided in the early phases of the construction. The science case for 10% SKA will be developed in detail during the course of 2006 by the SWG in close collaboration with the EWG.

Field-of-View: As for the full array.

2.4 Epoch of Re-ionisation Array

In the frequency range $\leq 0.1 - 0.3$ GHz, the SKA EoR array requires a collecting area of at least 0.5 km^2 in the core, with baselines up to 50 km to remove galactic foreground confusion. The $\leq 0.1 - 0.3$ GHz range is not included in Phase 1 because 10% SKA has the same collecting area as LOFAR at 0.1 GHz, and therefore is not expected to add substantially to EoR knowledge unless the EoR signal is primarily to be found in the FM bands which LOFAR cannot observe.

3. The Reference Design

The wide FoV, collecting area, frequency range and angular resolution foreseen for the SKA cannot be achieved cost effectively by a single antenna/feed design.

The Reference Design at the lowest end of the frequency range ($\leq 0.1 - 0.3$ GHz, the EoR array) will be based on the LOFAR, MWA, or LWA high-band antennas.

In view of the expected relative maturity of the different candidate designs for 0.3-25 GHz, the Reference Design for this frequency range is proposed to be Small Dishes with diameter of order 10m and two types of feeds - phased array feeds in the focal plane at frequencies from

0.3 to 3 GHz (PAF), and wide-band single beam feeds at higher frequencies (WBF). For convenience, the combination of PAF and WBF is designated "Smart Feed" (SF) and Small Dishes+Smart Feeds as SD-SF. Aperture Array tiles (AA) in the core operating in a frequency range of 0.3 – 1 GHz are the second component of the Reference Design receptors. The multiple independent fields afforded by AA will be very important in allowing surveys for transient radio sources along with transient studies triggered by events detected with other instruments. In addition, the multiple fields will be very important, in an operational sense, to allow parallel programs at the lower frequencies to be run efficiently.

A Reference Design consisting of SD-SF and AA combines the "radio camera" and "fish-eye lens/all-sky monitor" requirements from the science case, and combines "known" technology (SD and WBF) with new, and related, technologies (PAF and AA). The Reference Design can in principle provide the required sensitivity, cover the full frequency range, and provide the required FOV.

High frequencies are only feasible with dishes. With appropriate construction and/or new signal processing techniques it may be possible to achieve scientifically attractive A/T values at 20 GHz using cheaper, nominally lower-frequency dishes. An ambitious example might involve the use of PAFs to correct large-scale surface imperfections in lightweight reflectors.

The trade-off in collecting area of the SD vs AA components of the Reference Design will be a matter of optimisation and phasing as more information becomes available about cost and performance. For example, it may turn out that the first 10% of the collecting area is composed solely of SD. Cost information will be, of course, crucial in the decision whether the full frequency range can be covered.

4. Risk Factors

4.1 Technology maturity

Risk considerations have played an important part in framing the SKA Reference Design and its Phase 1 implementation. There are unknowns in all SKA approaches and projections are necessary in areas such as performance, cost, and suitability for rapid, industrial-scale construction. The accuracy of projections should improve greatly in the next few years with several key, funded, pathfinders becoming operational by 2010 (pre-SKA Phase 1). These instruments are:

- The ATA, demonstrating small dishes (6m) with wideband, single-beam, feeds operating from 0.5 to 11 GHz
- The KAT and xNTD, demonstrating wide-field techniques using small dishes (15m) and phased array feeds in the range 0.7 – 1.8 GHz
- The DSNA, demonstrating narrow-band high frequency performance up to 38 GHz for small dishes
- EMBRACE and 2-PAD, demonstrating dense aperture array (AA) technology in the band 0.7 – 1.4 GHz
- LOFAR, demonstrating EoR array antennas, data transport, processing and calibration, and new industry engagement models.

The dish-based technology will be more mature, evidenced by the fact that the three dish demonstrators (ATA, KAT, xNTD) will be substantial-scale, astronomically capable instruments. Despite the long-term science and economic potential of the dense AA concept and the progress to be expected in building EMBRACE and 2-PAD, the technical and astronomical demonstration of the concept will lag its dish counterparts.

The suggested form of SKA Phase 1 follows on closely from what will have been demonstrated by 2010. The choice of small reflectors as the basis of the design is conservative, offering inherent risk mitigation paths. For example, in the event that demonstrators fail to achieve astronomically-capable phased array feeds in terms of T_{sys} or the ability to achieve dynamic range targets, a fall-back is to place multiple-feed clusters on each dish, or to use smaller dishes, or even perhaps additional wideband, single-beam, feeds. Despite the familiarity of the basic reflector technology, the physical accommodation of multiple feeds in dishes needs further study. Lines of enquiry might include the applicability of foveated or similar density graded PAFs, focal box flipping, or offset feeds.

The Phase 1 choice also sits well as a subset of the full SKA Reference Design. For the SKA, one might use further technical development and demonstration (perhaps including high frequency PAFs and associated signal processing) to prove the feasibility of extending economically the Phase 1 upper frequency limit from 10 GHz to beyond 20 GHz. (Note the currently allowable drop in SKA $A_{\text{eff}}/T_{\text{sys}}$ at these frequencies outlined in Section 2.)

4.2 Feeds and Focal Plane Arrays

Over almost any foreseeable timescale, focal plane arrays (FPAs, either in the form of dense phased array feeds, PAFs, or sparser multiple-feed clusters, MPCs) are required to meet the goal of tens of deg^2 FOV above 1 GHz. Wide FOV, sub-1 GHz operation of the SKA before, say, 2015 also requires FPAs. In general, FPAs offer a natural risk mitigation path for aperture arrays in the band below 1 GHz; the relative proportion of dish and aperture array collecting area can be determined on the basis of the technical and economic outcomes of aperture array demonstrators (such as EMBRACE and 2-PAD and its SKA Phase 1 successors). In turn, SDs with wideband feeds offer a natural risk mitigation for FPAs at somewhat higher frequencies.

The endorsement of the PAF version of FPAs rather than conventional MFCs is also worth amplifying. While PAFs are a much more complex and challenging technology, they fully sample the focal plane, allowing close-packed, efficient beams to be formed, even in off-axis regions where the field distortion compromises badly the performance of conventional feeds. Generation of many, efficient beams increases greatly the science potential of the SKA via e.g. parameters such as total FOV and survey speed. From an engineering viewpoint, a wideband MFC (perhaps composed of corrugated horns) at low-GHz frequencies is likely to be large and heavy, complicating the dish structural design. Still, MFCs may ultimately have a place in the SKA, either as higher frequency FPAs or, possibly, in compact, limited-bandwidth, form at lower frequencies in the event that SD-PAF demonstrators fail to achieve their performance goals.

4.3 Dish diameter

Efficient operation at 0.3 GHz is the driving consideration behind selecting the dish diameter. This question can be approached from a number of perspectives. From the risk viewpoint, note that the suggested size of order 10m

- is being tested by demonstrators such as ATA, KAT, xNTD and DSNA

- gives efficient operation down to 0.3 GHz in the event that dense AA technology proves not to be feasible, or is too costly, for widespread deployment in the SKA
- gives a natural FOV of $\sim 1 \text{ deg}^2$ at 1.4 GHz which, when expanded using foreseeably attainable expansion factors of < 50 , gives a scientifically-attractive ultimate FOV of $< \sim 50 \text{ deg}^2$ at the same frequency
- is within a “flat” range of the SKA component cost model obtained with preliminary SD-FPA analyses.

Despite the attraction of a “single size fits all” dish diameter, consideration should be given, during the detailed system design, to use of dishes of smaller diameter for the higher frequencies. As an example, the FASR (Frequency Agile Solar Telescope, 0.1-25 GHz, 0.0025 km², 6 km maximum baseline) project includes three arrays which have decreasing dish diameter with increasing frequency. While smaller dishes are likely to be most attractive at high frequencies, particular outcomes from SKA demonstrator programs might also force consideration of them at frequencies in the ~ 1 GHz range. For example, a combination of poor PAF demonstration results, especially good AA results and attractive costing demonstrations of smaller dishes would require the project to re-visit its current recommendation of diameters of order 10m. Importantly though, the essential nature (SD-SF + AA) and the picture of the SKA Reference Design would remain unchanged

4.4 Industry involvement

To meet required short SKA timelines a very high level of industry involvement will be needed. With the limited engineering resources available in the SKA and associated scientific communities, delivery of the project will necessarily involve a change to the governing assumptions applied in previous radio astronomy undertakings. Industry will be responsible for constructing, commissioning, and perhaps operating, far more of the SKA than previous instruments. Early R&D collaborations are important for advancing key technologies on pathfinder timescales, and it is essential that the SKA Reference Design is able to be manufactured and deployed at realistic costs. The closer that chosen technologies can follow known manufacturing techniques (or relatively small variants thereof), the faster and cheaper the SKA can be built.

There is enough risk in the chosen Reference Design that its component elements will not all be off-the-shelf “appliances”, and it is clear that even its partial realisation in Phase 1 will stretch the project’s resources and organisational skills. However, in the judgement of the project there is a substantial likelihood that the base technologies of the Reference Design can be effectively manufactured, via relatively conventional industry processes, on the timescales needed.

4.5 Cost

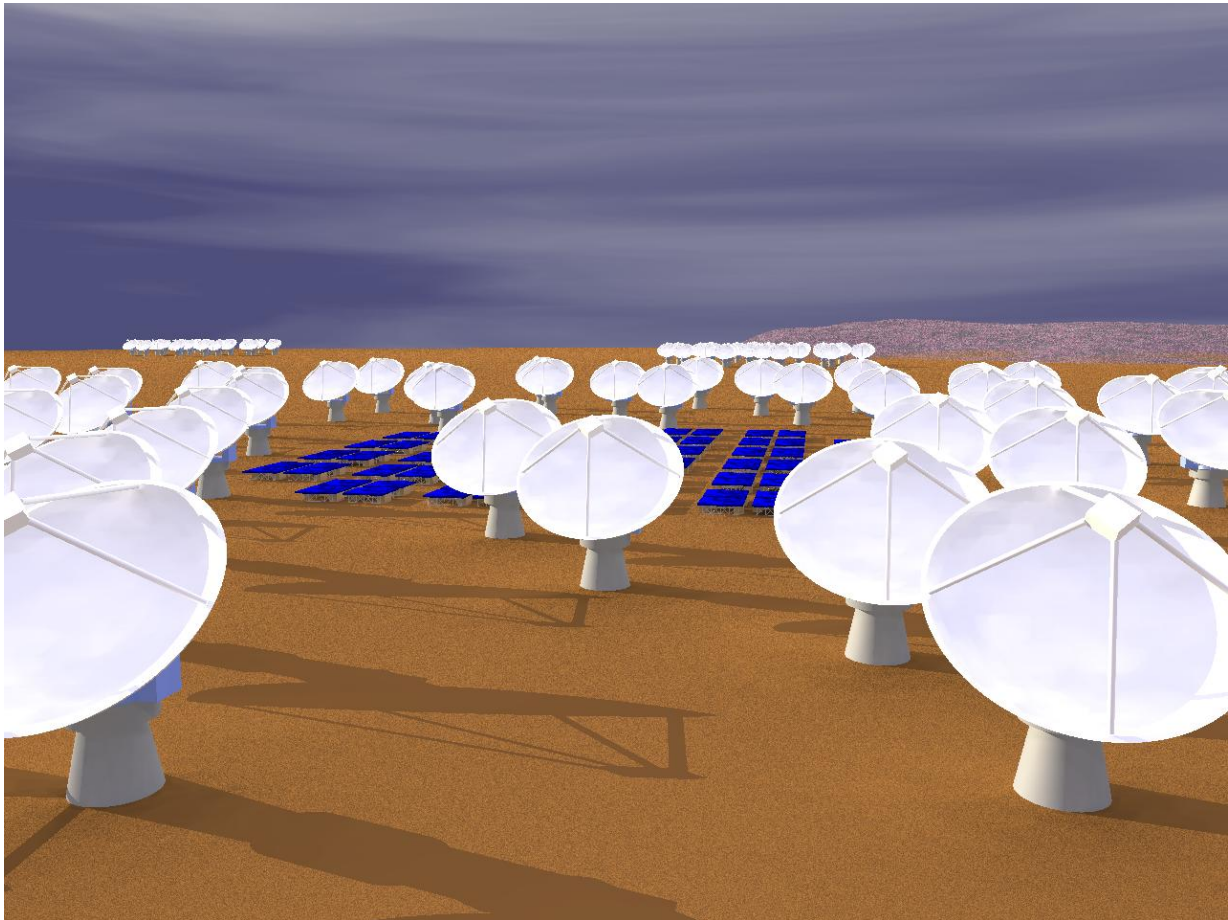
Delivery of the SKA within the target budget is a major challenge. While constraining the instrument specifications is imperative, technological and manufacturing uncertainties currently make even basic component cost estimation rather uncertain. Over the next few years the cost versus science return must be explored systematically as a function of frequency range, antenna type (SD, AA, EoR array), dish diameter, and type of feed.

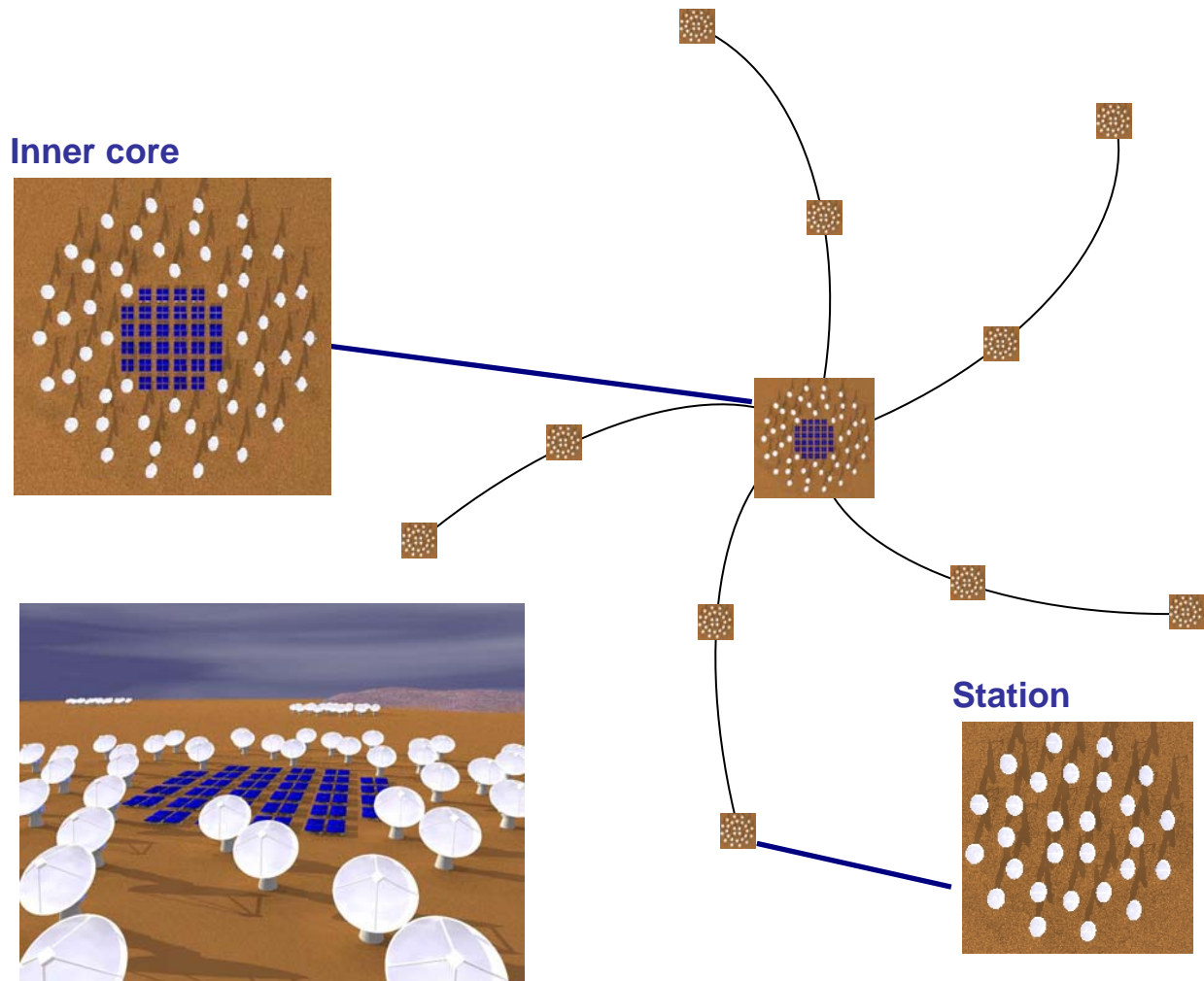
5. Image of the Reference Design

The picture of the Reference Design shows Aperture Array tiles in the inner core surrounded by an annulus of Small Dishes in the outer core, leading into spiral arms comprised of Small Dishes. Not shown are the wide-band dipoles for the EoR array.

The SKA animation, now in preparation, will be a fly through space and time as the array evolves.

The pictures that follow have been generated by Michael Kramer for this report. In subsequent versions, these pictures will be refined including, for example, more antennas in the central core.





6. Glossary

AA	aperture array
ATA	Allen Telescope Array (USA)
DSNA	Deep Space Network Array (USA)
EMBRACE	Electronic Multi-Beam Radio Astronomy ConcEpt (Europe)
EoR	Epoch of Reionisation
FASR	Frequency Agile SolaR telescope
FAST	Five-hundred-metre Aperture Spherical Telescope (China)
FoV	Field of View
FPA	Focal Plane Array, a generic wide field-of-view feed in a dish
GBT	Green Bank Telescope (USA)
KAT	Karoo Array Telescope (South Africa)
LOFAR	Low Frequency Array (The Netherlands)
LWA	Long Wavelength Array (USA)
MFC	Multiple-Feed Cluster, a class of FPA. Typically an array of horns, as in the Parkes multi-beam receiver

MWA	Mileura Wide-field Array (USA, Australia)
PAF	Phased Array Feed, a class of FPA
SD	Small Dish
SD-SF	Small Dish + Smart Feeds
SF	Smart Feed comprising FPAs and WBFs
WBF	Wide Band Feed
xNTD	extended New Technology Demonstrator (Australia)
2-PAD	two-polarization all-digital tile (Europe)

7. Acknowledgements

Following discussion on the definition of the Reference Design for the SKA in India in November 2005, the International SKA Steering Committee (ISSC) requested that the International SKA Project Office (ISPO) form a Tiger Team to investigate options for the Reference Design in more detail, prior to formal approval by the ISSC. Members of the Tiger Team were Arnold van Ardenne, Jaap Bregman, Jim Cordes, Peter Dewdney, Bryan Gaensler, Michael Kramer, John O'Sullivan, and Dick Thompson. Peter Hall and Richard Schilizzi (chair) took part from the ISPO. The ISSC approved the Reference Design on 16 January 2006.