Memo 100

Preliminary Specifications for the Square Kilometre Array

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, K. I. Kellermann

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Executive Summary

The Square Kilometre Array is a multi-purpose radio telescope covering the frequency range from 70 MHz to >25 GHz that will play a major role in answering key questions in modern astrophysics and cosmology. It will be one of a small number of cornerstone observatories across the electromagnetic spectrum that will provide astrophysicists and cosmologists with a transformational view of the Universe. This document provides sets of preliminary engineering specifications, derived from a balance of scientific requirements and technological capability, for a small number of implementation options for the SKA. Following review by an independent specification review committee in January 2008, an updated version of this document will serve as the starting point and roadmap for SKA design efforts and R&D projects around the world that are aimed at resolving technology and cost uncertainties. It is intended that this work will result in refined versions of this document.

The construction of a radio telescope with a collecting area approaching one million square metres across a wide frequency range is a major undertaking and will need to be implemented in phases in order to spread the cost impact. However phased implementation is an effective strategy for an aperture synthesis telescope which can start operating before construction is completed. The international project has adopted the following terminology to describe this phased approach: Phase 1 is the initial deployment (15-20%) of the array at mid-band frequencies, Phase 2 is the full collecting area at low and mid-band frequencies (~70 MHz to 10 GHz), and Phase 3 sees the implementation at higher frequencies of 25 GHz or more.

The five key science areas defined by the astronomy community as driving the specifications of the SKA, together with the Exploration of the Unknown, are described in detail in “Science with the Square Kilometre Array” (eds. C.Carilli and S. Rawlings). These play a prominent role in the considerations underlying this document. Clearly, the science capability of the SKA will evolve as the telescope is constructed. Phase I will enable revolutionary science at decimetre wavelengths, with a particular focus on pulsars and gravitational wave astronomy, magnetism, H I and the nearby Universe, and exploration of the dynamic radio sky. With its wider wavelength range and 5 times greater sensitivity, Phase 2 will transform our understanding of many key areas including: the formation of the first structures as the universe made its transition from a largely neutral state to its largely ionised state today; cosmology including dark energy via baryonic oscillations seen in neutral hydrogen; the properties of galaxy assembly and evolution; the origin, evolution and structure of magnetic fields across cosmic time; strong field tests of gravity using pulsars and black holes including measurements of black hole spin and theories of gravity, and the exploration of the dynamic radio sky with far greater sensitivity and instantaneous sky coverage. The high frequency capability of Phase 3 will enable detailed study of planet formation in proto-planetary disks and the detection of the first metals in the universe via observations of molecules such as CO, HCN and HCO^+.

Over the next four years, all facets of the SKA project from its detailed design, to site characterisation, to governance, procurement and funding will be studied in the context of the Preparatory Phase for the SKA, PrepSKA, prior to the submission of planned formal proposals for construction funding expected in 2012. In preparation for PrepSKA as well as the European AstroNet Roadmap and US Decadal Review, it is timely to revise the specifications in the light of current R&D knowledge, in order to provide a more clearly defined route forward through SKA design space.

Preliminary top-level specifications of the Square Kilometre Array have been developed following science-engineering trade-offs that have taken into account current knowledge of likely key technologies and their likely evolution, and cost at the time of construction. A number of possible implementations are proposed which are estimated to cost 300 M€ (NPV - net present value in 2007) for the first stage (Phase 1) of the array and 1,500 M€ (2007 NPV) for the full array at frequencies from ~70 MHz to 10 GHz (Phase 2). The Phase 1 and Phase 2 costs include 100 M€ and 500 M€ respectively for infrastructure, software, labour, management costs, and delivery; the remaining two-thirds in both cases is for hardware components. The third phase of the SKA Program, the extension to at least 25 GHz, is less well-defined at this stage, and the technical outlines and costs of its implementation are left to future studies.

Critical amongst these preliminary top-level specifications are the sensitivity of the array defined as effective area/system temperature (A_{eff}/T_{sys}), the survey performance ("speed") defined by a simple Figure of Merit, $(A_{eff}/T_{sys})^2$ x Field of View (FoV), the array configuration, and the data rate from the receptors to the data processing system (expressed in terms of the maximum baseline for full FoV spectral line or time domain observations). Particularly at lower frequencies, the SKA's high sensitivity will also imply much higher imaging dynamic range, the ratio of the brightest point in an image to the rms "noise", than current telescopes are capable of achieving. This consideration may impact the selection of the receptor technologies discussed below.

The three receptor technologies under consideration for the SKA are:

i. **Dishes + wide-band single pixel feeds**. This implementation of the mid-band SKA represents a low risk reference scenario for the 500 MHz to 10 GHz frequency range. The eventual upper frequency limit will depend on the outcomes of cost-effectiveness studies undertaken by various regional SKA projects. This scenario is capable of supporting most of the Phase 2 key science projects, and the Phase 1 science case. For key science topics requiring high fidelity imaging observations it is currently the technology of choice. In particular, the dish plus single pixel feed scenario provides the highest A_{eff}/T_{sys} for a given cost ceiling.

   The major challenges for dish + WBSPF include the following factors:

   - o Mass production of inexpensive dish antennas that have surface and pointing accuracies appropriate for the upper operating frequency, and have a diameter that is large enough to minimise diffraction losses at the lowest operating frequency,
   - o The large number of antennas (N=3,000, see Table 1) implies that the array data processor, i.e. correlator and beamformer, has to deal with massive data transport and processing rates which have both N, i.e. per dish, and N^2, i.e. per baseline, dependencies,
   - o The huge number of baselines implicit in this implementation provides a significant computing challenge.

   Dish diameter is the key parameter that controls the trade-off between the survey speed and instantaneous sensitivity metrics for the dish + WBSPF feed scenario. Different optimal dish diameters are obtained for fixed construction cost, depending on whether A_{eff}/T_{sys} or the survey speed metric is specified as a target figure of merit.

ii. **Dishes + Phased Array Feeds (PAFs)**. Most of the prime drivers for SKA science involve a large survey component at frequencies below ~3 GHz and, for much of this science, high survey speed can be traded for large A_{eff}/T_{sys}. Mutually-coupled PAFs at, or near, the focus of a dish are a cost effective way to increase the FoV and hence survey speed of a dish. This arrangement represents an intermediate step between dishes + SPFs and aperture arrays, giving a cost per unit area and total FoV which sits between the optical and all-electronic receptor solutions. When compared with an array of dishes with single pixel feeds, the costs are shifted from the aperture to digital electronics, offering cost reduction and performance enhancement with time. While high A_{eff}/T_{sys} is always preferable, since it provides both instantaneous sensitivity and survey speed, the innovative PAF technology can provide high survey speed at much reduced cost.

   The general challenge faced in designing any focal plane FoV expander is to obtain useful expansion factors while preserving adequate performance, measured in terms of sensitivity and beam quality, from off-axis beams. These beams are subject to aberration and the performance is maximized by the use of suitable optical parameters (e.g. large f/D) and/or a suitably complex electronic beam-former (in the case of the PAF). Particular cost drivers for dishes + PAFs are efficiency, system noise, frequency coverage, polarization purity, calibration stability, power consumption, weight, and RFI mitigation

iii. **Aperture arrays**. An aperture array (AA) is a large number of small, fixed antenna elements plus receiver chains which can be arranged in a regular or random pattern on the ground. A beam is formed and steered by combining all the received signals after appropriate time delays for phase alignment, this can be repeated simultaneously many times to create many simultaneous independent beams, yielding very large total FoVs. The number of useful beams produced, or total FoV, is essentially limited by signal processing, data communications and computing capacity. Aperture arrays can readily operate at low frequencies with large effective areas. Arrays using substantial digital processing systems are an inherently very flexible collector technology since the system can 'trade' FoV and bandwidth and hence the performance can be matched to that required by the experiment. It is also possible to tailor the processed FoV as a function of frequency, which provides FoV increasing substantially faster than the λ^2 for some experiments. This flexibility allows the FoV for a spectral-line survey to be a function of redshift and hence gives control of survey speed as a function of redshift.

   Cost drivers for aperture arrays are the frequency at which the sensitivity is optimised (the higher the frequency the higher the number of elements and the more costly), the frequency range over which the array is used, digitisation and signal processing requirements, and the cost of data transport from the array stations or patches to the correlator.

Cost modelling of the SKA has been an integral part of the analysis carried out in the document. This is not the costing of a specific final design, since such costing requires design finalisation with input from specialists and potential suppliers; one goal of PrepSKA is to produce a single design. For a project such as the SKA, true costing will be influenced very strongly by political, economic, and commercial considerations. While the present version of the cost model attempts to include some aspects of commercial drivers, such as economies of scale, the uncertainties are very large. However, the cost modelling performed provides a good guide to how costs scale with design considerations. Even in this respect though, large uncertainties remain especially when particular aspects of the system determine apparently optimal design solutions.

No detailed array configurations can yet be presented, although it is likely that a centrally condensed scale-free array configuration will be adopted. Trade-offs are needed to optimise performance against prioritisation of key science areas. ISPO Working Groups are currently carrying out an analysis of the Phase 2 configuration, to be completed in 2008. The Phase 1 configuration will be a subset of that for Phase 2 but is likely to include 75% of the collecting area within 5 km with the remaining 25% deployed out to several tens of kilometres and possibly one element at 100 km primarily for engineering test purposes.

Table 1 gives the preliminary specifications for representative implementations of the SKA. For the first two phases, these implementations factor-in the cost to meet the science specifications and allow identification of the specifications that are cost-driving outliers. Cost drivers have been prioritised within a fixed cost project, with a recognition that this process adds complexity since costs can be implementation-specific in ways which affect the overall balance of technologies selected. Indeed, the effect of this coupling between science goals and technology underlies much of this document.

Table 2 and Table 3 present the implementations for Phase 1 and Phase 2 in more detail. The considerations underlying these specifications are presented in the succeeding sections of this document. Choices of the particular implementations for Phase 1 and Phase 2 will be made in the course of the SKA design task coordinated by PrepSKA.

Table 1. Top-level specifications for various implementation scenarios. Acronyms are defined in Section 12 (Glossary).

15/11/07 (v2.3)	First Stage		Full SKA			
Parameter	**Phase 1** ***Mid-band –*** *inc. dense AA*		**Phase 2 scenarios** ***Low & mid-bands –*** *all inc. AAs to 500MHz*			**Phase 3** ***High band***
	WBF only	**WBF+PAF***	**WBF only**	**WBF+PAF***	**WBF+dense AA**	
Frequency Range: Low High	500 MHz 10 GHz	500 MHz 10 GHz	70 MHz 10 GHz	70 MHz 10 GHz	70 MHz 10 GHz	10 GHz 35 GHz
Survey speed ($m^4K^{-2}deg^2$)						
70 - 200 MHz			3×10^{9}	3×10^{9}	3×10^{9}	
200 - 500 MHz	1×10^{7}	1×10^{7}	2×10^{10}	2×10^{10}	2×10^{10}	
0.7 GHz	1×10^{7}	3×10^{7}	3×10^{8}	1×10^{9}	2×10^{10}	
1.4 GHz	2×10^{6}	3×10^{7}	1×10^{8}	1×10^{9}	4×10^{7}	
3 GHz	5×10^{5}	1×10^{5}	1×10^{7}	5×10^{6}	1×10^{7}	
10 GHz	2×10^{4}	5×10^{3}	5×10^{5}	2×10^{5}	4×10^{5}	
25 GHz						4.6×10^{4}
35 GHz						2.4×10^{4}
Min. sensitivity at 45° A_{eff}/T_{sys} (m^2K^{-1})						
70 - 200 MHz			4,000	4,000	4,000	
200 - 500 MHz	200	200	10,000	10,000	10,000	
700 MHz	2,000	1,100	12,000	7,000	10,000	
1.4 GHz	2,000	1,100	12,000	7,000	10,000	
3 GHz	2,000	1,100	12,000	7,000	10,000	
10 GHz	1,300	700	8,000	5,000	7,000	5,000
25 GHz						5,000
35 GHz						5,000
Configuration:						
core: < 1 km	50 %	50 %	20 %	20 %	20 %	20 %
inner: < 5 km	75 %	75 %	50 %	50 %	50 %	50 %
mid[†]: < 180 km	100 %	100 %	75 %	75 %	75 %	75 %
outer: <~3,000 km			100 %	100 %	100 %	100 %
WFoV for Surveys: *Spectral imaging / time domain*						
max baseline km	5	5	10	10	10	20
channels #	16,384	16,384	32,768	32,768	32,768	32,768
sample rate ms	0.1	0.1	0.1	0.1	0.1	0.1

* Sensitivity of PAF and WBF shown as equal

[†] The mid-range baseline lengths for Phase 1 range up to 50-100km

Table 2. Phase 1 technology combinations in the frequency range 500 MHz to 10 GHz. that are projected to cost 200 M€ for components. Note that 2a and 2b are alternative implementations of dish-based systems at the extreme ends of the spectrum of possibilities. 30 M€ is also needed for deployment of an aperture array - sparse or dense to be determined during the course of the PrepSKA Design Study from science and technical readiness considerations.

Frequency Range	Sensor	A_{eff}/T_{sys} m^2K^{-1}	Survey speed $m^4K^{-2}deg^2$	Cost
1) 500-800 MHz*	Dense Aperture Array	200	$1x10^7$	30 M€
2a) 0.5-10 GHz	490 15m dishes with PAFs (0.5-1.5 GHz) T_{sys}=50K effic=70%, FoV=20 deg^2 +WBSPF (1.5-10GHz) T_{sys}=35K, effic=65%	1200	$3x10^7$	170 M€
2b) 0.5-10 GHz	620 15m dishes with WBSPFs (0.5-10 GHz) T_{sys}=35K, effic=65%	2,000	$2x10^6$	170 M€

* or 100 – 500 MHz using sparse aperture arrays if science and technical considerations so dictate

Table 3. Three possible combinations of technologies for Phase 2 implementation in the frequency range 70 MHz to 10 GHz that are projected to cost 1,000 M€ for components. (Note that 3a to 3c are three alternative mid-band implementations)

Frequency Range	Sensor	A_{eff}/T_{sys} m^2K^{-1}	Survey speed $m^4K^{-2}deg^2$	Cost
1) 70-200 MHz	Sparse aperture array composed of tiled dipole arrays	4,000-10,000	$3x10^9$	125 M€
2) 200-500 MHz	Sparse aperture array composed of tiled dipole arrays	10,000	$2x10^{10}$	125 M€
3a) <500 MHz - 10 GHz	3,000 15m dishes/WBSPF T_{sys}=30K, effic=70%	12,000	$1x10^8$ at 1.4 GHz	750 M€
3b) 500 MHz - 10 GHz	2,000 15m dishes with PAFs (500 MHz-1.5 GHz) T_{sys}=35K effic=70%, FoV=20 deg^2 + WBSPF (1.5-10 GHz) T_{sys}=30K	7,000	$1x10^9$ $5x10^6$ at 3 GHz	750 M€
3c) 500 MHz - 10 GHz	Dense aperture array (500-800 MHz) + 2,400 15m dishes/WBSPF (800 MHz - 10 GHz), T_{sys}=30K, effic=70%	10,000 10,000	$2x10^{10}$ (500-800 MHz) $4x10^7$ at 1.4 GHz	150 M€ (AA) 600 M€ (dishes / WBSPF) total=750 M€

1. Introduction

The Square Kilometre Array has evolved over the years from a purely "hydrogen array" observing at frequencies of 1.4 GHz and below, to a multi-facetted science facility covering a frequency range from 70 MHz to at least 25 GHz and capable of answering many of the major questions in modern astrophysics and cosmology. Five key science areas have been defined by the astronomy community as driving the specifications of the SKA, and these play a prominent role in the considerations underlying this document. However, from the very earliest days of the project, it has been recognized that the telescope must be able to evolve its capabilities into new parameter space in order to maximize its discovery potential, noting that most telescopes spend their working lives investigating questions that are unknown at the time the telescope is funded. This has been designated as the Exploration of the Unknown.

The science goals have been translated into science requirements/specifications at different times in the life of the project, e.g. SKA Memo 3 by Ron Ekers, Memo 45 by Dayton Jones, and Memo 83 by Carole Jackson. A number of science-engineering trade-offs were examined by the Science Working Group in Memo 82 in response to questions by the Engineering Working Group and ISPO management These included the science case for multiple independently-steerable fields of view, the impact of limiting the field of view at high angular resolution, the case for high angular resolution below a few GHz, the case for frequencies between 200 MHz and 500 MHz, the case for high filling factor at high frequency, and the options for transient detection.

Using the SKA for surveys has emerged as a driving element for a number of the Key Science Programs. The issues involved in carrying out surveys, and Survey Speed Figures of Merit (SSFoM) have been examined at length in SKA Memo 81 by Melvin Wright et al, in SKA Memos 85 and 97 by Jim Cordes and in a further memo in preparation by Jim Cordes.

The earlier specifications were used as the basis of the SKA Reference Design published in early 2006 as Memo 69. This provided a model implementation of the SKA which has served to focus attention on a smaller number of potential technologies than had been the case before its publication. Over the last few years, several SKA Pathfinder Telescopes (LOFAR, MWA, ATA, ASKAP, MeerKAT) and SKA Design Studies (SKADS) have been funded, each of which is developing one or more aspects of the Reference Design technology in depth. In addition, SKA-relevant design knowledge is being generated by the EVLA, eMERLIN, eEVN and LWA. Underpinning much of this effort is a substantial body of work by many interested parties generated via the Science and Engineering Working Groups. In the process, some aspects of the Reference Design have been revised (e.g. for Phase 1) as the project has made progress and additional insights have been gained.

Integrating this distributed R&D and design knowledge into a costed design for the SKA ready for construction funding approval, will be carried out over the next four years, 2008-2011, in the context of PrepSKA and the TDP (see Section 2 and Annex 2),

It has been clear for some time that the development of an SKA with a collecting area approaching one million m^2 across the band from ~70 MHz to 25 GHz would need to be implemented in phases in order to spread the cost impact. In addition, phased implementation is an effective strategy for an aperture synthesis telescope which can start operating before it is all built. In March 2007, the International SKA Steering Committee (ISSC) adopted a resolution to this effect (see Annex 1).

In this document, we will refer to Phase 1 as the initial deployment (15-20%) of the array, and Phase 2 as the full collecting area SKA at low and mid-band frequencies (~70 MHz to 10 GHz). Phase 3 will extend the SKA to higher frequencies of 25 GHz and beyond. As noted in the ISSC Resolution, high-frequency arrays such as EVLA, e-MERLIN and ALMA will deliver decision pathways for the deployment of high-frequency SKA technology.

In preparation for PrepSKA as well as the European AstroNet Roadmap and US Decadal Review, and taking the ISSC Resolution into account, it is timely to revise the specifications in the light of current R&D knowledge, in order to provide a clearly defined route forward through SKA parameter space. A Tiger Team was established by the International SKA Steering Committee to revise the SKA specifications and propose a baseline implementation. Members of the Tiger Team were: Paul Alexander, Jim Cordes, Peter Dewdney, Ron Ekers, Andy Faulkner, Bryan Gaensler, Peter Hall, Justin Jonas, Ken Kellermann, and Richard Schilizzi (chair). Colin Greenwood assisted in the editing of this document.

The Tiger Team strategy has been to review the earlier documents on SKA specifications in particular to assess the reality of the specifications assumed until now and uncover the hidden assumptions. Key cost driving parameters have been identified, and the cost-performance estimation tool described in Memos 92 and 93 has been used to guide a detailed tradeoff analysis. This is the start of a process that will continue throughout the design and construction phase. A fixed-cost approach has been taken. The cost of Phase 1 is 300 M€, of which 200 M€ is assigned for components, and the remainder to infrastructure, software, labour, NRE, management costs, and delivery. This represents an increase of 50 M€ over the 250M€ mentioned in Annex 1, reflecting an increase in the ratio of component costs to other costs to the same level as for Phase 2. The cost of Phase 1+2 is 1,500 M€, of which 1,000 M€ is for components, with 500 M€ for infrastructure, computing, software, labour, management costs, and delivery. The results of the trade-off analysis have informed the proposals made by the Tiger Team for the specifications and representative implementations for Phase 1 and the full SKA at mid- and low-bands, and which are now presented to the international community for comment.

The preliminary specifications for Phase 1 and Phase 2 are presented in Section 9, and representative implementations in Section 10. Supporting material is presented in the other sections. Section 2 summarises the timescales foreseen for the development of the SKA. In Section 3, the key science is summarized for the full frequency range and collecting area of the SKA as well as for Phase 1. Section 4 presents the desirable science specifications for the SKA resulting from the key science case, including specific tables for survey speed and instantaneous sensitivity (A_{eff}/T_{sys}). Section 5 presents the cost-driving specifications. The three main SKA technology options, the technical challenges and cost drivers for each option, and the trade-offs and science implications for particular implementations are described in Sections 6, 7 and 8 respectively. In Section 11, the engineering decisions foreseen at particular points in the project development are summarised. Finally, in Section 12, the glossary contains an explanation of acronyms used in this document.

2. Engineering Timescale and PrepSKA

One of the practical motivations for producing more definitive SKA specifications at this point is to provide the basis for the forthcoming international system design. At its September 2006 meeting, the Engineering Working Group (EWG) foreshadowed the need for such a project and the subsequent European FP7 PrepSKA initiative, the drafting of which commenced in late 2006, provides a framework for the design effort. Most of the relevant effort occurs within PrepSKA Work Package 2 (WP2), which integrates, with minimal change, previous SKA design and demonstration milestones. The resulting timeline is summarized in Figure 1. More details of WP2 are contained in Annex 2 of this document.

PrepSKA (with its deliverables and reporting imperatives) is the umbrella for central and regional engineering work but the practical motivation for firming up the design - and hence specification - process is to meet the provisional 2012 SKA Phase 1 start of construction target. While some of the PrepSKA system design depends on receptor demonstrations in regional Pathfinders, many of the data transport, signal processing and computing design projects can be pursued within the context of a “base” system design, provided the overall SKA capability goals, and the required delivery timescales, are clear from the first-round specifications. More detailed engineering reviews, resulting in refined specifications, will be conducted in the course of PrepSKA and the regional programs. Information on the national and regional programs is given in the accompanying document “Status of Pathfinder Telescopes and Design Studies”

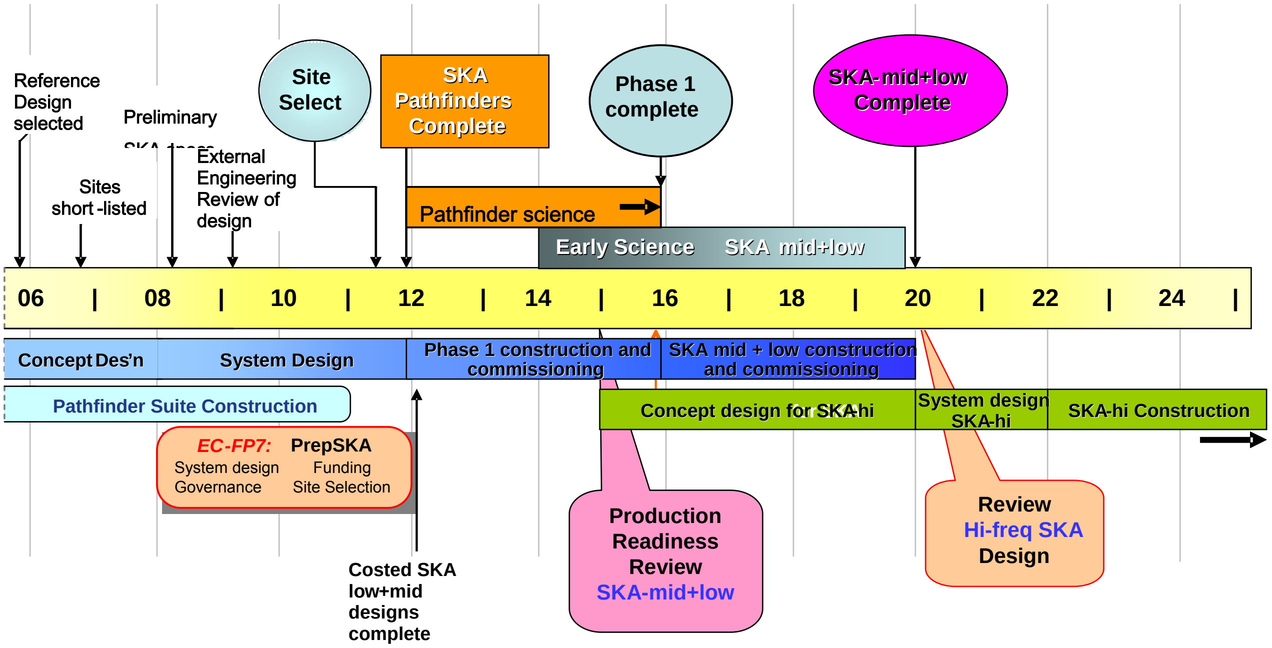


Figure 1. Overall SKA Time Line

3. The Science Case for the SKA

3.1. Key Science

The international community has developed a detailed and compelling science case for the SKA, as described in detail in New Astronomy Reviews, volume 48 (2004). The core of the science case is five Key Science Projects (KSPs); each KSP represents an unanswered question in fundamental physics or astrophysics, is science either unique to the SKA or for which the SKA plays a key role, and is something which can excite the broader community. The resulting five KSPs are discussed below.

Note that the science case as conceived in 2003-2004 was for the full set of SKA specifications in SKA Memo 45. The present document proposes a three-phase implementation of this facility as described in Section 1. In the following description of the five KSPs, some topics (3.1.1ac, 3.1.2abc, 3.1.3ab, 3.1.4ac, parts of 3.1.4b, 3.1.5c, parts of 3.1.5b) will be fully feasible or partially achievable with Phase 2. A smaller subset (3.1.1b, parts of 3.1.4b, 3.1.5a, parts of 3.1.5b) can only be executed with Phase 3.

3.1.1. Probing the Dark Ages

The focus of this KSP is the formation of the first structures, as the Universe made the transition from largely neutral to its largely ionized state today.

a. Reionisation

Recent observations have set the first constraints on the Epoch of Reionisation (EoR), corresponding to the formation epoch of the first luminous objects. Current data indicate that the intergalactic medium (IGM) perhaps gradually evolved from a fully neutral state at a redshift $z \sim 14$ to a largely ionised gas at a $z \sim 5.5$. The SKA is being designed to study both this process of reionisation and the first luminous objects which drove this process. Observations at frequencies below 200 MHz will provide the SKA with the unique and powerful capability to carry out direct "tomographic imaging" of the neutral IGM, during the transition phase from a fully neutral IGM during the dark ages, and then through to the current ionised Universe.

b. The First Metals

Operating at shorter wavelengths, the SKA will provide key complementary information on the physical processes involved in the formation of the very first galaxies. At wavelengths as short as 12 mm (25 GHz), the SKA opens a unique and powerful new window into the study of the first galaxies, through observations of the lower order molecular emission lines from common species such as CO, HCN and HCO^+. The lower order CO transitions provide the cleanest measure of the total molecular gas mass (the fuel for galaxy formation) and the best method for determining galaxy dynamics, and hence total mass.

c. The First Galaxies and Black Holes

The first supermassive black holes formed rapidly, as evidenced by the quasars observed at redshifts $z \sim 6$. Understanding how quickly supermassive black holes can form (particularly given the apparently close link between black hole and bulge mass for galaxies at the current epoch) is a common theme for next generation instruments. Currently, optical surveys are revealing the most distant quasars, and deeper surveys with an ELT may reveal even more distant objects. Conversely, deep radio continuum surveys with the SKA will be able to reveal the potentially obscured first generation of accreting massive black holes, while continuum and molecular SKA observations will provide direct images of star formation activity within the host galaxies.

3.1.2. Galaxy Evolution, Cosmology and Dark Energy

The aim of this KSP is to probe the structure of the Universe and its fundamental constituent, galaxies, by carrying out all-sky surveys of continuum emission and of HI to a redshift $z \sim 2$. HI surveys can probe both cosmology (including dark energy) and the properties of galaxy assembly and evolution.

a. Dark Energy

An HI emission-line survey is able to map out galaxies independently of dust extinction, while the resultant accurate redshift lets us locate the object's position in the three-dimensional cosmic web. Through such measurements, the SKA can deliver the most accurate measurement of the clustering pattern of galaxies ever achieved, providing tests of theoretical models for the growth of structure in the Universe and allowing us to pinpoint various cosmological parameters. Most notably, HI surveys with the SKA will permit an accurate quantification of "dark energy", which is believed to comprise 70 per cent of the current energy density of the Universe, and which is driving the acceleration of the cosmic expansion. One of the cleanest methods of measuring dark energy in the Universe is by accurately delineating the small-amplitude "acoustic oscillations" in the clustering power spectrum. This baryonic signature has a physical origin identical to the acoustic peaks already seen in fluctuations of the cosmic microwave background (CMB), which act as an accurate standard ruler for the experiment. The measurement of these oscillations as a function of redshift will permit an extremely accurate determination of way in which the equation of state of dark energy evolves with cosmic time, discriminating between different models for this mysterious phenomenon.

b. Galaxy Evolution

Neutral hydrogen is the basic ingredient for star formation and galaxy assembly. Only the SKA can provide a complete inventory of this material. In addition to the full HI picture, hydrogen surveys with the SKA can provide an unbiased view of the star formation rate in galaxies, free from dust and obscuration. The SKA will uniquely image the distribution of neutral hydrogen out to high redshift and in a wide range of environments. HI spectra also provide a kinematic probe of the depth of each galaxy's potential well, allowing direct tests of galaxy evolution models which deal with mass as well as light.

c. The Local Cosmic Web

On the largest scales, a filamentary "cosmic web" of galaxies, clusters, and superclusters is being revealed through a combination of theoretical and observational analyses. The strands of this web mark the pathways by which large-scale structure assembles. X-ray observations of high ionisation species may already be revealing local strands of this cosmic web, and future X-ray missions will undoubtedly give a more complete picture. However, these observations are limited to elements with low fractional abundances, and the metallicity of the gas is uncertain. By contrast, the SKA will be able to probe intergalactic hydrogen (potentially both the ionised and neutral components), offering a direct probe of the baryonic component of the local cosmic web.

3.1.3. The Origin and Evolution of Cosmic Magnetism

Magnetic fields are an essential part of many astrophysical phenomena, but fundamental questions remain about their evolution, structure, and origin. The goal of this KSP is to trace magnetic field evolution and structure across cosmic time.

a. The Rotation Measure Sky

An all-sky SKA survey of Faraday rotation can provide rotation measures (RMs) toward $>10^8$ background sources. This data-set will be a unique probe of magnetism in the Milky Way, nearby galaxies, and in distant galaxies, clusters and proto-galaxies. Using these data, we can map out the evolution of magnetised structures from redshifts $z > 5$ to the present, and can reveal what role cosmic magnetic fields have played in the evolving Universe. At the high end of its frequency range, the SKA will also have the capability of measuring Faraday rotation against the polarised CMB. Such measurements will allow the SKA to probe the weak initial fields (if they exist) that could act as the seeds for magnetism and structure at later epochs. At the same time, because CMB polarisation measurements are at frequencies high enough to be free from the effects of Galactic foreground Faraday rotation, they can be combined with longer wavelength data to infer the three-dimensional structure of the Milky Way's magnetic field.

b. The Cosmic Web

Synchrotron emission from shocks in the high-redshift IGM should be observable in sensitive low-frequency surveys for faint extended emission. Detection of such structures with the SKA will allow us to directly identify the magnetic field geometries that acted as the initial conditions for the first galaxies and clusters, and will demonstrate what role IGM fields have played in structure formation.

3.1.4. Strong Field Tests of Gravity Using Pulsars and Black Holes

The goal of this KSP is to identify a set of pulsars on which to conduct high precision timing measurements. The gravitational physics that can be extracted from these data can be used to probe the nature of space and time.

a. Direct Detection of Gravitational Waves

Pulsar timing arrays can detect low-frequency gravitational waves passing over the Earth by comparing timing residuals from a large number of pulsars widely distributed across the celestial sphere. Only millisecond pulsars can be timed with sufficient precision to make a detection possible. Binary super-massive black holes in the cores of galaxies are the most likely astrophysical sources, but relic gravitational waves from the inflation era and oscillations of cosmic super-strings in the early Universe may also be detected. With its huge sensitivity and ability to monitor a large number of pulsars, after five years or so the SKA will either detect gravitational waves from such systems, or will begin to put tight constraints on models for their origin.

b. Measurement of Black Hole Spin

Within general relativity (GR), black holes are the simplest possible objects, with all properties determined by their mass and spin. The measurement of the spin of a black hole would allow us to test GR descriptions such as the Cosmic Censorship Conjecture, which postulates the existence of an event horizon to hide the singularity. The SKA, through timing measurements of a pulsar orbiting a black hole, will provide the most likely means of detecting this effect. The timing measurements of a pulsar in a neutron star-neutron star binary have already been analyzed to determine the deformation of space-time within the binary. In a similar fashion, the signals from a pulsar in a neutron star-black hole binary should also contain information about the black hole spin, among other effects. Possible targets for an SKA observing program include a pulsar/stellar-mass black hole binary in the Galaxy, a pulsar orbiting an intermediate black hole in the centre of a globular cluster, or pulsars in orbit around Sgr A*, the super-massive black hole in the Galactic centre.

c. Theories of Gravity

Both Solar system measurements and pulsar timing have contributed to stringent constraints on deviations from GR in the weak-field limit. Any physics beyond GR is therefore expected to be detected in the strong-field limit. A general definition of a strong-field experiment is one where self-field effects need to be taken into account, such as is the case for the study of binary pulsars and black holes. Pulsar timing with the SKA will provide a rigorous examination of possible departures from the predictions of GR in this strong-field regime.

3.1.5. The Cradle of Life

This KSP aims to probe the full range of astrobiology, from the formation of prebiotic molecules in the interstellar medium to the emergence of technological civilisations on habitable planets.

a. Imaging Proto-planetary Disks

It is now clear that accretion disks are both the means by which the late stages of stellar accretion proceed and the environment in which planets form. Their study forms an integral part of essentially all major instruments operating at wavelengths from the visible to the radio.

Most observations of proto-planetary disks target either thermal emission or scattered starlight from them. A key aspect of the SKA is that it will need to observe at wavelengths near 1 cm, so that it will be sensitive to the thermal emission from dust grains of a comparable size. Planet formation can be generally understood as a hierarchical process, but a major uncertainty in our current understanding is how particles of order 1 cm in size ("pebbles") accrete to form larger objects, since the typical kinetic energies of pebbles is such that they should collide destructively rather than accrete to form larger objects.

The second major advance provided by the SKA will be the imaging of proto-planetary disks. For the nearest star forming regions, planets having semi-major axes of 1-5 AU around a solar-mass star have orbits that are ~10-100 mas in diameter. The SKA will have the highest angular resolution (~1 mas) of all of the major next-generation observatories aiming to study these systems. Furthermore, by being able to observe at frequencies for which disks will be optically thin, the SKA will be able to resolve the spectral energy distribution of these disks, and thus will be able to produce unique images of the locations at which on-going planet assembly is occurring. By observing disks at centimetre wavelengths, the SKA will be probing them at a stage in the planet assembly process for which our uncertainty is the largest.

b. Prebiotic Molecules

Many of the complex molecules found in space are also found in laboratory experiments specifically designed to produce prebiotic molecules under assumed primordial Earth-like conditions. This suggests that a universal prebiotic chemistry is at work in space. Thus, the study of prebiotic chemical evolution in interstellar clouds will be an ever increasing area of research to determine exactly how amino acids, complex sugars, and other important biomarkers are formed in space.

ALMA is designed to be a powerful probe of molecules in interstellar clouds. However, within the last few years, it has become apparent that a number of complex interstellar molecules of prebiotic interest emit via low-energy transitions more suitable to the longer wavelength observing range of the SKA. Thus, the SKA and ALMA will complement each other in the study of interstellar clouds, since the SKA will be able to observe low-energy rotational transitions of complex molecules, inaccessible to ALMA. For instance, a recent detection of glycolaldehyde (CH2OHCHO) with the Green Bank Telescope resulted from observations of transitions at frequencies ranging from 13 to 22 GHz.

c. The Search for Extraterrestrial Technological Civilisations

Detecting the presence of another technological civilisation would be prima facie evidence that the entire range of astrobiological processes - from planet formation to the origin of life to development of intelligence - are universal. With its sensitivity, the SKA will be without peer in Search for Extra-Terrestrial Intelligence (SETI) programmes because it will be able to search for *unintended* emissions. By contrast all SETI programs to date have only been sensitive to beacons, i.e., powerful broadcasts intended to be detected by other civilisations. The sensitivity of the SKA is such that its nominal detection threshold will be sufficiently sensitive that it could detect typical airport radar out to 30 pc, comparable to the distances for many of the currently known planets. Modest improvements in signal processing afforded by additional computing power should bring the SKA to a level where leakage radiation from transmitters with power only at the level of current broadcast television stations could be detected over interstellar distances.

3.1.6. Exploration of the Unknown

As has been detailed above, the Square Kilometre Array has been conceived as a telescope which will both test fundamental physical laws and transform our current picture of the Universe. However, the scientific challenges outlined above are today's problems; will they still be the outstanding problems that will confront astronomers in the period 2020-2050 and beyond, when the SKA will be in its most productive years? If history is any example, the excitement of the SKA will not be in the old questions which are answered, but the new questions that will be raised by new types of observations.

The SKA is a tool for as-yet-unborn users and there is an onus on its designers to allow for the exploration of the unknown. The SKA community have thus adopted an underlying philosophy for the SKA that this instrument be not only much more powerful than previous radio telescopes, but that it also be highly flexible, and have an operating philosophy which positively encourages and allows the astronomers of tomorrow to look at the sky and to examine their data in new and creative ways. We include "Exploration of the Unknown" as a goal for the SKA as part of a firmly founded expectation that the most exciting things to be discovered by the SKA are those that we have not yet conceived.

3.2. Headline Science for the SKA

The full SKA science case results in a wide set of demanding specifications. However, the above discussion illustrates that the KSPs have evolved into "themes" rather than specific projects, in that they collect together highly related but distinct experiments. One difficulty recognised with this situation is that the requirements of each experiment within a given KSP can be radically different, making it difficult to use prioritisation of the KSPs as a way of isolating the key specifications.

In 2005, the SKA Science Working Group (SWG) consequently set out a list of "Headline Science" projects, i.e., a subset of the full ensemble of SKA experiments which were seen at that time as constituting the most vital and highest priority component of each KSP. Since the science case continues to evolve, the “Headline Science” topics could potentially be revised in future iterations of the science case.

With this caveat in mind, the “headline science” topics, as decided upon in 2005, are as follows:

3.2.1. Probing the Dark Ages

- Mapping of redshifted HI from the Epoch of Reionisation

3.2.2. Galaxy Evolution, Cosmology and Dark Energy

- Galaxy evolution as a function of cosmic time (HI emission to $z=3$; HI absorption at $z > 3$)
- Dark energy via baryonic oscillations seen in HI

3.2.3. The Origin and Evolution of Cosmic Magnetism

- The rotation measure grid

3.2.4. Strong Field Tests of Gravity Using Pulsars and Black Holes

- Tests of gravity via timing of binary pulsars with neutron star and black hole companions
- Detection of nanohertz gravitational radiation using pulsar timing arrays

3.2.5. The Cradle of Life

- Planet formation in proto-planetary disks

3.3. The Phase 1 Science Case

Many aspects of the SKA KSPs require the capabilities of the full SKA, while historical experience with interferometers suggests that the SKA will undergo a significant construction phase. Moreover, it is possible that some aspects of the full SKA will be available much sooner than others; for example, the logistical aspects of constructing and emplacing the antennas in the core region of the SKA is likely to be considerably easier than the placement of antennas on continental baselines.

For these reasons, the SKA community has recognised that it is important to consider science topics that do not require the sensitivity, angular resolution or frequency coverage of the full SKA. Specifically, design and funding considerations have been focused on a formal milestone designated "SKA Phase 1", representing the stage in construction when the SKA has reached approximately 15-20% of its full capability.

Despite its reduced sensitivity compared to the full SKA, Phase 1 would nonetheless have a substantial scientific capability in its own right. To identify high-priority science for Phase 1, the Science Working Group (SWG) re-examined the science case for the full SKA, in order to identify experiments that could address important but currently unanswered questions in fundamental physics or astrophysics, excite the broader community, and which showcase the potential of the full SKA.

The text in the rest of this section was developed by the SWG on the basis of SKA Memo 69, which laid out proposed specifications for a Phase 1 SKA. The top-level specifications assumed were A_{eff}/T_{sys}=2,000, frequency range 0.3-10 GHz, and a field of view of 50 deg^2 below 1 GHz, 1-10 deg^2 for 1-3 GHz and $(1.4/freq)^2$ above 3 GHz. Below 1 GHz, these parameters translate into a Survey Speed Figure of Merit $((A_{eff}/T_{sys)}{}^2$. FoV see section 5.1.4) of $2x10^8$. These specifications were subsequently updated by the ISSC in March 2006, who changed the frequency range for Phase 1 to 0.1-25 GHz (the same as specified in Memo 69 for the full SKA). In March 2007, the specifications were further updated by the ISSC in their resolution (Annex 1) to focus Phase 1 on the mid-band frequencies (300 MHz to 3+ GHz) while retaining the option to include frequencies below 300 MHz. In the light of the ISSC decisions and further discussion at SKA2007 (September 2007), the specifications for Phase 1 are revisited later in this document, and, as a consequence, most but not all of the science presented in this section is achievable with the Phase 1 implementation presented in Section 10.

Using the criteria noted two paragraphs above, the SWG proposed the following areas of focus for science with Phase 1:

- Building Galaxies: Hydrogen and Magnetism;
- Pulsars and the Transient Sky;
- First Light: The Epoch of Reionisation.

3.3.1. Building Galaxies

Just as for the full SKA, surveys of HI and of Faraday rotation with Phase 1 will provide major advances in our understanding of how galaxies assemble and evolve. Three main experiments are envisaged with Phase 1:

i. A wide field HI emission survey, capable of detecting galaxy masses below 10^9 solar masses to a redshift of $z \sim 0.5$ over 300 deg^2. This will provide the first measurements of the HI mass function of galaxies outside the local Universe (extending at high masses out to a redshift $z \sim 1$), providing powerful tests of current models for galaxy formation;

ii. An all-sky RM survey, to a continuum sensitivity of 2 μJy at 1.4 GHz. This will yield Faraday rotation for $\sim 2x10^6$ background sources, providing a detailed three-dimensional map of the Milky Way's overall magnetic field geometry. These measurements will be the benchmark against which any credible theory for how cosmic magnetic fields are organised and maintained will be tested; and

iii. An all-sky survey for HI absorption against all continuum background sources brighter than 50 mJy. This will provide a comprehensive measurement of the amount and distribution of HI gas in galaxies and in intergalactic clouds over the redshift range $1 < z < 3$.

3.3.2. Pulsars and Transients

Phase 1 is more than sufficiently sensitive and versatile to revolutionise our view of the time-variable radio sky. Experiments that Phase 1 can undertake in the time domain include:

i. Phase 1 can deliver a greatly enlarged "pulsar timing array" (PTA) of millisecond pulsars. Such an array would be an order of magnitude more sensitive to gravitational radiation than any current effort. Furthermore, even if a direct detection of gravity waves does not eventuate via Phase 1, the establishment of an appropriate sample of pulsars and development of appropriate calibration techniques will be crucial tasks for this instrument;

ii. Studies of the double pulsar PSR J0737-3039 with Phase 1 will increase the current timing precision of this system by a factor of several, due to improved sensitivity and to increased time coverage. As a result, tests of General Relativity and alternative theories of gravity will surpass limits achievable in the solar system. Other binary systems will benefit similarly from the enhanced timing capabilities, and newly discovered relativistic systems will enable additional independent tests. Increases in computing power by 2015 will enable better acceleration searches than presently possible, opening up the possibility of finding even more compact and hence relativistic systems;

iii. About 300 millisecond pulsars with predominantly white dwarf companions in nearly circular orbits will be detected in a Phase 1 pulsar survey. These systems are ideal for studying possible violations of the equivalence principles and tests of tensor-scalar theories. Many of the white dwarf companions may be detectable with Gaia; combining this information with pulsar data will enable us to put strong limits on violations of the Equivalence principle, conservation laws, or preferred frame effects; and

iv. A Phase 1 with a large field of view will enable the discovery of potential or yet unknown transient sources. Source types that we can speculate the Phase 1 may detect include prompt emission from gamma-ray bursts, radio supernovae, gravitational wave sources, annihilating black holes, or extraterrestrial emitters. Other, longer time scale phenomena, such as bursting radio pulsars, intraday variables, and extreme scattering events, will be able to be properly studied for the first time.

v. A Phase 1 with high frequency capability ($\geq$ 10 GHz) would be able to survey the Galactic Centre and may yield the first discovery of a pulsar orbiting a stellar black hole, or pulsars orbiting the super-massive black hole in Sgr A*. Such sources can eventually be used to map out the gravitational potential in the Galactic Centre, and to measure strong-field gravitational effects;

3.3.3. First Light

The ability of the Phase 1 SKA to probe the neutral IGM in the 21cm line of neutral hydrogen will make it a truly unique probe of the formation of the first galaxies and the process of cosmic reionisation. The incomparable sensitivity of even the first stage of the SKA will allow the study of molecular gas, dust and star formation activity in the first galaxies, as well as the radio continuum emission from the first accreting massive black holes. Such objects will be obscured at optical wavelengths due to absorption by the neutral IGM. Specific Phase 1 projects relating to First Light include:

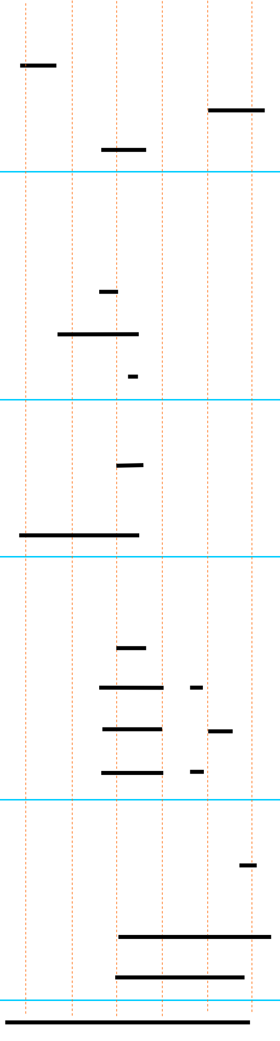
i. Phase 1 with a low frequency capability will be well suited to the direct observation of ionized bubbles (giant Stromgren spheres) around luminous quasars in a still significantly neutral IGM. Quasars that are luminous enough to create HI "holes" of angular size ~5-10 arcmin will probably be very rare, as deduced from an extrapolation of the SDSS discovery rate at redshifts $z \sim 6$. If quasar Stromgren holes can be detected and their structure studied, this will be an invaluable source of information on the supermassive black hole population at high redshifts and the nature of the ionising spectra responsible for the reionisation of the Universe; and

ii. Phase 1 with a high frequency capability will be able to achieve a substantial increase in sensitivity over the EVLA in studies of molecular line emission, thermal emission from warm dust and radio synchrotron emission from "normal" galaxies within the EoR. Current galaxy evolution models predict that continuum emission from typically ~1,000 such systems per deg^2 will be detected in a 12-hour synthesis.

4. Desirable Specifications for the SKA

Based on the Key Science projects described in the previous section, the resulting desirable top-level specifications are summarised in Table 4, with Table 5 giving references for survey speed entries. In Sections 5 to 8, these desirable specifications are confronted with the reality of their feasibility on the timescales involved, and the costs involved in relation to the target budget. Based on this analysis, current thoughts on achievable as opposed to desirable specifications are presented in Section 9.

Table 4. Desired specifications for the SKA



KSP ID	KSP Description	Frequency Range GHz	FoV	Sens-itivity	Survey Speed	Resn.	Base-line	Dyn. Range Driver	Poln. Driver
		0.1 0.3 1.0 3.0 10 30	deg^2	m^2/K	deg^2 m^4 K^{-2}	mas	Km		
1	**The Dark Ages**								
1a[†]	EoR				>~3x10^7		1	*	**
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				6x10^9		5		
2b[†]	Galaxy Evolution			20,000	1x10^9		10		
2c	Local Cosmic Web				2x10^7		0.5		
3	**Cosmic Magnetism**								
3a[†]	Rotation Measure Sky				2x10^8		10-30		**
3b	Cosmic Web				1x10^8		5		**
4	**GR using Pulsars & Black Holes**								
	Search				1x10^8		< 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				

[†] Headline science, see Section 3.2

* See Section 5.1.8 for explanation of Dynamic Range drivers

** See Section 5.1.6 for explanation of Polarisation Purity drivers

Table 5. Survey speed references for Table 4.

KSP ID	Reference for Survey Speed Spec.
1a[†]	Memo 83
2a[†]	Email exchanges with Rawlings/Blake, Apr 07
2b[†]	Memo 83
2c	Braun (2004) in "Science with the SKA"
3a[†]	Beck + Gaensler (2004)
3b	Feretti et al. (2004)
4 (search)	Memo 83

[†] Headline science, see Section 3.2

5. Cost-Driving Specifications

Sections 6 to 8 discuss challenges and cost issues for particular technologies but set out in this section are key specifications common to all SKA concepts. Also mentioned are a few economic constraints which, as they are determined, will feed back into a continuing refinement of SKA engineering specifications.

5.1. Top-Level Specifications

5.1.1. A_{eff}/T_{sys} as a Function of Frequency

This is a basic SKA sensitivity metric, determining directly the amount of collecting area constructed, the required efficiency of antennas, and the allowable noise contributions of feeds, RF coupling arrangements and receivers. When considered as a function of frequency it constrains receptor choices since particular technologies offer superior performance-to-cost characteristics in given parts of the radio spectrum.

5.1.2. Accessible Field-of-View as a Function of Frequency and Baseline

The accessible FoV specification, if stated as a science requirement, drives the choice of optimum receptor types within a given frequency band. Whether given as a science requirement or as a derived engineering quantity, the FoV helps define a maximum information rate from receptors, generating important secondary specifications for maximum data transfer rates, and signal processing and computing powers. In the simplest case the accessible FoV is the “primary beam” set by dish and single-pixel feed optics. In wide FoV technologies mooted for the SKA the accessible field is determined mainly by RF or digital processing operating on phased array elements. If the accessible FoV can be reduced on longer baselines, simpler and cheaper receptor technology and processing can be used outside the central parts of the SKA. One of the outcomes of the study reported in this document is that many SKA science requirements stated previously in terms of FoV turn out to be better given as survey speed requirements, effectively removing the FoV as a top-level specification for many science applications.

5.1.3. Processed Field-of-View as a Function of Baseline

The imaged FoV can be thought of as a “processed” FoV, an area on the sky which is potentially smaller than the maximum accessible FoV (see 5.1.2 above). To reduce cost, or even to make a given putative SKA economically feasible, one or more sub-regions of the accessible FoV may be selected for imaging or other science applications. Reducing the selected field size with baseline (angular resolution) has the effect of easing long-distance information data transfer (in the case where local station beamforming is used), processing and management requirements. Within specified limits, engineers envisage SKA observers being able to trade-off various parameters, such as number of sub-fields imaged within the maximum accessible FoV, bandwidth, spectral resolution, etc.

5.1.4. Survey Speed as a Function of Frequency

A traditional metric for survey capability is survey speed. As defined in SKA Memos 66 and 85, it is proportional to the product of $(A_{eff}/T_{sys})^2$, processed FoV and processed bandwidth, B. Often it is expressed without the bandwidth factor. It is used in this simplest form as a prime specification for the SKA given the instrument’s science ambitions (Section 3). An extensive description of metrics based on survey speed is given in an Appendix of SKA Memo 97 “The SKA as a Synoptic Telescope: Widefield Surveys for Transients, Pulsars and ETI” (J. Cordes) and will be summarised in a separate SKA memo. Assumptions that underlie the simplest expression of survey speed are that the entire effective area is usable in a survey, that the population of target sources is homogeneously distributed in Euclidean space, that the detection threshold (significance level) is unspecified, and that source emission is steady.

Using the simple form for survey speed, it is clear that for SKA science goals that involve large-scale surveys of steady sources, field of view can be traded against A_{eff}/T_{sys}. With new technology, the cost of better survey speed via expanded FoV (through either aperture arrays, PAFs or smaller dishes) may be lower than the cost of better A_{eff}/T_{sys}, providing the practical motivation for making tradeoffs. A survey speed specification alone may be insufficient for engineers, and SKA designers need to be aware of limiting A_{eff}/T_{sys} and FoV values as set out in Table 3. The bandwidth factor in the more complete survey speed expression needs to be considered, although the useable bandwidth differs between science applications. For the key HI surveys to be conducted by the SKA, wide bandwidths (hundreds of MHz) are highly desirable for providing maximal survey speed through velocity search space rather than sensitivity. An additional factor that needs to be considered for specific surveys is the minimum signal-to-noise required for detection. Net survey speed goes as the inverse square of this quantity and is thus radically different for continuum and spectral line surveys.

An extended figure of merit that makes explicit some of the extra factors relevant to SKA designs is

$$\mathrm{SSFoM} = B(N_{Fov}\ \Omega_{FoV}/N_{sa})(f_c\ A_{eff}/m\ T_{sys})^2,$$

where m is the minimum S/N for detection, Ω_{FoV} is the FoV of a single pixel, N_{Fov} accounts for field-of-view expansion with a multiple-pixel feed system in a LNSD approach and N_{sa} is the number of subarrays into which the collecting area is divided (to increase the total FoV at the expense of sensitivity). For aperture arrays, the product of number of beams and their solid angle replaces the $N_{Fov}\ \Omega_{FoV}$ factor in the above expression. General configurations allow only a fraction f_c of the total area to be used, assumed here to be the ``core" array. The extended expression follows from consideration either of solid-angle coverage or volume surveyed in Euclidean space. The form of SSFoM shows, by inspection, that tradeoff is between FoV, A_{eff}/T_{sys} and bandwidth. Discussion in this document focuses on tradeoffs between just the first two of these factors, effectively assuming that the processed bandwidth is the same for all technologies. This assumption needs to be investigated more closely.

Detection thresholds: Science tradeoffs between continuum, spectral-line and time-domain surveys should take into account the radically different S/N detection thresholds needed for a given level of statistical significance. The S/N threshold depends on the number of statistical trials done. For representative numbers, HI surveys require 2,000:1 more trials than a continuum survey; for SETI the ratio is 10^9:1 and for blind pulsar surveys with acceleration searches, the ratio is 10^{12}:1. For a fixed number of false alarm detections in a survey, the probability of false alarm will scale as the reciprocal of the number of trials.

Transient sources: The traditional survey metric presented above clearly fails for sources that are time variable. Surveys for transient sources introduce another factor, the probability P_t that a source is in the on-state when pointed at, written as

$$P_t(\eta, W, \tau) = 1 - e^{-\eta\tau\mathrm{eff}}$$

where η is the event rate, τ is the dwell time per direction in a raster scan or point-and-dwell survey, $\tau_{eff} = (\tau^2 + W^2)^{1/2}$ is an effective dwell time, and W is the event duration and τ the dwell time per direction. The probability factor is based on Poisson statistics and can be used to define a more general figure of merit:

$$\mathrm{TSFoM} = \mathrm{SSFoM} \times P_t(\eta, W, \tau)^{4/3}.$$

Optimization of TSFoM can be radically different from that for SSFoM because the net integration time on an event may be determined by the event duration W rather than by the observational dwell time τ in a survey.

Application of TSFoM must take into account the large phase space in event amplitude, rate and duration, as well as underlying source density in the survey volume. For example, fast, low-rate transients place a premium on total FoV that may override sheer sensitivity. However, dim but fast transients will require both large FoV and high sensitivity. Slow, frequent transients with $P_t \rightarrow 1$ can be handled in conventional imaging surveys.

Completeness of transient surveys needs to be considered further in the evolution of SKA specifications, a task that is beyond the current version of this document. It can be stated that all of the options given have their pros and cons with respect to coverage of the phase space for radio transients.

5.1.5. Angular Resolution as a Function of Frequency

Angular resolution requirements determine the maximum baselines in the SKA. Since there is a cost associated with deploying and operating multiple receptor types across a continent, specifying the angular resolution as a function of frequency allows engineers to determine which types of receptors are used in various geographical regions of the SKA (see Section 5.1.2). Note also the link between angular resolution and image size (Section 5.1.3) given finite data transport and processing resources.

5.1.6. Polarisation Purity

This specification is usually taken to mean “calibrated” polarisation purity, which implies that the constraint on the SKA engineering design is that the receptors be calibratable. This has consequences in the choice of the receptors themselves (in terms of, e.g., raw polarization performance and stability of cross-coupling), calibration algorithms and computing power. Results from Pathfinders and Design Studies are still pending but it is conceivable that polarisation demands could ultimately be a discriminant of receptor technologies, at least in the 300 MHz to 3 GHz range. In the present discussions, it is important that astronomers consider the effects of what may be, by present telescope standards, relatively poor “raw” polarisation performance, most obviously on observations in which little or no real-time or off-line calibration is feasible (e.g., some high time resolution modes).

Specific science drivers for high polarisation purity are as follows:

- The Epoch of Reionisation experiment (KSP 1a in Table 4) entails high polarisation purity because it requires detection of a weak spectral line signal at low frequencies, where Galactic synchrotron foreground emission is very bright. While most foreground signals have only a very gradual dependence on observing frequency (and so can be simply removed from the data), the Galactic foreground is highly polarised, and internal Faraday effects give this emission a very complex frequency dependence. Polarisation impurities will cause leakage of this polarised emission into the total intensity signal, and degrade the sensitivity of searches for the EoR. An approximate estimate of the polarisation purity required for this experiment is -30 dB, which would bring leakage from foreground polarised signals below that of the EoR emission. This purity needs to be reached over wide fields of view.
- For the experiments on Cosmic Magnetism (KSP 3), high polarisation purity is a crucial requirement. The focus of these measurements is the detection of polarisation and Faraday rotation from a large ensemble of sources: leakage of the total intensity signal into the other Stokes parameters will prevent such measurements. Since a typical extragalactic source has a linear polarisation fraction of a few percent, a purity of at least -30 dB over the entire field is required (after calibration and mosaicing).
- Pulsar timing experiments (KSPs 4a, 4b, 4c) rely on the precision of pulse arrival times to detect subtle time delays associated with gravity and General Relativity. A fundamental assumption underlying these measurements is that the time-averaged pulse profile of the sources being studied is invariant. However, pulsars can be highly linearly and circularly polarised, with the polarised pulse profile having a different shape to the total intensity profile. Polarisation leakage will distort the shape of the pulse, which when convolved with the pulse template will lead to incorrect arrival times. Since the effects being sought correspond to changes in the pulse arrival time of a tiny fraction of a microsecond, calibrated polarisation purity needs to be high, probably at the level of -40 dB at the centre of the field.

5.1.7. Total Bandwidth and Spectral Resolution

Bandwidth affects the sensitivity and survey speed of the SKA in continuum modes while the spectral (frequency) resolution determines the velocity detail available during line observations. Frequency resolution also sets a variety of smearing-related limits on observing parameters. From an engineering viewpoint data transport costs scale at least linearly with bandwidth, while processing costs scale directly with the number of frequency channels. In current thinking a large part of the frequency-domain processing (channelisation) could be done at the antennas, making the (substantial) antenna electronics cost a function of bandwidth and frequency resolution.

5.1.8. Imaging Dynamic Range

Imaging dynamic range (DR) [1] is the ratio of the brightest point in an image to the rms "noise" level in a region of the image devoid of emission. The rms noise level could be the result of thermal noise or it could be fluctuations resulting from irreducible, systematic errors in the telescope and/or imaging software. The maximum attainable DR for a particular telescope is reached after sufficient observing time, when the thermal noise level is less than the fluctuations caused by uncalibrated errors. Clearly DR is more of an operational measure of performance than a strict mathematical concept.

Successful accomplishment of many of the SKA science goals will require much greater DR than current instruments provide. This is particularly true for continuum observations, but spectral line observations may also be affected. Source counts provide a simple explanation - at a wavelength of 20 cm, on average there will be an 80-mJy source in each 1-deg^2 field-of-view. With a sensitivity of 10,000 m^2/K, the rms thermal noise on an SKA image will be about 8 nJy after 400 hours of integration, assuming a 400 MHz bandwidth. This integration period is a reasonable estimate for the longest available for a single field, and the DR needed to achieve this noise limit is 10^7 in a 1-deg^2 field-of-view. More routine 20-cm observations of a few hours might require a DR of 10^6.

Greater DR will be required for wider instantaneous fields-of-view. Sub-mJy sources come primarily from a population of star-burst and normal galaxies, and core-dominated AGN's. These objects have flatter spectra than the bright sources which tend to have redshifts less than one, and whose emission comes from steep-spectrum jets and lobes. As a result of these effects, the DR problems become more acute at longer wavelengths, although the impact of the increase will be reduced because there is less available bandwidth at longer wavelengths, so the thermal noise level is higher at the longer wavelengths. Moreover, source counts are typically determined in very favourable parts of the sky, away from really strong sources, extended emission, and the Milky Way. These occupy a substantial fraction of the sky in which even greater DR may be needed to reach very faint objects.

The DR of spectral line observations potentially need not be as great, since it should be possible to detect and isolate objects using both spectral and spatial information. But there are reasons why spectral-line observations could also require very high DR. For example, out-of-band continuum images are often subtracted from the image of total emission to enhance the contrast in the line. This standard technique will not work well if the side-lobe and error patterns are not identical in the two images being subtracted. This is not guaranteed at the level of even one part in 10^5. Simulated SKA observations could yield valuable information on this subject.

Spectral dynamic range, the ratio of the strongest features in a spectrum to the noise, is needed to prevent strong signals, typically RFI, from propagating across the spectrum as a result of non-linearities in the RF or digital sub-systems. The spectral dynamic range specification for the EVLA is 10^5. This could be a reasonable specification for the SKA as well, given that a low-interference environment is expected, but simulations will be needed to fully understand the interaction between spectral dynamic range and imaging dynamic range (DR).

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[1] Imaging dynamic range is to be distinguished mainly from spectral dynamic range, a similar concept in the spectral dimension only. Herein the full name is abbreviated to DR.

Polarization performance is another aspect of DR. Polarized emission is usually weaker by more than an order of magnitude than total intensity. Thus one might expect that bright sources would generate lower-level artefacts. However, even the seemingly straightforward determination of fractional polarization of weak sources still requires high-DR total-power images. Thus it might be possible to relax the DR specifications for polarization observations, but only for a restricted subset of science projects.

For many observations made with existing radio telescopes the integration-time per *u-v* sample is deliberately extended so as to average-out (smear) structure at the edges of the field. This tends to reduce the amount of data produced and improves the DR in the central area of the accessible field-of-view. In SKA-style surveys it will be necessary to image entire accessible fields-of-view all the time. Although there are large-area surveys observed with existing telescopes, the amount of data processing needed to remove artifacts could be too large to manage when scaled to SKA survey speeds.

Current large arrays (WSRT, VLA, ATCA) have been able to achieve DR of 10^5 or more in instances where the bright source is placed at the centre of the field, where artifacts are less likely to be generated. Achieving high DR will be much more difficult in situations in which the bright sources appear in random positions, such as near the half-power point of the antenna beam.

Sources of systematic error can be divided into time-variable and static errors. Static errors, however complex in origin, are much more amenable to calibration. In some cases, measures taken to transform a time-variable error into a static (or slowly varying) error could be very effective. For example, radiative scattering or far-out sidelobes from the SKA antennas will rotate against the sky unless the antennas are mounted on a suitable platform, such as an equatorial mount. If the scattering patterns are fixed on the sky, bright objects do not pass through the patterns to produce variable error signals. In general this approach will not be possible, and a-priori models of the sky and antenna patterns will likely be needed to remove these effects, possibly in real time signal-processing. This also applies to special objects such as the Sun. Almost surely, it will not be possible to reach the full sensitivity capabilities of the SKA during daytime observations.

The above discussion leads to one conclusion: DR must be carefully considered in SKA specifications. Moreover, it is unlikely that a DR specification of 10^6 - 10^7 can be achieved unless it is considered in the design of each telescope sub-system. In particular, despite their success in improving the imaging performance of current telescopes, it is unlikely that new or existing algorithms will be able reduce the effects of deficiencies in the telescope design, unless calibration and error-mitigation is considered early in the design process. Even if algorithms could improve imaging performance in principle, they may not be practical on the scale of the SKA.

The role of existing large telescopes and Pathfinders will be critical in evaluating the impact on DR of potential telescope components. For example, inclusion of proposed SKA sub-systems (antennas, feeds, PAFs, AAs, etc.) into existing telescopes could yield important information on their raw system performance. Large telescopes may be needed to detect the rather subtle errors that will ultimately limit SKA DR.

In summary

- The λ20-cm continuum DR will need to be 10^6 for routine observations and 10^7 where special processing effort is available, and likely not much less for spectral line and polarization observations. This is greater than existing large telescopes currently achieve.
- DR requirements will increase with wavelength and accessible field-of-view.
- DR is limited by an assembly of post-calibration, systematic errors in telescope systems and the imaging software. An analysis of each SKA sub-system will be needed to understand and potentially limit its contribution to the systematic error budget. This could be a major aspect of balancing cost and performance.
- Time-variable systematic errors are much more difficult to control than static errors. Modeling of telescope systems and simulated observations will be an important part of the design process. Existing large telescopes and Pathfinders could be utilized to better understand effects that limit DR and to measure the performance of new sub-systems and algorithms. The impact of

ionospheric and tropospheric phase fluctuations on achievable dynamic range needs to be investigated through simulations, along with careful measurements of the phase fluctuations at the two candidate sites.

5.2. Economic Constraints

As well as dealing with top-level science specifications SKA designers are confronted with economic realities such as the costs of transporting data, processing the data in custom signal processing engines and performing post-processing operations in commercial supercomputers. Infrastructure and operational costs applicable at a remote site will also place constraints on the system design, influencing e.g. the final choice of array configuration. In the sections following, representative estimates are made of what is likely to be affordable in the SKA. However, it is important to realise that as well as obvious breakthroughs in receptor technologies, the cost of other items also determines the information transport and processing capability of the SKA, and hence the achievable specifications. Many economic constraints (born out of technology maturity considerations) are epoch dependent, favouring a phased implementation approach such as that given in Section 10.

5.3. Demonstrated and Expected Receptor Performances

5.3.1. Tables of Parameters for Various SKA Technologies

In Table 6, current performance of Dish + WBSPF technologies is compared to specifications and goals for a number of key parameters. In Table 7, as similar comparison is carried out for Dish + PAF technologies based on current performance achieved through modelling and in bench tests. Table 8 shows this comparison for Aperture Array technologies.

Table 6. Dish + single pixel, wide-band feed

Parameter	Current	Phase 1	Phase 2
T_{sys}	40 K	35 K	30 K
Diameter	6 m	15 m	15 m
Efficiency	65%	65%	70%
Low freq. limit	1 GHz	500 MHz	500 MHz
High freq. limit	6 GHz	3 GHz	10 GHz
Frequency ratio	6:1	6:1	20:1
Instantaneous bandwidth	400 MHz (4 x 100 MHz IFs)	512 MHz	2048 MHz
Raw cross-polarization	-10 dB	-20 dB	-25 dB

Table 7. Dish + Phased Array Feed

Parameter	Current (Models & bench tests only)	Phase 1	Phase 2
T_{sys}	200 K	50 K	35 K
Diameter	Various	15 m	15 m
Efficiency	70%	80%	85%
Low freq. limit	700 MHz	700 MHz	700 MHz
High freq. limit	1.8 GHz	1.4 GHz	3 GHz
# elements	4x5	10x10	16x16
Instantaneous bandwidth	300 MHz	300 MHz	750 MHz
Raw cross-polarization	-20 dB	-20 dB	-20 dB

Table 8. Aperture Array

Parameter	Current	Phase 1	Phase 2	Comments
T_{inst} (+T_{sky}=T_{sys})	120 K	40 K	30 K	At low frequencies T_{sky} is important, so instrument noise, T_{inst}, is specified here
Low freq. limit	40 MHz	300 MHz	<70 MHz	Current low freq performance from sparse array: LOFAR
High freq. limit	1.5 GHz	1.0 GHz	1.2 GHz	Depends on performance-cost optimisation Current high frequency performance from EMBRACE – dense array
Mean bandwidth*	40 MHz	700 MHz	700 MHz	
Mean FoV*		250 deg^2	250 deg^2	
No. of independent steerable FoVs	2	1	≥4	Multiple FoVs enable longer integrations, to increase effective sensitivity (4 beams equiv. to 2 x T_{sys})
Scan angle range	±45°	±45°	±60°	
Raw cross-polarization	-20dB	-20dB	-20dB	At zenith
Data rate*		8 Tbs^{-1}	20 Tbs^{-1}	

* For a fully digital aperture array, the limiting specification is the total data rate from the array. This enables trading FoV or bandwidth as a function of frequency, which is necessary to tailor the response for a particular experiment.

6. SKA Technologies

6.1. Dish + Wide-Band Single Pixel Feed and Receiver

The dish + wide-band single pixel feed implementation of the mid-band SKA represents a low risk reference scenario for the 500 MHz - 10 GHz frequency range. The eventual upper frequency limit will depend on the outcomes of cost-effectiveness studies undertaken by various regional SKA projects, specifically the US TDP. This scenario is capable of supporting most of the Phase 2 key science projects, and the Phase 1 science case. It is therefore a credible final SKA scenario in its own right, and not merely a fall-back risk mitigation technology. For key science topics requiring high fidelity observations it is the technology of choice. In particular, the dish plus single pixel feed scenario provides the highest A_{eff}/T_{sys} for a given cost ceiling.

The dish antenna itself is intrinsically a wide-band device, with the nominal upper and lower operating frequencies determined by key physical specifications for the dish:

- The lowest operating frequency constrains the lower limit for the reflector diameter. $D > 20\lambda$ is a common guideline for moderately directive feeds. A 15 m dish has low diffraction losses down to 400 MHz, but will still operate well at 300 MHz, and avoid substantial dynamic range problems. If a folded optical configuration is used then the size of the Cassegrain or Gregorian subreflector is also constrained by the lowest operating frequency.

- The upper operating frequency determines limits on the reflector surface accuracy, structural stiffness and pointing accuracy, all of which are primary cost drivers for the antennas. For reference, Figure 2 shows the relative maximum gain, computed according to the Ruze formula, as a function of frequency for dishes of various surface accuracies. From this plot we determine that for an upper operating frequency of 10 GHz an rms surface accuracy of better than1.5 mm is required. At 10 GHz such an antenna would have a relative efficiency of ≈70%, which will be adequate for some C- and X-band science, given the large physical collecting area of the SKA.

- The USA, Canadian and South African regional development projects are investigating the use of moulds to form one-piece reflector surfaces. It appears that these various moulding processes provide a characteristic rms surface accuracy of better than ~2 mm, and hence the upper operating frequency may be fixed by this value. The nominal 10 GHz specification for the upper frequency looks like a viable value given the early data from the pathfinder projects.

In most existing dish-based telescopes the wide operating bandwidth of the reflector is partially spanned by a set of waveguide feeds and receivers with sub-octave bandwidths. The wide-band single pixel scenario specifies the use of novel feed antenna structures that are not limited to sub-octave bandwidths in order to reduce the cost and operational overheads associated with multiple receiver systems. Simultaneous access to a large contiguous frequency band provides simplified calibration and provides opportunities for “piggy-back” observing modes. The 20:1 frequency range implied by the SKA mid-band specification (0.5-10 GHz) may be addressable with a single wideband feed, but is likely to require multiple receivers to cover “reasonable” sub-bands. For instance two wideband feeds may be used to span the entire frequency range:

- a 3:1 feed covering 0.5-1.5 GHz optimized for HI science
- a 7:1 feed covering 1.4-10 GHz that provides adequate sensitivity and wide bandwidths across the L-, S-, C- and X-bands.

It might also be possible to develop feed structures that span the entire 20:1 frequency range, but are optimized for a number of sub-bands within this overall range, chosen on the basis of scientific importance.

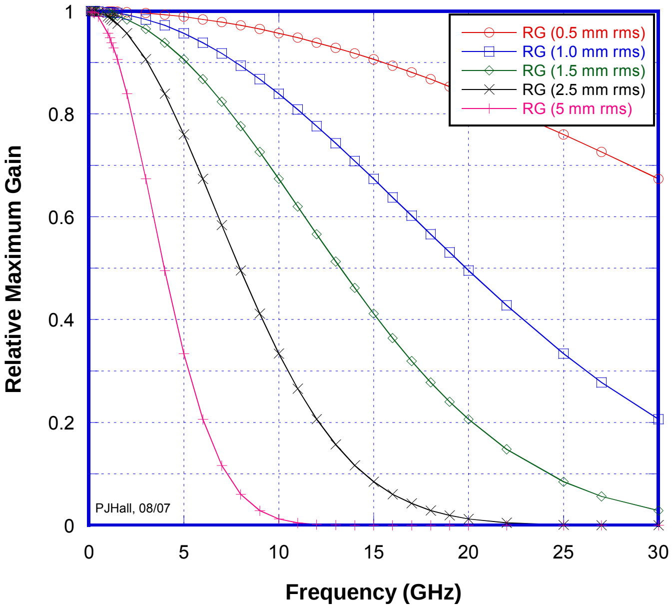

Figure 2. Relative maximum gain as a function of frequency for dishes of varying surface accuracy as predicted from the Ruze expression. Absolute gain at a given frequency is the product of the relative maximum gain and other antenna efficiency factors, including illumination efficiency.

A number of wide-band feed structures are currently being developed and evaluated by regional SKA projects. These feed structures can be categorized into two broad classes, as set out below.

- Log-periodic dipole-like structures:
  The Kildal 11 feed and the ATA pyramidal log periodic feeds already achieve 10:1 bandwidth radiation ability, but suffer from high T_{sys} penalties across much or all of the band. This is due to impedance mismatches and resistive losses. The Cortes/Cornell quasi self-complementary (QSC) feed is still in the design and prototyping phase, but computer models suggest that the impedance match of the feed will be good over a 10:1 frequency range. The illumination angle of these feeds is fairly independent of frequency because the physical size of the radiating elements scales with wavelength.

- Ridged horn structures:
  The ETS-Lindgren open boundary quadridge horn antenna is currently being adapted for radio astronomy use at Caltech/JPL. It also radiates across a 10:1 band, but suffers from large impedance mismatch ripples. The entire feed structure has to be cooled to achieve reasonable Tsys performance. The feed illumination angle is frequency dependent (varying by up to a factor of three across the band), but modifications using cooled absorbing material have reduced this problem.

These structures have demonstrated, or promise, efficient radiation over 10:1 bandwidths. None of the existing feeds show acceptable T_{sys} performance across the entire 10:1 bandwidth, hence it is prudent to specify a 6:1 frequency ratio in the first instance, thus requiring at least two feeds/receivers to cover the entire mid-frequency band.. Modern LNAs are already capable of 10:1 bandwidths, and hence a single feed/receiver package for this bandwidth appears feasible.

The sky noise contribution to T_{sys} has a broad minimum over much of the SKA mid-band, which argues for low receiver noise temperatures (T_{rec}) over the band. Cryogenic cooling of the LNA and the OMT and transmission line components that have ohmic losses are required to achieve low T_{rec} targets. The use of low-cost, high-reliability Stirling cycle coolers with these single pixel feeds is a technically feasible and cost-effective option, as demonstrated by the ATA.

The field of view (FoV) for the dish+single pixel feed concept is determined by the primary beam of the antenna, and is approximated to be $\pi/4(1.2\times\lambda/D)^2$ sr. The eventual dish diameter will be largely determined by cost optimization studies (see Section 8). For reference, Table 9 shows the FoV as a function of observing frequency for antenna diameters that are within the likely range of optimal values. The natural λ^2 dependence of the FoV (and hence survey speed) provides partial mitigation of severe survey requirements that are driven by the $(1+Z)^{-4}$ surface brightness dependence of redshifted HI sources.

Table 9. Natural primary beam field-of-view (in square degrees) for dishes of various diameters as a function of frequency (and HI redshift). Blank cells imply that the dish diameter is less than about 20 wavelengths, where diffraction losses begin to take effect and the beam becomes difficult to calibrate.

z	Frequency	Dish Diameter				
		6 m	10 m	12 m	15 m	20 m
3	355 MHz				11.8	6.6
2	473 MHz			10.4	6.6	3.7
1.5	568 MHz		10.4	7.2	4.6	2.6
1	710 MHz	18.4	6.6	4.6	2.9	1.7
0.5	947 MHz	10.4	3.7	2.6	1.7	0.9
0	1,420 MHz	4.6	1.7	1.2	0.7	0.4

Various optical path configurations and antenna mount geometries are possible with single-pixel feeds. The final configuration will be determined by detailed cost and performance modelling and results from the pathfinders. Symmetric optical configurations have traditionally been less expensive than offset designs, but the performance improvements provided by the unblocked apertures might outweigh the cost premium. This is particularly relevant to the stringent dynamic range requirements of the SKA. Careful mechanical design might also mitigate this cost premium of non-symmetric designs.

6.2. Dish + Focal Plane Array

There are two basic options for field-of-view expansion using focal plane arrays: multiple-feed clusters (MFCs) consisting of substantially non-interacting elements (such as horns), or mutually-coupled phased arrays. The general challenge faced in designing any focal plane FoV expander is to obtain useful expansion factors while preserving adequate performance, measured in terms of sensitivity and beam quality, from off-axis beams. These beams are subject to aberration and the performance is maximized by the use of suitable optical parameters (e.g. large f/D) and/or a suitably complex electronic beamformer (in the case of the PAF).

While MFCs do not sample fully the focal plane and do not offer the same capacity as PAFs for high quality off-axis beams with high efficiency and cancellation of spillover noise, such clusters have been used to great scientific advantage in a few existing telescopes, including the Parkes 13-beam and Arecibo 7- beam instruments. The main practical challenge with MFCs for mid-band SKA or Pathfinder applications is obtaining a sufficiently wide bandwidth with tractably small feeds. The Parkes 13-beam system, for example, gives only a 16% (200MHz) bandwidth centred at 1.37 GHz, even with large and highly-optimized stepped-circular feeds. Unlike the PAF, where the FoV is essentially constant over bandwidth ratios of >2:1, the sky coverage of an MFC can become very sparse indeed at the highest frequencies, severely limiting the attainable survey speed. At low frequencies the MFC becomes very large. SKA Memo 71 by Bruce Veidt provides a very useful comparison between MFCs and PAFs and includes a discussion of a number of factors impacting telescope performance. While no current SKA Pathfinder is pursuing the MFC route, the US Technical Development Program will re-assess the technology in the SKA context, especially its promise at the higher SKA frequencies to be accessed in SKA Phase 3.

With the Pathfinder emphasis on PAFs we restrict our discussion to this type of feed for the remainder of this document.

Various forms of dense phased arrays suitable for use in the focal plane of a reflector are being considered by astronomy groups around the world. These were first developed for radio astronomy by Rick Fisher at NRAO in the 1980s. In recent years the main developments have been at ASTRON in the Netherlands, the Hertzberg Institute in Canada, and at CSIRO-ATNF and Sydney University in Australia.

Phased array feeds at (or near) the focus of a dish are a cost effective way to increase the FoV and hence survey speed of a single dish. They represent a compromise between the aperture arrays and the single pixel feeds since they still get the concentrator cost advantage of the single dish, with decreased number of phased array elements per square metre of collecting area. When compared to an array of dishes with single pixel feeds the costs are shifted to digital electronics which will reduce in time, and which offer the potential to digitally enhance performance.

The ATNF is investigating linear connected arrays such as the checkerboard self-complementary array which is a dual polarization linear connected array with the "wires" tapered and fattened to the extent they are squares as in a checker or chess board. At ASTRON and DRAO Vivaldi arrays are being studied.

Much detailed work is still needed but the PAF electromagnetics are looking promising and measurements to date match the modelling. At ATNF a prototype 5 x 4 checkerboard PAF is undergoing range tests now and the first interferometer measurements will follow as part of the ASKAP project. At ASTRON, a 112 element dual polarization Vivaldi PAF has been deployed successfully on one antenna of the WSRT as part of the APERTIF project. At DRAO a 192-element dual-polarization Vivaldi array is equipped with receivers and a digital beam-former, and shortly will be undergoing tests in the laboratory and on a test antenna.

Because the aperture illumination is controlled by the digital beamformers the PAFs have the advantage of high aperture efficiency, low cross polarization and high beam symmetry. Furthermore, performance can be optimized for different experiments. For example, for an HI emission detection experiment one would maximize gain at the expense of far sidelobes but for a dynamic range limited continuum experiment one would sacrifice gain and use tapered illumination with low far sidelobes.

The “sweet spot” for dish size in PAF designs occurs with comparable cost in the dishes and the PAF electronics (See Section 8.2). This shifts the dish size balance to larger size dishes (15 m), possibly relieving constraints on operation at low frequencies. From a performance perspective, optimum PAF solutions may use dual reflector technology. Use of a dual reflector allows more effective RFI control and cooling options as well as providing new opportunities to mount the PAFs off-axis so more than one PAF, together with an on-axis wide band feed, are possible at the same time.

6.3. Aperture Arrays

Low frequencies can effectively use aperture arrays, AAs, as the collecting element. These cover the lowest frequencies 70 – 300 MHz and the critical frequencies from 300 MHz – 1 GHz to observe red shifted hydrogen from $z = 0.5$ to >15. At these frequencies, with relatively long wavelengths, the number of elements required for a given A_{eff} is practical. Indeed at the lowest frequencies, which require very large effective areas to counter sky noise, aperture arrays are the only practical collector technology. Aperture arrays using substantial digital processing systems are an inherently very flexible collector technology since the system can ‘trade’ field-of-view and bandwidth and hence tailor the array performance to that required by the experiment. The number of beams produced, and hence FoV, is essentially limited by processing and communications. AAs also have the characteristic that their sensitivity varies with scan angle, θ, whereby the effective collecting area is at a maximum on boresight (straight up) and reduces with scan angle due to i) geometrical projection of the array varying as $\cos(\theta)$

and ii) the modulation of the receiving elements themselves. The calculations in this document have used a mean sensitivity, which is the average sensitivity of the array when used for a survey, consequently there is the opportunity to have increased sensitivity for some observations close to the zenith.

Using aperture arrays to cover the low frequencies implies that to cover the frequency range for the SKA requires a dish based collector to work with the AA. There are major benefits for the dish system: it will not have to operate to frequencies much less than ~800 MHz, making small dishes practical electromagnetically and the feed systems such as PAFs much easier to implement. As discussed in Section 6.1 smaller dishes are cheaper for a given collecting area, have an inherently larger FoV and are easier to implement for high frequencies, but will require further improvements in the central processing systems to be affordable. The AAs and dish systems are very complimentary.

There are various element types and many different geometries for an AA station. The development programmes and systems - SKADS (with demonstrators EMBRACE and 2-PAD), LOFAR, MWA and PrepSKA - are studying the trade-offs in detail. Inherently there are two basic configurations, close packed (dense) and sparse:

- A dense array at least Nyquist samples the incoming wavefront by having elements spaced $\leq \lambda/2$. As the frequency reduces the array oversamples the wavefront resulting in the A_{eff} remaining roughly constant. The benefit is that there is a very tight control on the beam produced, with no array artefacts introduced. This type of array has the highest dynamic range capability of all AAs.
- A sparse array, as its name implies, has elements spaced further apart than $\lambda/2$. In the limit, each element can act independently and provide an element level A_{eff} which scales as λ^2. This is of great benefit, particularly at the lower frequencies where sky noise becomes dominant. The increasing A_{eff} increases the sensitivity and survey speed with increasing redshift (as does a single pixel feed on a dish), which helps counteract the decreasing flux density from the sources. The techniques for controlling the beam and sidelobes are being tested in LOFAR and MWA and being further developed as part of SKADS. In an interferometer such as the SKA, it is likely that a sparse array will be the preferred solution at frequencies <500 MHz.

A close packed array changes into a sparse array as the frequency increases and the spacing becomes $>\lambda/2$. The frequency range of the array is determined not only by the performance of the elements in the array configuration, but also by the signal transport, digitisation and processing. This is an important consideration at higher frequencies due to the number of receiving chains being implemented.

The number of elements required for a given sensitivity increases as a square law of the top frequency (assuming the spacing is $\geq \lambda/2$). The costs of a sparse array or close packed array, at a given frequency are therefore very similar for the same top frequency and sensitivity. This is clearly a very strong cost driver, hence the specification of this frequency/sensitivity point is important – and driven by the observational experiment requirements.

6.3.1. Implementation

The proposed AA *system* is illustrated in Figure 3. The basis of the implementation is as follows:

- To cover the frequency range from 70 MHz to ~1 GHz, the AA consists of at least two and possibly three element types.
- As far as possible the elements share the same back-end processing, therefore to a good approximation the AA cost scales simply as the number of elements and their frequency band. This is not quite correct since the lower frequency elements will be larger and there will be longer cable runs as the same number of elements are sparsed for low-frequency operation, but they may be able to have two or more analogue channels multiplexed into the same digital channel.
- The AA is a mix of sparsed AA and fully-filled AA over a range of frequencies where the wave front is fully sampled at the Nyquist rate (see Figure 3).

  - 70 MHz - 500 MHz (AA-lo): Coverage is shown using two arrays due to the frequency range. However, it is likely that one array can cover the range using, for example, large sparse Vivaldi elements. These can have up to 7:1 frequency range. Each element (when sparsed) has an effective area scaling as λ^2.
  - <500 MHz - ~1 GHz (AA-hi): This will be one array across the frequency range. The array is a close packed array for optimum dynamic range and sky noise performance. The sky noise is relatively low and constant in this frequency range, so the sensitivity remains reasonably constant. Above 800 MHz, the array becomes sparse, so the sensitivity falls; however, the survey speed performance is still very good due to the FoV.
- Instrument noise temperature, T_{inst} is the defined quantity for the AA. Since we are in high sky noise environment for AA-lo T_{inst} assumed to be 100K while it is 30K for AA-hi. This is then added to T_{sky} to make the total T_{sys}.
- The processing for the array enables a complete trade-off of FoV (number of beams) and bandwidth, plus the option of changing the number of digital bits per sample. The key parameter is therefore the data rate available from the array back to the correlator. In this case it is set at 8Tb/s per station. The result is that the HI dark energy experiment is practical by tailoring the FoV with frequency. For comparison purposes the system can support:
  - FoV of 250 sq deg, constant over the band 300 MHz-1 GHz
  - Bandwidth of 700 MHz
  - 8-bits per sample

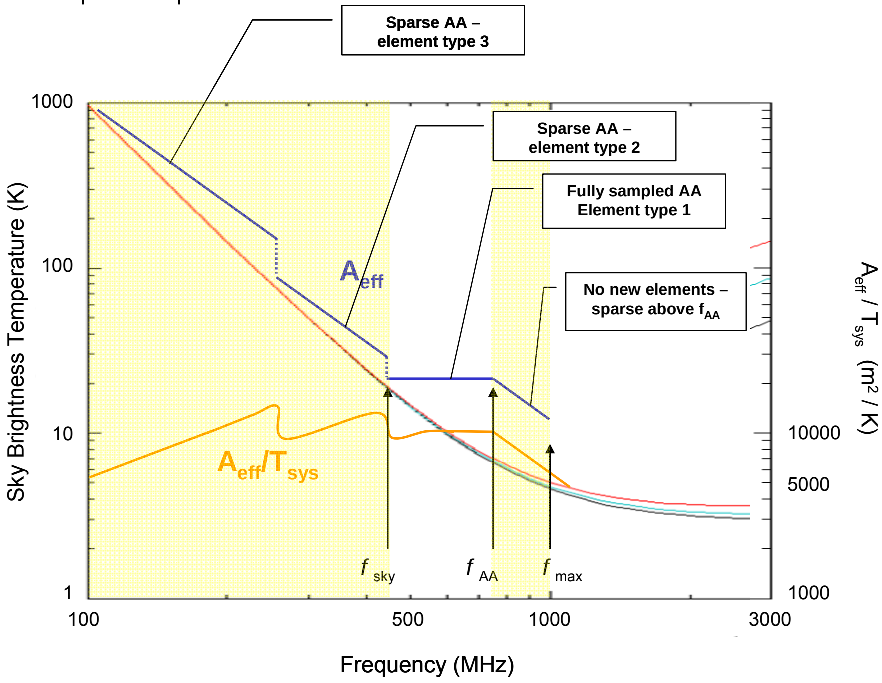

Figure 3. Aperture array type vs frequency shown in the presence of sky noise. The aim is to make the sensitivity reasonably constant by choosing sparse arrays at frequencies below ~450MHz where T_{sky} increase dramatically and to maintain high dynamic range where T_{sky} is relatively low, from 500 to 800MHz using close packed arrays.

The following assumptions are made about the performance of the AA:

- A fully sampled AA measures the incoming wave front at the Nyquist rate, and can, using appropriate processing, yield an aperture response function at least as good as an un-blocked paraboloid of the same projected area. For small AA diameters this may not true since the number of elements limits the range of apodization that can be applied to the AA. For a large, SKA sized, AA we have complete real-time dynamic control over the complex apodization function across the AA. This assumes that we are able to calibrate on an element-by-element level to remove systematics. Work within SKADS suggests this is practical using a combination of noise injection for each element together with absolute phase calibration from a near-field wide-band calibration source.

- Aperture arrays have the significant benefit that they will not shadow each other when closely spaced, which increases the system design flexibility particularly in the core. Aperture arrays being of fixed orientation, have a collecting area that is a projection of the geometric area in the direction of the observation. This reduces the mean A_{eff} available for a survey.
- When the AA is sparse it is no longer possible to fully reconstruct the incoming wavefront. This will limit the achievable dynamic range for continuum imaging, but detailed analysis will be required to determine how well a sparse array can perform in continuum. However, there will be excellent spectral dynamic range by direct digitisation followed by a high-accuracy poly-phase filter. Therefore, it is expected that the sparse AA will be able to reach the required dynamic range spec for HI imaging and EoR key science. Careful design of a sparse array geometry to minimise sidelobes will be required to ensure that the spectral dynamic range is achieved.
- There is a sensitivity minimum below which the AA cannot deliver survey science, despite increasing FoV. This is due to the systematics being too large for the required integration time. The limit needs to be determined; however, if it is much below the sensitivity used in the analysis (6,000 m^2 K^{-1}) this would lead to a very long integration time, suggesting that this is close to the limiting case.

It is assumed that AAs will only be deployed out to ~200 km as required for HI continuum observations. Longer baselines at sub-GHz frequencies can be provided by 15 m dishes since a large instantaneous FoV is not required for high angular resolution observations.

7. Technical challenges and cost-drivers for each of the three technology options

7.1. Dish and Single-Pixel Wide-Band Feed

The many dish concept implemented using single-pixel wide-band feeds (WBF) that cover the frequency range 0.5 GHz to 10 GHz and beyond attracts technical challenges that fall into two categories:

- Those that relate to the large number of receptors.
- Those that are specific to the WBF antenna

The first class of challenges include:

- The mass production of inexpensive small-to-medium (i.e. 6 - 15 m) dish antennas that have surface and pointing accuracies appropriate for the upper operating frequency, and have a diameter that is large enough to defeat diffraction losses at the lowest operating frequency, is a major challenge. The many dish concept implies the deployment of many thousands of dishes (see Figure 4) because of the ND^2 and $(ND)^2$ dependence, respectively, of the sensitivity and survey speed metrics. Regional pathfinder and development programmes (notably Canada, South Africa and USA) are currently producing prototype antennas that employ innovative fabrication techniques that promise to reduce the cost per surface area down by a factor of a few below current dish cost benchmarks, and in addition allow for mass production.
- The large number of antennas in a many dish implementation implies that the array data processor (i.e. correlator and beamformer) has to deal with massive data transport and processing rates which have both N (i.e. per dish) and N^2 (i.e. per baseline) dependencies. The architecture for the array processor has to be scalable so that it can be expanded to handle more baselines and greater bandwidth as the array grows through its various implementation phases, and must be able to track technology innovations and Moore's Law cost trends during the implementation and operational phases. This challenge is mitigated to some extent by the use of FX correlator architectures that allows the orthogonal parallelization of the compute task. It is likely that the eventual array beamformer will employ ASICs, reconfigurable logic (primarily FPGAs) and high-performance computing elements (e.g. multi-core processors). Packet-switched data transport fabrics (e.g. 10 Gigabit Ethernet switches) promise to provide solutions that are scalable and have their cost/performance driven by consumer demand. The CASPER collaboration is developing tools for integrating these data processing and transport elements.
- The massive number of baselines implicit in a many dish implementation provides a significant computing challenge. It is clear that innovative computing solutions, including reconfigurable high-performance computing platforms, will be needed to provide the necessary data processing pipeline, and constrain costs. Current imaging and calibration techniques will have to evolve to adapt to the massive volume of visibility data, and to achieve the specified spatial and spectral dynamic range.

The challenges that are specific to the WBF receptor mostly relate to achieving the specified per-dish sensitivity, i.e. A_{eff}/T_{sys}, over the full multi-octave frequency range. Table 10 lists some of the challenges pertinent to Dish + WBSPF and receiver technologies. Figure 4 shows how the number of dishes depends on dish diameter for various fixed constraint scenarios (fixed cost, Ae/Tsys and SSFoM). These numbers are very sensitive to aperture efficiency and T_{sys}, highlighting the need to obtain optimal sensitivity performance from the dish/feed receiver combination.

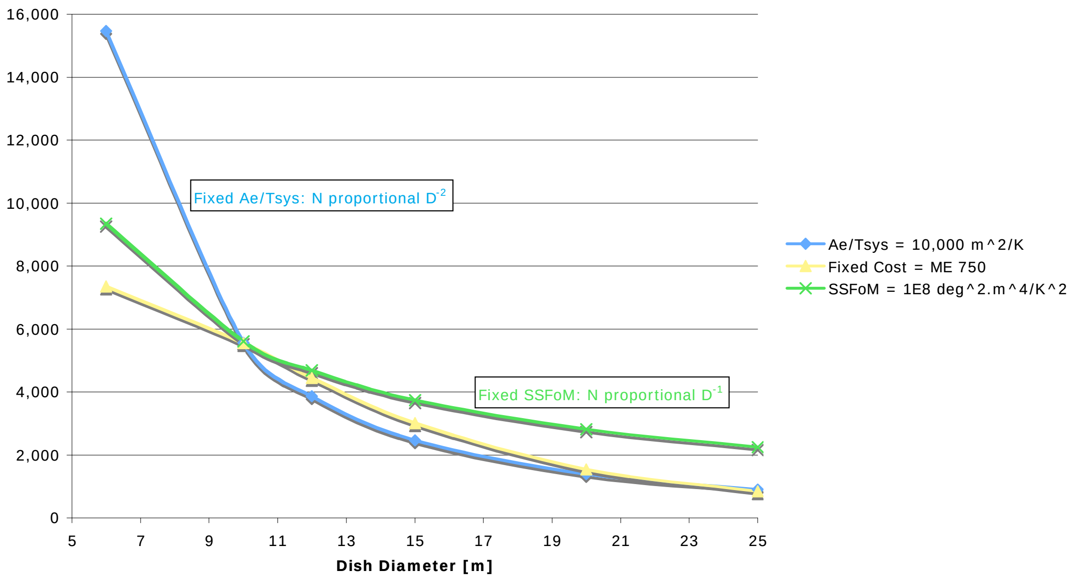

Figure 4. The dependence on dish diameter of number of dishes required to achieve various fixed constraint conditions (i.e. fixed cost, fixed sensitivity and fixed SSFoM). An aperture efficiency of 70% and system temperature of 30 K was assumed.

Regional WBF development projects associated with the SKA programme are addressing the following technical issues:

- The development of feed antenna structures that radiate over a 10:1 frequency range or larger, with the following characteristics:
  - Low and well-behaved return loss across the entire band, or equivalently a frequency-independent impedance.
  - A radiation pattern (i.e. gain) that is independent of frequency and provides a good compromise between high aperture illumination efficiency and low spillover loss.
  - Good cross-polarization rejection that is well-behaved across the band so that it can be corrected for in subsequent calibration processing.
- The design of LNAs that have the following characteristics:
  - Gain curves that are well-behaved across the entire band.
  - T_{rec} curves that are well-behaved and lie below the specified value across the band.
  - Input impedances that match the wide-band antenna structures (probably >50 Ω).
  - Most WBF structures are dipole-like and are well suited to balanced input LNAs.
- The dish antenna cost exceeds the receiver cost (see Figure 5 and Figure 6 in Section 8), so it is likely to be cost-effective to cryogenically cool critical components of the receiver/feed package in order to drive down T_{sys}. Temperature stabilization will be required in any case to ensure the gain and T_{sys} stability necessary to achieve the specified dynamic range. Integrated feed/receiver packages are required with the following characteristics:
  - Signal routing that reduces warm losses.
  - Low-cost cooling and temperature stabilization of key components.
  - Low mass, low power-consumption and low self-generated RFI.

Table 10. Challenges for dishes + wide-band SPF and receivers

Challenge	Consequences	Mitigation
Developing low-cost dishes with acceptable performance.	Reduced achievable A_{eff}/T_{sys}. Reduced upper frequency limit.	Collaboration with industrial partners to develop low-cost designs and manufacturing processes.
Cost and complexity of array data transport and processing.	Reduced achievable A_{eff} and/or instantaneous bandwidth.	Look at all site-specific options for implementation of optical fibre network implementation. Thorough cost/benefit analysis of the use of commodity (COTS) vs custom digital options.
Post-correlation computing.	Reduced spectral channels and field of view.	Development of efficient algorithms. Use of industrial best practice for high performance computing implementation.
Developing >10:1 feed structures with acceptable radiation properties for optimal dish illumination and good impedance matching.	Added cost and complexity of multiple feed/receiver packages. Reduced A_{eff}/T_{sys}	Coordinated R & D effort on custom wideband feeds.
Design of optical configurations that ensure low and stable sidelobe patterns, good aperture efficiency and low spillover contribution to Tsys.	Imaging dynamic range specification requires low and stable sidelobe pattern. Sensitivity, and hence survey speed, depend critically on aperture efficiency and Tsys.	Coordinated and thorough study of all optical path options, including symmetric and asymmetric configurations, prime and secondary focal positions, feed rotation and mount geometry.
Developing affordable and low T_{sys} feed/receiver packages.	Reduced achievable A_{eff}/T_{sys}.	Coordinated R & D effort on feeds, RF devices, feed and LNA cooling and system integration.
Developing wide-band feeds with good polarization characteristics over the entire FoV.	Reduced polarization purity in data products.	Coordinated R & D effort on various feed options, including tests on existing telescopes.

7.2. Dish + Phased Array Feed

There is no doubt that Phased Array Feeds (PAFs) for parabolic antennas can carry out the fundamental operation of forming a cluster of overlapping beams on the sky. The challenges are balancing performance measures against cost. The key performance measures at issue are efficiency, system noise, frequency coverage, polarization purity, and calibration/stability. Of secondary importance are power consumption, weight and RFI mitigation: factors that will influence cost (or the cost of antennas) directly. These performance factors will be influenced by the size of the field-of-view expansion (number of beams) and how the PAF is coupled to the antenna optics.

While the basic electromagnetic performance of PAFs can be modelled, it is difficult to include all of the above performance factors in a model or simulation. Thus a basic challenge is the effort of building prototypes and measuring their performance, ultimately testing with sensitive “real” radio telescopes. Carrying out this R&D while at the same time building large-scale telescopes that depend on PAFs requires careful risk-balance/project-management. Nevertheless, the rewards in performance and system cost - potentially affecting even the feasibility of high-survey-speed science experiments - are clearly worth a major effort.

The nature of the challenges and potential solutions or trade-offs are briefly discussed:

i. **Efficiency:** The relevant efficiency here is the fraction of a plane-wave signal that gets through to the output of a beam-former. In principle, PAFs can provide programmable, optimized illumination of the reflector, significantly better than a single-pixel feed. Potential resistive losses in the PAF elements should be small enough not to affect efficiency significantly. The extent to which PAFs can control the beam-shape depends on the number of elements in a particular beam-sum and on the spacing between elements in units of Airy Disk diameter, a function of the focal ratio of the antenna. In general, increasing either number will increase the cost proportionately. In all cases, forming beams farther off-axis to increase the field-of-view will be progressively more difficult.

   A dual-reflector antenna provides an increased focal ratio at the expense of requiring more elements. This will increase PAF cost, but the cost of the antenna itself may decrease because the potentially heavy, power-hungry PAF can be placed more conveniently at a secondary focus. The dual-reflector system will have lower system noise and other benefits (see sub-section vi below). In this one area alone, there are complex optimizations to be made. The dual-reflector system can also enhance the off axis performance.

ii. **System Noise:** The two most important sources of noise are the Low Noise Amplifiers (LNAs), and resistive or dielectric losses in the elemental antennas in front of the LNAs. The standard radio astronomy technique to reduce LNA noise is cryogenic cooling. This is certainly cost-effective when the number of receivers is small, since system noise can be traded for antenna area, which is expensive. However, as the number of receivers in the PAF approaches several hundred, spread over an area of more than a square meter, bulk cryo-cooling may not be the best solution. (Alternative techniques, such as delivering coolant to tiny cryostats surrounding the LNAs, have also been discussed.) The hoped-for solution is high-performance room-temperature LNAs that are closely integrated into the elemental array antennas. The close integration avoids loss in the antennas to the maximum extent possible. There are laboratory prototypes of room-temperature LNAs operating over 2:1 bandwidths near 30-cm wavelengths with respectable noise figures. But full integration has not yet been achieved. This is critical technology for the cost-effective success of PAFs.

   The standard cryogenic solution would probably preclude the close integration available to room temperature amplifiers in PAFs, and suffer some loss in the transition through the cryostat. An extreme solution at long wavelengths is to cryo-cool the entire array. If the loss in the antenna elements is too large even with integrated amplifiers, cyro-cooling may be the only answer. This will dramatically increase the cost of the PAFs at lower frequencies although it may be the option of choice if PAFs are extended to higher frequencies. The associated power consumption and weight will also increase the antenna and operating costs.

iii. **Frequency coverage:** Several designs of elemental antennas have bandwidth ratios of much more than 2:1. But utilizing much larger bandwidths can lead to greater changes in the impedance of the elements over frequency. This leads to difficulty in optimizing the performance of integrated LNAs over a large band. Not much work has yet been done in this area. A potential solution is to mount two PAFs off-axis on the antenna, each covering adjacent bands. Assuming that they are not required simultaneously, this solution would decrease the PAF costs since beam-forming electronics would be shared and the frequency range and hence number of elements in each PAF reduced.

iv. **Polarization Purity:** Off-axis feeds of any type will produce beams that exhibit squint (opposite polarization beams offset in the sky) and other deleterious polarization artifacts. In principle, including inputs from elements of opposite polarization in every beam-sum should permit the cancellation of these effects, perhaps even to an extent not possible with traditional feeds. Experiments will be needed to verify the level of polarization purity that can be achieved at the output of polarization-optimized beam-formers. Including additional inputs in the beam-sum to improve the polarization purity will clearly increase the cost.

v. **Calibration/Stability:**

   a. *Gain and phase:* Each of the elemental RF systems in the PAF will exhibit gain drift, especially if they are exposed to changes in environmental temperature. (Stable environmental temperature would be an advantage of cyro-cooled LNAs). More subtle effects may also occur such as changes in band shape. An additional effect could also be high sensitivity to small mechanical movements induced by gravity or vibration as the orientation of the array changes. A potential solution is the broadcast of a broad-band calibration signal (or a series of tones) from the vertex of the main reflector or from a sub-reflector into the PAF. Similar schemes have been used in VLBI systems. This could provide almost continuous calibration without significantly impacting interferometer data. This calibration solution would be quite inexpensive, but might have a digital processing or software impact.

b. *Beam-shape and Pattern Rotation:* There are many aspects to beam-shape calibration and stability. The first aspect, rotation of the assembly of beams (pattern rotation), is coupled to antenna design. The simplest antenna design utilizes an "alt-az mount", which will nominally cause the pattern to rotate against the sky. In principle, the beam-forming system could continuously adjust the position of the beams on the PAF by adjusting weights so as to stabilize the entire beam pattern on the sky. In practice, the discrete nature of arrays would likely induce rapid changes in beam-shapes and side lobes as the beams rotate. It is difficult to imagine how each beam-shape could be calibrated accurately as a function of time. Thus they might have to be corrected somehow "down stream" in a vast computing system. Although this has never been tried or simulated, the level of residual errors is expected to be high. The alternative is to de-rotate the PAF mechanically, or to de-rotate the entire reflector assembly. An examination of the most effective methods of de-rotation (e.g. equatorial mounts) is under way, but is not nearly complete at this time. A side benefit of de-rotating the entire reflector is that scattering lobes from feed legs (or other scattering objects) are also stabilized on the sky. If the PAF beam patterns are not required to change with time, it should be possible to measure (calibrate) them once – weights would be adjusted only to compensate for RF gain/phase changes.

vi. **Power Consumption, Weight, and RFI mitigation:** Power consumption and weight will tend to increase for all of the "solutions" suggested above, particularly if cyro-cooling is required. A dual-reflector antenna provides a much more cost-effective location for the PAF than a location at the prime focus. A large mass at the prime focus affects the structural design of the reflector and the feed support, as well as the design of the antenna mount. Mounting the PAF near the main reflector vertex will reduce all of these structural demands.

RFI mitigation (shielding) will not be required if digital electronics is excluded from the focal region. A requirement for heavy shielding and high power consumption would lead to exorbitant costs. The proposed solution is to transmit wide-band analog signals to the base of the antenna or an adjacent building that contains a shielded digital beam-former. (Note that analog beam-formers will not be practical in this application.) Wide-band optical fibre systems exist and have been used in radio telescopes, but they are unusual. Inexpensive, fully optimized commercial-off-the-shelf systems do not exist for the required bandwidths needed, but could be developed. Also, these data transmission systems are part of the analogue RF chain, and will have to be calibrated as part of that chain. A potential concern is tiny changes in bandshape induced by mechanical bending of cables in the antenna. Uncorrected bandshape errors are difficult to remove in data processing.

Another solution to the data-transmission problem is to digitize the signals in the focal region using an integrated RF-in, optical-out chip that never produces high-level digital electrical signals. Digital optical signals are delivered to the beam-formers via optical fibers connected directly to these outputs.

Only a small amount of investigation of this solution has been done but it is clear that cost-effective very short-haul links, either analogue or digital, are an important enabling technology for all phased array solutions, including PAFs.

A benefit of PAFs is the potential ability to "null" RFI emanating from a distant source. This can be done in principle by adjusting the weights in a constrained optimization, so as to leave the synthesized beam unaffected. This is probably not a high priority on the relatively interference free SKA sites.

vii. **Cost:** The cost of uncooled PAFs is dominated by the cost of the digital electronics. The rapid reduction in the "feature size" of silicon chips continuously decreases cost over time (Moore's Law). However, recently there has been a slowing of progress here, and the cost may not be reduced as quickly in the near future as it has over the past. An obvious production cost-reduction for large numbers of beam-formers can be achieved by careful design of the digital architecture so as to allow the maximum level of integration at all levels – logic on ASIC chips and chips on boards. ASIC's will be a necessity for these systems. Less visible but important progress has been made in packaging and circuit board density in recent years. This will also assist in reducing the cost of digital beam-formers.

   Note that cryo-cooling would likely increase the cost dramatically in the wavelength range useful for the redshifted HI-line, where the physical size of the array is large.

viii. **PAF - SPF hybrids:** The strong science drivers for survey speed and hence use of PAFs involve the more compact arrays so another trade-off is the maximum baseline for which the PAF is implemented. This also has an impact on the costs of the long haul links if all the large FoV information is to be delivered to the correlator. For all cost modelling in this report the FoV expansion is limited to antennas at distances < 50 km.

Notwithstanding these challenges, PAFs should play a major role in SKA survey performance if sufficient R&D resources are put into their development in the near future. Most of the challenges mentioned above can be mitigated or "traded" in system-design optimizations near 1 GHz frequencies. Table 11 summarises the challenges for dishes with Phased Array Feeds.

Table 11. Challenges for Dishes with Phased Array Feeds

Challenge	Consequences	Mitigation
Production-ready PAFs on SKA time scale	Reduced utilization of collecting area for surveys and hence lower survey speed	Coordinated R&D effort world-wide; "future-proofing" SKA/Pathfinder designs
Efficiency	Reduced effective area	More elements; larger f/D; smaller FoV; larger beam-former; choose low-loss element design
T_{sys}	Reduced A_{eff}/T_{sys}	Innovative uncooled LNAs; element/LNA integration; innovative cryo-cooling
Frequency Coverage	Reduced redshift coverage	Trade against A_{eff}/T_{sys} and use multiple-pass survey
Bandwidth	Reduced continuum sensitivity	Longer integration
Polarization Purity	Reduced polarization dynamic range	Larger beam-former; better PAF element design; more calibration effort/computing
Calibration/Stability	Reduced imaging & spectral dynamic range, image fidelity	Non-rotating antenna optics; solid mechanical construction; install gain/phase calibration system; innovative high-quality optical fiber short-haul transmission system
Power, weight, RFI	High capital, operating costs	Minimize active electronics at the focus; install PAF at secondary focus; install digital processing equipment away from focus
Cost	Reduced telescope capability	Adopt Design-for-Manufacture refinements; production prototypes

There is a wide parameter space that can be explored during performance - cost optimisation of the dish + PAF concept but an indicative summary is set out in Table 12. The component breakdown for the 15 m and survey speed 10^9 option is given in Figure 9.

Table 12. System cost (rounded to nearest 25 M€), number of dishes (N) and A_{eff}/T_{sys} (in m^2K^{-1}) and number of dual polarisation beams for various PAF scenarios that achieve a given survey speed specification at 1,420 MHz. T_{sys} is taken as 35K, and aperture efficiency as 70%. This analysis is based on the use of 10 GHz antennas, corresponding approximately to the 1.5 mm rms surface accuracy curve in Figure 2.

Survey Speed	Diameter	FoV[2] (sq. deg)	N dishes	A_{eff}/T_{sys}	N beams	M€
$3x10^8$ $m^4K^{-2}deg^2$	10 m	20	2,516	3,873	13	425
	12 m	20	1,752	3,884	18	400
	15 m	20	1,119	3,876	28	375
	20 m	20	633	3,898	49	400
	25 m	20	389	3,743	77	450
	30 m	20	278	3,852	110	500
	35 m	20	206	3,885	150	550
10^9 $m^4K^{-2}deg^2$	10 m	20	4,593	7,070	13	975
	12 m	20	3,193	7,078	18	850
	15 m	20	2,039	7,062	28	775
	20 m	20	1,139	7,013	49	775
	25 m	20	741	7,129	77	850
	30 m	20	516	7,149	110	925
	35 m	20	371	6,996	150	975

All these models assume that the PAF's with 20 square degree FoV are only used for antennas up to 50km distance from the core. If the use of PAFs is restricted to 5km, the total cost of the array is reduced by about 5%.

7.3. Aperture Arrays

The AA cost drivers relate strongly to the number of elements employed and their frequency ranges.

i. The AA-lo cost drivers are the required sensitivity and the precise lower frequency required for the EoR experiment. Particular issues are:
    - *the chosen frequency for sensitivity*. The sky noise increases drastically at frequencies <150 MHz, so to achieve a given sensitivity at 70 MHz requires many more elements than at 100 MHz.
    - *the frequency above which the array becomes sparse*. This affects the diameter of the array. A larger diameter will cost more in cabling and larger elements. The lower the frequency the more expensive an AA will be, so more expensive at 70 MHz (~300 m dia) than at 100 MHz (~200 m dia).
    - *digitisation and processing*. It is expected that the same digitisation and processing architecture as the AA-hi system will be used for AA-lo and it will be possible to pack multiple antenna signals per digital channel. The processing therefore becomes cheaper with the top frequency dependent on the number of signals that can be packed per channel. So, with a processing

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[2] For a PAF, FoV is not frequency dependent.

system bandwidth capability of 1,000 MHz, there can be 2, 3, or 4 signals packed depending upon the top frequency being below ~200 MHz, ~300 MHz or ~450 MHz respectively.

- *communication costs to the correlator*. The survey speed capability will depend upon the digital data rates from the arrays. While non-core stations are likely to share this capability with the AA-hi and the dishes, the core arrays are likely to be separate and will add communication cost and, of course, additional extra equipment cost to the central processing of correlator and post-processor.

ii. AA-hi cost drivers are i) sensitivity principally for the HI experiments, ii) the need for high dynamic range for the continuum surveys, and iii) total data rate for flexible survey speed as a function of redshift. Particular issues are:

- *the sensitivity at the high frequencies.* This determines the number of elements required, whether critically packed or sparse. Reducing the frequency at which the specification is made, or reducing the sensitivity reduces the element count and hence cost.
- *the absolute highest frequency that can be received*. This is primarily a restriction from the digitisation and processing, also the analogue signal transport has a cut-off frequency above ~1.2 GHz, after which it would be necessary to use more expensive technology.
- *the level of sparseness at the higher frequencies.* This might affect the communication costs. The beams will be smaller per station, due to the larger diameter, hence there are more beams required to cover the same field of view. The benefit of sparseness is the greater sensitivity at lower frequencies, which may mitigate the required communications bandwidth.

iii. An overall cost driver for AAs is the maximum baseline as a function of frequency (currently unclear for the EoR experiment)

Table 13 summarizes the challenges for AAs.

Table 13. Aperture Array Challenges

Challenge	Consequences	Mitigation
Developing 4:1 frequency range antenna elements	Requires 3 array structures to cover the frequency band	Use 3 different frequency bands
Processing capability within power budget	Reduced performance or higher cost if not met	Use a lower sensitivity system and possibly recover survey speed with additional FoV
Minimum T_{inst} – specification: AA-lo of 100 K AA-hi of 30 K	Reduced sensitivity or higher cost if not met. Less critical for AA-lo	Use a lower sensitivity system and possibly recover survey speed with additional FoV
Mechanical design and on-site construction for sparsed arrays. System design must be completed first	Increased cost	
Power requirements and cooling	Increased running costs	
Self induced RFI within acceptable limits		
Multiplexing channels for AA-lo to reduce total processing requirements	Increased costs	
Demonstration that systematics are calibratable	Inability to meet the required dynamic range	Review the experiments that can be supported
Maintainability and reliability within agreed limits	Increased costs	

8. Trade-offs and Science Implications

8.1. Cost Modelling

In this section we briefly review the input to the cost modelling discussed in this document and also outline the direction that this effort within the SKA project is taking in the near future. At this stage we are engaged in cost modelling of the telescope rather than costing of a specific final design. Real costing requires detailed input from specialists and potential suppliers. For a project such as the SKA, true costing will be influences very strongly by political, economic, and commercial considerations. While the cost model attempts to include some aspects of commercial drivers (such as economies of scale), the uncertainties are extremely large. The cost modelling performed provides a better guide to how costs scale with design considerations, however even in this respect large uncertainties remain especially when the relative costs of two aspects of the system are determining apparently optimal system configurations.

The cost modelling methodology used in this document is derived from two sources described in SKA Memos 92 and 93. In late 2006, the ISPO sponsored an effort to develop an SKA cost modelling tool. This contract was placed with the ATNF and an approach was developed which built upon earlier work discussed in SKA Memo 57. The result of this effort, which is used extensively in the current exercise resulted in a cost modelling tool which in its initial form supports modelling of dish-based solutions for the SKA with single-pixel and PAF receivers (SKA Memo 92). At the same time the SKADS project started a concerted effort to develop a costed system design for one possible realisation of the SKA including mid-frequency Aperture arrays (SKA Memo 93). Again the results of this work are used extensively here in the cost modelling of AAs.

Despite differences in implementation (discussed below) both cost-modelling efforts have the same logical structure. Ultimately for a specific system design a cost is determined by summing the cost of components by following the signal path through the system. Appropriate cost models are adopted for components which include (if appropriate):

- A cost performance model (e.g. cost as a function of dish diameter and surface accuracy),
- A simple financial model (e.g. cost as a function of purchase date),
- A model for expected performance as a function of time (e.g. the cost per operation within computing hardware dropping with Moore's law), and
- Economies of scale.

A number of aspects are not (currently) included, or only partially included, in the cost modelling. These include: Non Recurrent Expenditure(e.g. development costs), infrastructure, project delivery, management costs, and operations. Importantly, these constraints mean that it is not possible to consider, for example, total cost of ownership when considering different technology options. The cost models permit analysis of relative cost/performance of realisations of the SKA system as design parameters are varied. The modelling also includes a formal uncertainty analysis of these results. However, the results of course depend on the reliability of the input models and do not allow for wholesale changes in the underlying system design.

SKA Memos 92 and 93 give details of the specific assumptions concerning system design, signal paths and cost models which have been assumed. As a result of discussions at SKA2007, some parameters entering into some aspects of the cost modelling (in particular concerning the scaling of dish costs with surface accuracy and economies of scale) were modified for the latter calculations presented here. Some specific limitations of the cost modelling used here are worth noting. Since the emphasis of this document is on comparing different technology routes, costs which were deemed to be common between technologies are included only approximately. These include infrastructural costs and data transport - more discussion of the data transport costs and AA specific infrastructural costs are available in the two cited SKA memos. A very important cost driver emerges from any analysis which is the cost associated with data processing, particularly post correlator. The model adopted for this aspect of the modelling is based on SKA Memo 64 which we believe to be the best available input at the present time. Despite being a crucial cost driver, this aspect of the system has received at this stage relatively little consideration relative to the development work on other technology aspects. Costs are currently based on a single (possibly optimistic) algorithm architecture and on (likely pessimistic) scaling for the computational cost given the number of required operations. We note these limitations of the cost modelling presented here.

The implementations of the cost modelling discussed in Memos 92 and 93 are very different. The former approach (the “ISPO” approach) has been to implement a cost modelling engine in a high-level programming language - Python. Aspects of the system design and details of the cost model are implemented in Python as modules of the costing engine. The “SKADS” approach was to use Excel as the costing engine and to refine a system design with relatively robust component costing and cost models from a team of domain experts. Both approaches have strengths and weaknesses. The ISPO approach provides a very flexible, robust costing engine with excellent error/consistency checking, Monte Carlo modelling, and facilitates exploratory “what if” analysis. The disadvantages are that the underlying (cost) models are not easily accessible to the user and input from domain experts is more difficult to obtain and incorporate. The SKADS approach enables domain experts to have direct control over input to the cost modelling, but is time consuming to ensure consistency and makes “what if” analysis more difficult. Under the direction of the ISPO, the teams involved in the work to date have joined to work on a new cost modelling tool. This will be based on the existing “ISPO” cost modelling engine, but will be modified to enable cleaner access to different parts of the model by domain experts and designers. To further facilitate this, new interfaces will be provided and there will be a clean separation of the tool and the models which are input to the tool. The new system will also be able to support many realisations of the system design.

8.2. Dish + Single Pixel Feed

Dish diameter is the key parameter that controls the trade-off between the survey speed and instantaneous sensitivity metrics for the dish+single pixel feed scenario. Different optimal dish diameters are obtained when minimising the construction cost, depending on whether A_{eff}/T_{sys} or the survey speed metric is specified as a target figure of merit. All of the costing analysis that follows is based on outputs from the SKA cost tool (SKA Memo 92).

Figure 5 and Figure 6 show the dependence of array construction cost on dish diameter for both cases of target metric, using representative target metric values. Figure 5 shows the cost of building an array with a target A_{eff}/T_{sys} of 10,000 m^2K^{-1} with the performance assumptions listed in the caption. The optimum antenna diameter appears to be 15 m for this example. The location of this minimum was found to be fairly independent of target sensitivity, indicating that a WB-SPF SKA optimised for A_{eff}/T_{sys} should have antennas with a diameter around 15 m.

Figure 6 repeats this exercise for a target SSFoM of 10^8 $deg^2.m^4.K^{-2}$. This optimisation favours a smaller diameter of 10 m, and again the location of this minimum was found to be only weakly dependent on the target survey speed.

These two representative examples indicate that an SKA built using the dish+single pixel feed technology will consist of dishes with diameters in the range 10 m to 15 m, with smaller dishes favouring science demanding survey speed and larger dishes favouring high sensitivity experiments. This implies that at full sensitivity this scenario for the SKA will provide a FoV of order 1 deg^2 at 1,420 MHz, with a λ^2 dependence that increases the FoV (and hence survey speed) at lower frequencies. Sub-arraying provides a mechanism for dynamically trading sensitivity for FoV, but the resulting aggregate survey speed is decreased. Although dish+single pixel feed technology is the most appropriate for experiments requiring high sensitivity (A_{eff}/T_{sys}), it will not achieve (within reasonable cost bounds) the ambitious survey speed goals promised by wide-field technologies. Nonetheless, a dish+SPF approach can meet the requirements of many of the highlighted science areas.

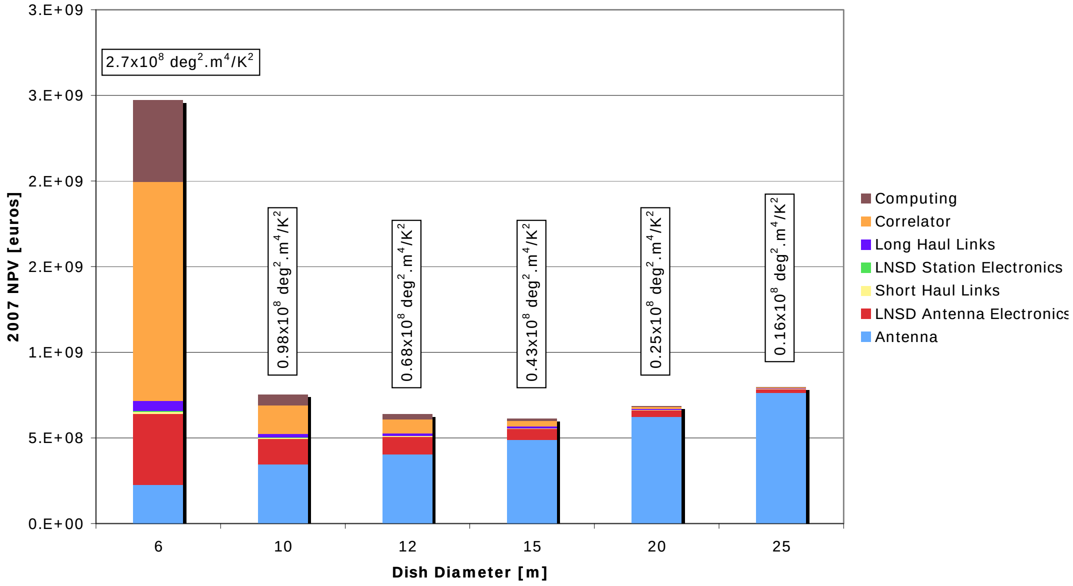

Figure 5. Array cost versus dish diameter for an SKA mid-band scenario with a target sensitivity of A_{eff}/T_{sys}=10,000 m^2K^{-1}. Specification values of 30 K for the system temperature and 70% for the aperture efficiency were assumed (as per Table 6). The SSFoM achieved for each of these scenarios is annotated above the relevant bar. Costs were calculated using the SKA costing tool and exclude software, infrastructure, management costs and project delivery. Maximum baseline for full FoV imaging was set at 10 km, the highest operating frequency was set to 10 GHz, and an instantaneous bandwidth of 2048 MHz was specified.

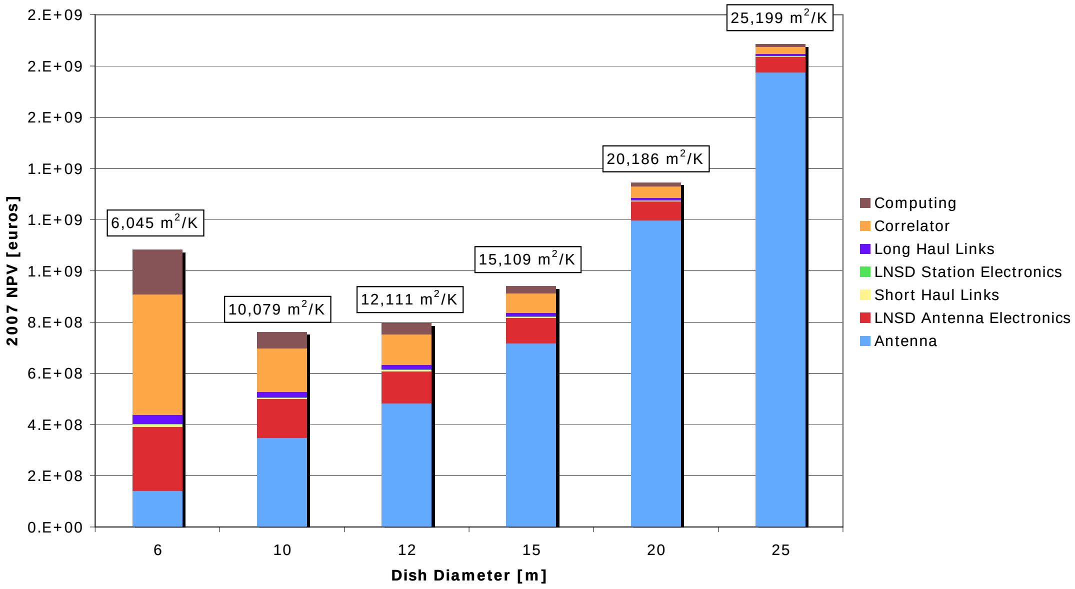

Figure 6. Array cost versus dish diameter for an SKA mid-band scenario with a target survey speed figure-of-merit of 10^8 $m^4K^{-2}deg^2$. Specification values of 30 K for the system temperature and 70% for the aperture efficiency were assumed (as per Table 6). The sensitivity achieved for each of these scenarios is annotated above the relevant bar. Costs were calculated using the web-based SKA costing tool (Memo 92) and exclude software, infrastructure, management costs and project delivery. Maximum baseline for full FoV imaging was set at 10 km, the highest operating frequency was set to 10 GHz, and an instantaneous bandwidth of 2048 MHz was specified.

Alternative optimisation analyses are illustrated in Figure 7 and Figure 8. In these figures the component cost is fixed at 750 M€ and achievable performance is plotted as a function of dish diameter. These plots show the same conclusion that 15 m dishes provide optimum sensitivity, while small dishes provide better survey speed. These plots also show the dependence of sensitivity and survey speed on frequency, highlighting the natural λ^2, FoV (and hence SSFoM) dependence and the effect of Ruze's formula on relative efficiency.

Aperture efficiency, system temperature and dish surface accuracy are strong cost drivers. For a given fixed construction cost it is possible to trade system temperature, built collector area and dish surface accuracy against each other. The current version of the SKA costing tool does not attempt to quantify in detail the costs of cryogenic cooling, so no trade-off study with respect to T_{sys} can be done at present. However, it is likely that it will be cost effective to employ cryogenic cooling in the feed/receiver package.

Survey speed can always be traded with survey duration, so none of the key survey projects are excluded by the relatively limited FoV of the technology. The only science objective that explicitly benefits from wide FoV is the detection of bright radio transients, but there is a complex trade between sensitivity and FoV for events with source-count statistics that have a steep dependence on flux density.

A_{eff}/T_{sys} and survey speed are both sensitivity measures that have to be considered in conjunction with a mixture of science requirements (surveys and pointed observations) and performance metrics, such as spatial and spectral dynamic range, the ability to address time-domain science, and polarization purity. At present there is no convenient tool for providing likely performance metrics in areas such as these for the various technology concepts, mainly because demonstration of the wide FoV technologies is still pending.

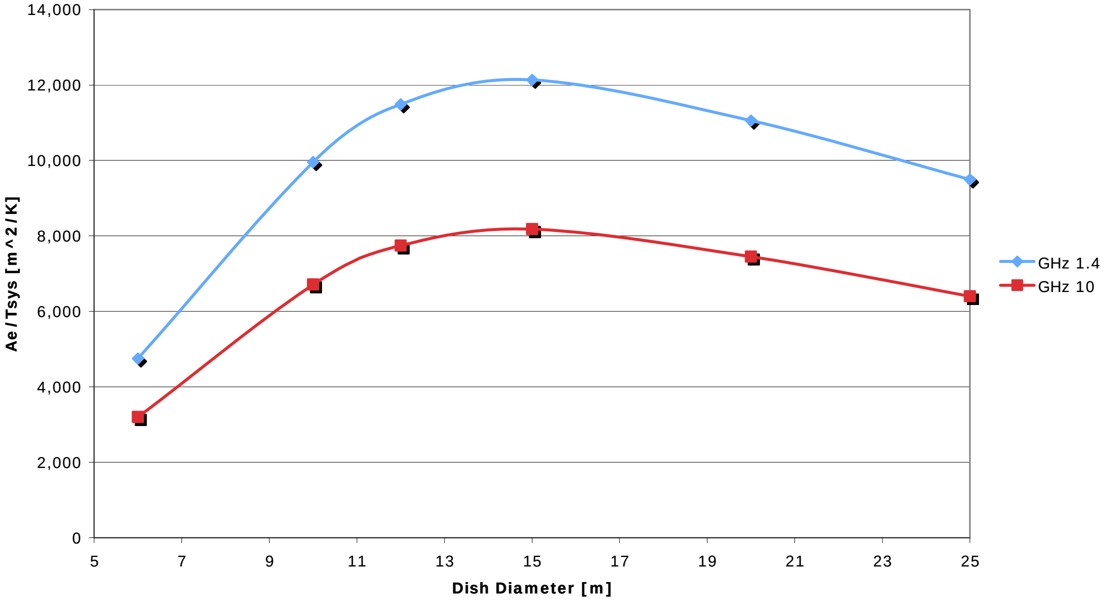

Figure 7. Dependence of point source sensitivity on dish diameter for a fixed component cost of 750 M€ (2007 net present value) for operating frequencies of 1.4 GHz and 10 GHz..

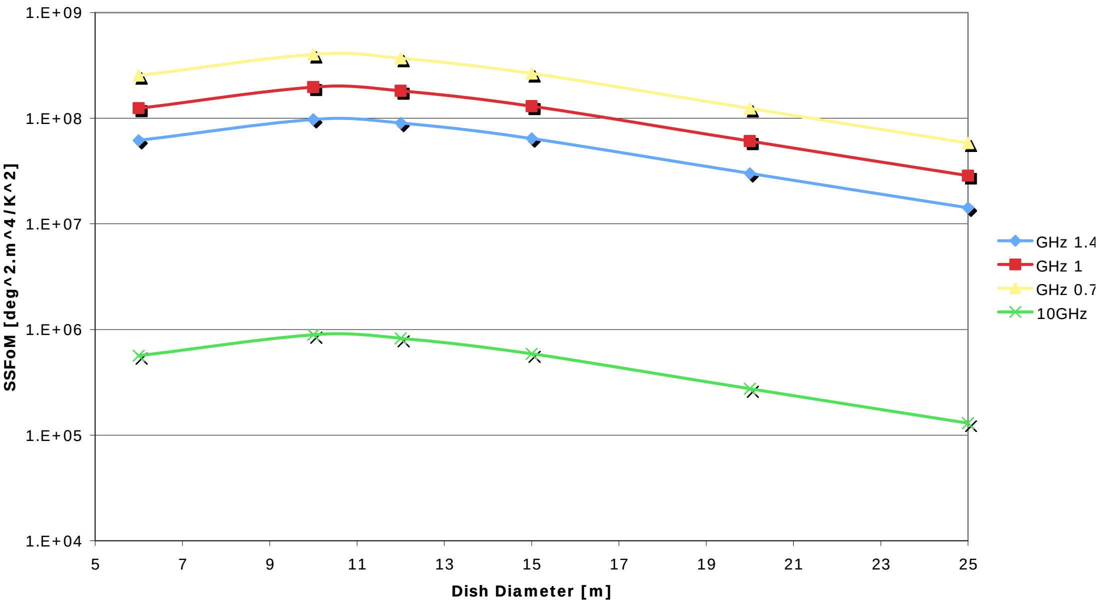

Figure 8. Dependence of SSFoM on dish diameter for a fixed component cost of 750 M€ (2007 net present value) for operating frequencies of 1.4 GHz and 10 GHz.

8.3. Dish + Phased Array Feed

Most of the prime drivers for SKA Science involve a large survey component at frequencies below ~3 GHz and, for much of this science, the survey speed can be traded for A_{eff}/T_{sys} (Table 4). However, it should be noted that there are additional constraints to consider when making the trade, such as those that arise from some pulsar surveys and timing follow-up. The PAF in small dishes provides a cost effective way to increase FoV and hence survey speed. With the PAF, costs are moved from aperture to digital electronics and these costs are decreasing in time. While high A_{eff}/T_{sys} is always preferable, since it provides both instantaneous sensitivity and survey speed, the innovative PAF technology can provide high survey speed at much reduced cost.

The cost difference is dramatic: the WBSPF achieves a survey speed of 10^8 m^4 K^{-2} deg^2 at 1.4 GHz for an NPV of 750 M€ and for the same survey speed the optimum PAF has 4 times lower cost. It is clear that innovative design approaches can dramatically reduce the SKA cost for surveys but the A_{eff}/T_{sys} for the WBSPF solution is higher than for the PAF for the same survey speed. With practical PAF solutions yielding FoV expansions of 50 or so, one need only build one-third the area of the WBSPF array and still obtain a factor of five advantage in survey speed. Whilst building only 1/3 the number of dishes results in an A_{eff}/T_{sys} of 1/3 that of the WBSPF array, for similar cost in the two SKA implementations one obtains the substantially higher survey speed with the PAF.

The cost breakdown for the PAF with SSFoM = 10^9 m^4 K^{-2} deg^2 is shown in Figure 9. The minimum cost occurs with dishes of 15 m diameter. There is more scope for improving array performance as computing costs drop with time. It should be noted that even with the maximum baseline for spectral line imaging reduced to 5 km the computing and correlation costs still dominate for smaller dish size. There is no cost-effective solution within SKA target budgets for PAF instruments with imaging baselines set greater than ~5 km, illustrating the practical trade-off between survey speed and data cube volume.

PAF optimisation involves complex tradeoffs between many of parameters including; F/D, prime focus or dual reflector, dish diameter, distance of focal plane from focus, focal plane array size, number of elements, element spacing, upper and lower frequencies and number of beams and beam former inputs. Exploration of this parameter space is well beyond the scope of this document but to compare the cost effectiveness of the main SKA options we need to explore costs as a function of frequency and dish size for both A_{eff}/T_{sys} and survey speed performance.

Efficiency and system temperature are strong cost drivers. With a 1,000-dish array, even adding the 200M euro needed to account for a 200k Euro per dish cooling cost would be attractive. Note that in the PAF cost estimates (Figure 9) an efficiency of 70% was assumed. This is conservative for a PAF but the 35 K T_{sys} assumption without cooling is probably correspondingly optimistic.

For a wideband PAF, the lowest frequency determines the physical size of the PAF and the upper frequency determines the number of elements. Since the beamforming electronics is a large fraction of the PAF costs it will be cost efficient to build a larger array but to only use the outer elements at the lower frequency end of the band. When this is done the FoV of the PAF will scale as λ^2. Although electromagnetic designs for bandwidths of >3:1 are possible this may not be the most cost effective solution since two separate off-axis PAFs have fewer elements and can share the expensive beam former. Designs with a combination of multiple off-axis PAFs and wideband feeds may lead to a broader range of options than considered in this document.

Clearly we need operational systems to verify the projected PAF performance. There is almost no experience at this time for operational systems installed in dishes but a number of arrays have now been constructed and are being measured. The analysis presented here uses the SKA cost tool (Memo 92). The PAF modelling in this tool is based on the ASKAP project prototyping and development and is expected to be realistic. Figure 9 shows PAF + dish array cost vs dish diameter for fixed SSFoM of 10^9 m^4 K^{-2} deg^2 at 1.4 GHz.

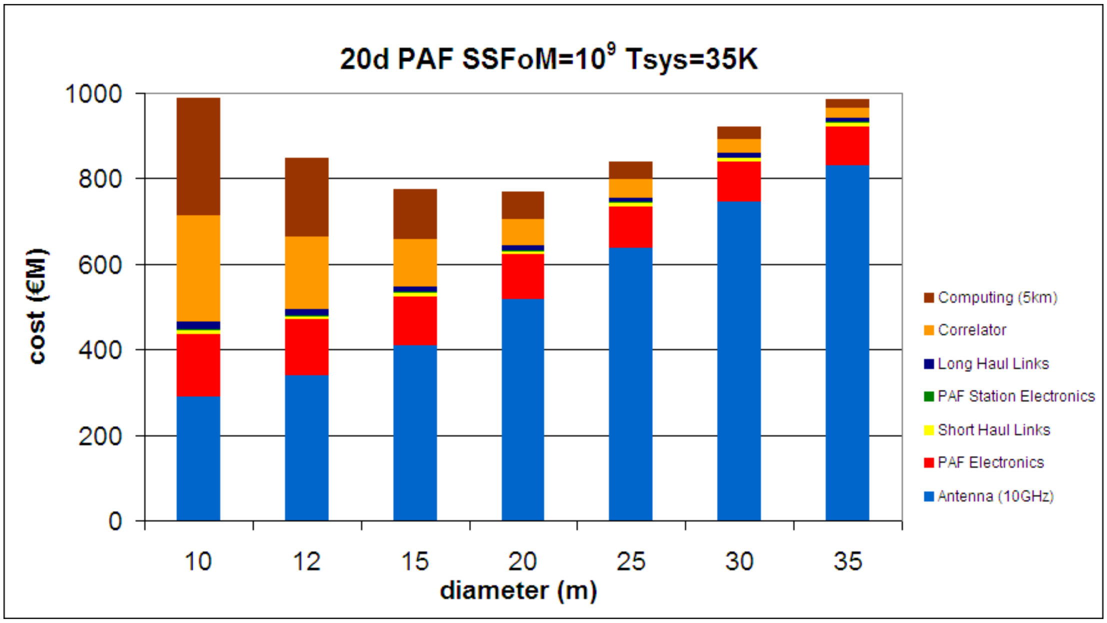

Figure 9. PAF + dish array cost vs dish diameter for fixed SSFoM of 10^9 m^4 K^{-2} deg^2 at 1.4 GHz. FoV = 20 deg^2 and A_{eff}/T_{sys} = 7,000. Assumes 10 GHz dish and PAF to 1.4GHz. Costs calculated using the SKA costing tool ver 1.1.1 (Memo 92).

The FoV expansion using the PAF provides high SSFoM but at the expense of A/T for a given cost. Figure 10 explores this trade-off. In each plot the total cost is held constant while the FoV is traded for A/T. For the dish + PAF the size of the phased array feed is changed (moving electronics costs into collecting area) and for the dish + single pixel wide band feed the dish diameter is changed (moving the cost of larger dishes into extra electronics for more small dishes). SPF solutions are plotted for the top (1.4 GHz) and bottom (0.7 GHz) of the PAF frequency range. For the single pixel feed the FoV scales with λ^2 but is independent of λ for the dish + PAF. The PAF has a system temperature of 35K and the WBSPF has T_{sys} = 30 K. Both have assumed efficiency of 70%.

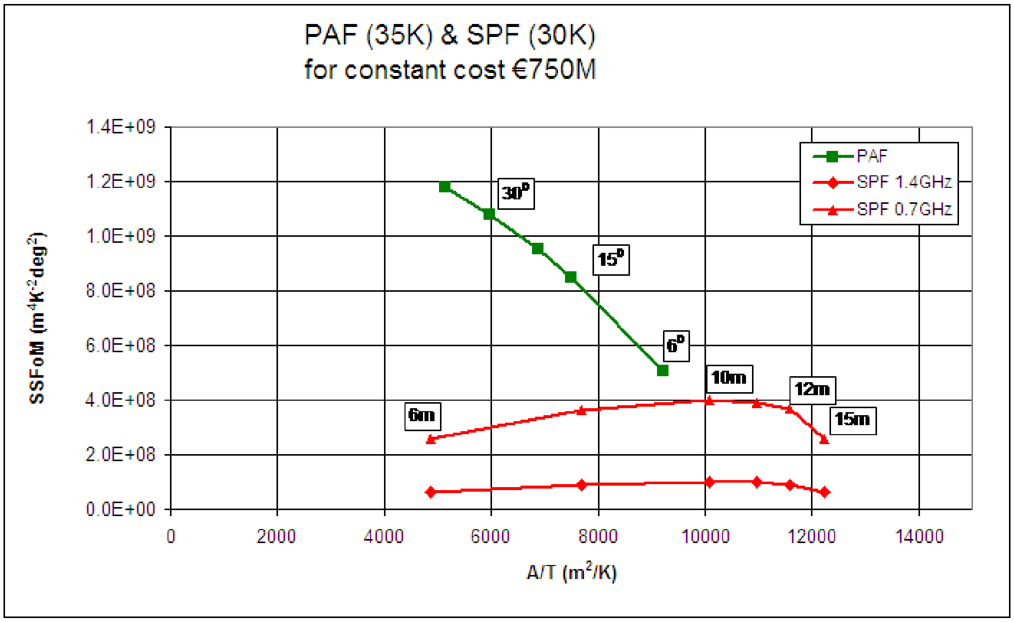

Figure 10. A/T v SSFoM for PAF and WBSPF arrays with the same fixed total cost of 750 M€. The PAF has T_{sys} = 35K and the WBSPF 30K. The values above the curves are the FoV (PAF) or dish diameter (WBSPF). The PAF is specified for 0.7 GHz to 1.4GHz (same FoV) and for the WBSPF separate curves are shown for 1.4 GHz and 0.7GHz. For the PAF, dish size is 15 m. All other parameters are the same; 10 GHz dishes and the maximum baseline for spectral line imaging is set to 5 km to constrain computer costs. Costs calculated using the SKA cost tool ver 1.1.1 (Memo 92).

For the PAF with 30^{o} FoV the SSFoM has excellent survey speed which is 7x the SPF at the top of the frequency band but its A/T is too low for some sensitivity limited science requirements. We can increase A/T for the PAF by reducing its FoV and moving some of the PAF electronics costs into more A/T. As seen in Figure 10, the increased A/T partially compensates for the lost SSFoM due to lower FoV. By going to FoV= 6^{o} we can increase A/T by 50% but with a factor of 2 loss in survey speed.

The WBSPF needs high A/T to get high survey speed and this is expensive. If we try to decrease the cost of the WBSPF by using smaller dishes to get larger FoV and higher survey speed we run into electronics costs for the large number of dishes and for the correlator because all possible elements in the aperture plane have to be correlated. The PAF avoids this cost by first computing beams pointing in different directions in the FoV and these do not all have to be cross correlated.

To choose between these options we will have to make the scientific trade-off between sensitivity (A/T) and survey speed (SSFoM) since we cannot have both for the same cost, but even with the better T_{sys} (30K) for the SPF (Figure 10) the PAF still has more than ten times higher survey speed at the top of the band. At the bottom of the band it is only a factor of two faster but, as already noted, this can be improved to close to the λ^2 factor with the same size beam former by adding more low frequency feed elements.

As a compromise between A/T and survey speed we have used a 20 square degree solution in the rest of this document.

8.4. Aperture Array

The previous sections have described the results of performance-cost analyses for the dish-based arrays based on use of the “SKAcost” tool (described in section 8.1 and SKA Memo 92), web-interface release 1.1.0. Aperture Array costings were done within a SKADS environment, which is now closely aligned with SKAcost and which will shortly be available as part of that tool. However for this document, the SKAcost tool could not be used for Aperture Arrays.

It is useful to revisit the cost scaling laws appropriate for an AA - a good approximation (valid for large element counts) is that the AA-specific cost scales as the number of elements; the cost per element includes the element itself plus its share of the signal path to the correlator. With this approximation the elements can be distributed between stations at will (within reason) for the same cost - this is equivalent to the situation where dish cost scales simply as $D^2 \propto A_{\mathrm{eff}}$.

For an AA consisting of N_s stations each with N_{es} elements the total element count and hence cost scales as $N_e = N_{es} N_s$. For a fully sampled AA, the effective area is ~ $N_e d^2$, where d is the element separation ($\lambda < 2d$); for a sparse AA the equivalent approximate result is ~ $N_e \lambda^2/4$. These results neglect element coupling and variations of A_{eff} with scan direction, but give the correct scaling behaviour. A conservative design is adopted in which the mid-frequency AA is taken to be a fully-sampled AA for best possible control of systematics and side-lobe levels in order to achieve maximum dynamic range. In this case, the station beam is given approximately by

$$\Omega_b \sim \frac{\lambda^2}{D^2} \sim \frac{\lambda^2}{\mathrm{N_{es}} d^2}$$

The number of beams required to produce a total instantaneous Field of View of the AA of Ω_F is:

$$N_b = \frac{\Omega_F}{\Omega_b} \sim \frac{\Omega_F \mathrm{N_{es}} d^2}{\lambda^2} \propto \Omega_F \mathrm{N_{es}} d^2$$

This is a function of frequency across the band - for an AA Ω_F itself can also be chosen to be a function of frequency. However, it is easy to show that this scaling for the mean number of beams averaged over the observing band always holds; to simplify the analysis the mean number of beams across the band is used below. The number of beams that can be processed from the AA will be limited by either the ability to transmit data to the correlator, or the capacity of the correlator, or the capacity of the post-correlator processor. The data rate from the correlator scales as

$$R_c \propto \mathrm{N_{ch}} \mathrm{N_s}^2 \mathrm{N_b} \propto \mathrm{N_{ch}} \mathrm{N_s}^2 \Omega_F \frac{\mathrm{N_e}}{\mathrm{N_s}} d^2$$

where N_{ch} is the number of frequency channels. The equivalent scaling for dishes is $N_{ch} N_{dish}^2$. For the SKA realisations considered, the high frequency dishes (with either single pixel feeds or PAFS) have significant correlator and post-correlator requirements and these dominate the requirements of the AA. Hence it can be assumed that R_c is fixed by the high-frequency dishes; provided the correlator is re-configurable this fixes the Rc for the AA. Then the FoV which can be processed scales as $\Omega_F \propto R_c / (N_{ch} N_s N_e d^2)$. The survey speed is then given by (see section 5.1.8)

$$\mathrm{SSFoM} = B(\mathrm{Nfov}\ \Omega_{\mathrm{FoV}}/\mathrm{Nsa})(f_c A_{\mathrm{eff}}/m\ T_{\mathrm{sys}})^2 \propto R_c N_e d^2 / (N_{ch} N_s T_{\mathrm{sys}}^2)$$

The AA cost, with B constant for consistency, for a given survey speed therefore simply scales as

$$\mathrm{COST} \propto N_e \propto \mathrm{SSFoM}\ N_s T_{\mathrm{sys}}^2 / d^2$$

The cost scales linearly with both survey speed and A_{eff} in this limit when the data rate from the correlator is fixed. For a given SSFoM the number of stations should be minimised and d should be maximised. The minimum number of stations is determined by the need to have sufficient aperture-plane coverage for high-dynamic range - this has been fixed at 150 as a minimum value. R_c is fixed by the high-frequency dish solution in which it is assumed that it is possible to process the data from ~1,200 dishes within 5 km (50% of the dishes) with single pixel feeds observing in spectral line mode at L-band.

The remaining trade-offs for the AA are then the upper frequency of the AA at which it is fully sampled as this determines d, and the distribution of the AA with distance from the core. Considering a fraction f of the AA is within 5 km, and allowing for a longer post-correlator integration time compared to L-band, the mean number of beams processed across the AA band is given approximately by $5\times10^6 / (f\ N_s)^2$.

To complete the trade-off analysis, an AA is considered which is able to achieve the specified science goals. The details of this are discussed in a forthcoming SKA memo. A key element of the analysis is the flexibility of the AA to be able to trade not only FoV for bandwidth, but also to tailor the processed FoV as a function of frequency, which is shown to require FoV increasing substantially faster than the λ^2 for some experiments. This flexibility allows the FoV for a spectral-line survey to be a function of redshift and hence control survey speed as a function of redshift. The system temperature at 800MHz is taken to be 36 K consisting of a receiver temperature of 30K and a sky contribution of 6K. By fixing the antenna separation appropriate for $\lambda/2$ spacing at 800MHz, a sensitivity within 5km can be obtained of 6,000 m^2/K for T_{sys}=36K at 800 MHz). The main low-frequency survey experiments can then be achieved with a survey speed of 2×10^{10} $m^4\ K^{-2}\ deg^2$. This gives a mean number of beams across the band of about 1200, a station diameter ~85 m and an instantaneous observed Field of View of 200 deg^2 at 700 MHz. 66% of the collecting area is within 5 km. The remaining collecting area needs to be distributed so as to avoid confusion in continuum surveys which gives an upper baseline length for the AA of ~200 km. The cost of such a system is ~ 150 M€. To provide higher-resolution imaging it will be necessary to cross-correlate AA and dishes over the frequency range in common between the technologies.

Including an AA in Phase 1 of the SKA offers the possibility of a high survey speed instrument and sky monitor at mid- to low frequencies. The instrument, while having a clear new scientific niche, will also act as a pathfinder for mid-frequency AAs, fully demonstrating the beam-forming technology and ability to achieve high dynamic range and polarization purity. For a cost per element chain twice that assumed for phase 2, ~10,000 m^2 of AA can be constructed for a budget of 30 M€. If a correlator and post-correlator processor are available which are designed for a 490-dish array equipped with 28-beam PAFs, then this processor will enable the AA to be configured as ~ten 40m stations with a survey speed in excess of 10^7 $m^4\ K^{-2}\ deg^2$.

9. Achievable SKA Specifications

As part of the process already outlined, we have taken the science specifications progressively developed in SKA Memo's 3, 45 and 83 and formed a new set of top-level SKA specifications which are now distributed over the three SKA construction phases. Our approach has considered the cost to meet the different specifications, allowing us to identify specifications which are cost-driving outliers, and to prioritise these within a fixed-cost project. This process adds complexity since costs can be implementation-specific in ways which affect the overall technology balance. Indeed, the effect of the coupling between science goals and technology underlies much of this document. Table 14 gives the top-level specifications which are the most important cost drivers. The subsequent notes (Section 9.1) discuss specific trade-offs in formulating these specifications; for a general overview of key specification and cost considerations refer to Section 5.

Table 14. Top-level specifications for various implementation scenarios.

15/11/07 (v2.3)	**First Stage**		**Full SKA**			
Parameter	**Phase 1** ***Mid-band –*** *inc.dense AA*		**Phase 2 scenarios** ***Low & mid-bands –*** *all inc. AAs to 500MHz*			**Phase 3** ***High band***
	WBF only	**WBF+PAF***	**WBF only**	**WBF+PAF***	**WBF+dense AA**	
Frequency Range: Low	500 MHz	500 MHz	70 MHz	70 MHz	70 MHz	10 GHz
Frequency Range: High	10 GHz	10 GHz	10 GHz	10 GHz	10 GHz	35 GHz
Survey speed (m^{4}K^{-2}deg^2)						
70 - 200 MHz			3 x 10^9	3 x 10^9	3 x 10^9	
200 - 500 MHz	1 x 10^7	1 x 10^7	2 x 10^{10}	2 x 10^{10}	2 x 10^{10}	
0.7 GHz	1 x 10^7	3 x 10^7	3 x 10^8	1 x 10^9	2 x 10^{10}	
1.4 GHz	2 x 10^6	3 x 10^7	6 x 10^7	1 x 10^9	4 x 10^7	
3 GHz	5 x 10^5	1 x 10^5	1 x 10^7	5 x 10^6	1 x 10^7	
10 GHz	2 x 10^4	5 x 10^3	5 x 10^5	2 x 10^5	4 x 10^5	
25 GHz						4.6 x 10^4
35 GHz						2.4 x 10^4
Min. sensitivity at 45^o A_{eff}/T_{sys} (m^{2}K^{-1})						
70 - 200 MHz			4,000	4,000	4,000	
200 - 500 MHz	200	200	10,000	10,000	10,000	
700 MHz	2,000	1,100	12,000	7,000	10,000	
1.4 GHz	2,000	1,100	12,000	7,000	10,000	
3 GHz	2,000	1,100	12,000	7,000	10,000	
10 GHz	1,300	700	8,000	5,000	7,000	5,000
25 GHz						5,000
35 GHz						5,000
Configuration:						
core: < 1 km	50 %	50 %	20 %	20 %	20 %	20 %
inner: < 5 km	75 %	75 %	50 %	50 %	50 %	50 %
mid[†]: < 180 km	100 %	100 %	75 %	75 %	75 %	75 %
outer: <~3,000 km			100 %	100 %	100 %	100 %
WFoV for Surveys: *Spectral imaging / time domain*						
max baseline km	5	5	10	10	10	20
channels #	16,384	16,384	32,768	32,768	32,768	32,768
sample rate ms	0.1	0.1	0.1	0.1	0.1	0.1

* Sensitivity of PAF and WBF shown as equal

[†] The mid-range baseline lengths for Phase 1 range up to 50-100km

To illustrate simply the gains expected during the development of the SKA, Figure 11 shows the progression of 1.4 GHz sensitivity, and Figure 12 the progression of the survey speed figure-of-merit at 1.4 GHz and 700 MHz. Existing instruments, upgrades and large-scale SKA Pathfinders are included, with the range of values reflecting current uncertainty in the performance of emerging technologies. In all likelihood, SKA-Phase1 will be augmented by whichever of the Pathfinders, ASKAP or meerKAT, is already in operation on the selected site. The resultant instrument offers significant advances over previous telescopes, especially in terms of the key survey speed figure-of-merit, where an order of magnitude improvement is clear.

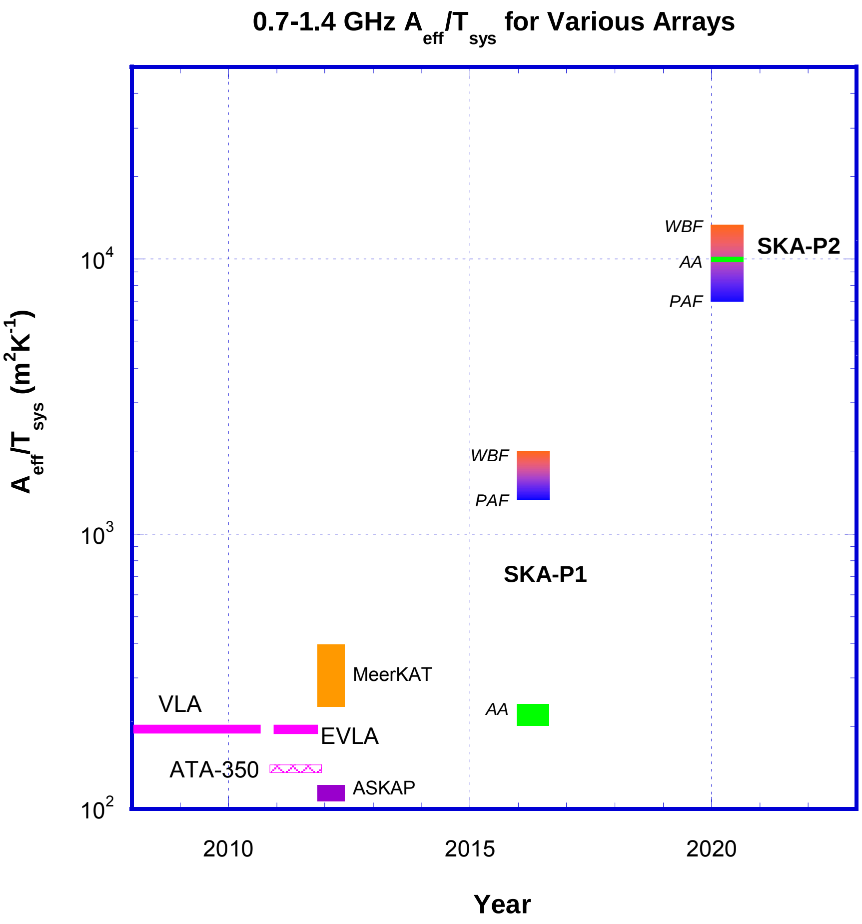

Figure 11. 0.7 GHz – 1.4 GHz A_{eff}/T_{sys} for Various Arrays.

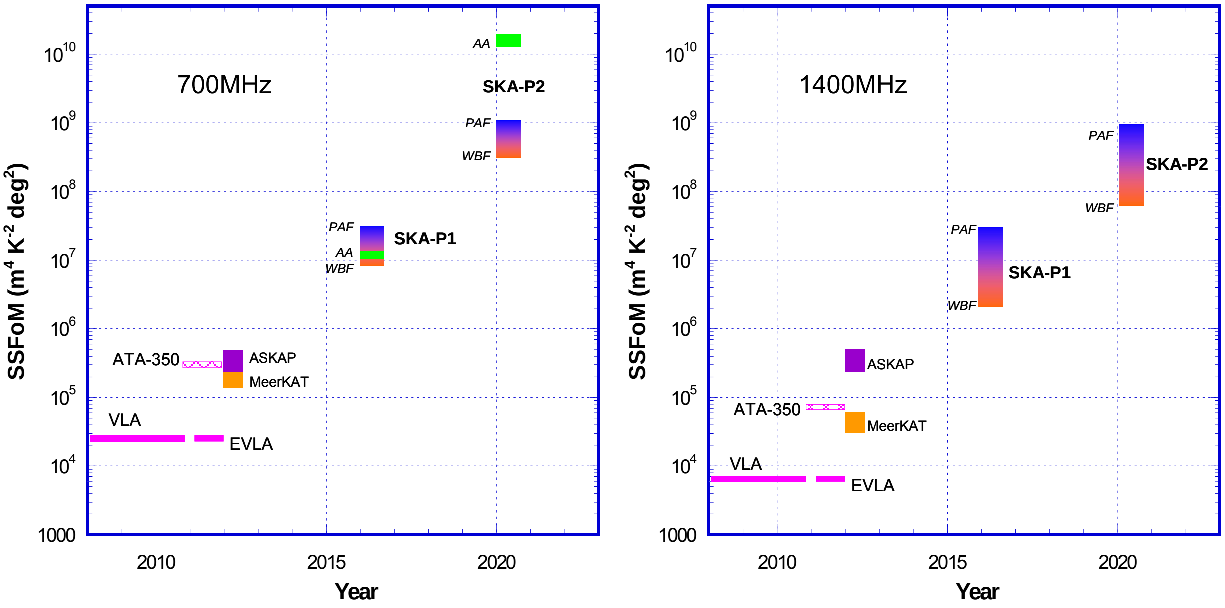

Figure 12. SSFoM for Various Arrays, for (left) 0.7 GHz, and (right) 1.4 GHz

9.1. Top-level Specifications

9.1.1. Frequency Range

Diameter and the high frequency limit are the main antenna cost drivers. The 10 GHz base-level specification in Phase 1 and 2 does exclude significant key science (molecules and CO in the Early Universe, and proto-planetary disks) as well as many other important science projects. As agreed by the ISSC in “Resolution on phased implementation of the SKA”, March 2007 (Annex 1 of this document), this key science is to be deferred to SKA Phase 3.

9.1.2. Survey Speed

For many of the SKA science drivers the basic requirement is survey speed (characterised as FoV.$(A_{eff}/T_{sys})^2$) which can be achieved through either FoV expansion or A_{eff}/T_{sys} sensitivity improvements. The desired survey speeds (see also Table 3) are largest at lower frequencies with the most extreme requirements for HI surveys increasing with redshift. This is ideal for the sparse aperture array solutions where A_{eff} scales naturally as λ^2. Around 1GHz, where detailed studies of HI and a number of continuum surveys (pulsars, polarization, AGN) will be carried out, survey speed requirements are best met by either the dense aperture or focal plane phased arrays. These are referred to as FoV expansion technologies in this document and represent solutions with the greatest uncertainty in technology. Given that mid-band WFoV technology choices are not yet possible, Table 14 specifies survey speed only at mid-band spot frequencies, reflecting the present uncertainty in cross-over frequencies between technologies. It is however clear that the dense AA is the only solution capable of meeting the dark energy survey speed requirement.

9.1.3. Sensitivity

The relevant science specification is the targeted source sensitivity (specified by A_{eff}/T_{sys}). This is closely linked to the survey sensitivity metric, FoV $(A_{eff}/T_{sys})^2$ as described in Section 5. The A_{eff}/T_{sys} specifications in this table are reduced from those in SKA Memo 45 to constrain total cost. This does not reduce the survey speed specification but may impact precise pulsar timing, some types of transients and, at high frequencies, proto-planetary disks and prebiotic molecules. The A_{eff}/T_{sys} specifications listed here are those needed to meet the specifications for non-survey science projects and for projects which require instantaneous sensitivity.

9.1.4. Field-of-View

For essentially all the key science drivers the FoV specification is really a survey speed specification so a separate FoV requirement is redundant and may be construed as an artificial technology driver. However, the likelihood of detecting new phenomena, including transients, is increased by viewing more of the sky. If SKA survey speed and cost using two receptor technologies are comparable, the technology delivering the wider FoV is preferred.

9.1.5. Configuration

The distribution of antennas with baseline for Phases 2 and 3 is that agreed on in previous memos. Longer baselines are not included in Phase 1 which is optimised for early survey science involving low brightness objects. Continuum observations of galaxy evolution and AGN and pulsar astrometry are seriously compromised in Phase 1. The Simulations WG and Science WG are engaged in an analysis of the Phase 2 configuration that will be completed in 2008; the Phase 1 configuration will form a subset of the Phase 2 configuration.

9.1.6. Signal Processing

Computing costs are dominated by factors which scale as the volume of the image cube. The limitation of 10 km baselines and 16k channels for spectral line imaging could compromise the high-z HI absorption surveys but since most of the FoV is empty, other algorithms may alleviate the impact of these constraints. 32k channels are desirable for the HI absorption blind surveys but may be too expensive as the number of channels also impacts correlator and computing costs. There is no analogous challenging technology limit for continuum image cubes.

The maximum time sampling rate is only a limit in correlation and imaging mode. For phased SKA operation, it should be possible to sample at up to the reciprocal observing bandwidth.

9.2. Other Top-level Specifications

Table 15 lists a number of additional important science-driven specifications. Unlike the specifications listed in Table 14, these additional specifications are unlikely to drive choices between SKA receptor technologies and are expected to be similar for all three phases of the SKA.

Table 15. Other top-level specifications

Parameter	Specification
Instantaneous bandwidth	
70-200 MHz	130 MHz
200-500 MHz	300 MHz
500-1,000MHz	500 MHz
> 1 GHz	25 % of centre frequency to a maximum bandwidth of 4GHz (goal 8 GHz)
Image quality (dynamic range)	
line	10^5
continuum	10^6
Beamformer capability	
Summed SKA beams inside 10 km diameter	50
Antenna	
pointing	to be determined
slewing	0.5 HPBW in 3 sec, 90 deg. in < 60 sec
Instrumental polarization (after calibration)	
field centre	- 30 db
field edge	- 25 db
Total power calibration	5 %

10. Implementation of Phase 1 and Phase 2

This section describes representative implementation strategies for the SKA based on the performance and cost analyses of arrays meeting the top-level specifications described in Table 14. While performance - cost (p-c) optimisation for the SKA is in its early phases (if only because many p-c input parameters are still to emerge from Pathfinders and Design Studies, see Section 8.1), the solutions outlined in this section support the view that a scientifically highly attractive instrument can be constructed within the 1,500 M€ (2007, Net Present Value) ceiling set for the total cost of SKA Phases 1 and 2.

10.1. Phase 1

We set out here implementations for the first stage of the SKA (Phase 1) and the considerations that underpin our proposals.

10.1.1. Budget

The cost is assumed to be 300 M€, including:
170 M€ for dish-based antenna systems
30 M€ for an aperture array (dense or sparse TBD)
100 M€ for infrastructure, NRE, software, management costs and delivery costs

10.1.2. Technology Choice

Progress made in the course of the PrepSKA system design concerning the technical maturity of the primary technologies, will guide decisions on the detailed design of Phase 1. The most likely implementation is a combination of
1) a dish solution based on both PAFs and WBSPFs in the central 5km core, and
2) a dish solution based on WBSPFs only in the outer part of the Phase 1 array,
The ratio of PAFs to SPFs will be decided during the course of PrepSKA.
In addition, 3) the first aperture array will be deployed as an all-sky monitor and to test imaging capabilities.

In Figure 11 and Figure 12 the two dish-based implementations are examined separately in order to highlight the potential differences in sensitivity and survey speed FoM provided by the two implementations. The WBSPF-only solution delivers better sensitivity (A_{eff}/T_{sys}) than the PAF solution, but the reverse is true for the SSFoM (see Figure 12). In practice, the SKA P-1 performance for sensitivity and survey speed is likely to lie between these two extremes.

a. Reflector size

The trade-off analysis described in Section 8 shows that reflectors with 12 to 15 m diameter are the appropriate choice to minimize the costs. However, a 15 m is to be preferred if they are to operate at frequencies down to 300 MHz as a risk mitigator for Aperture Arrays not proving viable. The number of dish-based systems to be purchased within the 170 M€ budget is strongly dependent on the surface accuracy and pointing accuracy required for the dishes. Dishes with an rms surface accuracy of 1.5 mm will provide aperture efficiencies of about 65% at 10 GHz with standard illumination efficiencies (see Figure 2), for a estimated cost of 230 k€ each in quantities of several hundreds.

Investigations of cheap dish technologies by the Canadian program, TDP, ASKAP, and MeerKAT by 2010 may lead to a clear choice of diameter and surface accuracy that will point the way forward for an affordable SKA meeting the specifications.

b. WBSPFs

The ATA feeds and receivers currently show a flat gain response and a T_{sys} of 40 - 45 K over a frequency range of 6:1, and a less flat response with higher T_{sys} at the extremities of their 0.5-11 GHz band. We assume that a flat gain response over a bandwidth of 7:1 will be achievable in Phase 1, allowing the full frequency range of 500 MHz to 10 GHz to be achieved with two feed/receiver systems covering the bands 0.5-1.5 GHz and 1.5-10 GHz.

c. PAFs

The cost of data processing for PAFs on baselines longer than 5-10 km may inhibit their widespread use at greater distances from the core, in which case, the majority of the dishes in the outer regions will be equipped with WBSPFs only.

The system temperature assumed is 50 K (Table 6), but the ASKAP project has a goal to reduce this to 35 K. If that effort is successful, Phase 1 will adopt this value as well.

d) Aperture arrays

Aperture arrays are the technology of choice for low frequency use, below where dishes are efficient, and capable of providing the very large A_{eff} required when system noise is dominated by sky noise. There are a number of early instruments expected to demonstrate this technology prior to Phase 1, principally LOFAR and MWA.

Processing and digitisation capability can now support higher frequencies up to ~1GHz, with expected system temperatures similar to the PAF, assumed to be 50K and working towards 35K. This technology can uniquely provide the extremely high survey speeds required for the dark energy experiment. Processing capability improvements are projected to continue over time.

The central processing requirements, both correlator and post-processor, are greatly reduced for high survey speed with aperture arrays. This is due to using a few large collector arrays, with many small beams scaling the processing requirement as N beams; rather than using many small dishes where correlation and calibration, scales as diameter, D^{-6} or even D^{-8}.

10.1.3. Phase 1 Science Performance (A/T, FoV, and Survey Speed)

Table 16 presents possible implementations for Phase 1 that are projected to fall below the target cost for components of 200 M€. Note that 2a and 2b are alternative implementations. It is proposed that 30 M€ be reserved in the budget for deployment of an aperture array - sparse or dense to be determined during the course of the PrepSKA Design Study from science and technical readiness considerations.

Table 16. Phase 1 technology combinations in the frequency range 500 MHz to 10 GHz

Frequency Range	Sensor	A_{eff}/T_{sys} m^2K^{-1}	Survey speed $m^4K^{-2}deg^2$	Cost
1) 500-800 MHz *	Dense Aperture Array	200	$1x10^7$	30 M€
2a) 0.5-10 GHz	490 15m dishes with PAFs (0.5-1.5 GHz) T_{sys}=50K effic=70%, FoV=20 deg^2 +WBSPF (1.5-10GHz) T_{sys}=35K, effic=65%	1200	$3x10^7$	170 M€
2b) 0.5-10 GHz	620 15m dishes with WBSPFs (0.5-10 GHz) T_{sys}=35K, effic=65%	2,000	$2x10^6$ at 1.4 GHz	170 M€

* or 100 – 500 MHz using sparse aperture arrays if science and technical considerations so dictate

Table 17 and Table 18 list the nominal Phase 1 science drivers (see Section 3.3 for description) and the performance of the two extreme Phase 1 implementations. The performance of a “mixed” dish array with PAFs/SPFs primarily in the centre and SPFs at larger distances would be intermediate between these two extremes. Note that the nominal A_{eff}/T_{sys} assumed by the SWG in its deliberations on Phase 1 science (Section 3.3) was 2,000 m^2K^{-1} and survey speed was $4x10^8$ so the performance of the implementations in Table 19 and Table 20 will suffer somewhat in comparison.

Table 17. Nominal Phase 1 science drivers vs the performance of Option 1+2a for the Phase 1 implementation (Dishes + PAFs + WBSPFs with overall 0.5 – 10 GHz coverage)

Topic	Suitable?	Comment
1.1 Building Galaxies		
1.1.a HI emission	Yes	The scope of this project will be reduced, but a survey of marginally acceptable breadth/depth could still be achieved.
1.1.b RM survey	Yes	
1.1.c HI absorption	Yes	Small FoV limits survey speed, but results would still be acceptable.
1.2 Pulsars & Transients		
1.2.a GC pulsars	Partial	15 GHz or higher required to fully defeat scattering for shorter period pulsars
1.2.b Pulsar timing array	Yes	Small FoV limits survey speed but not detection threshold.
1.2.c PSR J0737-3039	Yes	
1.2.d MSPs	Yes	
1.2.e Transients	Partial	Small FoV a limitation for rare events distributed across the whole sky.
1.3 First Light		
1.3.a Stromgren Spheres	No	Unless sparse AAs are available in the 100-500 MHz range
1.3.b Normal Galaxies	Partial	OK for radio synchrotron, partial for molecular lines, but not for thermal dust emission, which requires frequencies above 10 GHz

Table 18. Nominal Phase 1 science drivers vs the performance of Option 1+2b for the Phase 1 implementation (Dishes + WBSPFs with overall 0.5 – 10 GHz coverage)

Topic	Suitable?	Comment
1.1 Building Galaxies		
1.1.a HI emission	Yes	The scope of this project will be reduced, but a survey of marginally acceptable breadth/depth could still be achieved.
1.1.b RM survey	Yes	Small FoV and lower A/T limits survey speed, but results would still be acceptable.
1.1.c HI absorption	Yes	Small FoV and lower A/T limits survey speed, but results would still be acceptable.
1.2 Pulsars & Transients		
1.2.a GC pulsars	Partial	15 GHz or higher required to defeat scattering for shorter period pulsars
1.2.b Pulsar timing array	Yes	Small FoV and lower A/T limits survey speed but not detection threshold.
1.2.c PSR J0737-3039	Yes	Lower A/T will reduce the timing precision; no limitation due to FoV.
1.2.d MSPs	Yes	Lower A/T will reduce the timing precision; no limitation due to FoV.
1.2.e Transients	Partial	Small FoV a limitation for bright events distributed across the whole sky.
1.3 First Light		
1.3.a Stromgren Spheres	No	Unless sparse AAs are available in the 100-500 MHz range
1.3.b Normal Galaxies	Partial	OK for radio synchrotron, partial for molecular lines, but not for thermal dust emission, which requires frequencies above 10 GHz

10.1.4. Configuration

The locations of elements in the Phase 1 configuration must conform to those required for Phase 2. Note that the Simulations WG and Science WG are engaged in an analysis of the Phase 2 configuration that will be completed in 2008 and will inform the choice of Phase 1 element locations.

The Phase 1 science drivers require baseline lengths up to about 50 km.

Consideration of other important science areas requiring imaging with longer baselines, allied with the critical development of high fidelity imaging and calibration techniques, suggest that deployment of the elements in a centrally condensed scale-free array (CCSFA) is desirable.

Other considerations suggest that there should be at least one element at a distance of 100 km to understand technical issues associated with fibre transport of large volumes of data over these distances.

The trade-off is between the Phase 1 science drivers and these other considerations. It is proposed that the Simulations WG and Science WG investigate a configuration in which 75% of dishes are deployed within a diameter of ~5 km in a centrally condensed scale-free array, with the remaining 25% deployed out to distances of several tens of kilometres.

10.2. Phase 2

Possible combinations of sensor elements are considered that will provide the frequency coverage for the SKA from ~70 MHz to 10 GHz. As for Phase 1, progress in the technical maturity of the various combinations will guide decisions made in the course of the system design coordinated by PrepSKA.

10.2.1. Budget

The target cost of SKA Phase 1+2 is 1,500 M€ (2007 NPV). The expected cost of infrastructure (including fibre installation), computing, delivery, management costs and labour is ~ 500 M€. Thus the budget for 15 m dishes, PAFs, AAs and associated system electronics is 1,000 M€. The expected costs of the various sensors, or combinations of sensors, are given in Table 19 for SKA low-band and SKA mid-band, with the constraint that the total cost remains at, or below, 1,000 M€. Note that options 3(a) through 3(c) are alternative SKA mid-band implementations.

10.2.2. Phase 2 technology costs in the frequency range 70 MHz to 10 GHz

Table 19. Phase 2 technology combinations in the frequency range 70 MHz to 10 GHz. (Note that 3a to 3c are three alternative mid-band implementations)

Frequency Range	Sensor	A_{eff}/T_{sys} m^2K^{-1}	Survey speed $m^4K^{-2}deg^2$	Cost
1) 70-200 MHz	Sparse aperture array composed of tiled dipole arrays	4,000-10,000	$3x10^9$	125 M€
2) 200-500 MHz	Sparse aperture array composed of tiled dipole arrays	10,000	$2x10^{10}$	125 M€
3a) <500 MHz-10 GHz	3,000 15m dishes/WBSPF T_{sys}=30K, effic=70%	12,000	$6x10^7$ at 1.4 GHz	750 M€
3b) 500 MHz-10 GHz	2,000 15m dishes with PAFs (500 MHz-1.5 GHz) T_{sys}=35K effic=70%, FoV=20 deg^2 + WBSPF (1.5-10 GHz) T_{sys}=30K	7,000	$1x10^9$ $5x10^6$ at 3 GHz	750 M€
3c) 500 MHz-10 GHz	Dense aperture array (500-800 MHz) + 2,400 15m dishes/WBSPF (800 MHz - 10 GHz), T_{sys}=30K, effic=70%	10,000 10,000	$2x10^{10}$ (500-800 MHz) $4x10^7$ at 1.4 GHz	150 M€ (AA) 600 M€ (dishes / WBSPF) total=750 M€

The costs of full frequency coverage, given various possible technology development outcomes, are summarised in Table 20.

Table 20. Three SKA technology combinations with coverage from 70 MHz to 10 GHz and costing 1,000 M€

Technology combination (refer Table 19)	Comments
1 + 2 + 3a (Sparse AAs 70 MHz - 200 MHz and 200 MHz - 500 MHz + 3,000 dishes+WBSPF <500 MHz - 10 GHz)	Base system design: sparse AA combined with dishes and single-pixel feeds
1 + 2 + 3b (Sparse AAs 70 MHz - 200 MHz and 200 MHz - 500 MHz + 2,000 dishes and Phased Array Feeds (PAFs) and WBSPFs 500 MHz - 10 GHz)	Outcome if PAFs alone are viable as mid-band WFoV technology
1 + 2 + 3c (Sparse AAs 70 MHz - 200 MHz and 200 MHz - 500 MHz + dense AA 500 MHz - 1 GHz + 2,400 dishes/WBSPF 800 MHz - 10 GHz)	Outcome if AAs alone are viable as mid-band WFoV technology

10.2.3. Science Performance

Table 21 to Table 23 show, in summary form, the science performance corresponding to the technology combinations listed in Table 20. Some of the non-suitability is NOT inherent in the technology.

Table 21. Technology combination 1 + 2 + 3a: sparse AAs covering 70 MHz to 200 MHz and 200 MHz to 500 MHz, plus 3,000 15 m dishes equipped with a wide-band single-pixel feed covering <500 MHz to 10 GHz

Topic	Suitable?	Comment
Probing the Dark Ages		
a EoR	Yes	
b First Metals	Partial	Can probe limited subsets of molecules in z, rest-frequency combinations (e.g. CO 115 GHz transition for z>10) ; most observations of interest are above 10 GHz
c First Galaxies & BHs	Yes	Somewhat reduced sensitivity compared to desirable spec
Galaxy Evolution, Cosmology & Dark Energy		
a Dark Energy	No	Target parameter precision requires survey speed of $6x10^9$
b Galaxy Evolution	Partial	Low survey speed requires considerable scaling down in scope of survey
c Local Cosmic Web	Yes	
Cosmic Magnetism		
a Rotation Measure Sky	Yes	Small FoV limits survey speed for all-sky RM maps, but not detection threshold for very deep observations of individual fields.
b Cosmic Web	Yes	
GR using Pulsars & BHs		
a Gravitational Waves	Yes	Requires quality polarization, frequent sampling of pulsars, sensitivity is less than desirable but adequate
b BH Spin	Partial	Ok for non-GC pulsars. Sgr A* needs frequencies 15 GHz or higher to detect short period pulsars and get timing precision
c Theories of Gravity	Yes	Sensitivity is less than desirable but adequate;
Cradle of Life		
a Proto-planetary Disks	No	Requires frequencies > 10 GHz
b Prebiotic Molecules	Yes	Various aldehydes have transitions in the range 1-2 GHz and many other transitions are in the 8-9 GHz range.
c SETI	Yes	High sensitivity for targeted searches.
Exploration of the Unknown	Yes	Sensitivity is a key dimension of discovery space. Small FoV limits blind surveys for transient radio sources.

Table 22. Technology combination 1 + 2 + 3b: sparse AAs covering 70 MHz to 200 MHz and 200 MHz to 500 MHz, plus 2,000 dishes, phased array feeds and wide-band single-pixel feeds covering 500 MHz to 10 GHz.

Topic	Suitable?	Comment
Probing the Dark Ages		
a EoR	Yes	
b First Metals	Partial	Can probe limited subsets molecules in z, rest-frequency combinations (e.g. CO 115 GHz transition for z>10); most observations of interest are above 10 GHz
c First Galaxies & BHs	Yes	Substantially reduced sensitivity compared to desirable spec
Galaxy Evolution, Cosmology & Dark Energy		
a Dark Energy	No	Survey speed factor of 6 lower than desirable even with 20 sq. deg. FoV in the 550 – 950 MHz range, so get less precision than desired on DE equation of state parameters
b Galaxy Evolution	Yes	
c Local Cosmic Web	Yes	
Cosmic Magnetism		
a Rotation Measure Sky	Yes	
b Cosmic Web	Yes	
GR using Pulsars & BHs		
a Gravitational Waves	Yes	Requires quality polarization, frequent sampling of pulsars, sensitivity is less than desirable but adequate
b BH Spin	Partial	Ok for non-GC pulsars. Sgr A* needs frequencies of 15 GHz or higher to detect short period pulsars to get timing precision
c Theories of Gravity	Yes	sensitivity less than desirable but adequate
Cradle of Life		
a Proto-planetary Disks	No	Requires frequencies > 10 GHz
b Prebiotic Molecules	Yes	Various aldehydes have transitions in the range 1-2 GHz and many other transitions are in the 8-9 GHz range.
c SETI	Yes	
Exploration of the Unknown	Yes	Sensitivity and FoV are key dimensions of discovery space, the latter important for blind transient surveys.

Table 23. Technology combination 1 + 2 + 3c: sparse AAs covering 70-200 MHz and 200-500 MHz, plus a dense AA covering 500 MHz -1 GHz, plus 2,400 15 m dishes and wide-band single-pixel feeds covering 800 MHz-10 GHz

Topic	Suitable?	Comment
Probing the Dark Ages		
a EoR	Yes	
b First Metals	Partial	Can probe limited subsets molecules in z, rest-frequency combinations (e.g. CO 115 GHz transition for z>10) ; most observations of interest are above 10 GHz
c First Galaxies & BHs	Yes	Somewhat reduced sensitivity compared to desirable spec
Galaxy Evolution, Cosmology & Dark Energy		
a Dark Energy	Yes	Survey speed can be achieved below 800 MHz but falls off above 800 MHz
b Galaxy Evolution	Yes	
c Local Cosmic Web	Yes	
Cosmic Magnetism		
a Rotation Measure Sky	Yes	
b Cosmic Web	Yes	
GR using Pulsars & BHs		
a Gravitational Waves	Yes	Requires quality polarization, frequent sampling of pulsars, Sensitivity is less than desirable but adequate
b BH Spin	Partial	Ok for non-GC pulsars. Sgr A* needs frequencies of 15 GHz or higher to detect short period pulsars to get timing precision
c Theories of Gravity	Yes	Sensitivity is less than desirable but adequate
Cradle of Life		
a Proto-planetary Disks	No	Requires frequencies > 10GHz
b Prebiotic Molecules	Yes	Various aldehydes have transitions in the range 1-2 GHz and many other transitions are in the 8-9 GHz range.
c SETI	Yes	High sensitivity for targeted searches.
Exploration of the Unknown	Yes	Sensitivity and FoV are key dimensions of discovery space. Achieve wide field, blind-survey capability for transients below 0.8 GHz.

10.2.4. Configuration

Note that the Simulations WG and Science WG are engaged in an analysis of the Phase 2 configuration that will be completed in 2008. It is likely that a centrally condensed scale-free array configuration will be adopted with 50% of the collecting area in the central ~5 km, with a further 25% from 5 to 150 km and the final 25% from 150 km to 3,000+ km. Trade-offs are needed to maximise surface brightness sensitivity and dynamic range, and minimize confusion for continuum integration times of a few hundred hours over the entire frequency range.

11. Engineering Decisions and Time Line

April 2008	Set top-level SKA P-1 and SKA specifications following a review by the SKA Specifications Review Committee
March 2009	Set final specifications for SKA design options following a review of SKA concept design by the International Engineering Advisory Committee
January 2010	SKA P-1 First Design Review (1DR/P-1)
January 2011	Wide FoV First Design Review (1DR/WFoV)
September 2011	SKA P-1 Second Design Review (2DR/P-1)
December 2012	Wide FoV Second Design Review (2DR/WFoV)
January 2015	Production Readiness Review for the full SKA mid+low array

11.1. April 2008, set preliminary SKA P-1 and SKA specifications

Following the science-engineering iterations, the ISSC will be asked to approve the draft top-level specifications at its mid-term telecon in November 2007. The specifications will then be submitted for review in January 2008 by the SKA Specifications Review Committee (SSRC), and formal approval by the SSEC (as successor to the ISSC) in April 2008.

Key issues include:
- SKA P-1 upper and lower frequency limits
    - should SKA P-1 provide an EoR capability?
- Sensitivity vs survey speed vs frequency for SKA
- SKA P-1 configuration (surface brightness sensitivity vs. resolution and image quality)
- Likely evolution path from SKA P-1 to SKA P-2

Input information
- Preliminary specifications for the SKA
- SSRC report
- Science case for SKA P-1
- Magnificent Memo series detailing SWG responses to many of the tradeoff issues
- Preliminary results from the SKADS study of pre-P-1 scientific programs
- EWG White Paper series on SKA design issues
- SWG considerations on survey metrics
- Design Study and Pathfinder experience in SKA technologies

Desired outcome
The preliminary SKA P-1 and SKA P-2 specifications will set the scene for the development of the SKA Design from 2008 to 2011.

11.2. March 2009, set final specifications for SKA design options

PrepSKA, the FP7 Preparatory Phase for SKA is projected to start in April 2008. The dominant technical activity (Work Package 2, FP7 WP2) will be the integration of the national and regional R&D knowledge into the SKA Design by the ISPO Central Design Integration Team (CDIT). In the course of 2008, the senior engineers in the CDIT will transform the preliminary design specifications into more detailed SKA Design Concepts for the representative implementations based on those outlined in Section 10. The specifications for Design Concepts will be reviewed by the International Engineering Advisory Committee (IEAC) in December 2008. The ISSC will then approve the final specifications of the SKA design options to be carried forward in FP7 WP2.

Input information

- Preliminary specifications for SKA Phases 1 and 2
- IEAC report
- Interim results from TDP on dish, feed and receiver technologies
- Interim results from ATA, ASKAP, MeerKAT, and Canada on dish technologies
- Interim results from SKADS on AA technology
- Interim results from LOFAR and MWA on low frequency AAs
- Interim results from ASKAP and Apertif on PAFs
- Interim results from MeerKAT on MFCs

Desired outcome

Specifications for the SKA design work by the CDIT. Guidance given to pathfinders and design studies on the desired results from those studies for the international SKA design.

11.3. January 2010, SKA P-1 First Design Review

This Review will look in detail at complete designs for the SKA P-1 options and in particular at the cost and performance of key sub-systems including antennas. A decision on dish diameter during this review depends on prototyping efforts, information from the design studies, as well as on developments in FoV expansion technology

Input information

- Documents from PrepSKA WP2 integrating
    - Results from TDP
    - ATA astronomical results and technical performance
    - Final results from SKADS on AA technology
    - Results on ASKAP and MeerKAT systems and design
    - Canadian development of dish technology
- Mid-term results from PrepSKA WP2 sub-system prototyping

Desired outcomes

A recommendation that one system design stream be continued. Start of Initial Verification System development.

11.4. January 2011, Wide FoV First Design Review

This review will look at the cost and astronomical performance achieved in the major SKA wide-FoV Pathfinders and Design Studies, MeerKAT, ASKAP, Apertif, SKADS/EMBRACE, LOFAR.

Input information

- FP7 WP2 results on costs of implementing wide FoV technology
- Astronomical results and simulations from ASKAP
- Astronomical results and simulations from MeerKAT
- Astronomical results and simulations from Apertif
- Astronomical results from LOFAR/MWA
- Astronomical results and simulations from SKADS/EMBRACE and post-SKADS activity

Desired outcome

Recommendation on which wide FoV technology(s) should be further developed for SKA.

11.5. September 2011, SKA P-1 Second Design Review

This design review for SKA P-1 will evaluate progress in the cost and performance of dish system design approaches, taking into account the results of the first Design Review of WFoV, and the science requirements.

Input information
- Performance evaluation of FP7 WP2 Initial Verification System
- Results from TDP
- Results from ASKAP, MeerKAT and ATA
- Updated science requirements
- Report on the first wide FoV Review

Desired outcome
SKA P-1 system designs to be pursued beyond this point will be chosen. The dish diameter will be chosen if that did not occur in the first design review in January 2010.

11.6. December 2012, Wide FoV Second Design Review

This critical design review for the SKA wide-FoV technology will examine the cost and performance achieved using SKA P-1 as a development and demonstrator platform for wide FoV technology.

Input information
- Astronomical results and simulations on PAFs from ASKAP
- Results on AA tiles from post-SKADS activity, both as all-sky monitor and imaging array
- Astronomical results and simulations on MFCs from MeerKAT

Desired outcome
A decision to proceed with construction of one or two wide FoV options in SKA.

11.7. January 2015, Production Readiness Review for SKA mid+low

The final specifications will be set by reference to the initial specifications, contemporary science imperatives, operational experience with the Pathfinders, commissioning results from SKA Phase 1, and detailed costing derived from SKA Phase 1 build.

Input information
- Initial SKA specifications
- Updated science case
- Results from initial astronomical measurements with pre-P-1 SKA
- Astronomical results from ASKAP, MeerKAT, and ATA

Desired outcome
A complete description of the full array to be built, including the mix and deployment strategies of one or two wide FoV technologies.

11.8. January 2016, Set Top-level Specifications for SKA high-band array

Following science-engineering iterations, the SKA governing body will be asked to approve the preliminary top-level specifications for SKA high-band array. These will serve to define the framework for work on the concept design for SKA at frequencies above 10 GHz that will take place in the years to follow.

12. Glossary

1DR. First SKA Phase 1 Design Review.

2DR. Second SKA Phase 1 Design Review.

2-PAD. Dual Polarization – Phased Array Demonstrator

AA. Aperture Array.

AA-lo. Low frequency Aperture Array (70MHz to 300MHz).

AA-hi. High Frequency Aperture Array (<300MHz to ~1GHz).

AGN. Active Galactic Nucleus.

ALMA. Atacama Large Millimetre Array.

APERTIF. Aperture Tile In Focus.

ASIC. Application-Specific Integrated Circuit

ASKAP. Australian Square Kilometre Array Pathfinder.

ATA. Allen Telescope Array.

ATNF. Australia Telescope National Facility.

BH. Black Hole.

CASPER. Center for Astronomy Signal Processing and Electronics Research. See http://casper.berkeley.edu

CCSFA. Centrally Condensed Scale-Free Array.

CDIT. Central Design Integration Team.

CMB. Cosmic Microwave Background.

DR. Dynamic Range.

DRAO. Dominion Radio Astrophysical Observatory.

eEVN. e-European VLBI Network.

ELT. Extremely Large Telescope.

EMBRACE. Electronic Multi-Beam Radio Astronomy.

EVLA. Expanded Very Large Array

EWG. Engineering working Group.

FoV. Field of View.

FP6. European Framework Programme 6 (2003-2006).

FP7. European Framework Programme 7 (2007-2013).

GC Pulsar. Galactic Center Pulsar.

Gaia. A probe due for launch in 2011 by the European Space Agency.

GMRT. Giant Metrewave Radio Telscope.

GR. General Relativity.

IEAC. International Engineering Review Committee.

IGM. Intergalactic Medium.

ISPO. International SKA Project Office.

ISSC. International SKA Steering Committee.

IVS. Initial Verification System.

KAT. Karroo Array Telescope.

KSP. Key Science Project.

LOFAR. Low Frequency Array.

LNA. Low Noise Amplifier.

LNSD. Large-Number Small-Diameter.

LWA. Low Wavelength Array.

MFC. Multi-Cluster Feed.

MSP. Millisecond Pulsar.

MWA. Mileura Widefield Array.

MIRANdA. MIRA large-N, small-d Array, a component of ASKAP. This instrument was previously known as xNTD,

NPV. Net Present Value. This is a measure of the value of a future stream of benefits and costs converted into equivalent values today.

NRAO. National Radio Astronomy Observatory.

PAF. Phased Array Feed.

PrepSKA. Preparatory phase of the SKA.

PTA. Pulsar Timing Array.

RFI. Radio Frequency Interference.

RM Sky. Rotation Measure Sky.

SDSS. Sloan Digital Sky Survey. See www.sdss.org.

SETI. Search for Extra-Terrestrial Intelligence.

SSFoM. Survey Speed Figure of Merit.

Sgr A*. Sagittarius A*. A black hole at the center of the Milky Way.

SimWG. Simulations Working Group.

SKA. Square Kilometer Array.

SKADS. SKA Design Studies.

SPF. Single Pixel Feed.

SSRC. SKA Specifications Review Committee.

SWG. Science Working Group.

TDP. Technology Development Project for the SKA

TSFoM. Transient Source Figure of Merit

WBF. Wide-Band Feed.

WBSPF. Wide-Band Single Pixel Feed.

WSRT. Westerbork Synthesis Radio Telescope

ANNEX 1: ISSC Resolution on the phased implementation of the SKA

March 2007

The International SKA Steering Committee,

Recognising that:

- The SKA is a large project that will achieve transformational science
- Technology evolution and funding readiness suggest that deployment of science capability will require a phased approach
- An array telescope presents the opportunity for conducting transformational science as it is being built and reaches certain capability milestones, with a 10% capability being a particular such milestone

And noting that:

- Early science results from the SKA are of great interest to the broad scientific community (cosmology, galaxy evolution and gravity)
- Technology solutions to SKA scientific specifications map into three frequency bands: e.g. low: < 0.3 GHz; mid: 0.3 – 3 GHz; high: 3 to ≥ 25 GHz, with eventual frequency boundaries to be determined through ongoing technology development, with special attention given to the mid/high boundary
- Synergies with existing low-frequency projects (LOFAR, MWA and LWA) will influence SKA-program decisions and that high-frequency arrays such as EVLA, e-MERLIN and ALMA will deliver decision pathways for deployment of high-frequency SKA technology
- The first construction phase will address remaining technology risks for the full SKA
- Ongoing technology development will provide input that is crucial for making project decisions

Resolves to:

- Support a phased development of the SKA which progresses from the Pathfinder telescopes, to the first 10% of the SKA (designated Phase 1) with a restricted frequency range at a cost of about 250 M€, to the full SKA with the full frequency range
- Develop an SKA plan with a Phase 1 stage that initially focuses on the mid-band frequencies, while retaining an option to add collecting area at less than 300 MHz, based on the outcomes of existing observational facilities and developments in the theory of the Epoch of Re-ionization
- Use the Phase 1 results to guide the development and construction of the full SKA

ANNEX 2: PrepSKA Work Package 2 on SKA Design

A2.1 Overview

WP2 is a technical work package of four years duration. It is organized as a program covering system design and prototyping activities. Prototyping projects have been defined for each of the major SKA sub-systems in an arrangement mirroring that of the established international SKA engineering development structure. Specific objectives of WP2 are to produce:

- A costed top-level design for the SKA, and a detailed system design for SKA Phase 1;
- Advanced prototype SKA sub-systems specified in the course of (a), the sub-systems being based on technology development in current regional Pathfinders and Design Studies;
- Base technologies for SKA Phase 1 and critical wide field-of-view design technology extensions; and
- An Initial Verification System (IVS) which brings together the most advanced SKA Phase 1 technology components and demonstrates the functionality, cost effectiveness and manufacturability of the adopted SKA Phase 1 design.

In developing a costed top-level design, WP2 will build on technology developments being undertaken within the suite of international SKA Pathfinder telescopes and Design Studies, as well as other radio astronomical and industrial developments. The expenditure on SKA-related R&D around the world will be ~150 M€ from 2006-2010. The Design Studies are SKADS (FP6, Europe) and TDP (USA); the Pathfinders are the meerKAT (South Africa), ASKAP (Australia, Canada), ATA (USA), e-MERLIN (UK), EVLA (USA), LOFAR (Netherlands, Germany), APERTIF (Netherlands), MWA (USA, Australia), and LWA (USA).

Tasks within each WP2 project are led by an institute which is expert in the relevant field; lead institutes coordinate the input of their own and other expert contributors. WP2 projects themselves are coordinated and led by relevant domain specialists in the Central Design Integration Team (CDIT) to be formed within the International SKA Project Office (ISPO). There is a high degree of interdependency between the tasks and the ISPO, through the CDIT, will have the responsibility of coordinating activities across all of WP2.

The key areas of synergy between the Pathfinder activities and Design Studies and WP2 are:

- Receptor technologies (antennas, feeds);
- Wide field-of-view (WFoV) technologies;
- Signal transport and processing;
- Software and computing (including imaging and non-imaging applications).

The performance and cost goals of the SKA are ambitious and it has long been recognized that highly innovative engineering solutions are required to provide the required outcomes. The suite of Pathfinders and Design Studies demonstrates a commitment to innovation, and a wide-spread acceptance of the need to take risks. At the SKA project management level though, risk mitigation is a strong feature of SKA engineering development, with the most conventional receptor technology option for SKA Phase 1 - dishes and single-pixel wide-band feeds - being the starting point for the PrepSKA design. At the same time, strong links between WP2 and regional programs will allow the latest developments in wide field-of-view technologies - aperture array tiles (e.g. SKADS) and phased array feeds (e.g. ASKAP, APERTIF) - to be incorporated into SKA and Phase 1 designs if and when they become available. In fact, the Pathfinders and Design Studies, with their diverse but coherent technology developments, afford effective risk mitigation for all WP2 design and prototyping tasks. The envisaged design integration of the global R&D effort to be carried out by the ISPO-CDIT is shown schematically in Figure 13.

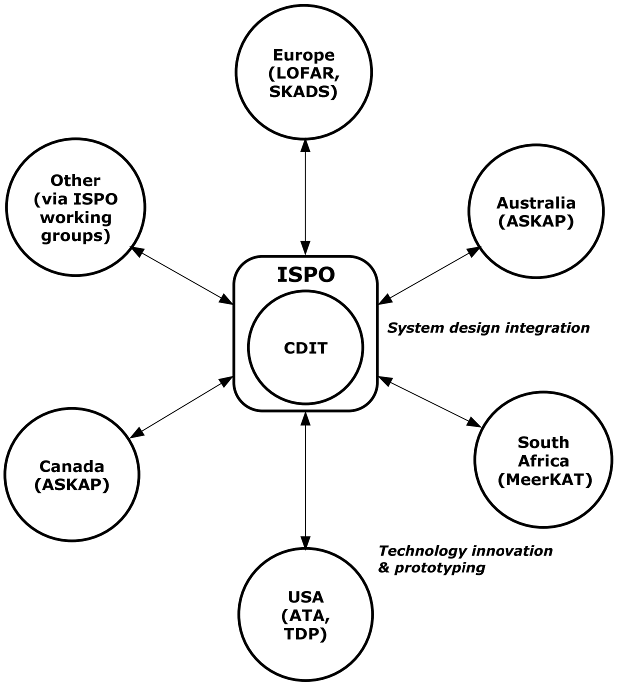

Figure 13. Schematic diagram showing the central coordination role to be played by the ISPO-CDIT in taking the technology innovation and prototyping carried out by regional programs to an integrated end-design for the SKA.

WP2 commences with design and specification tasks, which continue to produce insights into SKA design for the duration of the program. Approximately one year after program commencement, these tasks deliver the starting points for a series of SKA Phase 1 prototyping projects undertaken principally by contributing regional institutes. A year further on, these tasks feed into the specification and construction of the Phase 1 Initial Verification System, delivered jointly by the ISPO-CDIT and regional partners. At its conclusion WP2 will have provided a top-level costed SKA design and a detailed, verified, system design for Phase 1. Major reviews occur near the middle and end of the program, with design finalization and program completion being at the four-year point. A detailed breakdown of the WP2 projects, including timescale and resources, is available in the PrepSKA proposal. By design, WP2 is a fairly highly-geared program, with some 75% of the total resources (mostly in the form of manpower) coming from regional partners.

A2.2 Engineering Time Line in More Detail

Figure 1 (p12) shows the overall SKA timeline but it is also useful to summarize in more detail the engineering timeline for the next few years. In Figure 14 the PrepSKA WP2 study is overlaid on to the wider timescale to emphasize the important role of regional Pathfinders and Design Studies, especially in terms of key wide field-of-view technology options. Note that, while the present specification exercise (and ensuing review) sets initial specifications, the first year of PrepSKA develops these in a more detailed engineering context. Following the review by the International Engineering Review Committee (IEAC), engineering specifications will be set for the purpose of WP2 system and sub-system design.

SKA Phase 1 design reviews are held in the course of the PrepSKA program, with the first design review of wide field-of-view receptor technologies being held prior to the end of WP2. Furthermore, throughout the WP2 program there are strong formal links to regional projects, allowing developments in relevant technologies to be folded continuously into the system design.

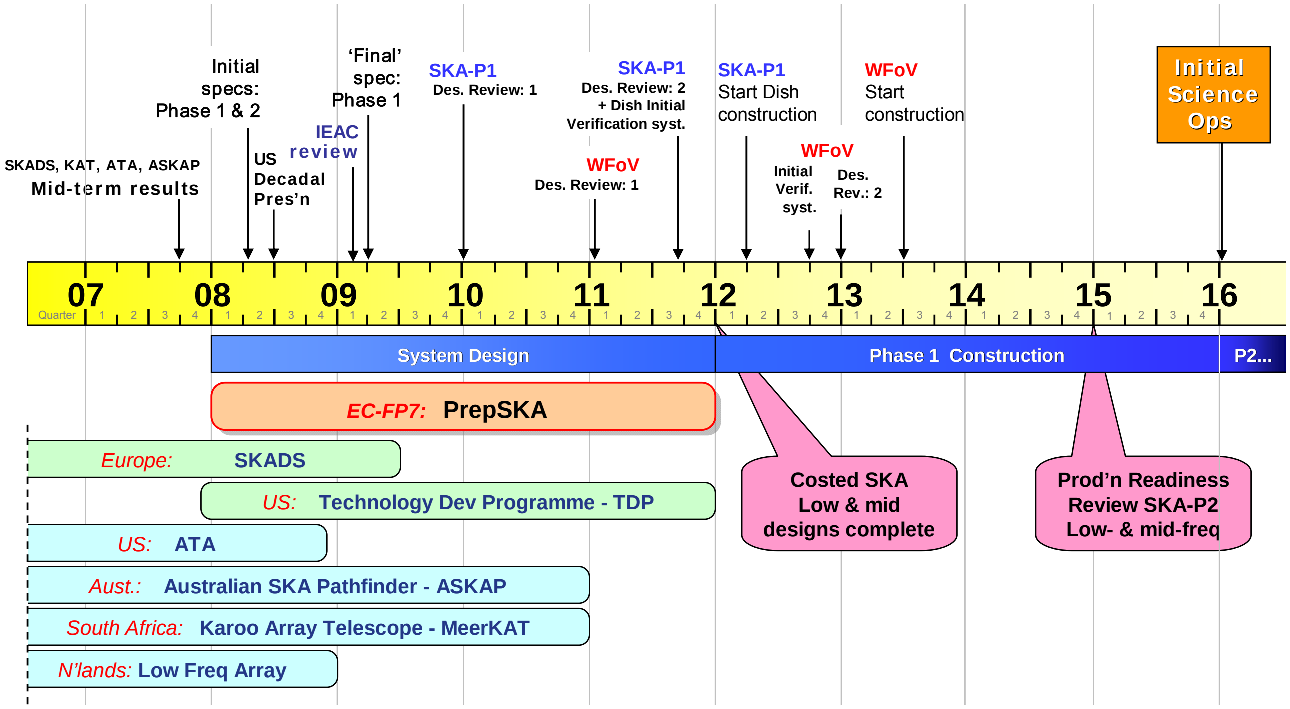

Figure 14. Detailed SKA engineering time line