The AAVP collaborators:

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Radio astronomy for 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, as 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 resulted. 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 250 “stations”, each with a total collecting area of ~2,500 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 <0.1 to 10 GHz corresponding to wavelengths of 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 - helping to unravel the secret of the mysterious Dark Energy which pervades the cosmos - the SKA will provide the ultimate test of one of the fun
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 AAVP station shows the three antenna technologies to be used to cover the proposed frequency range. In the AAVP approach simplest receptors 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. Courtesy SPDO.

3. Artist impression of sparse, dense and reflector receptors. Courtesy SPDO.

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, an advanced concept for SKA’s long wavelength receptors is being developed. This exploits the capabilities of “aperture-arrays” in which a large collector is composed of 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. With this implementation the SKA will essentially be a giant IT facility.
The Aperture Array Verification Program (AAVP) involves 15 participants from nine EU nations, Australia and substantial input from South Africa and the US. On the basis of results from the earlier SKADS R&D programme and drawing on results from current low frequency arrays, in particular LOFAR, the consortium is now engaged in the next development step. This is to verify the scientific feasibility and cost-effectiveness of an SKA Aperture Array system design. This is an important part of the EC-FP7 PrepSKA project led by the SKA Program Development Office (SPDO) and is under the umbrella of the European SKA Consortium (ESKAC).

AAVP is developing and selecting the necessary technologies which will enable construction of the SKA radio telescope beginning around 2015 and which will result in the required performance at an affordable cost. The programme is initially over three years commencing March 2010 and reporting in 2013 in line with the SKA schedule. The AAVP anticipates availability of funds from national funding agencies totalling £18 million. The AAVP Project Office is based at ASTRON in Dwingeloo and is coordinated by Prof. Arnold van Ardenne.

The AAVP focuses on the frequency range 70MHz to 1400MHz, which is the low and mid-frequency range for SKA. Key to this part of the design is the use of phased arrays in which signals from many small individual antennas are electronically delayed and combined such that the telescope can point in a given direction without making any mechanical adjustments. By normalising the signals and delaying 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 even allow more than one set of astronomers to use the telescope for independent measurements.
Universe in a box

The SKADS science team, under the leadership of the Rijks Universiteit Groningen, Oxford University and the Joint Institute for VLBI in Europe, have already performed 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 step of this work was 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 dilatation 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 lightweight and barely 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 atmosphere and 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 catalogue. 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 modelling 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 the sky. Ultimately, the simulated experiment will look like the output from the real SKA.

**Costing the SKA**
The SKA has to be affordable. This means that its cost per square metre of collecting area must be 5-10 times less than current radio arrays. Moreover, more than one collector technology will be required to cover the range of frequencies from <0.1 to 10 GHz. For the higher frequencies, it is most suitable to use small, low-cost, parabolic dishes of diameter around eight metres. Each dish is equipped with a single, wide-band “feed”, and there will be around 2,500 such dishes in the SKA. At the lower frequencies, various implementations of aperture array technology will be used, with either densely packed antenna elements or sparsely separated antenna elements.

All the many antennas in the SKA produce signals that must be sent along 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 many terabits per second will be required, and the central processing station will have to achieve a performance of hundreds of petaflops (>1017 operations per second) - a next generation super-computer. The network configuration and processing technologies to achieve this performance represent another major design effort in PrepSKA

The overall cost of the SKA is a subject of intense scrutiny. The SKA costing team led by the University of Cambridge, is using input from real experience from projects which have accurate cost figures. In particular,
input comes from LOFAR (Low Frequency Array currently under construction in Europe by a consortium led by ASTRON) and from e-MERLIN (a UK National Facility led by the University of Manchester). This cost model accurately predicts what will be 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 cost model is under continued development in close collaboration with the International SKA Project Office. The final cost model will be capable of modelling many different SKA configurations, and of determining their costs. In this way, the sky, telescope, and cost simulations all work together to design the SKA at an affordable price with the required performance.

The Aperture Array Verification System (AAVS)

AAVS aims to prove the technical and scientific performance of the phased aperture array concept through two key elements; a low frequency system called AAVS-low, ranging from 70 - 450MHz and a high frequency system called AAVS-hi ranging from 400-1400MHz. The AAVS-lo focuses on the 70-450MHz frequency range drawing extensively on experience from low frequency arrays around the world and in particular from LOFAR now in its final construction stage. It is constructed as a so-called sparse array where the element separation is more than half a wavelength at the lowest frequency. The performance and cost effectiveness of a single very wide bandwidth element will be tested while coupled with much more advanced processing technology to drive down the cost and power required for the low frequency array. An option of using a pair of antenna elements to cover the frequency range is also being investigated.

The AAVS-hi is constructed as a dense-array whose wideband performance is essentially independent of frequency. The concept was extensively studied in SKADS and resulted in two test systems: 2-PAD in the UK, and the Electronic Multi-Beam Radio Astronomy Concept (EMBRACE) which is presently the largest-scale demonstrator of high frequency aperture-plane phased-arrays. EMBRACE consists of two systems: one at Westerbork in

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 Four slightly tilted “tiles” in a substation. Passive cooling by ground connection through poles is being investigated.

8. Schematic overview of an SKA station showing the path for data processing.
the Netherlands, with a collecting area of 160 m² and one in Nançay, France with a collecting area of 90 m², each covering a frequency range from 900-1500 MHz and providing multiple beams on the sky. Lessons learned from these prototypes will be applied to AAVS-hi, but AAVS-hi will be much larger as it needs to prove astronomical imaging capability over a wide frequency range with dual polarization and over wide scan angles. AAVS-hi will be composed of tens of thousands of antennas, each with its associated electronics resulting in large numbers of the identical electronic components. The system will be distributed as ~14 stations, each of about 150m² collecting area. Mass production is thus essential for making an affordable SKA and the entire development therefore maintains a focus on cost, as well as on performance, with components designed emphasising reproducibility, and mass producibility.

The ultimate capability of an aperture-plane phase-array is realised by an entirely digital aperture array system. The signal from the sky is digitised immediately after reception at the antenna element, and from then on, only digital electronics are used. This implementation promises unprecedented flexibility and performance for a telescope, limited only by the available computing resources and speed of data transfer. The challenges are to limit the power consumption and to achieve the required data rates at an affordable cost. A fully digital solution can optimise 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.
Siting AAVS
The SKA siting decision is planned to take place during the AAVS development phase and the AAVS location ideally would be on the chosen site for SKA. Prior to that choice, AAVS will perform system testing at a remote, low RFI test site in Portugal. Already now, some EMBRACE tiles have been shipped for early testing and because of the excellent RFI conditions can now operate over their full design bandwidth from 500-1500MHz. The SKA could be the first green mega-science project. For development purposes, the AAVP can offer early engagement with industry at the Portuguese site, which has Europe’s highest solar intensity, to test sustainable energy systems.

9. Assembling EMBRACE tiles in its radome.
10. A “sea” of EMBRACE receiving tiles showing the mutually connected Vivaldi type antennas in the groundplane.
12. A next step toward cheap manufacturing techniques for AAVS.
13. The Portuguese Presidency showing interest for the EMBRACE tiles near the testsite in Moura as explained by Domingos Barbosa from PRAC. © 2006-2010 Presidência da República Portuguesa.
14. LOFAR nearing completion as it develops today in Europe. LOFAR offers a wealth of experiences for AAVP together with input from other low frequency arrays like MWA in Australia.

15. Visiting the 60MW solar power station near Moura in Portugal. Sustainable energies such as these are essential for the SKA.

16. The photographs show the desert like conditions at both sites ensuring a low level of terrestrial radio interference combined with a favourable ionosphere, resulting in excellent potential observing sites for the SKA.

The lowest picture shows the Portuguese testsite near Moura.

**The next phase: SKA Phase 1 and beyond**

Work has already started on preparing for the era after the initial AAVP. The present PrepSKA project, funded by the EC Framework 7 Programme, enables the creation of a core design and integration team currently located in Manchester, which coordinates world-wide activity in SKA development. PrepSKA provides the inputs which are used by the international SKA community and the national funding agencies, to make key decisions on the best design and production solutions and for the best site for the SKA.

The planning for the SKA project after PrepSKA will lead to SKA construction. This planning is going ahead and is expected to be implemented after 2011-2012. The concept design for the first phase of SKA construction has been approved. It requires the use of Aperture Arrays for a large low frequency system and also takes full account of the opportunities of the complete AA system developments within the AAVP. As SKA planning progresses, AAVP not only provides essential scientific and technological input to the International SKA design and development work, capitalizing on previous developments, but AAVP also consolidates the global effort on SKA Aperture Array developments.