Status of Pathfinder Telescopes and Design Studies

Edited by Colin Greenwood
International SKA Project Office

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Table of Contents

List of Figures

List of Tables

1. Introduction

Institutions participating in the SKA are now designing and building prototype systems, and design decisions for the full SKA will be based on the technologies demonstrated by these pathfinder telescopes and design studies. Many different technological solutions will be selected and integrated into the final instrument. This document provides a summary of the status of the pathfinder telescopes, design studies and other SKA-related R&D work, and has been generated from information provided by these projects.

The purpose of this document is to provide background information for the 'Draft Specifications for the Square Kilometre Array' report published on 10 September 2007. A more concise summary of this document will be produced in the future for Annex 3 of the Draft Specifications document.

2. Status of Pathfinder Telescopes and Design Studies

2.1 Allen Telescope Array (ATA)

The ATA, known formerly as the One Hectare Telescope, or 1hT, is a joint effort by the SETI Institute and the University of California, Berkeley. It is being built at the existing Hat Creek Observatory, run by the Radio Astronomy Lab at Berkeley, and located in the Cascades just north of Lassen Peak, CA.

The ATA is a centimeter-wave array that pioneers the Large-Number Small-Diameter (LNSD) concept of building radio telescopes. The ATA has four primary advantages for scientific studies over all major radio telescopes built to date: (i) wide field-of-view i.e. 2.45° at λ = 21cm, (ii) complete instantaneous frequency coverage from 0.5 to 11.2 GHz, (iii) multiple simultaneous backends and (iv) active interference mitigation. The instantaneous area of sky imaged is 17x that of the VLA. Active interference mitigation will make it possible to observe at frequencies of many terrestrial radio emitters.

The ATA will ultimately comprise 350 dishes (6.1m in diameter) and will make possible large, deep radio surveys that were not previously feasible. The pseudo-random arrangement of the telescopes on the ground places all of the telescopes well inside a 1 km circle, carefully located to provide a very high quality beam. The large number of antennas provides unprecedented control of unwanted sensitivity outside the primary beam.

The ATA is being constructed in 4 stages, the ATA-42, ATA-98, ATA-206, and ATA-350; each number representing the number of dishes in the array at a given time. By building the new telescope as an array, many areas on the sky can be studied at once. In addition, it is easy to expand an array by merely connecting more dishes into the system.

The design involves an off-centre reflector assembly to minimise the chance of terrestrial signals bouncing off the antenna structures and causing interference. A secondary mirror has been incorporated into the design to bounce incoming radio signals collected by the large (6.1m diameter) primary reflector back to the feed horn, where they are amplified and then sent to the control buildings. By introducing a secondary mirror and a surrounding shroud, the antenna is less likely to pick up noisy radiation from the (relatively hot) ground surrounding the telescope.

The key design specifications of the ATA are shown in Table 1.

Table 1. ATA design specification

Parameter	Specification
No. of elements	350
Element diameter	6.1 m
Total geometric collecting area	10 229 m^2
Frequency	0.5-11.2 GHz
Aperture efficiency	60%
Effective area	6,137 m^2
System temp.	42 K
A_{eff}/T_{sys}	146 m^2/K
Effective diameter	700 m
No. of beams	16 dual polarization
FoV	0.07-40 deg^2 (5 deg^2 at 1.42 GHz)

Key science projects to be conducted initially will include:

- Determining the HI content of galaxies over three quarters of the sky,
- Classifying 250, 000 extragalactic radio sources as active galactic nuclei or starburst galaxies,
- Exploring the transient sky,
- Surveying 1,000,000 stars for extraterrestrial signals with enough sensitivity to detect an Arecibo radar out to 300 pc within the range of 1-10 GHz,
- Surveying the 4×1010 stars of the inner Galactic Plane near the frequency of 1420 MHz for very powerful transmitters
- Measuring the magnetic fields in the Milky Way and other Local Group Galaxies,
- Detecting the gravity-wave background from massive black holes through pulsar timing, and
- Measuring molecular cloud and star formation properties using new molecular tracers.

For further information about ATA, see http://ral.berkeley.edu/ata/

2.2 APERture Tile In Focus (APERTIF)

APERTIF aims to increase the FoV and bandwidth of the Westerbork Sysnthesis Radio Telescope (WSRT) by using Focal Plane Arrays and all digital beamforming. It comprises 14 x 25m telescopes and is planned to become operational in 2009.

Target specifications for APERTIF project are shown in Table 2.

Table 2. Target specifications for APERTIF

Parameter	WSRT (@ 1.4GHz)	APERTIF Target
Aperture eff	60%	75%
T_{sys}	25 K	<50 K
A_{eff}/T_{sys}		100 m^2/K (all telescopes)
Instantaneous bandwidth	160 MHz	300 MHz
Beams	Single beam	25 dual polarised beams (50 in total).
Frequency range		850-1750 MHz
FoV		8 deg^2

2.2.1 DIGital Early Stage Tile In Focus (DIGESTIF)

DIGESTIF is a digital FPA demonstrator that has been installed in one of the WSRT dishes to test and evaluate beam forming strategy. Beam forming and correlation is performed offline, which means that many beam forming schemes can be evaluated without the need to re-measure. First light is expected in September 2007. DIGESTIF characteristics are summarised in Table 3.

Table 3. Summary of DIGESTIF specification

Parameter	Specification
Frequency range	1.0 – 1.7 GHz
Array size	80 x 80 cm
Dual linear polarization	Yes, Vivaldi elements
Number of elements	112
Instantaneous bandwidth	30 MHz
Number of receivers	60
Observation time	max 6.7 seconds per measurement
System temperature	100 K
Dish diameter	25 m

2.3 Australian SKA Pathfinder (ASKAP)

The Mileura International Radio Array (MIRA) is the Australian SKA Pathfinder (ASKAP) to be constructed in the Mid West region of Western Australia. MIRA comprises two instruments - MIRANdA and MWA. Together they form an SKA science and technology pathfinder, initially covering the frequency range ~80MHz to ~3 GHz.

The Australian Government has set aside AUS $56.7 million in its 2007-08 budget for the Australian Square Kilometre Array Pathfinder (ASKAP). This funding includes AU$51.7 million to CSIRO for construction of the ASKAP and AU$5 million for Australian Government engagement in the international SKA program, including participation in the proposed EU FP7 program to conduct a preparatory study for the SKA construction phase. The new funding adds to approximately $49.2 million already committed for the telescope.

As a result of the new funding the Australian SKA Pathfinder radio telescope will probably incorporate:

- an increase from 30, to possibly as many as 45, parabolic dishes equipped with phased array receivers, and a low frequency array of 512 antenna “tiles”,
- cooled phased-array receivers to increase sensitivity. CSIRO is well positioned to have a leading role internationally in the development of cutting-edge phased-array receiver technologies,
- a remote array-station in NSW linked to the telescope core in WA via !bre-optic infrastructure, demonstrating the “long baseline observing” that is a key feature of the full SKA, and
- key infrastructure and operations resources to demonstrate the Australian sites for the SKA, including a high
- bandwidth optic-fibre link between Geraldton and the WA telescope site, characterisation and maintenance of the radio-quiet zone, and suitable power solutions for the telescope and for the SKA remote array-station.

2.3.1 MIRANdA Project ((the MIRA large-N, small-d Array)

MIRANda (together with the Karoo Array Telescope in South Africa) has been tasked with demonstrating the scientific capability of the Small Dish + Focal Plane Array concept outlined in the SKA Reference Design.

MIRANdA, previously known as xNTD, is being developed as an international partnership between Australia (CSIRO) and Canada (NRC) to build an array of dishes capable of high dynamic range imaging and using wide-field-of-view phased array feeds. It will deliver the first element of the ASKAP – a thirty antenna radio telescope equipped with novel phased array feeds designed to increase the accessible field of view.

MIRANdA will be located at Boolardy Station, Western Australia, in one of the most radio quiet regions on Earth and a potential site for hosting the SKA. It will be built in 2008-2012 with the following characteristics:

- A six-antenna system operational 2010 Q2, with a 30-antenna system operational by 2012 Q2,
- The final system will have at least 30 dishes (possibly up to 45 with additional funding in place), each 12 m diameter,
- Each antenna equipped with a 10x10 FPA (“smart feed”),
- System temperature (T_{sys}) of 35 K
- Frequency range 0.7 – 1.8 GHz
- Instantaneous bandwidth 300 MHz
- At least 30 independent beams giving a total field of view of 30 sq deg over the entire frequency range
- Maximum baseline ~ 8 km
- Full cross-correlation of all antennas
- Correlator located at the ASKAP site, with a high-bandwidth fibre taking correlated data off-site for archiving and processing.

The MIRANda system parameters, in particular the frequency range and large field of view capability, are aimed at addressing the following Key Science Projects of the SKA:

- Strong field tests of gravity using pulsars and black holes
- The origin and evolution of cosmic magnetism
- Galaxy evolution, cosmology and dark energy

Thus, the science goals for MIRANda include:

- Understanding the evolution of the gaseous component of the nearby Universe,
- Determining the evolution, formation and population of galaxies throughout cosmic time,
- Understanding the interstellar medium of our own Galaxy and the generation and maintenance of its magnetic fields,
- Revealing the nature of the transient radio sky,
- Discovering and timing up to 1000 radio pulsars, and
- Providing a vital element of the VLBI network.

Although only 1% of the collecting area of the final SKA specifications, MIRANdA is a front-line scientific instrument in its own right which attacks ground-breaking science questions directly relevant to the SKA.

For further information about MIRANdA, see http://www.atnf.csiro.au/projects/mira/index.html

2.3.2 Mileura Widefield Array (MWA)

The "Mileura" in the project name refers to a station (i.e. livestock ranch) in outback Western Australia, roughly 300km inland from the coast and a few hundred kilometers north of Perth. This area has a number of characteristics suited to radio astronomy, such as excellent sky access, low RFI, dedicated infrastructure, and freedom to locate stations within a future geographically distributed array for optimum configuration.

MWA is an international collaboration between US, Australian and Indian institutions to build a wide-field, low-frequency dipole array, comprising 500 tiles operating in the frequency range of 80 to 300 MHz - right in the FM and TV bands.

The central theme of the MWA project, its demonstrators, and the full scale facility targeted for the next decade, is scientific exploitation of extremely wide fields of view. The combination of large collecting area with fields of view encompassing hundreds of square degrees is now in reach for frequencies below ~1.5 GHz. Instead of point source sensitivity, which depends on collecting area and system noise temperature, the MWA effort is directed at maximizing survey sensitivity and the ability to get large amounts of integration time on multiple targets of interest at the same time. Employing massive, yet now affordable, computational capacity, the MWA will achieve dramatically improved levels of survey sensitivity per unit cost.

The MWA will tackle one of the SKA key science projects: probing the dark ages. The instrument will detect the redshifted emission from the epoch of reionization, the era when the first stars and galaxies formed in the Universe. Other specific science goals of the MWA are:

- Continuous monitoring for possible coronal mass ejections from the Sun, and
- Detecting transients.

For further information about MWA, see http://www.haystack.mit.edu/ast/arrays/mwa

2.4 Deep Space Network Array (DSNA)

The telecommunications link between the Earth and spacecraft engaged in solar system exploration includes the Deep Space Network (DSN). This network, consisting of large antennas located approximately equally spaced around the Earth, is responsible for the delivery of telemetry to scientists from a multiplicity of spacecraft currently on mission, as well as for those planned in the future. There is a cluster of antennas at each of the three longitudes that make up the DSN. Each cluster currently consists of one to three 34-m beam-waveguide antennas and one 70-m Cassegrainian antenna. These are located in the USA, Spain and Australia. Although the current DSN assets support existing mission scenarios, it has been suggested that future missions will desire both greatly increased data rates and higher capacity.

JPL and NASA are developing plans for the eventual replacement of the DSN 70-m antenna by 2015, with a prototype implementation starting in 2009. The size and number of antennas for this will be finalized as part of that activity. Array-based options are being considered, specifically the installation of 1200x12m parabolic reflector antennas, equally split across the existing DSN locations. A site at each longitude will occupy roughly 10-12 square kilometres including facilities.

Each antenna will operate simultaneously at both X-band (8 to 8.8 GHz) and Ka-band (31 to 38 GHz) and will be configured with radio frequency (RF) electronics, including the feeds, low-noise amplifiers, and frequency converters, as well as the appropriate servo controls and drives. The array also includes the signal transmission and signal processing to enable the system to track from between 1 and 16 different signals.

The concept of using arrays to increase the sensitivity is not new for radio telescopes or to the DSN. What is new about this concept is the cost goals that have been identified to complete a project capable of replacing the downlink capacity of the 70-m antennas. The concept leverages the advances made in electronics, such as monolithic microwave integrated circuits (MMICs), cryogenics, and, in particular, the inexpensive fabrication of smaller reflector antennas. The result is that duplication of the downlink capability of a 70-m antenna is expected to be achieved for 10-20% of the cost of the 70-m antenna.

2.5 e-EVN

The European VLBI Network (EVN) is the world's most sensitive VLBI array; it consists of 16 large radio telescopes in Europe and Asia. VLBI is limited both operationally and in sensitivity by current equipment; e-EVN is a proposal to transform the capabilities of the EVN through the use of fibre-optic connections from the telescopes to the EVN correlator at JIVE in the Netherlands. This upgrade will result in a dramatic increase in sensitivity of the array and in its ability to respond quickly to targets of opportunity.

2.6 e-Merlin

MERLIN, developed in the early 1980s, consists of 7 telescopes located across England and connected by narrow-band microwave links. It was designed to provide sub-arcsecond resolution at centimetre wavelengths to study in more detail the radio galaxies and quasars imaged by the Cambridge aperture synthesis arrays.

The e-MERLIN upgrade is a project that will replace the microwave links by fibre-optic cables, thus increasing the bandwidth by a factor of 100. This will result in an order of magnitude improvement in the sensitivity of the array. In addition, its frequency coverage will be extended at the higher frequencies, which will increase the effective imaging resolution for continuum sources by a factor of three. e-MERLIN design goals include:

- High sensitivity (~1 microJy in 12 hours)
- Upgraded receivers for high-resolution continuum imaging at 10 - 50 mas
- Wide field imaging as standard mode (10 arcmin at 1.4 GHz; 17k pixel square images)
- Simultaneous continuum and multi-line spectroscopy
- Almost complete uv-coverage using MFS
- Sub-milliarcsecond astrometric capability
- Dynamic scheduling and on-the-fly imaging

e-MERLIN will provide radio images with a resolution comparable with or better than the Hubble Space Telescope and the new generation of optical, IR and sub-mm telescopes. It will complement the VLBI networks, which can provide much higher resolution but with much lower surface brightness sensitivity. The uniqueness of the e-MERLIN instrument will continue to be its combination of high sensitivity and high resolution. It bridges the gap between the resolution regimes of VLBI and other connected element radio interferometers.

e-MERLIN will be a natural pathfinder for SKA. It will provide glimpses of the science achievable with nano-Jy sensitivity and will be crucial as a test-bed for many of the techniques required to build SKA. e-MERLIN is very similar in size to the proposed SKA core (albeit having < 1% of the collecting area) and so the techniques of wide-band data transfer over several hundreds of kilometres, RFI mitigation and remote operation of telescopes will be developed using the upgraded array.

The scientific goals of e-MERLIN are to study:

- Structure of galaxies detected at sub-mm wavelengths,
- Star-formation rate as a function of redshift,
- Imaging of thermal and non-thermal jets from young stellar objects (YSOs),

- Imaging of circumstellar dust disks and methanol masers around YSOs,
- Physics of mass ejection in novae, planetary nebulae and evolved stars,
- Physics of jets via matched resolution images, such as radio/optical movies of M87,
- GRB hosts through the measurement of star-formation rates,
- Cosmological parameters through deep observations of gravitational lenses, and
- Microlensing in high-redshift dark matter haloes.

For further information about e-MERLIN, see http://www.merlin.ac.uk/e-merlin/

2.7 Expanded Very Large Array (EVLA)

The Very Large Array (VLA) was built in the 1970s and comprises 27 x 25m diameter antennas. The goal of EVLA project is to improve most of the key observational capabilities of the VLA by at least an order of magnitude. Originally, the project was divided into two phases. The objective of Phase I is to improve the sensitivity, bandwidth, spectral resolution and frequency coverage of the existing 27 element array by the application of modern technologies. Funding was provided for Phase 1 and work has commenced on this phase, with completion due by 2012. The objective of Phase II was to increase the angular resolution of the existing VLA by adding additional array elements around New Mexico. A proposal for Phase II was submitted to the National Science Foundation (NSF) in April 2004 but, in December 2005, the NRAO was notified that the NSF was unable to support the proposal.

The basic plan of Phase I is to replace the electronics with modern systems, whilst retaining the antennas, array design and infrastructure. This strategy is highly cost-effective because the cost of new interferometric facilities is dominated by antenna and supporting infrastructure costs.

The EVLA Project will provide a radio telescope of unprecedented sensitivity, resolution, and imaging capability by modernizing and extending the existing Very Large Array. When completed, the EVLA will provide the following capabilities:

- Sensitivity: Continuum sensitivity improvement by up to a factor of 5 (below 10 GHz) to more than 20 (between 10 and 50 GHz).
- Frequency Accessibility: Operation at any frequency between 1.0 and 50 GHz,
- Spectral Capability: The WIDAR correlator will provide many frequency channels (minimum of 16,384, up to 262,144), process the wide bandwidths and provide frequency resolution better than 1 Hz if necessary.
- Resolution: Angular resolution up to 200 / (frequency in GHz) milliarcseconds with tens of Kelvin brightness temperature sensitivity at full resolution.
- Low-Brightness Capability: Fast, high fidelity imaging of extended low-brightness emission with tens of arcseond resolution and microKelvin brightness sensitivity.
- Imaging Capability: Spatial dynamic range greater than 106, frequency dynamic range greater than 105, image field of view greater than 109 with full spatial frequency samplng.
- Operations: Dynamic scheduling, based on weather, array configuration, and science requirements. "Default" images automatically produced, with all data products archived.

The scientific goals of the EVLA project are not based on any specific observations or projects. Rather, the goals are to provide astronomers a powerful and flexible instrument for research into all astrophysical phenomena which emit (or reflect) detectable radiation in the radio band. However, the design of the EVLA has been driven by the following broad science themes:

- Magnetic Universe - measure the strength and topology of the cosmic magnetic field.
- Obscured Universe - image young stars and massive black holes in dust enshrouded environments.
- Transient Universe - follow the rapid evolution of energetic phenomena.
- Evolving Universe - study the formation and evolution of stars, galaxies and AGN.

There is no specific formal connection between the EVLA (1.3% of a square km) and the SKA, but the EVLA project is a demonstrator for most technical issues for the SKA, including:

- Array operation
- Digital antennas systems
- Wideband multi-bit data transmission over long distance
- Management of massive, complex correlators
- Archiving
- Spatially-variant gain calibration
- Wide-field imaging including beam corrections and non-coplanar imaging.
- \`e2e' data management, and
- Exploring the sub-mJy sky.

For further information about the EVLA, see http://www.aoc.nrao.edu/evla/

2.8 Five-hundred-meter Aperture Spherical Telescope (FAST)

The FAST will be constructed in the karst landscape of Pingtang county, Guizhou Province in southwest China and will act as a pathfinder telescope for the SKA, demonstrating innovative technologies that could be incorporated into the full SKA instrument. The FAST will be the largest telescope in the world, with the radius of its spherical surface being 300m, and with an overall diameter of 500m. Its main spherical reflector will be composed of 4,600 panels and occupy an area as large as 25 football fields. Its observation capacity will be 10 times over that of the world's current biggest *steerable* radio telescope.

The FAST's geometrical configuration will provide sky coverage of > 40° zenith angle. The simplified feed system will continuously cover most of the frequency range between 300 and 2000 MHz, with possible capability up to 5-8 GHz depending upon the cost.

Its main spherical reflector will allow both wide bandwidth and full polarisation capability while using standard feed design. In addition, its feed support system will integrate optical, mechanical and electronic technologies which will effectively reduce the cost of the support structure and control system.

Three outstanding features of the telescope are:

i. siting of the telescope in limestone karst depressions,
ii. active main reflector which corrects spherical aberration on the ground to achieve full polarization and a wide band without involving a complex feed system, and
iii. light focus cabin driven by cables and servomechanism plus a parallel robot as secondary adjustable system to carry the most precise parts of the receivers.

The FAST will enable astronomers to address many science goals, for example, neutral hydrogen line surveying in distant galaxies out to very large redshifts, looking for the first shining star, detecting thousands of new pulsars, etc.

A prototype of the main reflector has been built and the design and testing of the feed support system is almost complete (July 2007). The FAST is scheduled to be completed by 2013.

For further information about the FAST, see http://www.bao.ac.cn/english/home.asp.

2.9 Giant Meter Radio Telescope (GMRT)

The GMRT (run by the National Centre for Radio Astrophysics, or NCRA) consists of 30 fully steerable parabolic dish antennas of 45 m diameter in western India about 100 Km east of Mumbai. The antennas are arranged in a Y-shaped configuration covering an area equivalent to a 25 Km. diameter circle. The central square kilometre contains 14 antennas, randomly arranged, while the rest are distributed in three approximately equal arms. The antennas themselves do not have solid surfaces but instead the reflecting surface is made up of many thin wire "ropes". This works because at the long wavelengths we are using (21 cm and longer) the wires have the same effect as a solid surface. The use of wire instead of panels makes the telescopes lighter, cheaper and more stable in high winds.

GMRT has been operating since 2002 in the range 120 to 1450 MHz and is the largest synthesis radio telescope in the world at metre wavelengths.

For further information about the GMRT, see http://www.gmrt.ncra.tifr.res.in.

2.10 Karoo Array Telescope (KAT) / MeerKAT

The Karoo Array Telescope (KAT), a 1% SKA technology demonstrator, is currently under construction in the Northern Cape province of South Africa, near the proposed site for the core of the SKA. It will have 1% to 2% of the survey capacity of the SKA and so will be a world-class research instrument in its own right. KAT will demonstrate wide-field techniques using small dishes (15m) and phased array feeds in the range 0.7 – 1.8 GHz. A high-speed fibre-optic link will connect the KAT to the Centre for High-Performance Computing (CHPC) in Cape Town. The KAT is scheduled to be fully operational by 2010. It will be a working, integrated instrument with an aperture of at least 3,000m^2 ($A_{eff}/T_{sys} > 50$) and at least 10 steerable beams in 40 square degrees field of view.

The first step in the development of the KAT antenna is to design and construct a prototype (MeerKAT) at the Hartebeesthoek Radio Astronomy Observatory (HartRAO) by the end of 2007. This will make it possible to validate the mechanical design of an antenna for the KAT before starting with the production phase in the Northern Cape, thereby minimizing project risk. The lessons learned from MeerKAT will be incorporated into an updated design when the full array of 20 antennas is constructed.

The prototype will make it possible to conduct sensitivity tests of some of the key KAT science experiments. This will help the engineers to assess the suitability of critical elements of the KAT system design and will enable early testing of the telescope operational and science software chain.

Linking the prototype antenna to the existing HartRAO antenna will help build competence in interferometry and provide a test bed for evaluation of the KAT feed technology. This includes characterisation of the beam pattern, pointing and tracking accuracy, self-generated radio frequency interference (RFI), calibration and polarisation performance. The antenna will be designed to allow for tests of both horn cluster feeds and development of focal plane array feeds (FPAs), in collaboration with international partners. Table 4 summarises the technical specifications of the prototype antenna.

Table 4. MeerKAT antenna specifications

Parameter	MeerKAT Specification
Pointing Accuracy (deg)	0.04
Surface Accuracy (mm rms)	4
Frequency Range (MHz)	700 - 1700
Wind (Operational) km/h	20
Wind (Marginal Operation) km/h	36
Wind (Survival) km/h	160
Azimuth Rotation speed (deg/s)	1
Azimuth speed (deg/s)	0.5
Diameter	15
F/D	0.5
Lowest Natural Frequency (Hz)	3
Feed Mass (kg)	200
Feed Displacement (mm) - any direction	2
Feed Rotation (deg) any axis	0.02

For further information about the KAT, see http://www.kat.ac.za

2.10.1 Phased Experimental Demonstrator (PED)

PED is a test radio telescope interferometer currently under construction by the KAT project at The South African Astronomical Observatory (SAAO). PED will comprise 6 x 2.5m diameter steerable satellite TV dishes arranged as an interferometer and 1 x 3.5m diameter satellite TV dish with fixed pointing for drift-scan experiments. PED has a narrow bandwith (4 MHz), centered around the HI radio astronomy line at 1420 MHz.

The main goals of PED are to serve as a test bed for KAT/MeerKAT in the development of the software systems for monitor and control, remote operations, basic scheduling, basic tied array and interferometric imaging processing, and RFI mitigation.

In March 2007, PED achieved ‘first light’, i.e. the receive chain and dish drive electronics were connected for the first time and a scan across the sun was performed. This was later followed by a longer spectral integration on, and off, the galactic plane in order to detect the neutral hydrogen radio signal. Since ‘first light’, the team has focused on development of the site infrastructure and work towards more automated end-to-end single dish experiments, to be followed by interferometric experiments with the 6-dish array later in the year.

2.11 Low Frequency Array (LOFAR)

LOFAR is a generic Wide Area Sensor Network for astronomy, geophysics and precision agriculture applications. It comprises an array of simple omni-directional, electronic signals from which are digitised, transported to a central digital processor, and combined in software to emulate a conventional dish antenna. The cost is dominated by the cost of electronics and will follow Moore's law, becoming cheaper with time and allowing increasingly large telescopes to be built. There are 25,000 antenna, spread out over an area of ultimately 350 km in diameter, in the full LOFAR design. However, since funding is limited, LOFAR will be realised in several phases.

The LOFAR Phase 1 Baseline consists geographically of a Compact Core area (located in the northern Dutch province of Drenthe) and 45 Remote Stations. Each Remote Station will be equipped with 100 High Band antennas, 100 Low Band antennas, 13 three-axis vibration sensors (geophones), one to three microbarometers (for infrasound detection) and several auxiliary systems e.g. for weather monitoring and

GPS time/position measurements. In the Core area, with 2Km diameter, there will be 32 substations. For the astronomy application, there will be a total of 3200 High Band and 3200 Low Band antennas in the Core area. The number and configuration of geophones and microbarometers in the Core area is yet to be defined. The maximum baseline between stations in the Phase 1 Configuration is roughly 100km. Data transport requirements are in the range of many Tera-bits/sec and the processing power needed is tens of Tera-FLOPS.

For the astronomy application, the Low Band antenna will be optimised for the 30-80 MHz range. The High Band antenna will be optimised for the 120-240 MHz range. The FM band is suppressed in the antenna LNAs and in the receiver for both antennas to minimize intermodulation products from FM transmitters.

Remote stations will be connected by 10 GbE technology to the Central Processing systems. The sensor data will be dominated by the astronomical antennas (2 Gb/s, being the equivalent of a single dual-polarized beam over 32MHz, so 1x32MHz or 8x4MHz etc). The input section of the Central Processor is dimensioned such that 64 Core sub-stations and 50 Remote Stations can be accommodated simultaneously. The processing capacity is matched to the proposed scenario for EoR observations. For the astronomy application, Full Tied Array beamforming will be supported. Transient detection will be supported (probably using large collections of low-bandwidth beams). Buffering of the full sampled bandwidth and limited triggering (primarily UHECR detection) will be available at station level.

LOFAR is designed to see objects so far away that their radio signals were emitted just after the Big Bang. One expects in fact to be able to detect the very first objects. LOFAR will also provide unique insights into magnetic storms on the Sun and the solar wind, and how they affect the climate on Earth.

For further information about LOFAR, see http://www.lofar.org.

2.12 Long Wavelength Array (LWA)

The LWA will be a low-frequency radio telescope designed to produce high-sensitivity, high-resolution images in the frequency range of 10-88 MHz. This will be accomplished with large collecting area (approaching 1 square kilometre at its lowest frequencies) spread over an interferometric array with baselines up to at least 400 km, located mainly in the state of New Mexico. Current plans call for the start of operations in 2008. The basic specifications of LWA (as of January 2006) are shown in Table 5.

Table 5. Basic specifications of the LWA

Parameter	Required Specification	Desired Specification
Frequency Range	20 MHz to 80 MHz	10 MHz to 88 MHz
Angular Resolution	θ ≤ [8, 2]″	θ ≤ [7, 1.4]″
Largest Angular Scale at [20, 80] MHz	LAS ≥ [8, 2]°	LAS ≥ [16, 4]°
Baseline Range	100 m to 400 km	50 m to 600 km
Sensitivity at [20, 80] MHz	σ ≤ [1.0, 0.5]	σ ≤ [0.5, 0.1]
Collecting Area (m2)	Ae = 1 x 106	Ae = 4 x 106
Dynamic Range [20, 80] MHz DR ≥ [1x103, 2x103]	DR ≥ [2x103, 8x103]	
Δ vmax (per beam)	Δ v ≥ 4 MHz	Δ v ≥ 8 MHz
Δ vmin	Δ v ≤ 100 Hz	Δ v ≤ 10 Hz
Temporal Resolution	Δ τ = 10 msec	Δ τ ≤ 0.1 msec
Polarization	1 circular	full
Sky Coverage	z ≥ 40°	z ≥ 15°
Field of View at [20, 80]	= [8, 2]°	≥ [16, 4]°

Parameter	Required Specification	Desired Specification
MHz		
# of Beams	= 4 single pol.	≥ 4 single pol.
Configuration	2D array, N = 53 stations	2D array, N ≥ 53
Mechanical Lifetime	≥ 15 years for potentially long lifetime	

Key Science Drivers of the LWA are:

- Acceleration of Relativistic Particles in:
- Cosmic Evolution & the High redshift Universe
- Plasma Astrophysics & Space Science
- Transient Universe

For further information about the LWA, see http://lwa.unm.edu.

2.12.1 Long Wavelength Demonstrator Array (LWDA)

The LWDA is a test bed for the development of the LWA - it is located on the VLA site. In particular, the LWDA provides a useful testbed for software development, including monitor and control and software correlation.

During May 2007, an LWA team set up an outlier antenna to work with the LWDA as an interferometer. The outlier is the second of the Big Blade antennas currently at the LWDA site (aka BB2) and is located approximately 300 metres east of the 16 element LWDA. The LWDA and outlier are remotely configurable between various modes, including with multiple beams, and a number of innovative science programs are being considered to take advantage of these capabilities. For example, a transient monitoring program, taking advantage of its all-sky field of view, is being undertaken.

2.13 Square Kilometre Array Design Studies (SKADS)

SKADS is an international effort to investigate and develop technologies for the SKA. It focuses on the development of the Aperture Plane Phased Array (see Figure 1) which uses fast digital technology to make a flexible, multitasking telescope that can do many different astronomical observations all at the same time.

Figure 1. SKADS Array

SKADS is partly funded by the European Community Sixth Framework Programme, and includes partners from 29 institutes in 12 countries. For further information about SKADS, see http://www.skads-eu.org.

2.13.1 SKADS Benchmark Scenario

The SKADS Benchmark Scenario is a special case of the SKA Reference Design for which the low and mid frequencies are covered by a technology based on aperture plane phased arrays. The development of densely packed aperture-plane phased-arrays for the mid frequencies is the main technological thrust of SKADS. The project aims to provide a cost-effective technology which satisfies all the SKA science requirements.

2.13.2 Electronic Multi-Beam Radio Astronomy (EMBRACE)

EMBRACE is based on the Aperture Array concept targeting the science goals associated with observations to be conducted at low frequencies 0.1 – 2.0 GHz. The main objectives of EMBRACE are to demonstrate the technical and scientific potential of the Aperture Array concept using a low cost phased array station with the essential SKA functionality in combination with the Westerbork Synthesis array.

EMBRACE will comprise a network of aperture arrays including a ~625m^2 "core" located close to the existing Westerbork Synthesis Radio Telescope (WSRT), which consists of 14 x 25 m diameter dishes. In addition, a smaller demonstrator (~100m^2) will be built in Nançay, France.

The EMBRACE “core” will contain 625 tiles, ~10% of an individual SKA “station”. The core location will facilitate testing the stand-alone total power beams of EMBRACE in comparison to a “standard” 25m dish and also to test the complex voltage beams when EMBRACE is incorporated in a well-calibrated short-baseline (~3Km) interferometer. Operating EMBRACE in conjunction with the WSRT will enable a range of important astronomical tests to be performed.

The entire demonstrator will be made up of small tiles of approximately 1m x 1m. The EMBRACE demonstrator system will be on a scale several hundred times larger than The THousand Element Array (THEA), an array designed, built and successfully proven by ASTRON to demonstrate fundamental aspects of the aperture array concept.

EMBRACE will have no moving parts; the planar array will be steered electronically to allow multiple independent Fields of Views (FoV), i.e. it can point in different directions simultaneously. Such a flexible system offers the prospect of supporting many users to carry out separate astronomical programmes at the same time. This technology allows us to null out interfering signals. EMBRACE specifications are shown in Table 6.

Table 6. EMBRACE specifications

Parameter	Specification
Frequency:	400MHz –1550MHz
Polarisation:	Single Linear
Scan Volume:	Full hemispherical
No of indep. FOV:	2
T_{sys}:	<100 deg K@ 1GHz (aim for 50deg K)
Ant. element phase control:	3 or 4 bit
Instant. Bandwidth:	40MHz
No of digital beams:	8 of 20 MHz per FOV
Configuration	2D array, N = 53 stations
Mechanical Lifetime	≥ 15 years for potentially long lifetime

All tiles will be completed by the end of 2009, in time for inclusion as an SKA concept option.

2.13.3 2-PAD

2-PAD will be a dual polarisation, all-digital phased aperture array demonstration environment. It will consist of a digitisation and processing system located in a EMC shielded 'bunker', connected via copper analogue links to a number of alternative, trial antenna arrays both close packed and sparsed. The system will be relatively small with a collecting area of a few square metres. Objectives of this work package are to:

- Demonstrate an all-digital, dual polarization aperture array;
- Estimate the cost of an all-digital system implementation for the SKA;
- Demonstrate effective RFI mitigation techniques for an all-digital AA;
- Show the ability to accurately calibrate an aperture array;
- Estimate mean time between failures (MTBF) of an all-digital AA;
- Estimate power requirements for an SKA implementation;
- Produce test environments for both the all-digital demonstrator and a stand-alone beamformer, and
- Report on environmental and thermal management methodology.

The antenna testing, including beam forming, beam steering, polarization etc., requires an array which is in a typical electromagnetic environment for an SKA scale array, to constrain costs dummy elements will surround the demonstration array. Without the dummy modules, the electromagnetic environment of the active tile would be dominated by edge-effects not present in the full SKA. The design of the system will enable testing of newly developed devices as they become available e.g. improved LNAs and antenna elements.

Following assembly and integration of the all-digital system, it will be evaluated against simulations using functional testing of the system. The performance of the tiles will be assessed with both laboratory based and astronomical tests. Importantly, the laboratory tests comprise full RF testing in a large calibrated anechoic chamber allowing fundamental data to be known to high precision. This includes for co-polarisation and cross-polarisation measurements. 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.

Cost reduction studies will be on-going during design and development phases and forms an important element of the 2-PAD work packages.

2.14 US Technology Development Project (TDP)

In June 2007, the US SKA Consortium (17 institutions) was informed that it would be awarded $12M by the National Science Foundation for a "Technology Development Project for the Large-N/small-d Square Kilometre Array Concept". Funding will commence in November 2007. The TDP proposal was submitted by Cornell University on behalf of the US SKA Consortium, and includes work done across the US and international collaborators. The TDP takes specific note of the European FP7 preparatory phase proposal, and states that the US TDP is the "mechanism for US participation in the international design effort". The funding is for four years for end-to-end development, costing and preliminary design. It will be managed at Cornell University.

The primary work package in the TDP is "Antennas, Feeds and Receivers," which includes a study of antenna manufacturing methods, development of wideband feeds (WBFs) and receivers, studies of cryogenics, identification of optimal optical designs for the antenna for a range of feed types, including the WBFs developed under the TDP along with PAFs developed elsewhere around the world. Antenna diameters in the 6 to 15m range will be considered. One of the hardware deliverables is a fully outfitted, optimized SKA antenna.

A secondary work package is "Calibration and Processing," that includes consideration of algorithms for dealing with the full range of imaging, spectroscopic and time-domain science applications.

Included in the study is an analysis of the cost/performance as a function of operating frequency to help define the technical constraints on the upper limit of the mid-frequency range of the SKA. The scope of the proposal is to span the current SKA Reference Design up to an engineering design for construction of Phase I of the SKA in 2012.

The TDP's goals are the same as PrepSKA's and the two projects can be viewed as one. The TDP includes explicit interactions with the Australian, Canadian, and South African SKA efforts, particularly in the Antennas, Feeds and Receivers work package.