The SKADS consortium:

ASTRON (NL), The University of Manchester (UK), The Joint Institute for VLBI in Europe (NL),
L’Observatoire de Paris (FR), Istituto di Radioastronomia (IT), Fundación General de la Universidad de Alcalá (ES),
Max-Planck-Institute für Radioastronomie (DE), University of Oxford (UK), CSIRO (AU), Pushchino RAO (RU),
National Research Council (CA), National Research Foundation (SA), Torun Centre for Astronomy (PL),
Chalmers University (SE), University of Cambridge (UK), RUG Astronomical Institute (NL), University Leiden (NL),
Cardiff University (UK), University of Glasgow (UK), Swinburne University of Technology (AU),
University of Adelaide (AU), University of Sydney (AU), Université d’Orléans (FR),
Centre National de la Recherche Scientifique (FR), University of Leeds (UK), Universitat de València (ES),
OMMIC (FR), Instituto Superior Técnico-CENTRA (PT).

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Radio astronomy enters a new era
Over the years, radio astronomy has provided many fundamental break-throughs. The discovery of the Cosmic Microwave Background radiation proved to be the most dramatic confirmation of the Big Bang theory of the creation and evolution of the Universe. The discovery of fast rotating neutron stars, called pulsars, permitted tests of Einstein’s theory of General Relativity and confirmed the existence of gravitational waves. The high precision mapping of the Cosmic Microwave Background revealed the seeds of the first objects formed in the Universe. These discoveries have merited four Nobel prizes, all awarded to radio astronomers.

Innovations in technology have been the key to the success of radio astronomy. By pushing back the observational frontiers with state-of-the-art technology, new discoveries have always been the result. Now scientists and engineers around the world are working on the next leap in radio astronomy capability: The Square Kilometre Array.

The SKA will be a distributed interferometer array of over 100 “stations”, each with a total collecting area of~10000 m² (the size of two football pitches), and the whole system will be spread out over thousands of kilometres. It will cover radio frequencies from less than 0.1 GHz to 25 GHz corresponding to wavelengths of larger than 3 metres to 1.5 cm. The SKA will map the sky with a sensitivity up to a hundred times better than with existing radio telescopes, and this exquisite sensitivity will be combined with both high resolution and a large field-of-view, the ability to see a large amount of sky at a time. The result is an instrument with the capability to survey the entire sky visible from a single location of the Earth, in a very short time. The power of the SKA will inevitably lead to a transformation in our knowledge of the overall structure and evolution of the Universe. From the formation of the very first galaxies it will help to unravel the secret of the mysterious Dark Energy which pervades the cosmos. The SKA will provide the ultimate test of one of
1. The exponential growth of sensitivity of major radio astronomical telescopes over time and the projected sensitivity of the SKA.

2. This schematic representation of a SKA station shows the three antenna technologies to be used to cover the proposed frequency range. In the SKADS approach simple dipoles are used for the lowest frequencies; close-packed aperture-array tiles cover for the mid-frequency band and small parabolic dishes operate at the high frequencies.

3. Artist’s impression of the concentrated core SKA station with dishes and a central area covered by tiles making up the aperture-plane phased-array.

the fundamental theories of physics, General Relativity. It will also explore the conditions for the birth of galaxies, planets and life, and perhaps it may detect signals from other intelligent civilizations. And, as has been the case with previous dramatic technological advances in astronomy, the SKA will certainly produce many new and unexpected discoveries, adding to the long list of fundamental advances already made by radio astronomers.

Such a giant leap of observational capability demands radically new ideas in technology which will provide the required performance without a correspondingly high price-tag. Innovative ideas for collector systems, coupled with the exploitation of commercial developments in the areas of signal processing and data transport are necessary. Based on pioneering work carried out in Europe, a new concept for the SKA’s long wavelength receptors is being developed. This exploits the capabilities of “aperture-arrays” in which a large collector is composed of many small, low-cost, individual antenna elements. The signals from all the elements are added together electronically in phase to synthesise reception beams, and the result is a fast, extremely flexible system. In this realisation the SKA will essentially be a giant supercomputer.
The SKA Design Studies

The SKA Design Studies (SKADS) is an EC-funded project involving 26 participants from nine EU nations, South Africa, Canada and Australia, led by the Netherlands, the UK and France. The SKADS consortium is carrying out a detailed investigation of the scientific and cost-effectiveness of the new SKA concept, and is developing the necessary breakthrough technologies which will enable the radio telescope to be built at an affordable cost. The exciting potential of the SKA has attracted research institutes from several non-EU countries to join the consortium. The study is taking four years from July 1, 2005 when the European Commission committed 10.4 million Euro. Together with matching funds from national funding agencies, the total sum of 38 million Euro is dedicated to the study. The Project Office, based at ASTRON Dwingeloo, is responsible for the coordination of SKADS.

SKADS focuses on the frequency range 100MHz to 1500MHz, which is the low and mid-range for SKA. A key element of this part of the design is the use of phased arrays in which many small antennas act together to collect the incoming radiowaves. The signals from the individual antennas are electronically delayed and combined such that the telescope can point in a given direction without making any mechanical adjustments. By multiplying the signals and combining them in different ways, the telescope can observe in multiple directions simultaneously. This will give the telescope an unprecedented ability to observe a large part of the sky at once and allow more than one group of astronomers to use the telescope for independent measurements.
The SKADS science team under the leadership of the Rijks Universiteit Groningen, Oxford University and the Joint Institute for VLBI in Europe, is performing an in-depth study of the scientific potential of the telescope, while keeping a close-eye on its technical capabilities. Astronomers have ideas for the new science that SKA will open up for them, and these ideas are rigorously tested in the computer with the help of detailed, quantitative simulations. The first goal of this work is to make a computer model of the radio sky, without any artefacts or distortions from either the telescope itself or from man-made interference or from the Earth’s atmosphere. Astrophysicists simulate fundamental mechanisms involved in the formation of stars and galaxies, and the distribution of those celestial objects throughout the Universe. The computer then applies our knowledge of basic physics in order to determine how these objects radiate, and where they would appear in our maps of the sky. This leads to a virtual Universe populated by all kinds of astronomical objects, all behaving according to the hard rules of physics.

The SKA will be able to observe phenomena that have never been seen before, and which are impossible to observe with optical telescopes. One major goal is to monitor a pulsar going around a black hole which would be a probe of the strange gravitational effects predicted by Einstein’s General Relativity, such as the dilation of time, and the dragging of space-time itself around a rotating black hole. Astronomers also expect to observe the earliest objects ever formed in the Universe, born in the first few hundred million years after the Big Bang.

With its ability to probe an enormous volume of space in a short time, the SKA will make a 3-dimensional map of the distribution of galaxies. This catalogue of around a billion galaxies will provide unique information about the mysterious hidden components of the Universe, Dark Energy and Dark Matter, which together account for 96% of all matter and energy in the Universe. It will also shed light on the nature of the elusive neutrinos. Neutrinos are extremely light-weight and hardly interact with other forms of matter. But they are very numerous, and as they stream away from regions where galaxies are formed, they influence the scale on which the clustering of galaxies takes place.

By studying the distribution of galaxies in the Universe, we can derive information about the neutrino mass, as well as the nature of Dark Matter and Dark Energy.
The next stage of modeling is to feed the sky simulations into models of the telescope itself. In this way, we determine whether the design of the SKA is good enough, or whether some capabilities have to be improved. Using a telescope simulation software package called MeqTrees written at ASTRON, the astronomical signal is followed from the source in the sky through the entire chain of components in the SKA system until finally it appears as a spectrum, or map, or catalog. This includes the distortions suffered by the signal as it passes through the atmosphere, and the distortions from unwanted sources of noise as the signal makes its way through the telescope, receiver, amplifiers, and various electronics. This modeling is carried out for all the antenna elements in the SKA, which when added together in a process called aperture synthesis, creates the final result – a map of part of the sky. Ultimately, the simulated experiment will look like the output from the real SKA.

Costing the SKA

The SKA has to be affordable. Not only must its cost per square metre of collecting area be 5-10 times less than current radio arrays, but also more than one collector technology will be required to cover the range of frequencies from 0.1 to 25 GHz. For the higher frequencies, it is most suitable to use small, low-cost, parabolic dishes of order ten metres. Each dish is equipped with a single, wide-band “feed”, and there will be around 10000 such dishes in the SKA. All the many antennas in the SKA produce signals that must be sent to a central processing station to produce the final image of the sky. As a result, there is an enormous amount of data which must be transferred along optical fibres, some from as far away as 3000 kilometres. The rate at which data can be transmitted becomes a crucial parameter in the design of the SKA.
Data speeds as high as several terabits per second will be required, and the central processing station will have to achieve a performance of hundreds of petaflops ($>10^{17}$ operations per second) – a next generation supercomputer. The network configuration and processing technologies to achieve this performance represent another major design effort in SKADS. The overall cost of the SKA is a subject of intense scrutiny. The SKADS costing team, led by the University of Cambridge, is using input from real experience in particular from the LOFAR project, which is the Low Frequency Array currently being built in the Netherlands by a consortium led by ASTRON, and the e-MERLIN UK National Facility led by the University of Manchester, which have accurate cost figures. The SKADS cost model accurately shows which are the major expenses. For example relatively low-tech items such as cabling and infrastructure represent half of all costs, whereas the antenna elements are only one quarter. The SKADS cost model is under continued development in close partnership with the International SKA Project Office. The final cost model will be capable of modeling different SKA configurations, and determining their costs. In this way, the SKADS sky, telescope, and cost simulations all work together to design the SKA at an affordable price with required performance.

6. The figure shows a simulation of the ionisation of neutral hydrogen gas by the first luminous objects at different epochs in the history of the early Universe. Credit: The SKADS DS2-team.

7. Schematic depiction of the close-packed aperture array of antenna tiles for the SKA, standing on a platform above a radio-shielded bunker. The bunker houses the station data processing computers.

8. Schematic overview of an SKA station showing the path for data processing.
The Demonstrators: EMBRACE, 2-PAD and BEST

SKADS aims to prove the technical feasibility of the phased aperture array concept by building and testing prototypes. Three demonstrators are under construction: BEST, EMBRACE, and 2-PAD. The Basic Element for SKA Training (BEST) focuses on testing sub-systems and algorithms. The validity of some concepts that are at the heart of the SKA philosophy are being verified using a part of the large Northern Cross Radio telescope in Medicina, Italy. The effectiveness of electronic multi-beaming must be tested rigorously, and this involves electronically creating multiple pixels within the field-of-view of a single parabolic reflector. “Adaptive beam forming” will also be studied, which involves combining signals from separate receivers with the proper weighting in order to create a beam of a chosen shape in a given pointing direction. Finally, the BEST team is developing and testing algorithms for mitigating and possibly eliminating the effects of man-made radio frequency interference.

The Electronic Multi-Beam Radio Astronomy Concept (EMBRACE) is the world-first large-scale demonstrator for the aperture-plane phased-array concept. After reception of the signals from the sky by the low-cost Vivaldi antenna elements, analog beamforming is done using highly integrated phase shifter techniques. The integrated antenna elements are uniquely arranged, working together as “dense array” to achieve wideband reception required for the SKA. After that, digital processing techniques take over. The EMBRACE project, led by ASTRON, will consist of two systems: one at Westerbork in the Netherlands, with a collecting area of 300 m$^2$ and one in Nançay, France with a collecting area of 100 m$^2$. Each will cover a frequency range from 500-1500 MHz and provide multiple beams within ±45° of the zenith.
The individual receiving structures in each 1m² “tile” are Vivaldi antennas; each tile has 64 such antennas placed in parallel rows, and a dual-polarisation tile is being developed which uses a novel method for mechanically interlocking the individual antenna elements. Their so-called electromagnetic performance has been simulated extensively with antenna-design tools developed through SKADS first phase.

The combination of signals from the 64 antenna elements is carried out in a number of integrated analogue circuits called beam-former chips. This is where the phase shifts are applied in order to create beams in the chosen directions. Different implementations of the beam-former chip are under development at ASTRON and at Nançay.

The SKA will be an instrument composed of tens of thousands of antennas and tiles, each with large numbers of the same components. Mass production is essential for making an affordable SKA. The entire EMBRACE development therefore maintains a focus on cost, as well as on performance. EMBRACE components are designed with emphasis on reproducibility, and the ease of mass production.

The ultimate capability of an aperture-plan phased-array is realised with 2-PAD: for Dual Polarisation All Digital aperture array tile, the principally UK based development led by the University of Manchester, called 2-PAD: for Dual Polarisation All Digital aperture array tile. Technically, this concept exploits digital signal processing technology to the fullest extent. The signal from the sky is sampled immediately after reception at the antenna element, and from then on, only digital electronics are used. This concept promises unprecedented flexibility and performance for a telescope, limited only by the computer power and speed of data transfer. The challenges are to limit the power consumption and to achieve the required data rates at an affordable cost, however, the fully digital solution provides the maximum possibility for simultaneous observing, very wide bandwidths, precise calibration for the best possible beam, tailoring of the field-of-view at different frequencies for specific science, and post-observation analysis of transient signals. A technology demonstration system is being built as part of SKADS at Manchester’s Jodrell Bank Observatory. It will demonstrate solutions to the challenges of an all digital array: processing power, cost and the prevention of interference from the processing system. The 2-PAD technology would be a major step for the SKA, to be a “software telescope”, limited only by computer processing power.
The next phase: PrepSKA

Work has already started on preparing for the post-SKADS era. The PrepSKA project, partly funded under the EC Framework 7 Programme, will begin in 2008. It enables the creation of a core design and integration team located in Manchester which will coordinate world-wide activity in SKA development. This team will provide the input to be used by the international SKA community and the national funding agencies, to make key decisions involving the best design and production solutions and the best site for the SKA. The 2 candidate shortlisted sites (South Africa and Western Australia) are located on the southern hemisphere which has advantages for linking with other large telescopes at similar latitudes.

The EC considers the SKA as one of the major science facilities of the coming years and has listed the project as strategic for the future of European research infrastructure. SKADS provides essential scientific and technological input to the overall SKA development, and plays an important role in maintaining European cohesion around the SKA project.