Preparation for the SKA: PrepSKA

Proposal for UK national funding
in conjunction with the
EC FP7 SKA Preparatory Phase Study

Submitted by the UK SKA Consortium

Contents

Executive Summary

The Square Kilometre Array (SKA) will be one of the most complex scientific instruments ever built. It will, when fully deployed, consist of a continent-sized array of ~4000 dishes, with a novel flat panel aperture array component capable of all-sky imaging, and work in the frequency range 70MHz to ~25GHz. The array will be supported by an IT infrastructure designed to handle data rates comparable to the current internet traffic of the Earth.

The breadth of science that the SKA will address is truly remarkable; one should regard it as a fundamental physics facility as much as a telescope. It will be used to explore many of the major outstanding problems in astrophysics, cosmology and particle-astrophysics today. These include our understanding of the birth of the first stars and galaxies, study of the large-scale structure of the universe and the role of dark energy and hot and cold dark matter. Astronomers will also use the SKA to determine whether general relativity holds in the strong gravitational fields associated with massive black holes, understand the origin and evolution of cosmic magnetism, and explore the conditions required for life elsewhere in our galaxy. The SKA, uniquely for large scientific infrastructures (and only made possible by its phased construction plan), will be able to deliver ground-breaking science while still under construction.

The scale of the SKA means it can only be constructed as a global project; and so scientists and engineers from 19 countries are cooperating in an unprecedented effort to develop the technology required to ensure that the SKA is viable and affordable. Recently, the worldwide efforts have been brought to a focus here in the UK through two events: first, the STFC are coordinating a project with 24 partners from around the globe, which has received EC FP7 funding for a Preparatory Phase Study for the SKA (PrepSKA); secondly, the SKA Program Development Office (SPDO) moved to Manchester in February. The SPDO will serve as the central coordinating body for all SKA R&D around the world.

The funding of PrepSKA was a pivotal moment in the life of the SKA; the study provides funding for the first time for a central design integration team which will provide the crucial technical coordination role. PrepSKA also supports further site studies and vital agency-led work to understand the options for the governance, legal framework and procurement policy to construct and operate the SKA.

This proposal, a close collaboration of the Universities of Cambridge, Manchester and Oxford, requests funding of £9.89M (£8.76M plus £1.13M working allowance and contingency) from STFC to enable the UK to continue its key role in the development of the SKA. We have designed the work programme, which will run from July 2009 to March 2012, not only to be fully integrated with the global PrepSKA efforts, but also to ensure that we build upon the highly-successful SKADS work. The proposal has two major themes; the first focuses on the development of the SKA system architecture and the core technologies; the second concentrates on the evolution of the advanced digital aperture array, working alongside our European colleagues.

UK-PrepSKA has a significant number of major deliverables amongst which are the implementation of the SKA costing tool; the coding of simulation software which will study in detail the SKA signal path; the design of the fully integrated fibre optic data link and phase transfer system; the development of an efficient digital beamformer; the exploration and testing of the SKA data handling and processing algorithms; the detailed design of the mid-frequency aperture array; the delivery of an LNA and matched antenna element with Tsys < 50K at 800MHz; the demonstration of an analogue-to-digital converter with SKA performance.

The work will culminate in the construction of a Digital Aperture Array Verification System to complement the dish verification system that will be developed by our US and other colleagues.

1. Background

1.1 Status of the SKA Project

The SKA will be the most powerful radio telescope in the world: over 50 times more sensitive than existing telescopes and with at least 10000 times faster surveying speed. It will consist of an array of antennas with a million square metres of collecting area spread across 3000km covering a frequency range of ~70 MHz to ~25 GHz. The antennas will be linked to a central data processing facility by a wide bandwidth optical fibre network forming effectively the largest IT infrastructure on Earth.

The SKA will transform our ability to address the major outstanding problems in astrophysics, cosmology and particle-astrophysics today. These include our understanding of the birth of the first stars and galaxies, the study of the large-scale structure of the universe and the role of dark energy and hot and cold dark matter. Astronomers will also use the SKA to determine whether general relativity holds in the strong gravitational fields associated with massive black holes, understand the origin and evolution of cosmic magnetism, and explore the conditions required for life elsewhere in our galaxy.

The plans for the SKA construction take full advantage of the opportunity afforded naturally by interferometers to allow a phased approach to funding, construction and science. It is also planned to make major use of aperture array technology, which provides a huge advantage over traditional dish antennas for large fields of view at relatively low frequency. In aperture arrays, thousands of individual small antennas sample the electric field directly, and the signals are phased up electronically to generate large numbers of beams, which can be pointed without using any moving parts. Development of aperture arrays was the main theme of SKADS and forms an important component of PrepSKA. It is hoped to build the SKA in three phases: Phase 1 will be the initial deployment (15-20%) of the array at mid-band frequencies, and will include a significant aperture array component; Phase 2 will be the full collecting area at low to mid-band frequencies (~70 MHz – 10 GHz). Phase 3 will see the implementation at higher frequencies up to 25 GHz or more. Preliminary, but detailed, cost estimates are that Phase 1 will cost ~€300M and the full array (Phases 1 and 2) will require €1.5B. The costs for Phase 3 have not yet been investigated. Operational costs of the full array are expected to be ~€100M/year.

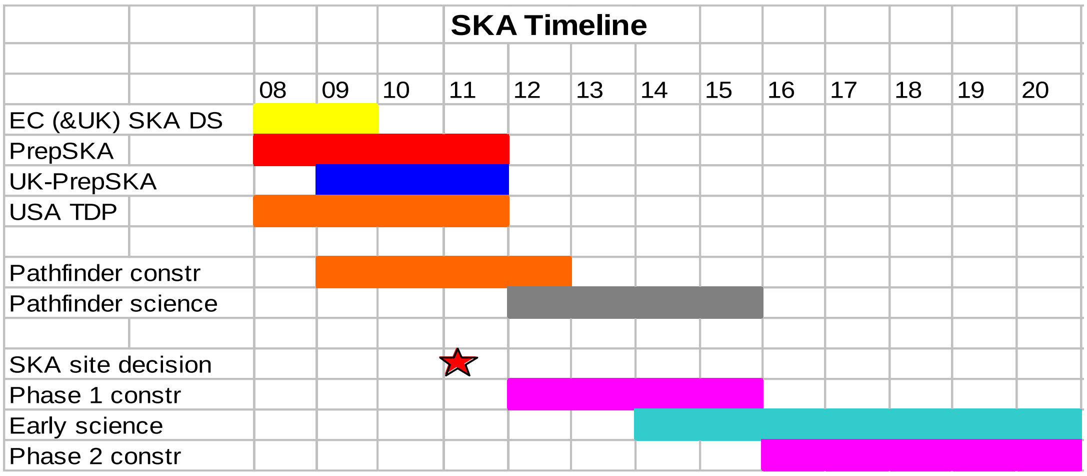


Figure 1: Current planned SKA timeline for Phases 1 and 2

There are 55 institutes in 19 countries around the world that are working together to plan the SKA and develop the technologies required. Total R&D funding committed in the period 2007-12 is ~€150M, which includes the UK contribution to the SKADS project. In addition, the two candidate host countries, Australia and South Africa, are constructing specific SKA pathfinder telescopes (Australia: ASKAP (~AU$100M/

€61M); S.Africa: MeerKAT (~ZAR800M/ €64M)). Other telescopes (e.g. e-MERLIN in the UK; LOFAR in the NL; ATA and EVLA in the USA) enable the exploration of specific aspects of SKA technology.

The SKA Science and Engineering Committee (SSEC), which governs all scientific and technical aspects of the project, and on which the UK currently has two members, has agreed the timeline for the SKA shown in Figure 1. The PrepSKA study, of which this proposal forms part, is aimed at ensuring that the delivery of this ambitious project can be achieved on the desired timescale.

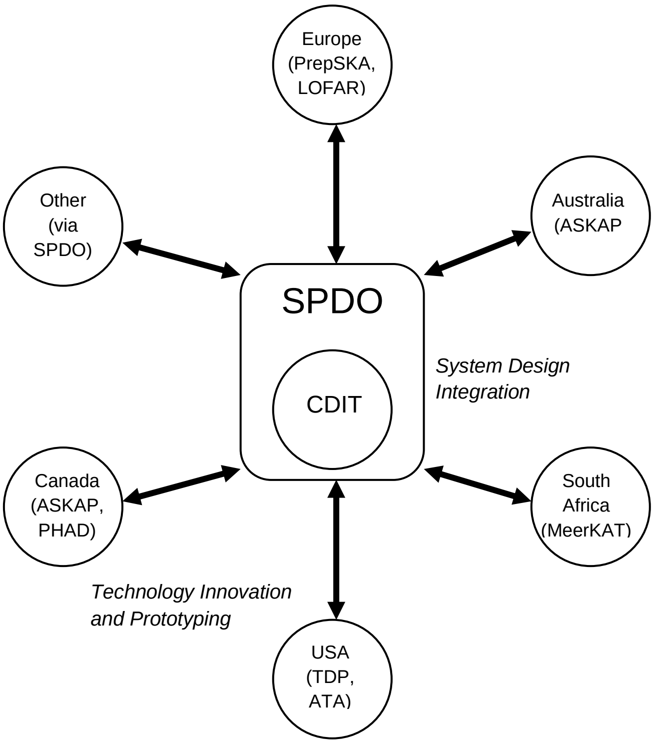
1.2 PrepSKA: A Preparatory Study for the SKA

In September 2006, the European Strategy Forum on Research Infrastructures (ESFRI) published its roadmap identifying Research Infrastructures of pan-European interest: SKA was named as one of 35 projects across all fields of science, and one of only 3 in astronomy and particle astrophysics. This initiative was followed up through the provision of EC funding under the FP7 Capacities Programme. Designated ESFRI projects submitted proposals for a preparatory phase study aimed at bringing them to the level of legal, financial and technical maturity required for implementation. A global consortium of 24 partners (8 funding agencies, 16 universities and astronomy organizations from Europe, Australia, Canada, South Africa and USA), led by STFC, bid for and was awarded €5.5M for the SKA Preparatory Phase Study, PrepSKA. The study builds on the highly-regarded work of SKADS and other R&D projects around the world. PrepSKA will enable scientists and policy-makers to develop the legal and policy framework for the SKA and to generate the detailed technical design for Phase 1 of the SKA. PrepSKA formally started on 1 April 2008 and will run until Q1 2012.

The PrepSKA partners will investigate several issues that need to be addressed before construction of the SKA can begin, which form the main workpackages (WP) of PrepSKA:

- What is the design for the SKA? (WP2)
- Where will the SKA be located? (WP3)
- What is the legal framework and governance structure under which SKA will operate? (WP4)
- What is the most cost-effective mechanism for the procurement of the various components of the SKA? (WP5)
- How will the SKA be funded? (WP6)

Figure 2: Relationship between major SKA R&D projects and the SPDO



The majority of the funding from the EC is being used to establish the Central Design Integration Team (CDIT), which will eventually have ~15 engineers and other staff and which is part of the SKA Program Development Office (SPDO). The CDIT, through the largest PrepSKA Work-Package (WP2), will be responsible for ensuring the integration of the R&D work from around the globe, including that to be funded via this proposal, in order to develop the fully-costed design for Phase 1 of the SKA, and a deployment plan for the full instrument. WP3 is focused on further characterising the two sites, through continued RFI measurement and the detailed investigation of SKA infrastructure costs. WPs 4, 5 and 6 are led by funding agencies (NWO, INAF and STFC respectively) and will, in a collaboration between agency representatives and scientists, address questions 3 through 5 above. The principal deliverables of PrepSKA will be a detailed design for Phase 1 and an implementation plan that will form the basis of a funding proposal to governments to start the construction of the SKA.

The generation of the major technical deliverables will be a complex task and will be coordinated by the CDIT working under the SPDO. WP2 activities are shared between SPDO-CDIT and existing engineering groups within regional consortia as shown in Figure 2.

Good communication between the SPDO-CDIT and regional teams is crucial. Each regional team is appointing a liaison engineer (in the case of UK-PrepSKA this will be the Project Engineer, Faulkner) who will have responsibility for strategic and operational links to the SPDO-CDIT, particularly to the domain specialists and system engineer. The liaison engineers will provide an active link between the SPDO-CDIT and regional engineering programmes.

1.3 The UK role and leadership in PrepSKA

The UK is playing a central, and arguably **the** leading role in the development of the SKA. This was recognised in 2007 when the SKA, alongside the E-ELT, was named as one of the two mega-facilities for astrophysics in the RCUK roadmap.

The original concept for the SKA grew out of discussions in the UK and the Netherlands in the early 1990s. Astronomers from Manchester, Oxford and Cambridge have been prominent in the SKA steering committee (Diamond being Chairman in 2005 and 2006), the SKA Science Working Group (Rawlings being vice-Chairman and International Project Scientist in 2004-2006) and in various engineering working groups. The UK, through an STFC grant, is the largest player in the current European SKA Design Study, which runs until mid-2009.

Whilst other countries have chosen to target their investment on pathfinder telescopes, the UK has developed international leadership in the R&D needed for the SKA itself. Under STFC leadership it plans to consolidate its position, through PrepSKA, by maintaining its successful three-site (Cambridge, Manchester, Oxford) R&D team that will be fully integrated with the global effort via the Manchester-based SPDO-CDIT.

During Diamond's tenure as Chairman of the international Steering Committee a group of interested national funding agencies formed the so-called informal Funding Agencies Working Group, Prof. Richard Wade of PPARC was named as the Chair of this working group. The agencies have met to discuss SKA approximately every 6 months since early 2006, the most recent meeting being in Perth, Australia in April 2008; STFC have continued to chair the meetings.

In 2007 the UK won the international competition to host the SPDO, which moved from the Netherlands to the University of Manchester in February 2008. The SPDO is the central organisation of the project and, under the International SKA Project Director, is responsible for the coordination of all SKA R&D around the world.

STFC's co-ordinating role in the EC-funded PrepSKA project and its continued chairmanship of the informal agencies group reinforce the critical role that the UK is playing within the SKA. In order to continue and to expand this role, with its huge potential effects for UK industry and science, it is essential that we build upon the work to date and ensure that the technical work we undertake is key to the success of the international project and that we establish ourselves as the principal players and leaders within the relevant globally agreed work-packages. The table below indicates those major work-packages, each cell is colour-coded to show which country is directing the particular work-package; red indicates the UK. The matrix demonstrates the major role that the UK is developing within the SKA project. This will place us in the enviable position of being recognised as the natural leaders of the SKA as it moves into Phase 1 construction and operations.

Table 1: Matrix showing the approved work packages within the global PrepSKA project. The colours indicate the countries leading particular activities, red indicates the UK - work-package titles **underlined and in bold** indicate those packages in which the UK is participating but not leading.

		T1	T2	T3	T4	T5	T6	T7	T8	T9
P1	***SKA design***	SKA concept exposition	SKA specification	**SKA life cycle study**	**SKA operation**	SKA support model	**SKA cost optimisation**	SKA Manufact-uring studies	SKA-P1 technical doc.	SKA system design
P2	***SKA-P1 Sub-system spec & integration***	SKA-P1 sub-systems specification							🟨	**CDIT**
P3	***Initial Verification System***	**IVS specification**	IVS manufacture	**IVS Int. & Test**	Demonstrator AA spec.	Demonstrator AA manufacture			🟥	**UK**
P4	***Dish design & optimization***	Dish design 1	Dish design 2	Dish design 3	Dish design 4				🟦	**ASTRON (NL)**
P5	***Feed prototyping***	Wideband single-pixel feeds	WFoV: Aperture array tiles	**WFoV: Phased array feeds**	WFoV: Multiple-feed clusters				🟪	**ATNF (Aus)**
P6	***Receiver prototyping***	**Low-noise amplifiers**	**Integrated receivers**	**New-gen. cryo solutions**					🟦	**NRF (ZA)**
P7	***Signal transport prototyping***	**Intra-antenna data links**	Intra-station data links	Station-core data links	LO and timing	Monitor & control			🟧	**TDP (USA)**
P8	***Signal processing prototyping***	Station DSP	**Correlators**	Interference mitigation	Non-imaging processors				🟩	**DRAO (CA)**
P9	***Computing specification & prototyping***	SKA computing & software spec	**Computing hardware**	**Software engineering**	Data products & VO plan	**Calibration**	**Post-corelator processing**		⬜	**Obs de Paris (FR)**
P10	***WP2 design study management PM***	CDIT project management							🟩	**INAF (IT)**

2. Scientific Justification

Our knowledge of the Universe underwent a revolution around the turn of the 21st century. Chiefly from observations of the Cosmic Microwave Background (CMB), many of the key cosmological parameters (H_0, Ω_M etc) of the Universe are now known to reasonable (~10%) accuracy and new and fundamental ones, such as the dark energy equation-of-state parameter w, have emerged, but are not yet usefully constrained. We now have redshift surveys of millions of galaxies, mapping out the local Universe's large-scale structure that both further constrains cosmological parameters and are beginning to constrain the hot-dark-matter content, and hence the absolute masses of neutrinos. We also have deep images charting the formation and evolution of galaxies and their stellar populations over a large fraction of the history of the Universe, and galaxies and quasars are known out to near redshift z=7. Observations of the recently discovered double pulsar have tested General Relativity (GR) rigorously in the weak-field limit. Exoplanets are known to be associated with a large fraction of stars.

Our theories and paradigms concerning all these observational facts are, however, either incomplete or potentially wrong. Dark energy does not sit easily with established theories like GR. Theoretical interpretation of neutrino oscillation experiments tell us we should be close to a detection of the signature of hot dark matter (neutrinos) in the power spectrum of galaxies, but there are not yet any hints of this signature. The formation and evolution of galaxies and their constituent stars cannot be understood without invoking poorly-understood feedback processes coupling jets from compact objects with their large-scale gaseous environments, and the role of magnetic fields remains mysterious. Theories suggest that GR might break down in the strong-field limit, but there are currently no systems available with which to make the requisite tests. The known exoplanets are Jupiter-sized, but are orbiting too close to their parent stars to have been born in situ.

As always there is much still to learn, but many of the deepest thinkers believe we may truly now be on the verge of unusually significant breakthroughs in our understanding of the Universe. Observations with transformational observational capabilities are required to push further forward, and the ESFRI/RCUK road maps includes two future "big-science" ground-based telescopes akin to the giant accelerators that now dominate much of particle physics. One of these, the E-ELT – an ESO-led 42m optical telescope – is planned to improve significantly on the next-generation optical telescopes being developed in the USA (e.g. the Thirty-Meter Telescope TMT). The other is the SKA which unites the whole radio astronomy community within a single global project.

The full science case for the SKA can be found in a 600-page book (Carilli & Rawlings 2004). In the limited space here we will focus on the ability of the SKA to deliver world-leading results by 2015, i.e. in its Phase 1 incarnation, and on the transformational science made possible in Phase 2 by full deployment of the novel technologies which are being pioneered in Europe through SKADS, and which will generate first science during Phase 1.

The current remaining design choices for the SKA are summarised in Table 1 of Schilizzi et al (2007). The ~10- and then ~100-fold increases in raw sensitivity ($A_{\mathrm{eff}}/T_{\mathrm{sys}}$) provided by SKA Phases 1 and 2 over current radio telescopes will prove critical to achieving scientific breakthroughs. To put this in context, similar sensitivity gains for observations of spatially resolved galaxies with photon-noise-limited optical telescopes would require upgrading from the current 10-m-class optical telescopes to 100-m and 1000-m diameter telescopes respectively!

However, the performance gains of the SKA will not be limited to those due to gains in raw sensitivity. The wide instantaneous fields-of-view (FOV) opened up by the focal-plane and aperture-array technologies will generate truly remarkable mapping speed increases over current radio facilities: by a factor ~1000 in Phase 1 and by ~10^6 in Phase 2. This means that all-hemisphere Phase 1 SKA surveys will be dominated by distant star-forming galaxies and will measure "blind" redshifts, via the 21-cm HI line, to redshift z~0.75. All-hemisphere Phase 2 SKA surveys will be dominated by distant normal (Milky-Way type) galaxies, and measure redshift to z~2. A small patch of sky from the SKADS continuum-sky simulations (Wilman et al. 2008) is shown in Figure 3.

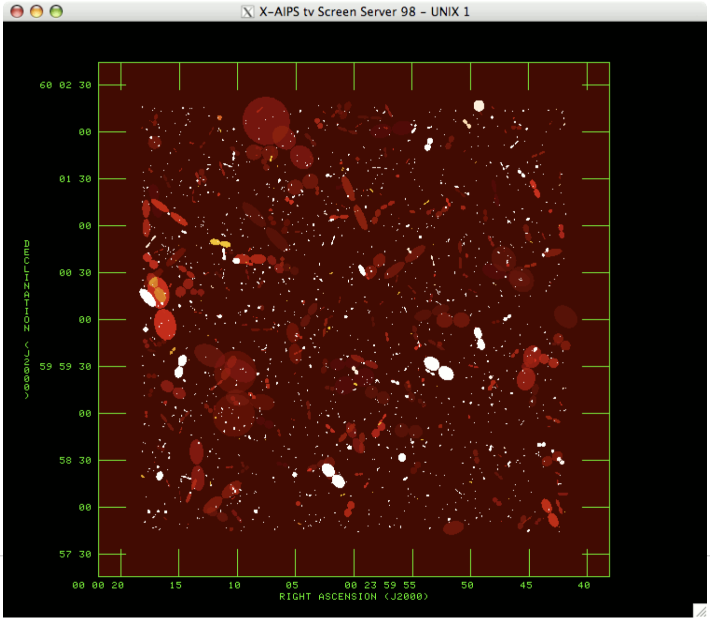


Figure 3: A small patch (roughly 0.001%) of the SKADS continuum sky simulation of Wilman et al. (2008): the full dataset is downloadable from the S^3 website or via the AstroGrid VODesktop.

The deepest current radio surveys would detect only ~10 of the brightest sources in such an area.

Before turning to the SKA **Key Science Projects (KSPs)**, it is worth emphasising the amazing discovery potential of the SKA. The data processing advances required by all realizations of the SKA will necessarily open up huge swathes of new parameter space, particularly in the time domain (Figure 4). It is clear that SKA discoveries beyond those we can presently guarantee are likely to have a huge impact on the KSPs: for example, very-high-z bright radio transients may provide the best background sources for studies of absorption lines in the EoR. Another example comes from the **Cradle of Life KSP** which, because it will largely be pursued in Phase 3 SKA after a significant period of digestion of data from ALMA, is the only one of the five KSPs not to be discussed in more detail here. Bursts of 0.001-10 mJy are expected from the nearest exoplanets on timescales of seconds to minutes due to interactions between their magnetospheres and parent-star winds. This entirely new way of detecting exoplanets looks set to yield new classes of object as well as new physical information on exoplanets such as their magnetic field strength and rotation rate (Zarka 2007).

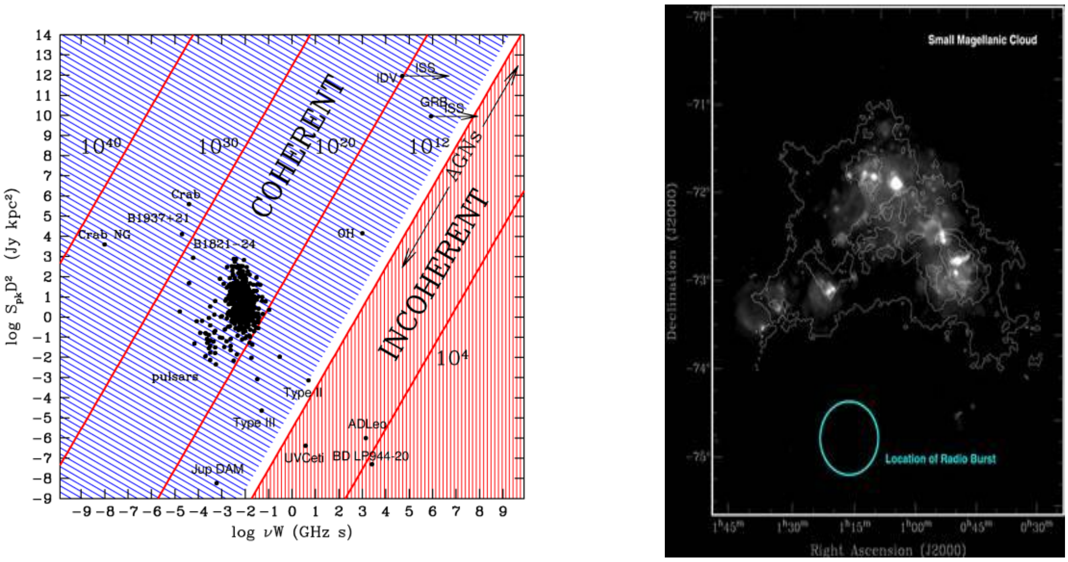


Figure 4: (Left) The phase space for radio transients (Wilkinson et al. 2004). Note the huge regions without known sources - regions the SKA will probe. (Right) The location of a single 30-Jy dispersed radio burst of less than 5 ms duration that because of its wide dispersion is extragalactic; with a brightness temperature ~ 10^{34} K, it is a coherent source. This is a new class of astronomical object whose physical origin is unknown: it may be the result of the collision of two Neutron Stars which would be a likely source of gravitational waves.

The ability to generate aperture array beams “on the fly”, and in widely separated directions, has both practical advantages (e.g. in nulling interference sources) and known science advantages (e.g. multiplexing of exoplanet searches, see above, and ‘pulsar-timing arrays’, see below), but also opens up interesting new discovery opportunities such as the time buffering of signals to allow a radio beam to be formed in some direction at times prior to the occurrence of some `triggering’ event. Such ‘Exploration of the Unknown’ is explored in the SKA science case book (Wilkinson et al. 2004), but the discovery potential is perhaps best illustrated by a recent example (Figure 4): a radio burst that for a few ms became one of the brightest sources on the sky, and remains enigmatic (Lorimer et al. 2007).

Despite the success of GR, the fundamental question remains as to whether Einstein had the last word in our understanding of gravity and this defines the **Strong-field Test of Gravity KSP**. The SKA will discover all the active pulsars in the Milky Way beamed towards us, providing the only chance we will have of finding any pulsar – black hole binaries in our galaxy, or a pulsar orbiting the super-massive Black Hole in the Galactic Centre. These systems would consist of accurate clocks orbiting in an ultra-strong gravitational field, and are unique in their capability to probe GR, specifically the No-Hair Theorem and the Cosmic Censorship Conjecture (Kramer et al. 2004). SKADs pulsar simulations[1] predict ~1000 ms pulsars forming a dense array of precision clocks on the sky. By looking for spatially-correlated distortions in the timing data in such a pulsar timing array (PTA), it will be possible to detect gravitational waves impinging on our Galaxy; indeed, the very limited PTAs available for study with current radio facilities are getting very close to the accuracy needed to detect the gravitational waves from the merging of distant super-massive black holes (Figure 5).

From the SKADS Virtual Telescope (SVT[2]) exercise, the following Phase 1 SKA results are predicted. Surveys will increase the number of known pulsars by factors of several, and thus likely uncover systems more exotic than the double pulsar, and perhaps the first fully relativistic binary. The timing precision on pulsars will be improved by a factor~10, with the aperture array providing an additional multiplex timing advantage. The PTA will contain ~30 pulsars yielding a detection of a background of gravitational waves at more than 5σ significance after a few years of timing. There are also likely to fruitful synergies with gravitational wave detectors: e.g. Advanced LIGO data can be used to generate a predictive alert in an error box on the sky containing a close (<300 Mpc) binary neutron star in-spiral and plunge. The Phase 1 SKA could then perform a rapid response search of this error box to reveal the prompt synchrotron emission from the coalescence itself. The present-day Universe is seemingly dominated by dark energy and dark matter, but mapping the normal (baryonic) content remains vital for understanding how galaxies form, as well as cosmology and particle-astrophysics. This defines the **Galaxy Evolution and Cosmology KSP**, two major aims of which are to make the first studies of high-z HI and to use the HI galaxy power spectrum *P(k)* to probe the dark energy *w* (Abdalla & Rawlings 2005) and the mass scale of neutrinos (Abdalla & Rawlings 2007). The key experiments will be deep fields and all-hemisphere surveys to measure *P(k).*

The Phase 1 SKA will undertake a deep survey to measure the HI mass function to redshift z~2, using the gravitational lensing boost of rich cluster targets to obtain measurements, or set constraints at still higher redshifts. This provides a fundamental measurement of the most abundant element in the Universe, which currently is measured in emission only to z~0.2. This evolution, and the corresponding evolution in the HI/H_2 ratio (which will come from combining SKA and ALMA results) provides the key to understanding the roles of gas accretion, galaxy merging and star formation in the evolution of galaxies (van der Hulst et al. 2004). It will also remove the major uncertainty in SKADS simulations (Figure 6) which currently are constrained only by the integral of the HI mass function inferred from the damped-Lyα lines of distant quasars.

The Phase 1 SKA all-hemisphere survey will detect ~10^7 galaxies and deliver multiple measurements (e.g. split by galaxy type, galaxy mass etc) of *P(k)* out to redshift z~0.35 and at least one (mildly shot-noise limited) measurement of *P(k)* out to z~0.75. For constraining *w* via measurement of Baryonic Acoustic Oscillations, SKA surveys will thus be competitive with the best available optical redshift surveys (e.g. with WFMOS) available by ~2015. The combination of the radio and optical approaches will be critical in understanding the effects of galaxy bias. The dramatic increase in survey volume in Phase 2 SKA (to z=2) will surpass all optical surveys until Euclid is launched, with once more a clear scientific synergy between SKA (sensitive to gas) and Euclid (sensitive to stars).

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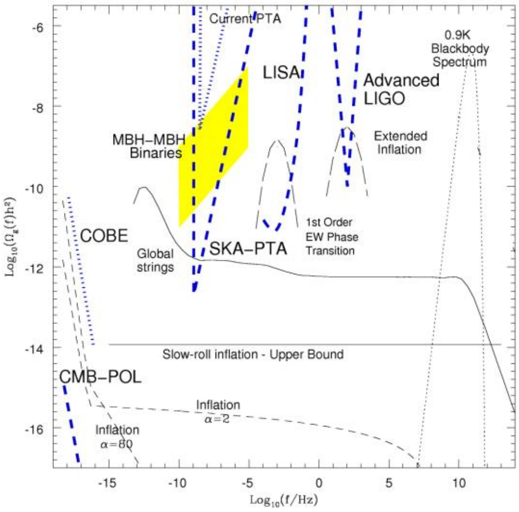
[1] The S^3 (SKADS Simulated Skies) website is http://s-cubed.physics.ox.ac.uk/

[2] The SKADS SVT exercise generated 30 `observing proposals' for early phases of the SKA (see http://webmail.jb.man.ac.uk/SKAwiki/VirtualTelescope. Username: SKA, Password: SKADS.)



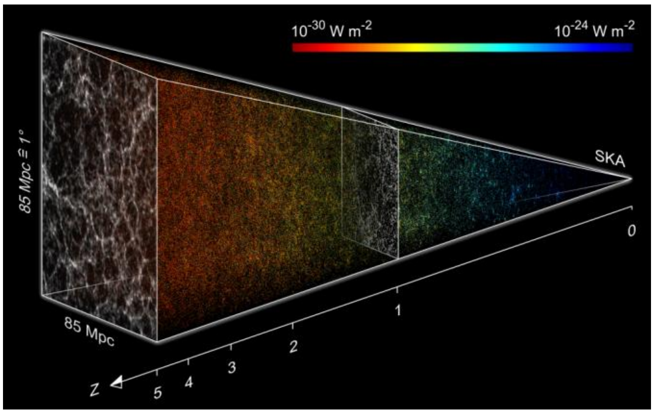
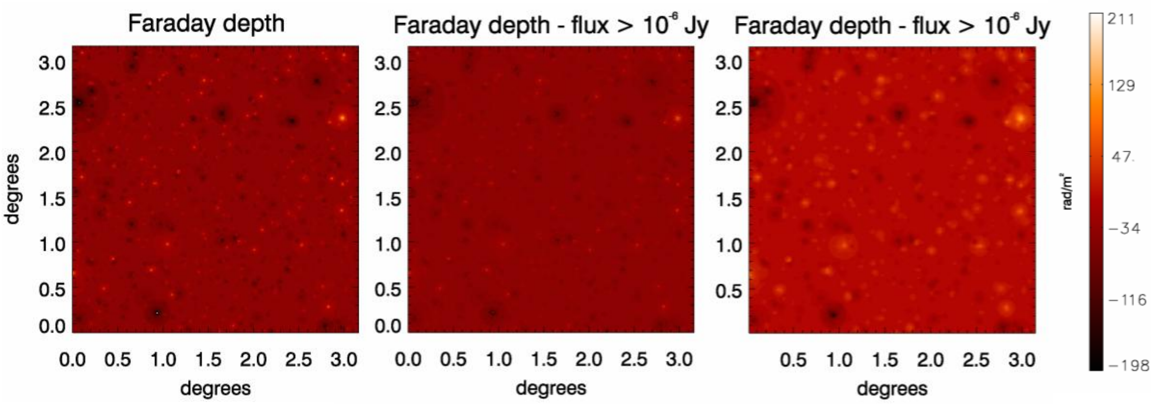


Figure 5: (Top left) The role of the SKA in the detection of gravitational waves via the SKA Pulsar Timing Array (SKA-PTA) from Kramer et al. (2004). The yellow shaded area shows the predicted gravitational wave signal from the merger of super-massive black holes. A straightforward conclusion from this plot is that the SKA seems guaranteed to detect gravitational waves whilst the Phase I SKA has an extremely good chance of doing so.

Figure 6: (Top right) A 3D view of part of the SKADS line simulations which contain ~10^8 simulated HI-emitting galaxies over ~20 deg^2, downloadable from the S^3 web page.

Figure 7: (Bottom) Faraday depth image of ~0.1% of the sky to be probed by SKA. The sky simulation (left) picks out clusters and groups. The middle panel shows the recovered RM sky against background sources brighter than 1 mJy and the right panel shows it smoothed.



Magnetism is one of the four fundamental forces but its origin in stars, galaxies, clusters of galaxies and the intergalactic medium is the open problem addressed by the **Magnetic Universe KSP**. The strongest limits on primordial magnetic fields are currently theoretical in the sense that very strong primordial fields would have induced such high magnetic stresses at the time of recombination that they would have easily observable effects on galaxy formation. Substantial progress in this area can be made with the Phase 1 SKA as a side product of the `HI all-hemisphere' surveys will provide spectro-polarimetric data for a dense (one every ~arcminute or so) grid of ~$10^{6.5}$ sources allowing, towards each, a Faraday Rotation Measure (RM) to be calculated. As RM is proportional to the line-of-sight field strength (as well as electron density n_e and path length l), this gives a unique way of probing the magnetic field in all these classes of object. An example is shown in Figure 7: a deep Phase 1 SKA pointing would detect ~50,000 radio sources behind ~10,000 clusters. By cross-matching these data with data from the Dark Energy Survey (DES; the DES SZ data measuring n_e and l), the magnetic field in clusters as a function of mass and redshift will be determined.

The baryons in the Universe, although now almost completely ionized, were once neutral and had to be re-ionized by some mixture of stars and accreting black holes. The epoch of re-ionization (EoR) sets a fundamental benchmark in cosmic structure formation, corresponding to the formation of the first luminous objects that act to ionize the neutral intergalactic medium (IGM), and is the subject of the **EoR KSP**. The SKA will image the neutral IGM at $z>7$ in HI emission or absorption, a truly unique probe of the process of re-ionization that is recognized internationally as the fundamental next step in our study of large-scale structure and cosmic re-ionization. SKA pathfinders like LOFAR have a good chance of obtaining the first statistical detections of an EoR signal, either by power-spectrum measurements or by absorption experiments towards the highest-redshift quasars or transient sources, but only the SKA will have imaging ability.

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3. Overview of the current and future technical programme

3.1 The UK contribution to SKADS

The Square Kilometre Array Design Studies, SKADS, is a €38M European project catalysed with €10.4M EC FP6 funding which has successfully attracted substantial national funding from across Europe. SKADS is a four year programme which started in July 2005 and will complete in June 2009.

The share of EC funds, which is indicative of national participation, is shown in Figure 8. As can be seen the UK is at the top, equivalent to the coordinating country, the Netherlands. Within the UK we have actual or de-facto leadership of:

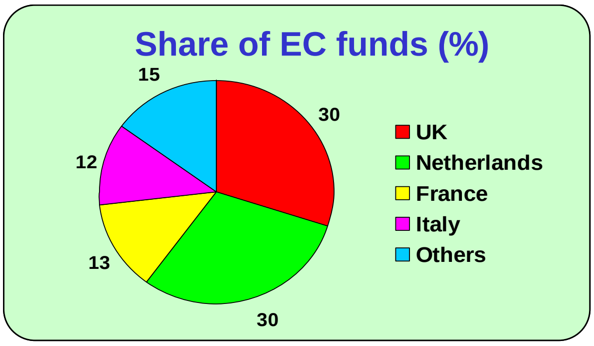
- Science simulation studies adopted by the SKA, DS2, – Oxford
- SKA data network and functional simulations plus the cost modelling tool, DS3 – Cambridge
- The advanced technical studies and all-digital aperture array demonstrator, DS4 – Manchester

These are the principal studies within SKADS apart from the manufacture of a large demonstrator, EMBRACE in DS5, lead by ASTRON.

The management of SKADS is shown below:

Coordinator:	Arnold van Ardenne	ASTRON
Board Chairman:	Peter Wilkinson	Manchester
Proj. Engineer:	Andrew Faulkner	Manchester
Proj. Scientist:	Steve Torchinsky	Obs. de Paris
Proj. Manager:	Andre van Es	ASTRON

Figure 8: National share of SKADS EC Funding



As can be seen the UK has taken strong leadership roles in SKADS, particularly in the overall programme management. This forms the basis of the strong UK position in UK-PrepSKA for the international SKA project.

3.2 Summary of Achievements during SKADS

The principal technical achievement for SKADS, with strong UK participation, is the acceptance by the International SKA community of the role of aperture arrays as the low frequency, very high survey speed collector technology of choice for the SKA. The focus of SKADS and subsequently one of the major activities in UK-PrepSKA, continuing our collaboration with European colleagues, is to demonstrate the practicality of high frequency (up to ~1GHz) aperture arrays in the SKA timeframe. Other groups around the world are working on other aspects of required SKA technology, e.g. the Technology Development Program (TDP) in the USA, which is focusing on high-performance, low-cost dishes (which are also the subject of active development work in Australia, Canada and South Africa); the phased array programmes in Australia (part of ASKAP), the Netherlands (APERTIF) and Canada (PHAD). Significant work on digital signal processing and software is being undertaken throughout the SKA consortium.

SKADS work by the UK has made very substantial advances in the scientific justification of the SKA through a successful suite of sky simulations, which makes strong statements for the projected results from the SKA and is now in use for the SKA internationally as the de-facto standard. The interest of the international community has been attracted by the concept of the “SKADS virtual telescope”, which had 30 proposals written by researchers for ‘observation time’.

The design and costing of the SKA, a major SKADS deliverable, is acknowledged internationally to be a vital task which must and will be continued through PrepSKA. By taking a very proactive role in the early stages of SKADS, the UK now has a lead position in cost modelling for the international SKA project. The software tool is being structured, written and maintained in the UK. This tool will be extended to incorporate the SKA functional simulator, a central role in the SKA.

There have been multiple technological achievements at the important sub-system level for the SKA. Major ones include:

- Conceiving of and building a novel receiving element technology that holds great promise for improved performance and lower implementation cost than current designs;
- Showing that the digital processing for an all-digital aperture array is feasible in the SKA timeframe and desirable scientifically;
- Demonstrating the feasibility of ‘phase transfer’ over fibre to SKA requirements. This enables a precise time standard to be distributed throughout the SKA system;
- Showing that there are potential solutions, requiring further development, for the ambient temperature low noise amplifier in multiple semiconductor technologies: silicon, gallium arsenide and indium phosphide.
- Creating a practical system design concept for an SKA scale, 1GHz aperture array of ~60m diameter and building a demonstrator, 2-PAD, which illustrates the important technologies required.

During this work the UK participants have been actively involving industry with a view to ensuring full *juste retour* for the UK. The major components of the UK SKADS programme are:

Science Contribution

- The UK, through Oxford, has the lead in delivering the science simulations for SKADS. This provides the basis of justification for the overall SKA specification. The successful SKADS science simulation programme DS2-T1 will not be pursued further within UK-PrepSKA. To maintain this crucial activity, and connect it closely with the analysis of data coming from the various SKA Pathfinders, the European SKA Consortium (ESKAC) have decided to submit a €4.5M EC FP7 Marie Curie Initial Training Network by 2 Sep 2008. This Path2SKA proposal {http://www-astro.physics.ox.ac.uk/~sr/Path2SKA.html } will support a cadre of 30 or so PhD students and young postdocs across Europe, and will be coordinated by Steve Rawlings at Oxford.

- Focus now is on researching the effects of a real telescope on the anticipated sky with the inherent systematic errors, distortions by the atmosphere, and sensitivity variations expected. This information is then used to develop detailed configurations of the SKA.

SKA System and Cost Modelling

- The UK, utilising its work on science simulations, has been heavily involved in the SKA functional simulations. These lead directly to understanding the cost of the SKA.

- Cambridge, working with groups in Australia and South Africa, has been leading the development of a major cost modelling tool which will be used internationally for developing the best design for the SKA and providing a convincing case to the funding agencies.

Wide-area Data transfer and time distribution

- The SKA will move >10^{15} bits/s of data: this is a major cost and development requirement. Manchester, building on its work on e-MERLIN and ALMA, has been studying the data transfer issues. This involves detailed projections with manufacturers and trial implementations for costing. The knowledge is being integrated into the design and cost modelling above and is crucial to the configuration decisions.
- The SKA requires the precise transfer of time, to a few ps (10^{-12} secs), across the whole array. Manchester, building on the work within e-MERLIN, has shown that the requirements for the SKA are achievable. This work will be further developed in PrepSKA.

Technologies for an all-digital aperture array

- The UK has taken the ambitious position of concentrating on an all-digital implementation of the aperture array system. This contrasts with the alternative approach being pursued by Dutch colleagues who are using analogue techniques for the first stages of beam-forming. A major contribution to SKADS by the UK is that we can now project that an SKA capable all-digital aperture array in the time-frame of the SKA is entirely feasible. Of course, substantial work is required for the optimum system design; this will occur within PrepSKA. The sub-systems being developed in SKADS for the all-digital aperture array are shown in Figure 9.

Antenna elements and array design

- The design and optimisation of the array and the elements themselves are subject to considerable design work in multiple institutions. Manchester is working on a number of designs and has made excellent progress on a particularly innovative design, the ‘Octagon Ring Antenna’, ORA which has great promise for both the best overall performance and with lowest cost.

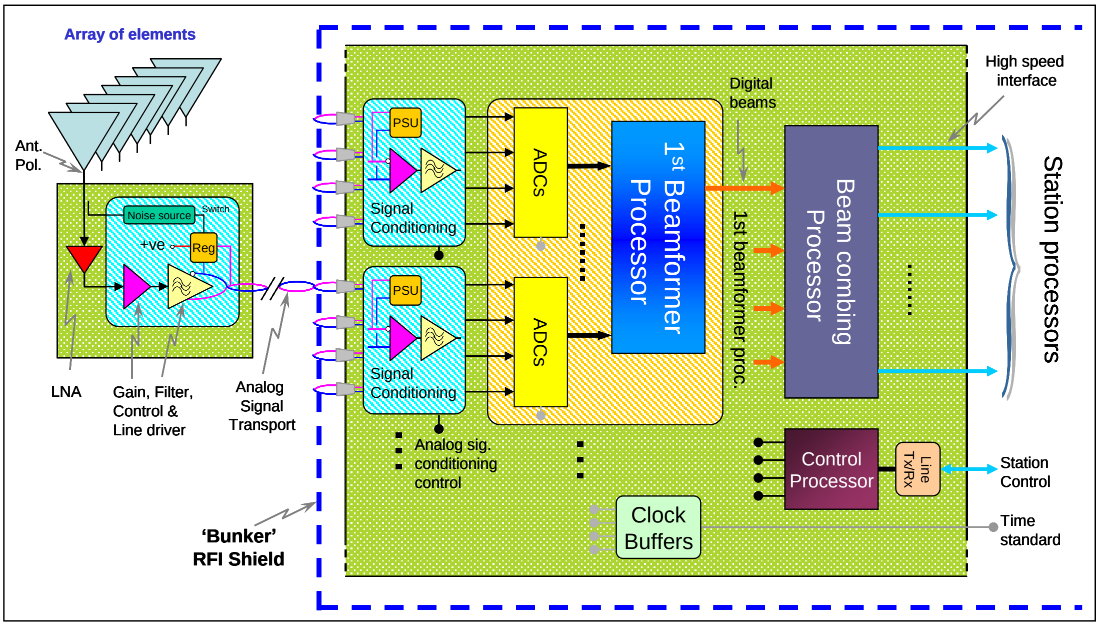


Figure 9: Signal chain for aperture array "Tile"

Low noise amplifier, LNA

- There are developments around the world for LNAs covering various semiconductor implementations: GaAs, InP, bulk silicon and SiGe. This part is a vital part of the design to minimise noise and thus reduce the costs for a fixed SKA sensitivity. In Manchester, we have been concentrating on a customised InP design, for which simulations predict encouraging results particularly for its ability to match over a wide-range of frequencies to the antenna element. If the tested performance meets expectations then it will be a significant contender as the most suitable LNA for the aperture array.

Analogue to Digital Converter, ADC

- A critical part of the all-digital aperture array is the ADC. This must be very fast, ≥2.4GS/s, and low power. Manchester undertook an InP based development to provide a suitable device. In the last few years silicon technology has made substantial progress such that it can now more than provide the required performance. A major advance in UK SKADS has been the retirement of the ADC as a major risk.

Processing and algorithm design

- The data processing load (>10^{16} operations per 256 element tile) was regarded as extremely challenging in 2005. It is currently still very expensive, however, within SKADS we have shown that with the anticipated mass-market devices of 2012, using 45nm design rules, the digital processing can be built for reasonable cost and power. The system can certainly be built using specific custom devices, ASICs, and it will probably be feasible using specialist fully programmable chips. 2-PAD, has been designed with a combination of programmable hardware, FPGAs, and a fully programmable beamformer processor and will be used as a demonstrator.

Mechanical and Physical design

- Notable work within SKADS is the development of a low-cost, shielded processing bunker essential to eliminate problems of self-induced RFI.

2-PAD Demonstrator

- The demonstrator is the culmination of a lot of developments discussed above. There is every expectation of this system being built within SKADS and will show the viability of an all-digital aperture array.

The UK contribution to SKADS is very successful, so far achieving more than had been anticipated; particularly with regard to leadership within the international community. The development of the all-digital aperture array for the SKA is not only proving to be viable, but is fully expected to be the technology of choice for the frequency range below 1GHz. All the deliverables within UK SKADS are expected to be met. The challenge facing us is to carry these developments to the next level of integration with minimal power consumption and cost, and maximal performance; this is a major focus of this UK-PrepSKA proposal.

4. The Proposed UK-PrepSKA Technical Programme

The proposed programme will build on the position we have established in the international project during SKADS. From a UK perspective, we aim to ensure that the UK maintains a leading role in the SKA project to maximise both the scientific return for the UK community and the returns to UK industry. From a wider perspective, we believe that it is important to the success of the SKA that the long-established radio-astronomical expertise within the UK is available to the international project during this crucial PrepSKA phase. To achieve this we have structured the programme into two technical themes with a clear overall management structure.

For the project management we request support for three senior posts: a Project Manager, a UK Project Engineer, essential to maintain technical links to the international project and help coordinate links to industry, and a Project Scientist to build upon our long-standing scientific leadership and ensure a strong link of the technical work to the UK community. In section 5 we discuss our project management plan.

Our planned technical work is focused in those areas where we have particular expertise and where we believe we can make a significant contribution to the project. We also consider carefully those areas where links to UK industry can be established/strengthened. The proposed work packages are tightly integrated into the international PrepSKA work programme (detailed links are given in the work package descriptions in Appendix A) and the emerging European Aperture Array Verification Programme, AAVP.

Theme A has four work packages which address generic technical areas which are crucial to the whole SKA project and hence place the UK at the centre of the SKA developments. Work package A.1 considers the overall SKA system design and builds on the leading position we have established during SKADS in this area: it is very closely integrated with the SKA Project Development Office, SPDO, with a strong emphasis on cost modelling and technical simulation. The UK, through eMerlin and work on ALMA, is already recognised as the leader in development of wide area fibre communications systems and the ability to transfer time over large distances, essential for any radio interferometer and in work package A.2 we will continue developments to ensure the performance and cost meets SKA requirements. Signal processing is a core technical challenge for the SKA and in work package A.3 we plan to progress our leading work in SKADS in defining an achievable and affordable fully digital signal processing system. The post-correlator processing and data management requirements for the SKA are much greater than for any previous radio telescope and demonstrating that the required processing and data handling can be achieved is a key engineering task for the international project and on the critical path for the SKA. In work package A.4 we tackle specific problems in this area as part of a collaborative effort for which UK expertise can make a significant contribution. Work packages A.2, A.3 and A.4 each offer good opportunities for engagement with UK industries.

Aperture array collector technologies, a central part of the overall SKA design, are being developed in Europe with the UK taking the lead on the most advanced, fully digital, concept. Theme B comprises those work packages which directly address aperture-array technologies. Work package B.1 takes forward our work on the receiving element and array design. In SKADS the UK work in this area focussed on developing very novel designs and here we plan to take the most successful of these through to full prototype and testing. In work package B.2 we consider the essential analogue elements of the data path which together with the electromagnetic design of the antenna determine the system temperature and overall array performance. For the critical low-noise amplifiers (LNAs) and matching to the antenna we are following two routes. Firstly, collaborating closely with leading groups worldwide already developing very promising LNAs, we will address the challenge of matching these devices to the antenna. Secondly, we will also continue our promising work from SKADS to design and fabricate an InP-based LNA, which potentially offers the best overall performance for the SKA. This task offers the potential for significant UK knowledge transfer. The mechanical infrastructure and environmental issues for the aperture array are considered in task B.3. In this area there is significant potential for UK industrial involvement. Calibration is key to providing the precision performance required for the SKA, this is studied and tested in task B.4. Aperture arrays have the great advantage in that the ‘surface’ can be dynamically adjusted electronically with regard to pointing, frequency and nature of the experiment provided the precise calibration coefficients can be determined.

The development work in all the tasks is very closely linked to the European AAVP within PrepSKA. The AAVP together with input from the low frequency arrays aperture-arrays LOFAR and MWA will provide the input to show that the aperture array design will reach the required specified performance on the SKA timescale. The specific UK role is in the construction of a small-scale verification system, the Digital Aperture Array Verification System, DAAVS, which will bring together the technology elements in B.1-B.4 together with input from our European collaborators. The construction and of the DAAVS is the subject of work package B.5.4.1 Theme A: SKA system design and core technologies

4.1.1 System Architecture and Technical Simulations (WP A1)

System specification and architectural design are central to defining the scientific direction and productivity of any telescope. We have led this process for the SKA within Europe and SKADS, and have had a major influence on the development of the international project.

Within PrepSKA, the system design and costing – which are intimately linked – will be *coordinated* by the SPDO. The aim of this work package is to support specific tasks which have been fully agreed with the international project, and a system design for the SKA will be a key deliverable of PrepSKA. Thus, the UK team will continue to have significant input to, and influence on, the international system design and specification towards an SKA design which has maximum scientific impact.

During the period of SKADS, the European SKA system design effort has been led by Alexander, Faulkner, Jones and Wilkinson, the scientific requirements have been greatly influenced by the work led by Rawlings, and Bolton has led cost modelling studies. Similarly, the technical simulations have been coordinated by Alexander, with EM antenna simulations led by Brown, digital processing simulations by Jones, and aperture-array performance simulations by Alexander. This work has involved input from all of the SKADS participants and has had a very significant impact on the international project. After publication of our initial costed system design concept for the SKA, we played a central role in the international work to define a new specification for the telescope along with possible architectural implementations. The outcome of this process is that it is now accepted that Aperture Arrays are the technology choice for frequencies below 500MHz in all architectural solutions considered. Furthermore, of the three architectures proposed for frequencies up to 1GHz, Aperture Arrays are the only option which provides sufficiently large survey speeds to fully deliver all the key science areas in this frequency range.

To enable this work to continue and develop through PrepSKA, we request support for four specific tasks. These will be an intrinsic part of the international project and their scope and deliverables are fully agreed with SPDO.

Cost and design tool

We plan to continue to develop the costing tool for the international project in close collaboration with SPDO. It is crucial to have a single tool for the whole SKA project in order to unify the design and costing process. The tool, and the models implemented using it, will be tested during the design and construction phases of the pathfinders. In July 2007, the international SKA project and the SKADS, ASKAP and MeerKAT projects agreed to construct a single costing and design tool, to be used for all pathfinder experiments as well as for the SKA. This is a major project and will continue to evolve throughout PrepSKA. The UK, at the request of the SPDO, is leading the work on the design and implementation of the tool. The tool is Python-based and implements a model for the system design in terms of components and design blocks. A complete realisation of the telescope is built out of a hierarchical structure of design blocks. The tool allows the detailed implementation of the engineering design associated with each design block to be defined and maintained by appropriate engineers, while maintaining the underlying integrity of the system design and information flow.

Aperture Array cost modelling and design coordination

The UK has very successfully coordinated the cost modelling of the conceptual system designs proposed during the SKADS project resulting in the production of the SKADS Benchmark Scenario, the first detailed design and costing for the SKA (see www.skads-eu.org). In PrepSKA, the conceptual designs developed within SKADS and elsewhere will be taken forward and combined into costed designs of complete systems. At least initially, this will be based on the three telescope concepts which the international project has determined to consider. Each of these includes an aperture array providing frequency coverage to 500MHz and dishes with single-pixel feeds at high frequencies. The three concepts differ in the mid-band frequencies below 1GHz, where high survey speeds are required to match the science requirements. Aperture arrays are again one of the possible concepts and indeed are the only one which delivers the required survey speed – the other two concepts are dishes with single-pixel feeds and dishes with focal-plane arrays. Europe will play the central role in taking forward the system design and specification of the aperture arrays. In SKADS this work has been led very successfully by UK and we plan to continue this work into the key system design and definition phase of PrepSKA. This will require taking input not only from the UK tasks, but also from all the other work within Europe which is contributing the PrepSKA work packages and the AAVP. Bolton will also work closely with the SPDO in developing the aperture array in each system design concept and in analysing these concepts to perform cost optimisation and cost / performance trade-offs.

Real time control and monitoring

The aim of this task is to prepare a detailed report on the requirements for the real-time control and monitoring system of the SKA. Cambridge will lead this task which involves a substantial element of coordination to obtain input from the Pathfinders and related projects such as eMERLIN and eVLA. A conceptual design for a cost-effective, highly robust, signalling sub-system for transporting SKA control and monitor (C&M) data will be developed. The goal is to provide the large, complex SKA with effective human interfaces and diagnostic tools for a range of users. The control system must accommodate a highly distributed architecture with a mix of receptor technologies, and must support a wide range of observing/operational modes. Cambridge will use existing expertise (Titterington) who will manage the task together with a real-time software engineer, and will lead the production of the final deliverables.

Technical Simulations

SKA technologies have to deliver demanding performance in order to meet the science goals at an affordable cost. Many of these technology related effects are interdependent and technical simulations essential to examine these interdependencies ahead of building prototype systems. Within SKADS we have already made significant progress. We have developed a *functional simulator* in which we simulate particular elements of the system which have a large impact on performance and/or cost. This has been very successful. We have developed approximate techniques for modelling the antenna response and beamformer to calculate the time-variable aperture-array primary beams and a few-element interferometer. Other simulations model the data flow in the network, finding optimised trenching and fibre routes. Together, these simulations form the functional simulator as originally envisaged. While intellectually linked, they are independent stand-alone simplified simulations.

Within PrepSKA, technical simulations of various parts of the overall system are required; in particular those for which the verification systems will not provide complete performance information. For the aperture array in particular we plan more detailed simulations, to model the real response of the system as accurately as possible, from the element response through to output of the station-level beam former. The aim is simulate the signal path with as few simplifications as possible from detection at antenna through the analogue chain, digitisation, polyphase filter, beam former and simple correlator. Whereas the SKADS deliverable are a series of reports, the deliverable from PrepSKA will be a simulation package which can be used in a variety of ways to examine the performance of the aperture array sub-system. Building on the work in SKADS, the simulator will be developed in stages adding additional complexity over time. This will ensure we are able to generate results early and determine what level of simulation detail is needed to answer our specific performance questions.

4.1.2 Data and Phase transfer (WP A2)

The digital data streams for each beam formed at an aperture array station in the SKA must be sent to the central processor for correlation. For the mid-frequency array, the total data rate per station is 16 Tb/s, and for the higher frequencies each dish generates 0.1 Tb/s. The total data rate for the SKA is approximately 4 Pb/s, which is of order 1000x larger than the rate for ALMA or EVLA and involves distances of thousands rather than tens of kilometres. For comparison, today’s global internet traffic volume is estimated at 15 Tb/s, and is expected to reach ~ 1 Pb/s by 2015. In addition to transporting the data from each station, each element of the SKA must be synchronised with sufficient accuracy for the whole array to act as a coherent interferometer.

The task of providing the detailed designs of the data transport and synchronisation systems will be led by Manchester. The fibre optics group at JBO carried out the optical design for the ALMA network, contributed to the EVLA design, and have designed, procured and are now commissioning the e-MERLIN network, spanning several hundred kilometres. This expertise is recognised internationally: Spencer chairs the SKA Signal Transport Task Force and McCool is a member of this group, established by the SKA Engineering Working Group.

In SKADS, effort has focussed on establishing the feasibility of transporting the required data volumes using low-cost links built from optical components, which are either readily available now or are just reaching the market now. The choice and cost of components depends critically on the link length. For links beyond 80km, amplifiers will be required and beyond 400km, signal regeneration will be used (see figure 10). This has allowed preliminary cost models to be built, which are now being refined as the design of the overall SKA layout progresses.

We have also shown in SKADS that coherent phase transfer can be done effectively using radio frequency modulation onto infra-red carriers over optical fibre systems. The modulated signal needs to be related to a standard clock frequency from which any local oscillator signals, sampling clocks and timing signals can be derived. In SKADS we implemented an optical version of the 1.5 GHz pulsed radio link system developed at JBO and used in MERLIN. The MERLIN system locks a high quality quartz oscillator at the remote telescope to a H-maser at JBO and measures the round trip delay over multiple-hop links up to ~250km to within a few ps, sufficient to meet the requirements of at least Phase 1 of the SKA. The advantage of the pulsed technique is that since single fibre is used for bidirectional measurements, it is not sensitive to temperature variations in a multi-core cable. Hence this technique may be very useful if, for reasons of cost, the SKA does not use deeply buried cables. Tests of the optical implementation have been carried out using installed fibres, some of which run above ground, over distances of up to 110km. The stability is better than 1 ps rms over 1 second, 2 ps over 1 minute and 4 ps over 10 minutes, for a link of 110 km in length. These experiments have demonstrated the feasibility of this approach for SKA; in PrepSKA the aim will be to design a low-cost and robust method of integrating the electronics with the station processor.

The next step to be covered by UK-PrepSKA is to build on the work from SKADS and extend the concepts to the larger scale required by SKA, with the particular aim of enabling Phase 1 to be constructed. The work will involve further study of components available in rapidly developing communication technology with the aim of cost reduction and resulting in a detailed design for Phase 1 SKA and projections for SKA Phase 2. In the event that a commercial system is chosen for parts of the transmission system, this design work will be an essential part of defining the requirements for a commercial system and, in particular, defining the interface requirements to a the digital processing back end. Possible trade-offs with new devices such as number of channels multiplexed per fibre, distance that can be covered in each link, complexity of the interconnect systems in the central processing facility, reliability and upgradeability, while reducing cost and power will be studied. Investigations of novel and possibly inexpensive methods of data transfer on short and long links will be made, leading to an optical link design. Scalability and integration are important issues for phase transfer, and these will be investigated. A fully integrated and cost optimised system suitable for deployment in the SKA will be designed.

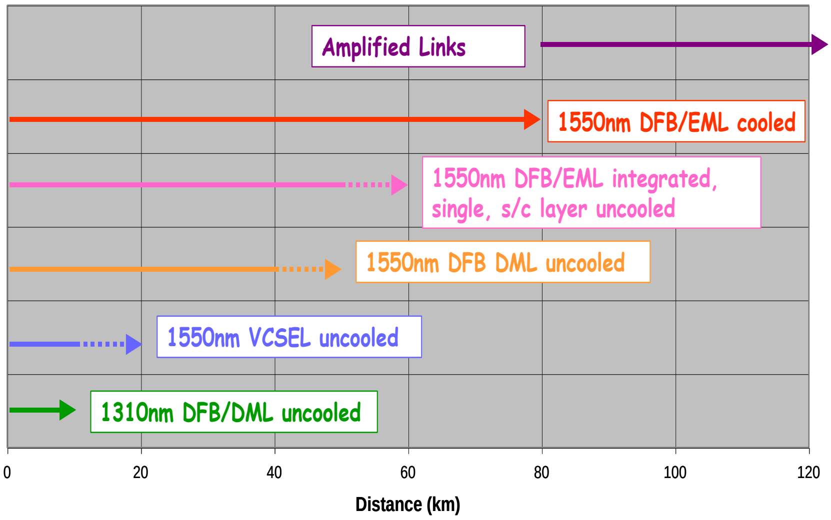


Figure 10: Range of infra-red laser diodes used in communications. DFB: distributed feedback, DML: directly modulated laser, EML: externally modulated laser, VCSEL: vertical cavity side emitting laser. Links beyond 80 km require amplification.

4.1.3 Real-time processing (WP A3)

The SKA will be a signal-processing based telescope. The aperture array concept can be seen as the ultimate electronic collector system and the all-digital concept which is being developed in the UK is the most demanding of all the signal processing requirements, as is illustrated in Figure 11. Although the amount of processing required is extremely high, work within SKADS has shown that the performance of the SKA is likely to be restricted by communications rate at all scales, in this case the communication capabilities between processing devices, boards and racks. We have therefore been aiming to develop technologies which combine very high processing rates with very large input-output bandwidths, in a ratio which is quite different to other high-performance systems such as supercomputers. This requirement is attracting interest from major industrial companies such as IBM and Intel, since solutions are likely to be important to other applications e.g. radar.

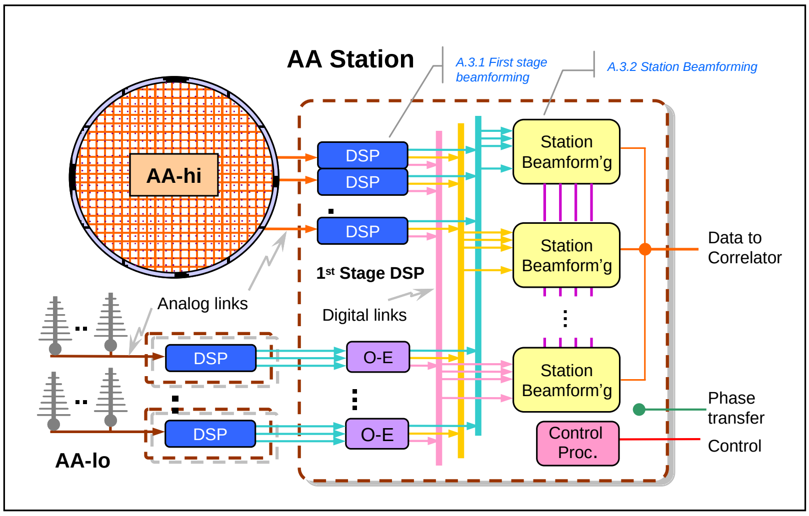


Figure 11: Aperture array showing processing

Within UK-PrepSKA we will concentrate our efforts on the detailed processing and communication requirements for beamforming within the aperture array system. However the technologies developed will be directly relevant to the other SKA signal processing requirements, namely the dish signal processing, the central correlator, and the gridding front-end for the post processor. It is clearly advantageous for the SKA as a whole to take a unified approach to signal processing hardware if possible. By concentrating on the most demanding signal processing task, the aperture array processing, we will be in a position to guide and inform the processing development for other parts of the system, co-ordinated via the SPDO.

Beamforming for the SKA

The key feature of the aperture array design is that all the formation of the station beams – the equivalent in a conventional radio telescope of the dish, its pointing structure, and the provision of multiple feeds – is done in digital processing rather than with physical structures. This means that the aperture array can in principle far exceed the performance of a conventional dish, as it can point in many widely spaced directions simultaneously, change pointing direction instantaneously, and (with provision of sufficient buffer memory) look back in time and point a beam at some transient event before it occurred. It also has the advantage that the aperture is not blocked by any feed or secondary mirror structure, which would introduce scattering and hence side-lobes, plus the aperture weighting can be dynamically altered to optimise for either aperture efficiency or beam response. Since every element can be controlled in amplitude and phase, it inherently has full ‘adaptive optics’ to compensate for errors in the instrument itself as well as distortions in the incoming wavefront due to the atmosphere. However, to achieve all this, a prodigious amount of signal processing capability is required, and the processing algorithms must be as efficient as possible to make best possible use of the hardware.

There are two kinds of processing which need to be performed on the data; in time-frequency space, to generate frequency channels, calibrate each one accurately for time, phase and polarisation and excise unwanted parts of the passband, and in position-angle space, to generate responses localised in direction from many antennas. These are loosely referred to as ‘channelising’ and ‘beamforming’ respectively. Channelising is conceptually easier, since it operates on a single data stream. There are many well-known algorithms for performing tasks such as bandpass filtering, bandshaping and generating multiple narrow frequency bands, and the computational requirements in terms of operations ($O(N\log N)$ for FFT-based algorithms such as the polyphase filter bank) and memory are easily stated. Processing takes place locally, by providing sufficient memory.

Beamforming requires the signals from many antenna elements to be brought together. The simplest beamformer, in which all the signals are brought together to a single processor, is not feasible for an SKA station which may have 65,000 dual-polarization elements. We must therefore implement a hierarchical beamformer in which the processing can take place in stages with minimal cross connections between elements at the same stage. The beamforming problem is then a complex interaction between the available hardware and the algorithms which must run on it.

Beamforming hardware

Beamforming algorithms all fall in to the category of linear operations, which can be implemented in matrix arithmetic. Matrix operations can be executed very efficiently in parallel hardware. The task of the main beamforming hardware is thus to carry out matrix-matrix or matrix-vector multiplications as efficiently as possible. Conventional computer processors do not remotely approach the throughput required to do the number of operations we require for a reasonable cost and power consumption, and nor will other typical processing architectures such as DSP processors or FPGAs. We are adopting two parallel approaches to solving this problem, continuing from work in SKADS. One is to use highly specialised programmable machines in which many (possibly thousands) of simple computing cores in one chip all execute the same instructions simultaneously. These single-instruction-multiple-data (SIMD) devices can achieve very high throughput while still maintaining programmability, and thus flexibility for improvement and development of algorithms. We are working closely with IBM who are developing a chip with very promising specifications, and during the course of PrepSKA we expect to take delivery of the first version of these devices, which are a derivative of the Cyclops multi-core processor which we are using as the beam-forming hardware for 2-PAD in SKADS. As well as the large internal processing power, these chips will also have a very large I/O bandwidth (more than 1 Tb/s) which is required in order to be able to beamform a reasonable number of antenna elements per first-stage beamformer. A beamformer for the DAAVS will be built using these processors.

The second approach is to abandon programmability and design a purely hardwired beamformer chip in which the only variation allowed is in the setting of the beamformer coefficients. A projected outline capability was considered as a sub-contract with Cambridge Consultants ltd in SKADS, which showed that the required performance for SKA Phase 1 can be achieved. This approach will very likely deliver higher performance in terms of operations per Watt and per cost, but we will need to be very confident that we have encapsulated all the required functionality. Another significant issue is the NRE required to develop an efficient, large-scale device. We will prototype the functionality of a hardware beamformer using FPGA hardware and make small-scale prototypes using multi-project wafers.

We will prototype the functionality of a hardware beamformer and make small-scale prototypes using multi-project wafers; we will then investigate the feasibility of incorporating this system into the DAAVS.

Beamforming firmware

Significant development is also required in algorithms. We will continue the work begun in SKADS and OSKAR (an EPSRC-funded collaboration with the Oxford E-science Research Centre) on decomposing the station beamforming problem into a tractable hierarchy with minimal loss of generality for the beams that can be produced. Multiple operation modes, for example full-sky at minimal bandwidth, will be supported. The interaction between beamforming and channelising, which have been treated as independent in SKADS, will be explored, with the intention of minimising total operation count and preserving the full system response (for example to very short pulsed signals). For any hardware implementation of the beamforming multiplications, generation and distribution of the beam coefficients is also a significant problem. The beam coefficient generation can either be a trivial problem, if purely pre-calculated coefficients are used or a non-trivial one if active suppression of variable RFI sources, dynamic ionospheric correction, and multiple nulls on bright sources are required, and we suspect the latter is more likely to be the case. We will investigate software and hardware requirements for the coefficient generation. All the algorithmic work has strong connections to task A.1 (simulations) and B.4 (calibration).

4.1.4 Post-correlator processing, transient processing and data management (WP A4)

The technical challenges facing the SKA do not stop at the point where interferometric UV data emerge from the correlator, or time-series data (as needed for transient sources like pulsars) emerge from each station. The PrepSKA project recognises the critical importance of designing and testing new algorithms to calibrate, process, and manage the datasets needed by all the Key Science Projects. The ability to make interferometric images reaching the thermal-noise level across wide fields with full polarisation is essential if the huge theoretical sensitivity gains of the SKA are to be realised in practice. The ability to characterise the time-variability of sources to high accuracy is essential for all studies of transient sources. Classification pipelines will be constructed making use of VO technology - with event stream being disseminated utilising the VOEvent standard protocols. The reduction and management of SKA data will require new techniques because of their huge size and complexity. Demonstrating that the post-correlator processing to produce the required data quality and within an affordable cost is an engineering requirement on the critical path to the SKA.

The computational challenge is a very strong function of the collecting area of the array or number of antennas (for fixed antenna size) – the problem can increase as the number of antennas to the fourth power. To achieve noise limited performance with the SKA will require increases in achievable dynamic range of between one and two orders of magnitude compared to current requirements.

To analyse data from the SKA pathfinders relatively modest advances on current technology are required to deliver adequate scientific results at affordable cost – the dynamic range requirements are comparable to current requirements and Moore's law enables their data streams to be processed using current approaches. The real challenge emerges for the SKA itself and must be solved as one of the key engineering challenges to be tackled within PrepSKA. In addition to algorithm development, sample implementations must demonstrate the ability to deliver on simulated SKA datasets (products of SKADS and, hopefully, Path2SKA, a separate FP7 proposal covering SKA science simulations which are explicitly not covered in PrepSKA) to properly quantify expected SKA performance. New algorithms and software for data management will benefit greatly from generic advances in e-Research, including astronomy-specific programmes like AstroGrid. Within UK-PrepSKA we concentrate on the core engineering challenge of how to ensure during the reduction pipeline data is routed to where it is needed so as to achieve minimal latency in the processor. Some effort will also be focussed on the design of the data access system building on expertise developed within AstroGrid.

Through SKADS, the astronomy groups in Cambridge, Manchester and Oxford have established new UK expertise in these areas, exploiting collaboration with e-Research centres and expertise within the UK. For instance, the knowledge and systems developed in creating the analysis pipelines for large ground based (e.g. UKIDSS/ VISTA) and space missions (Planck and Gaia) will be leveraged in order to meet the data challenges from SKA. Specific areas such as quality assurance and risk management, software design process, access to significant hardware for development and testing purposes, and so forth, will be directly relevant with PrepSKA. They have also built up close working relationships with the leading international astronomy algorithm/software groups (ASTRON, Haystack, NRAO and CSIRO) – the activities of which, over the PrepSKA period, will be dominated by the need to deliver working software for other projects (LOFAR, MWA, ALMA/eVLA and ASKAP respectively), We therefore expect that STFC funding of PrepSKA-UK will leverage UK international leadership within PrepSKA regarding the algorithms and software necessary for the SKA. A critical PrepSKA deliverable is a full simulation of the processing required for all critical types of SKA dataset, and this will establish the algorithmic and software basis needed for the calibration and processing software for the first stages of the SKA.

The challenges faced in designing algorithms and software for the SKA are much more demanding than those of simply dealing with larger datasets. For example, to achieve the huge dynamic ranges needed for deep SKA imaging and spectroscopy, the side-lobes of bright sources must routinely be removed to a level much better than one part in 10^7. This is a factor of 10 better than has yet been achieved with any dish-based radio synthesis telescope. Careful design of the SKA dishes and their primary calibration scheme will help, but the key to pushing further is to develop algorithms and software that, from the correlated data stream, can calibrate time- and direction-dependent errors due to, for example, dish pointing errors, complicated ionospheric phase screens etc. The UK-PrepSKA team will have ready access to e-MERLIN as a powerful test facility for high dynamic range imaging across wide bandwidths (4 GHz) and relatively wide fields (>0.5 degree diameter at 1.4 GHz). It will be possible to design, execute and process test observations to evaluate particular aspects of the algorithms being developed.

These challenges become particularly acute for solutions for the SKA where data arise from correlating aperture-array station beams since the aperture-array station beams etc are, by necessity, a complicated function of time and ionospheric conditions. Traditional `self-calibration' schemes are clearly inadequate in these cases, and although code platforms (e.g. the MEQTREESS ASTRON package) have been developed which are, in principle, capable of delivering more sophisticated self-calibration schemes their current performance means that they would run far too slowly on any envisaged hardware to be used in a system like the SKA. There are similar problems in extending time-domain observations to systems with the power of the SKA: e.g. accurate timing of pulsars requires high polarisation stability that can only be demonstrated by successfully calibrating a simulated data set in which realistic corruptions are introduced to account for imperfect beams, a changing ionosphere and other aspects of a realistic SKA. A further challenge for PrepSKA is to demonstrate that proposed algorithms can be parallelised with good throughput on achievable architectures so that they will scale to the full SKA problem.

The methodology employed in this UK-PrepSKA-UK work package will be to exploit the skills of the young UK algorithm/software team built up though SKADS, to design, implement and test the new algorithms and codes needed. The initial focus would be on simulating a system capable of calibrating and processing Phase 1 SKA data at affordable cost. The careful mapping of algorithms and code to a number of architectures (traditional clusters, multi-core systems, GPUs etc) will be essential in designing software systems that can be scaled up to the full SKA as technologies develop.

In summary, support for R&D in post-correlator and transient-processing within UK-PrepSKA-UK is essential if the UK is to secure an international lead in this key emerging technology for the SKA. This work is on the critical engineering path to the SKA. The UK is uniquely well placed to do so as a result of SKADS which has allowed the rapid build-up of UK expertise in radio astronomy algorithms and software, exploiting new collaborations between radio astronomy and e-Research areas like high-performance computing. As in all astronomical facilities, the quality of the SKA science output may be driven by the quality of data management after all basic processing, and a modest resource is requested in this area to ensure UK-PrepSKA successfully interacts with relevant activity in other areas of astronomy and in other disciplines.

4.2 Theme B: The aperture array evolution path

4.2.1 Elements and their distribution (WP B1)

The SKA benchmark designs adopt phased array technology as their sensor solutions over the frequency range from 70 MHz to 1 GHz. In SKADS it has been shown that for both cost and performance reasons this band must be split into two sub-bands. Across the low sub-band (70MHz to approximately 450MHz) the sensitivity is dominated by the sky background noise contribution and a sparse array (with element spacing greater than half the longest wavelength) is the only economically viable geometry. This provides the highest possible sensitivity for a given number of elements over a wide bandwidth, with the disadvantage of higher side-lobe levels. This type of geometry has been adopted by e.g. LOFAR; though the LOFAR system operates over a significantly narrower band than the SKA low-band array. The design of this array, in particular in the overlap region with the mid-frequency array has not been considered in SKADS in detail. However thinning array algorithms for potential use up to 1GHZ have been studied and it is proposed to build on this work to establish the low frequency array design.

The radiation pattern in sparse systems is known to be ill controlled, with high side-lobe levels at the higher edge of its frequency band. Work in SKADS indicates these high side-lobe levels will limit the dynamic range of the instrument, making it impossible to undertake the critical scientific missions of SKA at frequencies above approximately 450MHz. Therefore in the range 450 MHz to 1 GHz (the so called "mid-frequency array") a low-side-lobe design is essential, requiring a closely spaced aperture with antenna spacing, less than or equal to half the shortest wavelength, which Nyquist-samples the incoming electric field. This dense array has less effective area than a sparse array but also operates in the regime where the effective sensitivity can be improved significantly by reducing the amplifier noise temperature. The closely-packed array is a highly demanding electromagnetic design, particularly so as high accuracy polarization measurements are needed over the band and over a wide angle of main beam scan. This array has been the main focus of UK-SKADS (and indeed SKADS overall) where the cost per element, element type, grid and separation are all critical factors.

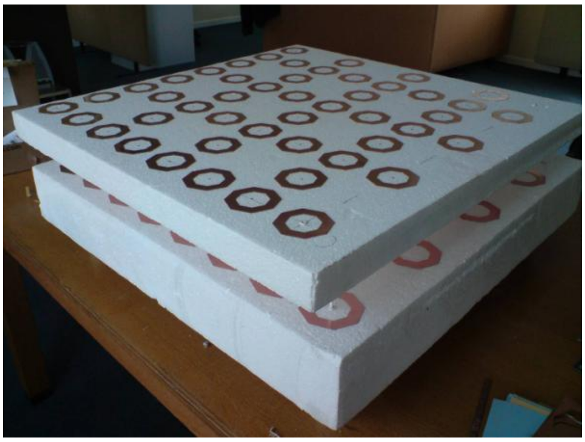


Figure 12: Prototype ORA array

UK-SKADS will demonstrate certain crucial elements of the technology of the mid-frequency array. From the electromagnetic viewpoint, dual-polarization element designs for a closely packed low-side-lobe array have been researched, including a new element design, the ORA (see figure 12) which offers the promise of easier calibration of polarization measurements, commensurate with the required mid-frequency array performance. UK-SKADS (via the 2-PAD small scale demonstrator) will provide proof of concept of high-accuracy polarization measurements from a phased array antenna.

The evolution path from SKADS (both UK and EC components) to a full SKA readiness solution requires several components: (1) evolution of the mid-frequency element design and array geometry, and development of a manufacturable, environmentally provable design; (2) integration with the LNA and associated components, commensurate with the cost/performance requirements; (3) design of the low frequency array; and (4) the overall system design to be detailed and fully quantified against performance targets based on the science mission. This final optimisation of the array design will involve accurate simulated sky models which have been developed as part of SKADS, and the integrated simulation activity described in Section 4.1.1. The planned PrepSKA activities will produce a defined technology solution for both Phase 1 SKA construction and later growth to the full SKA.

4.2.2 Analogue chain (LNAs, band-pass filter, gain chain, equalization) (WP B2)

Despite the description of the technology goals of UK PrepSKA as an 'all digital' telescope, there are significant advances in analogue electronics required in order to realize the system. Before the signals from each antenna element can be digitized ready for the subsequent processing, they must be amplified, filtered, transmitted from the element to the digitizing hardware, and presented to the digitizers in the optimum form. All this must be achieved, for the final SKA design, at a cost of a few Euros per element and at minimal power consumption. The aim over the course of UK PrepSKA is to develop the necessary technologies to provide these electronics in a suitably integrated form.

Low noise amplifiers and element matching

One of the most important technological elements of the SKA aperture array concept is the low-noise amplifier (LNA) which immediately follows the antenna element. The noise performance of the element-LNA combination directly controls the sensitivity of the entire system, and improvements in the noise performance lead directly to savings in the total collecting area that must be built to achieve a given system performance. The overall noise performance is a combination of the intrinsic noise generated by the amplifier, how well that amplifier is coupled to the receiving element, plus the noise that enters the element from the outside world. At the low end of the frequency range of the SKA AA (below ~300 MHz, in the range currently covered by LOFAR) the noise from the sky itself (largely from the Galaxy) is the dominant noise source and the LNA performance is not so crucial. However at the top end of the band the sky is relatively quiet and the total noise is dominated by the LNA and its match to the element.

High-performance LNAs are so crucial to the SKA that we are taking a parallel approach, which seeks to mitigate the risk of not producing an LNA design suitable for SKA Phase 1, while also giving the maximum chance of producing world-leading performance. We will develop MMIC designs based on a successful discrete-component active balun developed under SKADS, using several semiconductor foundries (OMMIC, Fraunhofer, and IBM), in collaboration with other SKA research groups at ASTRON and University of Calgary. These foundries provide a guaranteed production process which ensures that a viable LNA design will be available by the end of PrepSKA, through a foundry with a well-established process, and achieving the best noise performance possible with a commercial supplier. In addition, we will continue the work in the University of Manchester focussed on InGaAs-InAlAs pseudomorphic high-electron mobility transistors (pHEMTs), which aims to produce high gate-width transistors in an optical (1μm) lithography production process. By controlling the transistor properties more precisely than is possible in commercial foundries we hope to produce an LNA with even better noise performance across the aperture array frequency band. All the LNA work will be strongly co-ordinated with other SKA groups, to share best practice and avoid duplication of effort.

Gain, filtering and equalization and analogue signal transport

The LNA supplies the first level of amplification of the signal from the antenna and has the dominant contribution to the overall noise level, but this signal is still many orders of magnitude too small to be digitized. Depending upon the exact analogue chain configuration, up to 100 dB of gain must be supplied, along with filtering to define the passband, and compensation for frequency-dependent loss in components and cables. There is also a need to be able to inject calibration signals in to the signal path in order to measure gain and system temperature variations on an element-by-element level. In traditional radio telescope systems, all these functions would be provided by separate sub-systems, and this approach is necessarily being followed in the SKADS demonstrators, 2-PAD and EMBRACE. However, for the SKA the requirement for ultra low cost and power consumption means that the only feasible route is to integrate these functions into a small number of CMOS chips. Such radio-frequency integrated circuits (RFICs) are now relatively common, and there are a number of UK companies with world-leading products in this area. We plan to work with relevant companies to develop prototype versions of RFICs that will integrate the gain-chain requirements for aperture arrays and ensure technological readiness for SKA Phase 1 by the end of the PrepSKA development period.

Digitization

The analogue to digital converter (ADC) is another key technological component of the SKA all-digital aperture array concept. The current SKA specification calls for a maximum frequency for the aperture array of 800-1000 MHz. With a top observing frequency of 1 GHz, a maximum sampling rate of around 2.5 Gs/s is required (in order to Nyquist sample the signal with sufficient guard band to allow realisable filters). On the potential SKA sites, the level of RFI is low enough that when sampling a full-band signal, the digitizer is presented with Gaussian noise, i.e. the narrow-band RFI is swamped by the broad-band receiver noise. Gaussian noise can be accurately characterized with only 3 effective bits of quantization (in practice 4 bits would be required to provide for a slightly lower number of effective bits). The requirement for SKA is therefore for a 4-bit, 2.5 Gs/s ADC which can be effectively interfaced to the subsequent processing chips. In addition, a key requirement is very low power consumption: the ADC must consume only a small fraction of a Watt. (Note that 100mW of power consumption per analogue chain corresponds to approximately €1M per year running costs for the full SKA.) Although such ADCs are not yet commercially available, there is currently a great deal of industrial interest in fast, low-power ADCs due to the markets for hard-disk readout and the new ultra-wide-band (UWB) communications standard, and devices of the required specification are becoming available using standard CMOS processes. CMOS processes have the advantages that there are well-established mass manufacturing routes, and also give the possibility of integrating the ADC directly with the subsequent processing device. Within SKADS we have commissioned an industrial design study on CMOS ADCs from IBM, who are also investigating the possibility of incorporating the ADC units in to their multi-core processor chips (which is one of the architectures being considered for the digital beam-forming – see section 4.2.3) . We have also made contact with other academic groups whose research roadmaps expect to deliver ADCs with SKA specifications on the timescale of PrepSKA, and we will explore with them joint research programmes with the goal of delivering a prototype SKA-spec CMOS ADC device by the end of PrepSKA .

4.2.3 AA array infrastructural/environmental/shielding etc (WP B3)

This is a wide-ranging programme that has a substantial impact on the cost, performance and practicality of an aperture array system. The main deliverable is the mechanical and material design of an SKA size AA. This is not the same as building a demonstration system, which is also a deliverable; it must have a clear path to the much larger implementation for the SKA. There are many aspects of this task which can be undertaken by collaborating countries, particularly the DAAVS host and potential SKA sites.

The mechanical design of the aperture array covers not only construction and assembly techniques for the array and processing systems, it incorporates performance and cost related criteria including:

- Stability and ease of assembly;
- Environmental protection against solar radiation, rain, wind, UV, animal and insect life etc;
- Thermal control for the array front end array and processing systems: optimised designs for the cooling systems essential for the processing to remove excess heat;
- Mechanical mitigation of self generated radio frequency interference, RFI;
- Implications for overall system reliability: the AA is a very complex system, to ensure high mean time between failure, MTBF, and quick mean time to repair, MTTR, will require careful system design and good mechanical implementation;
- Testing of materials in the conditions found on the proposed SKA sites: choice of materials is essential for long lifetime, these will need extended life-testing on-site;
- Considerations of ground conditions.

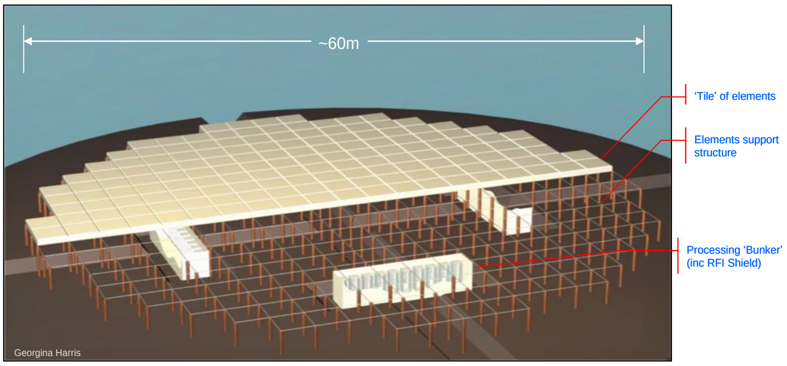


Figure 13: Cutaway of SKA scale AA. Note that the whole array will have a thermal and environmental covering, not shown.

A possible, even likely, concept for the SKA AA-hi is shown in Figure 13. It is constructed as a regular array of antenna elements with a total diameter of approximately 60 m, these are split into logical 'tiles' of ~ 16 x 16 dual polarisation elements. After local amplification the elements are connected to "bunkers" which house the digitisation and processing systems. The bunkers provide electromagnetic shielding to limit self-induced RFI. The design enables access for construction and servicing by raising the array on supports to which also provides a cavity underneath the array which can be thermally stabilised. There will need to be an environmental covering to exclude water, dust, insects etc. The bunkers will need active cooling since each bunker will dissipate of order 40kW. The principal requirement is to ensure that the electromagnetic performance is optimised. This means that the array needs to be completely regular with no discontinuities, for example at tile-to-tile interfaces. Physical stability is a major benefit of AAs, this is an essential part of being able to accurately calibrate the system for maximum dynamic range.

This task builds on the work and concepts already being developed in SKADS. There are many facets to the work that need detailed design and testing to prepare for the construction of SKA Phase 1. The work package has not been explicitly defined in the international PrepSKA programme, which is an oversight; the work will have to be done within Europe, as the design centre for AAs. There will be collaborative work particularly with ASTRON and other European contributors. Since there is no near equivalent commercial requirement the core work has to be done as part of PrepSKA, however, subsystems such as the RFI shielding design can have sub-contract design work performed.

4.2.4 Aperture Array Calibration (WP B4)

The all digital aperture array concept for the SKA envisages that the raw signals for several tens of thousands of individual receiving elements within one station will be combined together to form one (or more) station beams. Before this coherent addition of the signals, calibration coefficients will have to be applied to the data streams in real time. The aim of this task is to design and test a method for measuring these calibration factors and to characterise the properties of the telescope at the individual receiving element level. This calibration task will be critical to achieving the desired dynamic range performance of the telescope. Complex gain factors must be determined across the frequency band, measuring polarisation angles, characterising cross channel leakage and cross-polar response. Measuring changes in the overall system temperature will also be addressed and will have significant interaction with the analogue chain task. This task does not address such questions as absolute calibration, tropospheric or ionospheric calibration which will be addressed by other PrepSKA work packages (PrepSKA work packages 2.9.5, 2.7.5); results from the calibration programme discussed will be fed back into these areas.

Our calculations show that in order to achieve the required calibration accuracy, we will not be able to rely on calibration through observation of astronomical sources since the signal strength on the element level will be insufficient. Our concept is, therefore, to have an external source mounted at a sufficient height to illuminate the AA station. As part of the SKADS programme we will generate a conceptual design for a suitable calibration system. The main task of this programme will be to extend this into a full engineering design and construct a verification system for the calibration hardware.

This work will be a continuation of research conducted in SKADS and will exploit our experience in the area of hardware calibration from other projects. We will continue our close working relationship with ASTRON in this programme. There will be significant interaction with the beamforming algorithm development undertaken in A3-Signal Processing and noise injection hardware studied in B2-Analogue Chain; both of these work packages are being led by the UK. We plan to involve industry to produce a verification system for the calibration instrumentation on the DAAVS.

4.2.5 UK Contribution to the AA verification programme, AAVP (WP B5)

Aperture Arrays offer the possibility of the greatest step in survey speed of all technologies for the SKA. They will form the collector at low frequencies and will be the collector technology for the mid-band SKA (300MHz – 1GHz) if their cost/performance can be fully delivered. Europe has led this development via SKADS. During PrepSKA we, together with our European colleagues, have determined what needs to be demonstrated for the successful adoption and deployment (in Phase 1) of mid-band aperture arrays. This key aspect of PrepSKA is called the Aperture Array Verification Programme (AAVP) and is again led by Europe.

The details of the performance required to be demonstrated are under discussion internationally and are described in more detail in Appendix A (WP B5), however the requirements include:

Sensitivity: in terms of System Temperature, T_{sys}, required to be <50K

Performance: quality and knowledge of the beams formed to meet the demanding polarisation and dynamic range requirements of the SKA

Multi-beaming: ability to form many concurrent beams to meet the FoV requirements

Integration: both of the aperture array itself and with the higher frequency dishes

Construction: environmental, reliability and self induced RFI mitigation

Cost & Power: that the targets for capital and operational costs can be met for the SKA

To achieve these aims the AAVP will combine information from a variety of sources including the outputs of SKADS (EMBRACE and 2PAD), but including four developments:

1. EMBRACE-II: likely to be a 25-m equivalent AA station in the Netherlands which will enable the full astronomical calibration of aperture arrays to be tested via correlation with the WSRT. EMBRACE-II will use technologies available as the output of SKADS.
2. A small fully digital system, the Digital Aperture Array Verification System (DAAVS), which will enable integration and testing of next generation technologies.
3. Environmental testing of component technologies in an appropriate location in either Spain or Portugal.
4. Detailed technical simulations

The expectation is the each aspect of the AAVP will principally be funded by the main national proponents (including the Iberian part) with a programme of cross-work packages will be developed to ensure that all three nodes work together within the SKADS-derived management structure formally overseen by ESKAC. Our UK programme consists of the core technologies to which we are contributing (WP B1-B4), technical simulations (WP A1) and also delivery of the DAAVS for which we seek funds in this proposal.

The validation programme brings together global work on aperture arrays, which has crucial information from full scientific instruments at lower frequencies, LOFAR and MWA, through ongoing data from 2-PAD and EMBRACE built in SKADS to the advanced demonstrator the DAAVS being led by the UK. The large scale detailed work has to be done through simulation, confirmed from the hardware demonstrators, again led by the UK.

Table 2 illustrates how these different inputs will contribute to the questions which must be addressed by the AAVP within PrepSKA.

Source	**Description**	**Use in PrepSKA**	**UK Led?**
2-PAD	All-Digital AA demonstrator from SKADS	On going evaluation of designs for the all-digital array. UK based hardware test bed.	✓
EMBRACE	SKADS European AA using initial analogue beamforming	Performance tests on a larger hi-frequency AA	
LOFAR/ MWA	Low frequency AA scientific instruments	Major AA installations working at lower frequencies, can illustrate calibration, beam quality and use of AAs	
DAAVS	Next generation All-digital AA demonstrator	The evolution from 2-PAD. Greater integration, calibration facilities, based in an RFI quiet location. The subject of UK hardware development in PrepSKA	✓
EMBRACE +	Next generation analogue beamformer AA, led by The Netherlands	A larger array for demonstrating beam performance and manufacturing techniques	
Simulations	Simulation work from the elements, through 2500m^2 AA stations to the full SKA	A detailed performance evaluation of AAs and the SKA overall. This is the only viable technique to evaluate SKA scale arrays in PrepSKA. Reliability assessment, MTBF, and effects of element/tile failure for graceful degradation.	✓

DAAVS & 2-PAD

The Digital Aperture Array Verification System, DAAVS is a relatively small, high performance demonstrator showing pre-production technology for Phase 1. Ideally, it will be co-resident with the dish verification systems and may be used for an SKA system demonstration. This is an evolution from 2-PAD and will have a processing system that can support either AA-hi collectors or by plug exchange AA-lo collectors. This will enable cost effective development of both AA frequency ranges.

2-PAD will continue to be used for detailed testing and development particularly in the early stages of UK-PrepSKA. During the build phase of the DAAVS 2-PAD will be used as a local test-bed for the DAAVS sub-systems.

The DAAVS is targeted at efficiently testing the technical performance for SKA Phase 1, in particular T_{sys}, multi-beaming, RFI mitigation, calibration techniques, beamforming algorithms and material selection. While it will make astronomical observations for test purposes, it is not an astronomical science instrument.

The installation will consist of an RFI screened processing bunker, with four Tile processors each with 128 input analogue channels supporting up to 1GHz input frequencies, digitization and processing, targeted to be built on a single large circuit board. The Tile processor output will be combined using a station processor board. Achieving this level of integration will show substantial progress towards the SKA requirements. The bunker will also house imaging, control and calibration processors.

There will be two, alternative, AA-hi front-end arrays, operating from 300MHz to 1GHz, which will be configured as four 8x8 dual polarisation arrays. The use of two different AA-hi elements or topologies will enable comparisons on a significant array to be made. The collecting area for the AA-hi will be ~10m^2, combined with T_{sys} at 800 MHz of <50K, and very wide bandwidth will enable considerable technical design data to be collected. The AA-lo array will combine the two polarizations from each element onto a single analogue channel; this will enable the same processing system to be used. The system will be highly configurable: as a single collector for beamforming tests or as a small interferometer for imaging tests. It will also be able to mix use of the AA-hi and AA-lo collectors to show a full aperture array system for the SKA.

An important t part of the demonstrator is the integrated calibration systems, developed in section 4.2.6. These are key to the very high beam quality and performance required from the system. Detailed specifications and costings are shown in appendix A WP B5.

5. Project Management Plan

Project management of this programme will be key to its success. We request support for a Project Manager, the UK Project Engineer and a UK Project Scientist. Although for administrative reasons these posts are attached to specific institutions the post-holders will serve the whole project and where appropriate the wider UK community. The detailed role to be performed by each of these post holders is discussed below.

5.1 Management structure and consortium members

The UK-PrepSKA programme is an integrated part of the international SKA project: specifically PrepSKA and the European AAVP (Aperture Array Verification Programme). The STFC is of course the PI of PrepSKA and Professor Diamond is the coordinator. The technical work we propose here is a direct contribution to the international technical programme – Work Package 2 of PrepSKA. The management structure we propose reflects these crucial linkages. The Universities of Cambridge, Manchester and Oxford together form the UK technical SKA consortium. Although there are no formal industrial members of the consortium we expect significant involvement from UK industry via specific industrial contracts as discussed in the main part of the proposal.

The overall management of UK-PrepSKA will be governed by a Project Management Board (PMB). This will consist of:

1. Two academic representatives from each institution (voting members):
    - Cambridge: Alexander (project and Cambridge PI), A.N. other
    - Manchester: Diamond (Manchester PI), A.N. other
    - Oxford: Rawlings (Oxford PI), A.N. other
2. The senior UK-PrepSKA team members (non-voting members):
    - UK-PrepSKA Project Manager (TBA)
    - UK-PrepSKA Project Engineer Faulkner
    - UK-PrepSKA Project Scientist (TBA)
3. Representatives of the International and European SKA Projects (non-voting members):
    - International SKA Director Schilizzi
    - International Project Engineer Dewdney
    - European AAVP Coordinator van Ardenne (ASTRON)

The PMB will have two full meetings a year and a two further telecons: additional telecons will be scheduled as required. We expect the STFC will wish to have a steering committee overseeing the project and we propose that the steering committee meetings be scheduled immediately following the PMB meetings.

Detailed technical management of the project will be managed by a Project Technical Committee (PTC) which reports to the PMB. The PTC membership will be:
Project PI (Chair); Project Manager (Convener); Project Engineer and Scientist; Work package leaders and the International SKA Project Engineer.

Other key individuals will be invited by the Chair to join specific PTC meetings as required. There will be monthly telecons of the PTC and the PTC will organise two project workshops per year which may be scheduled at the same time as PMB meetings. Academic work package leaders will report via the PTC to the project PI.

Coordination with the international SKA project and the European project are crucial. This will be achieved as follows:

1. As indicated above senior members of the international and European projects will be members of the PMB and PTC,
2. The plans for the international Central Design and Integration Team (CDIT) include close involvement of individuals from contributing programmes, liaison engineers; the UK-PrepSKA Project Engineer, as UK-PrepSKA liaison engineer, will also be a member of the CDIT team.

Project Review Meetings and Design Review Meetings

During the period of the grant there will be two formal project review meetings for all Workpackages. The first of these will be scheduled for 01/10/10 (to coincide with the CDR for the DAAVS); the second will be scheduled for 01/10/11.

The design of the DAAVS will be built heavily upon our experience from SKADS and therefore the DAAVS PDR is scheduled for only six months into the project (04/01/10). A DAAVS CDR will be held nine months later (01/10/10), at which time a design for the DAAVS will be finalised.

Project Manager

A Project Manager for a project of this size is essential and we request support for a full-time position. The Project Manager reports to the project PI. They will be responsible for:

1. Maintaining technical links with the pathfinder projects and the US TDP.
2. UK-PrepSKA programme management
3. Planning and project schedule
4. Finance control and reporting
5. Communication and reporting within the project, STFC and PrepSKA / SPDO
6. Monitoring and action item tracking

They will manage the technical support team of the project (paid for via pooled labour computer officer support) who will provide:

- Web-based project tools (Wiki, central file store, calendar etc.);
- Setup and maintain a project CVS;
- Coordinate the use of communication tools (videcon, telecon).

The Project Manager will be responsible for the production of project planning documents and schedules, financial reports and progress reports. They will monitor the progress of the project (with technical evaluation from the Project Engineer) against the milestones and deliverables. They will convene project review meetings and the DAAVS PDR and CDR.

Project Engineer

We request support for a UK Project Engineer position to be held by Dr. Andrew Faulkner. He has served as European project engineer during SKADS and has established a very high international profile in this role. He serves on many task forces of the international project and the “Specifications Tiger Team”. The project engineer role is central to the success of the proposed technical programme. The Project Engineer will report to the Project PI.

He will also play a central role in working to engage UK industry with the SKA project.

He will be responsible for:

1. Overall technical oversight of the project: liaison with all work package leaders; monitoring technical progress; reporting to the PTC,
2. Considering changes to the technical work programme and advice the PTC and PMB,
3. Being the UK liaison engineer with the international PrepSKA project / CDIT and the AAVP; responsibility for technical coordination with international PrepSKA and AAVP,
4. Maintaining technical links with the pathfinder projects and the US TDP.

Project Scientist

The SKA has enthused a scientific community that extends well beyond that traditionally engaged in astrophysics by virtue of its ability to address fundamental problems across an extremely broad range of scientific problems. UK astronomers have already played a central role in defining and developing the SKA science case. As vice-chair, and then chair, of the International SKA Science Working Group Rawlings (Oxford) co-edited the book (Carilli & Rawlings 2004) setting out the science case and a subsequent volume aimed at SKA applications in cosmology, galaxy formation and astro-particle physics (Kloeckner et al. 2008). He has also led the European FP6 science simulation programme within SKADS (e.g. Wilman et al. 2008) that has provided ‘reference skies’ that have been adopted by the international SKA project as standards on which to base the technical simulations that will eventually be a crucial input to SKA design choices. The UK has played a dominant role in SKADS simulations with Oxford leading working on continuum and line surveys, Cambridge leading work on the magnetic universe, and Manchester leading work on pulsars and known, expected and unknown transients. With PrepSKA set to work towards a detailed and fully-costed design of Phase 1 SKA, the UK must capitalize on their international scientific leadership position in the SKA, particularly given the recent relocation of the SKA Project Development Office in the UK at Manchester.

We feel strongly that the time is ripe for the UK to have an identified UK SKA project scientist, and we here apply for 50% of the funding required for such a person over the duration of PrepSKA. This follows the very successful model used for ALMA, for which a UK project scientist was appointed (in Cambridge) at the time the UK ALMA Project Office was set up in RAL in 1999, i.e. at a similar time separation from ALMA operations as we are now from Phase 1 SKA operations.

To ensure close connection to the international project, whilst reaching out to the entire potential SKA user community in the UK, we feel that the Project Scientist should be located in Oxford where he can interact closely with the SKA simulations group set up and operated under EC-SKADS. Post-SKADS funding for this group will also be sought from the EC, as will be the other 50% of the salary of the Project Scientist (to be underwritten by Oxford University), making the Oxford-based UK Project Scientist a de facto European Project Scientist (the SKADS Project Scientist is in France). Rawlings, now vice-Chair of the European SKA Science Consortium, will be the PI of the submission of a FP7 Marie Curie Initial Training Network (to be submitted in Sep 2008) that will include funding for these and other elements associated with scientific planning for the SKA and the exploitation of SKA Pathfinders.

A UK SKA Project Scientist is well positioned to exert a disproportionately large influence over the international project, with a certainty that a suitably qualified individual would join the International Science Working Group (SWG). To attract an outstanding candidate that would be a credible international science leader, Oxford University has agreed that the Project Scientist would be offered a University Lectureship at the end of PrepSKA, and would be appointed as such together with a College attachment.

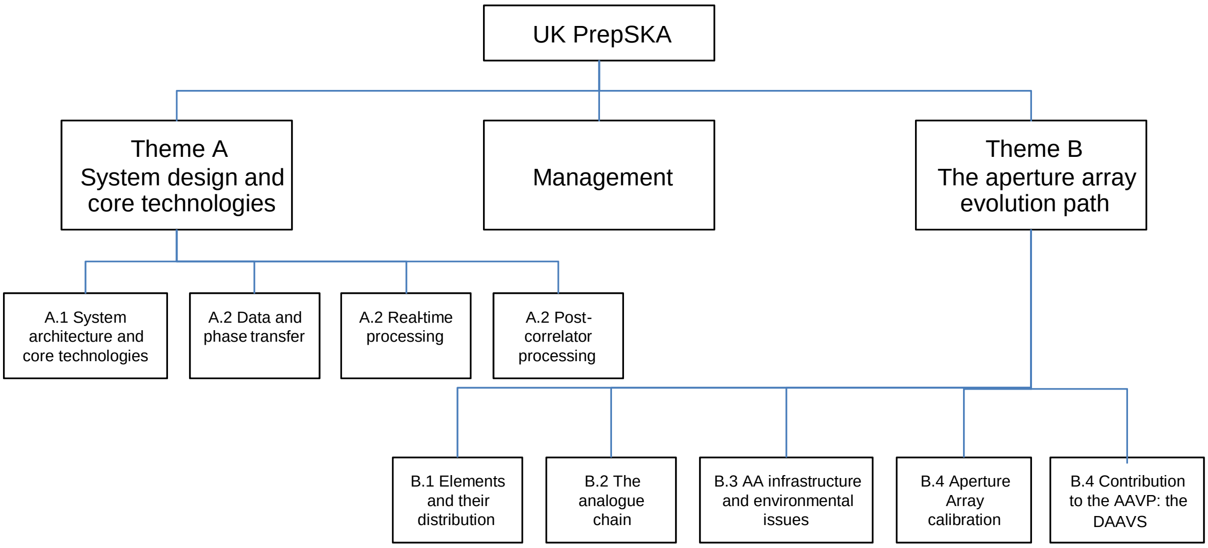
5.2 Change control procedure

The proposed UK-PrepSKA programme is fully integrated into and agreed with the international SKA project and the European AAVP. It is essential that any changes to the work programme continue to match the needs of the wider project. Equally, it is possible that the needs of the international project will develop over the period of PrepSKA with a consequent impact on UK-PrepSKA. We therefore propose the following change control procedures:

1. The PTC will consider and have authority to authorise small changes to the programme which do not alter the deliverables or change the budget.
2. Changes to the programme which would result in modified deliverables or structure of the programme will be considered by the PTC and must be discussed by the PMB. All such changes will be notified to the Steering committee and the Chair of the Steering Committee in conjunction with the Project PI will determine whether the Steering Committee, on behalf of STFC, should consider the proposed changes before they are put in place. Proposed changes may come from within the UK-PrepSKA project or they may originate from the international SKA project or the European project.

5.3 Work breakdown structure

The work breakdown structure is illustrated below. An overview of the scope of each work package is given in the introduction to Section 4.



5.4 Financial planning

This proposal presents the planned R&D programme which will form the UK contribution to the international PrepSKA project. The programme will start on the 1 July 2009 and follows on immediately from the European SKADS programme. The STFC award to support the UK contribution to SKADS has an end date which extends beyond the start date of PrepSKA: a significant fraction of the UK SKA technical team have as a result contracts which are supported on the SKADS grants which extend into the period covered by this programme. From 1 July 2009 we plan that all of the SKA technical team will work on the programme as discussed in this application although formally they will be supported for some months on the existing SKADS grants. The STFC support we seek covers the costs of the proposed UK R&D PrepSKA programme which are in addition to the SKADS funds we hold.

All the funds available from the EC PrepSKA grant for R&D work go to the support of the Central Design and Integration Team (CDIR) of the international project - no monies go to the UK teams or programme. The main role of the CDIT is to coordinate the work to be funded from various national programmes. This grant will support the UK's contribution to this international effort. Other major contributions include the Australian and South African pathfinder projects, the US SKA Technology Development Programme and within Europe significant national programmes in the Netherlands and France are already in place and further funds are being sought to support the full AAVP programme. As discussed in Section 5 we plan a management structure which ensures the UK programme fully fits into this effort. Links to the pathfinder projects naturally exist via this cooperative structure.

Overview of costs

Detailed costs for each work package and the overall programme are given in Appendix B. Costs presented are the STFC contribution to the project and are based on current FEC rules. Costs were estimated by our analysis of the work and hardware required for each work package. The required staff effort is then assigned as required to each work package. Where possible we seek to make use of the expertise available within the current team built up during SKADS and in large part the requested staff effort supports this core team. Some additional posts are required as well as pooled technical labour. All of these resources as well as academic FEC costs are justified in the detailed work package descriptions in Appendix A with summary financial tables for each work package, institute and the complete project in Appendix B.

The total requested new STFC contribution to this project is **£8.762m** plus **£1.13m** working allowance and contingency. An overview of how the WA and contingency have been derived is given in Section 5.9 together with the “owners” for each risk – details are presented in Appendix A for each work package. The breakdown of costs per work package is as follows

M: management	£941,166
A1: system design	£1,241,710
A2: data and phase transfer	£493,745
A3: real time processing	£1,237,731
A4: post processing	£1,258,981
B1: antenna and elements	£512,979
B2: analogue chain	£1,692,747
B3: infrastructure	£408,622
B4: calibration	£449,896
B5: AAVP	£1,255,403
Total cost to STFC	£9,892,997

5.5 Overall project schedule

The overall project Gantt charts are shown on pages 36 and 37. A list of deliverables is given in Section 5.8.

5.6 Technology and industry plan and technology exploitation

5.6.1 Background

The SKA needs a high level of technology development, over and above existing commercially available technologies but firmly within the road map of the electronics industry in cost/performance by the time it is fully deployed. The science requirements demand an instrument with state-of-the-art performance at low cost to meet its specification. In order to achieve this development we will continue to work closely with industry, not only as customers, but also as collaborators, steering and providing technological pulls. The scale of the SKA is such that securing industrial *juste retour* is important to offset the UK’s capital contribution to SKA construction. Funded collaborative R&D leads to two-way knowledge transfer; which is of mutual benefit and has the potential for further industrial spin-offs of the technology. We will ensure that SKA-industry connections flourish through the SKADS, PrepSKA and the SKA construction phases.

5.6.2 Current SKADS links with industry

As a result of meetings organised by STFC, including “UK science meets industry” and our own contacts we have let a range of contracts, from feasibility studies to the supply of hardware, with UK industry. In summary these are: Cambridge Consultants (architecture, analogue design and DSP study); BAe (phased array antenna element study); Roke Manor (phased array architecture study); EEP (supply of EM-tight container to house high-speed digital hardware); RFMOD (supply of innovative packaging for semiconductor devices); Selex/Galileo (design validation and testing of high-speed ADC); IBM-US (supply of advanced DSP hardware) and IBM-UK (study of high-speed low-power integrated CMOS ADC). In addition discussions are underway with INEX (U. Newcastle) to explore ways to enable UK production-readiness for advanced semiconductor devices developed within the programme. We are working closely with the Electronics KTN and Sensors and Instrumentation KTN, both for large KTN-industry meetings, with SKA stands and briefing sessions, and to arrange an ongoing series of SKA-industry meetings, now becoming more technology specific.

5.6.3 UK-PrepSKA Planning

We will continue the promotional and contact work with the KTNs and develop further existing and new contacts with UK industry through this programme. There are many opportunities for using the technologies being developed for the SKA, these include, for example:

System Architecture: The simulation techniques being developed are important to engineers building many different large scale systems.

Data Transfer: The telecommunications industry is looking ahead to Peta-bit/s systems, any low cost developments will be of direct interest to these companies.

Real Time processing: Optimal and large scale processing using parallel systems is at the centre of the computer industry roadmap, successful new algorithms and techniques will have a major impact.

Data processing and management: The huge amount of data produced by SKA will require novel parallel processing algorithms and data-base techniques of mainstream interest to the computer industry.

Antennas elements and Analogue chain: The work on phased arrays and LNAs is of direct relevance to radar and other RF communications systems, including the rapidly expanding development of RFID devices

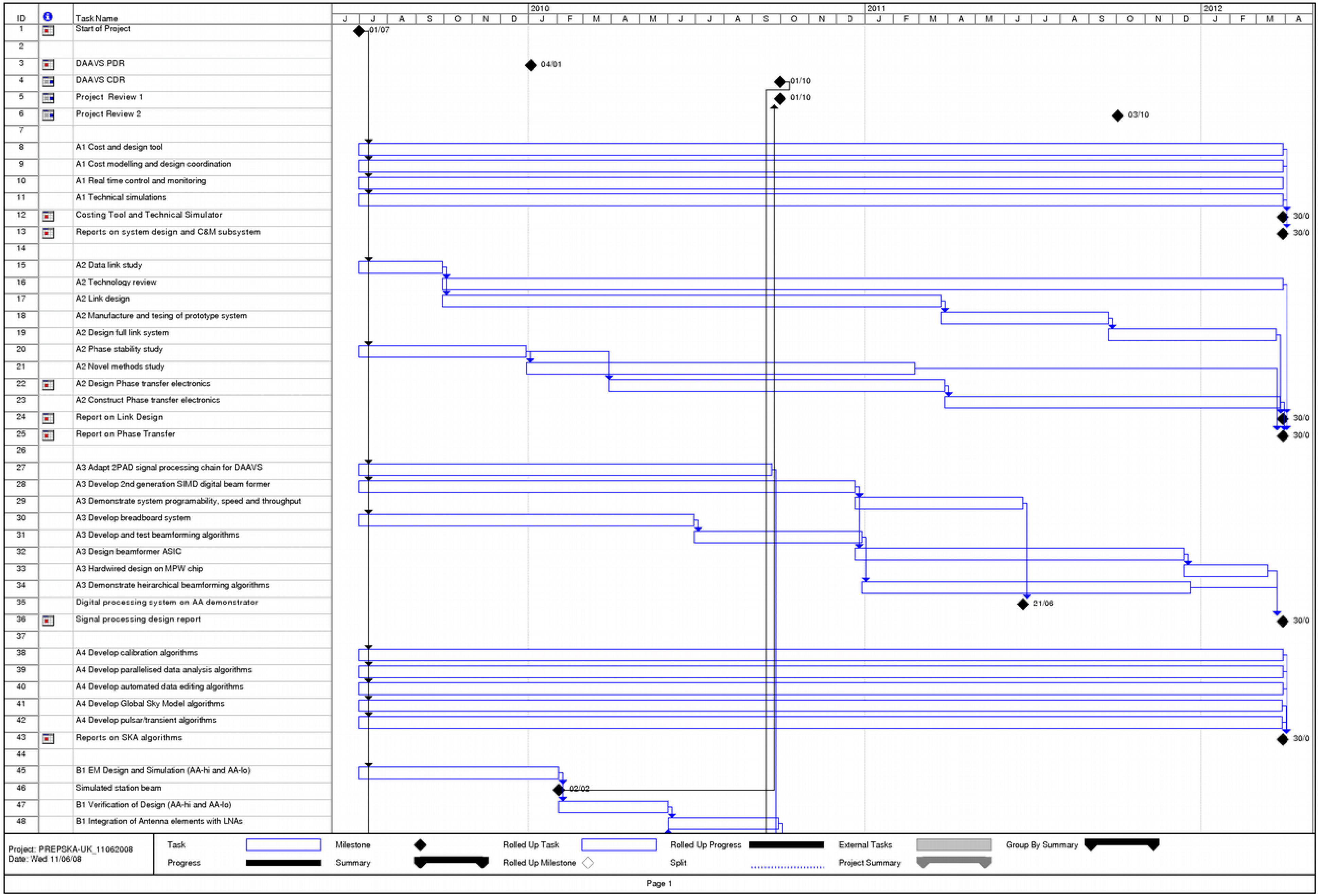
Infrastructure: The RFI elimination techniques are of importance in a wide variety of applications and the reduction of power consumption is of interest to all major systems

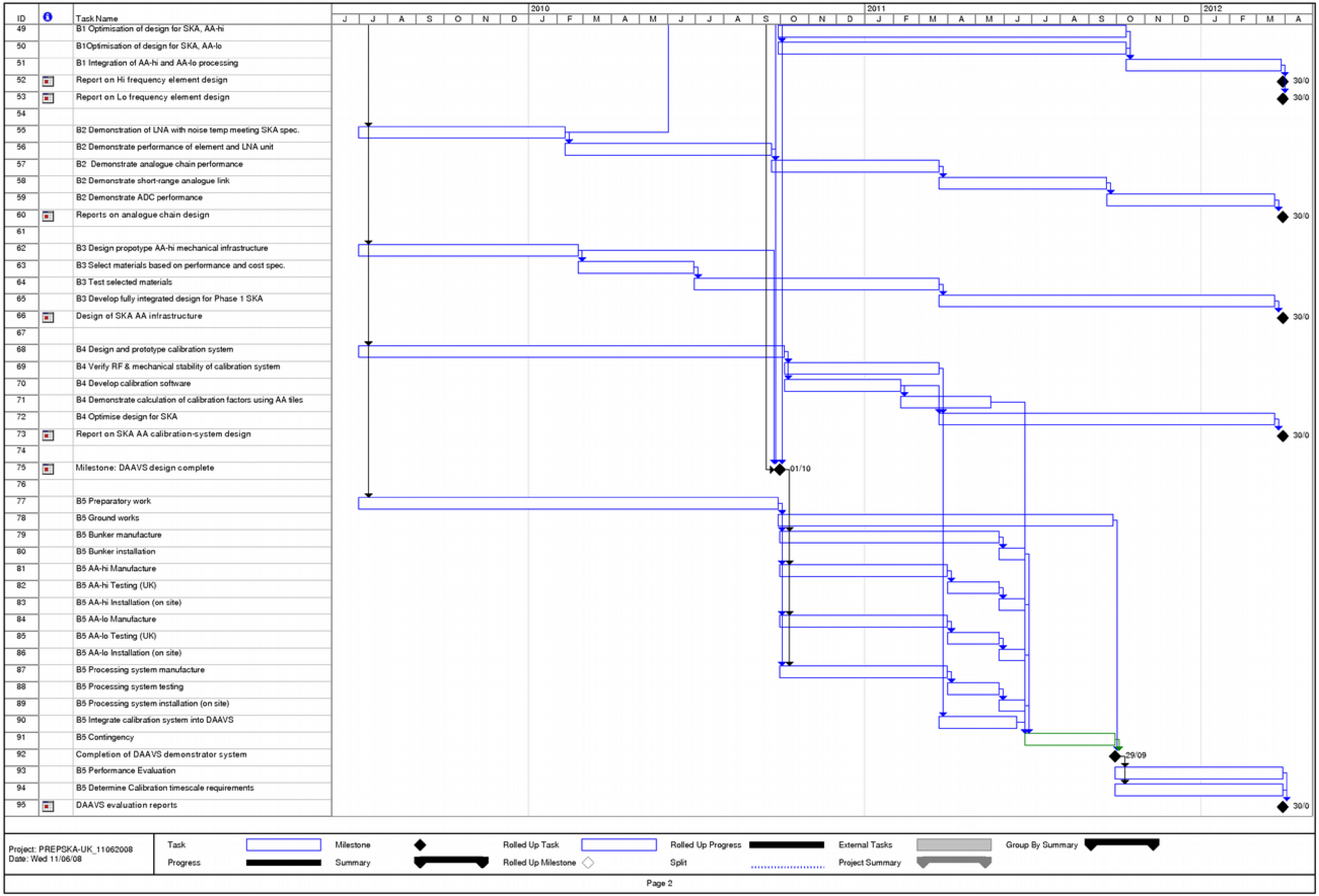
5.7 Science Exploitation plan

Science exploitation will result from this R&D programme during the operational phase of the SKA. Although completion of the full SKA is not anticipated until 2020, science exploitation will begin with the completion of Phase 1 in 2015. During phase 2 construction, science exploitation will continue and there will be continued increase in the capability of the instrument. This is a key aspect of the SKA development plan and exploits the fact that the instrument is an interferometer and therefore ideally suited to phased construction/exploitation. The key aim of the UK-PrepSKA programme is to maximise the science return to the UK community from the SKA by strongly influencing the specification and design of the instrument and undertaking particular work packages (importantly post-correlator processing) which ensures the UK will have the necessary knowledge and position in the project to maximise our investment. The Project Scientist will perform a key role in ensuring science input to the technical programme.

5.8 Project Deliverables

Deliverable	Description of output
A.1 D1	Costing tool
A.1 D2	Report on system design and cost / performance trade-offs for Aperture Arrays
A.1 D3	Requirements document for real-time control and monitoring SKA sub-system
A.1 D4	Technical simulator for AA
A.1 D5	Report on technical simulations
A.2 D1	Report on link design, including short and long links
A.2 D2	Report on scalable phase transfer
A.3 D1	Digital processing system on AA demonstrator
A.3 D2	Signal processing system design report
A.4 D1	Report and example implementation of Fourier-plane analysis techniques
A.4 D2	Report on solving calibration issues and example code implementations demonstrating scalability to SKA
A.4 D3	Report on solving transient detection issues and example code implementations demonstrating scalability to SKA
A.4 D4	Report on data flow, required data products and scalability to full SKA.
A.4 D5	Report on solving imaging issues and example code implementations demonstrating scalability to SKA
B.1 D1	Report including detailed design of mid frequency array element and array
B.1 D2	Report on low frequency array design and performance
B.2 D1	Actual system performance showing Tsys <50K at 800MHz. This tests the front end matching and integration.
B.2 D2	Demonstration of ADC with SKA Phase 1 performance: ≥2.5GS/s, 4 or 6 bit resolution, <100mW without data transmission.
B.2 D3	Demonstration of low power analogue link
B.2 D4	Reports on analogue chain design
B.3 D1	Design of SKA aperture array infrastructure
B.4 D1	Report on SKA AA Calibration-system design
B.5 D1	Evaluation report on AA performance for the SKA
B.5 D2	Test reports for the different array configurations of the DAAVS
B.5 D3	DAAVS demonstrator system


ID
Task Name
2010
2011
2012
J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A
1 Start of Project
01/07
2
3 DAAVS PDR
04/01
4 DAAVS CDR
01/10
5 Project Review 1
01/10
6 Project Review 2
03/10
7
8 A1 Cost and design tool
9 A1 Cost modelling and design coordination
10 A1 Real time control and monitoring
11 A1 Technical simulations
12 Costing Tool and Technical Simulator
30/0
13 Reports on system design and C&M subsystem
30/0
14
15 A2 Data link study
16 A2 Technology review
17 A2 Link design
18 A2 Manufacture and tesing of prototype system
19 A2 Design full link system
20 A2 Phase stability study
21 A2 Novel methods study
22 A2 Design Phase transfer electronics
23 A2 Construct Phase transfer electronics
24 Report on Link Design
30/0
25 Report on Phase Transfer
30/0
26
27 A3 Adapt 2PAD signal processing chain for DAAVS
28 A3 Develop 2nd generation SIMD digital beam former
29 A3 Demonstrate system programability, speed and throughput
30 A3 Develop breadboard system
31 A3 Develop and test beamforming algorithms
32 A3 Design beamformer ASIC
33 A3 Hardwired design on MPW chip
34 A3 Demonstrate heirarchical beamforming algorithms
35 Digital processing system on AA demonstrator
21/06
36 Signal processing design report
30/0
37
38 A4 Develop calibration algorithms
39 A4 Develop parallelised data analysis algorithms
40 A4 Develop automated data editing algorithms
41 A4 Develop Global Sky Model algorithms
42 A4 Develop pulsar/transient algorithms
43 Reports on SKA algorithms
30/0
44
45 B1 EM Design and Simulation (AA-hi and AA-lo)
46 Simulated station beam
02/02
47 B1 Verification of Design (AA-hi and AA-lo)
48 B1 Integration of Antenna elements with LNAs
Project: PREPSKA-UK_11062008
Date: Wed 11/06/08
Task
Progress
Milestone
Summary
Rolled Up Task
Rolled Up Milestone
Rolled Up Progress
Split
External Tasks
Project Summary
Group By Summary
Page 1



ID	Task Name
49	B1 Optimisation of design for SKA, AA-hi
50	B1Optimisation of design for SKA, AA-lo
51	B1 Integration of AA-hi and AA-lo processing
52	Report on Hi frequency element design
53	Report on Lo frequency element design
54	
55	B2 Demonstration of LNA with noise temp meeting SKA spec.
56	B2 Demonstrate performance of element and LNA unit
57	B2 Demonstrate analogue chain performance
58	B2 Demonstrate short-range analogue link
59	B2 Demonstrate ADC performance
60	Reports on analogue chain design
61	
62	B3 Design propotype AA-hi mechanical infrastructure
63	B3 Select materials based on performance and cost spec.
64	B3 Test selected materials
65	B3 Develop fully integrated design for Phase 1 SKA
66	Design of SKA AA infrastructure
67	
68	B4 Design and prototype calibration system
69	B4 Verify RF & mechanical stability of calibration system
70	B4 Develop calibration software
71	B4 Demonstrate calculation of calibration factors using AA tiles
72	B4 Optimise design for SKA
73	Report on SKA AA calibration-system design
74	
75	Milestone: DAAVS design complete
76	
77	B5 Preparatory work
78	B5 Ground works
79	B5 Bunker manufacture
80	B5 Bunker installation
81	B5 AA-hi Manufacture
82	B5 AA-hi Testing (UK)
83	B5 AA-hi Installation (on site)
84	B5 AA-lo Manufacture
85	B5 AA-lo Testing (UK)
86	B5 AA-lo Installation (on site)
87	B5 Processing system manufacture
88	B5 Processing system testing
89	B5 Processing system installation (on site)
90	B5 Integrate calibration system into DAAVS
91	B5 Contingency
92	Completion of DAAVS demonstrator system
93	B5 Performance Evaluation
94	B5 Determine Calibration timescale requirements
95	DAAVS evaluation reports

Project: PREPSKA-UK_11062008
Date: Wed 11/06/08

5.9 Risk register

A project risk register has been compiled and a summary is given below; full details are given in Appendix A. It is important to distinguish between risks to the PrepSKA project itself, i.e. that project deliverables will not be met, and risks to SKA in general, typically that the outcome of PrepSKA finds that it may not be possible to meet a particular performance goal within the expected cost. Since PrepSKA work packages are designed to produce designs to a particular performance goal, this distinction is not always clear, and so comments have been added to the risk register where appropriate.

This analysis has focussed on technical risks and has been used to derive a contribution to the project Working Allowance (WA). We propose adding an additional ~5% contingency to be held by STFC of £400k, taking the total WA plus contingency to £1130k

Risk-ID	**WP**	**WP Cost**	**Description**	**Score**				**Controls**	**Mitigation Actions**	**Owner**	**WA**	**Comments**
				L	**I**	**LI**	**Cat**					
R-A1-1	A1		Cost tool complexity	1	3	3	M	Regular project review	Additional resources inside/outside project	Alexander	80	
R-A1-2	A1		Insufficient computational power for full simulation	1	2	2	L	Regular project review	Extrapolate from prototype performance	Alexander	0	
R-A2-1	A2		Use of low cost devices for data links	1	4	4	M	Review external developments	N/A	Spencer	0	Risk for communication bandwidth of SKA
R-A2-2	A2		Performance of phase transfer system for high frequency	1	2	2	L	Tests with e-MERLIN at 22 GHz	N/A	Spencer	0	Risk for phase 3 SKA only
R-A3-1	A3		SIMD Chips	1	4	4	M	Parallel work on ASICs	Use FPGAs as prototypes for ASICs	Jones	150	

R-B1-1	B1		Mid frequency array element cost	1	2	2	L	Detailed cost modelling	N/A	Brown	0	Risk for sensitivity/survey speed of SKA
R-B1-2	B1		Mid frequency array element performance	1	2	2	L	Parallel development of LNA and antenna element	N/A	Brown	0	Risk for performance/cost of SKA
R-B2-1	B2		Receiver noise performance	1	3	3	M	Multiple routes for LNA fabrication	N/A	Missous	0	Risk for sensitivity/survey speed of SKA
R-B2-2	B2		Integrated gain chain chip re-spin	1	3	3	M	(built into schedule)	Additional round of chip fabrication	Jones	100	
R-B2-3	B2		Low cost/power ADC	1	4	4	M	Project Reviews	Use current generation devices	Jones	125	Risk for SKA
R-B3-1	B3		Radio interference from bunker	2	3	6	M	Testing and research in SKADS and PrepSKA	External consultancy	Spencer	50	
R-B3-2	B3		Site selection for DAAVS	2	3	6	M	Liaison with ESKAC, CDIT	UK Site	Garrington	150	
R-B4-1	B4		Calibration source stability	1	4	4	M	Project reviews	Additional effort for temp/power stabilization+ Position fix	Grainge	75	
										TOTAL WA	730	