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The Square Kilometre Array

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Proposal for UK national funding in conjunction with the EC FP6 Design Study

submitted by the

UK SKA Consortium

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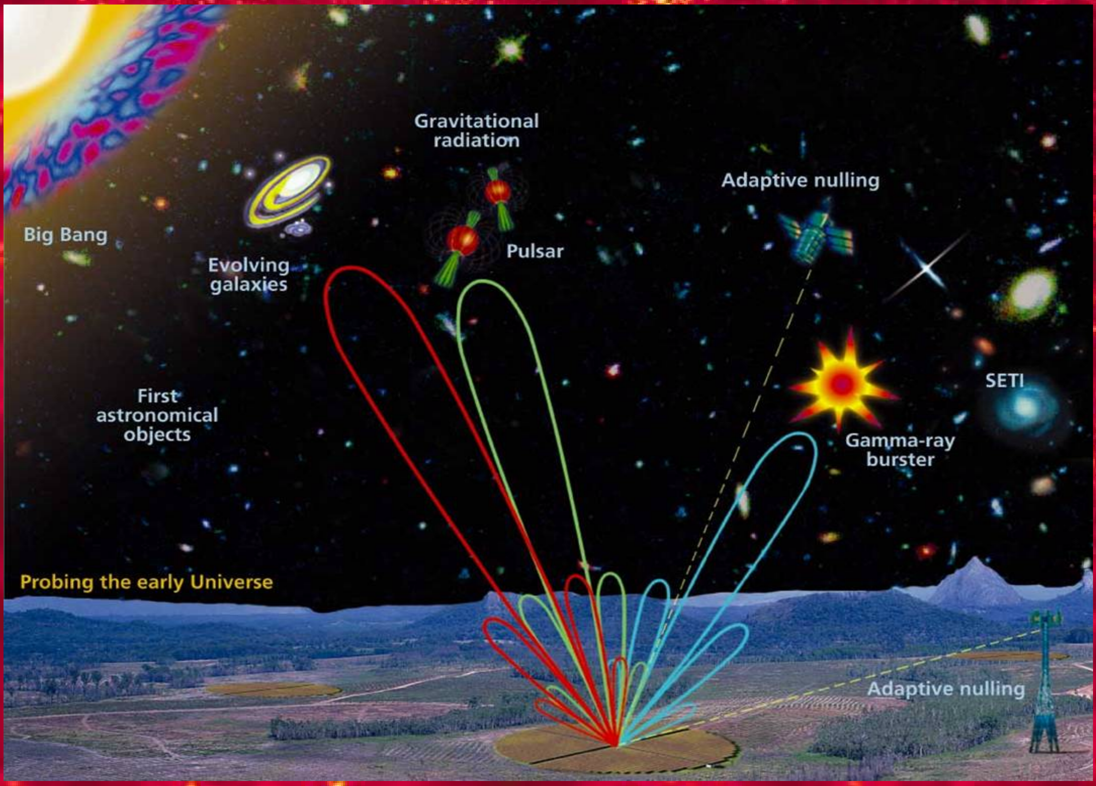

An international radio telescope for the 21st century

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Executive Summary

Radio astronomy plays a vital rôle in the study of the Universe since many physical phenomena are only - or most clearly - observed at radio wavelengths. Over the last 50 years, this has allowed radio astronomers to play a leading discovery rôle in astrophysics and cosmology – well-known examples are the after-glow of the Big Bang, neutron stars, gravitational radiation (via the binary pulsar), dark matter, black holes in galaxies, and gravitational lenses. Three of these discoveries have been awarded Nobel Prizes for Physics. Central to these discoveries have been innovations in technology pushing back the observational frontiers.

The international radio astronomy community has come together and agreed that the next major step in our observational capability at deci- and centimetric wavelengths should be the Square Kilometre Array (SKA). The Square Kilometre Array (SKA) therefore represents the future of *world* radio astronomy and is being planned on a fully global basis with Europe playing a leading role; completion is envisaged for ~2020. The SKA will be a distributed interferometer array of ~100 collecting "stations", each of area ~10,000 m^2, and spread out over 100s of km. The frequency coverage will extend from ~0.1 to ~20 GHz, realised probably in two frequency bands involving different collector technologies: low, ~0.1 GHz to ~1.4 GHz (the main concern of the European Design Study "SKADS") and high, ~1.4 GHz to ~20 GHz (being studied elsewhere, in particular the USA). The cost of the globally-funded project is likely to be of order £10^9 with a contribution from Europe of perhaps 40% with a comparable amount from the USA and the remainder from the rest of the world. Further information can be found on the international SKA web site http://www.skatelescope.org

When completed in the second half of the next decade, the SKA will be able map the sky with a sensitivity ~100 times greater than is currently possible and will be able to scan the sky >10^5 times faster than now. The SKA's power will lead to a transformation of our knowledge of the overall structure of the universe, of many of its fundamental constituents and of its evolution. The SKA may find the key to unlock the secret of Dark Energy, may test one of the bed-rock theories of physics, General Relativity, to destruction and will explore fundamental conditions for the emergence of galaxies, planets and life. It may detect signals from other intelligent civilizations. It is almost certain to produce many new and unexpected discoveries allowing radio astronomers in the 21st century to add to the long list of fundamental discoveries made by their predecessors in the last century.

A radio telescope array of this size is, however, not affordable (even at the level of £10^9) if one simply scales up present designs. Over the past 5 years this fact has driven an exhaustive consideration of new ideas for collector elements and for the exploitation of industrial developments in the areas of signal processing and data transport. An intense R&D phase is now required to determine the most cost-effective means by which to construct the telescope.

The European rôle: Within Europe, and with the pioneering work carried out in the Netherlands, we have developed a radically new concept for the SKA, in which the entire collector is composed of large areas of low-cost, low-noise phased-arrays with the beam formation carried out electronically. In this vision the SKA will essentially be a giant IT facility completely unlike any other astronomical instrument. This concept offers major advantages in terms of the efficiency of data-collection, in particular it offers the potential of very large fields-of-view and access for multiple simultaneous users; such an "all-electronic" telescope will therefore have unprecedented capability and flexibility of operation (see illustration on front cover). The upgrade potential will be based on the ability to process more data in real-time as computing power increases. In the SKA Design Study (SKADS) eight EU nations (led by the Netherlands and the UK) are cooperating to carry out a detailed investigation of the cost-effectiveness of this new concept and to develop necessary "breakthrough" technologies; its exciting potential has also attracted research institutes from four non-EU countries to join in. The European SKADS team has agreed on those aspects of the programme where the UK has the specific knowledge and skills to take on leadership roles.

The UK rôle: The development of the SKA is an enormously complex task and it is beyond the capabilities of an individual university group to make a major impact. In an unprecedented mobilisation the UK radio astronomy community has, therefore come together within a national SKA Consortium (consisting of the

Universities of Manchester, Oxford, Cambridge, Cardiff, Leeds and Glasgow and with a proposed link with UK industry). By working together in this way the UK is able to lead the SKADS programme in respect of:

- Computer simulations involving a marriage of a) quantitative astronomical calculations of a range of potential "skies" appropriate for the Key Science Projects and b) technical calculations to develop the SKA specification required for the delivery of the key science.
- Studies of the physical infrastructure and broad-band data transmission requirements of the SKA and of precise time and frequency distribution methods.
- Studies of the ways in which the data from the central processor can be most effectively handled and put to scientific use by the astronomer and the astronomical community. This will include studies of distributed, GRID-enabled pipelined reduction; data products, archiving and scientific exploitation; observing modes and the user view of the SKA
- R&D on "3rd generation" all-digital dual polarization phased array systems for radio astronomy and the construction and testing of a prototype array of a few square metres in area. This will complement the Dutch-led construction of a "2nd generation" single polarisation array in the Netherlands of several hundred square metres area (the EMBRACE demonstrator).

In respect of the 3rd generation array programme the UK is also forging strong links with industrial partners (BAE Advanced Technology Centre and Qinetiq) with specific knowledge and skills not available in the university system.

The aim is for the UK to take a leadership role in the SKADS R&D phase, and by forging links with UK industry, to ensure that UK PLC will be in the best possible position to play a leading roles in the design and construction of both the international science pathfinder (post 2010) and the full SKA (completion 2020).

Finance**:** The EC SKADS proposal was costed ~€38M. This will be made up as follows:

- ~€10M from the EC Framework 6 programme (final level to be confirmed)
- ~€28M from the partner countries.

We are presently assuming a UK share of ~€3.0M i.e. ~£2M of EC Framework 6 funds.

The UK SKA Consortium's programme has been modified since the SKADS proposal was submitted (see "The Context of this Proposal" next) and as a result the total UK programme (EC+PPARC) is costed at £8563k (£8848k including Working Allowances). Assuming a £2M contribution from EC FP6 the request to PPARC is therefore for £6563k (£6848k with WA) in the period starting 1/7/2005 and ending at 31/12/2008.

The context of this proposal

The EC Framework 6 Design Study Proposal "SKADS"

This bid for UK national funding for SKA R&D must be seen in the wider context of the international SKA activity and specifically of the R&D activity within Europe which is focused on the EC Framework 6 Design Study proposal "SKADS". The SKADS proposal was put together under the leadership of A. van Ardenne (ASTRON) and P. Wilkinson (Manchester). ***A copy of the European SKADS proposal has been sent with this UK proposal. We have therefore only summarised the salient points of the European proposal in this UK proposal for matching funds.***

SKADS has just (10 September 2004) been approved for funding within the EC. We currently anticipate that the EC will fund the Design Study at the level of about €10M (out of a total SKADS budget of ~€38M) but this amount has not yet been confirmed. The remaining funds need to raised from national contributions across Europe. Based on our ability to win appropriate UK funding, it is expected that the UK share of the EC SKADS funding will be in the range 30% - 33% i.e. €3.0M-€3.3M (£2M-£2.2M).

The UK, along with the other European partners and coordinated by ASTRON, will enter contract negotiations with the EC in October 2004. During this period the EC requires that a more detailed European SKADS project plan must be developed. This will, to an extent, inevitably feed back into the present UK plans which have themselves been significantly revised, compared with the SKADS proposal to the EC.

For the UK plan presented here, the most significant area where further refinement is needed involves the linkages between the main SKADS Design Studies (DS2; DS3; DS4; DS5 – see explanation in text) and the coordination of the revised UK programme with the European programme. These linkages will be clarified and finalised during the Europe-wide SKADS contract negotiation phase in October 2004. At this stage, therefore, the UK WPs within the main headings (DS2, DS3 etc) have largely been planned in isolation from each other, in the knowledge that the final stage of European-wide coordination is to come. ***Some (second-order) amendments will be required before a final UK SKADS proposal, fully coordinated with the European and international SKADS activities, can be completed.***

Finally there is also the potential involvement of South Africa to take into account. Currently we are actively exploring a scheme in which South Africa would send two engineers to work within the UK technology R&D programme. This contribution of ~10% of the technical manpower would gain South African access to the 3rd generation phased array technology. This technology could become a vital part of a proposed South African SKA Pathfinder instrument, for which significant funding is already in place (see section 9 and Annex I).

The PPARC SoI of September 2003 and changes to the UK plans in the past 12 months

The need for UK support of SKA R&D was first explained to PPARC in a Statement of Interest submitted by the UK SKA Consortium in September 2003 and positively reviewed by the Science Committee. In this SoI the funding request was estimated as ~£1M over three years for a total of just under £3M. However in the year since the SoI was submitted there has been much progress in UK, European and international SKA planning and as a result the funding request has increased. The principal reasons for this are as follows:

- The main stage of the European SKADS proposal exercise was undertaken after the SoI was submitted; the SKADS proposal was submitted to the EC on 4th March 2004. As is explained in the text, during the SKADS planning it was realised that length of the programme needed to be extended by a further 6 months and that a "3rd generation" phased array technology programme is needed to complement the "2nd generation" EMBRACE phased array demonstrator which at the heart of the EC SKADS proposal. The EMBRACE demonstrator was the main focus of our thinking on technical R&D at the time of the SoI.

- Following the PPARC-organised SKA meeting for industry on 18 Feb 2004, the synergies between the universities and some UK companies became apparent. In this proposal we have therefore included two companies (BAE Advanced Technology Centre and QinetiQ) as partners, although it is clear that other companies could also make valuable contributions. The direct costs of industry involvement exceed that in universities but the skills available within BAE ATC and QinetiQ are of immediate relevance and mitigate the risk in the technology R&D programme very significantly.

- New university instrumentation groupings are taking place, catalysed by SKADS.
  - A strong link has been forged within the new University of Manchester between the Jodrell Bank Observatory and the former UMIST Electrical and Electronic Engineering Department.
  - The University of Oxford is forming a new radio astronomy instrumentation group linked with RAL.

  Together with the strong Cambridge group a powerful "technical triangle" of universities is therefore being formed to drive the SKA R&D programme forward.

- During the discussions between the UK SKA Consortium and UK industry, after the SKADS proposal was submitted, it became clear that to bring focus to the programme a definite, albeit small-scale, "3rd generation" phased array demonstrator and associated test programme is needed, rather than just a set of independent design efforts as proposed in SKADS. This involves a range of additional hardware and associated costs. The international community made it clear in the SKA meeting in Penticton, Canada (July 2004) that both the EMBRACE + the UK tile demonstrator are required to establish the viability of the European phased array concept for the SKA.

- A further development programme is proposed here which is an addition to the SKADS proposal. This involves a study of the high precision frequency and clock distribution required for interferometry which will make use of the eMERLIN fibre network (modest capital-funding by PPARC). The UK radio astronomy groups can bring unique skills to bear in this area and the cost of this programme is modest.

- UK support of the International SKA Project Office is requested at €35k per annum for the duration of this Design Study– i.e. ~£23.5k per annum.

- To compensate for these additions the UK proposes to withdraw from some aspects of the SKADS plan
  - Cambridge no longer to be involved in radio frequency interference mitigation work.
  - Cambridge and Manchester no longer to be build EMBRACE copies in UK

The Committee should note that the size of the proposed UK technological R&D programme (~60 FTE) is smaller than already expended by The Netherlands (ASTRON) to take their phased array programme to its current state (80-100 FTE), which is a foundation of the SKADS technology R&D programme. We expect to minimise the UK start-up costs by close cooperation with our Dutch colleagues, utilisation of their experience and by the immediate involvement of UK industry.

In addition to these specific points we note that the international SKA community has now proposed that an international "science pathfinder" array (~5% of the SKA in area) be the next step, with funding to be sought immediately following the "technology selection" phase scheduled for 2008/9. The desire to build a first-stage science instrument as part of the overall SKA development, has placed more time pressure on technology development. If the phased array technology is to play a major role in the full SKA by the time it is completed 2020, it will need to form at least part of the science pathfinder. Finally we stress an important strategic issue. The last 12 months have not only seen an unprecedented mobilisation of the UK radio astronomy community behind the SKA concept but also a strong linkage forged with a leading Electrical Engineering Department (Manchester) and UK industry (BAE ATC and QinetiQ). This has led the UK SKA Consortium to make a strong bid for leadership within the overall European SKA programme. Although in political and scientific terms the UK is already playing, and will continue to play, a leading role in the European and international SKA arenas, it has so far made little or no specific technological contribution to the development of the SKA. As a result we run the risk of becoming bit-players in the design of the instrument and then in its construction. By taking a leadership role in the present technical R&D phase, the first major phase which is being coordinated internationally, and by continuing to forge links with UK industry, we will ensure that UK PLC will be in the best possible position to play a leading roles in the design and construction of both the science pathfinder and the full SKA.

1 Scientific Justification

1.1: Scientific context

The past decade has seen a revolution in our knowledge of the Universe and its contents.

We have entered an era of `precision cosmology', where the fundamental parameters ($H_0$,$\Omega_M$ etc) describing the emerging `standard model' in cosmology are known to about 10% accuracy. This has principally relied on astrophysics experiments at radio (CMB) and optical (high-redshift supernova and huge galaxy redshift surveys) wavelengths. To the surprise of most astrophysicists, this standard model includes dark energy as the dominant energy density in the present-day Universe, with dark matter the second largest contributor, and normal, baryonic, matter making up only 5% of the overall energy budget. A new discipline of particle-astrophysics has emerged.

Astrophysics experiments have begun to probe into the time of `first light' in the Universe, the `epoch of reionization', when the UV emission from the first stars and accreting supermassive black holes reionizes the neutral intergalactic medium. Gamma-ray bursts (GRBs) have been shown to be the largest explosions in the Universe, tracing the death of very massive stars to the earliest epochs. Supermassive black holes have gone from being a hypothetical bi-product of general relativity (GR), to being a fundamental aspect of all spheroidal galaxies and galaxy formation. Galactic `micro-quasars', or accreting black holes of a few solar masses, have been shown to have all the properties of their supermassive cousins, only on eight-orders-of magnitude smaller scales. It appears that one must understand extreme-environment astrophysics to understand galaxy formation and evolution and, of course, vice versa.

The recent discovery and analysis of the first known double pulsar (Lyne et al. 2004) illustrates the ways in which telescopes continue to be used for fundamental physics experiments such as tests of strong-field General Relativity.

Observations of pulsars have also provided firm evidence of two terrestrial mass exoplanets - planets around stars other than the Sun. More massive, Jupiter mass, exoplanets are now also known to be a common phenomenon associated with a significant fraction of main-sequence stars. A new constituent of our own Solar System has also been confirmed - the Kuiper belt objects - and these may provide the key to understanding the formation of the solar nebula. A new discipline of astro-biology has emerged.

To continue to address what are generally recognised (e.g. the PPARC Science Committee's Strategy Document, or the influential `From Quarks to the Cosmos' report from the USA) as the fundamental questions in astrophysics, particle-astrophysics and solar system science, it seems certain that the next step forward has to involve the world community collaborating on one or more `big science' ground-based telescopes akin to the giant accelerators which now dominate particle physics.

We argue here that the Square Kilometre Array (SKA) is poised to become the first of these `big science' astrophysics facilities. We argue also that the UK is supremely well placed to take a leadership role in the project. First, however, we demonstrate that the SKA is a revolutionary concept which, with UK and EC leadership, is guaranteed to yield transformational science.

1.2: Why the SKA is a revolutionary concept which will produce transformational science

The current internationally agreed specifications for the SKA are summarised in Table 1. The 100-fold in increase in raw sensitivity A_{eff} /T_{sys} with the SKA will be, in itself, transformational because for radio telescopes the sensitivity is proportional to A_{eff} and not $\sqrt{A_{eff}}$ as is the case for photon-noise-limited optical telescopes. Moving from telescopes like EVLA and e-MERLIN to the SKA represents a similar leap in raw sensitivity as moving from current 10-m optical telescopes to 1000-m diameter instruments! This means that an SKA Survey will be dominated by normal galaxies rather than the active radio galaxies which dominate current surveys. The SKA can detect normal galaxies in radio continuum to redshifts >10 in neutral gas (HI) to redshifts ~3.

Frequency Range	0.1 – 25 GHz Goal: 0.06- 35 GHz
Instantaneous Bandwidth	25% of central frequency
Sensitivity A_{eff} / T_{sys} (units of m^2 / K)	20000 in range 0.5 – 5 GHz
	5000 at 200 MHz Goal: 2500 at 60 MHz
Configuration	20% of A_{eff} within 1 km diameter
	50% of A_{eff} within 5 km diameter
	75% of A_{eff} within 150 km diameter
Resolution	< 0.02 / f (GHz) arcsec
FoV	1 deg^2 at 1.4 GHz Goal: 200 deg^2 at 0.7 GHz
Number of separated FoVs	1 Goal: 4 (present)
Instrumental Polarization	-40 dB

Table1: A summary of the basic SKA specifications

The European phased-array concept adds another transformational aspect to the SKA project. As illustrated in Fig. 1.1, phased arrays have the potential to (a) look in many directions at once without loss of sensitivity (`multi-fielding'); and (b) to have much larger instantaneous FoV (Field-of-View) than dish-based designs. As will be highlighted below, large FoV translates into the possibility of making `all hemisphere' surveys with the

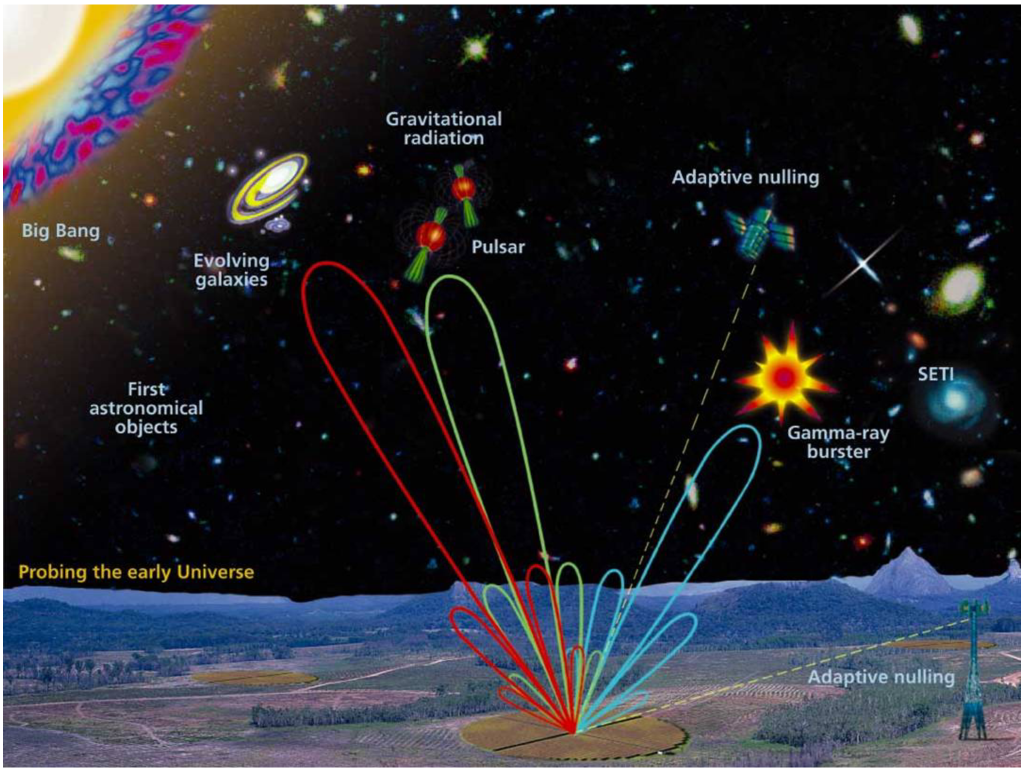

Fig 1 1: A schematic visualisation of the advantages of a multi-field-of-view aperture array system for radio astronomy. A single SKA "station" is shown in the foreground (with two more in the background) with many fields-of-view produced electronically and pointing in different directions. Each station has an area of ~10^4 m^2 and is made up of a hierarchy of fundamental antenna elements grouped together into "tiles" of a few m^2 in area; the size of these tiles (in wavelengths) sets the angular field-of-view (many degrees across) within which a wide range of other beam-forming options exist. The design of such a hierarchical station is at the heart of SKADS. As explained in the text in section 2.1 such a flexible system offers the prospect of supporting many users to carry out separate astronomical programmes coupled with the ability to null out interfering signals. At the sites being investigated for the SKA there will be no TV transmitters (bottom right) but the unwanted emissions from satellites will need to be dealt with.

SKA. This means that, e.g. for cosmological studies, the SKA will become, like the most successful CMB projects, limited by cosmic variance rather than limited FoV.

The multi-fielding capability of the SKA is an even more exciting prospect for new discoveries.
An SKA with independently-steerable fields-of-view and independently-steerable beams, provides users with a highly flexible and responsive instrument. This approach generically incorporates:

- a science survey advantage: required for a range of key science programmes requiring large amounts of telescope time and which would be impossible with conventional systems;
- a "community" advantage: many groups, including students and schools, can access the whole aperture simultaneously, allowing the operation of the SKA to resemble that of particle accelerators or synchrotron light sources;
- a multiplex advantage: simply by increasing the volume of data which can be collected;
- an adaptive beam forming advantage: "reception nulls" are steered to cancel out sources of radio frequency interference.

The different fields-of-view could, for example, be used for:

- imaging a deep field: integrating for long periods for the ultimate in sensitivity;
- studies of time variable phenomena: seeking transient radio sources and responding instantly to transient discovered in other wavebands;
- pulsar timing: finding and then picking out the unusual ones from 20,000+ pulsars for special attention;
- experimentation: not scheduled by standard peer-review.

The history of radio astronomy, stretching back over 70 years, tells us both that the largest radio telescopes of their day (of a wide range of types) have dominated the list of discoveries, and that what a telescope is "known for" is almost never what its proponents and designers built it for. The corollary is that while the *SKA will address many current outstanding problems in astronomy and astrophysics, in the period 2025 to 2050 (when the SKA will be in its most productive years), the excitement will come from the new questions that will be raised by the new types of observations it alone will permit.* For this reason, the SKADS proposal envisions a design that is highly-flexible, easy-to-use and has an operating philosophy which positively encourages the astronomers of tomorrow to look at the sky, and to examine the data in new and creative ways.

The `all digital' concept explored by this proposal might ultimately lead to an SKA in which the raw voltages at each element are saved at all times so that, provided the data can be stored, the database can be used to synthesise beams anywhere in the FoV of the elements at any time. A half-way house to this dream would envisage use of a digital data buffer which would save voltages such that, for example, a triggering event (e.g. a GRB) could be used to make an SKA observation in the direction of this event before it happened!

Finally, we note that radio astronomers have a long history of productive international collaboration built around a network of radio dishes forming a global interferometer. Recently, interferometric fringes have been obtained by combining data-streams from telescopes separated by seas and oceans, but connected via the internet. An `all digital' SKA could feed its data directly to a virtual Observatory utilising the e-science techniques of the near future,

1.3: The SKA Key Science Projects [KSPs]

A 600-page book describing the SKA science case has just been completed (Carilli & Rawlings 2004)[1] and demonstrates that the SKA will lead to major advances in almost all topics covered by astrophysics, particle-

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[1] Available at http://www.aoc.nrao.edu/~ccarilli/CHAPS.shtml

astrophysics and Solar System science. Here, we focus on five topics[2] which have been internationally agreed as our best guess as to the Key Science Projects [KSPs] for the SKA.

1.3.1: KSP I: The Cradle of Life

The emerging field of astro-biology – the search for life elsewhere in the Universe - is starting to address one of the oldest questions in science – are we alone? Evidence of the existence of exoplanets is now compelling, with more than 100 systems known. Although the closest analogy to our own Solar System is currently a 4-Jupiter-mass planet in a roughly circular 5.5-AU orbit around the G star 55 Cancri, ideas are being developed which should culminate in the discovery of Earth-like planets. Moreover, organic molecules – the building blocks of life – have been discovered both in interstellar space and in primitive objects such as meteorites.

The SKA, by virtue of its sheer sensitivity and resolution, is guaranteed to play a pivotal role in astro-biology. With the adoption of phased-array technologies, the extra multiplex benefit of multi-fielding (pointing at many target stars simultaneously without loss of sensitivity) is obvious, as is the desire to maximise FoV for blind searches.

Ignoring for now (see Sec 3.1.2) the possibility of direct detection of exoplanets, there are three main lines of SKA investigation which will provide unique astro-biological information.

- `Movies of planetary formation’. Radio waves can penetrate the dust in proto-planetary disks and image them at unprecedented sub-AU scales within the so-called `habitable zone’. This is not merely a matter of angular resolution: in the optical, the high contrast of scattered light from the disk with the stellar photosphere is hugely problematic; in the millimetre regime, the dust emission is optically thick and impenetrable. In these inner regions the dynamic timescale is of order 1 year so the SKA will be able to monitor the evolution of nearby proto-planetary disks as terrestrial planets form. Figure 1.2 shows the results of a numerical simulation, illustrating one of the key results expected from such `movies of planetary formation’. This application of the SKA requires high (~20 GHz) frequency to achieve the ~milliarcsec resolution required. At these frequencies there is no contrast problem as circumstellar emission dominates over photospheric emission by orders of magnitude. The SKA will be sensitive to the evolution of dust grains up to cm-sized `pebbles’ which is the critical first step in assembling giant planets like Earth.

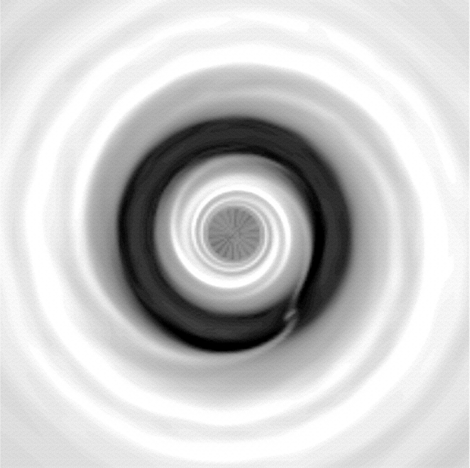

Fig. 1.2: A numerical simulation (Bryden et al. 1999) of a Jupiter mass planet within a proto-planetary disk. The dark region is essentially devoid of material apart from in the region of the planet where there is a small accretion stream. The wide gap, opened up by tidal interaction provide a strong marker of the presence of a planet, and the (potentially time-varying) gap structure constrains its properties.

- How did bio-molecules reach proto-planets? Stars and their planets form in molecular clouds, the chemistry of which is overwhelmingly organic. It is not known, however, how molecules, formed in

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[2] The Dutch national instrument LOFAR (Low Frequency Array) can be considered as a pathfinder instrument for one of the KSPs, ‘Probing the Dark Ages’

molecular clouds, are delivered to a terrestrial planet and form the bio-molecules responsible for the origin of life. Dust grains appear to provide the primary transportation mechanism for organic molecules from molecular cloud to proto-stellar nebula, but is certainly possible that shocks destroy the complex chemistry built up within the molecular cloud. The SKA may play a critical role in resolving such issues. The large moments of inertia of complex bio-molecules place their lowest-J rotational transitions in the radio waveband, where they will not be confused by the multiple transitions of simpler molecules.

- Can we detect Extraterrestrial Intelligence (ETI)? While not a stated part of PPARC strategy, there is little doubt that the detection of ETI transmissions would have far-reaching implications. We note simply that the SKA will, particularly with multi-fielding capability, have sufficient sensitivity to detect `leakage radiation' from nearby planets. Emission comparable in power to terrestrial TV transmitters could be detected in the nearest stars and the emissions comparable to the most powerful Earth-based radars could be detected in ~10^9 potentially observable solar systems.

1.3.2: KSP II: Strong-Field Tests of Gravity Using Pulsars and Black Holes

When probing the limits of our understanding of Einstein's theory of general relativity (GR), we are interested in extreme conditions that are not encountered on Earth or, indeed, in the Solar System. Despite the success of GR, the fundamental question remains as to whether Einstein had the last word in our understanding of gravity. Determining whether the, as yet accurate, theory of GR describes the gravitational interaction of the macroscopic world correctly, would either justify the current approaches to use GR as the basis of quantum gravity, or would imply that other alternative lines of investigations have to be followed.

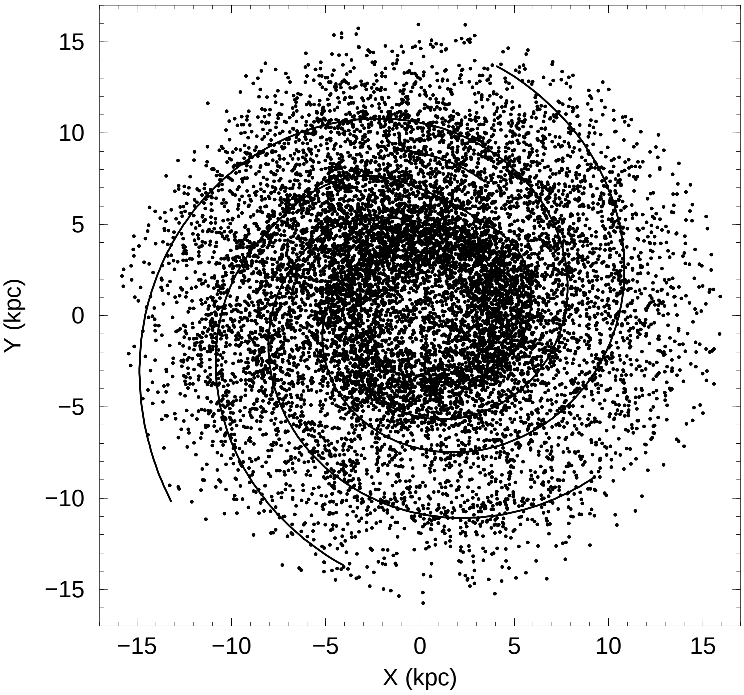

Fig 1.3: Illustration (Cordes et al. 2004) of the ~20,000 pulsars expected to be beamed towards us in the Milky Way in an SKA survey: the Galactic Centre is at the origin while the Sun is at (0.0,8.5) kpc.

The sensitivity of the SKA to study pulsars enables a number of fundamental tests of theories of GR in the strong-field limit. A Galactic Census of pulsars (Fig. 1.3) will discover essentially all of the active pulsars in the Milky Way beamed toward us. In this Census there will almost certainly be both pulsar-black hole binaries and pulsars orbiting the supermassive black hole in the Galactic Centre. These systems are accurate clocks orbiting in a strong gravitational field and are hence unique in their capability to probe the ultra-strong field limit of relativistic gravity. These measurements can be used to test fundamental aspects of GR such as the No-Hair theorem and the Cosmic Censorship Conjecture.

The No-Hair theorem states that the external gravitational field of an astrophysical (uncharged) black hole is fully determined by its mass and spin. Since the precise pulsar timing possible with the SKA can yield measurements of not only the mass and spin of the black hole but also the gravitational quadrapole moment of its external gravitational field, this theorem can, for the first time, be put to direct observational test.

The Cosmic Censorship Conjecture proposes that space-time singularities are always hidden within the event horizons of black hole, so that they cannot be seen by a distant observer, a corollary being that the gravitational collapse of a body always results in a black hole rather than a naked singularity. The measurement of a black hole with a dimensionless spin parameter exceeding unity would signal either the discovery of a naked singularity or a break down of GR. Again, this fundamental test is possible once the SKA discovers pulsar – black hole systems. The parameter space that awaits exploration with the SKA is illustrated in Fig. 1.4.

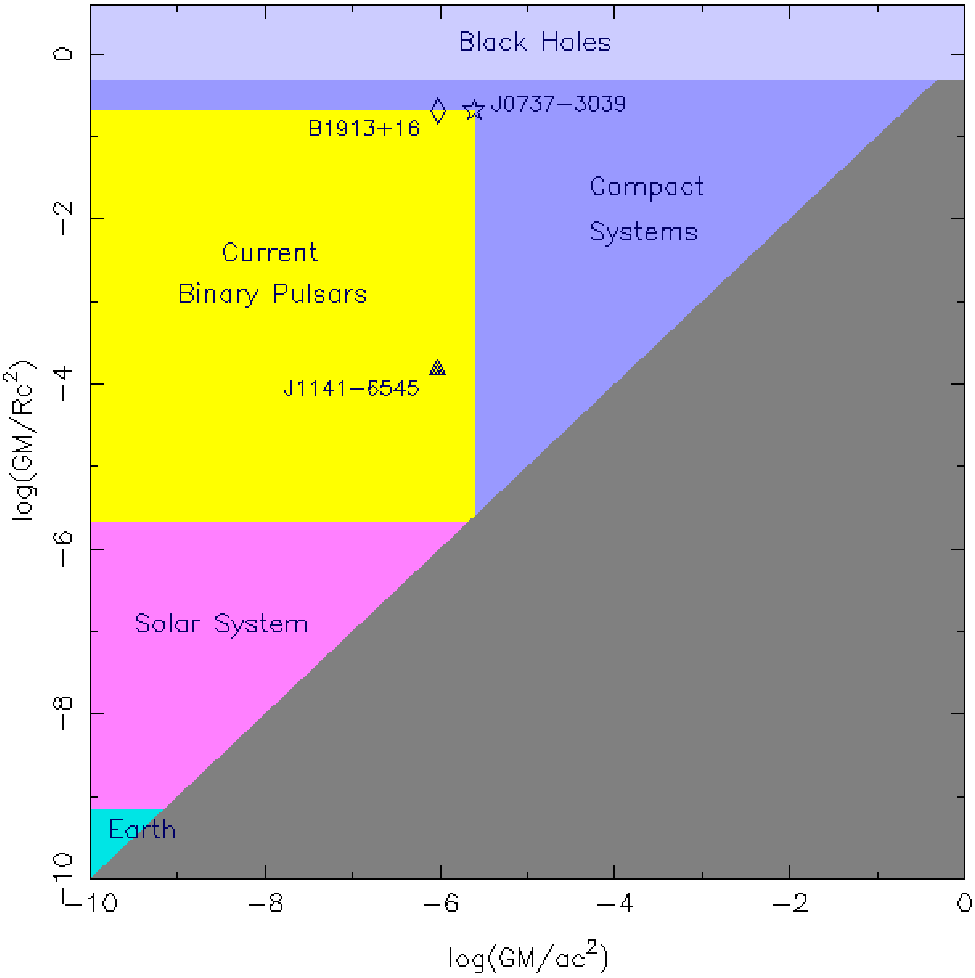

Figure 1.4: Parameter space of gravitational physics to be probed with pulsars and black holes. Some theories of gravity predict effects that depend on the compactness of the gravitating body which is shown here (y-axis) as a function of orbital size and hence probed gravitational potential (x-axis). The lower right half of the diagram is excluded as it implies an orbit smaller than the size of the body. The capabilities of the SKA are vital for exploring the upper right hand part of the diagram involving compact pulsar+black hole binary systems.

The large number (~1000) of millisecond pulsars to be discovered with the SKA will also provide a dense array of precision clocks on the sky. These clocks will act as the multiple arms of a huge gravitational wave detector, which can be used to detect and measure the stochastic cosmological gravitational wave background that is expected from a number of sources. The multi-fielding capability of a phased-array concept is obviously key for doing this efficiently. The frequency range covered by this `pulsar timing array'

(~nHz) complements the much higher frequencies accessible to Advanced LIGO (~100 Hz) and LISA (~mHz), and the extremely low frequencies probed by studies of the CMB and its `B-mode' polarization (~10^{-18} Hz), e.g. with CLOVER.

1.3.3: KSP III: The Origin and Evolution of Cosmic Magnetism

Magnetism is one of the four fundamental forces but its origin in stars, galaxies, clusters of galaxies and the intergalactic medium is an open problem in astrophysics. When and how were the first fields generated? Are present-day magnetic fields a result of dynamo action, or do they represent persistent primordial magnetism?

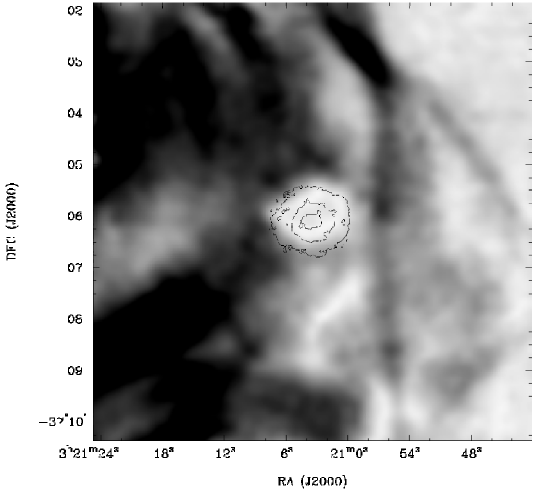

Figure 1.5: Example (1.4 GHz VLA) of how linearly polarized radio intensity from a background radio source (in this case, Fornax A) is modified (in this case, depolarized by Faraday rotation) by its passage through foreground magnetic fields [in this case within the spiral galaxy NGC 1310 (optical countours shown)].

What role do magnetic fields play in turbulence, cosmic ray acceleration and galaxy formation? Fortunately, radio astronomy (e.g. Fig. 1.5) provides techniques which can answer these questions, although the sensitivity of current instruments has been too low to push studies beyond the local Universe.

The SKA, particularly with the wide FoV provided by phased-array technology, can make `all hemisphere' surveys of (Faraday) rotation measures towards >10^7 background sources, providing a dense grid for probing magnetism in the Milky Way, galaxies, clusters of galaxies and, at high redshift, proto-galaxies. By mapping out the evolution of magnetised structures from redshifts z~5 to the present, it will be possible to distinguish between different origins for seed magnetic fields in galaxies, and assess the influence of fields on structure formation (Fig. 1.6).

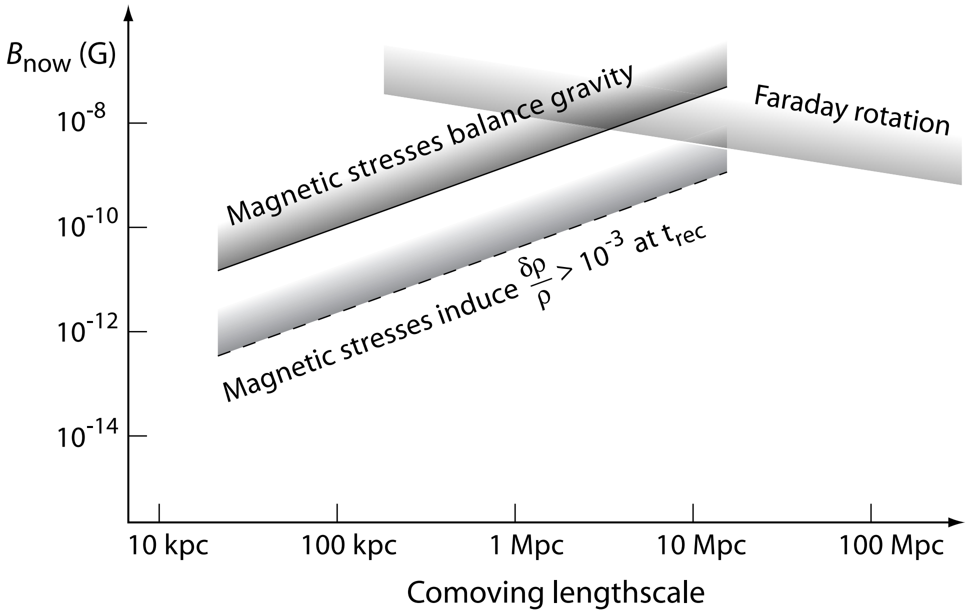

Fig 1.6: Theoretical and (current) observational limits on the magnetic flux density on various length scales at the time of recombination (Rees 2000) Magnetic field, present during the recombination era, could plausibly affect structure formation.

1.3.4: KSP IV: Galaxy Evolution and Cosmology

The present-day Universe is seemingly dominated by dark energy and dark matter, but mapping the normal (baryonic) content remains vital for both astrophysics -- understanding how galaxies form - and particle-astrophysics - inferring properties of the dark components. Redshift surveys of ~10^{5-6} galaxies out to redshift z~0.2 by both UK (AAT 2dFGRS) and USA (Sloan SDSS) groups have proved a necessary complement to CMB studies for current `precision' (i.e. 10%) measurement of the fundamental cosmological experiments. At the same time, radio telescopes have had only just enough sensitivity to detect a handful of galaxies in neutral gas (HI) at z~0.2.

The original motivation for the SKA (Wilkinson 1991) was to push studies of HI to z~2, and as HI is the most abundant element in the Universe, this obviously remains a `unique selling point'. This information is needed to understand how stars formed from gas within dark-matter over-densities. It is particularly vital to map out the respective roles of gas accretion and galaxy merging (van der Hulst et al. 2004).

With phased-array technology and hence a wide instantaneous FoV for the SKA, it has been shown (Abdalla & Rawlings 2004) that `all hemisphere' HI redshift surveys to z~1.5 become possible. This will yield an exquisite measurement of the galaxy power spectrum (Fig. 1.7) over volumes ~500-times larger than those probed by the 2dFGRS.

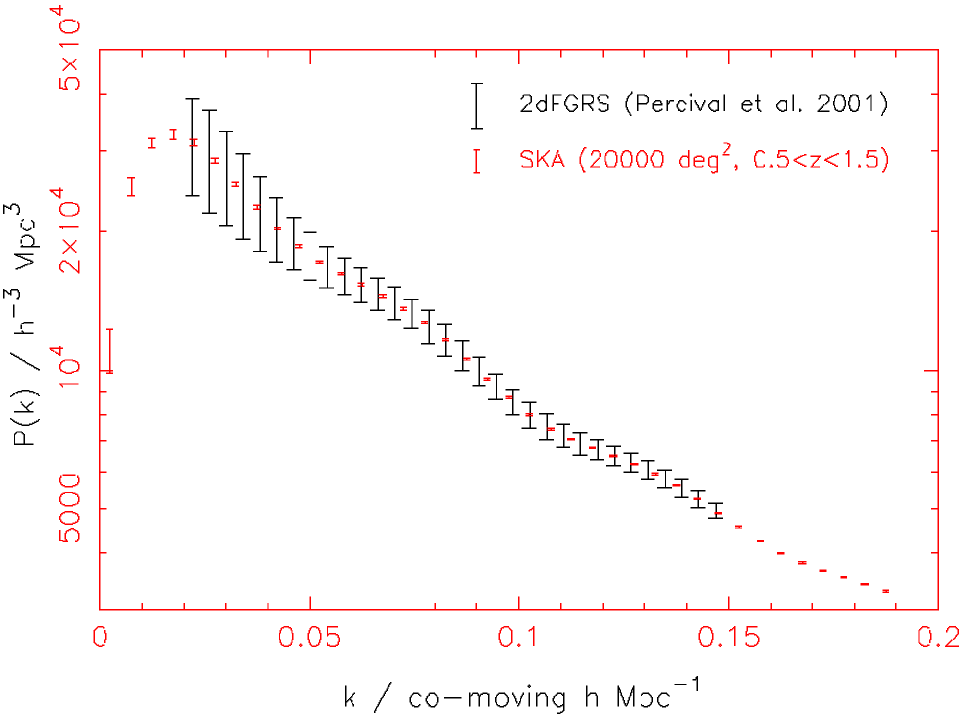

Fig 1.7: Simulated galaxy power spectrum (Blake et al. 2004) resulting from an `all hemisphere' SKA survey in HI. Note the small size of the error bars (reduced relative to 2dFGRS by a factor ~ √[relative volume] ~ √[500]), the lack of correlated errors (due to a sharp-k-space window function) and the extension to larger and smaller scales (the latter because the `non-linearity' scale moves to higher k at the higher redshifts probed by the SKA).

In combination with the CMB data to be available from Planck, this exquisite power spectrum will allow the first precise studies of the equation-of-state of dark energy (Rawlings et al. 2004). The key factor here is that, in CMB data alone, the `standard ruler' provided by the separation of the `baryonic wiggles' in the power spectrum is too imprecise for measuring the dark energy parameter w to better than 10% accuracy. The combination of Plank and SKA data breaks a degeneracy between w and the length of the standard ruler (the sound horizon at recombination), allowing both to be measured precisely.

The SKA will also be capable of other uniquely powerful cosmological studies. Again assuming a wide-FoV realisation (ie phased arrays), continuum surveys with the SKA will have a powerful combination of `all hemisphere' sky coverage and high and well-constrained angular resolution for weak gravitational lensing experiments. The dark-matter power spectrum measured from such a survey (Blake et al. 2004) will therefore have both low random uncertainties (compared to relatively large errors for SNAP due to its small sky coverage) and low systematic uncertainties (compared to potentially large systematic problems for ground-based optical weak lensing experiments with LSST). A comparison of constraints on dark energy using SNAP and the SKA is shown in Fig. 1.8.

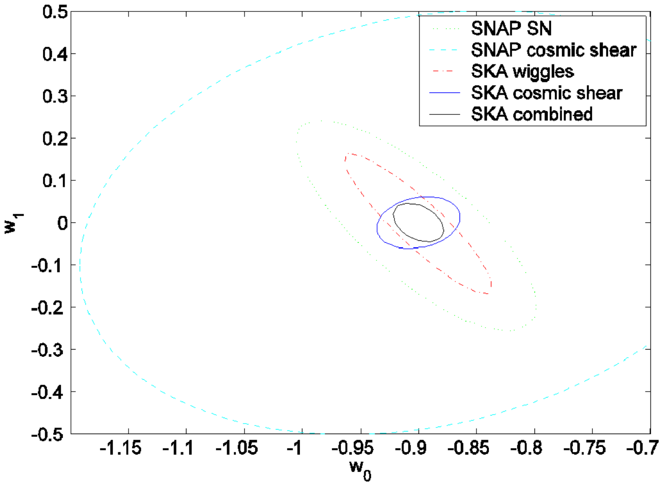

Fig. 1.9: Comparison (Rawlings et al. 2004) between (68%) confidence limits on w_0 and w_1, where the dark-energy parameter $w = w_0 + w_1 z$, for two SKA experiments (I: baryonic oscillations from the HI-galaxy power spectrum, and II: weak gravitational lensing) and two SNAP experiments (I: high-redshift supernova, and II: weak lensing).

A final cosmological (high frequency) experiment to note with the SKA is the precise (<1%) measurement of H_0 using extragalactic water mega-masers. As explained by Greenhill (2004), these systems can be used to measure reliable geometric distances which are sufficient large to overcome pecularities in the local Hubble expansion rate. The uncertainties in these distances (from mega-maser to mega-maser) will be uncorrelated, allowing the accuracy of H_0 to increase as $\sqrt{N}$, where N need only be a few hundred of the many thousand of water mega-masers to be discovered by the SKA. Precise knowledge of H_0 is vital for robust measurement of all cosmological parameters at the 1% level.

1.4.5: KSP V: Probing the Dark Ages

The baryons in the Universe are now almost completely ionized, but they were once neutral and had to be reionized by some mixture of stars and accreting black holes. The epoch of reionization (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). Recent observations of the Gunn-Peterson absorption troughs in high-redshift quasars imply that we are seeing the end of this key epoch of galaxy formation (`the Dark Ages') at redshift z ~ 6.5. The EoR looks, however, to be both protracted and complicated because CMB polarization studies have indicated a significant ionized component to the Universe at z ~ 15. The weakness of the magnetic hyperfine transition responsible for the 21-cm line of HI make radio astronomy the technique of choice for studying the EoR which, of course, is opaque at optical wavelengths.

The SKA will provide critical insight into the EoR in a number of ways. First, the ability of the SKA to image the neutral IGM in 21cm emission is a truly unique probe of the process of reionization, and is recognized by all as the next necessary and fundamental step in our study of large-scale structure and cosmic reionization (Fig. 1.9).

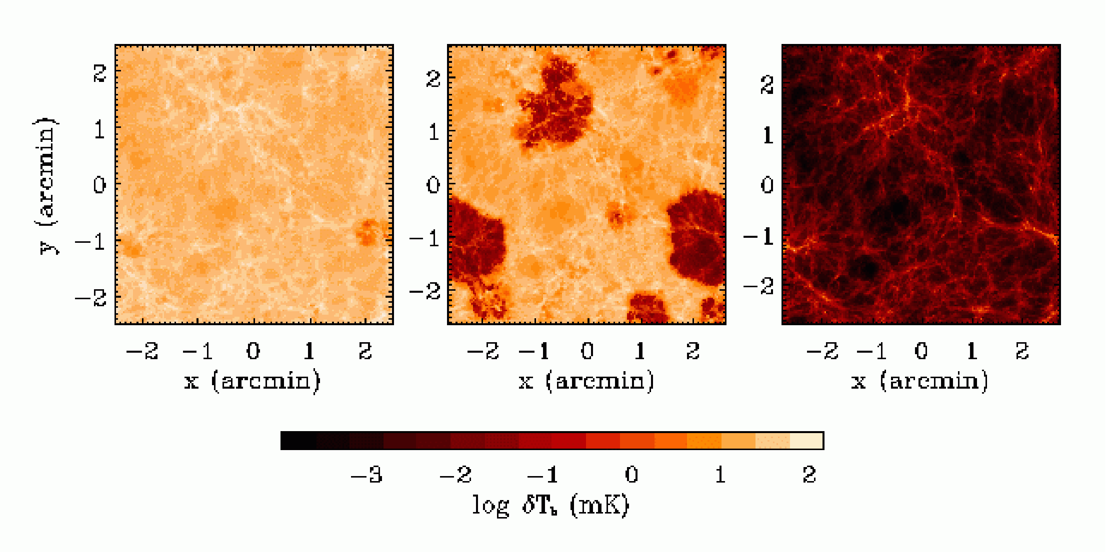

Fig. 1.9: The brightness temperature of the 21-cm HI transition at several redshifts, as predicted by the ``late reionization" simulation (Furlanetto & Briggs 2004). Each panel corresponds to the same slice of a simulation box (of transverse size ~ 15 comoving Mpc and `depth' 0.1 MHz) at redshifts z=12.1, 9.2, and 7.6, from left to right. The three epochs shown correspond to the early, middle, and late stages of reionization in this simulation.

Second, study of HI absorption toward the first radio-loud objects (Fig 1.10) is the only way to probe small to intermediate-scale structure in the neutral 'cosmic web', as well as HI in the first collapsed structures (proto-disks and mini-halos). Expected absorption signals include ~1% absorption by the mean neutral intergalactic medium (the `radio Gunn-Peterson' effect), deeper narrow lines arising in mild density inhomogeneitities (that after re-ionization give rise to the Lyα forest), and finally the possibility of detecting proto-disks and mini-halos – collapsed dark-matter halos whose virial temperatures are too small for atomic Hydrogen cooling to be efficient enough for stars to form. The importance of the SKA for following these early stages of galaxy formation cannot be over-stated.

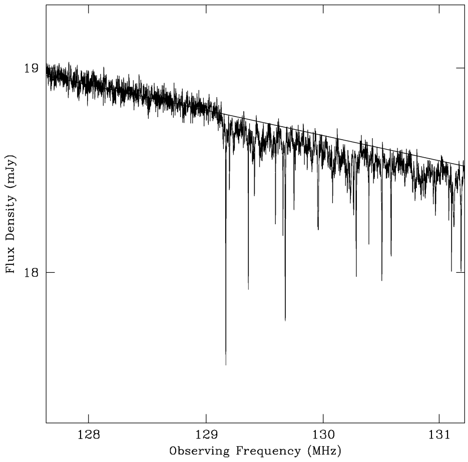

Fig. 1.10: Simulated SKA spectrum (Carilli et al. 2004) of a radio-loud object observed at z=10 (10 days integration). The onset of absorption by neutral Hydrogen is seen at 129 MHz.

Third, the incomparable sensitivity of the SKA allows for the study of the molecular gas, dust, and star formation activity in the first galaxies, as well as the radio continuum emission from the first accreting massive black holes. Once again these objects cannot be studied at optical wavelengths. The SKA will have sufficient sensitivity to detect radio emission from all accreting black holes, as well as star-formation activity in dwarf galaxies which, in some theoretical models, are only expected to form in the EoR (the input of energy to baryons during re-ionization, perhaps being sufficient to ensure that they can never again become bound to isolated low-mass halos).

1.4. Exploration of the unknown:

History tells us that enormous increases in sensitivity, survey speed and phase space covered (particularly for the SKA through opening up the time domain with transient source surveys) will lead to the discovery of new phenomena in the cosmos. The SKA offers astronomers in the 21st century an unparalleled opportunity to add to the many discoveries made by radio astronomy in the 20th century. Focussing on time domain observations, we note in Fig. 1.11 that huge regions of phase space are empty. This is most likely because radio astronomy has not yet had the technology to investigate these regions, not that they are genuinely devoid of sources.

Various ideas for investigating new phase space (in the time domain; see Fig 1.11) are discussed in Sec. 3.1.2, where it is shown that transient radio source surveys may discover emission from objects of direct relevance to all the KSPs as well as offering the opportunity of genuinely new discoveries.

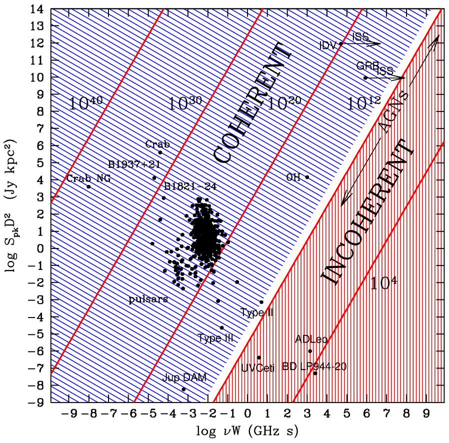

Fig 1.11: The phase space for radio transients (taken from Wilkinson et al. 2004). The x-axis is the product of the emission frequency and transient duration, or pulse width, W. The y-axis is the `pseudo-luminosity'. The sloping lines denote constant brightness temperatures. Note the huge regions without known sources.

2 UK Contribution to SKADS

2.1 The International Organisation of the SKA

2.1.1 International SKA Steering Committee (ISSC)

One of the challenges that faces the astronomical community as it plans the SKA, the first astronomical instrument to be planned globally from its inception, is the management of the project, both in the planning phase and in the design, development and construction phases. SKA is a ‘bottom-up’ concept, as are almost all successful scientific instruments, and the current management structure reflects that. The SKA project is currently managed by the International SKA Steering Committee (ISSC), which was formed by astronomers via a MoU signed at the IAU General Assembly in Manchester in 2000. The ISSC currently consists of 21 members and 2 at-large members. The membership of the ISSC represents all regions around the world interested in promoting the SKA and its science, and is made up as follows:

Australia: 2 members
Canada: 2 members
China: 1 member
Europe: 7 members (2 from UK: presently Wilkinson & Diamond)
India: 1 member
S.Africa: 1 member
USA: 7 members

The ISSC has an Executive Committee to ensure progress and continuity between its biannual meetings. The Exec. Cmte comprises the Chair, vice-Chair and past-Chair of the ISSC, the Secretary of the ISSC and the International SKA Project Director. The recently elected Chair of the ISSC is P.Diamond of the University of Manchester, he will serve until July 2006.

The principal roles of the ISSC are to promote the SKA as an international project; to be the primary forum for interactions among, and decisions of, the parties to the SKA MoU; to provide oversight and act as a coordinating body to establish agreed goals and timelines for the project; to develop a joint international and scientific proposal for the SKA, including an implementation and cost plan; and to establish and oversee advisory and working groups as necessary.

It is planned that the MoU that established the ISSC be re-written in 2005 with the cooperation of relevant funding agencies and other government bodies. Within Europe this will be preceded by a discussion on how radio astronomy should be organised in a more closely-knit way. The EC-funded RadioNet is a necessary step along this road but does not have the authority to speak for European radio astronomers.

2.1.2 International SKA Project Office (ISPO)

In order for the SKA to move forward in a coherent and planned manner the ISSC established the International SKA Project Office (ISPO) in 2002. The ISPO is headed by a Director (Prof. R.T.Schilizzi) and is hosted by ASTRON in the Netherlands. Key personnel within the ISPO are the Project Engineer (currently Dr. P. Hall on secondment from the ATNF) and the Project Scientist (currently Dr. S. Rawlings of Oxford University).

The ISPO, through the Director, is responsible for: the overall leadership and management of the joint development of the SKA design concept; coordinating institutions involved in SKA development to achieve a structured and efficient global effort; leading the generation, approval and implementation of a plan for concept development; stimulating development of the scientific goals and requirements of the project; stimulating outreach to the academic community and general public, as well as to industry and governments of the participating countries; managing the registration of Intellectual Property; reporting to the ISSC on a regular basis.

2.1.3 ISSC Committees and working groups and their roles

The ISSC has set up a number of working groups with full international membership who report to the ISSC through the ISPO. In addition, the ISSC anticipates the need to form 'ad-hoc' and independent advisory committees who will offer advice to the ISSC on science, engineering and site selection issues at the times of major reviews and/or decision points. The management structure is shown in Figure 6.

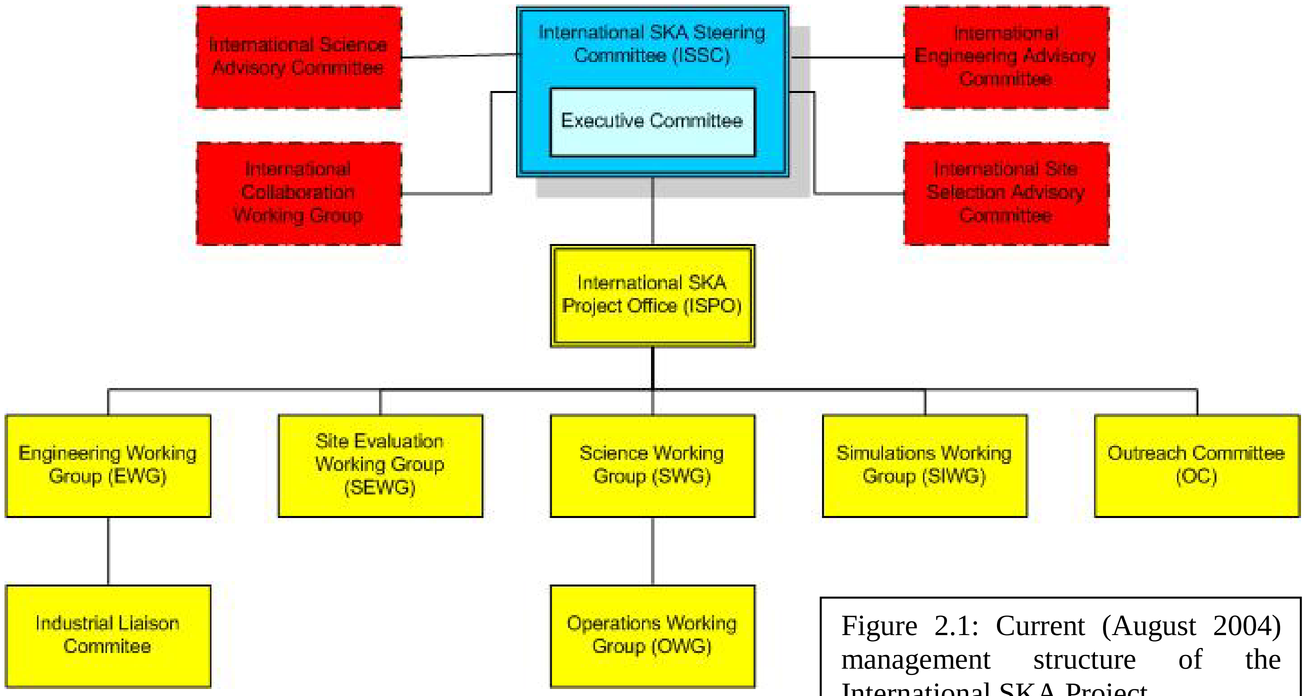

Figure 2.1: Current (August 2004) management structure of the International SKA Project

The role of the working groups is, briefly:

- Science Working Group (SWG): to develop and maintain a description of the science case that forms the basis of the SKA Science Requirements Document; to interact with the EWG in developing the Systems Definition Document; to interact with the SEWG on the science requirements for site selection; to coordinate, and carry, out science simulations in concert with the SIWG; to play an advocacy role for the project. The SWG is led by the SKA Project Scientist.
- Engineering Working Group (EWG): to develop a Systems Definition Document based on the Science Requirements Document; to develop a roadmap of engineering activities for the international SKA community leading to a reference concept, a reference design and a baseline definition of the design; to oversee, coordinate and stimulate the design and development of all elements required for the SKA. The EWG is lead by the SKA Project Engineer and has 6 sub-groups: antennas, RF systems, signal transmission, signal processing, interference mitigation and software engineering.
- Site Evaluation Working Group (SEWG): to establish the technical, infrastructural and environmental criteria for the evaluation of candidate sites for the SKA; to coordinate the environmental testing of the sites and to evaluate the results.
- Simulations Working Group (SIWG): to perform studies and simulations of SKA configurations in conjunction with the SWG, EWG and SEWG.

2.1.4 SKA Timescales

The ISSC has agreed the following timescale and milestones for the SKA Project:

- 2005-2008: Technical concept development
- 2005-2006: Site characterisation
- 2006Q3: Site selection
- 2008: Technology selection (GET LATEST ISSC DECISION)
- 2008: Formal proposal for Phase 1 of the SKA: a pathfinder with 5% of the full SKA collecting area on the selected site, globally funded.
- 2009: Construction starts on the pathfinder
- 2011: Formal proposal for full international funding
- 2014: Construction starts on full SKA
- 2020: Full operations

2.1.5 Prospects for international funding of SKA

The current target for the construction cost of the SKA is €1B (2002). It is expected that this will be split in the following way: 40% Europe, 40% USA and 20% Rest of the World. It will be a significant challenge to coordinate global funding of such a project; it may require a change in the culture, approach and mechanisms that exist in some countries for the funding of astronomy. Recently, the OECD Global Science Forum organised two meetings to discuss the particular problem of organising and funding such large-scale ground-based astronomy projects. The final report (July 2004) emphasised the need for a global science-based consensus view that brings together national and regional strategic plans, ultimately aiming for a long-term integrated vision – essentially a global roadmap for astronomy.

Whether such a process can be implemented remains to be seen, what is clear is that within Europe the radio astronomy community is not yet organised in the optimum way to procure and manage funding at the €400M level. Discussions are underway aiming at defining the optimum structure for the long-term health of radio astronomy in Europe and to enable Europe to participate and continue its leading role in the SKA.

2.2 The European SKA Design Study “SKADS”

2.2.1 Overview: the European vision for the SKA (for more details see the EC SKADS proposal)

The Key Science Projects of the SKA demand a combination of extremely high sensitivity and high-angular resolution observations in multiple, large fields-of-view in the low frequency range 0.1-1.7 GHz. A European consortium has therefore proposed a programme of research, SKADS, whose basic aim is to establish cost-effective technologies appropriate for these key low-frequency science goals. The SKADS proposal was been submitted for funding to the EU FP6 programme on 4 March 2004 and received highly favourable reviews from the EC assessors. These reviews have resulted in an EC decision on 10 September 2004, in full consultation with representatives from national funding agencies including PPARC, to fund the SKADS programme at an expected level of ~€10M (~£6.7M)

It has been agreed internationally that an SKA covering the frequency range ~0.1 to ~20 GHz is likely to involve two technological approaches for the collector systems with, however, a large amount common infrastructure for the data transfer, signal processing and data analysis systems. Solutions for the high-frequency range are being explored elsewhere, in particular the USA.

There are several possible technological solutions to the stringent observational demands on the SKA station technology in the low frequency range—but all of them involve the enabling technology of low-noise, low-cost phased arrays in one form or another. In a phased array the electrical length of the connections between the elementary antenna elements (or groups of them) is varied electronically, enabling “beams” to be formed in many directions at once. Such arrays can be deployed either as “aperture plane” arrays – large physical area systems in which the incoming electric field is collected directly, or at the focus of either parabolic or cylindrical antennas. In the latter case, the passive reflector provides the physical collecting area and the array maximises our ability to use the radio energy collected. A principal goal of the SKADS Design Study and its proposed demonstrator programme is, for the first time, establish the viability of “aperture plane” array technology for radio astronomy.

Phased arrays are well known to antenna engineers and have been much-used in the aerospace and military arenas. Pulsars, whose study provides one of the SKA’s key science drivers, were discovered in Cambridge, with a low-frequency (~80 MHz) phased array employing several beams and won their discoverer a Nobel Prize. In general, however, phased arrays have been little used in radio astronomy and certainly not in the sophisticated form which we envisage for SKA. With the march of technology we believe that the time has come for a paradigm-shift in radio telescope design and our principal goal in SKADS is to establish the credibility of large-area phased arrays (aperture arrays) for the SKA. *Aperture arrays offer the possibility of a quantum jump in terms of the size and number of independent fields-of-view and other operational flexibilities and also of forging a fundamental link with IT technologies whose unit costs are continuously reducing with time.*

The low-frequency “electronic SKA” of the type we are proposing to develop in SKADS, would be very different to any current telescopes in any waveband and would be continuously upgradeable as computing power and memory becomes cheaper. As part of the drive both to increase the flexibility while reducing the cost of the SKA it will make use of the emerging technology of “software radio” where, in contrast to the previous and current generation of receiver and signal processing equipment, which uses special-purpose hardware, the next generation will inevitably exploit the convergence of radio and digital computing technologies—replacing hardware with firmware or software and allowing unprecedented versatility via the use of programmable processing engines. It will also use commercial off-the-shelf components or systems where possible.

2.2.2 The structure of the FP6 Design Study Proposal SKADS

The SKADS Design Study has been structured as a series of separate strategic Design Studies including both feasibility studies and technical preparatory work (EC SKADS Fig 2.2). The feasibility studies are essentially “paper” exercises relevant to the design and costing of the SKA network and infrastructure, an overall assessment process and a project plan. The technical preparatory work mainly involves developing hardware R&D associated with establishing the cost-effectiveness of our specific solutions for an SKA “station”. Each of these Design Studies has been sub-divided into coherent Design Study Tasks with clear aims, milestones and deliverables. At all stages we have been particularly cognisant of the need to provide outcomes in measurable and verifiable form.

SKADS comprises the following Design Studies (DS):

- **DS1 Managemen**t: task to provide the Europe-wide co-ordination of this complex and highly inter-related project;
- **DS2 Science and Astronomical Data Simulation**s: the development of instrument specifications based on a quantification of key science drivers and a study of the technical requirements associated with the delivery of the science;
- **DS3: The Network and its Output Data**: an end-to-end study of the network, data handling and physical infrastructure from collection to the delivery of data to the astronomical users and its efficient use by them;
- **DS4: Technical Foundations and Enabling Technologies**: the design of a cost-effective antenna system comprising an SKA “station” enabling beam forming within fields-of-view in many directions simultaneously, this will involve a range of hardware to develop the technical foundations and enabling technologies;
- **DS5 Aperture Array Demonstrator “EMBRACE”**: the construction of a ~500 m^2 engineering demonstrator array for the phased array vision of an SKA “station”, which will explore the practical issues involved in different multi-beam collection and signal-processing concepts;
- **DS6: Cylindrical Concept Demonstrator**: a study to prove the viability and scalability of the cylindrical concentrator array concept;
- **DS7: Assessment of Preparatory Work and Studies**: a continuous process of critical assessment;

- **DS8: Overall System Design and Preliminary SKA Plan**: an overall system design (involving technology foresight) and a preliminary, multi-component plan of how to realise the SKA.

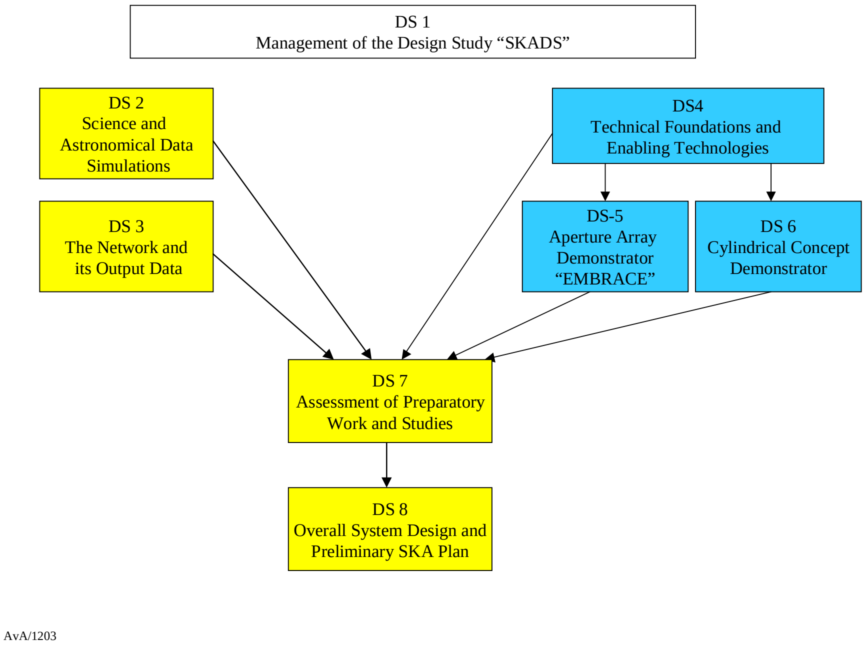

Fig. 2.2: The main linkages of the Design Studies within SKADS. The feasibility and assessment studies DS2,DS3,DS8,DS8 are shown in pale boxes. The technical preparatory work (DS 4, DS5,DS6) are shown in dark boxes.

2.2.3 The timeliness of SKADS

The international selection of the technical design i.e. the optimum architecture (or architectures), is scheduled for 2008/9. A strong driver of the international community is the desire to present a unified and well worked-out concept for the SKA in time for the next US National Science Foundation's "Decadal Review" of astronomy, for which consultation starts in 2009. In order for any concept to be considered in the 2008 selection process the proponents must have constructed and tested "engineering/proof-of-concept demonstrators" (DS5; DS6) and must have undertaken and assimilated a wide range of complementary R&D, scientific and technical feasibility and assessment studies (DS2; DS3; DS4; DS7; DS8). As well as testing the concept's ability to deliver the science goals a principal target is to establish cost equations of the systems and sub-systems and to estimate the derivatives with time (i.e. technology foresight) and area (i.e. economies of scale). The current phase is the precursor phase where the cost-effectiveness of the various possible approaches to delivering the SKA science programme is being developed. After the technology concept selection in 2008/9, the whole world will come together to design and construct the SKA, and the very best technologies available will be sought for its construction.

2.2.4 European-wide project management in SKADS

The European-wide management plan for SKADS can be found in section 4 of the SKADS proposal. The manner in which this plan impacts the UK programme will be discussed in Section 6 below.

2.2.5 Link with RADIONET

The EC FP6 RadioNet I3 is a collaboration of existing radio astronomy facilities and technology groups focused on improving the current suite of European facilities for the benefits of European users. It is coordinated by P. Diamond (Manchester). RadioNet is a 5-year programme and is expected to have a long-term structuring effect on radio astronomy in Europe; one of its networking activities will be studying, and possibly beginning the implementation of, models for the future structure of radio astronomy in the era of the SKA. It is vital that there be strong, formal and visible links between SKADS and RadioNet over and above those that exist within the institutes participating in both programmes.

2.3 Summary of the principal UK roles in SKADS

Here we list the main UK roles which have now been negotiated and agreed within SKADS. The detailed manpower requested in each of the areas is given in Annex A, where the UK work packages within each of the SKADS Design Studies are described in detail.

DS1 Management: coordination of the EC SKADS programme will be carried out by ASTRON. It is likely that a senior UK scientist (e.g. Prof. P. Wilkinson, Manchester) will be Chairman of the SKADS Board. The EC-funded Project Engineer, a senior member of the management team, will be located in the UK.

DS2: Science and astronomical data simulations: will be coordinated by the Joint Institute for VLBI in Europe (JIVE).

DS2-T1: Science Simulations: to be coordinated by the University of Oxford.
DS2-T2: Astronomical Data Simulations: to be co-ordinated by JIVE.

The DS2-T1 and DS2-T2 programmes are intimately connected and the UK will play leading roles in both tasks.

DS3: The Network and its Output Data: will be coordinated by the University of Cambridge.

DS3-T1: Network Infrastructure and Data Transmission: will be coordinated by the University of Manchester.
DS3-T2: Array Data handling distributed computing and real-time control: no UK role.
DS3-T3: Data reduction and analysis ”SKA for the User”: will be coordinated by the University of Cambridge.
DS3-T4: A study of siting and related issues: no UK role.

DS4: Technical Foundations and Enabling Technologies: will be coordinated by the University of Manchester. The University of Manchester intends to recruit a new Chair of Radio Astronomy Technology who will lead this overall programme. A radio instrumentation group is being started-up in Oxford. It is likely that in the EC contract negotiations significant changes will be made to the European-wide SKADS DS4 Tasks to accommodate the UK programme and we have provisional agreement on this restructuring with the SKADS executive. The UK role will now be focussed towards the design and development of a “3rd generation” phased-array tile.

DS5: Aperture Array Demonstrator “EMBRACE”: will be coordinated by ASTRON. There will be a significant level of UK input into this design study and regular meetings with our Dutch and French colleagues to coordinate the links with DS4. In the SoI of September 2003 it was envisaged that the UK would have a larger role in EMBRACE than is now foreseen. Nevertheless in this proposal we request funding to support beam-forming strategies developed in DS3 and DS4 directly to EMBRACE.

DS6: Cylinder Array Demonstrator: will be coordinated by Instituto di Radio Astronomia; no UK role.

DS7: Assessment of Preparatory Work and Studies: will be coordinated by the Observatoire de Paris.

DS7-T1: Continuous Assessment: will be co-ordinated by the Observatoire de Paris; UK role via Project Engineer.
DS7-T2: Design Reviews: will be coordinated by the Observatoire de Paris; UK role as part of whole Study.

DS8: Overall System Design and Preliminary SKA plan: to be coordinated by the University of Manchester. No additional resources are requested to support this Design Study.

DS8-T1: Overall System Design: will be coordinated by the University of Manchester.
DS8-T2: Preliminary SKA plan: will be coordinated by ASTRON.

2.4 Contribution from Universities

The UK SKA consortium consists of the Universities of Manchester, Oxford, Cambridge, Cardiff, Leeds and Glasgow. Here we outline the expertise that this UK consortium will bring to the SKADS programme.

The university partners generically bring to the project:

- the SKA and SKADS projects themselves, with their novel and challenging requirements which force the development of new technology;
- a wide knowledge base in astronomy
- innovative semiconductor device design and manufacturing capability;
- an existing knowledge base on generic antenna systems design including phased arrays;
- an existing capability in overall radio astronomy systems design.

Science/knowledge base for DS2: The UK has one of the largest and strongest astronomy bases in Europe and is well placed to carry out simulations associated with all aspects of the Key Science Projects, but in particular those areas especially associated with the multi-beam low-frequency concept being explored within SKADS. As detailed in section 3.1.1 the addition of Cardiff, Leeds and Glasgow to the main three universities ensures complete coverage of science expertise in the Key Science Project areas. The deep knowledge of synthesis imaging of the staff and former students trained at the Universities of Cambridge (several of whom are now at the University of Oxford) and Manchester means that they will be able to play a leading roles in the feasibility studies of the overall array performance.

Knowledge and Technical Base for DS3: The heritage of synthesis imaging, involving baselines from metres to 1000s of kilometres, within the UK community is unmatched across Europe. The UK community also has great e-science strengths, for example in developing the GRID, in Astrophysical Virtual Observatories and in data archiving (for MERLIN and ALMA). Uniquely in the world, pairs of dark fibres being installed for the eMERLIN array will be available in a large-scale network for unique local oscillator distribution tests. Finally the close link being forged with UK industry can bring in knowledge of large scale infrastructure projects.

Knowledge and Technical Base for DS4: Both Manchester and Cambridge Universities have a long track record for innovative instrumentation spanning many decades, both individually and, more recently, in collaboration on projects such as the Very Small Array. The Microelectronic Materials and Devices group (Prof. Mo Missous) and the Communications and Microwave Engineering group (Prof. Tony Brown, Dr Rob Sloan) at UMIST will bring unique experience relevant to radio astronomy technology development. Prof. Missous is a world-expert on semiconductor materials and has recently been the recipient of a £2M state-of-the-art Molecular Beam Epitaxy machine from VG Semicon now housed in a new laboratory in the UMIST main building (see also section 12). Prof. Brown is an antenna and communications engineer whose skills are ideal for the design of the SKA radio receptors and who has long experience in the antenna industry. The University of Manchester is advertising for a Chair of Radio Astronomy Technology and associated lectureship. It is expected that the appointees will have high-level expertise in signal processing techniques. Oxford University are in the process of appointing a new Head of Instrumentation specifically directed towards work on the SKA. The appointee will have a demonstrated track record of technical expertise in aperture synthesis arrays.

2.5 Contribution from Industry

In order to ensure that the UK plays one of the leading international roles in SKA R&D, we have sought to involve UK industry from the start. These links were first formed at a PPARC-sponsored meeting on 18 February 2004 where the possibilities and potential of engineering R&D on the SKA were presented to representatives of industry. Partnerships are being formed with BAE Advanced Technology Centre (Chelmsford) and Qinetiq (Malvern).

The generic advantages of industrial collaboration are threefold:

- Technology-risk reduction: by leveraging existing technological knowledge from commercial/military experience.
- Time-risk reduction: the SKADS project has internationally-driven timelines and requires us to leverage in current expertise as soon as possible.
- Cost-risk reduction– the "industrial scale" of SKA means that industrial involvement and knowledge of low-cost manufacturing, is vital. It is to be noted that even the full SKA represents only an intermediate scale of project in terms of industrial economies of scale. While very large compared with all previous radio astronomy requirements and previous phased array requirements anywhere it is small compared, for example, with military procurements and mobile phone industry volumes.

BAE ATC (Great Baddow) brings to the project

- an existing base of knowledge, in particular on digital phased arrays – but also across wide range of relevant radio and signal processing technologies
- the ability to assist in defining the initial scope/specification of parts of the SKADS programme in particular all aspects of the 3rd generation tile
- subject to the provision of funding – additional skilled manpower into the newly-defined work programme.

Qinetiq (Optronics Division; QUEST Section) brings to the project:

- wide experience on design and testing of monolithic microwave integrated circuits (MMICs) for military and large-scale commercial customers
- complete system simulations using extensive suite of design tools
- fully-automated (or manual) on-wafer measurements
- ability to package semiconductor devices in-house
- subject to the provision of funding – additional skilled manpower into the newly-defined work programme.

BAE ATC and Qinetiq are already working together with the University of Birmingham on a programme to develop vehicle-vehicle communications systems. There is, therefore, a close precedent for the type of cooperative programme we are proposing.

2.6 Strategic Overview of the UK role

In addition to first proposing the SKA idea, UK astronomers play leading roles in the international committees and hence are able to place both the European and UK activities in the international context.

> International SKA Steering Committee: P. Wilkinson and P. Diamond (Manchester) are members; P. Diamond is now Chair of the ISSC for a term of two years.
>
> International Science Working Group: S. Rawlings (Oxford) has been vice-Chair and will now become Chair (and International Project Scientist); M. Kramer (Manchester) and M. Hoare (Leeds) are members.
>
> International Engineering Management Team: R. Spencer (Manchester) is a member.
>
> International Antennas Working Group: K. Grainge (Cambridge) is a member.
>
> European SKA Consortium: P. Wilkinson, P. Diamond, A. Lyne (Manchester), S. Rawlings (Oxford) already members. P. Wilkinson is Chair of ESKAC for the next two years.
>
> SKADS Interim Executive: P. Wilkinson and P. Diamond (Manchester) are members.

Other leading scientists and engineers in the UK SKADS team will join these committees if and when the UK SKADS programme gets underway.

3 Technical specification

3.1 DS2: Science Simulations

3.1.1 Background: the necessity of detailed simulations led by the UK

In 2008/9, the international project management will reach a decision concerning the underlying technology (or technologies) for the SKA. The project must either choose one from several radically different design realizations, or recommend a `hybrid’ solution in which different technologies are chosen for different frequency ranges. The over-arching theme of this UK SKADS design study is that the UK positions itself so that it can lead the world in (a) getting this decision right; and then (b) exploiting the full scientific promise of the SKA and its precursor or `pathfinder’ instruments.

If the decision goes in favour of a reflecting-concentrator-only design (e.g. dishes, like the VLA, and almost all current radio telescopes), then the instantaneous FoV will be similar to the degree scales currently achieved by radio and optical telescopes. Such an SKA would only be able to look (at full sensitivity) in one direction at a time and its operation and science exploitation would, although obviously scaled-up dramatically in sensitivity, follow procedures familiar to traditional radio astronomers.

If, however, the decision goes in favour of a hybrid design, in which low-frequency (0.2-2 GHz) operation exploits phased-array technology, then the SKA could look in many directions at once (with full sensitivity) and become a truly revolutionary scientific instrument. Its scientific operation would then be more akin to the multi-beam/multi-user facilities used by particle physicists. As described in Section 1, such an instrument could quickly revolutionize many areas in fundamental physics (e.g. tests of the Cosmic Censorship Conjecture and the No-Hair theorem), particle astrophysics (e.g. precise studies of the equation-of-state of dark energy), astronomy (e.g. studies of galaxy formation within the epoch of reionization and the origin of magnetic fields) and solar-system science (e.g. `movies of planet formation’, astrobiology and SETI). It will also have incredible discovery potential for finding genuinely new phenomena.

Detailed simulations lie at the heart of influencing the international SKA design decision in 2009. They must provide robust quantitative answers to three questions:

1. What is the gain in science from adopting phased-array technology at low frequencies? This will be achieved by producing detailed ‘Year in the Life’ plans for a dish-only SKA and a hybrid (e.g. phased array + dish) SKA. We anticipate that this will produce a compelling case in favour of employing phased arrays below ~2 GHz, but we need water-tight arguments to convince not only ourselves, but the entire international SKA community.
2. Assuming a phased-array-based solution, what are the trade offs between the key design parameters (e.g. sensitivity, FoV etc), the science output and the cost? This will provide the detail needed to determine the optimum SKA hybrid realization within what is a very likely to be a fixed cost envelope.
3. Are there any technical `show stoppers’ which are likely to compromise the science achievable with phased arrays? It is not yet certain where the balance lies between problems and opportunities regarding the novel features of phased-array technologies.

The UK science simulation effort will be undertaken as part of a coordinated international effort in which the UK has already established a leadership role (e.g. Rawlings as International Project Scientist; Rawlings and Kramer as `shepherds’ for two of the five KSPs [Key Science Projects]). This can only be maintained and expanded if the most critical quantitative simulations are performed in the UK.

The UK will take leadership roles where simulation work can exploit existing expertise in areas central to both the SKA KSPs and PPARC’s strategic aims: e.g. in astrobiology, pulsars and radio synthesis imaging (Manchester); in cosmology, particle astrophysics and galaxy/AGN redshift surveys (Oxford); in magnetic fields, star formation, low-frequency surveys and mapping algorithms (Cambridge); in HI surveys (Cardiff); in proto-planetary disks and high-energy cosmic rays (Leeds); and in radio transients and gravitational waves (Glasgow). PDRA support of these activities will cement the UK’s lead in scientific simulation work for the

SKA, and allow for a detailed quantitative examination of the scientific advantages of employing phased-array technology over traditional approaches utilizing just arrays of parabolic reflectors.

In other important scientific areas (e.g. molecular line emission at high redshift), we will work closely with our international colleagues (in Europe [as part of the FP6 programme] and/or in the USA or elsewhere) who have agreed to lead the international simulation efforts. These science areas typically require much higher frequency capabilities than are likely to be possible with phased arrays, although sometimes (e.g. earliest epochs of reionization) they require ultra-low-frequencies where LOFAR[3]-like technology is likely to be upgraded for the SKA , or require 0.2-2 GHz capability but do not match UK expertise or PPARC's strategy (e.g. SETI).

Proper management and coordination of these worldwide activities is ensured by the international SKA project structure, the EC FP6 programme (SKADS) and the UK SKADS management (DS8). Much of the international SKA simulation activity will exploit the supercomputing facilities of Swinburne University, Melbourne, Australia which is already being used for preliminary SKA work by research students at Oxford.

3.1.2 Science simulations: aims, structure and work packages

Each of the KSPs outlined in Section 1 are concerned with distinct scientific areas which typically utilise very different capabilities of the SKA, although, in a few cases, data useful for more than one KSP can be collected via a single SKA survey. Also, each KSP typically consists of a set of scientifically linked SKA experiments, which can demand a range of SKA capabilities and/or modes of operation. Some radio astronomical techniques (e.g. transient source surveys) have the potential to have significant impact on several of the KSPs. Finally, the `Exploration of the Unknown' (Section 1) is a crucial aspect of the SKA for which the key design driver is flexibility to investigate new regions of phase space.

This complicated web of inter-related scientific demands and technical requirements complicates the design of a comprehensive science simulation programme. To maximize efficiency, there needs to be a coherent international simulation effort, within which investment by PPARC is required to secure the leadership role for the UK for which it is now so excellently positioned.

The simulation work undertaken in the UK will focus on established strengths. Most of these simulations are expected to quantify the huge benefit of large FoV and multi-beaming/multi-fielding as delivered by phased-array technology at moderate (0.2 to 2.0 GHz) frequencies. The fraction of the key science focused in this frequency regime is very high; the need for large FoV is driven by the importance of huge sky area (`all hemisphere') surveys; the need for multi-beaming is driven by monitoring programmes of time-varying sources such as pulsar timing. The excellent match between KSPs and UK expertise is not accidental. First, the writing of the revised science case (Carilli & Rawlings 2004) has included input from ~20 UK scientists, and adding `Exploration of the Unknown' to the five standard KSPs, the critical science case chapters were written by UK authors in three out of the six cases (Kramer et al., 2004; Rawlings et al., 2004; Wilkinson et al., 2004). The excellent match between UK expertise and intermediate-frequency science is also not accidental. This is the result of the rich heritage of work on pulsars and extragalactic radio sources using the radio synthesis arrays at Jodrell Bank and the Cavendish, and the build up of new radio astronomy groups (e.g,. at Oxford) which have exploited these and other international radio facilities (VLA, VLBA, WSRT, ATCA, GMRT etc) in a multi-waveband context.

The areas in which the UK is the obvious choice to lead the international simulation effort define the twelve work packages in this area. These consist of six science simulation programmes (in essence, modeling the sky and assessing the demands imposed on basic SKA design parameters like FoV), five technical simulation packages (in essence, understanding the technical limitations imposed by the various specific SKA realizations) packages, and one management package. The simulation packages are now described in the context of the five KSPs plus `Exploration of the Unknown'.

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[3] LOFAR (Low Frequency Array) is a Dutch national project principally aimed at frequencies (<200 MHz) below those of major relevance to four out of the five SKA KSPs.

- Astrobiology (KSP I, Cradle of Life). The SKA will be the first instrument capable of detecting line emission from low-order rotational transitions of amino acids and other complex Carbon biomolecules, and to follow their progress from molecular clouds to proto-planets. This work will be led by Millar (Manchester) and will involve Leeds. The plan is to make the first models of the protoplanetary disk environment from which realistic abundances of biomolecules can be estimated. These will be used to estimate the line strengths observable with the SKA to determine basic requirements like the optimal frequency range (i.e. determine the crucial detectable biomolecular transitions) and the baseline distribution needed for SKA astrobiology experiments. This programme (DS2-T1-WP6) will form a central part of international KSP I activity, and requires 2 FTE[4]s.

  The overlap with the technical simulations needed for other (chiefly extragalactic HI) line work is substantial, so that the associated technical simulations will be undertaken under work package DS2-T2-WP2 (justified below).

  Considering the overall international effort on KSP I, astrobiology (line) simulations will be led in the UK, with the `movies of planet formation' (continuum) simulations, as well as SETI simulation work, to be led by colleagues in the USA.

- Pulsar surveys (KSP II, Gravity). SKA observations of pulsars will allow fundamental physics experiments such as strong-field tests of gravity using pulsar/black-hole systems and new probes of GR including tests of the Cosmic Censorship Conjecture and the No-Hair theorem. This work will be led by Kramer (Manchester). The plan is to simulate the number of pulsars beamed towards us in our Galaxy, the fraction of these that are millisecond pulsars (those that will eventually form an immense `pulsar timing array' for detecting gravitational waves) and the number of `exotic' (e.g. pulsar/black-hole) systems to be discovered. They will make a quantitative comparison of SKA pulsar surveys (and timing follow-up) with basic design parameters like FoV (crucial for the initial finding surveys) and baseline distribution (crucial for accurate astrometry of the pulsars). This programme (DS2-T1-WP4) represents the most important simulation work needed for KSP II, which is `shepherded' internationally by Kramer, and requires 1.5 FTEs.

  For SKA pulsar science, very detailed technical simulations are crucial in a number of areas. For finding pulsars from blind searches, the full FoV needs to be synthesized at high time resolution, representing huge design-dependent constraints on processing and storage. For timing pulsars, at least ~50 pencil beams need to be formed in at least four independent fields of view. The loss of efficiency by attempting such observations with a conventional (e.g. dish) SKA design needs to be quantified (it will be large because a conventional array will need to be split into sub-arrays, with concomitant loss of sensitivity, if it is to point in several directions at once). This work (DS2-T2-WP4) will require 2 FTEs.

  The UK needs to maintain international scientific leadership of KSP II, but the Manchester group will continue to work closely with international colleagues, chiefly in the USA, Canada, The Netherlands and Australia. These collaborating groups will focus on other areas of simulation such as those needed for the `pulsar timing array', and those needed to use pulsars as probes of the interstellar medium.

- Polarization surveys (KSP III, the Magnetic Universe). The SKA will be the only instrument capable of studying the evolution of magnetic fields in the Universe, and therefore the only means by which we can hope to understand the origin of these fields. This work will be led by the Cambridge Group who are world-renowned for their work on the polarization of extragalactic radio sources. They will produce a set of simulated polarized skies, bracketing the major uncertainties in extrapolating from existing datasets and theory. They will determine the relative science returns of different SKA realizations, and quantify the tradeoffs between critical parameters like FoV and sensitivity. These science simulations (DS2-T1-WP3) are central to KSP III, and require 2 FTEs.

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[4] We define 1FTE as being 12 person-months of activity

The achievement of scientifically-useful `all-hemisphere' polarization surveys will be critically dependent on polarization purity (and calibration) which is expected to be highly dependent on SKA realization. The first ever dual-polarization phased array tile is a deliverable from DS4, but the output from polarization technical simulations (DS2-T2-WP3) are also needed to determine the purity (calibration) specifications that need to be achieved in the eventual `science-grade' SKA tile. These technical simulations will require 1.5 FTEs.

The UK simulation effort will focus on the `all hemisphere' rotation measure (RM) survey which represents the major SKA resource required to address the scientific aims of KSP III (the possibility with the SKA of using spectropolarimetry to measure RMs, means intermediate frequencies may be optimum for this survey, allowing full benefit from the FoV advantages of the phased array concept). International colleagues, principally in Germany, Italy and the USA, will focus on simulating other SKA techniques relevant to KSP III, namely Faraday tomography (which will certainly require higher-frequency capability) and Zeeman-splitting techniques.

- HI surveys (KSP IV, Galaxy Evolution and Cosmology). Originally the prime motivation for the SKA (Wilkinson 1991), the huge redshift surveys of HI-emitting galaxies made possible by the SKA remains one of its unique selling points as they will yield fundamental advances in galaxy evolution, cosmology and particle astrophysics (e.g. through studies of dark energy). Work led by Rawlings (Oxford) will, in collaboration with Cardiff and R. Battye (Manchester), produce a set of simulated line (HI) skies, bracketing the major uncertainties in the extrapolation from existing datasets and theory. These model skies will, after simulated observation with different SKA realizations, allow proper quantitative comparisons (of, e.g., dishes versus phased arrays) and design constraints (e.g. what instantaneous FoV is the minimum needed for a phased-array tile). Optimum methods of extracting key information on galaxy evolution, cosmology (in general) and dark energy (in particular) will also be investigated in collaboration with Silk, Ferreira and others. These simulations (DS2-T1-WP2) are central to KSP4 (Galaxy Evolution and Cosmology) which is `shepherded' internationally by Rawlings (Oxford), and will require 2FTEs.

  The main technical worries facing line surveys, both extragalactic and galactic (e.g. astrobiology, see above), are issues of band-pass stability (and calibration) and RFI. Existing datasets (principally from the GMRT) and technical simulations will together provide a fantastic training ground for establishing acceptance criteria on these SKA-design-dependent parameters. For astrobiology applications, there is the additional complication that the signal (as well as the instrumental band pass response and RFI) is likely to be time varying. These technical simulations (DS2-T2-WP2) will require 1.5 FTEs.

  After delivery of the simulated skies to the international project, UK simulation effort will focus on the measurement of the galaxy power spectrum from an `all hemisphere' HI survey which has been identified as critical to particle astrophysics and cosmology applications such as the study of the dark energy equation-of-state (Abdalla & Rawlings 2004). The UK must maintain world leadership in this area. International colleagues, principally in Holland, France, Canada and Australia, will focus on simulating deeper HI surveys which are focused more on probing questions in galaxy evolution rather than cosmology. Other (potentially critical) SKA cosmological experiments possible with the SKA, e.g. measurement of H_0 using extragalactic water masers, are high-frequency experiments to be simulated by colleagues in the USA.

- Continuum surveys (KSP IV and KSP V, the Epoch of Reionization). Continuum surveys with the SKA will have the sensitivity to detect star-forming galaxies to sufficiently high redshift that it will possible to map out the evolutionary histories of the full range of known galaxies from dwarves to giant ellipticals. These same surveys will find all the AGN, both `radio loud' and 'radio quiet', in the observable Universe, and HI absorption against these objects will provide a unique probe of `mini-halos', proto-galaxies and the intergalactic medium within the (optically opaque) Epoch of Reionization (Carilli et al. 2004). Distortions of the shapes of the radio emission from normal high-redshift galaxies by weak gravitational lensing will provide uniquely powerful measurements of the dark-matter power spectrum, having huge influence on the cosmological aims of KSP IV. Work led by Rawlings (Oxford) will produce a set of simulated continuum skies (bracketing the uncertainties) which will be delivered to the international project. After simulating observations with various SKA realizations, the design implications (e.g. what distribution of baselines is needed for the weak lensing experiment) will be studied. This programme (DS2-T1-WP1) will require 2 FTEs.

A follow-on programme of technical simulations (DS2-T2-WP1) will exploit expertise at Manchester to study the major practical worries of achieving the continuum sensitivities implied by the SKA's huge sensitivity. Amongst these, techniques for achieving the huge dynamic ranges (up to 10^{10}) deserve the closest investigation. It is not yet clear how these dynamic ranges might be achieved in a conventional SKA design given the extraordinarily tight constraints it implies on primary beam shapes, pointing and calibration. It is also not yet clear whether the use of phased arrays alleviates or exacerbates these difficulties, so a technical programme of simulation is needed to investigate the various techniques (ranging from electronic nulling to software self-calibration) which can counteract the `problem' that phased arrays are sensitive to all radio sources above the horizon.

After delivering simulated skies to the international project, UK simulation effort will focus on methods of deriving the dark-matter power spectrum from weak lensing (for KSP IV) and on exploring the reionization epoch using HI absorption against continuum sources (for KSP V). International colleagues, principally in France, Holland and the USA, will lead simulation efforts on tomography of the reionization-epoch IGM, the other major aspect of KSP V.

- Transient surveys (all KSPs and Exploration of the Unknown). Even the very limited (to date) exploration of the time domain for radio astronomical discovery has led to spectacular results exemplified by the discovery of pulsars, but the novel capabilities of the phased-array SKA concept (seeing in many directions at once) will revolutionize this situation with the SKA. Exploration of the time domain has been emphasized as an obvious way in which the SKA will open up phase space for discovery, ie `Exploration of the Unknown' (Wilkinson et al., 2004). However, despite the uncertainties, theoretical expectation of what is likely to be out there in the transient radio sky, means that one can envisage ways in which transient survey science can have major impacts on the existing KSPs. For example: direct detection of low-frequency radio bursts from the interaction between solar-winds and the magnetospheres of exoplanets (KSP I); measuring baryon densities and magnetic fields in the cosmic web using dispersion and rotation measures towards giant pulses from extragalactic pulsars (KSPs II & III); radio pulses associated with cosmological gravitational wave sources (KSP IV); and Gamma-ray-burst afterglows from the first stars within the epoch of reionization (KSP V). Focusing on these KSP-based programmes, the simulation work will be led by Woan (Glasgow), a choice driven by local expertise in astronomy, space weather and gravitational waves. This broad-ranging simulation programme (DS2-T1-WP5) will require 2 FTEs.

  Transient source surveys are very demanding on SKA design specification (fast time sampling, digital data buffers etc) but in many cases can trade-off imaging capability for time resolution. The capabilities of doing both targeted searches (e.g. of stars to find exoplanets), of blind searches (e.g. to find the unknown), and of responding to events quickly (or even, via a data buffer, before they happened!) are clearly hugely dependent on SKA realization (and extremely limited with conventional dish-based telescopes). For the phased-array concept, a programme of technical simulations (DS2-T2-WP5) will explore (for example) what size and type of data buffer is needed to carry out retrospective observation of phenomena ranging in characteristic timescale from nanoseconds (for ulta-high-energy cosmic rays; UHECRs) to months (for high-redshift Gamma-ray-burst afterglows); expertise in Leeds will be exploited to address issues relevant to UHECRs which are a source of noise for some of the KSP-based projects, but signal for those interested in looking for the `GZK' cut-off.

Although the work packages have been designed such that they can be pursued (largely) to exploit expertise at individual UK institutes, there are a few areas where a PDRA will rely on the work of another PDRA, justifying (of course) the need for careful overall management of the project (DS2-WP1). The manager will be based in Oxford to ensure close connections with the European and International efforts (for which Rawlings has overall responsibility), but will travel regularly to oversee the whole UK DS2 programme. The areas of overlap of the work packages are detailed in the accompanying Gannt charts (e.g. design-dependent constraints on polarization purity studied in DS2-T2-WP3 are needed for technical simulation work on pulsar timing in DS2-T2-WP4).

3.2 DS3: The Network and its Output Data

3.2.1 Introduction

The aim of DS3 is to consider the issues associated with producing the most cost-effective overall architectural design for the SKA "network" (see Fig 3.1 but interpreted in the broadest sense) which satisfy the specifications established in DS2 and deliver the scientific objectives to the end-user. The work within this design study is closely focussed on the specific requirements and costs associated with a *fully phased-array telescope*. Furthermore, within the context of DS3 we may assume that all signal paths are fully digital and consider the telescope on scales larger than that of an individual tile (in this case taken to be the smallest correlatable element). Complementary work will be undertaken within the proposed US design study; for the US study the specific considerations associated with the LNSD design study will be considered. Where there are common aspects close collaboration between the two studies will be put in place.

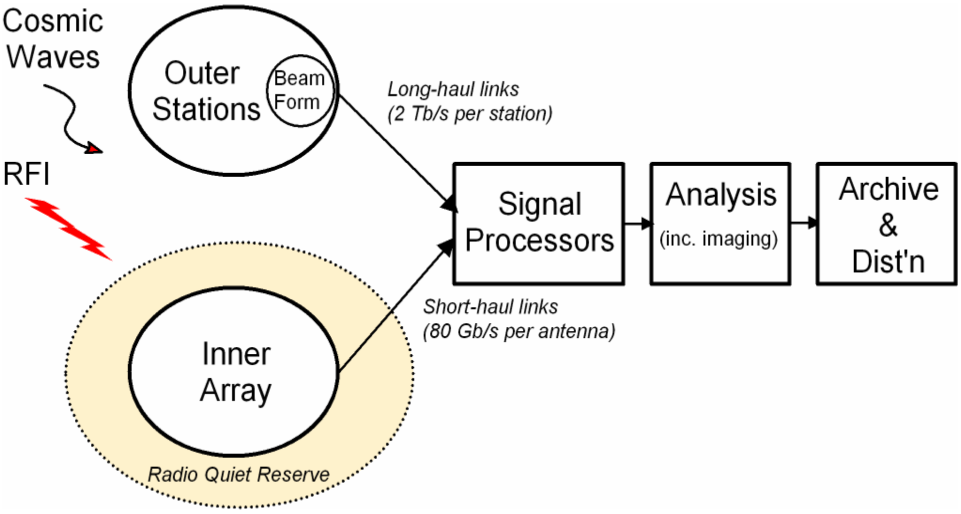

Fig 3.1 A current international visualisation of the network proposed for the SKA. The Inner Array and outer stations (see Fig 3.2) receive the cosmic radio waves but are also subject to man-made RFI which must be dealt with via a range of strategies in both hardware and software. It is envisaged, however, that the central few 100km of the SKA will be located within a nationally and internationally agreed radio quiet reserve. The central processing activity has been schematically broken down into sub-units but these are not hard and fast boundaries. The signal and data processing at the station and central processor and how the user interacts with data via the international GRID and AVOs, are major parts of DS3.

DS2 will produce a specification for the performance of the SKA at a detailed level, for example the required imaging fidelity (coverage of the Fourier domain, sidelobe levels etc), sensitivity, temporal and spectral coverage and polarization capability. DS2 will also produce a requirement for the imaging and surveying speed and flexibility. Within DS3 these aspirations will be assessed and refined in terms of achievable performance taking into account technologies which are likely to be available within the time scale of the project and importantly the cost implications of delivering and maintaining the overall telescope. Additionally we will consider how the science will be delivered to the end-user astronomer.

The overall coordination of DS3 will be undertaken by the UK consortium and much of the work will also be done in the UK and is discussed in detail below. DS3 is divided into the following four tasks – work to be undertaken within the UK consortium is identified (UK) the rest will be undertaken by non-UK SKADS participants (SKADS).

Task 1 is concerned with the physical infrastructure of the network in particular the hardware provision for the physical network: the distribution of clock and local oscillator and the potential role of opto-electronics (UK); the hardware requirements for efficient data transport (UK); the economic distribution and provision of electrical power (SKADS).

Task 2 is concerned with the nature and cost effective provision of the physical processing elements within the network and central processor (correlator): the cost and performance of commercially available processing elements from embedded processors to massively parallel systems (SKADS); the nature and provision of real time control software (SKADS); the overall costs of software provision (SKADS).

Task 3 is concerned with the conceptual design of the overall telescope and network architecture. The task will analyse and model the total flow of data and information both within the physical network and also in the broader sense by considering the way the end-user astronomer interacts with the telescope. Specific work packages address: the logical and physical structure of the network including data flow and processing elements (UK); the management of the data flow considering experience in other projects (UK); data products and archiving (UK); the achievability and costs of providing highly-distributed GRID-based software (UK); the way in which the astronomer interacts with the telescope from initial scientific concept to fully reduced data (UK); monitoring and visualisation of raw data and telescope performance (SKADS).

Task 4 is concerned with siting issues for the telescope: the requirements from the site in terms of the local and projected radio-quietness, typical ionospheric conditions etc. (SKADS); the requirement of the site for the provision of infrastructure such as access, power etc. (SKADS); assessment of the bids against the requirements of the project with particular emphasis on those aspects particular to a phased-array design (SKADS).

We now discuss each aspect of this design study in which the UK is involved.

3.2.2 Hardware provision for the physical network

The two aspects of the design study concerned with the transmission of signals are clearly related. We will investigate technologies for the physical infrastructure which deliver the of coherence (phase transfer) for interferometric observations at frequencies up to at least 2-GHz and preferably 30 GHz can be made with SKA, and which provide solutions to the data transmission problem.

The preliminary SKA design indicates that extremely high data transmission rates will be required. In some observing modes data rates before correlation are likely to be 1 Tbps from a single correlatable element (e.g. the data rate from a single tile). An important aspect of the overall SKA design philosophy is that while it is very unlikely that the full power of the SKA can be achieved in the first few years of operation, a clear upgrade route should be identified and costed over the lifetime of the telescope. One part of the system which is very likely to not be upgraded is the physical infrastructure of the data transmission system and the provision of phase-coherent signals. It is important therefore to put in place a system capable of delivering as close to the maximum data rates as can be achieved. Fibre optic technology potentially offers ideal solutions to both of these problems being low loss, having high intrinsic bandwidth and relatively low cost.

Phase Transfer (DS3-T1-WP01)

The SKA requires coherence to be maintained over antenna separations ranging from metres to 3000 km, either by the distribution of a Local Oscillator or, for a completely digital system, the distribution of a clock. We will investigate the use of fibre optics for distances up to ~150km (the inner core of the SKA) where this technology appears to be the most advantageous solution, and consider a range of options for the array as a whole. The eMERLIN fibre optic network will be utilised for SKA tests – the eMERLIN fibres will be installed by 2005, but the telescope will not be fully operational until 2007 giving us a unique window of opportunity.

Maintenance of coherence requires accurate determination of the path lengths (to an rms deviation equivalent to <0.6 psec if coherence loss of less than 1% is required at 30 GHz). The path length in fibre varies with temperature, and it is important to limit the rate of change of path length. This is achieved in the EVLA and ALMA by careful temperature control (Durand and McCool 2004), however it is inevitable that parts of the fibre link will not necessarily be well controlled – e.g. the sections of fibre on the antennas and at splice junctions in access pits. Accurate path length determination requires continuous go-and–return measurements. Limits set by non-reciprocal behaviour of fibre (due to polarisation mode dispersion), the stability of lasers in a multi-laser system, and non-linear effects in optical amplifiers require investigation before a design can be established. The link lengths are such that even with the low loss of fibres, optical amplifiers and repeater stations will be required.

Data Transmission (DS3-T1-WP02)

In this work package we will assess the emerging technologies likely to be available over the time-scale of the SKA project. We will maintain close contact with industry to gain insight in how communications technology is evolving.

Local area networks, making use of multi-mode fibre optic connections, are currently used over short distances, and developments of this technology are likely to provide the data rates required for the SKA on scales up to a few kilometres. Interference between the modes limits the maximum distance that multimode devices can be used and solutions on scales of 10s of kilometres are likely to require mode fibres. Direct modulation of the laser however results in frequency chirp, which currently limits the bandwidth and maximum range of devices to a few Gbits/sec and to propagation distances of order 10 km. We will assess developments in this and similar technologies which could deliver Tbps rates over several 10s km and determine whether multiple fibres or DWDM techniques will be required to reach Tbps rates. High data rate links beyond a few kilometres currently require externally modulated laser, single mode fibre and amplification. Current links have matured at 40 Gbps per wavelength, with 160 Gbps achievable in the near future. The long links out to 3000 km are such that the cost of laying fibre becomes significant, and here it may be more efficient to share use with telecommunication links. This could be via dark fibre lease or as managed bandwidth. The essential use of routers and switches in a telecommunication system adds unnecessary expense. However recent developments in wavelength switching may provide some solutions. The UKLight research network has been set up in the UK to test protocols and performance of such a system, though it emulates wavelength switching using conventional routers, giving a net data rate of 10 Gbps. We will draw on the experience of those involved in the UKLight and related projects to assess the likely solutions available to the SKA.

3.2.3 The overall architecture of the network

The SKA will be a quantum leap forwards as compared with current telescopes. The low-frequency “electronic SKA” of the type we are proposing, would be very different to any current telescopes in any waveband. For any interferometer consisting of n receiver elements we must combine their outputs either by forming correlation products (n(n-1)/2 in total) or by weighted addition. The traditional design of an imaging interferometer from the early One-mile and 5-km telescopes to the current generation of eVLA, eMERLIN, GMRT and ALMA all consist of a relatively small number (n) of large collecting area antennae which are correlated. In principle for the SKA the basic receiver elements could be taken to be the individual wide-band antenna elements (see DS4) which form the building blocks of the entire telescope and which have a field of view of the entire observable sky. The vast number of these basic elements (~10^8) mean that in practice they will be formed into “tiles” – phased arrays of ~100 basic elements and about 1 m^2 collecting area. These tiles have multiple dynamic beams and form the basic correlatable element of the SKA. Within DS3 we are concerned with the positioning, interconnectivity and combination of the signals from these elements together with the associated data flow and analysis.

In practice the instrument will be limited by our ability to perform the digital signal processing and manage the flow of data. Current interferometers form all correlation products – for the SKA even taking n as the number of tiles (10^6) forming all correlations gives n(n-1)/2 ~10^{12} at a data rate which can be as high as 1 Tbps. This amount of processing cannot be realistically achieved on the timescale of the SKA. The problem is reduced in 3 ways (i) by reducing the data rate from each tile (ii) performing phased additions instead of correlations (iii) distributing the processing and using dedicated hardware. The architecture of the SKA is very hierarchical. A preliminary concept envisages grouping the tiles into “stations” formed by phased addition each of collecting area 10^4 m^2, the ~100 stations connected by a broad-band optical fibre network resemble a more traditional instrument on the larger scale. This concept provides a useful paradigm for considering the likely operation of the telescope especially in “back-of-the-envelope” studies; a major task within DS3 will be to deliver tools which can be used to properly assess the performance of design concepts and help optimise the network architecture to meet the science objectives. On the largest scale the distribution of collecting area is likely to resembles the “station” model and in Figure 3.2 one possible distribution of such stations is illustrated; the required sampling of Fourier space which determines the precise location of receiver elements will be a major output from DS2.

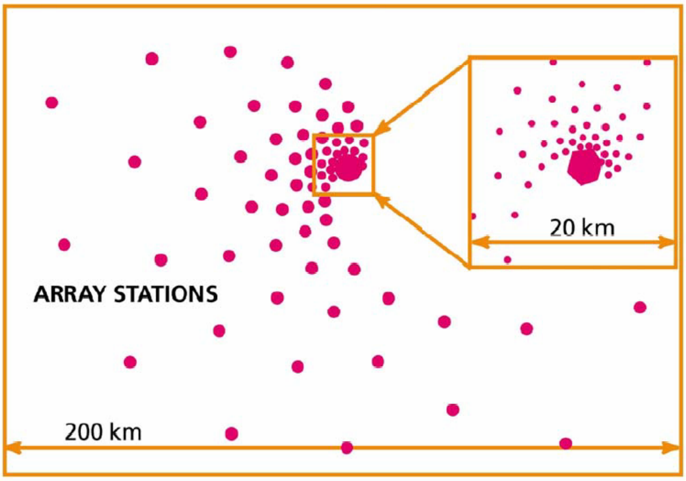

Figure 3.2: A schematic of one possible SKA configuration. The collecting elements and tiles are concentrated into stations each with a collecting area ~10^4 m^2. About 50% of the stations will lie within the central 5 km region (the “Inner Array”) with the majority of the remainder lying withi ~200km. A small fraction ~10% will be sited at distances out to 3000km.

Three work packages are devoted to this central problem of the telescope architecture (DS3-T3-WP01, DS3-T3-WP02, DS3-T3-WP03) and a further work package (DS3-T3-WP04) considers the closely related problem of the overall management of the data flow within the network architecture. To understand the tasks undertaken in these packages we now consider the imaging problem.

The output of each element is a complex voltage V_i; the only operations we wish to perform are additions or pair-wise multiplications in both cases also including specified phase-factors and amplitude modulation. The correlation products sample the Fourier transform of the sky brightness distribution at locations in Fourier space determined by the projected antenna separation (baseline) in a suitable 3D coordinate system for wide fields of view. Additions reduce the number of independent sampled points in Fourier space and represent a convolution. This process is precisely analogous to formation of the primary beam of a single large collector – the radiation falling on the collector is averaged and detected at the focus. An equivalent view is that the response of the instrument is determined by taking the sky brightness and multiplying by an apodization function determined by the weighted addition of correlation products and convolving with the Fourier transform of the distribution of projected baselines.

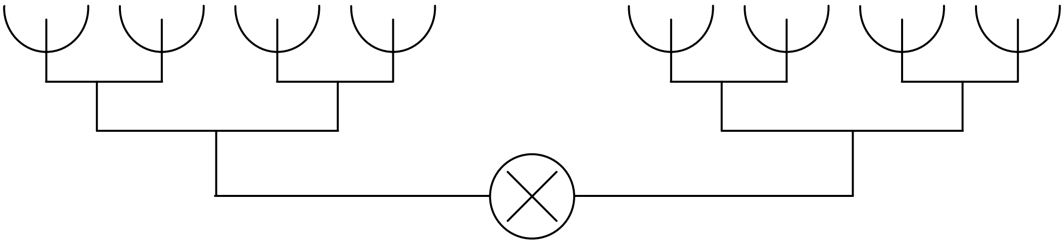

Figure 3.2. Schematic representation of an array with two groups of phased receiver elements which are correlated.

The connection to normal interferometric imaging can be made by considering the simple case when the output of two groups of m elements are each combined by additions with suitable phase factors and then the combined output of each group is correlated. For a 1D array the apodization function is just a standard grating response. From basic optics it is clear that for suitably chosen complex weights we can have up to m primary responses (beams) on the sky. This case forms the basis of the "station" paradigm in which 10^4 elements are combined to give a chosen number of beams with low side-lobe levels. It is clear however that more complex combinations of additions and multiplications give additional benefits.

For the SKA we must design an architecture which meets a number of requirements:

- To provide a flexible responsive tool with an adaptive response on the sky able to image many independent regions simultaneously to maximise scientific productivity.
- To provide the sidelobe levels and coverage of Fourier space required by the science drivers.
- To provide good nulling of interfering sources by placing a zero of the telescope response on each interfering source and following the source in time.
- Have a data flow which can be achieved within the predicted capacity of the fibre network and within cost.
- Have a computational requirement which can be achieved using a mixture of off-the-shelf and specialised processors and which can be delivered within the overall cost envelope.

The first and most important requirement which will be addressed by DS3-T3-WP01, -WP02 and -WP03 is a simulation code for the network architecture. A generic telescope simulator is being developed by the SIWG coordinated by the University of Swinburne, Australia; this simulator will take as input model skies and simulate the entire observing process including atmospheric transmission, interference modelling, data collection through to producing a model output data stream. We will provide input to this generic simulator in the form of a module specifically aimed at the phased array concept. Additionally our simulation package will model the data flow and logical/physical structure of the network (receiving elements, fibre infrastructure and processing elements). The simulator will be used to test the performance of different models for the telescope architecture against the scientific requirements. We will then begin to optimise the design of the architecture, many aspects of which are likely to be strongly constrained. For example, although the logical connectivity of elements within the network and the location of processors is a design variable, the physical location is not – the main processing power must be centrally located to minimise maintenance costs and avoid long data transfer paths after correlation (correlation increases the data flow rate).

In task DS3-T3-WP04 we will consider other technical aspects of the management of the data flow. Importantly we will look at the problem of the SKA in the light of experience which is being built up in other areas, particularly PPARC areas such as the work for the Large Hadron Collider and that for the Gravitational Wave experiment GEO600.

3.2.4 Data analysis

The SKA will produce un-paralleled amounts of data. Raw data from each element must be either phased or correlated; this, real-time, aspect of the data analysis pipeline is being considered in DS3-T3-WP01. The correlation of signals from antenna elements merely serves to increase the data rate although reduction of the bandwidth and integration of the data greatly reduces the amount of raw data emerging from the telescope. Even so, the total size of data sets produced by the telescope is enormous. The preliminary SKA science requirement (Jones 2003) require a maximum integration time of 0.1s, 10^5 spectral channels in full polarization and assuming a typical number of baselines to image a 1 square degree field of 10^6 (Carilli 2002) gives a data rate of approximately 10 TByte per second of correlated data for each of many independent beams. Traditional instruments pass these data to the astronomer to reduce using a fairly standard reduction pipeline of calibration, followed by iterative imaging / deconvolution / self calibration and largely to perform this analysis off site. Such an approach is only feasible for the SKA if Moore's law holds at its current rate until 2020. Furthermore, as discussed below, such an observing model may not be appropriate for the SKA.

It is essential that we obtain from the outset an analysis of the data analysis problem and assess (a) how much processing can end users undertake if they are provided with grid-enabled software; (b) how much processing must be undertaken using the observatory hardware and what are the implications for the telescope design; (c) what are the likely costs of providing grid enabled software both for end users and at the observatory. What is unusual about the SKA is that algorithmic developments are closely linked to the architecture of the instrument. In design study DS3-T3-WP05 we investigate ways in which data can be analysed using new algorithms and making use of the natural architecture of the telescope as a computational grid. The work is closely linked with questions of the overall architecture and the requirements of the science drivers – these aspects are being studied in DS3-T3-WP01 and the DS2-T2 work packages.

To illustrate the intimate linkage between architecture and algorithm we consider a particular case suggested by Wright (2004). Wide field mapping will be a pre-requisite for the SKA and a hugely challenging computational problem. Simply taking existing algorithms and approaches and parallelising them will be a first step, however the architecture of a phased array with a distributed grid of processing elements strongly suggests that we should consider novel approaches. For example the visibilities, $V_{ij}^* = V_i V_j^*$, which are functions of the baseline separation $B_{ij} = B_i - B_j$ between antennae i and j are related to the sky brightness distribution in a direction s by a Fourier relationship:

$$I(\boldsymbol{s}) = \underset{\text{all baselines}}{\int} V_{ij}(\boldsymbol{B}_{ij}) \exp(-2\pi i\nu \boldsymbol{B}_{ij}.\boldsymbol{s}/c)\ \mathrm{d}^3\boldsymbol{B}$$

In 2D the usual method of analysis involves gridding the observed visibilities onto a regular uv-grid and doing the inversion using an FFT. For the SKA we must consider (i) the much larger number of visibility data and the need for wide field imaging. In this case an algorithm based on a direct FT may be advantageous. We can re-write the Fourier inversion explicitly in terms of individual antennae:

$$I(\boldsymbol{s}) = \underset{\text{all baselines}}{\int} \left(V_i(\boldsymbol{B}_i) \exp(-2\pi i\nu \boldsymbol{B}_i.\boldsymbol{s}/c)\right) \left(V_j(\boldsymbol{B}_j) \exp(-2\pi i\nu \boldsymbol{B}_j.\boldsymbol{s}/c)\right)^* \mathrm{d}^3\boldsymbol{B}$$

the phase factors (exp($-2\pi i\nu B_j.s/c$) are antenna based and therefore could be applied on an antenna-by-antenna basis yielding a direct FT at less cost than other wide-field techniques (Wright 2004). The implications of such an algorithm are that the data product is not the visibilities, but a final image and significant ability to do multiple rounds of self-calibration driven by scientific objectives are lost. A solution in this case may be to archive the antenna outputs, V_i, and use grid technology to distribute the above calculation as needed by observers.

To determine the feasibility of algorithms of this sort for the SKA we will consider how proposed algorithms may be implemented for the SKA architecture and observing models so that we can determine:

- constraints on how the processing in distributed within the array;
- the relative amount of central processing compared to distributed processing required and a cost analysis of the various options;
- an assessment of the amount of software effort which is likely to be required for implementing such grid-enabled codes (input to DS3-T2).

Relationship to RadioNet

There will be close cooperation with this work package and related work packages within RadioNet. In particular, ALBUS, one of the Joint Research Activities within RadioNet is developing and implementing new algorithms and methodologies for calibration and imaging. Although the focus of ALBUS is software for European VLBI the underlying aim which is the efficient analysis of large interferometric data sets is central to the issues faced by the SKA. This SKA Design Study work package will complement the existing effort within RadioNet (which itself has links and coordination with software development within the U.S. NRAO) by focusing on specific issues relevant to the design and specification of the SKA.

3.2.5 The end-user astronomer

The SKA we are planning is so radically different from current instruments that the conventional way in which the user interacts with the instrument and its data requires a complete re-evaluation. “SKA for the User” DS3-T3-WP06 and -WP07 are specific studies to address these issues within SKADS. Traditional use of telescopes has mostly followed the “peer-reviewed application for time”, “scheduling of individual observations” and finally “analysis and exploitation by observers of specific projects”. This is coupled with access to archive data. An alternative model is “undertake a systematic scientific programme” then “make data products available to all via a Virtual Observatory”. Traditionally radio interferometers have delivered un-calibrated “visibility” data to the astronomer the analysis of which is often viewed as a task “for a specialist”. This choice is made to preserve in the archive the most flexible data product. However for many purposes a further level of reduced data is the output used by the community – examples include the many important surveys (3C, 4C, … and recently the NVSS and FIRST VLA Surveys). At the same time significant efforts have been put in to produce good quality first-pass pipelined data for example for MERLIN. The new generation of radio telescopes (eMERLIN, eVLA and ALMA) will provide as a central data product essentially calibrated visibility data; end-user astronomers will further process data via pipelines (linked to an AVO interface); the raw visibility data will be archived and be the principle data product. A challenge for the SKA will be to provide end users with data products which maximise the scientific output of the instruments and make them as accessible as possible, but at the same time determining on an archival system which maximises the possible information which can be extracted from the data.

The unique nature of the SKA will have significant implications for the operation of the facility and the way the user interacts with the telescope. In particular we will examine the following aspects of the end-user interaction with the telescope.

Proposal stage. The nature of the SKA, and in particular the observing speed and multi-tasking observing capability via many independent beams raises important issues with respect to how users gain access to the telescope. At one extreme it is certain that consortia of observers will wish to undertake substantial surveys as is envisaged by the main science drivers. Such proposals are likely to require large fractions of the available telescope observing time and some direct peer-reviewed application procedure will, as now, be required. At the other extreme an astronomer may need targeted observations on a relatively small number of objects requiring an almost insignificant fraction of the total observing time of the instrument. Indeed such an observer will probably interact via an AVO and will not be interested in whether the data reside in an archive or represent new observations. How are these later requirements to be met? Is it possible to construct a model in which new observations are triggered by an AVO request; if so how should these observations be prioritised? Can a system be constructed which efficiently anticipates the likely requests of observers? In this case can, or indeed should, there be any concept of proprietary data and what implications are there for the archiving of raw data?

Observing modes. The science drivers define a set observational requirements for the telescope. These requirements must be re-evaluated in terms of the possible observing modes available to an end user.

End-to-end user environment. The close integration between proposal, data reduction and AVO access suggested by the flexibility of the SKA may suggest that a new model for the end user interface to the telescope is required. One possibility is to use a single software portal for access to all the functions of the telescope. This should not only incorporate proposal and operation modes, AVO-type access, data reduction, but also access to user support functions and facilitate scientific dialogue between astronomers. In particular within this work package we will investigate state-of-the-art systems which provide shared resources and a development environment tailored to collaborative research programmes.

The level of user support required for observers will depend on the details methods by which users interact with the telescope resource. An estimate of the required level of user support (and associated costs) for different user-interaction models will be developed.

3.3 The technology development overview

3.3.1 Background: the necessity of a significant technological development programme led by the UK

The idea for a Square Kilometre Array originated in the UK (Wilkinson 1991), and UK scientists have been in the vanguard of assembling the international structures to plan and develop the concept. It is a fact, however, that virtually none of the technological development to date has taken place in the UK, and as a result of their investment in R&D, technical leadership currently resides mainly in the Netherlands, Australia and the USA. As a result the UK runs the risk of becoming a bit-player in the design of the SKA and then in the construction of a £1B international facility. This is completely inappropriate, given the UK's role in conceiving and nurturing the concept to its current stage, and given the UK's broad-based knowledge and skills base in relevant technologies. Our intention is, therefore, to take a leadership role in the present technical R&D phase, the first major phase being coordinated internationally, and in so doing to forge strong links with UK industry. By this means we will ensure that the UK will be positioned to play a leading role in the design and construction of both the science pathfinder in the period 2010-2013 and the full SKA up to 2020. In collaboration with our colleagues within SKADS, most importantly in the Netherlands, we have identified the technological development required from the UK over the next ~4 years.

3.3.2 The long-term vision

The long-term vision driving the European-led phased array concept for the SKA is of a highly flexible system, with background-limited rf performance, which collects and processes "every photon which falls on the array", from all directions and in a given frequency band. The system should be configurable at the observer's will to provide the widest possible range of processing options and this capability should be available to many observing teams simultaneously. *This is a revolutionary new paradigm for radio astronomy.* To bring this vision to fruition the SKADS team must fully explore a hierarchical phased array architecture, from the design of the fundamental antenna element to the tile configuration to the station configuration. The underlying philosophy is to employ a scaleable, modular, approach to facilitate future upgrades, in particular as digital electronics and computing power advances.

Why cannot we just scale-up existing phased-array designs? The answer is two-fold. First their cost per-unit-area is too high and second their capabilities are not optimized for radio astronomy (receive only) use but invariably for radar (transmit and receive) applications. In the latter, minimising the system noise level and maximizing the main beam efficiency are not such critical design drivers as they are for radio astronomy. Also the bandwidth required for radio astronomy is far greater than for commercial applications. Astronomical applications place different demands on our knowledge of the beam-shape and sidelobes compared with radar applications. The SKA will be a multi-fielding *imaging* instrument with extraordinary instantaneous sensitivity coupled with the requirement to integrate on selected areas of sky for hundreds of hours; as a result each field-of-view will be full of cosmic radio sources. In order to deliver the required dynamic range ($>10^7$: 1) and image fidelity the overall reception pattern must be extremely well-understood at all times. We cannot simply change the complex antenna weights to suppress sidelobes at the expense of main beam efficiency—in contrast to the radar situation there is no way to increase the signal level from a distant radio source! Achieving this control of the reception pattern requires a highly-accurate beam-forming system coupled with a sophisticated understanding of the behaviour of close-packed antenna elements as a function of angle from the zenith. Achieving the required level of understanding is one of the aims of SKADS. Another problem to be understood and overcome is the effect of RFI mitigation techniques; for example creating and steering reception nulls, inevitably affects the entire reception pattern.

3.3.2 Overview of the UK SKADS technology programme.

The purpose of this technology development programme is to demonstrate, by the date of the SKA concept decision in 2009, that phased arrays are a viable choice for the SKA low-frequency system. As major practical steps towards this vision, the European SKADS team has identified two complementary development programmes, which must proceed in parallel, and which together are necessary to establish the viability of the phased array concept for the SKA. These are:

1. The EMBRACE radio astronomy demonstrator phased array (DS5) which will be ASTRON-led but with significant UK involvement, which will demonstrate a large-area phased array using a development of existing tile technology developed at ASTRON.

2. A programme to develop the next generation tile technology necessary for the final SKA design, which will be UK-led (DS4).

Since the SKADS proposal was submitted (March 2004) there have been significant changes in the UK community's thinking about its roles in DS4 and DS5. Most importantly the vital need to develop and test a specific 3rd generation all-digital phased array tile has been agreed both internationally and with our SKADS partners. However, the details of how the SKADS DS4 programme will be modified to encompass this more extensive UK programme have not yet been finalised. This will be the major task of the SKADS team during the contract negotiations with the EC in October 2004. In describing the UK's role we have, therefore, not retained the structure in the SKADS proposal but have concentrated on the R&D required for the delivery of the 3rd generation tile.

The strategic overview of the SKADS planning for phased array development is encapsulated in Fig 3.3

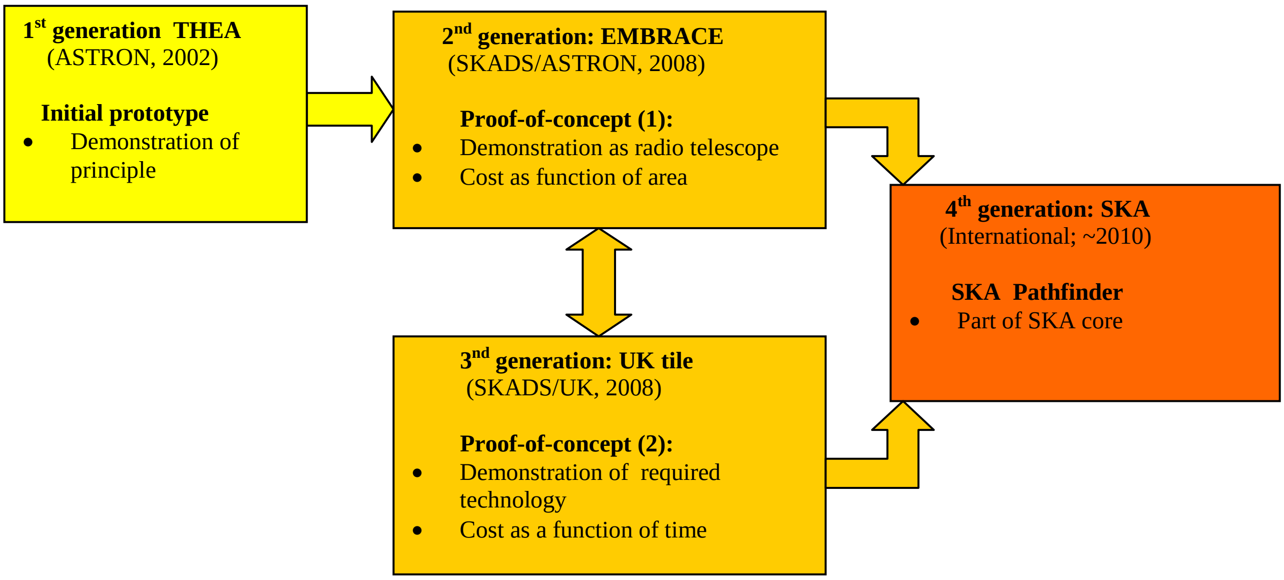

Fig 3.3 : The strategic relationship between the SKADS phased array developments required for the SKA

To explain why it is necessary to develop and test a 3rd generation tile we first have to summarise the reasons to construct EMBRACE. The requirement is to demonstrate that a phased array, of a size comparable to that of a conventional medium-sized paraboloidal radio telescope, can perform predictably and well as a multi-field radiometer with wide-angle scanning capabilities and at least two independently controlled fields-of-view. *An array of such a size and performance at decimetre wavelengths has never before been constructed.* The programme will be led by ASTRON, building on the expertise they have developed in the THEA programme[5]. Since it is critical to deliver and test EMBRACE before the end of this Design Study we cannot expect to optimise all aspects of the design, which will therefore be a ("second-generation") evolution of the existing ("first-generation") THEA design. The principal features of the EMBRACE programme can be briefly summarised as follows:

- Exploration of the performance of a large area (100s square metres) phased array, thus prototyping an entire SKA "station"
- RF performance requirements: T_{sys}=100K; single polarisation
- Analogue plus digital beam forming at tile level for current practicality
- Demonstration of "station" beam forming from the EMBRACE array
- Gathering information on the cost equation for phased arrays and its derivative with respect to economies of scale.

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[5] More details of the ASTRON THEA project can be found at http://www.astron.nl/tl/thea.htm

The requirement to design, construct and make astronomical tests of a significant area of phased array in EMBRACE within 3 years after start-up, limits the system performance which can realistically be achieved. The EMBRACE technology, *by itself*, will be insufficient to demonstrate the aperture array concept for the SKA. It is therefore vital to develop the next generation technology in terms of rf performance and beam-formation architectures if we are to be confident of meeting the SKA science requirements. This is the goal of the SKADS DS4 programme. Since the submission of SKADS proposal in March 2004 the UK Consortium has extended the goals to include a demonstrator tile as a definite deliverable to prove the technology that will be required for the SKA. The goals of the UK tile programme can be briefly summarised as follows:

- Next generation RF performance requirements:
    - T_{sys} < 50K (survey speed is proportional to $[1/T_{sys}]^2$)
    - dual polarisation (vital for several of the KSPs),
    - full bandwidth
- Demonstration of an all-digital beam forming architecture, the long-term solution for maximum flexibility
- Gathering information on the cost equation for phased arrays and its derivative with respect to economies of scale.

Both projects together will demonstrate that the phased array concept can be implemented within the overall SKA cost envelope. At the recent meeting of the SKA community in Penticton (July 2004) the UK plans for a 3rd generation technology demonstrator were endorsed as a vital part of the European programme.

3.3.4 Specifics of the UK Technology Programmes

In essence we are proposing to form three design and build teams, combining the UK's academic and industrial expertise:

1. *Electromagnetics* (optimized antenna elements, tile configuration, mutual coupling and matching)
2. *Innovative semiconductor components* (ambient temperature, low-noise amplifiers optimised for radio astronomy; high speed, low-cost analogue-to-digital converters).
3. *Digital signal processing and beam formation* (for the prototype all-digital tile and for EMBRACE)

These teams will then come together to carry out the fourth major area of technology development, the manufacture, integration and testing of the prototype digital tile. We now give an overview of the tasks involved. More details are given in section 3.3.5.

DS4-WP01: Design specifications

The first critical phase of the UK programme is to define in quantitative detail the scope and specifications of the technical work involved in the 3rd generation design, build and test programme. Some of specifications of the 3rd generation tile (the current status is in Annex J) can be set already on very basic grounds or on the basis of the current international SKA science specification, but many others require an in-depth review involving cost-performance trade-offs. The generic programme challenges include:

- Fundamental rf performance requirements
- Electromagnetic compatibility requirements
- Beam formation flexibility required
- Manufacturability and Cost
    - Required levels of integration
    - Reduction of chip and assembly costs
    - Low cost packaging
- Testing: The SKADS team needs to understand the beam, sidelobe and polarisation performance to a very high level in order to achieve the required dynamic range for the full SKA.

DS4-WP02–WP08: The front-end collector system

The aim for these work packages is to design a front-end system in modular form (see Fig 3.4) with sufficient performance that it will not need to be upgraded during the lifetime of the SKA.

- **DS4-WP02:** Dual polarized antenna elements in a closely-coupled array with well understood mutual coupling properties, high polarisation purity and sidelobe properties
- **DS4-WP03,04,05:** Low-noise, low-cost amplifiers, optimised for radio astronomy applications and operating at ambient temperatures
- **DS4-WP03,06,07:** High performance, low-cost analogue-to-digital converters (ADCs) associated with each element of the dual-polarised antenna
- **DS4-WP08:** Digital filtering of the broad-band data stream from each ADC into narrower bands to facilitate subsequent digital processing in the hierarchical beam-forming system

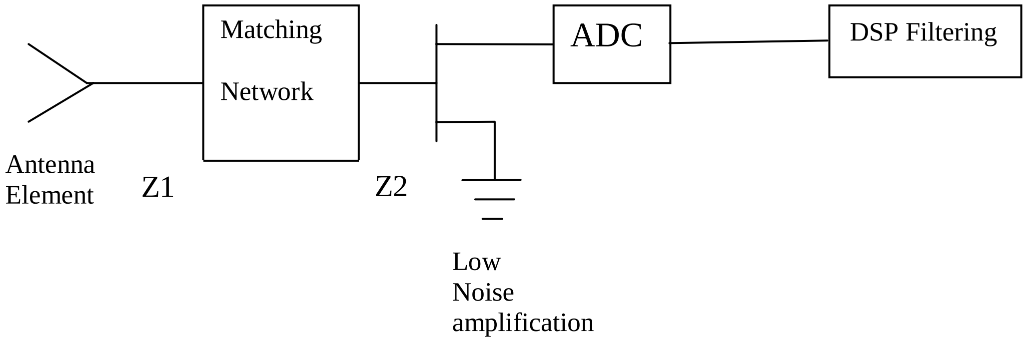

Figure 3.4 Schematic of a digital antenna module; up to ~200 such modules (two for each dual-polarised antenna) will be integrated to form the “front-end” of the 3rd generation tile

DS4-WP11: The distributed signal processing engine at tile level

This workpackage will investigate the architecture and hardware solutions for signal processing at the tile level, and explore the use of commercial or customized hardware and firmware/software solutions for signal processing and combination. It will interface with the station-level beam-forming effort in DS3 and with the construction of beam-forming hardware in EMBRACE.

DS4-WP09, WP10, WP12–WP19: Production and testing of the 3rd generation tile

We are designing a complex device. By integrating the modules and other sub-systems and then testing a tile in detail we will encounter and have to overcome emergent problems along the way. The final test programme will establish confidence in the design and our particular approaches. Without this build and test programme will never be able to convince the international community of the viability of the phased array concept for the SKA.

To demonstrate the practicality of the new technology development described above, we will, therefore construct and test a small area (few m^2) of collecting area. Because the SKA will eventually be an industrial scale device it is important to start, right from the beginning, with a structured approach to manufacture of any prototype. This is part of the reason for involving industrial collaborators. By this means quality control over the design, construction and test phase can be maintained and monitored and the experience gained will inform the issues of manufacturability for the full SKA.

- **DS4-WP09,10** Module integration – integrating the key technologies of antenna, LNA, ADC and digital filtering into a single manufacturable unit and defining its test requirements.

- **DS4-WP12** Production of tile's worth of element-level DSP
- **DS4-WP14** Infrastructure of tile
- **DS4-WP15** Fabricate modules
- **DS4-WP16** Manufacture tiles
- **DS4-WP17** Integrate tiles
- **DS4-WP18** Test tiles
- **DS4-WP19** Cost reduction

3.3.5 Technical details of the DS4 technology development

Antenna and antenna configuration development.

Unless the fundamental electromagnetic performance of a phased array is understood to a high order of accuracy, it will never be possible to move forward to a design of the full SKA employing this concept. At the heart of any phased array system is the individual radiating element. The THEA array, which represents the current state of the art in radio astronomy phased arrays, uses Vivaldi antennas (see Figure 3.5) with a bandwidth ratio of about 2.5:1. The broadest frequency range that is being considered for the low-frequency SKA band is 0.1 to 2 GHz, a 20:1 ratio. For a successful application of the aperture array concept the antenna must have well-behaved radiation pattern and polarization properties over this whole band, as well as a good impedance match to the front-end amplifier. The antenna must also be realizable in large quantities at low cost. No current antenna design meets all these criteria, and a very significant research and development effort will be necessary to produce a suitable design.

Traditionally multi-octave element designs operate with an input match (VSWR) of order 2.5: 1. This level of match is entirely incompatible with achieving the low noise temperatures demanded by radio astronomy (the VSWR losses will dominate). This is one crucial area that SKA differs from more traditional applications of phased arrays. Initial considerations show that the high frequency end of the band (~2 GHz) is more critical for noise temperature and hence impedance matching than the low-end frequencies. Accordingly there is the possibility of using input impedance profiling as part of the overall element design optimization process. As in any array, element impedance optimization is complicated due to mutual coupling within the array. Hence the element performance is affected by the array geometry within the array environment due to mutual coupling considerations.

A second constraint on the element design is the size of the element. In conventional multi-octave designs the element is of the order half a wavelength in extent at the lowest frequency. Taking this approach, the element would be several wavelengths at the highest frequency. This sets the inherent minimum element separation. With a minimum array separation of several wavelengths it is not possible to control the energy in the grating and sidelobes to low levels which is important at the high end of the frequency band. On the other hand if a suitable element could be developed the efficiency of the element at the low frequencies will be limited due to its small size. Therefore a trade-off is clear between array configuration and element size. This cannot be considered independently from the array geometry that drives the mutual coupling issues.

In simplistic terms, in a multi-octave array a spacing of less than one wavelength at the highest frequency means that at the lowest frequencies the separation is very small (possibly less than a tenth of a wavelength in SKA). At these small separations the coupling will dominate the array performance and array will essentially operated as a current sheet. For electrically small elements, closely-spaced, it is probable the coupling will not result in higher order modes (although this must be confirmed with detailed calculations), but will cause major input impedance variations across the array. In practice this means to form a beam in a certain direction will require complex weights considerably different from a simple linear phase weighting. Importantly, due to the frequency dependence of the coupling, these weights may change rapidly with frequency. At the higher frequencies the coupling changes, with required weights probably being more stable but the possibility of higher order modes increasing. Thus we see that the array geometry and detailed element design combined effect not just ultimate radiation performance but also the digital beam forming strategies.

Another major driver for SKA is the cross-polarisation performance with scan angle - a high degree of polarisation purity is needed for at least two of the Key Science Drivers (pulsar timing and the Magnetic Universe). In practice cross polarisation is given by the element design and by any higher order modes effects introduced by the coupling.

Due all to the above considerations, preliminary designs for SKA are postulating the band is split into two: the low end from 150MHz to around 500MHz, the high band 500MHz to 2 GHz. Element types to be studied include:

- Shaped exponential slots in both stripline (Vivaldi-type) and fin-line
- Optimised wire structures
- Dielectric loaded elements

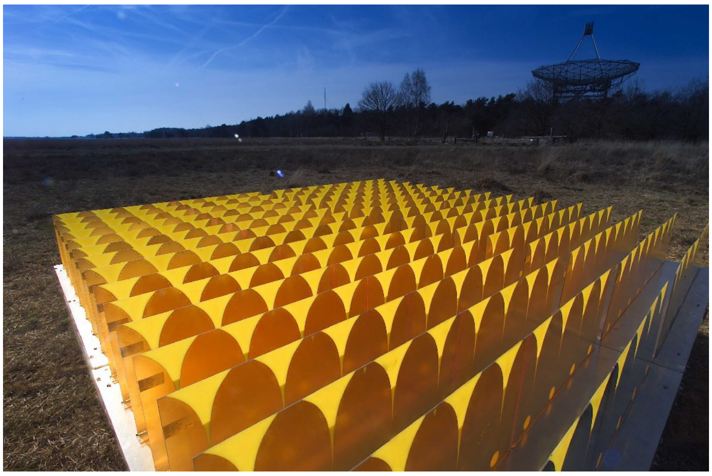

Figure 3.5 A single-polarization Vivaldi-antenna array designed and built by ASTRON for the THEA project. This “1st generation tile is ~1 metre on a side.

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Element /LNA interface

The noise performance of LNAs is strongly dependent on the input impedance. Since the impedance of antenna elements varies as a function of frequency it will be necessary to introduce a matching circuit between the antenna element and the low noise front end in order to minimise the VSWR and hence the noise temperature. The interface between the antenna element and the LNA therefore needs to be optimised. The desired multi-octave bandwidth design must be cheap and easy to fabricate. The aim of this area of the design study is to produce a multi-section matching network, which may be partly on-chip and partly on the actual antenna element, that matches element to LNA. It is proposed that this investigation will implement Carlin’s real-frequency technique (an iterative algorithm to solve impedance matching problems) to achieve good match between these two highly mismatched components. In accordance with Fano’s bandwidth limitation theorem it would be a mistake to treat each component separately and match both to the system 50 Ohms. Series source feedback may also be employed in the LNA design to shift the optimum noise figure or measure match to a region compatible with the receiving element. Clearly then for optimum performance the matching network cannot be designed in isolation from both LNA or antenna element and will be optimised with respect to both.

The antenna and array development will be a collaborative effort between the University of Manchester Communications Engineering Group, who have extensive experience in antenna design, BAe Systems, who have developed many phased array radar systems and have the largest near-field antenna measurement facility in the country, and the Cavendish Laboratory (University of Cambridge), who have considerable experience of radio astronomy antennas and far-field testing. Two PDRAs at each of Cambridge and

Manchester for 2 years will work on parallel developments, allowing several different antenna concepts to be explored, with an additional part–time person based in Manchester who will travel frequently between the sites to provide co-ordination and coherence between the various activities.

Semiconductor and device development

For the successful implementation of the digital aperture array concept, active semiconductor devices of an exceptional level of performance/cost ratio will be required. The front-end low-noise amplifiers (LNAs) must deliver very low noise performance at ambient temperature (or at a temperature achievable by cheap thermo-electric cooling) over a very broad fractional bandwidth, at very low cost per device. The analogue to digital converters (ADCs) must deliver extremely high sampling rates (around 4 GHz) with low power dissipation and low cost. To achieve this performance level, a programme of device development is required that includes work on development of semiconductor materials and the transistor structures that are formed on them, as well as the circuit design and integration of the LNAs and ADCs themselves. Once the processes for device and material fabrication have been established, mass manufacture can be licenced to existing industry.

Materials development

The semiconductor development programme proposed here is unmatched elsewhere in the world. Even the highest-performance devices currently used for astronomy are based on standard semiconductor foundry processes. This programme will develop customized wafer and fabrication processes that are optimized for the circuit design, with feedback between all stages of the device fabrication. It will combine the capabilities of the Microelectronic Materials and Devices (MMD) Group at the University of Manchester (UM), the Microwave Engineering Design and Measurements group at QinetiQ and the radio astronomy group at UM, Jodrell Bank Observatory (JBO). The semiconductor devices will almost certainly be based on advanced epitaxial compound semiconductor materials. The MMD Group has two Molecular Beam Epitaxy (MBE) reactors including one of the most advanced facilities in Europe. In the last year the facility has benefited from both a large SRIF (£750K) investment and a substantial donation from VGSemicon (£2m) to establish a truly world class facility for growth, assessment and device fabrication on up to 8” substrates. The materials assessment laboratory is equipped with automated full mapping metrology equipment. The total investment in equipment and infrastructure is in excess of £4m.

The MBE growth programme will concentrate on putting together the materials systems and device structures that are relevant to the particular requirements of the SKA, including high linearity and high breakdown voltages. Complex simultaneous parameter optimisation of both materials and layout will be used in order to maximise the performance of the final devices.

Low-noise amplifiers

Despite the fairly low frequency requirements for the European SKA concept, it is not possible to simply buy the active elements of the SKA receivers from commercial manufacturers. Although the requirements of commercial and military (C&M) communication receivers seem similar to those of radio astronomy, there are in fact major differences that would compromise the SKA’s performance.

- Lowest possible amplifier noise contribution. C&M receivers typically operate with a background noise temperature of ~300K (emission from the ground) while in radio astronomy the combination of sky noise and residual ground emission to the overall receiver system temperature is typically of order 10K. Hence the low-noise amplifier (LNA) temperature contribution is extremely important for radio astronomy applications but normally has only a modest impact on C&M applications. C&M amplifiers are thus not optimized for very low noise perfomance.

- Highly linear behaviour. The mixing of out-of-band interfering signals in components with non-linear characteristics leads to spurious in-band inter-modulation products, which limit the achievable noise level. If this mixing occurs in the first amplifier then nothing further can be done. A requirement of radio astronomy amplifiers is, therefore, highly linear behaviour over a wide range of input signal levels. If this is achieved the unwanted interfering signals can be filtered out before affecting the rest of the receiver and the data collection system. A further advantage of achieving highly linear behaviour is that the gain of the amplifier is less likely to be modulated by large out-of-band signals.

- Breakdown voltage. Experience with discrete low noise devices in radio astronomy is that these have a relatively low breakdown voltage(~2volts). This limits handlability and survivability with inherent cost implications for large scale production.. One key goal for the semiconductor programme is to provide a high breakdown voltage (target~5v) whilst maintaining low noise and high linearity.

- It is further noted that existing commercial LNA devices may sometimes be acquired from US companies, very often funded from US military sources. These are not optimised for radio astronomy usage. Before such devices can be acquired a US government export licence must be issued which, among other contractual conditions, means producing detailed ‘end-user’ statements. These limit the subsequent use of any devices procured and even then the quantity is severely restricted and the cost high. There is, therefore, a demand within the radio astronomy community to source the new devices we require for the phased array SKA concept within Europe

The key to achieving the device of choice for the SKA is both materials and topology (lithography) driven. We aim to achieve a powerful combination of semiconductor materials structures with “modest” lithography (0.5 to 1 µm gate length (L_g)) to significantly advance the state of the art in LNA without recourse to aggressive scaling ($L_g \leq 0.1$ µm) and its consequent high cost, as is the case presently. The use of modest lithography tools will result not only in high yields but also much more importantly in low cost manufacturing, a key driver for the implementation of the international SKA project. The MBE/lithography studies in here aim to specifically address these issues by fully comprehending the parameters space at play in the realization of advanced receiver circuits for the SKA

Analogue to digital converters

Most conventional receiver systems require one or more stages of downconversion after the LNA. For a phased array system this adds considerable complexity in terms of local oscillator distribution and cost and limits instantaneous bandwidth. By developing a high performance analogue to digital converter (ADC) it is possible to consider the use of a direct digital receiver approach for the SKA receiver front-end. Direct digital receivers offer considerable advantages over conventional receivers in that they allow digitisation closer to (or at) the antenna. These advantages include reduced size, weight and power, increased flexibility/functionality and improved noise immunity. Importantly for SKA , this also means the overall performance will be limited by the back end (digital beamformer) not the front end (rf) components. As technology develops during the life of SKA the flexibility and performance of the instrument can be upgraded by improving the digital beamforming process without the need for front end refurbishment. What is needed is the development of high sample-rate analogue-to-digital converters (ADCs) to facilitate digital signal processing of wideband microwave signals at up to 2 GHz.

Existing high-speed ADC architectures fall into three basic categories, the all parallel “flash” architecture, the folding/interpolating architecture and the subranging architecture. Another architecture that has gained popularity in recent years is the oversampled ADC. This approach employs delta-sigma modulators operating at many times higher than the Nyquist sampling rate to trade resolution in time, to resolution in amplitude. An architecture study will be undertaken at the start of this work package to determine the optimum approach for the SKA application.

With the integrated LNA and ADC circuits constituting the major technological backbone in the phased array concept of the SKA, a comprehensive, advanced semiconductor epitaxial growth, design and fabrication will be a key feature of the overall SKA programme. The major aim of this study is not only to deliver increased functionality above and beyond what is available today but also to deliver it in a cost effective manner, sometimes up to two orders of magnitude less cost than is possible today using off-the-shelf components. This will be possible because the UK consortium will have at its disposal state-of-the-art production equipment for growth and fabrication of advanced semiconductor structures, a first in the history of UK radio astronomy. This will make possible specific designs and fabrication uniquely tailored for the SKA, and thus shape particular UK scenario planning for the array concept, a situation impossible to pursue in the commercial arena, as access to the semiconductor materials and new architecture is simply not possible.

Digital signal processing and beam forming

In the digital tile concept, all signal processing, from the individual element level onwards, is done in digital hardware. This will necessarily be done by a hierarchical signal architecture, but the first level in the hierarchy is particularly significant. It is here that the raw output from the digitisers is first processed, and where the highest data rates and clock speeds are encountered. The DSP elements employed will face stringent requirements for performance vs cost, and for electromagnetic compatibility (since they must be in close proximity to the RF and A/D electronics). Since the subsequent signal processing is unlikely to be able to cope with the full signal bandwidth (around 1.5 GHz) instantaneously, the role of this element is to select the observing band (which can be of quite general shape, including nulls to deal with RFI if necessary). The appropriate hardware must be selected, algorithm design for the range of possible processes carried out, and a prototype system designed, built and tested.

In conventional synthesis radio telescopes, the different parts of a plane wave arriving from a radio source along the primary axis of one of the collecting elements are brought together in phase at a single point using the geometric properties of a paraboloid. It is the size of this paraboloid that determines the maximum instantaneous field-of-view of the instrument. In SKADS, we propose to receive radiation from individual elements on the scale of a wavelength, to amplify and digitize the signals and to add the signals together with appropriate delays in order to emulate the properties of a paraboloid, for waves coming from not just one, but from multiple directions in the sky simultaneously.

In traditional phased arrays, the combination of the signals to form the beam is done using analogue phase shifters and combiners, acting on the RF signal from the elements. The number of elements that can be combined and the number of output beams is fixed by the architecture of this hardware beam combination. In contrast, we intend to demonstrate a completely digital beam-forming system in which a wide range of numbers of elements can be combined and varying numbers of beams formed. In principle digital beamforming is not new;it has been used on a small scale by the defence community for some years. What is completely new is to utilise this on the scale , bandwidth and cost considerations of SKA.

The digitized and frequency filtered signals from the elements will be fed into a hierarchical beam combination network that will output a set of beams of variable pointing direction and angular size. In principle beams representing combinations from single elements up to an entire station (~10^6 elements) are possible, although there will be practical limitations to that range. Part of the design study will be to investigate the most appropriate hardware with which to implement the signal processing. General-purpose microprocessors are very flexible and easy to program, but are not optimised for very high data processing rates. Digital signal processing (DSP) processors and Field Programmable Gate Arrays (FPGAs) combine highly efficient signal processing power with the ability to be re-programmed in real time to implement different beam-forming strategies. Depending on the processing architecture adopted there will likely be different types of hardware employed in different parts of the system.

THEA provided the first demonstration of beam-forming using such phased arrays, and EMBRACE (SKADS DS5) will advance the techniques further. However, unlike THEA, which uses a correlator to perform the imaging, within a tile (and within a station) all the beam-forming needs to be accomplished through a linear addition of signals, with appropriate time-delays or phase rotations and gain factors to control the beam-shape and side-lobe levels. This will be a highly compute-intensive process and the degree of functionality achievable is likely to determined by the available computational resource.

We will briefly consider the feasibility of carrying out the required operations entirely digitally. In all SKA concepts so far, the final images or beams result from the synthesis of the full aperture, by combining the data from a number of distributed *stations*, each having a compact effective collecting area (A_s) of order 10^4 m^2. The beam-forming at station-level may be performed by the use of single large reflectors, or by combining the signals from a large number (N_p) of smaller elements, generically called patches, of collecting area A_p. These patches may for instance be small parabolic reflectors, or in the aperture array concept, collections of quasi-omnidirectional antennas, with a number per patch of N_a. The patches define one or more (N_f) fields-of-view (FOV, each of angular area ~ λ^2/A_p sr) within which multiple (N_b) station beams (each of angular area ~ λ^2/A_s sr) may be formed by combining the signals from all patches with appropriate phases. If we identify a patch with a 'tile' of area ~1m^2, then $N_p \sim 10^4$ and $N_a \sim 100$.

The fundamental operation for both frequency filtering and beam-forming is the multiply-and-accumulate (MAC), and digital signal processing (DSP) devices can be rated by the number of MAC/s they can perform on fixed word-length data. For example, the Xilinx Spartan-3 low-cost field-programmable gate array (FPGA) is quoted at 276 GMAC/s on 18-bit data, at a cost of \$100 per chip. With a conservative estimate of the cost of the embedding circuitry, this gives 1 GMAC/s/\$ as the current cost of DSP. Assuming Moore's law holds until 2015 (a likely date for beginning construction of the full SKA), the equivalent value then will be 250 GMAC/s/\$.

If each element is filtered individually, a number $N_a N_p \sim 10^6$ digital filters will be required per station, each clocking at twice the maximum RF frequency B_{RF} (~2 GHz) , and implementing N_{tap} MACs per sample, where N_{tap} is the order of the digital filter – typically 512. This results in a total filtering DSP requirement of $2B_{RF} N_a N_p N_{tap} \sim 2 \times 10^{11}$ MAC/s, costing under \$10,000 per station in 2015, a negligible fraction of the estimated cost per station.

Turning to the beam forming at the patch level, in the simplest case in which beams are formed by weighted addition of signals from each element, for every FOV formed each patch has to perform $8 N_a B_{IF}$ MAC/s, (where the prefactors are ×2 for Nyquist sampling, ×2 for complex data and ×2 for polarizations, and B_{IF} is the 'IF' bandwidth after the digital filtering and re-sampling). The largest possible value for this is when all N_a fields of view are formed at full bandwidth, and works out to \$800 per patch, or \$8,000,000 per station – clearly excessive, but also producing a data rate that could not possibly be correlated downstream. More reasonable values of $N_f = 10$ and $B_{IF} = 500$ MHz give a cost per station of \$200,000.

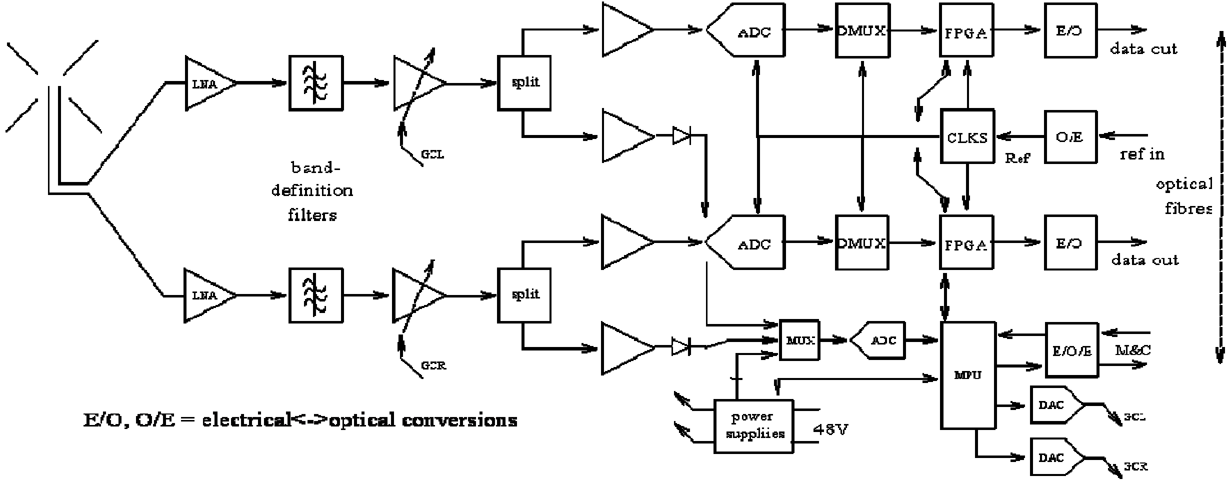
Finally the beam-forming at the station level, by a similar argument, requires $8 N_f N_p$ BIF MACS, at a cost of only \$2,000 for the whole station! The maximum output data rate from the station is then $8 N_f N_p B_{IF}$ words/s or around 10^{16} bits/s, requiring about 10^5 100 Gb/s optical fibres. Clearly this argument is highly simplified since the latter stages of the processing are likely to be limited by i/o rather than computing power. Nevertheless it shows that it is possible to provide, at reasonable cost, sufficient computing power within a station to produce data at a rate that will saturate the data transport network. It is thus feasible to contemplate a fully-digital beam-forming system for the SKA.

It is our intention in this design study to explore the many trade-offs in conducting the beam-forming at tile level and to design a practical digital beam-former for a purely digital tile which demonstrates the multiple field-of-view capability of such a tile. This work-package will need to draw on the experience of the Dutch group with THEA and be coordinated with the beam-forming aspects of EMBRACE, as well as the network architecture activities in DS3-T1. We will be concentrating here on the beam-formation at the patch (ie near-element) level, but keeping close contact with the Dutch effort at the near-station level, with the view that by the end of the overall design study we will have a clear integrated plan for beam formation all levels. The signal processing design effort will be carried out at Oxford, partly using expertise available at RAL, and at Manchester. Design consultancy will be provided by Qinetiq Real-time Embedded Systems Division (Malvern) who have extensive experience in designing fast digital signal processing systems and who will transfer the best available industrial practice in this area to the university sector.

System integration and production of a small-scale demonstrator

In order to demonstrate the performance of the digital tile concept, a small number of tiles will be built and tested. This will involve the integration of the technologies developed in the three other areas, and in itself forms a technology development programme of similar scale.

The first phase of the integration is the formation of an element 'module'. This consists of a single antenna, its front-end low-noise amplifier and other gain stages, the A-D converter and the digital filter (see Figure). It is here that the problems of integration of sensitive analogue detectors with fast digital electronics on the same substrate will be addressed, along with issues such as shielding, power supplies, clock distribution and many other engineering issues. These will be crucial to the success of the concept demonstrator. Although the integration effort will be based in Manchester, inputs from all the individual hardware development teams will be required.



The Element-Electronics Package

The next level of integration is at the tile level (where a tile is ~1m^2 of collecting area, about 100 modules). The infrastructure of the tile (mechanical systems, power supplies, packaging and environmental control) will have to be designed and constructed. The tiles will also contain a number of ‘dummy’ elements to simulate the electrical properties of a larger array. Tests will consist both of ‘indoor’ beam-pattern testing in the BAesystems near-field test facility at Great Baddow, and ‘outdoor’ testing using bright astronomical sources. To facilitate the testing of the complete few-tile system, which will incorporate new designs of antenna, LNA, A/D and digital filters, it is important that the beam-former is thoroughly tested before it is integrated with the rest of the experimental system. There are two obvious ways in which to do this: a ‘bench’ system, consisting of digital noise generators with programmable degrees of correlation, which can simulate the outputs of the individual array elements; and a ‘field’ system, consisting of a number of antennas with digitizers producing real astronomical signals. For test purposes these antenna systems could have much inferior performance compared to the real system elements, and could be constructed from off-the-shelf components. Both methods have their advantages and disadvantages, and could have broadly similar costs. An early task will be to determine the most cost-effective testing solution.

It is recognized that is a phased array for SKA, with all the potential science benefits this brings, is unlikely to be realized if the solution is too expensive. Traditionally phased arrays have been considered high cost (although highly flexible). This has been due to the high cost of modules (normally transmit as well as receive, often at a few GHz operational frequency). Recently this view is changing with simple phased arrays being introduced for cellular telephony base stations. Based on this recent experience we can see a high probability of keeping the module costs realistic. SKA has a number of features which inherently allow lower costs: it is receive only, has an upper frequency less than 2 GHz, and there will be large eventual production volumes. Nevertheless, an important activity throughout the design, integration and testing process will be a careful consideration of manufacturability and cost-reduction issues, with the end of being able to recommend, by the end of the design study, a manufacturing route for the phased array concept within the cost envelope demanded by the international project.

4 New technology

As outlined in Section 3.3, the SKA executed as a phased array is a unique concept, whose science goals require levels of technical performance far different from existing phased array technology, yet at a low unit cost. With ultra wide bandwidth and all digital beam-forming providing the ultimate flexible multi-user environment, the phased array offers a new approach to meeting both the current SKA science goals and will enable future many new ways of undertaking innovative radio astronomy science.

However, to meet the goals of the SKA is technologically challenging. The radio astronomy application has very different performance needs to other civilian and military applications. Most phased arrays require a small fraction of the SKA bandwidth and no existing array demands the noise temperature targets of the SKA. These and other factors (such as polarization purity) together with the cost target demand innovative research and technology development. A number of key technologies are involved and the UK SKA Consortium has assembled three teams (electromagnetics; optimised devices; digital beamforming) to design, construct and test prototype systems.

5 Industrial Benefits

The SKA design study is exploring and developing technologies and skills which are of direct and current interest to UK industry. The explicit links and interaction with industry during the course of the study will not only enable industrial expertise to be utilized to the benefit of our scientific goals, but also will ensure that the outputs of the study feed back into an industrial context as far as is possible. We see three distinct areas in which the outputs from the design study will be of direct benefit to industry:

1. **Direct application of new technologies**. The technologies developed under this design study will feed back directly into the knowledge base of our industrial collaborators (BAe systems and Qinetiq). Although the outputs of this design study will be placed in the public domain it is clear from our discussions with BAe and Qinetiq that the generic problems we are addressing are of direct relevance to the wider interests of these companies. Knowledge and expertise generated within this design study, will benefit the wider interests of these and related companies.
2. **Positioning UK industry for the development phase of the SKA**. The SKA itself will be a project in which the majority of the final instrument cost will be in the mass production of receiver elements, integrated electronics and digital signal-processing hardware. The leadership role that the UK intends to take in the SKA project and hence the development of technologies for the telescope in collaboration with UK industry should position UK industry extremely well to win construction contracts for the SKA.
3. **Training**. The technologies of the SKA overlap strongly a broad range of technologies which are central to UK industry. These include not only the electromagnetic and novel devices being developed within the study (clearly relevant to companies such as BAe, and Qinetiq), but also more generally the telecommunications industry – in DS3 for example we are concerned with state-of-the-art data transfer and computational efficiency and in DS4 with the production of low-cost, hig performance phased arrays. We will therefore train individuals in skills directly relevant and transferable to industry.

We are cognizant of the need to extend outreach to UK industry via a web-site and other conventional means, for example articles in industry journals. While the PPARC-sponsored industry day (18 Feb 2004) was highly successful in many ways we see two limitations of the industrial links we have achieved so far:
1) Neither we, nor the PPARC Industrial Liaison Officer, knew about all the relevant companies to invite.
2) Of the companies who attended the meeting on 18 Feb 2004 it has, so far , only been possible to include two (Qinetiq and BAE ATC) in the programme. We very much wish to retain contact with the other attendees at the 18 Feb meeting and will look for other contacts, particularly in the area of software and DSP

6 UKSKADS Management Plan

The SKADS project will be complex, encompassing more than 30 institutes throughout Europe, Australia and S.Africa. The UK component of SKADS is, in itself, a broad proposal with involvement from 3 major partners (Manchester, Oxford and Cambridge) and other smaller partners (Leeds, Cardiff and Glasgow). In addition, there will be 2 industrial partners (BAe and Qinetiq) both of whom will be sub-contractors to the University of Manchester. Any management structure will have to be able to control the UK component of the project and be seamlessly integrated within the European SKADS.

If the project is approved then six separate grants will be submitted from the participating universities for the work described in the UK work packages.

The overall UK project management will be governed by a UKSKADS Project Management Board (PMB), which will consist of the Principal Investigator (PI: Prof. Peter Wilkinson, Manchester) and Institute Team Leaders (new Chair of Radio Astronomy Technology at Manchester; Dr. Steve Rawlings and the new Head of SKA Instrumentation (Oxford); Dr Paul Alexander and Dr Peter Duffet-Smith (Cambridge); Dr Melvin Hoare (Leeds); Dr Steve Eales (Cardiff); Dr Graham Woan (Glasgow)).

Within each of the three principal institutions there will be a Project Manager (PM). The Manchester PM will be designated as the overall PM. The PMs at Oxford, Cambridge and Manchester will run DS2, DS3 and DS4 respectively. In addition, each of the three major partners will appoint an Academic Coordinator (AC) who will act as the liaison between the project teams and the local academic staff. At each institution, the PM will hold weekly meetings with the local teams, consisting of the AC, the work package leaders and others actively involved in the project work.

A UKSKADS Project Management Team (PMT), consisting of the PMs and ACs and other co-opted project personnel, will hold regular joint meetings, either in person or by telecon. The PMT meetings, chaired by the overall PM, will deal with issues of interfacing between the work at the institutions and overall progress of the project. The Oxford PM will be responsible for ensuring the day-to-day coordination and progress of the DS2 work being undertaken at Leeds, Cardiff and Glasgow. The DS teams will meet, both in person or by telecon, on a regular basis.

Quarterly, the PMT will meet in conjunction with the PMB. The PMB will review the progress of the project and make recommendations to the PMT through the overall PM. Formally, the PMB will be responsible for the overall management of the project, with each institute responsible for the internal management of its activity, reporting to the PMB through the overall PM.

The connections to the European SKADS will be strong since it has been agreed that the European Project Engineer will be based at Manchester. In addition, the UKSKADS PI will be a member of the European SKADS Board and its Executive committee (in fact, he is also the co-I of the European proposal); the Institute Team Leaders from Oxford and Cambridge will also be members of the European SKADS Board. The Oxford PM will also serve as UKSKADS Project Scientist (PS), since DS2 is the primary science component of the project. There will be regular meetings and telecons of the overall UK PM and PS with their European counterparts. In addition, there will be regular working meetings of the engineers and scientists involved in the individual work-packages across Europe.

The role of the overall UK Project Manager will be:

- To prepare and maintain the overall UK project plan. This will involve ensuring regular reports from work package leaders are received and the information distilled as well as informing work package leaders of the crucial dates for the deliverables.
- To organise and present the major design reviews, including ensuring all documentation is prepared and circulated.
- To monitor the financial status of the overall project.
- To provide the link to and interface with the overall European SKADS project.
- To prepare and present reports to the PMB, the PPARC oversight committee and the European SKADS Board.

The roles of the internal project managers will be:

- To manage the design study activity within each institute, in liaison with the institute Project Scientist and the overall PM.
- To manage resource assignment and conflict in conjunction with other major project managers in the institute.
- To run the individual studies: DS2 (Oxford), DS3 (Cambridge) and DS4 (Manchester)
- To manage working allowance on the work packages within the institute.
- To chair weekly progress meetings.
- To report progress to the overall Project Manager.
- To provide documentation for design reviews, and documentation for reports to the PMB, the PPARC oversight committee and the European SKADS Board.

PPARC will appoint a UKSKADS oversight committee. This committee will have no managerial jurisdiction within the project, but will provide advice to PPARC and the PMB regarding the progress and status of the project. The management structure is summarised in Figure 6.1.

There will be three major design reviews, coordinated with the European SKADS project, to which external reviewers will be invited. The first will be a conceptual design review (CoDR) 6 months following the start of the project, at which the basic concepts will be reviewed prior to more detailed design. The second will be a mid-term review, coordinated with the European SKADS mid-term review, to evaluate progress towards the UK deliverables. There will be a final project review.

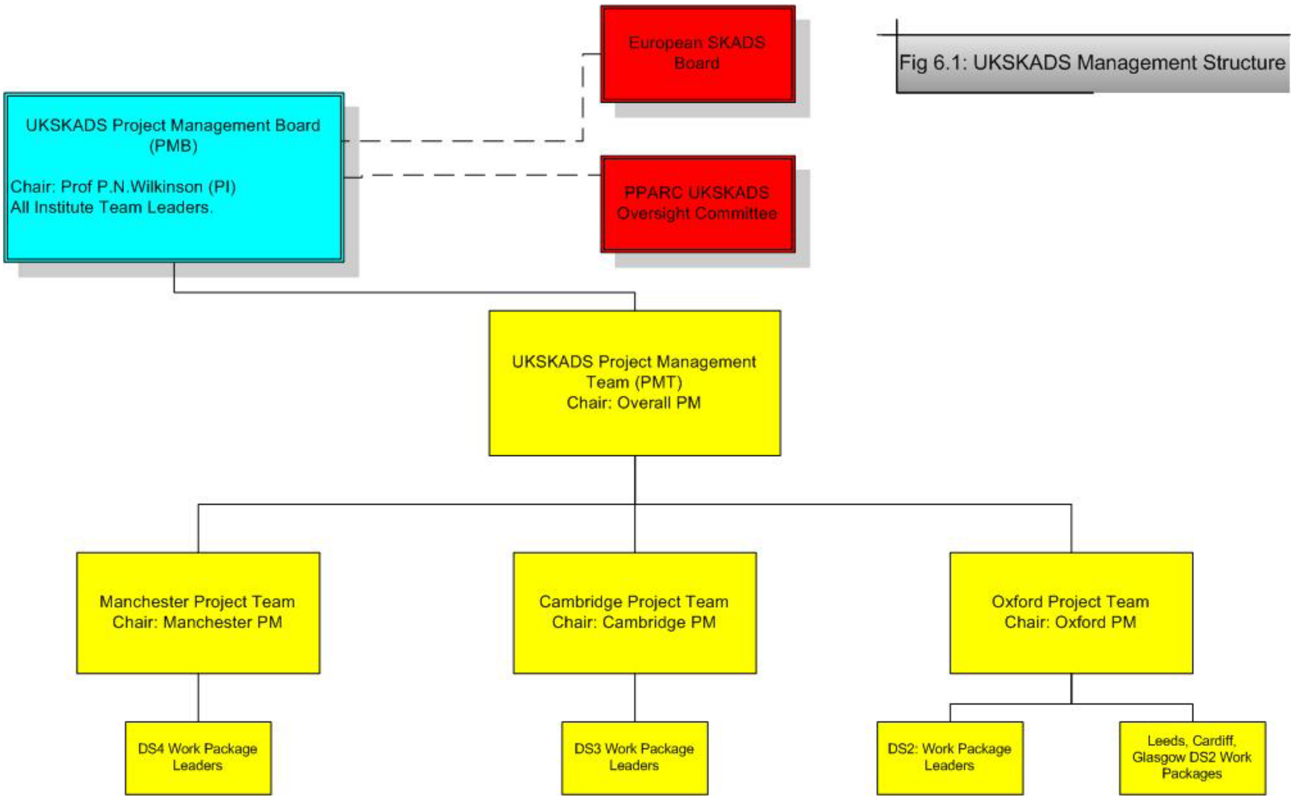


Fig 6.1: UKSKADS Management Structure

7 Risk Analysis

The existing PPRP definitions for levels of risk are appropriate for the production of a science instrument but are not appropriate for a technology R&D project. The proposers have, therefore, defined the following risk categories:

1) Solution available off the shelf (or requirement is only a report).
2) Straightforward application of available technology but some development required.
3) Significant R&D required and high confidence in success.
4) Significant R&D required but chance technology will not succeed
5) No solution yet apparent

Specific risk analyses using these definitions are included in each of the WPs. We concentrate here on two top-level strategic issues.

Security of Collaborator Funding:

The news that the EC have agreed to provide funding for the SKADS proposal is very welcome. However, a condition of that funding is that the partners must obtain more than two-thirds of the total from national sources. The promise of EC money will, no doubt, provide the trigger for release of the required matching funds. However, a question that must be addressed is: will the level of national funding finally secured by the SKADS partners enable the currently envisaged programme to proceed and if not how might this affect the UK programme?

One of the pivotal components of SKADS is the ASTRON-led EMBRACE programme for whose construction significant capital funds are required. The main issues which need to be addressed and finalised over the next two months (during which the EC contract negotiations will take place) are:

- The cost of the EMBRACE demonstrator.
- The sources for capital funds for EMBRACE: ASTRON is seeking funding from NWO but the level of this funding has not yet been finalised. However, our Dutch colleagues are confident that funding will be forthcoming and their track record in this area is well-established.

In the PPARC SoI of September 2003 the UK indicated that it would also seek to contribute capital to the EMBRACE programme. Given the new requirement to demonstrate a 3rd generation tile within the SKADS programme the UK has had to adapt its plans in essence as follows:

- not to produce UK-based copies of EMBRACE for test operation in Manchester and Cambridge
- instead to construct a complementary 3rd generation tile
- to undertake frequency and clock distribution tests using optical fibres

Therefore, we are currently not proposing to make a capital contribution to EMBRACE

Considering the above, the strategy to mitigate against the risk of inadequate funding for EMBRACE is to:

- Reduce the size of the EMBRACE array
- Commit a larger fraction of the EC SKADS funds to EMBRACE

As has been stressed before, the UK 3rd generation tile programme is an essential complement to the EMBRACE programme – both are needed to demonstrate the feasibility of the aperture array solution for the SKA. The UK has assembled a critical mass of effort (from universities and industry) to develop the 3rd generation tile and the UK programme is not strongly affected by the final scope of the EMBRACE programme

International Technology Selection

There is an unquantifiable risk that some of the technology being developed in SKADS will not be chosen for the SKA in the international technology selection in 2008/9. We can, however, identify many parts of the UK programme which will certainly be essential in defining the SKA:

- DS2: Science and astronomical data simulations (all are needed)
- DS3: The Network and its output data (all are needed): but in particular we note:
  - broad band data and clock distribution via optic fibres is unique to the UK
  - SKADS will lead to the development of world-leading expertise in GRID-enabled technologies
- DS4: Technical foundations and enabling technologies
  - 3rd generation phased array feeds have a direct application at the focal plane of parabolic antennas (see section 9 and Annex J for an emerging use in the SKA context) and in a range of non-astronomy applications.
  - the innovative semiconductor device development is unmatched in the SKA community and can find an application whatever collector concept is selected
  - digital beam-forming solutions: SKA will certainly involve complex beam forming from each station; the UK study of a more complex problem will enable it to make a major contribution to the final SKA design.

The Committee should note that unless we engage in this R&D activity we run a 100% risk of being unable to tell whether or not the SKA could realise its full scientific potential according to the European vision.

8 Data acquisition, distribution and analysis

None of the UK led SKADS design studies will produce large quantities of astronomical data. Verification of the third generation phased array tile being developed in DS4 are detailed in work package DS4-19; here we have include a request for resources to analyse the test data. The majority of the information output of this research and development project will be in the form of reports and papers which will be distributed to the international SKA community and published in recognized journals.

9 Scientific Exploitation

EC-funding of SKADS Design Study does not allow for the construction of in instrument to deliver new science. However a potential opportunity has very recently emerged to use the 3rd generation tile technology to enable exciting new science to be delivered within 5 years. We first summarise this possibility and then summarise the current international planning for the period immediately after the intensive international deisgn phase, of which SKADS is a major part.

Proposed South African Pathfinder

Appendix I contains a summary of the South African thinking regarding the link with the SKADS R&D programme and the developing plans for a SKA science pathfinder to be built in the Northern Cape. South Africa has identified a compelling national interest in constructing an SKA-related science instrument. The present concept for the pathfinder involves an array of 25 parabolic dishes of diameter 12m. The 3rd generation phased array technology developed in SKADS will be employed at the focus of each dish to increase the field-of-view, and hence the surveying speed, by more than an order-of-magnitude compared with conventionally-fed dishes. South Africa has already committed funding at a level of ~R50M (£4M) to support SKADS and the pathfinder and is actively considering funding up to twice that amount. *No commitment of additional UK support for the SA pathfinder is requested here.* .

Continuation of the SKA project after the SKADS Design Study

In the medium term the international project plan calls for the construction of a science pathfinder as a 10% cost instrument starting in ~2010 and costing £20M for the UK as a 10% share. This pathfinder will form part of the core of the full SKA which will begin serious construction in ~2015. Our vision give the best possible chance that UK industry is intimately involved in these phases.

The UK SKADS programme will have assembled a team of scientists and engineers who will have developed the range of skills needed to take leading roles in the construction and scientific exploitation of the SKA. The ramp up of full SKA activity will coincide with the ramp-down of eMERLIN support and scientific exploitation in the second half of the next decade. PPARC support of eMERLIN is currently ~£2.1M p.a.

10 Data Rights

This proposal involves study and research/development of relevant technology. Data rights is therefore interpreted as rights to the knowledge developed under this programme.

In this context, we note the proposed technology element for this programme involves both UK academic partners and a substantive element from UK industry. This raises the issue of intellectual property rights and future exploitation potential. The costs from all industrial partners included in this proposal are based on all foreground rights in the IPR (that is Intellectual Property developed as a result of funding from this project) will rest with the UK academic community. This ensures these are available for future dissemination to ensure eventual cost effective implementation of the overall SKA.

11 Costs to PPARC

	2005 (£k)	2006 (£k)	2007 (£k)	2008 (£k)	Total
Total cost of UK programme	1299	2530	2642	2092	8563
Estimated EC contribution	287	571	571	571	2000
Estimated cost to PPARC	1012	1959	2071	1521	6563

Notes:

1. The aim is to take a leadership role in the European R&D phase, and by forging links with UK industry, to ensure that UK PLC will be in the best possible position to play a leading roles in the design and construction of both the international science pathfinder (post 2010) and the full SKA (completion 2020). New university instrumentation groupings are taking place, catalysed by SKADS.
    - A strong link has been forged within the new University of Manchester between the Jodrell Bank Observatory and the former UMIST Electrical and Electronic Engineering Department.
    - The University of Oxford is forming a new radio astronomy instrumentation group linked with RAL.

    Together with the strong Cambridge group a powerful “technical triangle” of universities is therefore being formed to drive the SKA R&D programme forward in cooperation with UK industry.

2. The EC costs can only be estimates since we do not yet know the level of funding we have secured from the EC and the share of this which will be spent in the UK. These figures will become clear during contract negotiations in October 2004. We have entered the currently anticipated amount (assuming a 30% share of €10M) and taking a flat EC spend profile. As risk mitigation we have built in a PPARC contingency of 15% into the programme (see Annex E).

3. As noted in the initial section on the context of this proposal the total estimated costs have risen compared with those in the SoI of September 2003 for the following reasons

- During the EC SKADS planning it was realised that length of the programme needed to be extended by a further 6 months and that a “3rd generation” phased array technology programme is needed to complement the “2nd generation” EMBRACE phased array demonstrator which is at the heart of the EC SKADS proposal. The EMBRACE demonstrator was the main focus of our thinking on technical R&D at the time of the SoI.

- We have included two companies (BAE Advanced Technology Centre and QinetiQ) as partners. The direct costs of industry involvement exceed that in universities but the skills available within BAE ATC and QinetiQ are of immediate relevance and mitigate the risk in the technology R&D programme very significantly.

- After the SKADS proposal was submitted, it became clear that to bring focus to the programme a definite, albeit small-scale, “3rd generation” phased array demonstrator and associated test programme is needed, rather than just a set of independent design efforts as proposed in SKADS. This involves a range of additional hardware and associated costs. The need for this programme has been confirmed in a letter from the International SKA Director (sent with this proposal).

- A further development programme is proposed for the high precision frequency and clock distribution required for interferometry. This will make use of the eMERLIN fibre network (modest capital-funding by PPARC). The UK radio astronomy groups can bring unique skills to bear in this area and the cost of this programme is modest.

- UK support of the International SKA Project Office (ISPO) is requested at €35k per annum for the duration of this Design Study– i.e. ~£23.5k per annum. The ISPO budget, validated by the International SKA Steering Committee, has been sent with this proposal.

- To compensate for these additions the UK proposes to withdraw from some aspects of the SKADS plan
    - Cambridge no longer to be involved in radio frequency interference mitigation work.
    - Cambridge and Manchester no longer to be build EMBRACE copies in UK

The Committee should note that the size of the proposed UK technological R&D programme (~60 FTE) is smaller than already expended by The Netherlands (ASTRON) to take their phased array programme to its current state (80-100 FTE), which is a foundation of the SKADS technology R&D programme. We expect to minimise the UK start-up costs by close cooperation with our Dutch colleagues, utilisation of their experience and by the immediate involvement of UK industry.

4. We draw attention to the strong possibility of South African manpower, at the 6fte level, reducing the cost to PPARC, probably in the area of DS4 and the 3rd generation tile development.

5. There could be flexibility in the spend profile, particularly in the first year. A significant part of the current spend involves the industrial involvement and it may be possible to negotiate a spend profile with the companies which mitigates any problems for PPARC cash flow while preserving the overall funding to each company. It may also be possible to negotiate with the three major universities to help with the early PPARC cash flow problems, associated with new staff working at those universities, while preserving the overall funding to each university.

12 Costs to be noted

The discussion on the level of the EC contribution to this study is given in the section “Context of this proposal” on page 5.

12.1 Staff in kind contributions

Staff in kind contributions are listed in Annex F. They total 10.2 FTE [6]at Cambridge; 9.5 FTE at Oxford; 8.6 FTE at Manchester; 2.15 FTE at Cardiff; 0.7 FTE at Leeds and 0.7 at Glasgow

PhD students funded from a variety of sources will be an integral part of the UK SKADS programme. Some preliminary simulation work from self-funded students has already been undertaken at Oxford.

12.2 Manchester in-kind contributions

The University of Manchester will advertise two new positions in radio astronomy in September 2004 as part of a programme to stimulate the UK contribution to the development of instrumentation for observational astronomy but in particular the SKA. These positions will be a Chair of Radio Astronomy Technology and a linked lectureship in radio astronomy. The person appointed to the Chair will assume leadership of the UK SKA technology programme and in conjuction with the EC-funded SKADS project engineer will coordinate the UK SKA technology R&D activity programme. The University will also provide essential infrastructure for this project. This includes: test facilities at Jodrell Bank Observatory; the 192-processor Beowulf cluster at JBO; the £2M state-of-the-art Molecular Beam Epitaxy machine from VG Semicon, now housed in a new laboratory in the UMIST main building. The programme outlined in DS4 will be impossible without this latter contribution and its range of associated semiconductor test facilities. The optical fibres installed for the eMERLIN project (funded largely via the University and the North West Development Agency) will be made available for the test programme outlined in DS3-T1, transforming it from simply a paper exercise. Finally electromagnetic and electronics laboratories located with the new University of Manchester will provide a full range of specialist test equipment and a development facility. In view of its major contribution to the UK SKA technical development the University proposes that Manchester be regarded as the UK SKA Technology Coordination centre (UK STCC).

12.3 Cambridge in-kind contributions

The technical work conducted on this project in Cambridge will benefit greatly from facilities paid for and maintained by the University. These include a well-equipped electronic laboratory at the Cavendish which provides access to expensive test equipment such as network analyzers, vector voltmeters, power meters and spectrum analyzers. These will be essential for the measurements proposed in the DS3 and DS4 programmes. The University also maintains Lords Bridge, which is an excellent site for making low-radio-noise measurements and will shortly be refurbished to provide a new construction facility and workshops. Various tasks within DS3 will rely on access to the Cambridge-Cranfield High Performance Computing Facility, which is a private computing facility within the Universities of Cambridge and Cranfield run by a consortium of Departments.

12.4 Oxford in-kind contributions

The University of Oxford and the CLRC Rutherford Appleton Laboratory (RAL) will advertise two new positions in radio astronomy in October 2004, as part of a programme to stimulate the UK contribution to the development of instrumentation for observational astronomy for current and future telescopes. Both positions will be academic (departmental) lectureships held jointly between Oxford and RAL, and both will be associated with positions in Oxford Colleges. One of these positions is earmarked for a `Head of SKA instrumentation' who will be exempt from teaching duties, and who will be expected to work full time on research associated with developing technologies relevant to the SKA. The second position is earmarked for more general areas of `radio instrumentation' and will be associated with a Tutorial Fellowship at an (as yet unknown) college. As these jobs are not yet advertised, no names can be attached to these positions, but

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[6] We define an FTE to mean 12 person-months of activity

Oxford/RAL anticipates appointing candidates at a senior level (equivalent to RSIII posts). The Oxford instrumentation group is being re-organised to include a new electronics laboratory for which specialist test equipment for radio astronomy will be purchased. Laboratory space at RAL will also be made available for SKA-related activity. Oxford University has also recently used internal funding to appoint a two-year `radio astronomy post-doc' who will develop infrastructure (e.g. AIPS management, collaboration with JIVE, analysis of GMRT data) relevant to the SKA programme.

12.5 Cardiff in-kind contributions

Cardiff is the data-analysis centre for the GEO 600 gravitational wave telescope and much of the software used in that project (e.g. Triana) has natural extensions to the SKA programme. The Cardiff group is also leading PPARC's GridOneD project whose aim is to develop data and resource discovery tools for distributed computing with remote data archives, which again has obvious relevance to the SKA. The department currently has a 160-processor Beowulf cluster and the university is funding the purchase of a 200-node cluster (200 GBytes of RAM and 50 TBytes disc space) for the general use of the Physics and Astronomy faculty. These resources will be made available for the SKA simulations described in DS2.

12.6 Leeds in-kind contribution

Leeds University will provide access to a SRIF-funded 96-node cluster for use in the cosmic ray simulations proposed in DS2. In addition, a University funded Ph.D. student will spend a significant proportion of their time on this work.

12. 7 Glasgow in-kind contribution

The simulation work at Glasgow will exploit a 24-processor Beowulf cluster.

References

Abdalla F.B, Rawlings S., 2004, MNRAS, in press

Blake C.A, Abdalla F.B., Bridle, S.L., Rawlings S, 2004, in `Science with the Square Kilometer Array', eds Carrili, C., Rawlings S., in press

Bryden G., et al, 1999, ApJ, 514, 344

Carilli, C., 2002, SKA Memo 24

Carilli C., Rawlings S., `Science with the Square Kilometer Array', in press[7]

Carilli C., et al., 2004, in `Science with the Square Kilometer Array', eds Carrili, C., Rawlings S., in press

Cordes et al., 2004, in `Science with the Square Kilometer Array', eds Carrili, C., Rawlings S., in press

Furlanetto S., Briggs F., 2004, in `Science with the Square Kilometer Array', eds Carilli, C., Rawlings S., in press

Durand S.J., McCool R., 2004, Proceedings of SPIE, Paper 5496-64, in press

Greenhill L., 2004, in `Science with the Square Kilometer Array', eds Carrili, C., Rawlings S., in press

Jones D., 2004, SKA Memo 45

Kramer M., et al., in `Science with the Square Kilometer Array', eds Carrili, C., Rawlings S., in press

Lyne A.G., et al, 2004, Science, 303, 1153

Rawlings S., et al, in `Science with the Square Kilometer Array', eds Carrili, C., Rawlings S., in press

Rees, M., 2000, 'New Perspectives in Astrophysical Cosmology', 2nd edition, Cambridge University Press

van der Hulst et al., in `Science with the Square Kilometer Array', eds Carrili, C., Rawlings S., in press

Wilkinson P.N., 1991, "The Hydrogen Array" in `Radio Interferometry: Theory, techniques and applications', IAU Colloquium 131, ASP Conference Series, Vol 19, p428.

Wilkinson P.N. et al, in `Science with the Square Kilometer Array', eds Carrili, C., Rawlings S., in press

Wright M., 2004, SKA Memo 46

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[7] All publications available on line at http://www.aoc.nrai.edu/~ccarilli/CHAPS.shtml

Annex A: Work Packages

The EC SKADS project comprises eight Design Studies (DS) of which the UK is taking a leading role in DS2, DS3 and DS4 and DS8, although for the DS8 the UK is not requesting specific funding. The titles are:

DS2 Science and Astronomical Data Simulations
DS3 The Network and its Output Data
DS4 Technical Foundations and Enabling Technologies
DS8 Overall System Design and Preliminary SKA Plan

Each Design Study is then broken into separate Tasks (DSXX-TYY).

Within each Task we have identified component work packages for each of these tasks and these are therefore labelled DSXX-TYY-WPZZ.

The exception to the above is in DS4, where the programme has evolved significantly since the original SKADS proposal. The component tasks are no longer relevant to the revised programme and so work packages are simply labelled DS4-WPZZ.

The UK project plan comprises:

DS2-WP01	DS2 and Oxford Management
DS2-T1-WP01	Science design drivers for continuum surveys
DS2-T1-WP02	Science design drivers for line surveys
DS2-T1-WP03	Science design drivers for polarization surveys
DS2-T1-WP04	Science design drivers for pulsar surveys
DS2-T1-WP05	Science design drivers for transient-source surveys
DS2-T1-WP06	Science design drivers for astrobiology
DS2-T2-WP07	Technical design drivers for continuum surveys
DS2-T2-WP02	Technical design drivers for line surveys
DS2-T2-WP03	Technical design drivers for polarization surveys
DS2-T2-WP04	Technical design drivers for pulsar surveys
DS2-T2-WP05	Technical design drivers for transient-source surveys

DS3-WP01	DS3 and Cambridge Management
DS3-T1-WP01	Coherent signal distribution via fibre optics
DS3-T1-WP02	Data transmission requirements for SKA
DS3-T3-WP01	Network Architecture
DS3-T3-WP02	Network requirements for time resolved experiments
DS3-T3-WP03	Network requirements for experiments involving imaging and spectral-line observations
DS3-T3-WP04	Management of the data flow
DS3-T3-WP05	The application of distributed, GRID-enabled data reduction for the SKA
DS3-T3-WP06	Data, archiving and scientific exploitation
DS3-T3-WP07	The SKA in operation: users, observing modes and user support

DS4-WP01	Initial design study of the system architecture
DS4-WP02	Antenna element design and impedance optimization
DS4-WP03	MBE Growth of RF front-end devices
DS4-WP04	Integrated LNA Design
DS4-WP05	Integrated LNA Fabrication
DS4-WP06	Analogue to Digital Converter design
DS4-WP07	Analogue to Digital Converter Technologies
DS4-WP08	Element-level DSP design
DS4-WP09	EMC self-compatibility; "gain block" and element module integration
DS4-WP10	Test of element module
DS4-WP11	Develop digital beam former for a tile

DS4-WP12	Interconnect design
DS4-WP13	Back-end system at tile level: build and test
DS4-WP14	Infrastructural Design of Tile
DS4-WP15	Fabricate a tile’s worth of module
DS4-WP16	Manufacture tile infrastructure
DS4-WP17	Integrate tile
DS4-WP18	Test tile performance against specification
DS4-WP19	Cost reduction studies
DS4-WP20	Project management

DS2-WP01 – DS2 and Oxford Management

Background

Oxford will coordinate Design Study 2 (DS2) for the project as well as take a leading part in the work packages which constitute DS2. The majority of the work packages for FP6-DS2 will be undertaken within the UK; these DS2 work packages are distributed among the UK SKA consortium so as to make best use of the existing expertise. There is considerable interdependence between these work packages and therefore an associated high risk. To minimize this risk, careful management of the effort is required. This work package provides that management (MDS2) enabling the coordination and consolidation of the output from the constituent work packages of DS2. The final consolidated report from DS2 will analyse all the scientific and technical trade-offs between SKA design and science output. It will include a ‘Year in the Life of the SKA’, observing schedules for both a conventional (dish) SKA realization and a phased-array ‘tile’ concept (as studied in DS4).

Additionally, the total effort at Oxford which is contributing not only to work packages in DS2 but also to DS3 and DS4 (and the smaller groups at Cardiff, Leeds and Glasgow who mostly contribute to DS2), must be properly managed to enable the outputs to be delivered on time to the rest of the design study. This work package therefore also provides for management of the Oxford (plus Cardiff/Glasgow/Leeds) contribution to the design study (MOX). MDS2/MOX management tasks will be provided by a single experienced PDRA, who will also have the title of UKSKADS Project Scientist.

This person will report to the Oxford Institute Team Leader (Rawlings, Oxford), be responsible for interfacing with parallel efforts in the EC and internationally, and have responsibility for the DS2 and Oxford/Cardiff/Glasgow/Leeds academic travel budgets.

Input

Work Package	Description
SKADS DS1	Overall management and coordination of the design study
DS2-T1-WP1,2,3,4,5	Reports on science drivers
DS2-T2-WP1,2,3,4,5	Reports on technical drivers

Tasks

- Define DS2 schedule and monitor, coordinate and modify milestones and (if necessary) deliverables for all DS2 work packages [MDS2].
- Chair telecons, co-ordinate agenda and provide minutes and actions [MDS2].
- Organise and manage team meetings and communication between participants in DS2 [MDS2].
- Manage travel budget for DS2 [MDS2].
- Review and modify internal DS2 reports [MDS2].
- Deliver final reports from DS2 work packages, including a ‘Year in the Life of the SKA’, observing schedule for competing SKA realizations [MDS2].
- Interface with parallel efforts in EC, especially with coordinators of FP6-DS2-T1 (Rawlings, Oxford) and FP6-DS2-T2 (Garrett, JIVE) [MDS2].
- Interface with parallel efforts internationally, through the Science Working Group led by International Project Scientist (Rawlings, Oxford) [MDS2].
- Monitor and coordinate milestones, deliverables and tasks undertaken at Oxford, reporting as needed to the coordinator of each DS [MOX].
- Provide technical support and guidance for Oxford work [MOX].
- Monitor financial spending (including travel) by Oxford/Cardiff/Glasgow/Leeds academics [MOX].

Output

Description	**Work Package**	**Date delivered**
Project schedule for DS2	All DS2 work packages.	10/2005
Consolidated DS2 report on science drivers	DS8-T1-01	06/2007
Consolidated DS2 report on technical drivers	DS8-T1-01	12/2008
Final consolidated report for DS2, including ‘Year in the Life of the SKA’	DS8-T1-01	12/2008

Justification

Staff effort

The UKSKADS Project Scientist (incorporating MDS2 and MOX tasks) is obviously needed for the full length of the programme (3.5 FTEs) and to efficiently undertake this crucial management and coordination tasks must be highly experienced (Spine Point 15). The final consolidated report for DS2 will include a ‘Year in the life of the SKA’, a detailed comparison of the science return of novel SKA technologies (eg. those studied in DS4) and conventional designs. The scientific and technical judgement required by the MDS2 manager requires appointment at a senior (RSII) level.

Under this work package we provide a consolidated list of standard computer equipment and consumable items as well as travel required for DS2, and by Oxford/Cardiff/Leeds/Glasgow academics.

Equipment/Consumables

For computer equipment and comsumables we have adopted rates of £2.0k and £0.7k per fte respectively. Thus for the MDS2/MOX manager (3.5 fte) and all other fte’s requested under DS2 (19.5 fte) the totals over the period of the programme are: £46k (computer equipment) and £16.1k (consumables).

Exceptionals

DS2 activity will involve regular (weekly) telecons or, occasionally, video conferences. Weekly telecons lasting ~ 1 hour, involving ~ 3 sites, costing ~ 25p per minute per person gives £4.1k in total.

Travel

The travel budget consolidates travel requirements for the MDS2/MOX manager, all PDRAs supported by DS2, and all Oxford/Cardiff/Glasgow/Leeds academic staff travelling for reasons directly connected with the UK SKADs programme (e.g. monthly project meetings, bi-monthly EC meetings and half-yearly international meetings).

We start with PPARC guideline figure of £1.8k for 19.5 PDRA FTEs, giving a total of £35.1k

We add to this four exceptional, month-long visit to Swinburne (by PDRAs delivering simulations to the international community), costing £24k.

The UKSKADS Project Scientist position (3.5 fte) will be associated with exceptional travel costs – within the UK, within Europe and internationally - which we estimate at twice the guideline figure (i.e. £3.6k per fte) thus totalling £12.6k, plus one long trip to Swinburne (£6k).

For academic staff from Oxford, Cardiff, Leeds and Glasgow, we estimate that the cost of their UK/EC travel on UK SKADS business (including attending international meetings etc) by multiplying the `in-kind' FTEs for Oxford (9.5 FTE) by the standard £1.8k to obtain £17.1k. The same calculation for the 3.2 FTEs from Cardiff/Glasgow/Leeds yields a further £5.4k, giving a total of £22.9k for academic travel.

Total travel for DS2 is therefore: £100.6k

DS2-T1-WP1 – Science design drivers for continuum surveys

Background

The aims of this work package are to simulate the sky to be seen by the SKA in radio continuum, and hence to determine the trade-offs between fundamental design parameters of the SKA (e.g. sensitivity, FoV, frequency range, angular resolution), and the key science achievable with radio continuum surveys. Compared to current radio telescopes, the SKA will have 100-times greater $A_{\mathrm{eff}} \; / \; T_{\mathrm{sys}}$ and much wider bandwidths, resulting in an increase in continuum sensitivity by factors (dependent on frequency) up to ~1000. With its capacity to carry out deep surveys, reaching ~nJy levels, the SKA will become the premier instrument for key studies in astrophysics, particle-astrophysics and cosmology. It will allow studies of the star-formation history of the Universe into the Dark Ages (before reionization) and uniquely powerful cosmological studies, such as those based on weak gravitational lensing, will be made possible. The most useful SKA sensitivity for continuum surveys will come from the longer baselines connecting outlying stations to the inner (~5 km) SKA core.

Detailed simulations of internationally-agreed SKA Key Science Projects (KSPs) are needed to determine the science achievable, at fixed sensitivity (i.e. cost), as a function of FoV, frequency range and angular resolution. Sky simulations will be based on `semi-analytic' techniques and utilise constraints from existing observations at non-radio wavebands (including the latest results from Spitzer); they will account for uncertainties in extrapolating to SKA sensitivities (ie a set of simulations, bracketing uncertainties, will be produced); and they will account for all sub-populations, i.e. AGN, starburst galaxies and normal galaxies. The UK has established leadership roles in both KSP V [the Dark Ages], and KSP IV [Galaxy Evolution and Cosmology], for which SKA continuum surveys will be vital.

The output from these simulations will be used to determine basic requirements for design parameters of the SKA such as instantaneous field of view (FoV) which, adopting the technologies studied in DS4, can also be improved by factors ~100 over conventional dish-based facilities. Simulated continuum surveys are also required as input for DS2-T1-WP2 and DS2-T1-WP3.

Input

Work Package	Description
DS1-00	Overall management and coordination of the design study
DS2-WP1	DS2 and Oxford management

Tasks

- Assess available data constraints, establish contacts with all relevant workers and outline proposed algorithm for simulation [0.4 FTEs].
- Write initial report on simulation method [0.1 FTEs].
- Implement continuum sky simulation, developing code using local resources [0.5 FTEs].
- Run code on Swinburne supercomputer and deliver final simulation [0.2 FTEs].
- Analyse code output for star-formation history and HI absorption (focussing on highest-redshift objects in the Dark Ages) and weak gravitational lensing [0.3 FTEs].
- Write report on frequency range and angular resolution requirements for KSPs IV and V [0.1 FTEs].
- Further analysis of code output, focussing on the trade-offs between FoV and science return [0.2 FTEs].
- Write report on FoV requirements for KSPs IV and V [0.1 FTEs].
- In collaboration with DS2 management (MDS2), write final report [0.1 FTEs].

Output

Description	**Work Package**	**Date delivered**
Report on simulation method	DS2-T1-WP1	01/2006
Deliver simulated continuum surveys	DS2-T1-WP2 DS2-T1-WP3 DS2-T2-WP1	08/2006
Report on frequency and resolution requirements for continuum surveys	DS2-T1-WP1	01/2007
Report on FoV/key science tradeoffs	DS2-T1-WP1	05/2007
Final report	DS8-T1-01	06/2007

Justification

Staff effort

A PDRA for 24 months [2 FTEs] is required to undertake this work which, given the timescales and experience required, is too demanding for a PhD student, but well suited to an energetic young PDRA. This PDRA will need to be, or become, familiar with semi-analytic models, multi-waveband observational datasets, radio astronomy and the SKA . The PDRA will need to report to DS2 management (MDS2) and follow linked efforts (internationally) to simulate other scientific applications of SKA continuum surveys.

DS2-T1-WP2 – Science design drivers for line surveys

Background

The aim of this work package is to determine the trade-offs between fundamental design parameters of the SKA (sensitivity, FoV, frequency range, angular resolution) and the key science achievable with line, principally HI, surveys. The value of $A_{\rm eff} / T_{\rm sys}$ for the SKA will be ~100-times greater than for current radio telescopes, resulting in a corresponding increase in line sensitivity. Deep SKA surveys will be able to detect the neutral Hydrogen (HI) content of galaxies to early epochs (to redshifts z~ 4). 'All hemisphere' SKA surveys may, depending on sensitivity and FoV, be able to pinpoint ~10^9 galaxies out to z~1.5 allowing revolutionary studies of large-scale structure (e.g. the galaxy power spectrum), cosmology and particle astrophysics (e.g. through studies of the equation of state of dark energy). The most useful SKA sensitivity for HI surveys will come from the baselines in the inner (~5 km) SKA core.

The influence of the SKA in these areas will be determined by basic design parameters such as instantaneous field of view (FoV) which, adopting the technologies studied in DS4, can potentially be improved by factors ~100 over current facilities. Detailed simulations of internationally-agreed SKA Key Science Projects (KSPs) are needed to determine the science achievable, at fixed $A_{\rm eff} / T_{\rm sys}$ (i.e. cost), as a function of FoV, frequency range and temperature sensitivity. These simulations must utilise constraints from existing observations at non-radio wavebands, and must account for uncertainties in extrapolating to SKA sensitivities. The UK has established a leadership role in KSP IV, [Galaxy Evolution and Cosmology] for which SKA line surveys are vital.

Input

Work Package	**Description**
DS1-00	Overall management and coordination of the design study
DS2-WP1	DS2 and Oxford management
DS2-T1-WP1	Simulation of the continuum sky

Tasks

- Assess available data constraints and outline proposed algorithm for simulation [0.2 FTEs].
- Write initial report on simulation method [0.1 FTEs].
- Implement line sky simulation, developing code on local resources [0.5 FTEs].
- Run code on Swinburne supercomputer, and deliver final simulation [0.2 FTEs].
- Analyse code output for galaxy evolution (e.g. evolution of HI mass function) and cosmology (e.g. baryonic oscillation experiment) key science [0.3 FTEs].
- Write report on frequency range and angular resolution requirements for key science [0.1 FTEs].
- Further analysis of code output focussing on the tradeoffs between FoV and science return [0.2 FTEs].
- Write report on FoV requirements for key science [0.1 FTEs].
- Using simulated line sky and simulated continuum sky from DS2-T1-WP1, analyse extent to which line and continuum surveys can operate in tandem [0.2 FTEs].
- In collaboration with DS2 management (MDS2), write final report [0.1 FTEs].

Output

Description	**Work Package**	**Date delivered**
Report on simulation method	DS2-T1-WP1	11/2005
Deliver simulated line surveys	DS2-T2-WP2	06/2006
Report on frequency and resolution requirements for line surveys	DS2-T1-WP2	11/2006
Report on FoV/key science tradeoffs	DS2-T1-WP2	03/2007
Final report	DS8-T1-01	06/2007

Justification

Staff effort

A PDRA for 24 months [2 FTEs] is required to undertake this work which, because of timescales and expertise needed, is too demanding for a PhD student. A young, energetic PDRA with a suitable background would be most appropriate. The PDRA will assess the key datasets available and design an algorithm for the simulation (likely to be a semi-analytic calculation in which free parameters are fixed by constraining datasets). After code development in the UK, the final simulation will be run on the Swinburne supercomputer. The outputs of these simulations will initially be analysed to determine the trade-offs between science return (in KSP IV) and frequency and spatial resolution, establishing best estimates and uncertainties in things like the required temperature sensitivity. These results will be reported to the DS2 management (MDS2) to allow comparison with efforts (internationally) on simulating other scientific applications of SKA line surveys. Further analysis of the code output will establish trade-offs between key science output and FoV, leading to a report to MDS2. The PDRA and MDS2 will then collaborate on a final report to the UK management.

DS2-T1-WP3 – Science design drivers for polarization surveys

Background

The aims of this work package are: (i) to simulate the polarized sky to be mapped by the SKA; and (ii) to determine the trade-offs between fundamental design parameters (sensitivity, FoV, frequency range, bandwidth, angular resolution, polarization purity and spectropolarimetric capabilities) for the internationally-agreed Key Science Project KSP III, the Magnetic Universe. The high polarization purity of the SKA will allow detection of the relatively low linearly polarized fractions (<1%) from most astrophysical sources seen down to μJy levels, whilst its spectropolarimetric capability will enable surveys of Faraday rotation measures (RMs) and intrinsic polarization position angles.

A statistical approach is required to characterize the geometry and evolution of magnetic fields in galaxies, in clusters and in the IGM from high redshifts through to the present, so surveys of at least ~10^7 extragalactic radio sources and, in the Galactic Plane, all ~20,000 pulsars available are needed. Surveys of, for example, RMs will represent an increase by a factor ~10^4 over current surveys. Simulations of various different effects are needed: what scale sizes are essential; how much of the sky must be observed; what accuracy is required in determining fractional polarization and position angle; the value of deep, compared with, relatively shallow surveys. The scientific benefit of high-frequency work (e.g. Faraday tomography in dense regions of the Galactic plane) needs to be properly quantified.

Input

Work Package	**Description**
DS1-00	Overall management and coordination of the design study
DS2-T1-WP1	Science design drivers for continuum surveys
DS2-T1-WP4	Science design drivers for pulsar surveys

Tasks

- Assess available data constraints, establish contacts with all relevant workers, and assess appropriate methods for carrying out the modelling [0.2 FTEs].
- Investigate the percentage polarization expected in galaxies which will be acting as the RM probes out to the highest redshifts, incorporating both normal galaxies and AGN [0.2 FTEs].
- Investigate what is expected in the way of polarization and depolarization at high redshifts [0.2 FTEs].
- Use existing models of magnetic fields in the Milky Way, proto-galaxies, galaxies and clusters to make initial simulations of RM surveys with the SKA [0.2 FTEs].
- Incorporate possible models of a primordial magnetic field to investigate the levels at which it may be possible to detect this using Bayesian methods [0.4 FTEs].
- Write initial report [0.1 FTEs].
- Use outputs from DS2-T1-WP1 and DS2-T1-WP4 to refine the initial simulations of RM surveys with the SKA [0.3 FTEs].
- Run code on Swinburne supercomputer and deliver final simulation [0.2 FTEs].
- Analyse the trade-offs between KSP III science and frequency coverage, resolution, bandwidth, field of view, polarization purity and spectropolarimetric capability [0.2 FTEs].
- Write report on these trade-offs [0.1 FTEs].
- In collaboration with DS2 management (MDS2), write final report [0.1 FTEs].

Output

Description	Work Package	Date delivered
Report on magnetic field models	DS2-T1-WP3	07/2006
Deliver simulated polarization surveys	DS2-T2-WP3	02/2007
Report on key science trade offs	DS2-T1-WP3	05/2007
Final report	DS8-T1-01	06/2007

Justification

Staff effort

A PDRA for 24 months [2FTEs] is required to undertake this work which is too demanding for a PhD student given the timescales involved and the experience required. A young, energetic PDRA with a suitable PhD background is likely to be most appropriate. The PDRA will assess the key datasets available, or to be available before the simulations are performed, and design an algorithm for the simulation. The code will be developed using local resources but developed so that it can be run on the Swinburne supercomputer. The outputs of the simulations will be analysed to determine the frequency coverage, resolution, bandwidth, field of view, polarization purity and spectropolarimetric capability required of the SKA to carry out the key observations for the study of the magnetic universe. The result of this work package will provide input needed for DS2-T2-WP3. All results will be reported to the DS2 management (MDS2) to allow comparison with parallel efforts of the international community. The PDRA and MDS2 will then collaborate on a final report to the UK management.

DS2-T1-WP4 – Science design drivers for pulsar surveys

Background

The main aims of this work package are (i) to provide a detailed sky simulation of all pulsars beamed towards us in the Milky Way; and (ii) to determine the trade-offs between fundamental design parameters of the SKA (e.g. sensitivity, field of view, frequency range) and the key science achievable with finding, timing and studying pulsars. The UK leads the world in pulsar research and has established a leadership role in the SKA Key Science Project KSP II [tests of strong-field gravity with pulsars]. With the 100-times boost in sensitivity, the SKA will detect every pulsar (~20,000) beamed towards us in the Milky Way, find pulsars in external galaxies, pinpoint ~1,000 millisecond pulsars and should find the first known pulsar-black hole systems. By finding pulsars and timing them with a precision increased by two orders of magnitude over what is currently achievable, truly fundamental questions in physics and astrophysics will be addressed.

Detailed simulations are needed to determine the requirements that are compatible with achieving the goals of KSP II at fixed cost, as a function of FoV, frequency range and sensitivity. These simulations must utilise constraints from existing pulsar observations, the currently known pulsar population and achievable timing precision. They must account for uncertainties in extrapolating to SKA sensitivities. The simulation of the population of pulsars (and binary pulsars) will be used to investigate the scalability of timing precision with sensitivity, and to determine the optimal observing parameters both for search and timing observations. Pulsar sky simulations will be output to DS2-T1-WP3, where their simulated polarization properties are used to investigate the magnetic Universe.

Input

Work Package	Description
DS1-00	Overall management and coordination of the design study
DS2-WP1	DS2 and Oxford management

Tasks

- Assess available data constraints and outline proposed algorithm for simulation [0.1 FTEs].
- Write initial report on simulation method [0.1 FTEs].
- Implement and run pulsar sky simulations, developing code on local resources [0.4 FTEs].
- Run code on Swinburne supercomputer and deliver final simulations [0.2 FTEs].
- Develop timing algorithms that ensure scalability of precision with signal-to-noise ratio for follow-up timing observations [0.2 FTEs].
- Study impact of sensitivity on timing precision versus rate of observation (i.e. large FoVs with independent beams versus sub-arraying and limited sensitivity) [0.2 FTEs].
- Write report on frequency range and other observing parameter requirements for KSP II [0.1 FTEs].
- Write report on FoV requirements for KSP II [0.1 FTEs].
- In collaboration with DS2 management (MDS2), write final report [0.1 FTEs].

Output

Description	Work Package	Date delivered

Report on simulation method	DS2-T1-WP4	08/2005
Deliver simulated pulsar surveys	DS2-T1-WP3 DS2-T2-WP4	05/2006
Analysis of follow-up timing precision	DS2-T1-WP4	11/2006
Report on key science trade-offs	DS2-T1-WP4 DS2-T1-WP3	12/2006
Final report	DS8-T1-01	01/2007

Justification

Staff effort

A PDRA for 18 months [1.5 FTEs] is required to undertake this work which, because of the timescales and expertise required, is far too demanding for a PhD student. The PDRA can be young provided he has the necessary background in pulsar research. She/he will assess the key datasets available and design an algorithm for the simulation. The challenging part of the required work is the scientific input needed for the development of realistic pulsar population models, the development of high-precision timing methods and their scalability with signal-to-noise ratio. While the simulation may require the use of the Swinburne supercomputer, the set-up of the simulations and the detailed interpretation of their outputs will be done in the UK. The result of this work package will provide the input needed for DS2-T2-WP4. All results will be reported to the DS2 management (MDS2) to allow comparison with parallel efforts by the international community. The PDRA and MDS2 will then collaborate on a final report to the UK management.

DS2-T1-WP5 – Science design drivers for transient source surveys

Background

The aim of this work package is to identify the science return from SKA studies of transient (burst) sources as a function of the key design parameters of the SKA. A burst source is one with significantly variable (non-periodic) emission on timescales of a month and below. This includes a wide variety of potential sources ranging from slowly-varying sources (e.g. afterglows from very high-redshift Gamma-ray bursts [GRBs]) varying on timescales t ~ months to ultra-rapid burst sources, such as high-energy atmospheric cascades of cosmic-ray hadrons and neutrinos (ultra-high-energy cosmic rays [UHECRs],) that could extend down to timescales t of a few nanoseconds.

Transient source surveys are potentially important to all the Key Science Projects [KSPs], and sources of transient radio emission that are not yet included in KSPs (e.g. UHECRs) still need to be studied in the sense that they might be considered to contribute noise rather than signal. KSP science from transient (burst) sources includes: direct detection of exoplanets [KSP I]; measuring baryon densities and magnetic fields in the cosmic web using extragalactic pulsars [KSPs II & III]; radio pulses associated with gravitational wave sources [KSP IV]; and Gamma-ray-burst afterglows from the epoch of reionization [KSP V]. The opening of the time domain in radio astronomy gives a high chance of discovering genuinely new phenomena, and although this cannot be simulated, the gain in searchable phase space needs to be quantified.

There is clearly a wide and disparate range of scientific return from SKA burst surveys, and a key task is to evaluate how much science can be done with each source class as a function of frequency, bandwidth, FoV, array deployment, sensitivity and time resolution. This will require extensive modelling of each source class to assess the relative merits and trade-offs associated with each SKA design. We must quantify the advantage of the SKA realizations studied in DS4 which, unlike conventional designs, will be able to monitor simultaneously many widely separated patches of sky.

Input

Work Package	Description
DS1-00	Overall management and coordination of the design study
DS2-WP1	DS2 and Oxford management

Tasks

- Identify expected burst sources and the principal parameter components of the source classes [0.5 FTEs].
- Model the expected populations and parameters for each class of burst source [0.5 FTEs].
- Write report on primary burst-source science consistent with the base SKA design parameters [0.1 FTEs].
- Establish constraints on SKA design from the strongest burst-source science drivers (in the presence of potential noise from other burst sources like UHECRs), including the trade-offs between accessible science and primary SKA design parameters, particularly time resolution, frequency range, sensitivity and FoV [0.5 FTEs].
- Write report on the properties of the scintillating sky for input to DS2-T2-WP1 [0.1 FTEs].
- Investigate gain in phase space for new discoveries as a function of SKA realization [0.1 FTEs]
- Write report on the dependence of burst-source science return on primary SKA design parameters [0.1 FTEs].
- In collaboration with DS2 management (MDS2), write final report [0.1 FTEs].

Output

Description	**Work Package**	**Date delivered**
Report on source parameterisation	DS2-T1-WP5	08/2006
Report on source scintillation	DS2-T1-WP5 DS2-T2-WP1	04/2007
Report on source science / SKA parameter relationships	DS2-T1-WP5 DS2-T2-WP5	05/2007
Final report	DS8-T1-01	06/2007

Justification

Staff effort

We request a PDRA for 24 months (2 FTEs) to carry out this work. The PDRA will have to carry out extensive modeling of a wide range of burst sources to determine the dependence of burst science on the primary design parameters of the SKA. The key to this is the development of a strategy for a principal component analysis, identifying common themes between these different classes of source and expressing the overall science return in terms of the SKA performance for each. This is a demanding task, suitable for a young energetic PDRA, but well above what could be usefully tacked by a research student.

DS2-T1-WP6 – Science design drivers for astrobiology

Background

The aim of this work package is to determine whether the detection of molecules of biological significance in proto-planetary disks (PPDs) with the SKA is possible, and if so what design implications this has. We will investigate the detection of the lowest energy transitions of complex molecules which, because of their large moments of inertia, will be found at frequencies suitable for observation with phased arrays. Currently, high-frequency (millimetre and sub-millimetre) searches for bio-molecules such as glycine are hampered by the interstellar line forest which makes their detection and identification extremely difficult. The leap in sensitivity at radio frequencies with the SKA has great potential to resolve this problem as, at radio wavelengths, the molecules which dominate the forest at higher frequency, such as methanol and methyl formate, have very few transitions available. For example, glycine conformer I has about 80 lines in the 0.2-2.0 GHz range, while methyl formate has less than 10. Nevertheless, it is possible that at low frequencies and high sensitivity, complex molecules provide their own line forest.

Current models of PPD chemistry indicate that most chemical activity occurs in the inner 1-20 AU where molecules are evaporated from dust grains into a warm dense gas. Thus the SKA has the brightness sensitivity to detect molecules at mK levels or below, and the spatial resolution (on the order of 0.1 arcsec) to map the inner regions of the PPDs at ~1 GHz. Such high resolution implies long baselines, in marked contrast to the diffuse HI emission from galaxies (studied in DS2-T1-WP2) which places most emphasis on baselines in the 5 km core of the SKA. A particular issue is that the continuum at low frequencies is provided by free-free emission which may vary with time, likely on timescales of weeks to months, as may also emission from the molecules due to rotation, advection and turbulence in the disk. Thus the repeatability of observations needs to be understood in this context.

Input

Work Package	Description
DS1-00	Overall management and coordination of the design study
DS2-WP1	DS2 and Oxford management

Tasks

- Collate spectroscopic data on complex bio-molecules [0.2 FTEs].
- Evaluate and adopt the best published PPD physical model [0.1 FTEs].
- Calculate rotational line spectra expected for bio-molecules as a function of position in the disk to determine which species are best observed [0.2 FTEs].
- Write initial report on spectroscopy and detectability of bio-molecules [0.1 FTEs].
- Develop a physical and chemical disk model to incorporate complex molecule formation [0.4 FTEs].
- Investigate the nature, including variability, of the free-free continuum by implementing models including that of an X-wind [0.3 FTEs]
- Calculate the emergent rotational line spectrum at low frequencies as a function of position in the disk [0.2 FTEs].
- Write report on the optimum frequency range and angular resolution requirements to meet the key science objectives [0.1 FTEs].
- Calculate the line spectrum for a variety of disk parameters [0.1 FTEs].

- Investigate the influence of SKA design parameters (e.g. FoV, multi-beaming) on detection of bio-molecules in PPDs [0.2 FTEs].
- In collaboration with DS2 management (MDS2), write final report [0.1 FTEs].

Output

Description	Work Package	Date delivered
Report on 'optimum' tracers	DS2-T1-WP6	12/2005
Report on FoV/key science tradeoffs	DS2-T1-WP6 DS2-T2-WP2	01/2007
Final report	DS8-T1-01	06/2007

Justification

Staff effort

A PDRA for 24 months [2 FTEs] is required to undertake this work which, because of the timescales and expertise required, is too demanding for a PhD student. It would be suitable for a young energetic PDRA with the right background in astrochemisty/astrobiology.

The PDRA needs to collect the basic spectroscopic data for complex and bio-molecules, several of which have been studied in the lab at 20 GHz, and calculate transition frequencies and line strengths over the 0.2-2.0 GHz frequency range adopting a physical model for a PPD. This will allow an optimum estimate of the observable line strengths for various input abundance distributions, but a more accurate calculation will require the development of a linked physical-chemical disk model to determine likely molecular abundances and distributions in a 2-D disk. Unlike observations at higher frequencies, the continuum background is provided by free-free (and not dust) emission. Thus, the detectability and variability of molecular line emission and absorption will need to be considered carefully. The PDRA will calculate synthetic spectra to determine frequencies at which strongest intensities occur, line widths, and line densities for input to the technical package DS2-T2-WP2.

DS2-T2-WP1 – Technical design drivers for continuum surveys

Background

The aim of this work package to make a quantitative assessment of the ways in which specific realisations of the SKA compromise the science achievable for a given a set of fundamental design parameters. The most important pratical limitation for continuum surveys is likely to be dynamic range (i.e. can the theoretical noise limits be reached in the presence of a sky full of bright, sometimes variable, radio sources). Existing radio synthesis instruments use arrays of dishes which have a small (diffraction-limited) field of view (FoV), but the phased array concept (studied in DS4) is sensitive to radiation from all sources above the horizon.

Simulations of the radio continuum sky from DS2-T1-WP1 provide an input to this work package. These simulations will include the bright sources known in the real sky (with flux densities up to ~1000 Jy) as well as extended emission from the Galactic Plane. The effects of the ionosphere need to be added to the simulated radio sky. Dynamic ranges as high as ~10^{10}:1 will need to be achieved, requiring new algorithms and special techniques like ‘nulling’. An investigation of this problem requires: (a) specifying tolerances on the polar diagrams of the elements (e.g. dish or phased-array tile); and (b) specifying pointing constraints for the elements. New ‘self-calibration’ algorithms for delivering the dynamic ranges needed to reach the theoretical SKA sensitivity will be investigated. Input from DS2-T1-WP5 is needed to assess the effects of time-varying sources in the sky where the time variation can be intrinsic, due to propagation effects or both.

Input

Work Package	**Description**
DS1-00	Overall management and coordination of the design study
DS2-WP1	DS2 and Oxford management
DS2-T1-WP1	Simulation of the continuum radio sky
DS2-T1-WP5	Characterisation of effects of scintillation.

Tasks

- Add the effects of the ionosphere to the simulated continuum sky from DS2-T1-WP1 [0.2 FTEs].
- Taking input from DS2-T1-WP5, include the effects of source scintillation [0.1 FTEs].
- Use this model to investigate dynamic range limitations with conventional (dish) telescopes [0.2 FTEs].
- Use this model to specify the polar diagram and pointing constraints as a function of SKA realization, i.e. dish versus phased array, and as a function of uv coverage [0.5 FTEs].
- Investigate ‘next generation’ self-calibration algorithms related to self calibration, i.e. maximum entropy and tessellation algorithms [0.3 FTEs].
- Write report on dynamic range limitations on SKA sensitivity as a function of realization and uv coverage [0.1 FTEs].
- In collaboration with DS2 management (MDS2), write final report [0.1 FTEs].

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Output

Description	**Work Package**	**Date delivered**

Report on continuum surveys	DS2-T2-WP1	11/2008
Final report	DS8-T1-01	12/2008

Justification

Staff effort

A PDRA for 18 months [1.5 FTEs] is required to undertake this work which is too demanding for a PhD student but suitable for a young PDRA. The PDRA will add the effects of the ionosphere (including scintillation, taking input from DS2-T1-WP5) to the simulated radio continuum sky from DS2-T1-WP1. This model will be used to determine whether the dynamic range limitations of existing datasets (e.g. deep fields from the VLA and MERLIN) are understood. The model will then be used to extrapolate to simulated observations with the SKA using the Swinburne supercomputer, and its array simulation software, to investigate the effects of different uvcoverage. Constraints on the polar diagrams and the pointing of the SKA elements (both dishes and phased arrays) will be derived.

DS2-T2-WP2 – Technical design drivers for line surveys

Background

The aim of this work package is to make a quantitative assessment of the ways in which specific realisations of the SKA compromise the science achievable (given a fixed set of the fundamental design parameters of sensitivity, field of view, frequency range, angular resolution) . For line observations the most important of these are likely to be spectral dynamic range, bandpass stability, the problems of calibration over large instantaneous bandwidth (i.e. can weak, often broad, emission and absorption lines be detected in the presence of bright line and continuum sources) and radio frequency interference (RFI). It is these problems, rather than theoretical noise, which limit existing radio telescopes, whether single dishes or arrays, and will be exacerbated by the huge increase in sensitivity of the SKA.

Simulations of both the continuum- and line-emitting sky from DS2-T1-WP1 and DS2-T1-WP2 will provide input to this work package. These simulations will include the bright sources known in the real sky (with continuum flux densities up to ~1000 Jy) as well as extended line and continuum emission from the Galactic Plane. Huge quantities of data targeting HI emission (to redshift z ~ 0.4) and absorption (to z ~ 5) exist (e.g. from the GMRT) but few detections have been made because of the difficulties of reaching theoretical limits with current-sensitivity telescopes. Such datasets will be used to assess effects of bandpass stability, calibration and RFI, and to cast these in terms of tolerances as a function of SKA realization, i.e. dishes versus phased arrays.

Input will also be taken from DS2-T1-WP6 to assess technical limitations of SKA observations of proto-planetary disks for astrobiology experiments. The main complicating factor here is the time variability of both the continuum emission from the target sources and the background sky. Strategies for detecting and studying bio-molecular emission in the presence of this variability include using multi-line observations and the trade-offs between absolute sensitivity, resolution and multi-line coverage.

Input

Work Package	**Description**
DS1-00	Overall management and coordination of the design study
DS2-WP1	DS2 and Oxford management
DS2-T1-WP1	Simulation of the continuum radio sky
DS2-T1-WP2	Simulation of the line-emitting radio sky
DS2-T1-WP6	Astrobiology simulations

Tasks

- Understand the true limitations of existing datasets targeted at line emission (in both emission and absorption) at high redshift. [0.4 FTEs]
- Add to the continuum and line sky models (outputs from DS2-T1-WP1 and DS2-T1-WP2) the effects of these limitations, parameterised as simply as possible, e.g. bandpass stabilities quadratic in wavelength and linear in time [0.4 FTEs].
- Use the resulting model to specify the tolerances on these parameters as a function of SKA realization, i.e. dish versus phased array [0.3 FTEs].
- Accepting input from DS2-T1-WP6, investigate effects of time-varying signals for astrobiology applications [0.2 FTEs].

- Write report on limitations on SKA line sensitivity as a function of realization, RFI environment and nature of signal [0.1 FTEs].
- In collaboration with DS2 management (MDS2), write final report [0.1 FTEs].

Output

Description	**Work Package**	**Date delivered**
Report on line sensitivity	DS2-T2-WP2	11/2008
Final report	DS8-T1-01	12/2008

Justification

Staff effort

A PDRA for 18 months [1.5 FTEs] is required to undertake this work which, because of timescales and experience required, is too demanding for a PhD student but suitable for a young, energetic PDRA. Existing datasets will be used to determine how SKA line sensitivity might be compromised by bandpass stability, calibration and RFI issues. Tolerances on these parameters will be calculated as a function of SKA realization and RFI environment. The problem will be generalized to include time-varying signal as might be expected in astrobiology experiments.The PDRA will liase with the DS2 manager (MDS2).

DS2-T2-WP3 – Technical design drivers for polarization surveys

Background

The aim of this work package is to make a quantitative assessment of the ways in which specific realizations of the SKA (dish or phased array, uv-plane coverage, number of correlations, data flow rate etc.) affect the fundamental design parameters (sensitivity, field of view, frequency range, spectral and angular resolution) required to achieve the scientific aims. For polarization observations the most important limitations are likely to be (a) dynamic range and its impact on the acceptable level of cross-polarization; and (b) the problems of calibration presented both by the instrumental polarization and by the effects of the ionosphere. Existing radio synthesis instruments use arrays of dishes which have a small (diffraction-limited) field of view (FoV), but phased array `tiles' (studied in DS4) are sensitive to radiation from all the sources above the horizon and do not track like dishes – this may present particular problems since beam-shapes and side-lobe levels will be different for different polarizations, and these differences change with time.

The outputs of DS2-T1-WP3 and DS2-T2-WP1 will provide inputs to this work package. It will investigate how well individual polarizations (and hence Stokes parameters) can be measured as a function of SKA realization, i.e. dishes versus tiles, and the trade offs with the key science achieved. This requires: (a) specifying tolerances on the intrinsic instrumental polarization, its variation with time and the acceptable level of cross-polarization; (b) investigating the effects of the ionosphere across the whole set of baselines and the related calibration issues (which may restrict the frequency range over which polarization observations can usefully be made); (c) looking at the problems associated with complicated beam-shapes and side-lobes levels which are different for the two polarizations; and (d) the particular problems presented by non-tracking elements. These analyses will have a direct input into the design of dual-polarization tiles (DS4).

Input

Work Package	**Description**
DS1-00	Overall management and coordination of the design study
DS2-WP1	DS2 and Oxford management
DS2-T1-WP3	Simulation of the polarized radio sky
DS2-T2-WP1	Technical design drivers for continuum surveys

Tasks

- Understand the true limitations of existing low-frequency (GMRT/VLA) polarization datasets due to cross polarization and calibration (instrument plus ionosphere) issues [0.3 FTEs].
- With input from DS2-T2-WP1, include the effects of the ionosphere and scintillation on the polarization simulations from DS2-T1-WP3 [0.2 FTEs].
- Use these polarization sky models to investigate the effects of the different polarization responses of all the elements as a function of SKA realization, i.e. dishes versus tiles [0.2 FTEs]
- Analyse the impact of the huge dynamic range on the acceptable levels of cross-polarization [0.3 FTEs].
- Specify the tolerances on these parameters as a function of SKA realization [0.3 FTEs].
- Write report on technical design drivers for polarization surveys [0.1 FTEs].
- In collaboration with DS2 management (MDS2), write final report [0.1 FTEs].

Output

Description	**Work Package**	**Date delivered**
Report on polarization surveys	DS2-T2-WP3	11/2008
Final report	DS8-T1-01	12/2008

Justification

Staff effort

An experienced PDRA is requested for 18 months [1.5 FTEs] to perform this assessment work, which, given the timescales and skills needed, is too demanding for a PhD student. The PDRA will investigate the effects of the ionosphere (specifically those relating to Faraday rotation by the ionosphere) on the polarization simulations from DS2-T1-WP3, with input from low-frequency polarization observations made, for example, with the GMRT and VLA. The models of the polarized sky will be analysed in terms of the effects of different uv coverage and different polarization responses of the antennas as projected onto the sky. Constraints on the polar diagrams for each polarization and the instrumental calibration requirements (for both dishes and phased arrays) will be derived.

DS2-T2-WP4 – Technical design drivers for pulsar surveys

Background

The aim of this work package is to quantify ways in which specific realisations of the SKA compromise the science achievable for pulsar surveys [given a fixed set of the fundamental design parameters of sensitivity, Field-of-View (FoV), and frequency range]. For observations of pulsars, large bandwidths have to be sampled with very high time resolution (typically at the Nyquist rate). Search (blind survey) observations have to synthesize the full FOV. Follow-up pulsar timing observations need at least 4 independent FoVs, with about 50 synthesized beams. There are many potential trade-offs that need to be studied to quantify the science output from a given SKA realization.

The size of the independent FoVs, their number, and the exact number of synthesized beams
required to study gravity using pulsars and black holes (SKA Key Science Project KSP II), need to be established from the input of sky simulations from DS2-T1-WP4. In particular, studies of a ‘multiple-dishes with sub-arrays’ concept (i.e. reduced sensitivity) versus a phased-array concept must be performed. An important constraint is that any array configuration must provide a dense core to enable high sensitivity for blind surveys. However, long baselines are also required in order to provide astrometric observations for the discovered pulsars. An optimum compromise needs to be established that also ensures high polarization purity (requiring input from DS2-T2-WP3) and large frequency coverage.

Input

Work Package	Description
DS1-00	Overall management and coordination of the design study
DS2-WP1	DS2 and Oxford management
DS2-T1-WP4	Simulation of the pulsar sky
DS2-T2-WP3	Technical design study of polarization

Tasks

- Implement the results of pulsar sky models (output from DS2-T1-WP4) and study the impact of array configurations on processing requirements for pulsar searching and timing [0.4 FTEs].
- Analyse science return of follow-up observations for various array configurations (e.g. dense cores versus long baselines for astrometric observations) [0.3 FTEs].
- Establish different observing scenarios for different FoVs arrangements (size, number, number of synthesized beams) focussing on the trade-offs between FoV and science return [0.3 FTEs].
- Write preliminary report on pulsar survey science requirements and start to liaise with DS2-T2-WP5 concerning potential joint pulsar and transient surveys [0.1 FTEs].
- Use models to specify the tolerances on key parameters as a function of SKA realization, i.e. dish versus phased array. [0.3 FTEs].
- Write report on science return from pulsar surveys as a function of possible SKA designs [0.1 FTEs].
- Study the technical requirements and the effects of possible limitations on the science return, parameterised as simply as possible, relating findings to results from DS2-T2-WP3 [0.4 FTEs].
- In collaboration with DS2 management (MDS2), write final report [0.1 FTEs].

Output

Description	**Work Package**	**Date delivered**
Preliminary report on pulsar surveys	DS2-T2-WP4	08/2008
Report on pulsar surveys	DS2-T2-WP4	11/2008
Final report	DS8-T1-01	12/2008

Justification

Staff effort

A PDRA for 24 months [2 FTEs] is required to undertake this work which, given the timescales involved and the skills needed, is too demanding for a PhD student but suitable for a young, energetic PDRA. The PDRA will study the complicated parameter space of various SKA designs, including hybrid systems. The PDRA will compare the requirements stemming from KSP II to the various possibilities and will derive a solution that is compatible with the outcome of the sky simulations performed in DS2-T1-WP4. Constraints on the technical design of the SKA will be derived. The outcome of the simulations will be a system matrix, describing minimum FoV, frequency range, sensitivity and array configuration, which will allow determination of the trade-offs between science return in KSP II.

DS2-T2-WP5 – Technical design drivers for transient source surveys

Background

The science drivers for transient (burst) source surveys impose stringent demands on the performance of the SKA, and the aim of this work package is to determine how the best combination of these requirements can be achieved in specific SKA realizations. This includes both wide-field (blind) survey observations (e.g. to search for GRB afterglows), and targeted monitoring (e.g. to look for exoplanets around stars) of many putative burst sources. Radio astronomy at high time resolution and sensitivity and wide field of view (FoV) is a barely explored region of the overall signal parameter space, and this work package will also assess the likely impact on its exploration resulting from design-dependent restrictions on the performance of the SKA.

The effort in this work package will concentrate on assessing the implications of the sky simulations from DS2-T1-WP5 for SKA design. The importance of `triggered' burst searches needs to be assessed, particularly the scientific return on having a large data buffer, enabling the SKA to carry out retrospective observations. There are many burst source types that are attractive targets for the SKA, with characteristic timescales ranging from nanoseconds to many days, and the interplay between performance targets (e.g. size of data buffer) and scientific return is non-trivial. The possibilities of combining at least some aspects of transient source surveys and pulsar surveys (from DS2-T1-WP4 and DS2-T2-WP4) will be investigated within this work package.

Input

Work Package	Description
DS1-00	Overall management and coordination of the design study
DS2-WP1	DS2 and Oxford management
DS2-T1-WP4	Science design drivers for pulsar surveys
DS2-T1-WP5	Science design drivers for transient source surveys
DS2-T2-WP4	Technical design drivers for pulsar surveys

Tasks

- By maximising burst-source science as detailed in DS2-T1-WP5, study the quantitative impact on SKA design parameters [0.4 FTEs].
- Determine how different realisations of the SKA would perform, both in terms of science return and the ability to probe unexplored regions of parameter space [0.7 FTEs].
- Write report on how the SKA design can best be tailored for carrying out targeted and survey observations of burst signals [0.1 FTEs].
- Assess the joint impact of SKA realisations on both the burst and pulsar surveys (DS2-T1-WP4 and DS2-T2-WP4) and investigate the possibility of joint surveys [0.2 FTEs].
- In collaboration with DS2 management (MDS2), write final report [0.1 FTEs].

Output

Description	Work Package	Date delivered

Report on transient surveys	DS2-T2-WP5	07/2008
Final report	DS8-T1-01	12/2008

Justification

Staff effort

A PDRA is requested for 18 months (1.5 FTEs) to perform this assessment work, which is too demanding for a PhD student. The PDRA will assess the complex interaction between the large range of burst-type sources that the SKA can usefully study and the technical challenges that these studies imply. The breadth of the science return possible from burst sources makes this a particularly challenging investigation, and the PDRA will make quantitative assessments on the relative merits and trade-offs involved. This investigation needs to be carried out for the various SKA designs (including those studied in DS4 and dish-element designs) to give a quantitative assessment of the science return from each.

DS3-WP01 – DS3 and Cambridge Management

Background

Cambridge will coordinate Design Study 3 (DS3) for the entire project, as well as take a leading part in the work packages which constitute DS3. The majority of the work packages for DS3 will be undertaken within the UK; these work packages are distributed among the UK SKA consortium so as to make best use of the existing expertise. There is considerable interdependence between these work packages and therefore an associated risk. To minimize this risk, careful management of this effort is required. This work package provides that management (MDS3), enabling the coordination and consolidation of the output from the constituent work packages of DS3. Additionally, the total effort at Cambridge which is contributing to work packages in DS2, DS3 and DS4 must be properly managed so that the outputs can be delivered on time to the rest of the design study. This work package therefore also provides for management of the Cambridge contribution to the design study (MCAMB).

Details of the management and reporting structure are given in Section 6 and are not repeated here. The MDS3 and MCAMB roles are central to the programme.

Input

Work Package	Description
SKADS DS1	Overall management and coordination of the design study

Tasks

- Monitor coordinate and modify milestones and if necessary deliverables for all DS3 work packages.
- Organise and manage team meetings and communication between participants in DS3.
- Sit on and report to the regular meetings of the Project Management Team.
- Attend and produce reports for meetings of the Project Management Team with the Projct Management Board.
- Monitor and coordinate milestones deliverables and tasks undertaken at Cambridge reporting as needed to the coordinator of each DS.
- Provide technical support and guidance for DS3 and Cambridge work.
- Monitor financial spending within Cambridge.
- Report on progress of DS3 to the steering committee.

Output

Description	Work Package	Date delivered
Project schedule for DS3	All DS3 work packages.	01/2006
Coordinate production of final consolidated report for DS3.	DS8-WP01	12/2008

Justification

Staff effort

A PDRA for the full length of the programme (3.5 fte) is required to undertake this crucial management and coordination task. The post is requested at spine point 15 to reflect the management role and the required level of experience essential to this post.

Under this work package we provide a consolidated list of standard computer equipment and consumables items and travel required for DS3. Specific items of equipment are discussed under the specific work packages.

Computer Equipment/Consumables

For computer equipment and consumables we have adopted rates of £2.0k and £0.7k per fte respectively. Thus for the MDS3/MCAMB manager (3.5 fte) and all the other fte's requested under DS3 (21.3), the totals over the period of the programme are:

£49.5k (computer equipment) and £17.4k (consumables).

Exceptionals

DS3 activity will involve regular (weekly) telecons or, occasionally, video conferences. Fortnightly telecons lasting ~ 1 hour, involving ~ 3 institutions, costing ~ 25p per minute per institution or £1.17k per year

Total over the period of the programme £4.1k

Travel

The travel budget consolidates travel requirements for the MDS3 and MCAMB manager, all fte's supported by DS3, and all academic staff travelling for reasons directly connected with the DS3 programme (eg. monthly project meetings, bi-monthly EC meetings and half-yearly international meetings).

We start with PPARC guideline figure of £1.8k for the 21.3 fte's giving a total of £38.3k.

We add to this the cost of trips and extended visits to Swinburne for the fte's associated with work packages T3-01, -02 and -03 to a total of £6k

For the MDS3/MCAMB manager position, UK and European travel will total £0.3k per month. The total travel for the MDS3/MCAMB manager is therefore £12.6k.

For academic staff we take the UK/EC travel on DS3 business to be 10.2 fte at £1.8k per fte.
Total travel for academics on DS3 business is therefore £18.4k.

Total travel for DS3 is therefore £75.2k

DS3-T1-WP01 – Coherent signal distribution via fibre optics

Background

The aim of this work package is to investigated the use of fibre optics for maintenance of coherence so that interferometric observations at frequencies up to at least 2 GHz and preferably 30 GHz can be made with SKA. The SKA requires coherence to be maintained over antenna separations ranging from a few metres to 3000 km. Fibre optic technology potentially offers ideal solutions to both of these problems: the low loss of fibres (0.2 dB at 1550 nm), high intrinsic bandwidth (potentially around 15% of the optical frequency) and relatively low cost give many advantages over coaxial cable, waveguide or free-space systems. Current designs indicate that 75% of the collecting area is within 150 km of the core of the instrument, and the design study will focus on achieving phase coherence on scales of a few hundred km. The study will make use of the optical fibres which are being installed for eMERLIN; these will be available for test measurements in 2005.

Maintenance of coherence between oscillators or clocks requires accurate determination of the path lengths (to an rms deviation equivalent to <0.6 ps if coherence loss of less than 1% is required at 30 GHz). The path length in a fibre varies with temperature, and it is important to limit the rate of change of path length. This is achieved in the EVLA and ALMA by careful temperature control (S. Durand and R. McCool, SPIE Paper 5496-64, Glasgow, 2004), however it is inevitable that parts of fibre link will not necessarily be well controlled – e.g. the sections of fibre on the antennas and at splice junctions in access pits. Accurate path length determination requires continuous go-and-return measurements. Limits set by non-reciprocal behaviour of fibre (due to polarisation mode dispersion), the stability of lasers in a multi-laser system, and non-linear effects in optical amplifiers require investigation before a design can be established. The link lengths are such that even with the low loss of fibres, optical amplifiers and repeater stations will be required.

Input

Work Package	Description
DS3-WP01	Management and coordination of DS3 work packages

Tasks

1. Review current work on phase and time transfer on fibres at JBO, EVLA, ALMA and in HEP accelerators.
2. Set up phase stability measurements in the laboratory at JBO and on installed fibre eMERLIN using test equipment to characterise performance without phase correction
3. Develop a single-hop design for phase transfer over 15 km
4. Produce a prototype phase transfer system for a 15-km link, using test equipment and specially designed hardware.
5. Make measurements on the link including non-reciprocal effects, suggest design improvements and report on results
6. Develop designs for multi-hop links spanning up to 400 km
7. Produce a prototype multi-hop link, using existing equipment and new hardware where necessary.
8. Make measurements on an installed multi-hop link, suggest design improvements and report.
9. Produce final report.

Output

Description	Work Package	Date delivered
Prototype 15-km link	DS3-T1-WP01	01/2006
Prototype multi-hop link	DS3-T1-WP02, DS8-WP01	03/2007
Final report	DS8-T1-WP01	06/2007

Justification

Staff effort

A PDRA for 24 months (2 fte) is required to undertake this work. The PDRA will assess the current knowledge in the area and then design, construct and test first the 15-km single-hop link, then the multi-hop link. The PDRA will then produce the final report on the use of fibre optics for phase-coherent signal transmission. The level of complexity of the project requires appropriate background experience which is much more than that expected for a student. The work will also require a large element of research rather than application of established techniques, hence the need for a PDRA rather than an engineer. It is quite possible that the final scheme will be patentable.

The prototype construction will require technician support (0.8 fte) and input from a radio frequency engineer to the design of the prototype links (0.2 fte).

Equipment

The equipment needed for the construction of the prototype links has been defined based on recent experience at JBO: Signal generator £1k; Control computer with Lab-view licence £2k; 4 lasers £10k; 4 Modulators £4k; 4 Temperature and power controllers £4k; 4 Wavelength lockers £16k; 4 Optical filters/Muxes £6k; 4 Optical Isolators £4k; 4 Optical Circulators £4k; 4 Optical splitters £2k; 4 Optical amplifiers £12k; 4 Photodiodes £4k; 4 Phase-locked oscillators £4k. The simplest way of making comparative phase measurements in the laboratory at radio frequencies of 0.1–2 GHz is to use a vector voltmeter at each end of a link. An Agilent 8508A vector voltmeter is available at JBO, a further one is required. Unfortunately these are no longer manufactured, but refurbished units are available at £10k. An alternative is to use a vector network analyser, but these are much more expensive.

Total cost of equipment £83k

Consumables

Power supplies, connectors, patch cords, miscellaneous electronic components £5k

DS3-T1-WP02 – Data transmission requirements for SKA

Background

The aim of this work package is to investigate high bandwidth data transmission via fibre optics. The SKA is likely to be limited by our ability to transfer data at sufficiently high rates; the preliminary design (which will be refined within other studies in DS3 and DS2) indicate data rates in excess of 50 Tbps from a "station" equivalent to a single 25-m antenna. The data rate at any point in the telescope depends crucially on its topology and this is being studied within WP-DS3-T3-01 and related work packages. However it is clear that we must investigate the maximum data rates that can be achieved. Fibre optic technology is currently the most likely technology for the infrastructure. In this work package we will investigate the various technological options based on a fibre network. Close contact with industry is required in order to gain insight in how communications technology is evolving; the final report is scheduled for the end of the design study in order to minimise extrapolation in this rapidly evolving field.

Local area networks making use of fibre optic connections are currently used over short distances. They may offer an easily available and low cost solution to SKA data transfer problem in he inner 1 to 5 km, though other hardware solutions involving arrays of laser diodes (e.g. VCSEL arrays) may also offer good solutions. SKA data rates are high compared with current practice, but use of the techniques available in future local area networks is attractive. Interference between the fibre waveguide modes limits the maximum distance that multimode devices can be used. Beyond ~1 km single mode fibre is preferred, where the diameter of the fibre core is such that only one mode can propagate. Direct modulation of the laser however results in frequency chirp, which limits the bandwidth to a few Gbps and maximum range of devices to around 10 km. Improvements in the range and bandwidth of these devices are continually being made and so it may be possible to reach several 10's of km with multi-gigabit rates in future. However multiple fibres or DWDM techniques with wavelength stable devices will probably be required to reach Tbps rates.

High data rate links beyond a few km currently require externally modulated lasers and single mode fibre. Spans of more than ~15 km require amplification, this can be via EDFAs or by Raman amplifiers. Current links have matured at 40 Gbps per wavelength, though 80 and 160 Gbps systems have been tested.

The long links out to 3000 km are such that the cost of laying fibre becomes significant, and here it may be more efficient to share use with telecommunication links. This could be via dark fibre lease as in e-MERLIN or as managed bandwidth. Current managed bandwidth costs for the bandwidths we require are high. The essential use of routers and switches in a telecommunication system adds unnecessary expense. However, recent developments in wavelength switching may for our purposes be helpful. For example, a research network (UKLight) has been set up in the UK to test protocols and performance of such a system, though it emulates wavelength switching using conventional routers, giving a net data rate of 10 Gbps. The expectation is that all-optical networks will be installed in the next few years and these should have the capacity that SKA requires. University staff at Manchester and Cambridge are participating in the ESLEA UKLight exploitation programme and experience gained in that project will give valuable input to this work package.

Input

Work Package	Description
DS3-WP01	Management and coordination of DS3 work packages
DS3-T3-WP01	Report on distributed processing and data transfer capacity
DS3-T1-WP01	Prototype multi-hop link

Tasks

1. Initial report on best available technology currently in use.
2. Design study of short (< 5 km) links, investigate various technologies likely to become available in the next decade, produce an interim report on short link technologies.
3. Study of intermediate distance (1-15 km) link technologies and report.
4. Study of links requiring amplification (distances from 15 to 150 km) and report
5. Study of long (up to 3000 km) links and report
6. Produce a final report including current and estimated future costings, including sections on the impact of likely future technology advances.

Output

Description	Work Package	Date delivered
Initial report of the best available technology with simple extrapolation to 2010; the aim is to use this as a basis for design studies in DS3.	DS3-T3-WP01	10/2005
Final report including costings of likely technologies for data transmission over all distances relevant to the SKA	DS8-T1-WP01	12/2008

Justification

Staff effort

Support for 18 months (1.5 fte) is required to undertake this work. A full assessment of existing and emerging technologies is required. This will involve close liaison with relevant industries and research groups involved to assimilate current knowledge and make a realistic extrapolation of available technologies in 2010 – 2020. The work will benefit from an experienced fibre optic engineer with contacts in industry. Therefore the 1.5 fte requested will support the existing fibre optic engineer at JBO who has considerable experience in the design of data transmission systems, and has designed the links used in the EVLA, ALMA and eMERLIN.

Equipment

An AutoCAD license is required for this work (£ 1k)

DS3-T3-WP01 – Network Architecture

Background

A fully digital phased array radio telescope provides a uniquely flexible instrument; by correlating every receiving element with every other receiving element one can in principle image simultaneously the entire field of view of a single element. In practice the instrument will be limited by our ability to perform the digital signal processing and manage the flow of data through the telescope. Traditionally an interferometer has consisted of receiver elements together with a central dedicated processor – the correlator – which does all the processing. It is clear that this model is inappropriate for a phased-array SKA concept. Even if we consider the telescope to consist of n 1 m^2 tiles, the number of correlations required is equal to $n(n-1)/2$ or $\sim 10^{12}$ correlation at a data rate which could be as high as 32 Gbps from each tile at full spectral resolution. It is immediately apparent that this degree of processing cannot be produced on any realistic timescale.

This problem is mitigated in two ways. Firstly, not all the elements are correlated with all the others and secondly dedicated distributed processing hardware can be incorporated as part of the design of the telescope. For example, by having s stations with m elements per station ($n=m\times s$) which are phased together, the total number of correlations is reduced to $b\times n + b\times s(s-1)/2$ where b are the number of independent phased beams. If each station in this model had a collecting area of 10^4 m^2 (equivalent to a ~110 m antenna) the number of correlations is only $\sim 10^4$. The trade off is in the imaging fidelity, field-of-view and reduced sampling of the Fourier plane. The Fourier Transform of the phased elements of a station form the primary beam of the station on the sky; the correlated data which sample the aperture-plane (essentially the Fourier transform plane of the sky brightness distribution) are convolved with the aperture response of each station.

In practice, more complicated schemes are required which produce an overall telescope capability which is matched to the science requirements, while taking into account the constraints of achievable data-flow rates, processing power and cost. The aim of this work package is to investigate the network architecture and distribution of computational elements which maximises the scientific return subject to realistic cost constraints on the computational elements and data transfer limitations.

In investigating the network architecture we must account for constraints of varying types:

- The imaging, spectra and time-domain requirements of the key science drivers. These include the required imaging fidelity, side lobe levels, spectral, angular and time resolution.
- The minimisation of the response to bright confusing sources. Confusing sources and predictable sources of interference (e.g. satellites) can be mitigated against by ensuring the telescope response is small (nulled) in the direction of such interference. This will happen at all levels from individual tiles to the overall response of the telescope.
- The response (or beams) of the basic elements forming the network – these will either be individual tiles or elements or area approximately 1 m^2.
- Achievable data rates through the network and cost of the infrastructure.
- The required amount of processing and availability / cost of the processing resource. The processing resource will be a mixture of distributed processing and a central massively parallel processor.

Input

Work Package	Description
DS3-WP01	Management and coordination of DS3 work packages
DS2-T1-WP01 to -WP05	Science requirements from the key scientific drivers.
DS3-T1-WP02	The report on current estimates of the data transfer rates obtainable with current technology projected to 2010 will be used as a basis for modelling.
DS3-T2-WP01	Reports on correlation computing needs.
DS4-T0	Initial estimates of the data rates from tiles and in particular the digitisation rate will be used as a basis for modelling.

Tasks

- Review current hardware capabilities for off the shelf technology: micro processors and data rates over fibre or other means. Produce a conservative extrapolation to 2010. Write report of this initial survey.
- Develop a model for the telescope which calculates: the telescope response on the sky (number of beams, side-lobe levels, image fidelity); data-rates; required processing power.
- Apply model to initial straw-man design for the distribution of collecting area and requirements for imaging spectroscopic and timing observations.
- Develop software to implement this model within the generic telescope simulator being developed at University of Swinburn (Australia).
- Incorporate improved estimates of the necessary data rates and processing required from studies of the science objectives. This will be on-going throughout the duration of the work package. After delivery of the simulation code (04/2007) there will be close interaction with each of the DS2-T2 work packages to input and test using the simulation code constraints developed from the science drivers.
- Investigate existing tools for optimization of network problems and determine their applicability to the specific problem of network architecture for the SKA.
- Optimise the array design and network topology taking as constraints the maximum sustainable data rates, processing power and performance requirements determined by the scientific simulations.

Output

Description	Work Package	Date delivered
Report on distributed processing and data transfer capability.	DS3-T1-01	01/2006
Network simulation code	DS2-T1-all, DS3-T3-02, DS8-T1-01	04/2007
Final report	DS8-T1-01	12/2008

Justification

Staff effort

This is a central part of the design study obtaining an overview of the phased-array concept, data flow and computational problem in the light of real-world constraints. Substantial work is required to develop a model for all the aspects of the network and build this model into the framework of the generic telescope simulator so that it can be made widely available. The staff effort required for each aspect of the work package is estimated as follows:

1. Assess and extrapolate efficiency of computational elements: 0.25 fte
2. Develop a model for the telescope response, data flow and computational cost: 0.5 fte
3. Software development for model implementation 1.5 fte
4. Application of model incorporating changing estimates from science drivers 0.5 fte
5. Development and implementation of optimisation strategies 1.25 fte
6. Writing reports, attendance at meetings, interface with Swinburn group 0.5 fte

Total 4.5 fte

Equipment

The modelling code will be designed to run on multi-processor machines; final development code will be run at the University of Swinburn supercomputer facility. For the development 2 small Beowulf clusters are required – these will be also used for DS3-T3-WP05 grid-enabled software. These clusters will be located at Cambridge and Oxford; management will be provided by existing Computer Officer staff at Cambridge. For ease of management we will use rack-mounted blade solutions.

Two 16-node Beowulf rack-mounted blade servers £40k.

Milestones

- Initial report 01/2006
- Initial model for the data flow and architecture 04/2006
- Simulation code developed 04/2007
- Optimisation of network architecture design 09/2008
- Production of final report 12/2008

DS3-T3-WP02 – Network requirements for time resolved experiments

Background

A key science driver for the SKA is to use Pulsars and Black holes as a test of gravity in the strong field limit. This science requires wide bandwidth, simultaneous spectral coverage, wide field of view and importantly high temporal resolution (better than 1 μs) . In determining the constraints on the telescope for time-resolved experiments we will concentrate on this key science driver, although the considerations will also apply to other experiments requiring time-resolved data. Observations of known pulsars demand very accurate timing measurement. A key aspect of the programme will also be the search for new pulsars. Pulsars are identified by periodic (but not harmonic) signals; these periodic signatures are dispersed by delays in the inter-stellar and inter-planetary plasma. Search algorithms must therefore search in this dispersion-measure – time domain resulting in a very computationally intensive problem. For example, at JBO a dedicated system, COBRA, is used for such searches and analysis of pulsar observations from the single dish Lovell telescope. Careful consideration needs to be made of the computational requirements and data rates for the SKA in order to deliver this key science programme.

The aim of this work package is to turn the detailed science requirements for this key programme into quantified constraints on the network architecture. To assess proposals for the architecture against these constraints and determine an optimal strategy for achieving the science goals within the wider context of the telescope performance and constraints imposed by computational power, data flow and cost.

Input

Work Package	Description
DS2-T2-WP04	Detailed requirements based on a careful analysis of the science for the pulsar key science driver.
DS3-T3-WP01	Network model and simulation code.

Tasks

- Cast the output of the science simulations of the key programme on tests of strong gravity in terms of constraints on the network architecture. This will take input from DS2-T2-WP04.
- Update the model and simulation software for the network to accommodate these constraints.
- Assess network architectures in the context of these constraints and update the optimum network architecture considering also the constraints of other science drivers.
- Assess the effect of compromises enforced by the constraints of processor power, data flow, cost etc. on the deliverable science.
- Update the above as the output of DS2-T2-WP04 is refined.

Output

Description	Work Package	Date delivered
Report on the implications for the network of the ideal requirements of time-resolved experiments.	DS3-T3-WP01	01/2008
Updated network simulation code	DS3-T3-WP01	06/2008
Final report	DS3-T3-WP01, DS8-WP01	12/2008

Justification

Staff effort

1.25 FTE are required to undertake this work. An excellent understanding of the science drivers is required and there will be close collaboration with DS3-T3-WP01 to achieve the scope of the work package. The PDRA will need to become acquainted with the model and software tools developed under DS3-T3-WP01 and update the code to take account of the specific constraints imposed by time-resolved experiments.

Equipment

See standard equipment under DS3-WP01.

Milestones

- Determine constraints on network architecture from outputs of the DS2 design studies in a form suitable for integration into the simulation code (01/2008)
- Update simulation code (06/2008)
- Analysis of implications and final report (12/2008)

DS3-T3-WP03 – Network requirements for experiments involving imaging and spectral-line observations

Background

A key science driver for the SKA is to observe redshifted neutral hydrogen. This forms part of two key science programmes (Probing the dark ages; Evolution of galaxies and large-scale structure) and is likely to be a widely used mode for the telescope. This science requires near complete frequency coverage at wavelengths longer the hydrogen 21-cm line, wide field of view for surveying and excellent imaging fidelity. A key aspect of the programme will to search for neutral hydrogen, HI, signatures as being localised in both space and frequency domains and seen either in emission or absorption. Searching for such signatures will involve a systematic and computationally costly pattern matching process. While it is likely that some of the analysis will be performed off-line by many observers, the volume of data produced from a near-complete survey of the universe (or at least that region observable from the SKA site) out to a redshift of 10 or more will be so large as to require special consideration as to how the data can be processed.

The aim of this work package is to turn the detailed science requirements for these key programmes into quantified constraints on the network architecture. To assess proposals for the architecture against these constraints and determine an optimal strategy for achieving the science goals within the wider context of the telescope performance and constraints imposed by computational power, data flow and cost. The work package will also address the question of whether the computational problem of spectral-searches can be distributed over the distributed processing available within the network together with the central processor.

Input

Work Package	Description
DS2-T2-WP1, DS2-T2-WP2	Detailed requirements based on a careful analysis of the science for continuum imaging and line survey key science drivers.
DS3-T3-WP01	Network model and simulation code.

Tasks

- Cast the output of the science simulations of the key programmes on continuum imaging and HI line searches in terms of constraints on the network architecture.
- Update the model and simulation software for the network to accommodate these constraints.
- Consider how the spectral searches may be achieved given the processing power available within the network both in the central processor and the distributed processing elements.
- Assess network architectures in the context of these constraints and update the optimum network architecture considering also the constraints of other science drivers.
- Assess the effect of a compromises enforced by the constraints of processor power, data flow, cost etc. on the deliverable science.
- Update the constraints as the output of the DS2 tasks is refined.

Output

Description	Work Package	Date delivered
Report on the implications for the network of the ideal requirements of experiments requiring spectral-line searches	DS3-T3-WP01	03/2008
Updated network simulation code	DS3-T3-WP01	08/2008
Final report	DS3-T3-WP01, DS8-WP01	12/2008

Justification

Staff effort

1.5 fte of PDRA effort is required to undertake this work. An excellent understanding of the science drivers is required and there will be close collaboration with DS3-T3-WP01 to achieve the scope of the work package. The PDRA must take the developing output of DS2-T2-WP1 and -WP2 and update the simulation code taking into account the specific constraints of these programmes.

Equipment

See standard equipment under DS3-WP01.

Milestones

- Determine constraints on network architecture from outputs of the DS2 design studies in a form suitable for integration into the simulation code (01/2008)
- Update simulation code (06/2008)
- Analysis of implications and final report (12/2008)

DS3-T3-WP04 – Management of the data flow

Background

Efficient handling of the large data rate from SKA will be a major issue. While the SKA itself will present major new challenges in data handling and analysis, many other projects are facing a similar many-order of magnitude increase in the data rates. Many of these project areas (gravitational wave detection, ALMA, particle physics) must solve their problems well in advance of the SKA. Therefore it is very clear that the SKA can benefit from the experience and expertise available in these other fields.

The aim of this work package is to explore how this knowledge can be effectively transferred into the SKA, where there are synergies and where the problems facing the SKA are unique and hence where the greatest effort will need to be concentrated. We will investigate and analyse: the data flow in a highly distributed scenario drawing on expertise from the LIGO Scientific Collaboration (specifically with GEO600); particle physics experiments such as LHC; telescopes such as ALMA, eMerlin and eVLA.

The synergies between the problems faced by these different projects will be identified as well as the differences. The output of this work package will include an assessment of what skills, software and knowledge can be (a) directly transferred and (b) transferred with modification to the SKA project.

Input

Work Package	Description
WP-DS3-WP01	Coordination and management of DS3
WP-DS3-T3-WP01	An initial assessment of the data flow requirements in the telescope.

Tasks

- Become familiar with the data processing tasks facing GEO600, the ALMA project and the UK particle physics community.
- Produce a detailed critical comparison of the SKA problem compared to these areas.
- Determine how the experience and expertise gained in these other areas can be integrated into the SKA design study and into the final SKA design thereby reducing costs and mitigating risks.

Output

Description	Work Package	Date delivered
Interim report on areas of direct interest o the current SKADS where existing knowledge may be fed into DS3 design tasks.	DS3-T3-WP01, -WP02, -WP03, -WP05	03/2006
Final report	DS3-WP01, DS8-WP01	12/2006

Justification

Staff effort

A PDRA for 18 months (1.5 fte) is required to undertake this work. The PDRA will work closely with the GEO600 team, the ALMA team and the particle physics community in the UK. The PDRA will determine what can be input to the SKA project from these studies. The PDRA must have sufficient time to assimilate the information from these various fields and produce a coherent report based on input from these various sources as well as take input from other DS3 studies.

Equipment

See standard equipment under DS3-WP01.

Milestone

- Review of current expertise in related areas, interim report (03/2006)
- Production of final report (12/2006)

DS3-T3-WP05 – The application of distributed, GRID-enabled data reduction for the SKA

Background

The SKA will produce un-paralleled amounts of data. Raw data from each element must be either phased or correlated; this, real-time, aspect of the data analysis pipeline is being considered in DS3-T3-WP01. The correlation of signals from antenna elements merely serves to increase the data rate although reduction of the bandwidth and integration of the data greatly reduces the amount of raw data emerging from the telescope. Even so, the total size of data set produced by the telescope is enormous. The preliminary SKA science requirement (Jones 2003) assumes a maximum integration time of 0.1s, 10^5 spectral channels in full polarization and assuming a typical number of baselines to image a 1 square degree field of 10^6 (Carilli 2002), which gives a data rate of approximately 10 Tbyte per second of correlated data for each of many independent beams. Traditional instruments pass these raw data to the astronomer to reduce using a fairly standard reduction pipeline of calibration, followed by iterative imaging / deconvolution / self calibration and largely this analysis is performed off site. Such an approach is only feasible for the SKA if Moore's law holds at its current rate until 2020.

The aim of this design study is to investigate ways in which the data rate from the telescope can be analysed using new algorithms and making use of the natural architecture of the telescope as a computational grid. The This work package links closely with those investigating the overall architecture of the network (DS3-T3-WP01) and the output of scientific simulations (DS2-T2) where the scientific requirements generated in DS2-T1 are formed into a set of detailed constraints on the telescope design. In this work package we consider how new approaches can be implemented within the architecture of the telescope and the efficiency with which this can be achieved.

In this work package we therefore consider in detail how proposed algorithms may be implemented for the SKA architecture so that we can determine:

- constraints on how the processing is distributed within the array;
- the relative amount of central processing compared to distributed processing required and a cost analysis of the various options;
- an assessment of the amount of software effort which is likely to be required for implementing such grid-enabled codes (input to DS3-T2).

Relationship to RadioNet

There will be close cooperation with this work package and related work packages within RadioNet. In particular, ALBUS, one of the Joint Research Activities within RadioNet is developing and implementing new algorithms and methodologies for calibration and imaging. Although the focus of ALBUS is software for European VLBI the underlying aim which is the efficient analysis of large interferometric data sets is central to the issues faced by the SKA. This SKA Design Study work package will complement the existing effort within RadioNet (which itself has links and coordination with software development within the U.S. NRAO) by focusing on specific issues relevant to the design and specification of the SKA.

Input

Work Package	Description
DS3-WP01	Management of the DS3 tasks
DS3-T3-WP01	Nature of the network architecture

Tasks

The amount of effort required to complete each task is shown in parantheses.

1. Assess state of parallel software development in RadioNet and for ALMA; establish contacts and links to relevant workers within RadioNet (0.3 fte).
2. Assess tools and protocols for development and management of grid software for applicability to the SKA problem and for use in the design study. This will include: scheduling methods (e.g. Globus, Condor); message passing interfaces (e.g. MPI and PVM in a grid environment); grid enabled development tools. (0.4 fte)
3. Initial report (0.15 fte)
4. Investigate and implement on a BeoWulf cluster existing parallel imaging methods and code; existing code and analysis from RadioNet and NRAO will be re-used as appropriate (1 fte).
5. Investigate alternative strategies for simple imaging case which may be better suited to a grid architecture – input to RadioNet (1.25 fte).
6. Implement imaging case in a grid environment. This will start with a local grid based on the BeoWulf cluster plus other hardware and then link sites within DS3. The use of the National Grid Service will also be investigated and possibly utilized for testing. The code will also be run on a dedicated distributed memory machine for comparison – Cambridge HPCF (1.15 fte)
7. Evaluate the efficiency of code in grid environment compared to running on a dedicated distributed memory machine (0.1 fte)
8. Evaluation of the grid-enabled implementation in comparison with the SKA architecture; update methodology and implement (0.6 fte).
9. Estimate of additional cost of developing grid-enabled technology; input to analysis of software costs for the SKA (0.1 fte).
10. Final report and analysis of needs of SKA with respect to grid enabled data reduction. (0.2 fte).

Output

Description	Work Package	Date delivered
Initial report on grid-enabled processing	DS3-T1-WP01	01/2006
Prototype grid-enabled example code	DS3-T1-WP02, DS8-T1-WP01	06/2008
Final report	DS8-WP01	12/2008

Justification

Staff effort

5.25 fte’s are required to undertake this work. The detailed analysis of required effort is shown against each task above. The task will be managed from Cambridge, but will involve personnel in both Cambridge and Oxford. Cambridge will provide Computer Officer support as an in-kind contribution from HEFCE funded staff for managing the BeoWulf clusters. Interaction with other sites involved in the design study will also required to test grid-enabled methodologies; Cambridge will provide necessary technical support from HEFCE funded resources.

Equipment

For development, access to local parallel machines is required. This will be achieved by using Beowulf clusters at each site participating in this task. These clusters will also be used for the development and initial implementation of the array architecture model (DS3-T3-01); the costs for these clusters is included in this task description.

Milestones

- Initial report on grid-enabled processing (01/2006)
- Working simple parallel imaging code taken in large part from existing sources. (09/2006)
- Implementation of simple imaging example in a grid environment (06/2007)
- Prototype grid-enabled example code (06/2008)
- Final report (12/2008)

DS3-T3-WP06 – Data, archiving and scientific exploitation

Background

A challenge for the SKA will be to provide end users with data products which maximise the scientific output of the instruments and make them as accessible as possible. However it remains likely that pipelined data reduction will never produce the very best which can be achieved for a given data set and in some experiments the end user astronomer may need to push the data to the limits. Therefore we need to consider what data products are needed and how should these be archived? The raw data rate from the SKA can be several Tbytes per second depending on the observing modes; careful consideration needs to be given to the archiving of raw data compared to partially reduced data in terms of the real cost involved compared to the possible scientific benefit. Indeed with a flexible instrument such as the SKA re-observation rather than long-term archiving may in many cases be a lower-cost option.

This work package addresses these issues of data products and archiving in terms of maximising the scientific output as a function of cost. In addition to the types of data product which should be produced we will also consider how the archive should be structured to optimise scientific output. The work package will also consider how these considerations impact on the SKA design. Finally, the end-user astronomer will access much if not all of the data products via the Astrophysical Virtual Observatory; the work package will address the interface to the AVO necessary for SKA data products. For this work package we will build upon the work being undertaken within RadioNet and for the ALMA project on related issues.

Input

Work Package	Description
DS2 all	Requirements from the science simulations for data products
DS3-T3-WP01 DS3-T3-WP05	Achievable data rates, processing power and the possibilities for on-line and on-site data recduction.

Tasks

- Review current work within RadioNet and the ALMA project on data archives for radio astronomy and the nature of the proposed data products and interface to the AVO. Develop working links with relevant people working within RadioNet, AstroGrid and the ALMA project.
- Produce a report on the current state of the art of data archives for radio astronomy and interface to the AVO.
- Extract and assimilate from the analysis of the main science drivers the types of data products needed to deliver this science and look for synergies between the data products from different science drivers.
- Determine options for data archival and how these relate to the science drivers. Assess the technical requirements for the data archive and examine whether existing technologies (projected to 2010 – 2020) can provide the necessary archive infrastructure.
- Provide a preliminary assessment of the costs of maintaining the archive for different archival strategies.
- Produce a report covering: the required data products from the SKA needed to meet the science drivers; archival strategies and their scientific benefits together with cost estimates for providing and maintaining a given strategy; the interface to the AVO and access to the SKA data products and archive.

Output

Description	Work Package	Date delivered
Initial report on current state of the art	DS8-T1-WP01	08/2008
Final report	DS8-WP01	12/2008

Justification

Staff effort

A PDRA for 12 months (1 fte) is required to undertake this work. The PDRA will assess the current knowledge in the area, proposed data products for radio astronomy and the interface to the AVO. The PDRA will interact with relevant people working on related areas within RadioNet, the ALMA project and AstroGrid to benefit from existing knowledge and expertise. It will be necessary to consider what data products are required for the SKA and this will require the PDRA to assimilate the output of the various science simulation design tasks and produce a consolidated analysis of the necessary data products for the SKA. A related analysis will be to consider archival strategies and associated costs. The main output of this design study will be a detailed report drawing together information from a wide variety of sources and its production will be a large element of the time spent on this work package.

Equipment

See standard equipment under DS3-WP01.

Milestones

- Review of state of the art practice.
- Final Report.

DS3-T3-WP07 – The SKA in operation: users, observing modes and user support

Background

The unique nature of the SKA will have significant implications for the operation of the facility and the way the user interacts with the telescope. In this work package we consider implications for the telescope design and operational modes of the user interaction with the telescope from observing proposal stage through to data reduction and science exploitation.

(A) Observing Proposal stage. The nature of the SKA, and in particular the observing speed and multi-tasking observing capability via many independent beams raises important issues with respect to how users gain access to the telescope. At one extreme it is certain that consortia of observers will wish to undertake substantial surveys as is envisaged by the main science drivers. Such proposals are likely to require large fractions of the available telescope observing time and some direct peer-reviewed application procedure will, as now, be required. At the other extreme an astronomer may need targeted observations on a relatively small number of objects requiring an almost insignificant fraction of the total observing time of the instrument. Indeed such an observer will probably interact via an AVO and will not be interested in whether the data reside in an archive or represent new observations. How are these later requirements to be met? Is it possible to construct a model in which new observations are triggered by an AVO request; if so how should these observations be prioritised? Can a system be constructed which efficiently anticipates the likely requests of observers? In this case can, or indeed should, there be any concept of proprietary data.

(B) Observing modes. The science drivers define a set observational requirements for the telescope. In this work package these inputs will be assimilated and reduced to a consistent set of required observing modes of different complexity.

(C) Data visualisation. The volume of raw data produced for a given programme will prohibit detailed investigation of the data as is now common in interferometric data analysis. Pipelined data reduction (especially interference rejection and calibration) will reduce the need for such intervention for most users, however for more specialist observing and diagnostic investigation, data visualisation will be desirable. Possible methods of data visualisation appropriate to the SKA will be considered building on the work being undertaken within the ALBUS project of RadioNet. This aspect of this work package will be undertaken by JIVE.

(D) End-to-end user environment. The close integration between proposal, data reduction and AVO access suggested by the flexibility of the SKA may imply that a new model for the end user interface to the telescope is required. One possibility is to use a single software portal for access to all the functions of the telescope. This should not only incorporate proposal and operation modes, AVO-type access, data reduction, but also access to user support functions and facilitate scientific dialogue between astronomers. In particular within this work package we will investigate state-of-the-art systems which provide shared resources and a development environment tailored to collaborative research programmes.

(E) The level of user support required for observers will depend on the details of the methods by which users interact with the telescope resource. An estimate of the required level of user support (and associated costs) for different user-interaction models will be developed.

Input

Work Package	Description
DS2-all	Required observing modes for specific science projects.
DS3-T3-01	Limitations on desired observing modes implied by the achievable telescope architecture.

Tasks

Details of tasks (A), (B), (D) and (E) to be undertaken within the UK are given here.

1. (A) Review best practice in proposal submission, evaluation etc. in existing radio observatories and the plan for eVLA, eMERLIN and ALMA.
2. (A) Consider how the model translates to the case of the SKA.
3. (A) Assess different models for the way astronomers gain access to the resources of the SKA paying particular attention to the flexibility and observing speed of the instrument.
4. (A)Produce an interim report on issues concerning user access to the SKA resource (c.f. proposal submission and evaluation).
5. (B) Assimilate input from DS2 studies on requirements for observing modes and from DS3 studies on achievable architecture.
6. (B) Produce a consolidates set of observing modes.
7. (D) Investigate software systems for support of collaborative research and their applicability to an integrated user portal for the SKA and produce an interim report.
8. (E) Produce a final report on the user interaction with the telescope resource and cost estimates for its provision under various models.

Output

Description	Work Package	Date delivered
Interim report on user access to the telescope.	DS8-T1-01	01/2008
Interim report on software for facilitating collaborative research.	DS8-T1-01	04/2008
Produce a consolidated set of observing modes.	DS8-T1-01	07/2008
Final report.	DS8-T1-01	12/2008

Justification

Staff effort

A PDRA for 15 months (1.25 fte) is required to undertake this work. The breakdown between the various tasks will be A: 0.4 fte; B 0.3 fte; D 0.45 fte; E 0.1 fte. The PDRA will need to assimilate information from a variety of sources as well as obtain input from the available expertise within the project in the form of current and former directors of major observatories.

Equipment

See standard equipment under DS3-WP01.

Milestones

- Interim report on user access to the telescope (01/2008)
- Interim report on software for facilitating collaborative research (04/2008)
- Produce a consolidated set of observing modes (07/2008)
- Final report (12/2008)

DS4-WP01: Initial design study of the system architecture

Background

The ultimate design drivers for the SKA are given by the science goals, but translating these into engineering specifications is a non-trivial task. For example, the sensitivity goal of the system is not given by a defined physical area, but by the physical area divided by the system temperature. This may be achieved by a large area of lower sensitivity or a small area of higher sensitivity – whichever is the easier and cheaper to realize. Design tradeoffs such as this pervade the entire system, and the goal is to maximise the system performance per unit cost, taking into account all issues of practicability and manufactureability. This work package is to assess these tradeoffs quantitatively and thus define design, test and measurements specifications, and risk mitigation strategies, for the later workpackages.

Input

Work Package	Description
DS2	Interim SKA science specification; interim tile specification

Tasks

1. To construct a computer model to allow the design tradeoffs to be analysed quantitatively, and thus provide a design tool that will be useful throughout the whole design study. The deliverable from this task is a computer model (probably in the form of a spreadsheet) that will be used to set the design specifications of each individual component, and will allow the impact of variation in component performance (eg LNA noise temperature) to be assessed.

2. Assessment of risk mitigation strategies. If it is not possible to develop the complete digital tile with full bandwidth, area and performance, it will be important to decide in which ways the design study can be de-scoped with minimal loss of output, ie still delivering a credible design for a possible SKA architecture. De-scoping options include: reduced RF bandwidth; analogue beam forming (in part); reduced number of tile elements. This task will provide a report assessing the de-scoping options so that if difficulties are encountered in later WPs there is a strategy for ensuring that the overall design study objectives are still met.

3. Definition of test and measurement strategies and specifications for the later workpackages, defining clear performance goals against which the individual component and complete tile can be compared. Deliverable is a set of specifications and test goals for the design and test workpackages.

Output

Description	Work Package	Date delivered
Computer model of inter-relations between element performances and system performance	WP2,3,4,5,8	23/12/05
Risk mitigation strategy report	WP2,3,4,5,8	15/09/05
Specification of design parameters	WP2,3,4,5,8	22/12/05
Specification of test strategies	WP7,10,15	16/03/06

Justification

Staff effort

This WP will require 0.5 FTE of PDRA efforts to develop the modeling of the system and 0.5 FTE to draft the test and measurement specifications. To carry out the work within the timescale will require two individuals working in parallel. This work will be carried out in close collaboration with the senior academic staff in the main technical areas, totalling 1 FTE of university-supported effort.

Equipment

Computing facilities for the modeling and specifications will be provided by the host institutions of the PDRAs as an in-kind contribution.

DS4-WP02 – Antenna element design and tile array configuration

Background

The third generation tile design is crucial to the success of the SKA. It is most unlikely that the unique antenna performance targets can be met in full at affordable cost through the use of any designs known today. Innovative design and development will be essential for success. To meet the demanding, yet crucial, technical and cost requirements within the timescale needed for the current studies a team has been assembled to leverage both leading academic and industrial know how. The University of Manchester (Communication Engineering Group) has a strong background in ultra wide band phased arrays in commercial radar and communications applications; the University of Cambridge brings array antenna knowledge within the radio astronomy context and BAESystems has developed and produced phased arrays for defence radar uses.

It is envisaged that the whole SKA will consist of about 10^6 tiles, each of which will comprise many antenna elements. Major drivers for the SKA antenna design include:

- ultra wide bandwidth operation
- maximization of the field of view and multi-beam operation;
- dual polarization capability as required by the science programme;
- a high degree of polarization purity;
- accurate impedance matching at the high end of the frequency band to ensure the lowest possible system temperature;
- background-limited system temperature at the low end of the frequency band; and
- devising in-field real–time module test diagnostic monitoring.

As a result of these considerations, preliminary designs for SKA are postulating that the low-frequency band (~0.1 – 1.7 GHz) is split into two. Study of such hybrid designs forms part of this work package.

Given the challenging intial specifications it is imperative to explore as many new approaches as possible within the time constraints. A work programme has been designed so that as far is possible critical design technologies are studied in parallel by the team before selecting a final solution. A design review after an initial period will select and integrate the best combination of features from the studies.

Parallel research programmes will take place in Cambridge, Manchester and BAESystems. Whilst these will be separate studies, it is important to facilitate cross fertilization of ideas throughout the programme. In addition to meetings and using web communities, we intend to employ a roving technology assistant to ensure maximum efficiency with minimum duplication of effort. This innovative management approach to the team has been used successfully in industry and allows one individual to work in depth with each team to foster the essential communication. The studies will make use of advanced electromagnetic modelling tools, as well as testing of promising prototype designs. It is also essential that the element design is considered in conjunction both with the tile array geometry studies and with the interface into the receiver front end of WP03. By these means we will maximize the chance of designing the best-performing and most cost-efficient third-generation phased-array antenna for radio astronomy.

Input

Work Package	Description
DS4-WP01	Antenna element specification

Tasks

1. Review the existing literature on broad-band, wide-field antennas.

2. Tile array configuration studies including impact on element size, array sidelobes, polarisation requirements.

3. Simulate, construct and test candidate antenna element designs.

4. Construct compliance matrix of candidate designs with respect to science and technical requirements.

5. Investigate the merits of hybrid designs to cover the full low-frequency SKA band.

Output

Description	Work Package	Date delivered
Third generation antenna element design and tile array configuration	WP 09	10/7/2007

Justification

Resources: PDRA totalling 10 FTE; 1 FTE technician; 0.4 FTE computer support officer; £20k hardware costs; total of £120k for BAE systems

Staff effort

- Cambridge: Will investigate in detail about six different element designs, and in addition consider the splitting of the tile into multiple wavebands. Each design will be simulated and the more successful ones constructed and tested at Lord’s Bridge Radio Observatory. These tasks will require PDRA support at the level of 4.5 FTEs to October 2007 . In addition, this activity will require technician support for this work at the level of a quarter of a post over this period totaling 0.5 FTE.

- University of Manchester (Communication Engineering Group): Will investigate both the tile array configuration and element designs. Possible modification of ultra-wide-band antenna element designs developed in radar and communications applications will be considered. Existing, proven, software modelling will be used prior to build and test of laboratory protypes using existing facilities with UoM (anechoic chamber). Full time research assistants for two years, totaling 5.5 FTE plus 0.5 FTE technician and 0.4 FTE computer support officer.

- BAESystems: By utilizing design software and expertise developed for military applications , complimentary studies will both validate and extend the work in Cambridge and Manchester. This programme allows innovative design from the academic communities to be integrated with the expertise of one of the UKs leading phased array companies. Total cost is £120k.

DS4-WP03 – MBE Growth Of Semiconductor RF Front End Devices

Background

The current state-of-the-art in low noise pHEMT technology relies on a combination of both InGaAs-InAlAs structures (grown on InP) coupled with sub-micron gate lithography (down to 30-nm gate length) to achieve a noise figure ~0.3dB (i.e. ~25 K) in the 2 to 4 GHz range but with breakdown voltage < 2V. These devices represent the state-of-the-art in the laboratory and are not optimised for field (e.g. radio astronomy) usage.

Our aim in this programme is to improve the breakdown voltage at least up to 5 V and improve on linearity (flatter g_m versus v_{gs} curve). In terms of the SKA project specifically, the frequency band below ~ 2 GHz is getting ever more used in commercial applications with the resulting signals being a long-term concern despite the fact that the SKA will be sited in a region of the world with very low population density. We therefore stress again that achieving high linearity is a must. The doped Channel FET approach should provide for device with high linearity and high breakdown voltage, however the issue of simultaneously achieving low-noise is not entirely certain and as such this device structure is a good candidate to study.

To the best of our knowledge this is the first time that such studies aimed specifically at ***room temperature operation to match radio astronomy requirements*** will be undertaken.

Input

Work Package	Description
WP01	Initial design study of the system architecture; Science specification in terms of noise temperature and frequency bands.

Tasks

1. Develop new pseudomorphic High Electron Mobility transistor (pHEMT) and Doped Channel Field effect transistor (DCFET) specifically for radio astronomy applications as dictated by the SKA both in the InGaP-GaAs and InAlAs-InGaAs systems.

2. Optimise InP-InGaAs DHBT structures for high speed, low power ADC architectures.

3. Investigate the epitaxial co-integration of pHEMT and HBT for new advanced MMIC concepts (*low device count AND low power consumption ICs*).

4. Explore the possibility of significant improvement in device performance by tuning low noise, high breakdown and high linearity.
5. Address the issues of “quantum manufacturability” (i.e. wafer uniformity, repeatability and low cost), critical path for the implementation of the international SKA.

Output

Description	Work Package	Date delivered
pHEMT wafer structures	WP04, WP05	01/09/2005
DCFET wafer structures	WP04, WP05	02/02/2006
HBT wafer structures	WP06, WP07	02/02/2006
LNA wafers	WP04, WP05	01/02/2007
ADC wafers	WP06, WP07	05/03/2007

Justification

Resources: 1 Full time RA (3.5FTE), 20 wafers per year @£1300 each (10 experimental (including calibrations) and 5 each for LNA and ADC Programmes)

Staff effort

- The programme defined above contains a number of challenging technical tasks directed at demonstrating the capabilities of novel prototype discrete and integrated LNA and ADC devices operative in the SKA low frequency band. The most demanding task of this project is undoubtedly the growth aspect and this will be undertaken a PDRA under the supervision (and with the help) of Professor Missous who has been running the V90H system for over 11 years and has grow over 1700 wafers on this system. The assessment of the structures and devices will be extremely well suited to the PDRA who will undertake all aspects detailed above.
  Further support on materials assessment will be provided Dr J. Sly, the senior experimental officer responsible for the MBE and clean room facilities.

Equipment

- **Already in place (see costs to be noted)**

Consumables

- Consumables funding is requested to support the MBE epitaxial growth and materials assessments. This will amount to £1300 per wafer to cover substrates, source materials, and Liquid Nitrogen and MBE machine consumable costs. We anticipate up to 10 experimental (discrete device) wafers and 5 wafers each for LNA and ADC programmes.

DS4-WP04 LNA Design, Analysis and Test

Background

Development of high-performance low noise amplifiers (LNA) is a critical requirement for successful realisation of the SKA receiver front-end. There are stringent specifications in terms of operating bandwidth (0.1 to 2GHz), noise temperature (<50K), linearity and cost. This will require development of customised active device technology, and the use of new design techniques, since commercial off the shelf (COTS) components are not optimised for such radio-astronomy applications.

The aim of this work package is to understand the critical active device drivers, from a circuit design perspective, that will allow the desired LNA performance to be realised. At present it is felt that InP device technology is the most likely candidate capable of satisfying the SKA receiver requirement, hence most emphasis in WP03 will concentrate on this semiconductor material. However, it is also intended to undertake a semiconductor technology study to identify other potential material systems and active device technologies/developments that might be worthy of further consideration by the year 2010.

The work undertaken in WP03 (MBE Growth of semiconductor RF front-end devices), WP05 (Integrated LNA Fabrication) and this work package are strongly inter-linked. During the course of WP04 a “feedback route” will be established by using a low noise amplifier benchmark simulation test bed to allow the effect of active device performance to be better understood at the circuit level. It is intended to undertake sensitivity analysis circuit simulations to guide and help optimise active device processing iterations. This unique feedback approach, between circuit and device level performance, will allow an ideal solution to be more rapidly converged upon than if circuit processing were undertaken in isolation. Hybrid and integrated circuit LNA demonstrators will be constructed, using the best transistors developed in WP03/WP05, and their performance evaluated with respect to satisfying the SKA front-end specification.

Input

Work Package	Description
WP01	INITIAL DESIGN STUDY OF THE SYSTEM ARCHITECTURE
WP02	ANTENNA ELEMENT DESIGN AND IMPEDANCE OPTIMISATION
WP03	MBE GROWTH OF SEMICONDUCTOR RF FRONT END DEVICES
WP05	INTEGRATED LNA FABRICATION

Tasks

1. A study will be undertaken to compare and contrast the performance of Si, SiGe, GaAs, InP, InSb and GaN semiconductor technologies. Current capability and likely future developments will be considered in order to identify which active device type offers the most benefit for realising the SKA receiver front-end in the 2010-2014 timescale.
2. Establish benchmark LNA simulations to provide performance feedback for device process development in WP03. Areas to be considered to include effect of gate length, gate width, access resistance, number of gate fingers and channel doping profile.
3. Perform RF on wafer (RFOW) measurements on device wafers fabricated in WP03 (a maximum of 6 iterations), extract scaleable equivalent circuit model.
4. Undertake LNA design techniques simulation study – determine optimum design approach, including consideration of circuit topologies best suited for achieving wide operating bandwidth, linearity, low noise temperature, high yield and low cost.
5. Design, manufacture and test of hybrid LNA using discrete devices developed in WP03 (two iterations)
6. Design and test of integrated circuit LNA

Output

Description	Work Package	Date delivered
REPORT ON ASSESSMENT OF SEMICONDUCTOR TECHNOLOGIES FOR REALISING SKA FRONT-END	WP03	01/07/2005
REPORT ON LOW NOISE AMPLIFIER DESIGN TECHNIQUES	WP03, WP05	07/10/2005
HYBRID LNA DESIGN REPORT	WP03, WP05	16/03/2006
HYBRID LNA MEASUREMENT REPORT	WP06	10/01/2007
REPORT ON MMIC LNA DESIGN	WP06	29/11/2007

Justification

Resources: Staff (see below) at commercial rate; software upgrade £20k and RFOW probes £5k

Staff effort

- 1 full time senior scientific staff, ½ part time test engineer, ½ internal project manager (QinetiQ)

Equipment

- Software and hardware upgrade to FOCUS tuner measurement system is requested at a cost of £20K. This will allow improved accuracy and faster throughput of noise parameter extraction.

Consumables

- RFOW probes (3 pairs over the programme duration) will be required to allow detailed device assessment. Approximate cost £5,000

DS4-WP05 – Integrated LNA Fabrication

Background

In this WP the LNAs are fabricated on wafers and basic DC and RF tests are performed in Manchester for quality control on these wafers. The purpose of this is to screen those wafers to be sent to Qinetiq for the more extensive and time-consuming “full-wafer mapping” and final testing. During the course of WP05 a strong “feedback path ” must first be established by using DC tests on discrete low noise transistors (the essential element in the LNA) as benchmarks to allow the effect of materials and active device performance to be harnessed prior to the design and fabrication of the complex LNA circuits.

The work undertaken in WP03 (MBE Growth of semiconductor RF front-end devices) and WP04 (LNA Design, Analysis and test) are strongly inter-linked with this work package.

Input

Work Package	Description
WP03	MBE GROWTH OF SEMICONDUCTOR RF FRONT END DEVICES
WP04	LNA DESIGN, ANALYSIS AND TEST

Tasks

1. Develop passive components technology library
2. Low noise discrete devices measurements and parameter extraction
3. Investigate effect of gate *width* (optimise gate width with respect to noise).
4. Design and fabricate 50 Ω and non-50 Ω input impedance LNAs and correlate with antenna impedance.
5. Study effect of leakage current on InP pHEMT performance.
6. Study “doped-channels” FET to reduce leakage significantly and improve linearity at the same time.
7. Optimise RF performance with respect to noise performance. Thus need to know how noise changes with channel *length*. The optimal choice of channel length is not necessary the smallest gate length one can achieve (as has been the case traditionally). This is because the noise properties (and indeed all other properties) of the transistor change rapidly as the channel length is decreased.
8. Investigate if noise figures can be improved by not just using the minimum channel length. The actual noise performance at the circuit level might be improved not by using the minimal channel length, despite the fact that g_m is decreased.

Output

Description	Work Package	Date delivered
Discrete pHEMT chips fabrication	WP03 and WP04.	03/10/2005
Discrete DCFET chips fabrication	WP03 and WP04	02/10/2006
Integrated LNA chip fabrication stage 1	WP03 and WP04, WP09,15	06/03/2008
Integrated LNA chip fabrication stage 2	WP19, SKADS DS8	30/12/2008

Justification

Resources: 5.85 FTE , 100mm Karl suss Deep UV Aligner (Used) £76k, Sputtering machine £58k, Masks and Processing at £13k per year.

Staff effort

- The programme defined above contains a number of challenging technical tasks directed at demonstrating the capabilities of novel prototype discrete and integrated LNA circuits. The most demanding task of this project is undoubtedly the MMIC processing which this will be undertaken by a 3.5 FTE PDRA under the supervision of Professor Missous and with considerable help from Dr J. Sly, the senior experimental officer responsible for the clean room facilities (a total of 0.35 FTE over 3.5 years). A 2FTE PDRA (associated with Jodrell Bank Observatory) will perform DC characterisation and be closely involved with the LNA design and simulation and RF measurements at QinetiQ. A closed loop will be established between the MBE growth, the LNA processing, LNA design and RF measurements in an effort to produce the most optimum LNA circuits for the SKA. This will be a unique way of advancing the state of the art, unrivalled elsewhere in the world of radio Astronomy.

Equipment

- A high uniformity 100mm Kark Suss Mask Aligner with deep UV optics is requested at a cost of £76k (used). The extensive fabrication facility at our disposal is already capable of processing 100 mm wafers (commonly called 4” wafer) apart from the lithography which is currently limited to 2” wafer size and ~ 0.8µm resolution. The acquisition of the used 100mm Mask Aligner will allow us both to work with 4” wafers and to explore the smaller feature size (~ 0.25µm). These capabilities are vital for producing the MMIC and ADC circuits which will range in sizes to up to 4mm^2 and necessitate high-uniformity lithography processing for high yield, low cost manufacturing.

- A high uniformity sputtering machine is also sought whose role would be not only to provide the high precision NiCr resistors needed for the integrated LNA circuits but also for the thick metallisations and tracks that make up the integrated circuits for both LNA and ADC. The cost of the Sputter coater is £58k.

Consumables

- Masks at £8k and processing costs at £5k per year (Contributions). By opting for fairly large lithography optical features (> 0.5µm) the costs of masks is kept at a minimum. (<£1000 per process mask).

DS4-WP06 – ADC Design, Analysis And Test

Background

The technology requirements for high performance ADC’s are extremely demanding and a careful balance between circuit complexity and processing yield will have to be made. This is due to the simultaneous requirement for optimised rf and dc device characteristics with large-scale integration (LSI) complexity. A typical wideband n-bit ADC can be divided into three primary components. The first is a sample and hold (S/H) circuit, which provides non-slewing voltage samples uniformly spaced in time. The second is a quantiser, which quantises the held voltage into 1 out of 2^n binary codes and finally a wideband amplifier is used to amplify the analogue input signal to a level compatible with the full scale voltage range of the quantiser. Other components that may need to be developed are logic gates, clock drivers and clock distribution circuits.

ADC design for higher resolution and dynamic range based on band-pass sigma-delta modulator for possible application in the SKA will also be investigated with emphasis on low device count and low power consumption. The overall aim of the programme is the demonstration of effective designs commensurate with high SKA performance and low cost, a situation that is not commercially possible yet. Commercial GaAs ADC with up to 8 bit resolutions and 6 Gs/s will soon appear in the market but at costs that are simply prohibitive (>$1000 /pc) for implementing in the SKA and at prohibitively high power consumption (few Watts. No InP-based ADC (as proposed here) exist in the market place yet. The research programme for this work package aims to produce low power consumption (<< 1 Watt) and low cost (< few $/pc) integrated ADC. These are critical for SKA.

In Year 1, work will concentrate on active device design, development and test. The work undertaken in WP07 (Analogue to Digital Converter Technologies) and this work package are therefore strongly inter-linked. A similar feedback approach will be adopted, as was used for LNA active device development/design, between the processing and circuit design activities. Program goals include demonstration of mixed-signal integrated circuits using device technology developed in WP07. A range of building block components will be designed and tested during the course of this work package to give confidence in the design approach, and process robustness, prior to detailed design and fabrication of complete ADC functions. The ultimate goal is the realisation of high speed, low power consumption, ADC’s to meet the requirements of the low frequency European SKA concept: a wireless receiver with wideband channels: 2 to 4 bits at 3 to 4 GS/s and minimum power dissipation (< 3 V supply).

Input

Work Package	Description
WP01	INITIAL DESIGN STUDY OF THE SYSTEM ARCHITECTURE
WP03	MBE GROWTH OF RF FRONT-END DEVICES
WP07	ADC TECHNOLOGIES

Tasks

1. Undertake ADC architecture study, identify optimum architecture for SKA receiver front end (flash vs. folding/interpolating vs. oversampled).
2. Identify the required transistor performance (f_t, input capacitance, V_{be} matching /dc tracking) and determine how good these parameters need to be for successful circuit design.
3. Analyse performance trade-off’s versus processing complexity and transistor count.
4. ADC device characterisation and modelling – establish feedback route into WP07 to assist with device processing iterations
5. Provide assistance to WP07 in developing integrated circuit capability – identify passive component building blocks and specify performance required.
6. Undertake layout of passive component test mask

7. Assemble passive and active component library (to include RFOW passive component assessment and model derivation) – compilation of design library database and DRC rules.
8. Design and assessment of ADC component building blocks (to include sample and hold, wideband amplifier and comparator designs). Two design iterations to be undertaken.
9. Design and assessment of integrated ADC
10. Consideration of packaging options (die attach, grounding, thermal dissipation)

Output

Description	Work Package	Date delivered
REPORT ON InP HBT DEVICE MEASUREMENTS	WP07	10/11/2005
IC DESIGN RULES ESTABLISHED	WP07	28/04/2006
REPORT ON RECOMMENDED ADC ARCHITECTURES	WP07	12/06/2006
DESIGN REPORT ON ADC BUILDING BLOCKS	WP07	01/11/2006
REPORT ON ADC BUILDING BLOCK COMPONENT PERFORMANCE	WP07	01/05/2007
ADC INTEGRATED CIRCUIT DESIGN REPORT	WP07	5/05/2008
FINAL REPORT ON MMIC DEMONSTRATOR RESULTS	WP07	28/11/2008

Justification

Resources:

- Staff as below at commercial rate; membrane differential probe £10k,

Staff effort

- 2 full time senior scientific staff, 1 part time test engineer, Project manager

Equipment

- Purchase of a membrane differential probe is requested to allow ADC measurements on wafer (estimated cost £10K).

Consumables

- None envisaged as standard RFOW probe costs are considered in WP04

Risk Assessment

Assumptions / dependencies

- Component testing will be performed using RFOW measurement techniques, no costings have been included for demonstration of the ADC in a module/packaged environment.

- A single design/process/test iteration has been assumed for the integrated ADC demonstration.

- The ability to be able to demonstrate a functional ADC is dependent upon developing a repeatable and reliable fabrication process.

DS4-WP07 – Integrated ADC Technologies

Background

The ultimate goal of this programme is the realization of high speed, low power consumption Analogue to Digital Converters (ADC) to meet the requirements of the low frequency European SKA concept which will involve medium to high resolution at 3 to 4 GSamples/s and a minimum power dissipation (< 3 V supply).

In the past, the poor GaAs technology available suffered from severe “backgating”, low frequency 1/f noise, and poor uniformity has limited A/D performance to low resolution (typically 2 bits). This technology was associated with ion-implantation. It is now possible to synthesise materials based on InP technology which exhibits low 1/f noise, high uniformity. As a result high-resolution, low-power consumption ADCs can now be designed and fabricated. No such devices are currently available in the market.

This programme therefore seeks to develop high sample-rate analogue-to-digital converters (ADCs) to facilitate digital signal processing of wideband microwave signals at up to 2 GHz. The programme goals include demonstration of mixed-signal integrated circuit technology using DHBT, E/D-mode HEMTs (InAlAs/InGaAs/InP), and possible topologies including mixtures of both. The programme also involves characterization and modelling of the E/D HEMTs, design, fabrication, and test of suitable amplifiers, track-hold circuits, comparators, and digital logic circuits for ADC implementation. The initial plans call for an ADC with a target sample rate of 4 GS/s and with 2 to 4 bits resolution. A number of circuit topologies will be investigated with “flash” being prominent.

Input

Work Package	Description
WP03	MBE GROWTH OF SEMICONDUCTOR RF FRONT END DEVICES
WP06	ANALOGUE TO DIGITAL DESIGN, ANALYSIS AND TEST

Tasks

1. Investigate resolution (# bits) vs. circuit complexity; this involves a study of ADC architectures and low component count strategies (Delta Sigma architectures).
2. Develop and fabricate InP DHBT devices.
2. Develop and fabricate Schottky diodes for sample/hold circuits.
3. Develop and fabricate Thin Film Resistors: NiCr or Ti/Au.
4. Develop and fabricate MIM Capacitors: Si_3N_4 vs. Polyimide.
5. Fabricate and test Track and hold circuit.
6. Fabricate and test Amplifiers/Folding Amplifier.
7. Fabricate and test Digital Logic circuits.
8. Fabricate ADC circuits
9. Investigate die attach and packaging e.g. epoxies vs. soldering, thermal considerations

Output

Description	Work Package	Date delivered
Passive component Library development	WP03 and WP06.	03/07/2006
Basic Building block development	WP03 and WP06.	01/03/2007
ADC MMIC fabrication stage 1	WP03 and WP06, 09	24/04/2008
ADC MMIC fabrication stage 2	SKADS DS8	30/12/2008

Justification

Resources: 5 FTE; Masks and Processing at £18k per year

Staff effort

The programme defined above contains a number of extremely challenging technical tasks directed at demonstrating a number of high-speed ADC architectures. The most demanding task of this project is undoubtedly the Integrated circuit processing which this will be undertaken by a 3.5 FTE PDRA under the supervision of Professor Missous and with considerable help from Dr J. Sly, the senior experimental officer responsible for the clean room facilities (contribution already counted in WP05). A 1.5 FTE PDRA (associated with Jodrell Bank Observatory) will perform DC characterisation and be closely involved with the ADC design and simulation and measurements at QinetiQ. A closed loop will be established between the MBE growth, the ADC processing, ADC design and measurements in an effort to produce the most optimum ADC circuits for the SKA. Like the LNA programme this will be a unique way of advancing the state of the art, unrivalled elsewhere in the world of radio astronomy.

Equipment

- The high uniformity 4” mask aligner and sputter coater requested for the LNA programme will alos be extensively used in the ADC programme. No specific request here.

Consumables

- Masks at £8k and processing costs at £10k per year. By opting for lithography with optically-defined features of ~ 1µm the costs of masks is kept at a minimum. (<£1000 per process mask).

DS4-WP08 – Element-level DSP design

Background

In the digital tile concept, all signal processing, from the individual element level onwards, is done in digital hardware, including frequency band and primary beam synthesis. This will necessarily be done by a hierarchical signal architecture, but the first level in the hierarchy is particularly significant. It is here that the raw output from the digitisers is first processed, and where the highest data rates and clock speeds are encountered. The DSP elements employed will face the most stringent requirements for performance vs cost, and for electromagnetic compatibility (since they must be in close proximity to the RF and A/D electronics). At the single-element level, the first process is necessarily operating in frequency space rather than spatial combination, and thus can be characterized as a digital filter or channel synthesizer. Since the subsequent signal processing is unlikely to be able to cope with the full signal bandwidth (around 1.5 GHz) instantaneously, the role of this element is to select the observing band (which can be of quite general shape, including nulls to deal with RFI if necessary). The appropriate hardware must be selected, algorithm design for the range of possible processes carried out, and a prototype system designed, built and tested. In the final SKA, if a solution to the element-level DSP can be found that is able to preserve the RF bandwidth, it would form part of the fundamental infrastructure of the telescope that would not need to be upgraded, unlike other parts of the signal processing chain (data transport network and correlating power).

The most likely candidate for DSP hardware is the Field Programmable Gate Array (FPGA), which is available in many types and is well suited to problems requiring high data throughput and flexible implementation of a variety of different but related algorithms. FPGAs are widely used in industrial and military applications, and we have discussed the transfer of this technology with Qinetiq's Embedded Systems Division. Qinetiq will be able to act as consultants to the project, providing expertise and design software. The PDRAs working on this workpackage (and on DS4-WP11 and DS4-WP13) will work closely with Qinetiq in the development of the DSP systems for SKADS, thus bringing into the UK astronomical community the expertise in fast programmable logic that will be essential in order to play the leading role should the digital tile concept be adopted for the SKA.

Input

Work Package	Description
DS4-WP01	Specifications and test requirements
DS3-WP??	Specifications and limitations on distribution of clock signals at the tile level

Tasks

1. Review of available DSP hardware and programming tools, and selection of suitable device(s) and systems for subsequent use.
2. Design of algorithms for flexible implementation of frequency-space processing on the element-level data stream (working closely with Task 1 as hardware and algorithms must be jointly optimized).
3. Construction of single-board DSP element and test setup to allow testing of full-bandwidth signals, including de-multiplexing and clock interface hardware.

Output

Description	Work Package	Date delivered
Prototype DSP element for integration into prototype elementary module	WP09,10	4/06/2007

Justification

Staff effort

- A dedicated PDRA or engineer is required for the duration of the workpackage to carry out the design, construction and testing effort.

Equipment

- Prototype multi-layer circuit boards will be needed to test the FPGA layout design: two off at 5k per board
- FPGAs are expected to be available at reduced cost through the Xilinx University Programme. 5k for devices.
- ***** ‘production’ costs should go with WP15 but will include at least 40k for multi-layer boards, 12k for FPGAs plus staff and Qinetiq effort ****

Other

- Qinetiq Embedded Systems Division will provide consultancy and design tools for the DSP design effort at the level of 125 days, 0.5k per day ie 62.5k. This will give the project access to all the relevant expertise, experience and design infrastructure that would otherwise have to be built up from scratch.

Risk Assessment

Work Package	Cost (£)	Risk Factor	Risk	Effect of Risk	Mitigation
DS4-WP11	???	2	DSP system does not reach required spec within schedule	Programme delay	Increased level of consultancy from Qinetic 25 days of extra Qinetic effort 12.5k

DS4-WP 09 Element module integration

Background

The element electronics are being developed at the chip and module level in a number of individual work packages. The feasibility of the whole concept depends on the integration of these components and some standard components into an assembly capable of operating successfully without it interfering with itself or its neighbours. Given that the input is an antenna, a key aspect of the integration is to prevent any output, desired or not, from coupling back into a receiving element or, internally, into early stages in the amplifying chains, and to do so at minimal cost.

There are no frequency translations in the module and yet there needs to be a lot (~100dB) of gain to get the amplified received signal and noise to drive adequately the analogue-to-digital converters. The potential for self-interference is large. Areas to be addressed will include shielding, filtering, power supply control, optical fibre coupling and environmental protection.

Some similar issues occur in conventional phased array systems, while others are unique to the SKA. Accordingly this WP will draw heavily on the experience of BAeSystems along with the UK radio astronomy community.

Input

Work Package	Description
DS4-WP1	Systems Architecture
DS4-WP2	Antenna-Element Design and Impedance Optimisation
DS4-WP4	Integrated LNA Design
DS4-WP6	Analogue-to-Digital Converter Design
DS4-WP8	Element-Level DSP Design
DS4-WP10	Test of Element Module

Tasks

1. Develop initial module design and EMC modeling
2. Build prototype module
3. Test and optimize
4. Modify design to incorporate results of tests
5. Build final prototype.

Output

Description	Work Package	Date delivered
Design of module	DS4-WP15	13/09/2007

Justification

Staff effort

This work package is the first time that the various components of the element module are brought together in a realistic configuration. Experience has shown that unless sufficient expertise is applied in initial design and optimization of the integration task the risk of failure is high. Therefore input from BAESystems will be utilized in combination with experience gained within the radio astronomy community on low noise architectures.

5FTE’s total over the programme (2 FTE at Manchester 1.5 each at Cambridge and Oxford)

Equipment

Consumables £10k for fabrication of test modules

Other

BAeSystems: Effort   £60k

DS4-WP10: Test strategy for element module

Background

As part of the element module design package, suitable element module tests must be considered to ensure hardware is adequately tested prior to integration. Due to the highly integrated nature of each module (for performance and cost reasons), this test strategy is far from obvious. WP01 will define the overall scope of the tests needed to demonstrate technical performance. This work package takes these overall requirements from WP01 and translates these into detailed test plans.

Three levels of test plan will be developed. The first level is a draft full set of tests to be applied to the element module (including environmental tests). These will be necessary once the module is in a proven state and before any future major builds. However these tests are probably not cost effective on the prototype build envisaged as part of this programme. Accordingly a sub-set will be developed for the actual prototype hardware for use in WP13 .In addition, a first draft production test plan will be derived for consideration on the next phase of SKA. We note here that the cost of test in production can be a highly significant cost factor. This final test phase is therefore informing and being informed by the cost reduction studies.

Input

Work Package	Description
DS4-WP1	Initial design study of system architecture
DS4-WP4	LNA Design Analysis and Test
DS4-WP6	ADC Design Analysis and Test
DS4-WP8	Element Level DSP design

Tasks

1. Review the overall tests requirements from WP-01.

2. Develop a draft overall test plan for future SKA modules, including full range of environmental testing.

3. Based on this test plan, develop an economic subset to be applied to the actual prototype modules in the present programme.

4. Produce first draft of a production test strategy appropriate for ~10^8 modules to inform the cost reduction studies (a full test being impossible for all modules).

Output

Description	Work Package	Date delivered
Overall test plan for future SKA modules	WP 19	28/08/2007
Test plan for prototype modules	WP 18	17/9/2007
Production module test strategy	WP 19	17/12/2007

Justification

Resources: Total 0.25 FTE PDRA (part effort over ~5 months)

Staff effort

- Major function is to attend technical meetings with BAESystems, Qinetiq and university partners, collate and produce the reports required by this work package
- BAESystems: included in WP2 and WP9
- Qinetiq: included in WP4 and 6.
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DS4-WP11 – Develop digital beam-former for tile

Background

The purpose of this workpackage is to develop the fundamental architecture and hardware implementation for the digital beam forming at the tile level. It will be done in close collaboration with Qinetiq Real-Time Embedded Systems Division who have highly relevant experience in fast real-time digital processing systems. Qinetiq will provide expertise and development tools, resulting in transfer of their technology to the universities where it will be available to the SKA project. The output will be a tested minimal DSP system capable of taking input data and processing it at the appropriate data rates, plus an architecture design for the whole beam-forming system.

Input

Work Package	Description
DS4-WP01	Specifications and test requirements

Tasks

1. Review of available DSP hardware and programming tools, and selection of suitable device(s) and systems for subsequent use.
2. Design of algorithms for flexible implementation of beam forming, including formation of nulls for RFI rejection. (working closely with Task 1 as hardware and algorithms must be jointly optimized).
3. Construction of single-board beam-forming and test setup to allow testing of full-bandwidth signals, including de-multiplexing and clock interface hardware.
4. Test single-board beam-forming prototype.

Output

Description	Work Package	Date delivered
Prototype beam-forming unit leading into design of multi-tile beam former.	WP13	11/12/2006

Justification

Staff effort

- Two dedicated PDRAs are required for the duration of the workpackage to carry out the design, construction and testing effort, and to liase with Qinetiq to ensure that the relevant expertise is transferred to the university sector.

Equipment

- Prototype multi-layer circuit boards will be needed to test the FPGA layout design: two off at 5k per board
- FPGAs are expected to be available at reduced cost through the Xilinx University Programme. 5k for devices.

Other

- Qinetiq Embedded Systems Division will provide consultancy and design tools for the DSP design effort at the level of 250 days, 0.5k per day ie 125k. This will give the project access to all the relevant expertise, experience and design infrastructure that would otherwise have to be built up from scratch.

DS4-WP12 Link to EMBRACE

Background

DS4 (new technology development) and DS5 (EMBRACE) are carried out in parallel in order demonstrate all the technologies required for the SKA in the timescale of the SKADS programme overall. While these are complementary design studies, there is a need to maintain links between the different efforts to ensure that their outputs are compatible, provide cross-fertilization of ideas and avoid duplication. This workpage provides the necessary manpower and resources to provide ongoing links between DS4 and DS5.

Input

Work Package	Description
DS4-WP01	Specifications and test requirements

Tasks

Maintaining

Output

Description	Work Package	Date delivered
Inputs principally to the tile-level beam-forming work packages and to the final DS report	WP11, WP13, DS8	31/12/2008

Justification

Staff effort

Part of one PDRA is required to liase between the UK design effort and the EMBRACE effort in the Netherlands, totalling 2.25 FTE over the whole design study.

DS4-WP13 – Tile beam former and readout build and test

Background

The digital beam-former design is completed under DS4-WP11. This workpackage covers the construction of sufficient beam-forming hardware to test a tile (ie ~100 elements). It will also be necessary to develop a test setup allowing the beam-former to be tested independently of the element module front-ends.

Input

Work Package	Description
DS4-WP01	Specifications and test requirements
DS4-WP11	System architecture and prototype beam-former design.

Tasks

1. Construction of digital beam former for tile
2. Assessment of best test procedure for beam-forming hardware
3. Construction of test setup producing input signals to beam-former.
4. Conduct tests on back-end system to verify system performance.

Output

Description	Work Package	Date delivered
Back-end system for integration into tile test system	WP17	11/02/2008

Justification

Staff effort

- A dedicated team of PDRAs is required for the duration of the work package to carry out the design, construction and testing effort. In order to complete the package in the time available the team will consist of 2 PDRAs at each of Oxford and Manchester (totaling 4 FTE), liasing with QinetiQ.

Equipment

- 16 Multi-layer circuit boards at 5k per board: 80k. Other electronics, high-speed backplanes etc 20k.
- FPGAs are expected to be available at reduced cost through the Xilinx University Programme. 64 devices at 0.75k: 48k

Other

- Qinetiq Embedded Systems Division will provide consultancy and design tools for the DSP design effort at the level of 125 man-days, 0.5k per day ie 62.5k. This will give the project access to all the relevant expertise, experience and design infrastructure that would otherwise have to be built up from scratch.

DS4-WP14: Infrastructural Design of Tile

Background

An important part of the prototype tile development is the infrastructure design. This includes:

- mechanical design/drawing including tolerance analysis
- environmental packaging (as appropriate for test environment)
- electrical design (in particular power supplies)
- thermal design – depending on heat dissipation from modules(in particular A/D converters)
- clock(/LO) distribution (as required)

It is noted that while full environmental protection /thermal design is not anticipated some consideration of methodology behind this must be included in the study as it historically can be a be a cost driver. Hence this work package comprises a preliminary analysis of thermal and environmental considerations (drawing directly on the industrial experience of BAESystems) and a set of drawings and specifications for the actual prototype hardware, including mechanical support structure.

Input

Work Package	Description
DS4-WP01	Antenna specification
DS4-WP9	EMC and Element module integration
DS4-WP10	Test plan
DS4-WP13	Back end design and build

Tasks

- Review the overall performance requirements driven by WP-01
- Review module requirements for thermal and EMC design
- Develop a preliminary mechanical, electrical and thermal design
- Based on the overall mechanical design, develop a detailed economic subset to be built for the actual prototype tile, including and test fixtures, alignment aids etc
- Prepare design report and detailed drawings.

Output

Description	Work Package	Date delivered
Detailed drawings and build specification for prototype tile.	WP 15	12/02/2008

Justification

Resource: 1.1 FTE (see below); BAESystems £30k

Staff effort

- University of Manchester: One part-time research assistant for 0.8 FTE in year 3. Two draftsmen ~6 weeks for preparation of drawings All equivalent to a total of 1.1 FTE.

- BAESystems: total of £30k

DS4-WP 15 – Fabricate active and dummy modules

Background

We will need to construct sufficient modules, tiles, and supporting infrastructure to prove the prototype tiles and the inter-tile communication. We propose to construct two active tiles and to surround these with sufficient dummy elements so that the active tiles have the correct electromagnetic environment. Without these latter elements the performance of the active tiles would be dominated by edge-effects which will not occur in the full SKA. The proposed requirement is:

- sufficient modules to populate fully two active tiles of modules (~250)
- sufficient mechanical infrastructure to support twelve tiles (cf. WP16); and
- inexpensive dummy modules to fill ten other tiles

Input

Work Package	Description
WP09	Module design

Tasks

1. Construct and test ~250 active modules (two tiles)
2. Construct ~1250 dummy elements (antenna plus load for 10 tiles)

Output

Description	Work Package	Date delivered
Components for active modules	WP17	05/06/2008
Components for dummy modules	WP17	05/06/2008

Justification

Resource: 1.5 technician FTE; £102k consumables

Staff effort

- Fabrication effort will be required at Manchester, Cambridge and Oxford. We estimate one full time technician post at each establishment for 6 months, equivalent to 1.5 technician-level FTEs.

Consumables

- We have looked at the costs associated with the THEA project, and, together with experience gain in phased arrays elsewhere, determined that the modules to fill one tile will cost about GBP £45k. This

includes the antenna elements, the low-noise amplifiers, the A-to-D converters and the FPGAs. The two tiles will therefore cost £90k.
- A further sum of £12k will be required for the dummy modules to fill twelve tiles.

DS4-WP16 – Manufacture tile infra-structure

Background

The requirements of the antenna testing, including beam forming, beam steering, polarization etc., dictate that we construct an 12-tile array. As explained in WP15 in order to constrain costs, we propose partially filling with real modules and filling out the rest with dummy modules. This ensures that each active element is surrounded by elements (dummy on the edges) thus providing the same the mutual coupling as will occur in practice. Therefore this work package comprises the construction of the infrastructure for 12 tiles.

Input

Work Package	Description
WP14	Design of tile infrastructure

Tasks

1. Construct 12 tile infrastructure

Output

Description	Work Package	Date delivered
12 tiles worth of infrastructure	WP17	13/08/2008

Justification

Resource: £42k for manufacture

Staff effort

- Propose to sub-contract manufacture

Consumables

- From previous experience with THEA, we estimate that the cost of the infrastructure per tile will be approximately GBP 3.5k. Twelve tiles will therefore require funding at the level of GB 42 k.

DS4-WP 17 – Integrate Tile

Background

The various components of the proposed third-generation phased-array tiles, which have been designed, developed and tested separately in the preceding work packages, will be assembled in this work package. Design mismatches will be identified and overcome.

Input

Work Package	Description
WP13 – Tile Beamformer : build and test	Completed tile beamforming system
WP15 - Fabricate a tile's worth of modules	Completed front-end modules
WP16 - Manufacture tile infrastructure	Completed infrastructure

Tasks

- Integrate element modules onto tile infrastructure
- Ensure mechanical and electrical compatibility.
- Connect and test clock distribution.

Output

Description	Work Package	Date delivered
Completed tiles	WP18	20/10/2008

Justification

Resource: 0.5 FTE technician

Staff effort

- Based upon our experience with previous experiments, integrating the various sub-components to give completed tiles will require 1.5 technician posts for 4 months, equivalent to 0.5 FTE.

DS4-WP18 – Test tile performance against specification

Background

Once assembly and integration of the third-generation tiles have been completed, they must be verified through end-to-end functional testing of the system. The performance of the tiles will then be assessed with both lab-based and astronomical tests. The output of this work package, a report which details the performance and flexibility of operation of the fully digital phased array concept, will provide essential input to the international SKA technology selection procedure.

It is envisaged that the lab-based testing will include radiation pattern testing in the fully-calibrated test chamber operated by BAESystems. We estimate that we will need to test of order 100 radiation patterns at each of 3 sample frequencies, including cross-polarisation parameters.

Input

Work Package	Description
WP17 – Integrate Tile	Completed tiles

Tasks

1. Prepare infrastructure at astronomical test site.
2. Measure tile noise performance.
3. Measure full antenna beam patterns: both intensity and polarization responses.
4. Correlate the outputs of the tiles and observe bright astronomical and satellite sources.
5. Demonstrate the system’s flexibility by measuring its performance in its various different observing modes
6. Compare results against specification and provide data for final report on phased array feasibility study.

Output

Description	Work Package	Date delivered
Report on performance of third generation phased array tile	SKADS DS8	31/12/2008

Justification

Resource: 3 FTE; consumables £5k; exceptionals £72k

Staff effort

- The range of activity and problem-solving nature of this package requires predominantly the use of experienced PDRA effort. This package marks the culmination of several parallel research programmes and expertise from each of these areas will be needed during the testing phase. We therefore request support for 6 posts for a period of 6 months, giving a total of 3 FTEs of effort.

Consumables

- A small allowance of £5k for electronic components and computer consumables is requested for this testing.

Exceptionals

- Use of BAe anechoic chamber and antenna beam measuring facility; total cost £72k

DS4- WP19: Cost reduction studies

Background

Experience elsewhere has shown that a production cost sensitivity must be included throughout the design process. This work package includes effort at Manchester and in industry to leverage existing expertise. We note some reasonable idea of what has to be built has to be available before concluding any input from advanced manufacturing / assemble techniques. Accordingly this work package extends over the design/development cycle with effort back-end loaded and most effort is applied once realistic technical alternatives have been identified. Most effort is place on the module cost although later exercises may need to be carried out on the backend costs once the computational requirements for this are better defined.

Input

Work Package	Description
DS4-WP1	Antenna specification
DS4-WP2	Antenna Element
DS4-WP3	Materials and devices
DS4-WP4	LNA Design
DS4-WP5	Integrated LNA Fabrication
DS4-WP6	A to D converter design
DS4-WP7	A to D converter technologies
DS4-WP8	Element Level DSP
DS4-WP9	EMC and Element Module integration
DS4-WP14	Infrastructure design of tile

Tasks

1. Review overall design decisions with respect to maximising cost effectiveness
2. Review final prototype design with respect to manufacturability in quantity
3. Recommend possible low cost manufacturing techniques and cost sensitive component analysis

Output

Description	Work Package	Date delivered
Report on cost effectiveness and possible cost reduction approaches	SKADS DS8	25/09/2008

Justification

Resource: 0.8 FTE

Staff effort

- University of Manchester Total effort over programme: 0.8 FTE (0.1 year 1; 0.1 year 2; 0.6 year 3-4)
- BAESystems: cost included in previous work packages.
- Qinetiq: cost included in previous work packages.
  .

DS4-WP20 – DS4 and Manchester Management

Background

Manchester will coordinate the overall UK SKADS effort as well as Design Study 4 (DS4). Manchester will also take a leading part in the work packages which constitute DS4. The majority of the work packages for DS4 will be undertaken within the UK; these work packages are distributed among the UK SKA consortium so as to make best use of the existing expertise. There is considerable interdependence between these work packages and therefore an associated risk. To minimize this risk, careful management of this effort is required. This work package provides that management (MDS4), enabling the coordination and consolidation of the output from the constituent work packages of DS4. Additionally, the total effort at Manchester which is contributing to work packages in DS2 and DS3 must be properly managed so that the outputs can be delivered on time to the rest of the design study. This work package therefore also provides for management of the Manchester contribution to the design study (MMAN). The manager will also work in coordination with the SKADS Project Engineer, to be located in Manchester, whose role is to link together the whole of the European SKADS programme.

Details of the management and reporting structure are given in Section 6 and are not repeated here. The MDS4 and MMAN roles are central to the programme.

Input

Work Package	Description
SKADS DS1	Overall management and coordination of the design study

Tasks

As overall Project Manager:

- To prepare and maintain the overall UK project plan. This will involve ensuring regular reports from work package leaders are received and the information distilled as well as informing work package leaders of the crucial dates for the deliverables.
- To organise and present the major design reviews, including ensuring all documentation is prepared and circulated.
- To monitor the financial status of the overall project.
- To provide the link to and interface with the overall European SKADS project.
- To prepare and present reports to the PMB, the PPARC oversight committee and the European SKADS Board.

As DS4 Manager

- Monitor coordinate and modify milestones and if necessary deliverables for all DS4 work packages.
- Organise and manage team meetings and communication between participants in DS4.
- Sit on and report to the regular meetings of the Project Management Team.
- Attend and produce reports for meetings of the Project Management Team with the Projct Management Board.
- Monitor and coordinate milestones deliverables and tasks undertaken at Manchester reporting as needed to the coordinator of each DS.
- Provide technical support and guidance for DS4 and Manchester work.
- Monitor financial spending within Manchester.
- Report on progress of DS4 to the steering committee.

Output

Description	Work Package	Date delivered
Project schedule for DS4	All DS4 work packages.	01/2006
Coordinate production of final consolidated report for DS4.	SKADS DS8-WP01	12/2008

Justification

Staff effort

A PDRA for the full length of the programme (3.5 fte) is required to undertake this crucial management and coordination task. The post is requested at spine point 15 to reflect the management role and the required level of experience essential to this post.

In view of the increased work load involved in coordinating the overall UK SKADS effort and additional 1.5 FTE at spine point 6 is allowed for a Project Management Assistant.

Under this work package we provide a consolidated list of standard computer equipment and consumables items and travel required for DS4. Specific items of equipment are discussed under the specific work packages.

Computer Equipment/Consumables

For computer equipment and consumables we have adopted rates of £2.0k and £0.7k per fte respectively. Thus for the MDS4/MMAN manager (3.5 fte) and all the other fte's requested under DS4 (55.8 fte), the totals over the period of the programme are: £118.5k (computer equipment) and £41.5k (consumables).

Exceptionals

DS4 activity will involve regular (weekly) telecons or, occasionally, video conferences. Fortnightly telecons lasting ~ 1 hour, involving ~ 3 institutions, costing ~ 25p per minute per institution or £1.17k per year .Total over the period of the programme £4.1k

In addition this work package is required to meet half of the UK's subscription to the International SKA Project Office (ISPO). This cost is calculated on the basis of the UK's representation on the International SKA Steering Committee and is £23.5k per year. Over the 3.5 years of the project this amounts to £82.25k.

Together these two items total £86.35k

Travel

The travel budget consolidates travel requirements for the MDS4 and MMAN manager, all fte's supported by DS4, and all academic staff travelling for reasons directly connected with the DS4 programme (eg. monthly project meetings, bi-monthly EC meetings and half-yearly international meetings).

We start with PPARC guideline figure of £1.8k for the 55.8 fte's giving a total of £100.4k.

For the MDS4/MMAN manager position, UK and European travel will total £0.3k per month. The total travel budget for MDS4/MMAN manager is therefore £12.6k.

For academic staff, we take UK/EC travel to be 8.6fte at 1.8k per fte. Total travel for academics on DS4 business is therefore £15.5k.

Total travel for DS4 is therefore £128.4k

Annex B: Financial Summary

These tables show complete cost including EC contribution. Caveat about further iteration linking with European Partners after contract negotiations in October 2004.

Summary of Total Costs for the UK SKADS

Costs are k£ averaged over the 3.5 years of the project

Staff numbers given in FTE

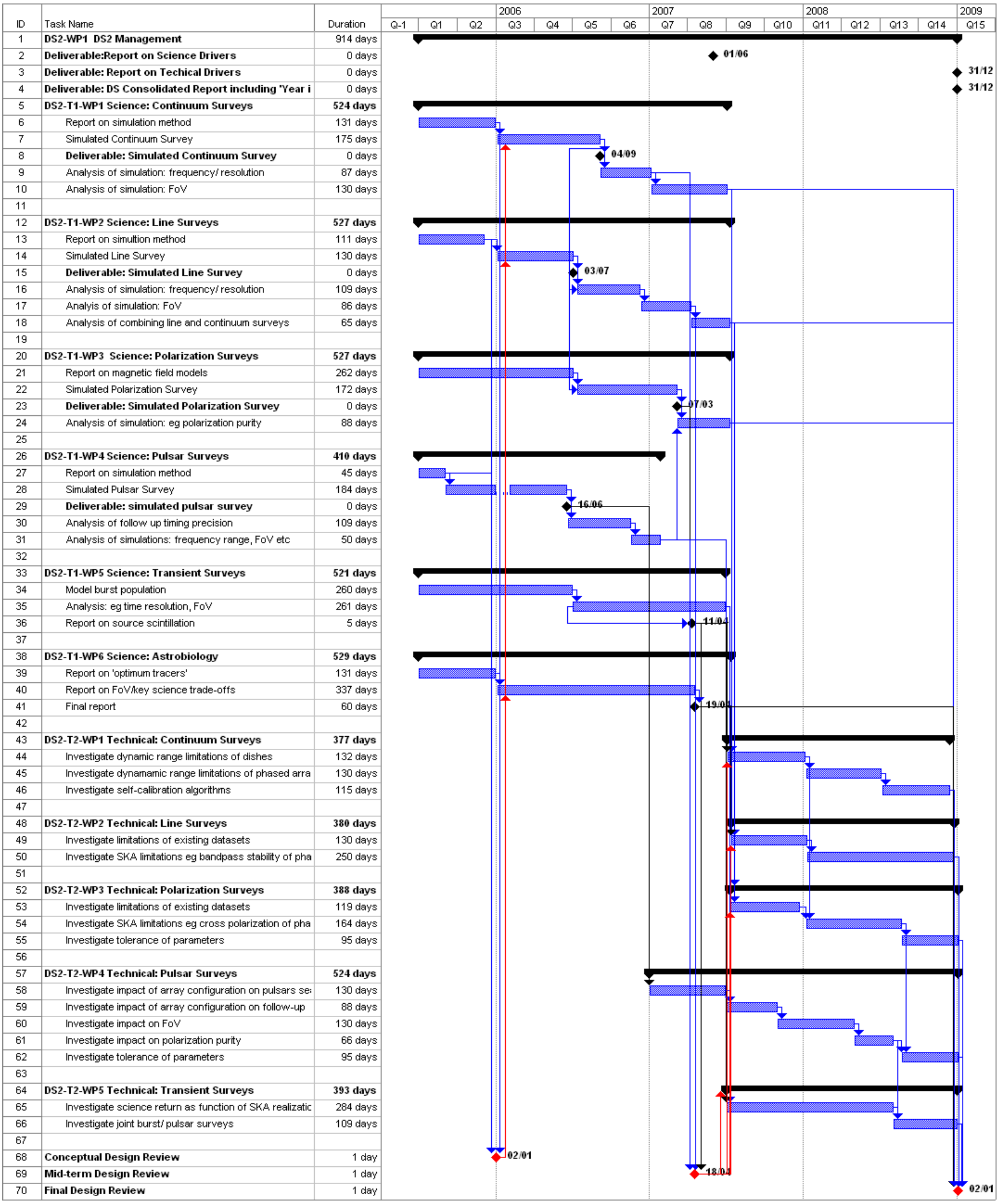
		MAN	CAM	OXF	CDF	GLS	LDS	Total FT sp6	Total FT sp15	PDRA Cost	Travel	Consumabl	Equipment	Industry	Exceptiona	Secretary	IT Support	Staff Total	Overhead	Total	WA
DS2-WP01	DS2 and Oxford Management			3.5					3.5	139	100.56	16.10	46.00		4.10	14.18	26.78	179.46	82.55	428.77	20.22
DS2-T1-WP01	Science design drivers for continuum surveys			2.0				2.0		55								54.75	25.19	79.94	
DS2-T1-WP02	Science design drivers for line surveys			2.0				2.0		55								54.75	25.19	79.94	
DS2-T1-WP03	Science design drivers for polarization surveys		2.0					2.0		55								54.75	25.19	79.94	
DS2-T1-WP04	Science design drivers for pulsar surveys	1.5						1.5		40								40.40	18.58	58.98	
DS2-T1-WP05	Science design drivers for transient-source surveys					2.0		2.0		55								54.75	25.19	79.94	
DS2-T1-WP06	Science design drivers for astrobiology	2.0						2.0		55								54.75	25.19	79.94	
DS2-T2-WP01	Technical design drivers for continuum surveys			1.5				1.5		44								44.45	20.45	64.90	6.49
DS2-T2-WP02	Technical design drivers for line surveys			1.5				1.5		44								44.45	20.45	64.90	6.49
DS2-T2-WP03	Technical design drivers for polarization surveys		1.5					1.5		44								44.45	20.45	64.90	6.49
DS2-T2-WP04	Technical design drivers for pulsar surveys	2.0						2.0		59								58.80	27.05	85.85	8.58
DS2-T2-WP05	Technical design drivers for transient-source surveys					1.5		1.5		44								44.45	20.45	64.90	6.49
Total DS2		5.5	3.5	10.5	0.0	3.5	0.0	19.5	3.5	689	100.56	16.10	46.00	0.00	4.10	14.18	26.78	730.21	335.90	1232.87	54.76
DS3-WP01	DS3 and Cambridge Management		3.5						3.5	139	75.21	17.33	49.50		4.10	15.26	28.82	182.58	83.98	412.70	20.22
DS3-T1-WP01	Coherent signal distribution via fibre optics	3.0						3.0		82			83.00					81.50	37.49	201.99	17.85
DS3-T1-WP02	Data transmission requirements for SKA	1.5							1.5	62			1.00					61.70	28.38	91.08	9.01
DS3-T3-WP01	Network Architecture		4.8					4.8		135			40.00					134.73	61.97	236.70	19.67
DS3-T3-WP02	Network requirements: for time resolved	1.3						1.3		37								37.28	17.15	54.42	5.44
DS3-T3-WP03	Network requirements: imaging and spectral-line			1.5				1.5		44								44.45	20.45	64.90	6.49
DS3-T3-WP04	Management of the data flow				1.5			1.5		42								41.65	19.16	60.81	9.12
DS3-T3-WP05	GRID-enabled data reduction for the SKA		3.5	2.0				5.5		157								157.30	72.36	229.66	
DS3-T3-WP06	Data, archiving and scientific exploitation	1.0						1.0		29								28.70	13.20	41.90	
DS3-T3-WP07	The SKA in operation		1.3					1.3		36								36.23	16.66	52.89	
Total DS3		6.8	13.0	3.5	1.5	0.0	0.0	19.8	5.0	762	75.21	17.33	173.50	0.00	4.10	15.26	28.82	806.10	370.81	1447.04	87.80
DS4-WP01	Initial design study of the system architecture	0.5	0.5	0.5				1.5		40				0.00				40.05	18.42	58.47	5.85
DS4-WP02	Antenna element design and tile array configuration	6.0	5.0					9.0	2.0	323			20.00	141.10				323.10	148.63	632.83	
DS4-WP03	MBE Growth of semiconductor RF front-end devices	3.5						3.5		99			91.00	0.00				99.20	45.63	235.83	
DS4-WP04	LNA Design analysis and test							0.0		0				416.00				0.00	0.00	416.00	
DS4-WP05	Integrated LNA Fabrication	5.9						5.9		168			180.00	0.00				167.92	77.24	425.16	42.52
DS4-WP06	Analogue to Digital Converter design analysis and test							0.0		0				667.60				0.00	0.00	667.60	
DS4-WP07	Integrated Analogue to Digital Converter Technologies	5.0						5.0		142			63.00	0.00				142.25	65.44	270.69	
DS4-WP08	Element-level DSP design	2.0		2.0				4.0		107			15.00	73.40				107.00	49.22	244.62	12.50
DS4-WP09	Element module integration	2.0	1.5	1.5				5.0		140			10.00	70.50				140.00	64.40	284.90	
DS4-WP10	Test strategy of element module	0.3						0.3		7				0.00				6.83	3.14	9.96	
DS4-WP11	Develop digital beam former for a tile	3.0		2.0				5.0		134			15.00	288.50				134.30	61.78	499.58	12.50
DS4-WP12	Link to EMBRACE	2.3						2.3		65				0.00				64.79	29.80	94.59	
DS4-WP13	Tile beam former and readout build and test	2.0		2.0				4.0		116			148.00	249.70				116.20	53.45	567.35	12.50
DS4-WP14	Infrastructural Design of Tile	1.1						1.1		32				74.00				31.71	14.59	120.30	
DS4-WP15	Fabricate modules	0.5	0.5	0.5				1.5		44			142.00	35.30				44.45	20.45	242.20	
DS4-WP16	Manufacture tile infrastructure							0.0		0			42.00	0.00				0.00	0.00	42.00	4.20
DS4-WP17	Integrate tile		0.5					0.5		15				0.00				15.05	6.92	21.97	
DS4-WP18	Test tile performance against specification	1.0	1.0	1.0				3.0		90			5.00	84.60				90.30	41.54	221.44	26.37
DS4-WP19	Cost reduction studies	0.8						0.8		23				0.00				22.99	10.58	33.57	
DS4-WP20	DS4 and Manchester management	5.0						1.5	3.5	182	128.43	41.48	118.50	0.00	86.35	36.52	68.99	287.06	132.05	793.87	26.51
Total DS4		40.8	9.0	9.5	0.0	0.0	0.0	53.8	5.5	1728	128.43	41.48	849.50	2100.70	86.35	36.52	68.99	1833.19	843.27	5882.92	142.94
Total		53.0	25.5	23.5	1.5	3.5	0.0	93.0	14.0	3179	304.20	74.90	1069.00	2100.70	94.55	65.96	124.59	3369.50	1549.97	8562.82	285.50

Total:	8848.33

	Totals	Year 1 07/05 - 12/05	Year 2 01/06 - 12/06	Year 3 01/07 - 12/07	Year 4 01/08 - 12/08	Y1 FTE	Y2 FTE	Y3 FTE	Y4 FTE
DS2 Staff									
DS2-WP01	138.5	18.5	38.4	39.8	41.8	0.50	1.00	1.00	1.00
DS2-T1-WP01	54.8	13.1	27.3	14.4	0.0	0.50	1.00	0.50	
DS2-T1-WP02	54.8	13.1	27.3	14.4	0.0	0.50	1.00	0.50	
DS2-T1-WP03	54.8	13.1	27.3	14.4	0.0	0.50	1.00	0.50	
DS2-T1-WP04	40.4	13.1	27.3	0.0	0.0	0.50	1.00		
DS2-T1-WP05	54.8	13.1	27.3	14.4	0.0	0.50	1.00	0.50	
DS2-T1-WP06	54.8	13.1	27.3	14.4	0.0	0.50	1.00	0.50	
DS2-T2-WP01	44.5	0.0	0.0	14.4	30.1			0.50	1.00
DS2-T2-WP02	44.5	0.0	0.0	14.4	30.1			0.50	1.00
DS2-T2-WP03	44.5	0.0	0.0	14.4	30.1			0.50	1.00
DS2-T2-WP04	58.8	0.0	0.0	28.7	30.1			1.00	1.00
DS2-T2-WP05	44.5	0.0	0.0	14.4	30.1			0.50	1.00
	0.0								
IT support	26.8	4.1	8.2	7.6	7.0				
Secretarial	14.2	2.2	4.3	4.0	3.7				
Total DS2 Staff	730.2	103.3	214.7	209.2	203.0	3.50	7.00	6.50	6.00
DS2 Overhead	335.9	47.5	98.7	96.2	93.4				
	0.0								
DS2 Equipment	46.0	7.0	14.0	13.0	12.0				
DS2 Travel	100.6	14.8	29.5	28.6	27.7				
DS2 Consumables	16.1	2.5	4.9	4.6	4.2				
DS2 Exceptionals	4.1	0.6	1.2	1.2	1.2				
DS2 Area Total	**1232.9**	**175.7**	**363.0**	**352.8**	**341.4**				
DS3 Staff									
DS3-WP01	138.5	18.5	38.4	39.8	41.8	0.50	1.00	1.00	1.00
DS3-T1-WP01	81.5	26.2	41.0	14.4	0.0	1.00	1.50	0.50	0.00
DS3-T1-WP02	61.7	0.0	0.0	19.9	41.8			0.50	1.00
DS3-T3-WP01	134.7	13.1	41.0	43.1	37.6	0.50	1.50	1.50	1.25
DS3-T3-WP02	37.3	0.0	0.0	7.2	30.1			0.25	1.00
DS3-T3-WP03	44.5	0.0	0.0	14.4	30.1			0.50	1.00
DS3-T3-WP04	41.7	0.0	27.3	14.4	0.0		1.00	0.50	
DS3-T3-WP05	157.3	13.1	34.1	57.4	52.7	0.50	1.25	2.00	1.75
DS3-T3-WP06	28.7	0.0	0.0	28.7	0.0			1.00	
DS3-T3-WP07	36.2	0.0	6.8	14.4	15.1		0.25	0.50	0.50
	0.0								
IT support	28.8	2.9	7.6	9.6	8.7				
Secretarial	15.3	1.5	4.0	5.1	4.6				
			0.0						
Total DS3 Staff	806.1	75.4	200.1	268.1	262.5	2.50	6.50	8.25	7.50
DS3 Overhead	370.8	34.7	92.1	123.3	120.8				
	0.0								
DS3 Equipment	173.5	45.0	97.0	16.5	15.0				
DS3 Travel	75.2	8.9	20.5	23.6	22.3				
DS3 Consumables	17.3	1.8	4.6	5.8	5.3				
DS3 Exceptionals	4.1	0.6	1.2	1.2	1.2				
DS3 Area Total	**1447.0**	**166.2**	**415.4**	**438.5**	**426.9**				

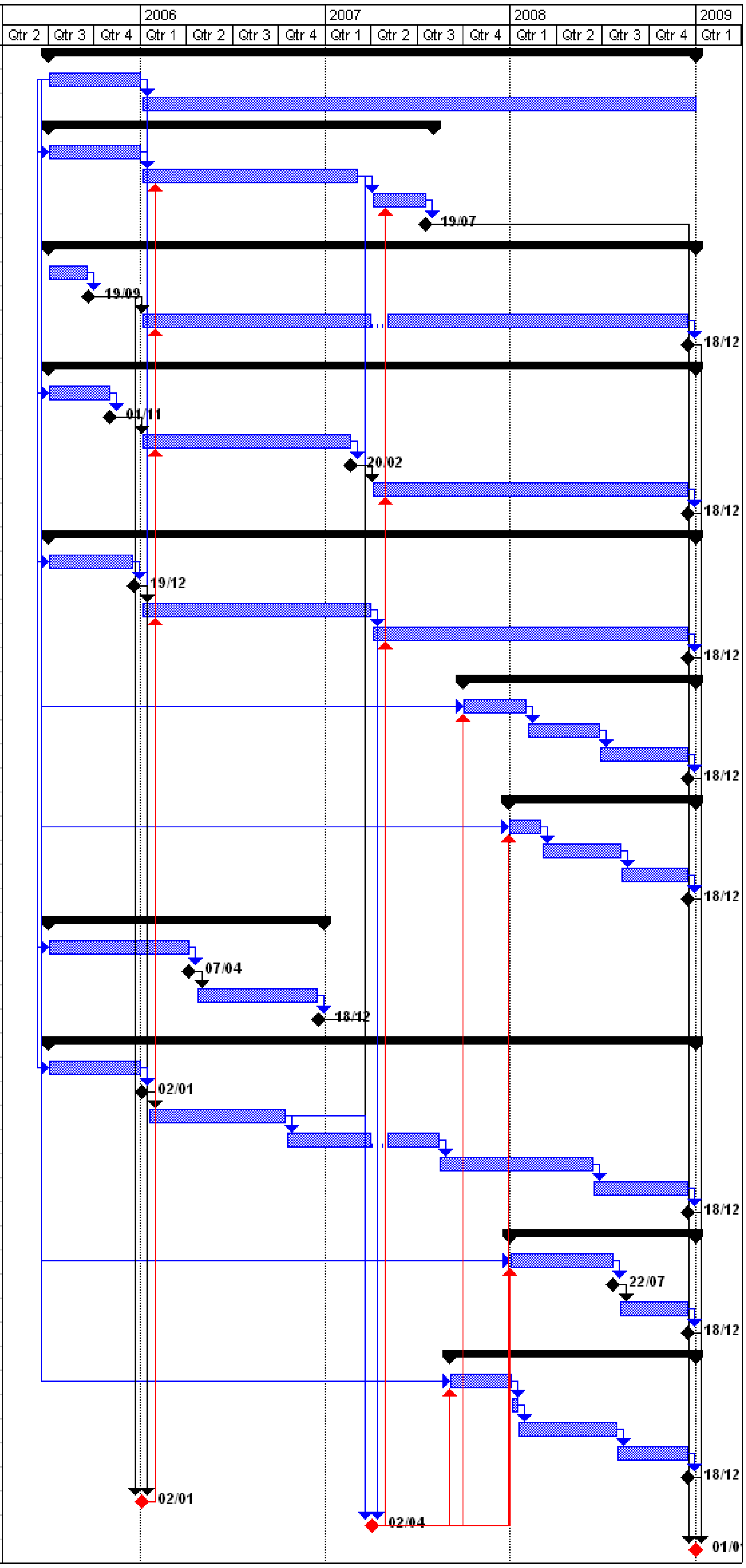
	Totals	Year 1 07/05 - 12/05	Year 2 01/06 - 12/06	Year 3 01/07 - 12/07	Year 4 01/08 - 12/08	Y1 FTE	Y2 FTE	Y3 FTE	Y4 FTE	
DS4 Staff										
DS4-WP01	40.1	31.4	2.7	2.9	3.0	1.2	0.1	0.1	0.1	1.50
DS4-WP02	323.1	70.9	174.9	77.3	0.0	2.5	6	2.5		11.00
DS4-WP03	99.2	13.1	27.3	28.7	30.1	0.5	1	1	1	3.50
DS4-WP04	0.0	0.0	0.0	0.0	0.0					0.00
DS4-WP05	167.9	14.4	30.0	60.3	63.2	0.55	1.1	2.1	2.1	5.85
DS4-WP06	0.0	0.0	0.0	0.0	0.0					0.00
DS4-WP07	142.3	13.1	41.0	43.1	45.2	0.5	1.5	1.5	1.5	5.00
DS4-WP08	107.0	52.4	54.6	0.0	0.0	2	2			4.00
DS4-WP09	140.0	0.0	68.3	71.8	0.0		2.5	2.5		5.00
DS4-WP10	6.8	0.0	6.8	0.0	0.0		0.25			0.25
DS4-WP11	134.3	52.4	81.9	0.0	0.0	2	3			5.00
DS4-WP12	64.8	0.0	19.1	20.1	25.6		0.7	0.7	0.85	2.25
DS4-WP13	116.2	0.0	0.0	86.1	30.1			3	1	4.00
DS4-WP14	31.7	0.0	0.0	28.7	3.0			1	0.1	1.10
DS4-WP15	44.5	0.0	0.0	14.4	30.1			0.5	1	1.50
DS4-WP16	0.0	0.0	0.0	0.0	0.0					0.00
DS4-WP17	15.1	0.0	0.0	0.0	15.1				0.5	0.50
DS4-WP18	90.3	0.0	0.0	0.0	90.3				3	3.00
DS4-WP19	23.0	2.6	2.7	8.6	9.0	0.1	0.1	0.3	0.3	0.80
DS4-WP20	181.6	18.5	52.1	54.2	56.9	0.5	1.5	1.5	1.5	5.00
	0.0									0.00
IT support	69.0	11.5	23.0	19.4	15.1					0.00
Secretarial	36.5	6.1	12.2	10.3	8.0					0.00
Total DS3 Staff	1833.2	286.4	596.5	525.7	424.6	9.9	19.8	16.7	13.0	59.25
DS3 Overhead	843.3	131.7	274.4	241.8	195.3					
	0.0									
	0.0									
DS4 Industry	2100.7	316.1	654.0	720.1	410.5					
DS4 Equipment	849.5	182.7	146.5	290.4	229.9					
DS4 Travel	128.4	20.8	41.8	36.3	29.5					
DS4 Consumables	41.5	6.9	13.8	11.7	9.1					
DS4 Exceptionals	86.4	12.3	24.7	24.7	24.7					
DS4 Area Total	**5882.9**	**957.0**	**1751.7**	**1850.6**	**1323.5**					
Project Total	**8562.8**	**1298.9**	**2530.1**	**2641.9**	**2091.9**					

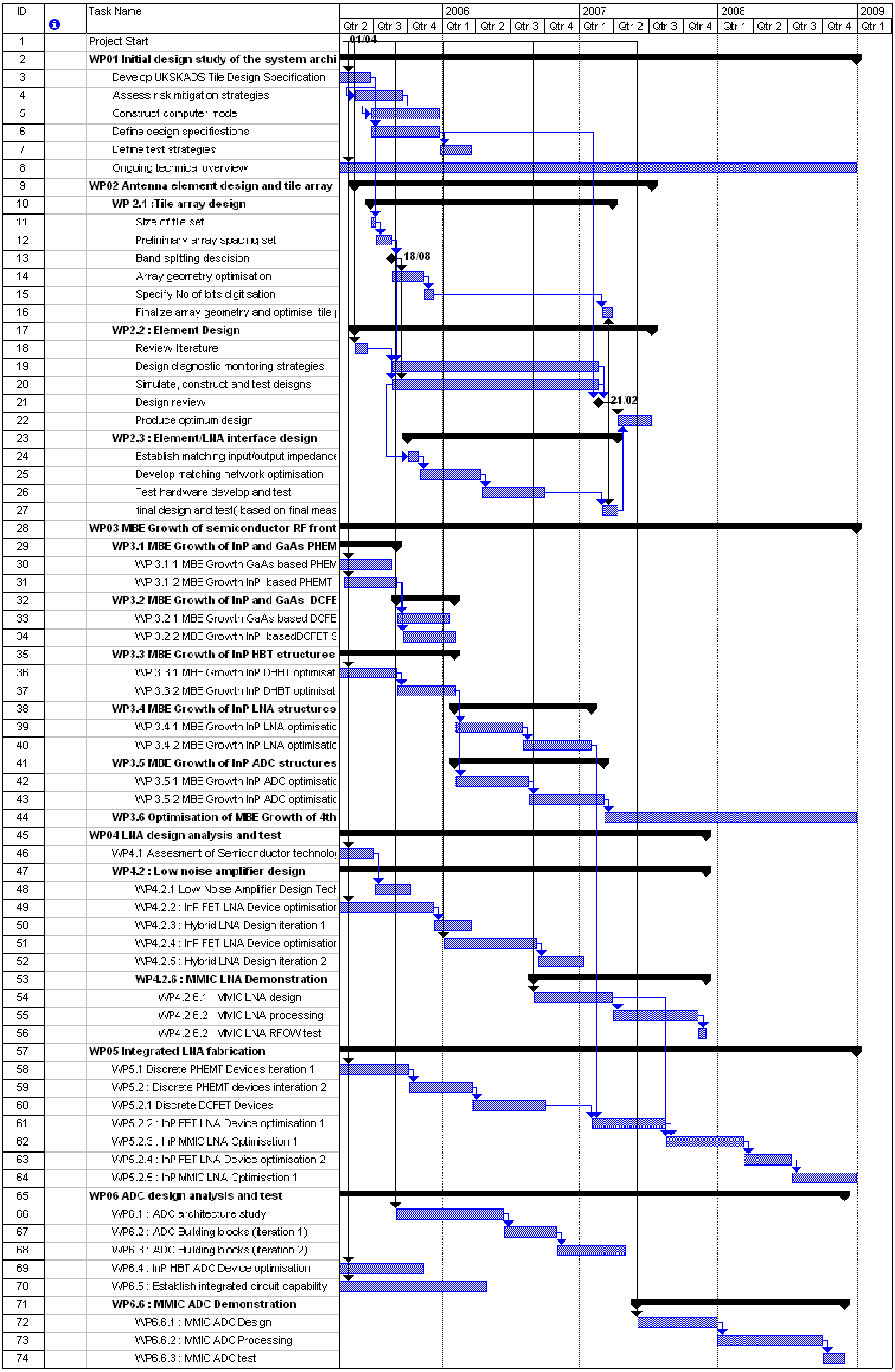
Annex C: Gantt Charts



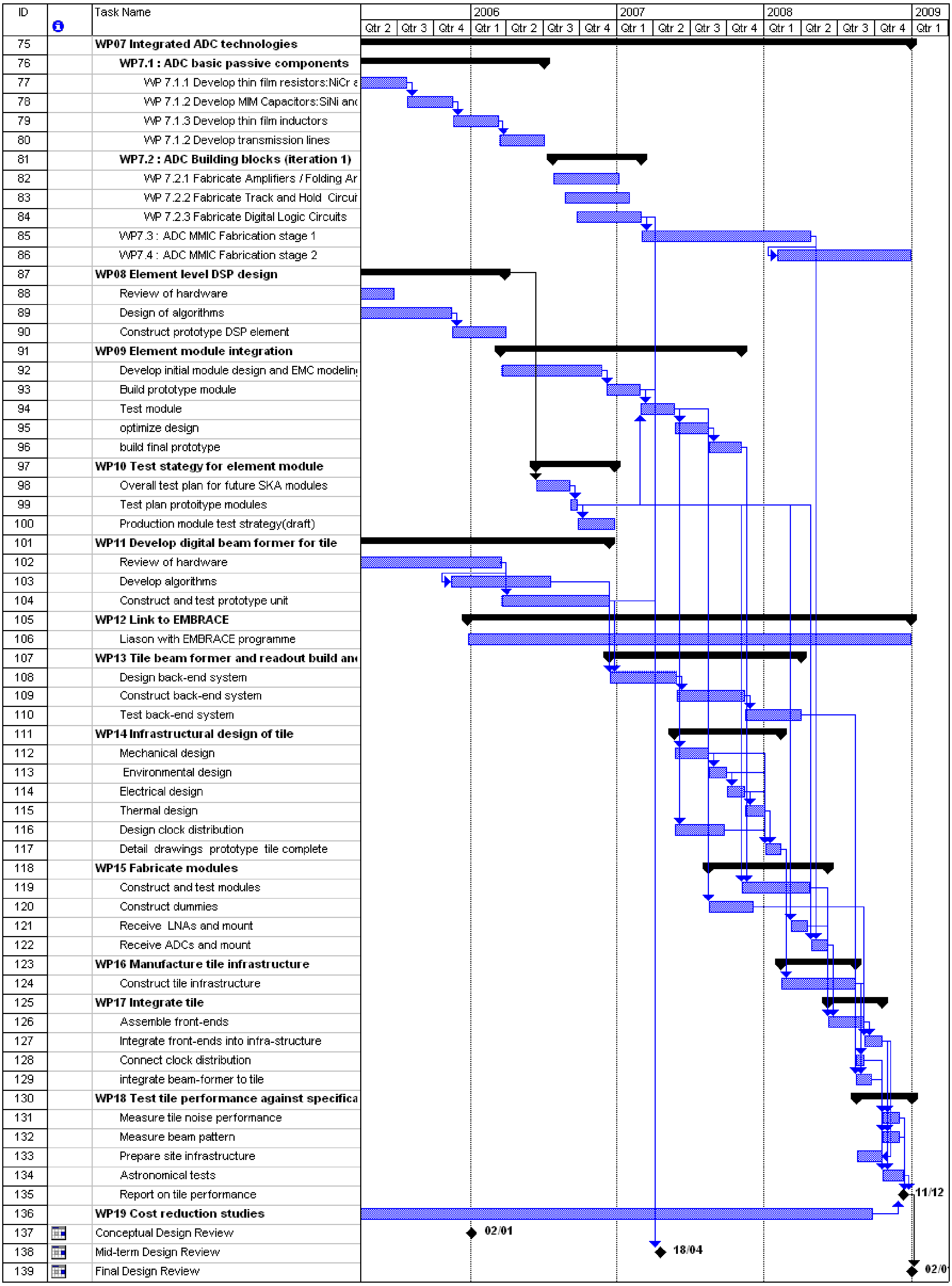
ID	Task Name	Duration
1	**DS2-WP1 DS2 Management**	914 days
2	**Deliverable:Report on Science Drivers**	0 days
3	**Deliverable: Report on Techical Drivers**	0 days
4	**Deliverable: DS Consolidated Report including 'Year i**	0 days
5	**DS2-T1-WP1 Science: Continuum Surveys**	**524 days**
6	Report on simulation method	131 days
7	Simulated Continuum Survey	175 days
8	**Deliverable: Simulated Continuum Survey**	0 days
9	Analysis of simulation: frequency/ resolution	87 days
10	Analysis of simulation: FoV	130 days
11		
12	**DS2-T1-WP2 Science: Line Surveys**	**527 days**
13	Report on simultion method	111 days
14	Simulated Line Survey	130 days
15	**Deliverable: Simulated Line Survey**	0 days
16	Analysis of simulation: frequency/ resolution	109 days
17	Analyis of simulation: FoV	86 days
18	Analysis of combining line and continuum surveys	65 days
19		
20	**DS2-T1-WP3 Science: Polarization Surveys**	**527 days**
21	Report on magnetic field models	262 days
22	Simulated Polarization Survey	172 days
23	**Deliverable: Simulated Polarization Survey**	0 days
24	Analysis of simulation: eg polarization purity	88 days
25		
26	**DS2-T1-WP4 Science: Pulsar Surveys**	**410 days**
27	Report on simulation method	45 days
28	Simulated Pulsar Survey	184 days
29	**Deliverable: simulated pulsar survey**	0 days
30	Analysis of follow up timing precision	109 days
31	Analysis of simulations: frequency range, FoV etc	50 days
32		
33	**DS2-T1-WP5 Science: Transient Surveys**	**521 days**
34	Model burst population	260 days
35	Analysis: eg time resolution, FoV	261 days
36	Report on source scintillation	5 days
37		
38	**DS2-T1-WP6 Science: Astrobiology**	**529 days**
39	Report on 'optimum tracers'	131 days
40	Report on FoV/key science trade-offs	337 days
41	Final report	60 days
42		
43	**DS2-T2-WP1 Technical: Continuum Surveys**	**377 days**
44	Investigate dynamic range limitations of dishes	132 days
45	Investigate dynamamic range limitations of phased arra	130 days
46	Investigate self-calibration algorithms	115 days
47		
48	**DS2-T2-WP2 Technical: Line Surveys**	**380 days**
49	Investigate limitations of existing datasets	130 days
50	Investigate SKA limitations eg bandpass stability of pha	250 days
51		
52	**DS2-T2-WP3 Technical: Polarization Surveys**	**388 days**
53	Investigate limitations of existing datasets	119 days
54	Investigate SKA limitations eg cross polarization of pha	164 days
55	Investigate tolerance of parameters	95 days
56		
57	**DS2-T2-WP4 Technical: Pulsar Surveys**	**524 days**
58	Investigate impact of array configuration on pulsars se	130 days
59	Investigate impact of array configuration on follow-up	88 days
60	Investigate impact on FoV	130 days
61	Investigate impact on polarization purity	66 days
62	Investigate tolerance of parameters	95 days
63		
64	**DS2-T2-WP5 Technical: Transient Surveys**	**393 days**
65	Investigate science return as function of SKA realizatic	284 days
66	Investigate joint burst/ pulsar surveys	109 days
67		
68	**Conceptual Design Review**	1 day
69	**Mid-term Design Review**	1 day
70	**Final Design Review**	1 day

ID	Task Name	Duration
1	**DS3**	**914 days**
2	Produce schedules	131 days
3	Final Report	783 days
4	**DS3-T1-01**	**544 days**
5	Prototype 15-km link	131 days
6	Prototype multi-hop link	304 days
7	Investigate long link properties	76 days
8	Final Report	10 days
9	**DS3-T1-02**	**914 days**
10	Review Current Technologies	56 days
11	Initial Report	10 days
12	Studies for long link technology	750 days
13	Final Report	10 days
14	**DS3-T2-01**	**914 days**
15	Review of Current Technology	87 days
16	Initial Report	10 days
17	Estimation of power/costs	294 days
18	Interim Report	10 days
19	Determine upgrade routes/real-time cost	446 days
20	Final Report	10 days
21	**DS3-T3-01**	**914 days**
22	Review Current Technology	121 days
23	Initial Report	10 days
24	Develop telescope model	323 days
25	Investiage and Optimise topology	446 days
26	Final Report	10 days
27	**DS3-T03-02**	**328 days**
28	Review of network requirements	90 days
29	Update of simulation code	102 days
30	Assess network configurations	126 days
31	Final Report	10 days
32	**DS3-T3-03**	**264 days**
33	Review of network requirements	46 days
34	Update of simulation code	113 days
35	Assess network configuration	95 days
36	Final report	10 days
37	**DS3-T3-04**	**391 days**
38	Review of similar data task	200 days
39	Interim Report	10 days
40	Application of experience to SKA	171 days
41	Final Report	10 days
42	**DS3-T3-05**	**914 days**
43	Review existing expertise	131 days
44	Initial Report	10 days
45	Implementation of existing codes	195 days
46	Simple grid implementation	195 days
47	Develop Prototype code	217 days
48	Evaluation of efficiencies	135 days
49	Final Report	10 days
50	**DS3-T3-06**	**262 days**
51	Review current knowledge	145 days
52	Inital Report	10 days
53	Application to SKA	97 days
54	Final Report	10 days
55	**DS3-T3-07**	**348 days**
56	Review of current methods	87 days
57	Interim Report on user access	10 days
58	Produce observing modes	141 days
59	Investigate collabarative support	100 days
60	Final Report	10 days
61	**Project conceptial review**	2 days
62	**Project mid-term review**	2 days
63	**Project final review**	2 days





ID	ℹ	Task Name
1		Project Start
2		**WP01 Initial design study of the system archi**
3		Develop UKSKADS Tile Design Specification
4		Assess risk mitigation strategies
5		Construct computer model
6		Define design specifications
7		Define test strategies
8		Ongoing technical overview
9		**WP02 Antenna element design and tile array**
10		**WP 2.1 :Tile array design**
11		Size of tile set
12		Prelinimary array spacing set
13		Band splitting descision
14		Array geometry optimisation
15		Specify No of bits digitisation
16		Finalize array geometry and optimise tile
17		**WP2.2 : Element Design**
18		Review literature
19		Design diagnostic monitoring strategies
20		Simulate, construct and test deisgns
21		Design review
22		Produce optimum design
23		**WP2.3 : Element/LNA interface design**
24		Establish matching input/output impedance
25		Develop matching network optimisation
26		Test hardware develop and test
27		final design and test(based on final meas
28		**WP03 MBE Growth of semiconductor RF front**
29		**WP3.1 MBE Growth of InP and GaAs PHEM**
30		WP 3.1.1 MBE Growth GaAs based PHEM
31		WP 3.1.2 MBE Growth InP based PHEMT
32		**WP3.2 MBE Growth of InP and GaAs DCFE**
33		WP 3.2.1 MBE Growth GaAs based DCFE
34		WP 3.2.2 MBE Growth InP basedDCFET S
35		**WP3.3 MBE Growth of InP HBT structures**
36		WP 3.3.1 MBE Growth InP DHBT optimisat
37		WP 3.3.2 MBE Growth InP DHBT optimisat
38		**WP3.4 MBE Growth of InP LNA structures**
39		WP 3.4.1 MBE Growth InP LNA optimisatic
40		WP 3.4.2 MBE Growth InP LNA optimisatic
41		**WP3.5 MBE Growth of InP ADC structures**
42		WP 3.5.1 MBE Growth InP ADC optimisatic
43		WP 3.5.2 MBE Growth InP ADC optimisatic
44		**WP3.6 Optimisation of MBE Growth of 4th**
45		**WP04 LNA design analysis and test**
46		WP4.1 Assesment of Semiconductor technolo
47		**WP4.2 : Low noise amplifier design**
48		WP4.2.1 Low Noise Amplifier Design Tech
49		WP4.2.2 : InP FET LNA Device optimisatior
50		WP4.2.3 : Hybrid LNA Design iteration 1
51		WP4.2.4 : InP FET LNA Device optimisatior
52		WP4.2.5 : Hybrid LNA Design iteration 2
53		**WP4.2.6 : MMIC LNA Demonstration**
54		WP4.2.6.1 : MMIC LNA design
55		WP4.2.6.2 : MMIC LNA processing
56		WP4.2.6.2 : MMIC LNA RFOW test
57		**WP05 Integrated LNA fabrication**
58		WP5.1 Discrete PHEMT Devices Iteration 1
59		WP5.2 : Discrete PHEMT devices interation 2
60		WP5.2.1 Discrete DCFET Devices
61		WP5.2.2 : InP FET LNA Device optimisation 1
62		WP5.2.3 : InP MMIC LNA Optimisation 1
63		WP5.2.4 : InP FET LNA Device optimisation 2
64		WP5.2.5 : InP MMIC LNA Optimisation 1
65		**WP06 ADC design analysis and test**
66		WP6.1 : ADC architecture study
67		WP6.2 : ADC Building blocks (iteration 1)
68		WP6.3 : ADC Building blocks (iteration 2)
69		WP6.4 : InP HBT ADC Device optimisation
70		WP6.5 : Establish integrated circuit capability
71		**WP6.6 : MMIC ADC Demonstration**
72		WP6.6.1 : MMIC ADC Design
73		WP6.6.2 : MMIC ADC Processing
74		WP6.6.3 : MMIC ADC test



ID		Task Name
75		**WP07 Integrated ADC technologies**
76		**WP7.1 : ADC basic passive components**
77		WP 7.1.1 Develop thin film resistors:NiCr
78		WP 7.1.2 Develop MIM Capacitors:SiNi an
79		WP 7.1.3 Develop thin film inductors
80		WP 7.1.2 Develop transmission lines
81		**WP7.2 : ADC Building blocks (iteration 1)**
82		WP 7.2.1 Fabricate Amplifiers / Folding Ar
83		WP 7.2.2 Fabricate Track and Hold Circui
84		WP 7.2.3 Fabricate Digital Logic Circuits
85		WP7.3 : ADC MMIC Fabrication stage 1
86		WP7.4 : ADC MMIC Fabrication stage 2
87		**WP08 Element level DSP design**
88		Review of hardware
89		Design of algorithms
90		Construct prototype DSP element
91		**WP09 Element module integration**
92		Develop initial module design and EMC modelin
93		Build prototype module
94		Test module
95		optimize design
96		build final prototype
97		**WP10 Test stategy for element module**
98		Overall test plan for future SKA modules
99		Test plan protoitype modules
100		Production module test strategy(draft)
101		**WP11 Develop digital beam former for tile**
102		Review of hardware
103		Develop algorithms
104		Construct and test prototype unit
105		**WP12 Link to EMBRACE**
106		Liason with EMBRACE programme
107		**WP13 Tile beam former and readout build an**
108		Design back-end system
109		Construct back-end system
110		Test back-end system
111		**WP14 Infrastructural design of tile**
112		Mechanical design
113		Environmental design
114		Electrical design
115		Thermal design
116		Design clock distribution
117		Detail drawings prototype tile complete
118		**WP15 Fabricate modules**
119		Construct and test modules
120		Construct dummies
121		Receive LNAs and mount
122		Receive ADCs and mount
123		**WP16 Manufacture tile infrastructure**
124		Construct tile infrastructure
125		**WP17 Integrate tile**
126		Assemble front-ends
127		Integrate front-ends into infra-structure
128		Connect clock distribution
129		integrate beam-former to tile
130		**WP18 Test tile performance against specifica**
131		Measure tile noise performance
132		Measure beam pattern
133		Prepare site infrastructure
134		Astronomical tests
135		Report on tile performance
136		**WP19 Cost reduction studies**
137	▦	Conceptual Design Review
138	▦	Mid-term Design Review
139	▦	Final Design Review

Annex D: Project Milestones and Deliverables

Overall Project Milestones:

1. Conceptual design review 02/01/06
2. Mid-term review 18/04/07
3. Final review 02/01/09

DS2 Milestones (see WPs and GANTT chart)

1. Delivery of simulated continuum sky 04/9/2006
2. Delivery of simulated line sky 03/07/2006
3. Delivery of simulated polarisation sky 07/03/2007
4. Delivery of simulated pulsar sky 16/06/2006
5. Report on science drivers 01/06/2007
6. Report on technical drivers 31/12/2008
7. Consolidated report (inc. "Year in the life of SKA for both dish and phased arrays") 31/12/2008

DS3 Milestones

1. Delivery of prototype 15-km link 01/2006
2. Initial report on use of the grid for data analysis in SKA 02/2006
3. Delivery of prototype multi-hop link 03/2007
4. Delivery of network simulation code 04/2007
5. Report on software for facilitating collaborative research 04/2007
6. Implementation of example grid-enabled code 06/2008
7. Production of a set of consolidated observing modes 07/2008
8. Reports on data transmission and archive strategy 12/2008
9. Final report on network architecture 12/2008

DS4 Milestones

1. Final design specifications 22/12/2005
2. Antenna element design selection: 27/02/2007
3. MBE growth LNA structures complete 01/07/2007
4. MMIC LNA demonstration complete 29/11/07
5. MMIC ADC demonstration 28/11/2008
6. Digital beam former for tile 11/12/06
7.. Integration of test tile complete 20/10/08
8. Report on tile performance 31/12/08

Annex E Risk Analysis

The key for the risk levels used below is as follows:

1) Solution available off the shelf.
2) Straightforward application of available technology but development required.
3) Significant R&D required and high confidence in success.
4) Significant R&D required but chance technology will not succeed.
5) No solution yet apparent.

Contingency

The main factor effecting the overall risk is the uncertainty in EU funding. We therefore include a contingency of 15% to cover this uncertainty.

DS2 Risk Analysis

Work Package	Risk Factor	Risk	Effect of Risk	Mitigation (and working allowance)
DS2-WP0 DS2 and Oxford Project Management	3	Insufficient resources to cover all requirements	Schedule delay, or impaired results	10% WA staff effort
DS2-T1-WP1 Continuum simulations (science)	2	Insufficient resources to obtain full set of simulations	Restricted simulation set	Accept poorer constraints on design
DS2-T1-WP2 HI simulations (science)	2	Insufficient resources to obtain full set of simulations	Restricted simulation set	Accept poorer constraints on design
DS2-T1-WP3 Polarization simulations (science)	3	Efficiency loss due to imperfect interaction with DS2-T1-WP1	Restricted simulation set	Accept poorer constraints on design
DS2-T1-WP4 Pulsar simulations (science)	2	Insufficient resources for full exploration	Restricted analysis of timing follow-up	Accept poorer constraints on design
DS2-T1-WP5 Transient simulations (science)	3	Insufficient resources to consider all likely transients	Restricted number of transient sources investigated	Accept poorer constraints on design
DS2-T1-WP6 Astrobiology (science)	4	Model fails to yield reliable predictions	No design constraints from astrobiology	Further investigations - 15% WA staff effort
DS2-T2-WP1 Continuum surveys (technical simulations)	3	Difficulties investigating self-calibration for phased arrays	Uncertainties about efficacy of self calibration	Descope science objectives or 10% WA staff effort
DS2-T2-WP2 Line surveys (technical simulations)	3	Insufficient resource to cover all requirements	No consideration of time-varying (astrobiology) signal	Descope science objectives or 10% WA staff effort
DS2-T2-WP3 Polarization surveys (technical simulations)	3	Difficulties investigating polarization purity for non-tracking elements	Uncertainty in likely performance of phased arrays	Descope science objectives or 10% WA staff effort
DS2-T2-WP4 Pulsar surveys (technical simulations)	3	Efficiency loss due to imperfect interaction with DS2-T2-WP3	Uncertainty in achievable timing precision	Descope science objectives or 10% WA staff effort
DS2-T2-WP5 Transient surveys (technical simulations)	4	No reasonable extrapolations of data buffering capability	Uncertainty in performance of data buffer	Descope science objectives or 10% WA staff effort

Work Package	Risk Factor	Risk	Effect of Risk	Mitigation (and working allowance)
DS3	3	Insufficient resources to cover all requirements	Schedule delay, or impaired results	10% WA staff effort
DS3-T1-01 Coherent signal distribution	3	Failure to apply current technologies to longer baselines	Difficulty in planning full SKA design	Additional investigations 15% WA staff effort
DS3-T1-02 Data transmission requirements	2	Emerging technologies not able to provide required throughput	Difficulty in planning upgrade path for SKA	Adjust future specification 10% WA staff effort
DS3-T3-01 Network Architecture	2	Overrun on development of simulator code	Restricted functionality of network simulation code	Additional Investigations 10% WA staff effort
DS3-T3-02 Network requirements for time resolved experiments	2	Overrun on development of network model	Restricted functionality of network simulation code	Additional investigations 10% WA staff effort
DS3-T3-03 Network requirements for imaging and spectral-line observations	2	Overrun on development of network model	Restricted functionality of network simulation code	Additional investigations 10% WA staff effort
DS3-T3-04 Management of the data flow	2	Overrun on information gathering	Final report incomplete	Additional investigations 15% WA staff effort
DS3-T3-05 The application of distributed, GRID-enabled data reduction for SKA	3	Difficulty implementing grid-enabled code	Difficult to plan future likely developments	Build in difficulty into costing of software development for the SKA
DS3-T3-06 Data, archiving and scientific exploitation	1	Difficulty in extrapolating current knowledge to SKA context	Uncertainty in final data products	Accept current model for data products for array
DS3-T3-07 The SKA in operation: users, observing modes and user support	1	Insufficient specification of required observing modes and mode of user interaction	Uncertainty in future observing mode specification	Accept current model for types of observing modes

Work Package	Risk Factor	Risk	Effect of Risk	Mitigation
DS4-WP01	3	Extra effort required to complete useful model and specifications for later work packages	Programme delay	10% WA on staff effort.
DS4-WP02	3	The meeting of all the science requirements can not be met.	Some science can not be addressed	Rescope scientific programme in order to reduce technical specification
	3	Experimental measurements invalid due to inadequate understanding of mutual coupling in small test pieces	Initial prototype impedance measurements inaccurate	Build and re-test larger arrays of prototype elements
DS4-WP03	2	MBE down for unspecified amount of time.	Wafers not available for LNA and ADC programmes.	*Two MBE machine at our disposal makes risk very low indeed. No mitigation required.*
DS4-WP04	2	High performance InP devices not available from WP03	Reduced performance LNA at room temperature	Thermoelectric cooling to achieve desired noise performance or buy-in components from US foundry (Qinetiq can outsource on 3-month timescale – risk cost reflects the latter option).
	2	Unable to establish repeatable integrated circuit capability	Integrated LNA circuits not available to programme	Design InP based LNA MMIC using a US foundry
DS4-WP05	2	Processing difficulties leading to out of spec MMICs. (Especially noise performance)	Reduced performance at room temperature	Thermoelectric cooling of LNA to achieve desired noise performance. Use 10% WA.
DS4-WP06	3	Device processing is not capable of achieving device yield	Unable to produce functioning ADC	Use external InP HBT foundry process
DS4-WP07	4	New Development of high speed ADC.	Suitable devices not available on time	Buy in commercial devices (low resolution, High power dissipation and high cost) but use for proof of concept.
DS4-WP08	2	DSP system does not reach required spec within schedule	Programme delay	Increased level of consultancy from Qinetic 25 days of extra Qinetic effort 12.5k
DS4-WP09	4	Late agreement of component specifications	Delay in completion	Improved management and resources
	3	Late delivery of components	Delay in completion	Early identification of critical items
	2	Inability to find/employ suitable skill	Delay in completion	Early identification of critical items
	2	Underestimation of sizes/power/M&C	Redesign of package	Build in some margins
	3	Inadequate screening/filtering	Redesign of package/components	Build in margins
DS4-WP10	1	None: Report will be produced		
DS4-WP11	2	DSP system does not reach required spec within schedule	Programme delay	Increased level of consultancy from Qinetic 25 days of extra Qinetic effort 12.5k
DS4-	4	DSP system does not reach required spec	Programme delay	Increased level of consultancy from Qinetic

WP13		within schedule		25 days of extra Qinetic effort 12.5k
DS4-WP14	2	Time for detailed design too short	Delay in build programme and cost increase in labour	Increase design/drawing effort – overlap mechanical and electrical design. Requires increased effort.
DS4-WP15	3	Module cost exceeds budget	Potential overspend	Build fewer active modules to meet budget. This results in a reduced test program, that is a single tile will be fully tested but tile to tile beam forming will not be tested.
DS4-WP16	2	Infrastructure costs overbudget	Overspend	Working allowance of 10% of consumable costs
DS4-WP17	2	Mechanical or electronic integration issues	Schedule delay	Modify infrastructure; 20% WA of staff effort
DS4-WP18	3	Delay in completing all necessary testing	Schedule delay	20% WA of staff effort
DS4-WP19	1	None: report will be produced		
DS4-WP20	3	Insufficient resources to cover management requirements	Schedule delay	10% WA of staff effort

Working allowance summary

Work Package	**Working allowance (k£)**
DS2-WP01	20.2
DS2-T1-WP01	
DS2-T1-WP02	
DS2-T1-WP03	
DS2-T1-WP04	
DS2-T1-WP05	
DS2-T1-WP06	6.5
DS2-T2-WP01	6.5
DS2-T2-WP02	6.5
DS2-T2-WP03	8.6
DS2-T2-WP04	6.5
DS2-T2-WP05	
DS3-WP01	20.2
DS3-T1-WP01	17.8
DS3-T1-WP02	9.0
DS3-T3-WP01	19.7
DS3-T3-WP02	5.4
DS3-T3-WP03	6.5
DS3-T3-WP04	9.1
DS3-T3-WP05	
DS3-T3-WP06	
DS3-T3-WP07	
DS4-WP01	5.8
DS4-WP02	
DS4-WP03	
DS4-WP04	
DS4-WP05	42.5
DS4-WP06	
DS4-WP07	
DS4-WP08	12.5
DS4-WP09	
DS4-WP10	
DS4-WP11	12.5
DS4-WP12	
DS4-WP13	12.5
DS4-WP14	
DS4-WP15	
DS4-WP16	4.2
DS4-WP17	
DS4-WP18	26.4
DS4-WP19	
DS4-WP20	26.5

Annex F: HEFCE-funded Personnel

Members of the UKSKADS Project Management Board are indicated by the † symbol.

Cambridge Personnel

Name	Position	Percentage Effort	PPARC funded	Comments
Paul Alexander	Lecturer	35%	No	†
Helen Brimmer	Computer Officer	50%	No	
Peter Duffett-Smith	Lecturer	35%	No	†
Dave Green	Lecturer	20%	No	
Steve Gull	Professor	10%	No	
Mike Hobson	Reader	10%	No	
Anthony Lasenby	Professor	5%	No	
Malcolm Longair	Professor	25%	No	
Rachael Padman	Lecturer	35%	No	
Martin Rees	Professor	10%	No	
John Richer	Royal Society Fellow	5%	No	
Julia Riley	Lecturer	35%	No	
Paul Scott	Emeritus Lecturer	15%	No	

Oxford Personnel

Name	Position	Percentage Effort	PPARC funded	Comments
Joanne Baker	Royal Society Fellow	10%	No	
Katherine Blundell	Royal Society Fellow	10%	No	
Garret Cotter	Temporary Lecturer	35%	No	
Gavin Dalton	Lecturer	10%	No	
Roger Davies	Professor	5%	No	
Pedro Ferreira	Lecturer	10%	No	
Lance Miller	Lecturer	5%	No	
Philipp Podsiadlowski	Lecturer	10%	No	
Hans-Rainer Kloeckner	Post-doc	50%	No	
Steve Rawlings	Professor	35%	Part, *	†
Joe Silk	Professor	10%	No	
Sukyoung Yi	Temporary Lecturer	5%	No	
Head of SKA instrumentation	Lecturer	50%	No	†
Radio Instrumentation Lecturer	Lecturer	25%	No	

* PPARC funded until October 2006.

Manchester Personnel

Name	Position	Percentage Effort	PPARC funded	Comments
Brian Anderson	Senior Lecturer	10%	No	
Richard Battye	Lecturer	10%	No	
Anthony Brown	Professor	25%	No	
Richard Davis	Reader	20%	No	
Phil Diamond	Professor	10%	No	
Michael Kramer	Reader	20%	No	
Andrew Lyne	Professor	10%	No	
Tom Millar	Professor	10%	No	
Mo Missous	Professor	25%	No	
Alan Pedlar	Reader	10%	No	
Neil Roddis	Senior Engineer	10%	Half	
Rob Sloan	Senior Lecturer	10%	No	†, PI
Ralph Spencer	Reader	10%	No	
Peter Wilkinson	Professor	10%	No	†

New lecturer	Lecturer	25%	No	
New Chair of Radio Technology	Professor	50%	No	

Cardiff Personnel

Name	Position	Percentage Effort	PPARC funded	Comments
Jonathan Davies	Reader	10%	No	
Mike Disney	Professor	10%	No	
Steve Eales	Professor	20%	No	†
Joseph Romano	Lecturer	15%	No	
B. Sathyprakash	Professor	5%	No	

Leeds Personnel

Name	Position	Percentage Effort	PPARC funded	Comments
Jeremy Lloyd-Evans	Senior Lecturer	5%	No	
Melvin Hoare	Senior Lecturer	10%	No	†
Johannes Knapp	Senior Lecturer	5%	No	

Glasgow Personnel

Name	Position	Percentage Effort	PPARC funded	Comments
Graham Woan	Senior Lecturer	10%	No	†
Martin Hendry	Senior Lecturer	10%	No	

Annex G: Collaborators in the SKADS programme

- ASTRON, NL
- The University of Manchester, UK
- The Joint Institute for VLBI in Europe, NL
- L'Observatoire de Paris, FR
- Instituto di Radioastronomia, IT
- Fundacion General de la Univ. De Alcala, ES
- Max Plank Institute fur Radioastronomie, DE
- University Of Oxford, UK
- CSIRO, AU
- Puschino RAO, RU
- National Research Council, CA
- National Research Foundation, SA
- Torun Centre for Astronomy, PL
- Chalmers University, SE
- University of Cambridge, UK
- Kapteyn Astronomical Institute, NL
- University Leiden, NL
- Cardiff University, UK
- University of Glasgow, UK
- Swinburne University of Technology, AU
- Univ. of Adelaide, AU
- University of Melbourne, AU
- University of Sydney, AU
- The University of New South Wales, AU
- University d'Orleans, FR
- Centre National de la Recherche Scientifique, FR
- University of KwaZulu-Natal, SA
- University of Leeds, UK
- Universidad de Valencia, IT
- OMMIC, FR
- BAe Systems: AdvancedTechnology Centre, UK
- Qinetiq Ltd, UK

Annex H: Public Outreach

The International SKA project puts a high priority on public outreach, and the `Outreach Committee' meets regularly. UK SKADS activity will build on this established structure.

Information on the SKA for the public is available on the internet[8] including a downloadable two-page flyer presenting basic information for the public on the current SKA Key Science Projects [KSPs].

The project is currently gathering together as much visual material as possible which will shortly be available as pictures and movies on the public outreach page.

The international project office regularly issues press releases which often result in significant coverage in the media. Individual countries also heavily promote the project (see for example the fantastic efforts in South Africa where the core of the SKA itself might be sited[9]).

Links to web pages organised by the International Project can be found on the web pages of groups in the UK SKA consortium[10] and pages describing UK SKADS activity will be developed.

The SKA will feature prominently in the new Jodrell Bank Visitors' Centre which will be completed towards the end of the period covered by this proposal.

Members of the UK SKADS consortium regularly appear on radio and television with, for example, Prof Wilkinson recently discussing the SKA on the `Sky at Night'. As the SKA project gathers pace, we anticipate that these media opportunities will increase. The SETI aspect of the SKA programme is obviously of immense interest to the general public.

All members of the UK SKADS consortium regularly give lectures to the public which, also as the SKA project gathers pace, will increasingly feature the SKA in general and UK SKADS activity in particular. Visits to schools by UK SKADS consortium members will also be an important aspect of the programme. As emphasised in the proposal, the beam of an `all electronic' SKA could quite easily be made available to schools via whatever has replaced the internet by ~2020.

The public outreach programme of Jodrell Bank is well known and UK SKADS public outreach will build on this expertise.

The collaboration with RadioNet is another means

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[8] http://www.skatelescope.org/pages/Page_genpub_m.htm
[9] http://www.ska.ac.za/press.html
[10] http://www.jb.man.ac.uk

Annex I: Potential links with South Africa

In this appendix we present an edited version of text provided by Prof. Justin Jonas (Director Harteebesthoek Radio Observatory and head of SKA development in South Africa) in the following sections:

- A1: Rationale for South African involvement in SKADS
- A2: Specific proposal for a South African SKA pathfinder
- A3: Preliminary Science Drivers for the pathfinder

In the last section we add recent UK thinking on the science impact of the pathfinder:

- A4: UK suggestion for Neutral Hydrogen studies of large-scale-structure using the South African pathfinder instrument: R. Battye (Manchester)

AI1: Rationale for South African involvement in SKADS

South Africa's bid to host the SKA is strengthened by our participation in international SKA technology programmes and other initiatives that demonstrate our competence in the core technologies of the SKA.
The construction in South Africa of a technology and/or science pathfinder for the SKA is an expedient way to achieve the above. Such participation is consistent with the identification of astronomy as one of the strategic science platforms. Local funding for our SKA project is conditional on the delivery of a science capable demonstrator, rather than just a technology pathfinder. There are persuasive reasons for South Africa to preferentially align itself with the European SKADS programme. These include:

a. Our traditional links with European institutions.
b. The existence of counter-trade obligations by European industries that have competence in SKA-related technologies (including BAe, Saab, MAN).
c. The potential for IP generation within the SKADS programme and the emphasis on generic technologies.
d. The exciting science opportunities provided by the SKADS technologies.

Initial thoughts of building an aperture array based on the SKADS programme in South Africa proved to be premature and inappropriate. The EMBRACE demonstrator will be too expensive to build an aperture large enough to be of scientific value. It will also be limited to a single polarization. No value would be added to the European project or our own scientific infrastructure by simply replicating the European demonstrator here in South Africa. The focal plane phased array is physically similar to a single aperture plane phased array "tile". The performance requirements for a focal plane phased array are far less demanding than for an aperture array because of the limited range of "look angles". Some of the beamforming performed by electronics in an aperture array is done by diffractive optics when using a focal plane phased array. An aperture array tile is easily converted into a focal plane array, hence the development cost of a focal plane array would largely be borne by the SKADS programme.
Advantages of the focal plane hybrid include:

a. The ratio of collecting aperture to phased array tile area might be larger than 100, hence reducing the cost of the instrument and reducing the sensitivity of the overall cost to the (highly) uncertain phased array tile cost.
b. The performance demands for a focal plane array are far less arduous than for an aperture array.
c. Focal plane phased arrays are the subject of the Pharos Joint Research Activity which is part of the fully funded RadioNet FP6 Integrated Infrastructure Initiative (I3). We would have access to the Pharos deliverables.
d. The technology of reflecting collectors is mature and risk-free.
e. The diffractive beam provides some RFI mitigation.

Compromises presented by the focal plane hybrid include:

a. The instantaneous field of view is restricted because of the diffractive beamforming. Still allows multi-beaming, but individual beams not as independent as for aperture array.
b. Mechanical moving elements are introduced.

AI2: Specific proposal for a South African SKA pathfinder

1. An array of 25 12-metre dish concentrators located at a radio quiet site in the Northern Cape. This configuration will provide an equivalent aperture to a single 60-m dish, i.e. about the same aperture as Parkes radio telescope which is the largest single dish in the southern hemisphere. This corresponds to an aggregate aperture of 2800 m^2.
2. Operating in the L/S-band frequency range of 1-2.3 GHz which complements the frequency coverage of the existing 26-metre dish at HartRAO which only operates above 1600 MHz. This frequency range includes both the HI and OH spectral line bands. The lower limit of 1 GHz might move up or down, depending on science case and technology limitations.
3. The focal plane arrays used with these dishes would be based on the technologies developed in SKADS DS4 and DS5. DS5 (i.e. EMBRACE) tiles would not be suitable because of their single polarization capability and 100 K noise temperature. DS4 outputs (i.e. fully digital, dual-polarization tiles with 50 K performance) are expected to be suitable.
4. The antenna array would initially as a tied array with back-end beamformers. A correlator will be considered if the science case is compelling and the budget allows for it.
5. The array configuration and baseline distribution will be decided by the science case, but it is unlikely that baselines longer than 1km will be necessary.
6. Modest S-band dishes do not need high surface or pointing precision. Rms surface accuracy of ~4-mm and rms pointing accuracy of ~0.1 deg is satisfactory at S-band (minimum wavelength of 13-cm).
7. An 8x8 element focal plane array might be adequate, but 12x12 is likely to be the maximum required. This would be roughly 1-m^2 of SKADS patch. The use of a concentrator therefore gives a multiplier effect of about 100. Field of View (FoV) would probably be about 10 deg.
8. An important contribution that this instrument will make to the development of the SKA is the use of multiple independent beams for survey observations. The number of beams will largely be driven by budget constraints, but currently we envisage 10 beams.
9. An important factor is that this is a scalable architecture. Construction can be matched to cash flow, and future expansion can be accommodated by adding additional antennas and digital backend electronics.
10. This will be a software telescope that will make extensive use of configurable logic and cluster computing. These are generic technologies that have market value. Moore's law will drive performance and functionality upgrades for at least the next twelve years.

AI3: Preliminary Science Drivers

1. Pulsars: Parkes is the most effective pulsar discovery machine currently operating. Matching the Parkes sensitivity at L/S-band would allow the monitoring of all pulsars in the Parkes catalogue. Multi-beaming would allow efficient and continuous monitoring of timing and flux variations of pulsars. New enigmatic classes of pulsar have been discovered recently (e.g. pulsars with a duty cycle < 10%, pulsars producing sporadic giant pulses, pulsars in binary systems). VLBI astrometry would establish distances of nearby pulsars. The sensitivity of the instrument will allow single-pulse monitoring, which will be useful for studying GR effects and observing giant pulses.

2. Intermediate redshift HI: A survey of neutral hydrogen (HI) associated with galactic clusters in the redshift range $0<z<0.5$ will provide information on cosmic large-scale structure (LSS). Gas in the cores of galaxy clusters is hot and ionized, but cooler neutral gas may exist around clusters. This survey needs somewhat higher resolution than the Parkes telescope in order to avoid confusion. Interferometer baselines of the order of 100 m would be well matched to the angular scale of this cosmic web of HI. Longer baselines would over-resolve the structures and not add to the sensitivity of the instrument. A survey that extends the Parkes HIPASS HI survey of galaxies would be an important contribution that the instrument might make.

3. VLBI: The extension of the HartRAO facilities to L-band will enhance the capabilities of the European VLBI Network (EVN), and the increased collecting area over the existing 26-m dish at the OH bands would be scientifically useful. Multi-beaming allows simultaneous tracking of phase calibrator and target sources during VLBI scans, which will provide extremely precise astrometry

(this will aid astrometric studies of pulsars). Sensitive L/S-band VLBI experiments with Australia would use the long E-W baseline to conduct parallax and proper motion studies of isolated and binary pulsar systems.

4. Monitoring of maser and continuum sources: The increased sensitivity of the array over the existing dish and the multi-beaming capability will vastly extend the impact of the research based on the long-term monitoring work that is currently done at HartRAO. The increased sensitivity would allow work on extragalactic megamasers.

AI4: UK suggestion for Neutral Hydrogen studies of large-scale-structure using the South African Pathfinder instrument: R. Battye (Manchester)

Design parameters : We propose that the instrument be sensitive to the range of frequencies corresponding to HI at redshifts below 1.3 (600-1500MHz) with an instantaneous bandwidth of 20%. The overall collecting area would be around 3000m^2. Each dish would be fitted with a 25 element FPA which is partially cooled to give noise temperatures ~30K. The total field-of-view of such an instrument would be about 50 deg^2 at 1GHz and if the dishes are arranged in region of ~200m across, the synthesized beam would be 5 arcmin at 1GHz and the array would 10% filled. Such an instrument would be more than 50 times more powerful in terms of survey than the Parkes multi-beam array which has performed the most significant LSS survey using HI to date. Coupled with the excellent RFI environment expected in the RSA and the good-band pass calibration expected for such an array, this would provide an significant (~2 orders of magnitude) improvement of the best HI imaging currently available at this resolution.

Targets : Since the synthesized beam gets larger with redfshift, while objects of a fixed size get smaller, the most obvious targets for observations with such an instrument would be change as a function of redshift. At low redshifts the targets would be ordinary spiral galaxies, allowing for a significant improvement on the HIPASS and HIJASS surveys. At intermediate redshifts (z~0.4) galaxy clusters would be the most obvious targets and at even higher redshifts larger structures contributing to the cosmic web would be observable. It should also be possible to make large-scale maps of the HI brightness temperature which could, for example, be cross-correlated with those of the CMB observed by WMAP and PLANCK.

Science : Most LSS surveys to date have focussed on the starlight detected in the optical and IR wavebands. Using HI as the tracer provides a complementary view of the universe since the gas is cold. It is often suggested that they may even be unbiased. It should be possible to use information from these surveys to constrain the cosmological expansion history in a similar way to currently being done using 2dF and SDSS for galaxies, and likely to done in the near future for galaxy clusters using the SZ effect and X-ray emission. In addition to the large galaxy and galaxy cluster catalogues expected such surveys would provide unprecedented information on the evolution of the neutral gas component of the universe allowing the star formation history of the universe to be explored.

Annex J: Draft specification of 3rd generation tile

Category	**Aspirational specification or published specification for SKA**	**Specification for 3rd generation tile in SKADS Design Study**	**Limiting factor(s)**
Frequency Coverage	0.1 – 1.7 GHz	~0.5 → ~1.5 GHz	Choice of antenna element for best EM performance as a function of frequency and mutual coupling in a close-packed array
Maximum scanning angle of independent fields-of-view	+/- 60 degrees from forward direction	as for SKA	Capabilities of software or hardware beam-forming system
Beam formation and predictatbility of sidelobe level of coherent patch	Not yet defined – eventual output of SKADS DS2	First-order estimates from DS4-WP1	o Full quantitiative understanding of behaviour of software or hardware beam-forming system o mutual coupling as a function of elements' position in array and pointing angle o computing requirements depending bit rate produced by tile (see also bandwidth requirement)
System temperature	Natural background–limited across the whole band	< 50K at 1.4 GHz	o First transistor performance (<20K as a goal – may be achievable with 0.5 micron gate) o Matching transistor to the antenna with a network with minimum loss.
Polarisation properties	o Dual polarization o Residual error -40dB (total power) in FoV centre -30dB at FoV edge (after routine calibration)	As for SKA	o EM performance of antenna element as function of frequency o Mutual coupling as below
Instantaneous RF Bandwidth	0.1-1.7 GHz for everything	0.5-1.5 GHz for the hardware sub-systems for the tile. Final specification from DS4-WP1	o Final bandwidth set by the digital processing system at the time of completing the tile demonstrator o Analogue-to-digital converter (ADC) design o Bandpass flatness

Analogue to Digital converter (ADC)	Not specified	Final specification from DS4-WP1	○ Device material and circuit design ○ Linearity requirements ○ Cost
LO and clock distribution	○ Phase noise on LO < 1 degree? ○ Time transfer accuracy 1 psec over 100s metres for station and 1000s km for array	Final specification via DS4-WP1	○ For immediate digitization need to keep all clock waveforms locked at tile/station level
Power dissipation per tile	TBD	Final specification via DS4-WP1 – not a driver for 3rd generation tile	○ Material for active device ○ Thermoelectric cooling efficiency?
Environmental tolerance	Not specified but work with ○ -20C→ +80C ○ Rain ○ Lightning ○ UV-radiation ○ Dust penetration ○ Wind ○ Fauna	Final specification via DS4-WP1 – not as much of a driver for 3rd generation tile	○ Cost and effect on RF performance ○ Longevity of solutions
“Cleanliness” of power supply to individual receivers	Not defined	To be specified in DS4-WP1	○ Component quality and design
Reliability/MTBF	Not yet defined	To be specified in DS4-WP1	○ Component quality and design
Calibration/monitoring system per tile	Not yet specified	To be specified in DS4-WP1	To be discussed in DS4-WP1
Manufacturing	Not yet specified	To be discussed in DS4-WP1	○ integratibility of antenna and receiver system ○ packaging design
Cost per complete tile	€500 per square metre assuming cost of entire SKA is €1B	TBD – but note 3rd generation tile may be different from an SKA tile –for which it may not be possible to afford an all digital solution for the beam formation.	Essentially everything!

COMMENTS ON INDIVIDUAL SPECIFICATIONS

Frequency:

- SKA specification extends down to 0.1 GHz to observe highly redshifted atomic hydrogen. Upper limit set by the requirement to observe atomic hydrogen (1.42 GHz) and hydroxyl (1.67 GHz).
- SKADS R&D tile need not cover this whole band. Study needs to assess where to split the band (current working guess is 0.5 GHz) is part of the cost-benefit analysis at start of programme
- Study to assess the cost-benefit of using 2 or 3 sizes of element to cover the SKA band: for each element size there has to be a separate receiver/ digitizer chain.

Maximum scanning angle of independent fields-of- view

- Assessment of beam forming strategy part of initial assessment study

Beam formation and predictability of sidelobe level of a coherent patch

- Specification of beam-forming accuracy for tile to form part of initial assessment—followed by detailed modelling during study. Assessment of beam-forming accuracy for the full SKA, and its effect on dynamic range, is part of the DS2-T2 task.
- Do we form beam before or after correlation? Ideally retain flexibility of linear processing, in principle in any order, so can form many different kinds of beams – limit will be communications bandwidth between stations – want to be able to use as flexibly as possible
- Beam efficiency → effective area per square metre
- Mutual coupling needs to be understood to what level? Major modelling job
- Complex weights need to be reproducible to what level? Major modeling job
- One approach is to form n-fields-of-view with m beams in each?
  OR
- A more general system (limited in BW) with choice of how to use the data in terms of frequency/spatial coverage etc set at run time. get a description of this from MJ
- Ideally don't limit yourself in advance but then is the data BW for this very large?
- What can we demonstrate on the timescale of this programme? No-one has yet achieved simultaneous observation over two F-O-V. Need to show it is scalable → for this study we need to investigate scalability first?
- To avoid having to do delay compensation, the received bands will be subdivided into frequency channels narrow enough that "beams" can be formed by phasing and addition. Initially, for compatibility with EMBRACE, a few bands up to ~40MHz wide will be considered.

System temperature

- Tsys= 50K (ambient temperature operation) is half that of the EMBRACE demonstrator specification but twice that of standard cryogenically-cooled LNA at 1.4 GHz. and is a good current target for operation at 1 +/- 0.5 GHz in SKADS tile. Will eventually need to improve to <25 K to get close to natural-background-limited performance.
- Need to generate a plot of the total background temperature contributions in the band 0.1-1.7 GHz
- Bottom end of SKA band (<500 MHz) is easier in terms of achieving background-limited noise temperature e.g. >300K contribution from the galactic synchrotron radiation at f=150 MHz with spectral index of 2.7
  (i.e. $T_{galaxy} \propto f^{-2.7}$)
- Current LNA performance with commercially-available devices can be improved with optimized combination of material and device structure. Study to address what limits fundamental transistor performance in MMIC circuits.
- Modest (<20%) loss in ideal performance arising from MMIC architecture acceptable if costs go down faster as a result.
- Study to address performance gain from thermo-electric cooling

Polarisation properties

- SKA specification set by pulsar timing requirements. Pulsars are highly polarized; need to obtain an accurate integrated pulse profile
- Spec. refers to residual error after calibration *not* to instantaneous cross-talk. Typical total power cross-talk in current radio astronomy horn systems is -20 dB but can be calibrated.
- Below ~0.5 GHz polarization measurements matter less due to plasma effects in galaxy and ionosphere

Instantaneous Bandwidth

- Goal is to digitize the rf directly (option 2) – but this is the higher risk approach for the design of the ADC; the mixer/IF/tunable narrow band approach (option 1) is lower risk and should start study there.
- Start off by looking at LNA and ADC and not the mixer – to avoid the LO distribution issue.

- Basic paraemeters are : sampling frequency; Number of bits per sample and linearity
- How much can be done to assess the mixer solution without hardware implementation? – mostly can be done in the initial paper feasibility exercise
- Bandpass flatness is an issue – the US EVLA (Extended Very Large Array) has specified 5 dB peak-to-peak (on broad-brush grounds) across the band to minimize the variation of spectral density into the ADC (which generates white digitization noise at sqrt(1/12) bit rms).
- More important is the repeatability of this variation – should be possible to achieve high uniformity from element to element with the integrated design being envisaged.
- Bandpass repeatability also important for observations of spectral line absorption at low optical depths against faint backround sources

Analogue to Digital Converter (ADC)

- Number of bits dominated by
  1) rfi headroom i.e to preserve information for subsequent rfi excision algorithms
  2) accuracy of beam-nulling requirement
  3) flexibility of complex beam- weighting flexibility
- Assess rfi from satellites (GPS,GLONASS INMARSAT) as primary sources. Initially assume local rfi is zero (but see comments below)
- If could guarantee that always want to average a million samples before doing anything else then can use 1-bit
- ADC design gets exponentially harder as # of bits increases. An 8-bit device would need 1000s transistors per chip → but then have concern about yield.
- Why not use commercial ADCs?
  1) at anything like the “desired level” are very expensive
  2) have high power dissipation (5 watts)
  3) we want to be able to integrate them into a module to save eventual costs
- ADC programme should start simple and build up (also interest from Hunt Engineering.)
- Pollution by digital switching noise may be a problem: Got to shield the antenna at 120dB level from self-generated signals at ~0 dBm. Digitization at high frequency means that harmonics are not in band and do not create additional problems

LO and Clock Distribution

- LO and time transfer between stations will be transferred by go-and-return techniques on optical fibre – the pertinent issue for DS4 is coherent distribution at the tile level
- Sampling clock coming in on a fibre and a digital bit stream going out on another one
- If no LO then all we are concerned with is the sampling clock. – not a problem for the specific tile deliverable

Power Dissipation per Tile

- Minimization is highly desirable for an array covering 1 million square metres
- Local heat generation may not be significant compared with solar heating. Part of initial assessment study
- Assess if thermoelectric cooling is a a viable possibility in the light of the power requirements of the entire SKA array

Environmental Tolerance

- Temperatures listed are the operational environment for the device, outside the package. Where the device generates its own heat then the temperatures will be higher
- Much experience with these issues in industry – but not in a low cost environment

Reliability/MTBF

- Fault tolerance investigation for phased arrays are part of the initial assessment study.
- Rule-of-thumb is that at 150C→ 1 million hours per transistor for GaAs technology

Calibration/monitoring system per tile

- Specification is part of initial assessment study
- Impossible to calibrate individual tiles via natural radio sources
- Use holography to determine which parts has failed/and to calibrate the system in amp and phase.
- Make use of GPS signals as exemplified by ASTRON in THEA
- Incorporate noise adding radiometers?
- What other system-health monitoring desirable/ affordable?

Manufacturing

- Industry experience is that phased arrays usually work out at:
  1/3 manufacturing
  1/3 testing
  1/3 packaging
- For full SKA probably can’t afford connectors, chip has to talk directly to chip

Cost per tile

- Cost of actual deliverable of the 3rd generation tile will be much larger than €500
  - At 2x100 elements per square metre need to make the ADCs cheap – however this is the requirement for the SKADS DS4 demonstrator tile – for the SKA the ambition to digitize and control all elements is too great and we will have to beam-form 100-1000 elements into a coherent patch before digitization (see top-level comment).
- Power target and cost target are challenging – but we need 10^9 components in some cases and hence gain economies of scale
- Device costs at 200 systems per square (for a fully-filled system) metre are a major issue
- Cost/complexity may well force into an initial analogue beam forming system for the final SKA tile to reduce the digitization requrirments by orders of magnitude
- Estimates for multiple copies cannot be too far from final SKA
- Costs can be pushed down in universities?
- Can reduce costs if make array more sparse have grating sidelobes N.B. don’t thin uniformly so as to provide all spacings – but just fewer of them.
- Need to think about the analogue system to make a 1m coherent patch for the final SKA model