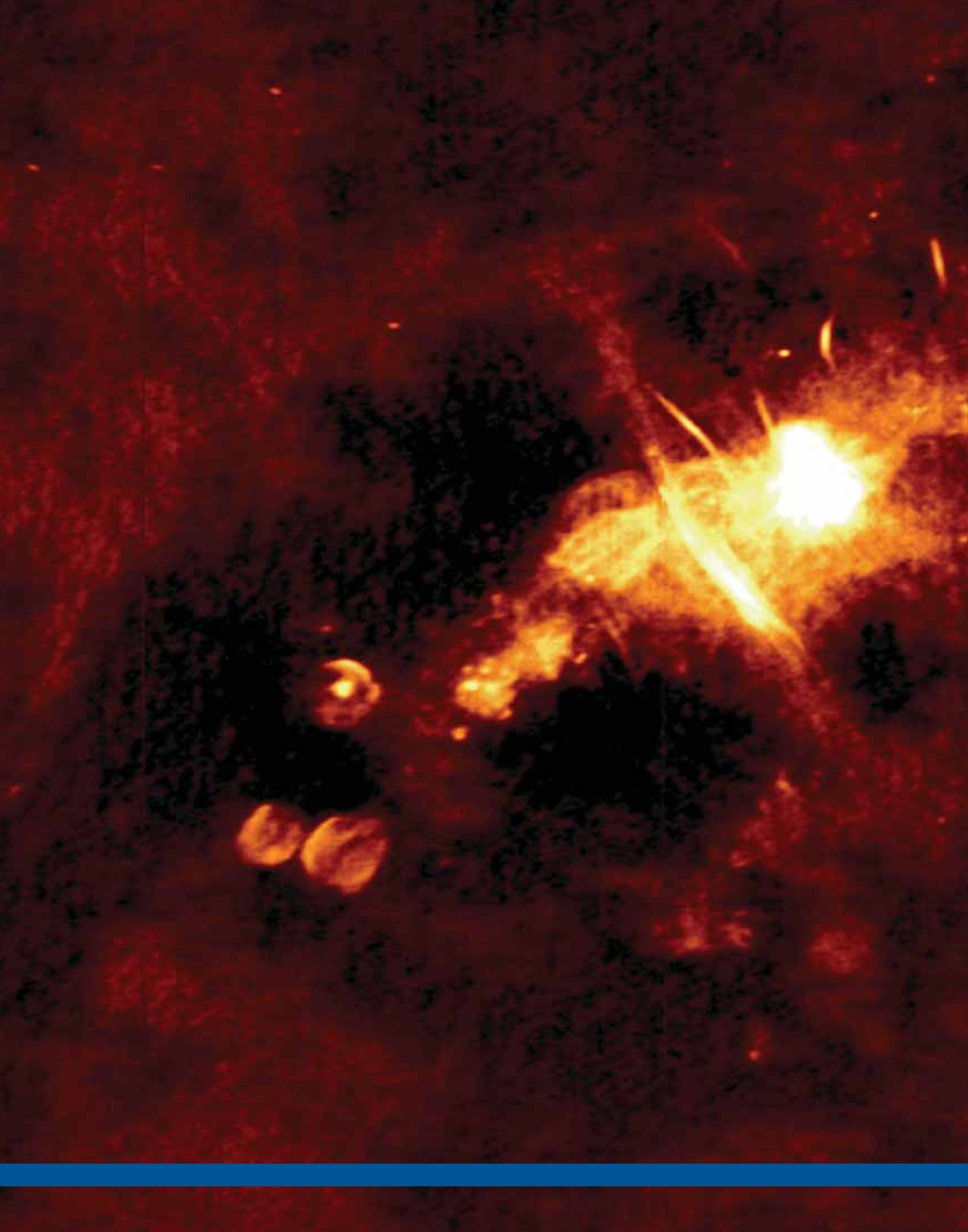
The Square Kilometre Array

The International Radio Telescope for the 21st Century

SKA
SQUARE KILOMETRE ARRAY

www.skatelescope.org



The Square Kilometre Array

The international radio telescope for the 21st century

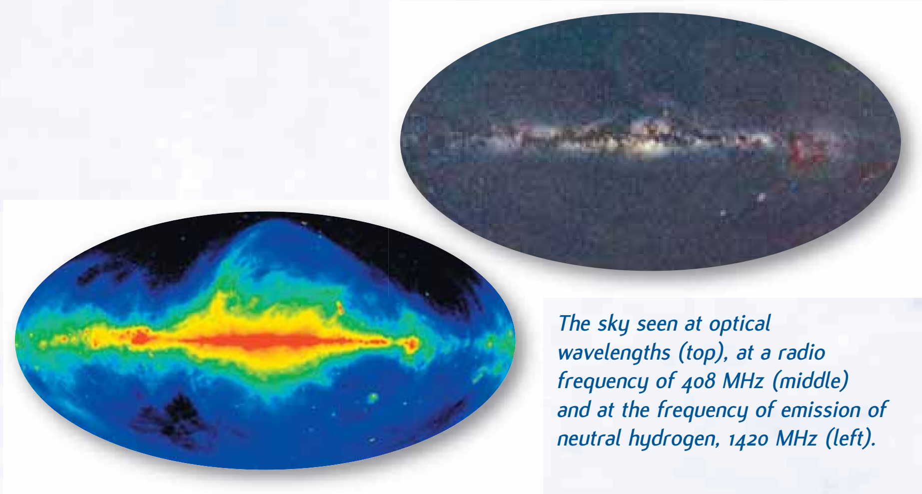
New developments in astronomy, fundamental physics and particle astrophysics have brought scientists to the point of being able to probe the origin and evolution of the Universe as a whole.

To attack these fundamental questions, a new generation of astronomical facilities is needed with a revolutionary new radio telescope, the Square Kilometre Array, playing a critical role.

Recent, innovative technological developments in both computing and radio frequency devices have made it possible and affordable for the SKA to be built before 2020. With a million square metres of radio-wave collecting area, the SKA will be 50 times more sensitive, and be able to survey the sky 10,000 times faster, than any imaging radio telescope array ever built.

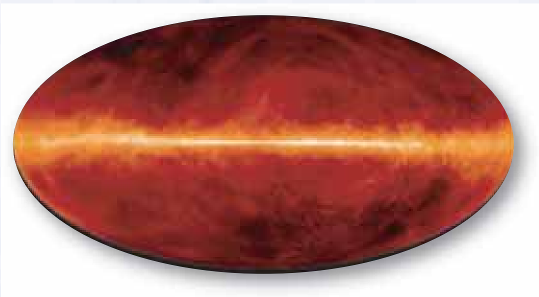
By observing farther back in time, over a large volume of space, with enhanced sensitivity and spatial resolution, the SKA will answer many of the fundamental questions we are asking now, and many more that we do not yet know to ask.

Meeting of the International SKA Steering Committee in South Africa



The sky seen at optical wavelengths (top), at a radio frequency of 408 MHz (middle) and at the frequency of emission of neutral hydrogen, 1420 MHz (left).

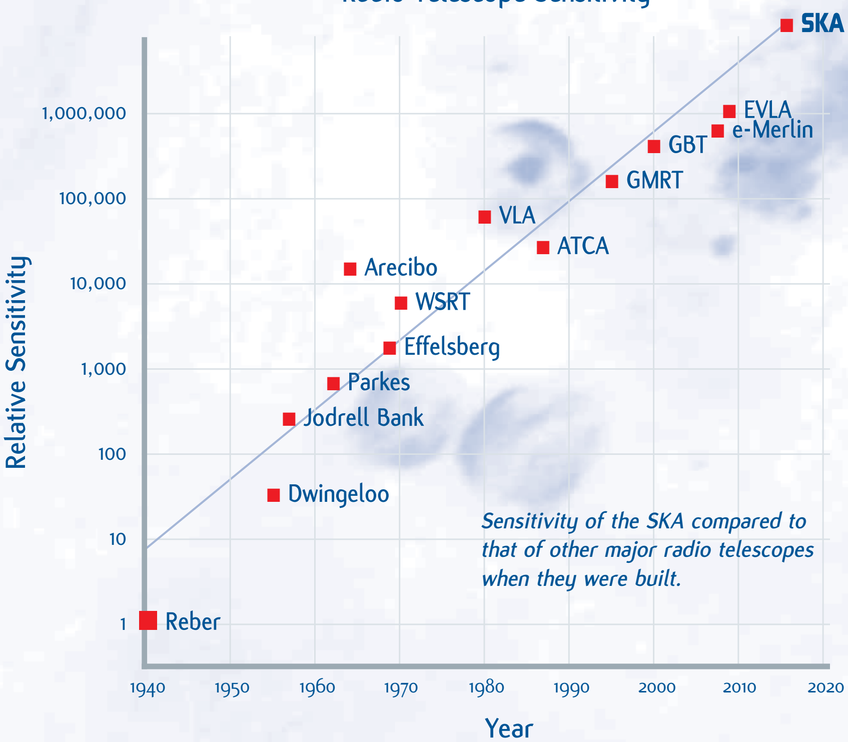
Radio Sky



Using radio telescopes we can study the Universe in unique ways. For example, radio waves penetrate dust, allowing us to look into regions such as centre of our Galaxy, which is completely obscured at optical wavelengths.

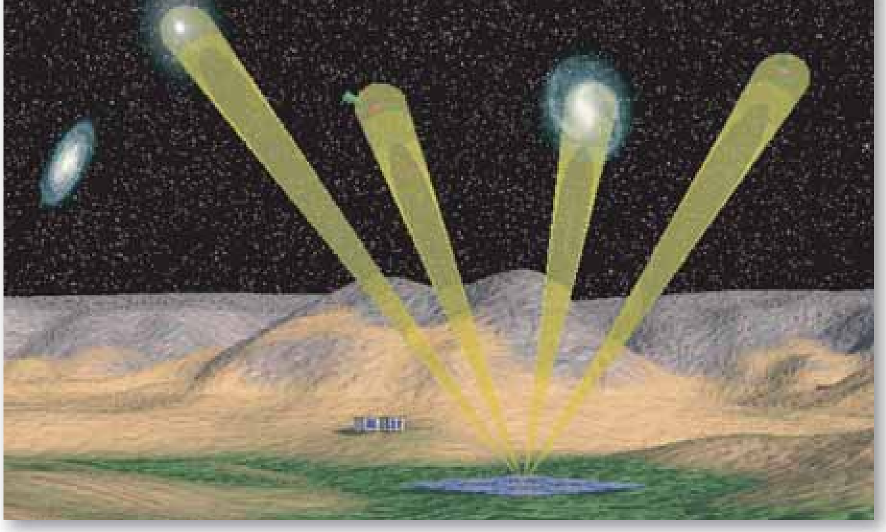
Radio astronomy has produced some of the greatest discoveries of the 20th century, and three Nobel Prizes in Physics. Central to these discoveries have been innovations in technology pushing the observational frontiers of sensitivity as well as spatial, temporal and spectral resolution. One such innovation in technology - radio interferometry - was also awarded a Nobel Prize for Physics. The SKA will carry on this tradition of innovation by combining fundamental developments in radio frequency technology, information technology and high-performance computing.

Radio Telescope Sensitivity



Sensitivity of the SKA compared to that of other major radio telescopes when they were built.

The SKA will be the world's premier imaging and surveying telescope with a combination of unprecedented versatility and sensitivity that will open up new windows of discovery.



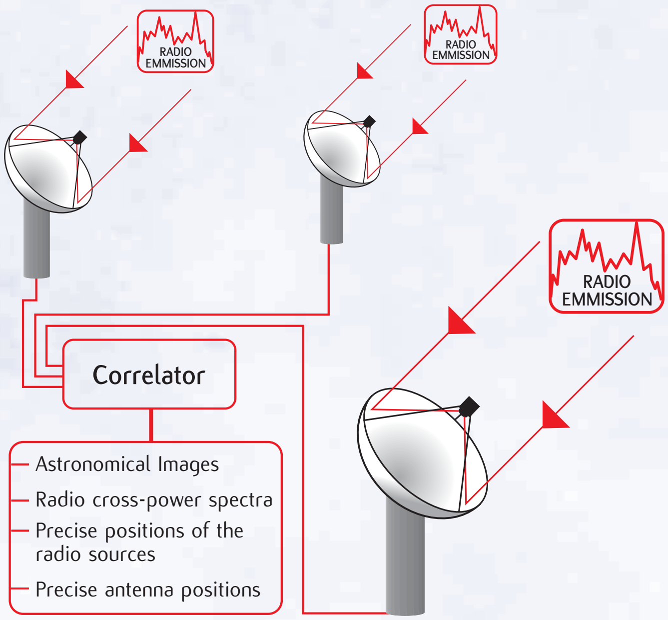
Introduction

The SKA - A revolution in Astronomy

The SKA will be an aperture synthesis instrument. Signals from separated antennas will be combined digitally to simulate a telescope having a diameter equal to the largest antenna separation - more than 3000 km for the SKA. This will give an extremely high angular resolution, so that the SKA will produce the sharpest pictures of the sky of any telescope.

The SKA will also have a very large field-of-view (FOV). The goal is a FOV at frequencies below 1 GHz of 200 square degrees, and a FOV of 1 square degree (about 5 full moons) at higher frequencies. One exciting development being explored is the use of phased-array technology to provide multiple FOVs. This would dramatically increase the survey speed of the SKA or enable multiple users to observe different pieces of the sky simultaneously. The goal of achieving a large sky coverage with multiple FOVs is a major driver of the challenging signal processing and computing specifications for the SKA.

The combination of a very large FOV with enormous sensitivity and diverse operation modes means that the SKA will provide nothing less than a revolution in the way that we explore the Universe.



An aperture synthesis telescope consists of many independent receiving elements whose signals are combined at a central processing site, forming a high-resolution image of the observed object

Management Structure of the SKA collaboration

IN BRIEF

The SKA Project is a collaboration between institutions in 18 countries including Argentina, Australia, Brazil, Canada, China, France, Germany, India, Italy, The Netherlands, New Zealand, Poland, Russia, South Africa, Sweden, United Kingdom and the United States. The collaboration is led by an international steering committee and a jointly funded SKA Project Office. All activities are supported by international working groups studying the many specific issues that are relevant for making the SKA a reality.

The SKA will:

- revolutionise our understanding of the Universe by providing answers to questions about its complexity and the laws of fundamental physics by which it is governed
- be the next-generation radio telescope for the global community
- have up to 1 million square metres of effective collecting area
- be the largest telescope in the world: having 50 times the sensitivity and 10,000 times the survey speed of present imaging instruments
- be completed by 2020 with a life-span of at least 50 years
- be continuously upgradeable as computer power increases
- have half of the collecting area concentrated within a 5 km region, with the remainder extending out to at least 3000 km
- be sited in a radio-quiet location for uninterrupted observations
- use new technology antennas, signal transport, signal processing and computing in a marriage between radio frequency (RF) technology and information and communication technology (ICT)
- have a target budget of 1 billion Euros

TIMELINE

Concept

1994
International Working Group

1995
Start of Prototyping

2000
Signing of first Memorandum of Agreement

2005
Signing of extended Memorundum of Agreement

2006
Site Ranking Decision

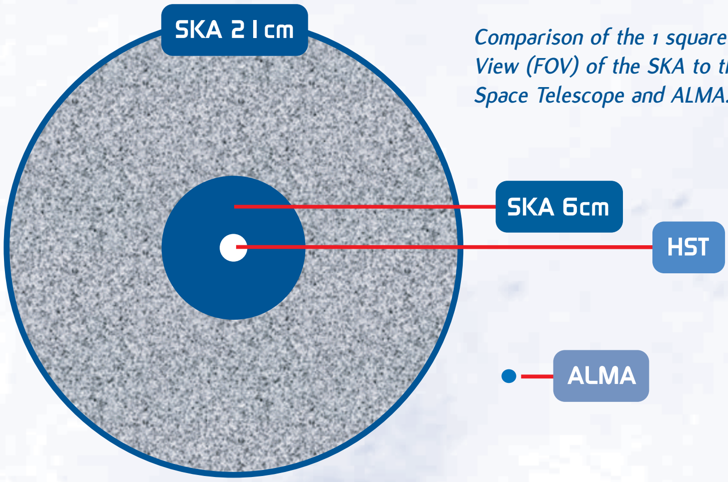
2009
Final Technology Decision

2010
Construction of pathfinder on site

2013
Early Science

2014
Construction of full array

2020
Full SKA operational!

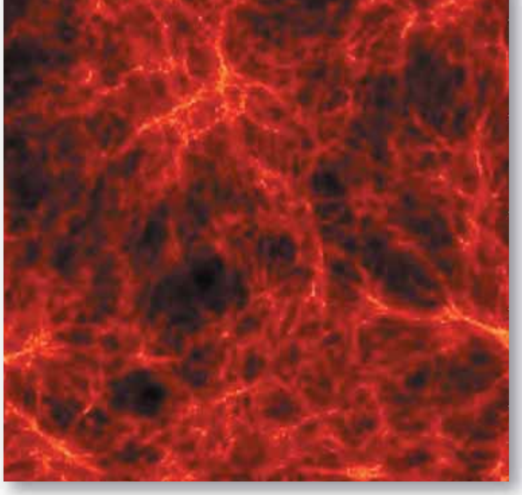


Comparison of the 1 square degree Field-of-View (FOV) of the SKA to that of the Hubble Space Telescope and ALMA.

Specifications

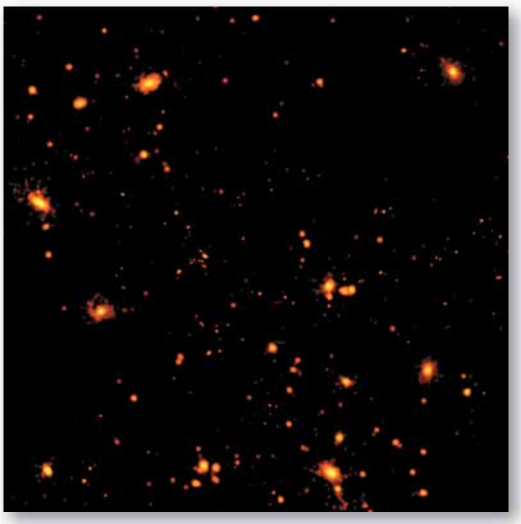
The final design of the SKA will be determined from the outcome of the extensive prototyping that is currently underway. The design goals are listed in the following table.

Parameters	Design Goals
Frequency range	100 MHz to 25 GHz
Sensitivity (area / system temperature)	20,000 m^2/K (or G/T ~ 68 dB/K) between 0.5 and 5 GHz, 10,000 m^2/K up to 25 GHz
Field-of-view	1 square degree at 1.4 GHz and 200 square degree at 0.7 GHz; target is 4 simultaneous FOVs, each with full sensitivity
Angular resolution	<0.1 arcsecond at 1.4 GHz
Instantaneous bandwidth	25% of band centre, max 4 GHz
Spectral (frequency) channels	10,000 per band per baseline
Calibrated polarization purity	10,000:1
Synthesized image dynamic range	>1,000,000:1 at 1.4 GHz
Imaging processor computation rate	10^{15} operations/second
Telescope output data rate	1 TByte per minute (typical)



(Left) Simulated image showing the neutral hydrogen sky as seen by the SKA, revealing the structure of the cosmos. (Below and left) Comparison of current radio observations (top) and a simulation of SKA observations (bottom) showing the greatly increased number of faint galaxies experted in observations of the continuum radio sky.

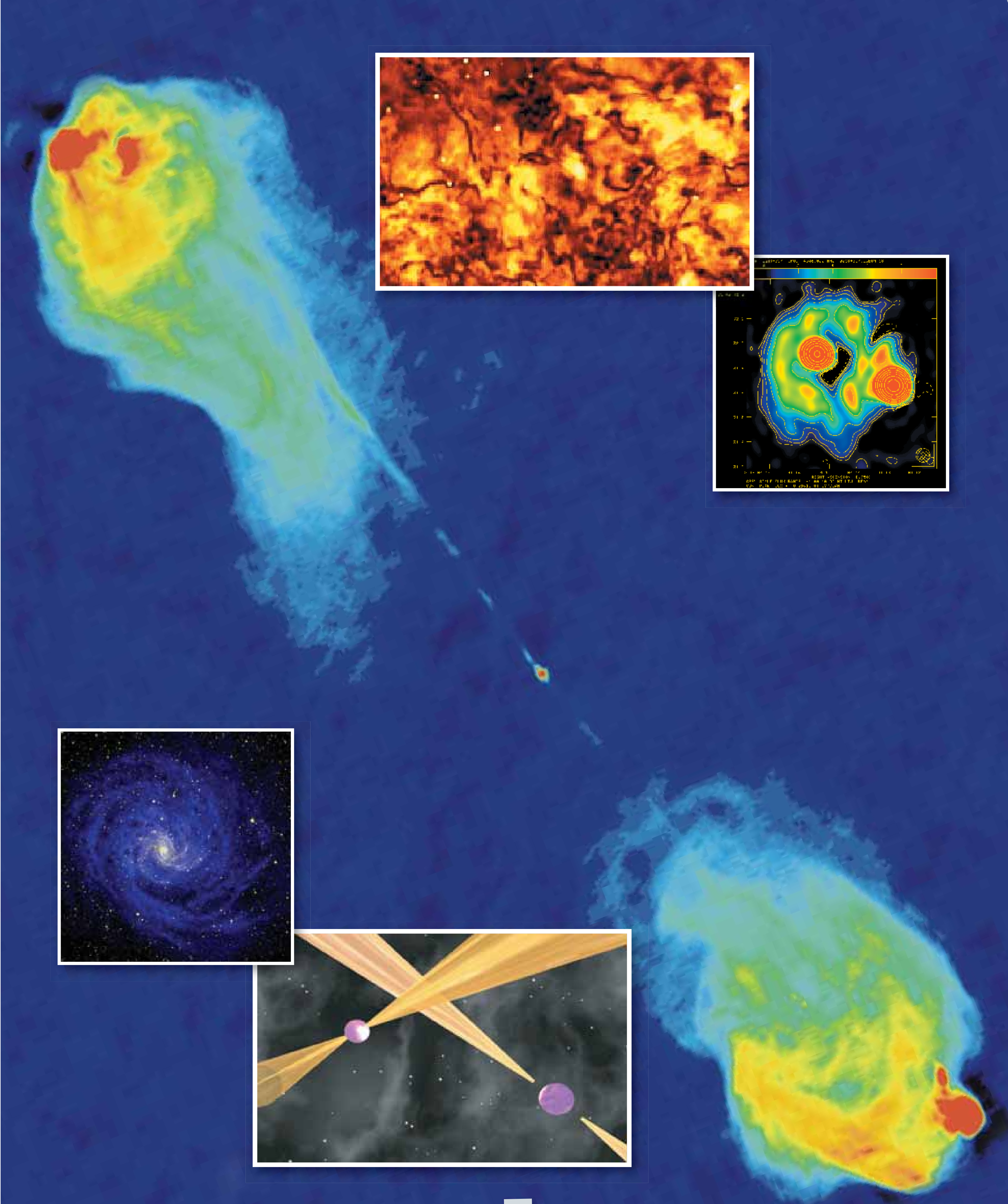
Transformational Science

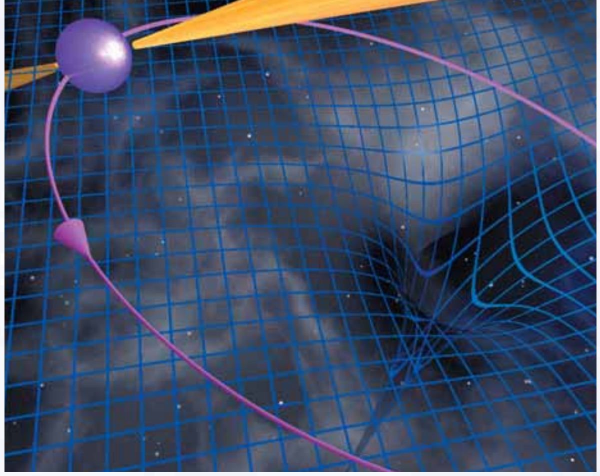


The SKA will be a highly flexible instrument designed to address a wide range of fundamental questions in astrophysics, fundamental physics, cosmology, particle astrophysics and astrobiology. It will be able to probe previously unexplored parts of the Universe. The diverse spectrum of scientific topics that the SKA can tackle is presented comprehensively in the SKA Science Book (published as New Astronomy Reviews, Vol 48, 2004). From this wealth of possible science a number of key science projects addressing physics beyond our current understanding have been selected:

- Extreme tests of general relativity with pulsars and black holes
- Evolution of galaxies, cosmology, dark matter and energy
- Probing the Dark Ages - the first black holes & stars
- The Cradle of Life - searching for life and planets
- The origin & evolution of cosmic magnetism

Our understanding of the Universe and its fundamental physics and complexity will be transformed by the SKA.





A pulsar discovered in orbit around a black hole will provide the most extreme test of Einstein's description of gravity.

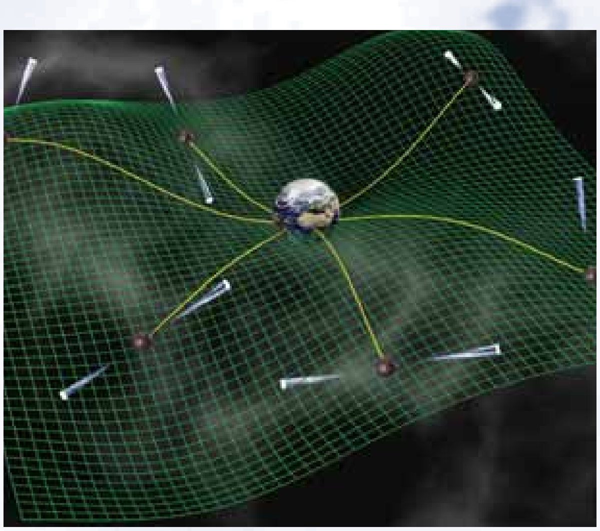
Key Science Projects

Strong-field tests of gravity using pulsars and black holes

Was Einstein right or will general relativity eventually fail?
What are the properties of black holes?
Are there still ripples in space-time from the early Universe?

Einstein's theory of general relativity has passed all tests with flying colours, so far. But, it may still not be the last word in our understanding of nature's most fundamental force - gravity. Scientists around the world are struggling to find a theory of "quantum gravity" which would combine gravitation with the bizarre world of quantum physics.

The SKA will discover tens of thousands of the Universe's best clocks - pulsars - some of which will orbit black holes. These systems can be used to put Einstein's theories to the most extreme test ever, in particular general relativity's description of black holes.



The SKA can also discover space-time ripples left over from the early Universe by detecting the Gravitational Wave Background from cosmic strings or merging supermassive black holes. Using pulsars, the SKA will act as a huge gravitational wave detector, and will be sensitive to nano-Hz frequencies which are not accessible by current or future gravitational wave detectors.

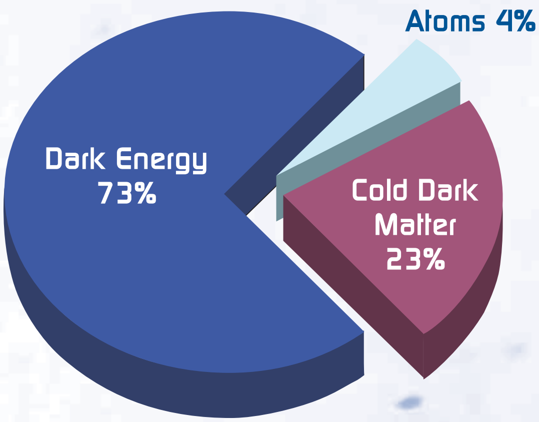


Illustration of the recent finding that the majority of the Universe is filled with some unknown "dark energy" and the yet to be identified cold dark matter. There may also be a significant fraction of hot dark matter. Only a small fraction of the Universe is made up of the normal matter that consists of atoms.

Galaxy evolution, cosmology and dark energy

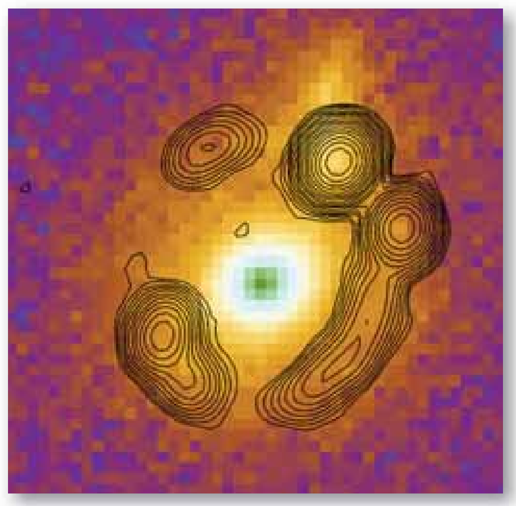
What is the mysterious dark energy?
How are galaxies born and how do they evolve?

The evolution of the Universe and the formation of large scale structure appears to be governed by the strange action of a "dark energy". Apart from the observed fact that dark energy has caused a recent acceleration in the expansion of the Universe, its properties are virtually unknown.

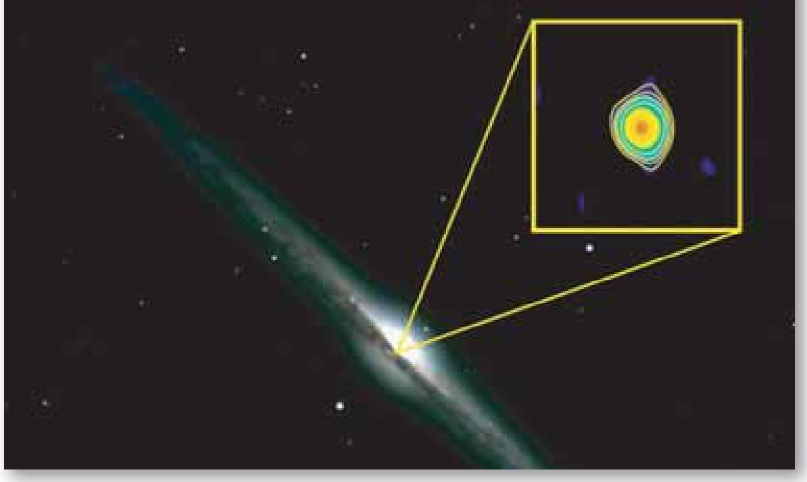
The structure of the Universe can be determined by observing the cosmic distribution of nature's most fundamental and abundant element - neutral hydrogen (HI). Studying HI with the SKA will also be essential for understanding galaxy formation and evolution.

The SKA's sensitivity will enable HI to be traced out to the furthest reaches of the Universe. Using the HI detected in billions of galaxies to map the evolving matter distribution, the SKA will measure the geometry of the Universe and test whether dark energy is a vacuum energy or something more exotic (like evidence of genuinely new physics or extra dimensions). Gravitational lensing, also observed with the SKA, serves as an independent probe of dark energy, dark matter and the growth of structure.

The SKA and its wide field-of-view will allow the accurate determination of the rate of evolution in the "equation of state" of dark energy with cosmic time.



Combined optical (Hubble Space Telescope, colours) and radio (MERLIN, contours) image showing the gravitational lens system B0631+519 where dark matter associated with two galaxies produces multiple images of a background source.



Supermassive black hole observed at radio wavelengths in the centre of a galaxy.

Key Science Projects

Probing the Dark Ages

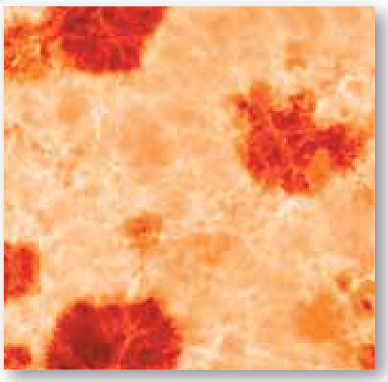
What happened after the big bang and before the first stars and galaxies formed?
Which came first - stars or galaxies?

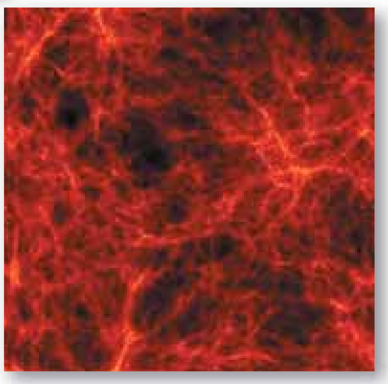
The first objects to form after the big bang ended the "Dark Ages" by re-ionizing the intergalactic medium.

Radio emission from the HI 21-cm line and molecular lines like those from carbon monoxide (CO) provide the best observational windows through which to observe directly the era when gas was first turned into stars in galaxies.

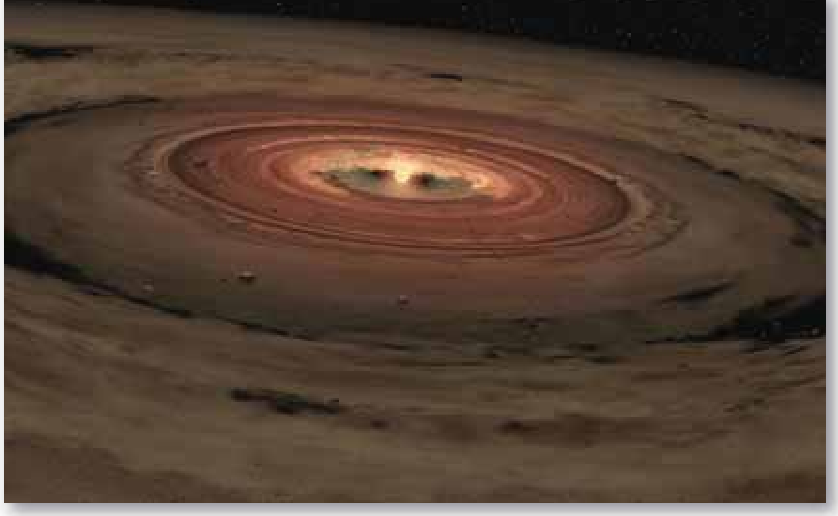
The SKA will observe the very first black holes, stars, and galaxies that shaped the development of the Universe during this important time. Almost every massive black hole in the observable Universe, even those accreting during the dark ages, will be detectable.

The SKA will provide detailed pictures and full 3-D maps of the early "cosmic web" of neutral gas, essential to understand the Universe that we live in today.





The panels show snapshot simulations of the HI Universe evolving with time (from top to bottom). The dark regions correspond to highly ionized regions (such as those around protogalaxies) and the bright regions are dense, neutral pockets of gas.



Artist's impression of a planetary disk formed around a star.

Key Science Projects

The cradle of life

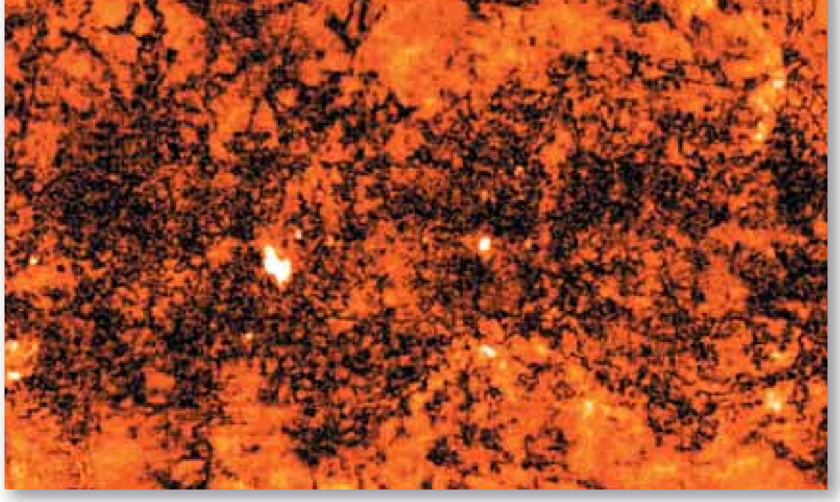
Are we alone in the Universe?

Are there Earth-like planets around other stars?

What are the organic molecules in star forming regions that are relevant to the formation of planets and life?

One of the most fundamental questions contemplated by humanity is whether we are alone in the Universe. We suspect that Earth-like planets orbit at least some of the other stars in our galaxy, and these may be home to other technological civilizations today. Receiving a signal transmitted by a civilisation in outer space would settle this question forever! The SKA will be so sensitive that it will be able to search for signals no stronger than those generated for TV and radar by 20th century technology on our own planet.

By studying the process of planet building around young stars, scientists using the SKA will reveal how Earth-like planets are formed. With its unique spatial resolution and sensitivity the SKA can zoom into the gaps in the forming planetary disks close to stars where Earth-like planets are likely to be located.



Part of the Milky Way seen in polarised radio light.

Key Science Projects

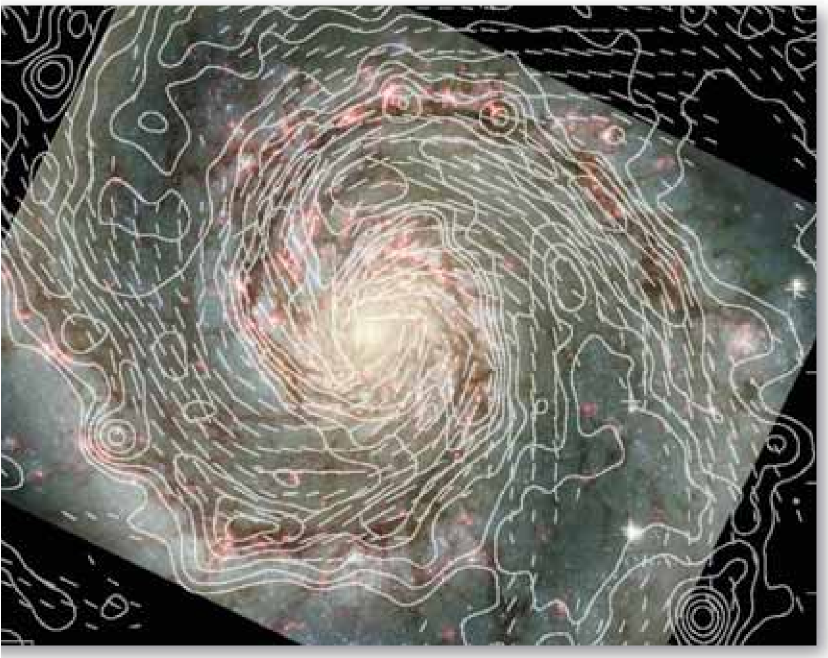
The origin and evolution of cosmic magnetism

Is the Universe magnetic?
How does magnetism affect the formation of stars and galaxies?
Where has magnetism come from?

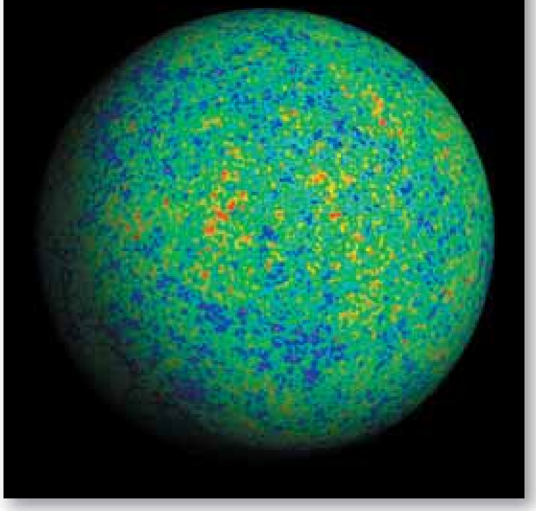
We find magnetic fields almost everywhere in the Universe, with field strengths varying by a factor of 10^{20} between the cosmic magnetism in interstellar and intergalactic space and the extreme fields found on the surface of compact collapsed stars. Even though magnetic fields seem to play an important part in the formation and evolution of celestial sources, and of the Universe, we do not understand how cosmic magnetism forms in the first place.

Radio observations are the key, and often the only, means to study this. The SKA will detect millions of faint polarised sources that can be used to study the magnetic field throughout the Universe.

The resulting 3-D maps of the Milky Way, nearby galaxies and intergalactic space will be used to study the processes that formed the fields observed today.



Optical image of a spiral galaxy (Hubble Heritage/NASA/STScI) with the magnetic field determined from radio observations superimposed.



Fluctuations in the cosmic microwave background projected onto a sphere.

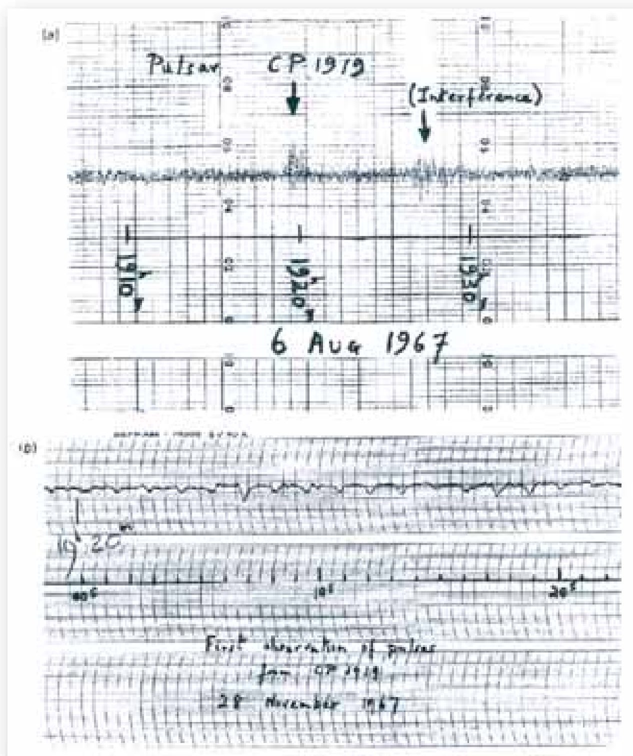
Exploration of the unknown

Can we predict everything in the Universe on the basis of what we know now? What else will we discover when exploring the cosmic frontier?

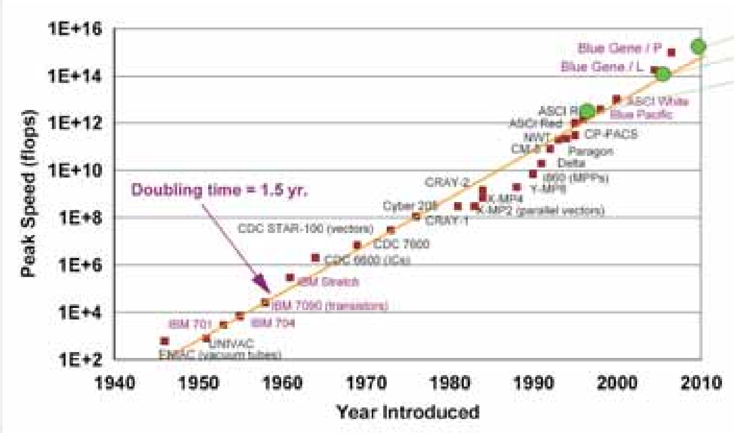
Radio astronomy is responsible for many of the fundamental discoveries in physics and astrophysics in the last century. The list is long and includes:

- The Cosmic Microwave Background
- Quasars
- Pulsars
- Gravitational Lenses
- Dark Matter
- Masers
- Gravitational Waves
- The first extra-solar planets

and many more. Many of the discoveries happened unexpectedly, so we should be prepared for the possibility. The SKA will be a versatile, multi-purpose instrument whose flexibility allows us to expect the unexpected. The unique sensitivity, the many independent beams on the sky, and the extremely large field-of view make the SKA a discovery machine. We cannot predict what we will find but we can predict that it will surprise us.

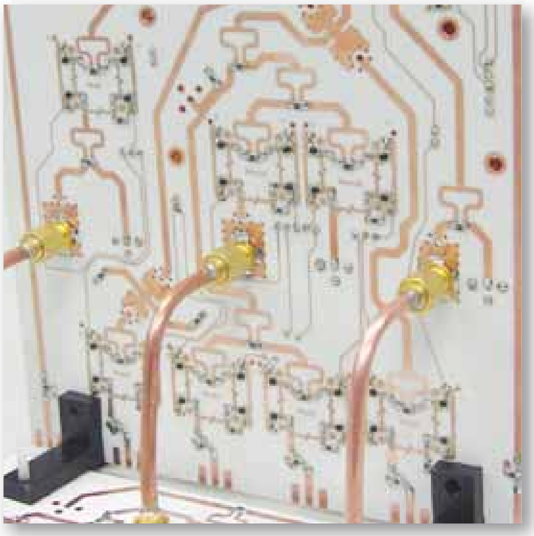


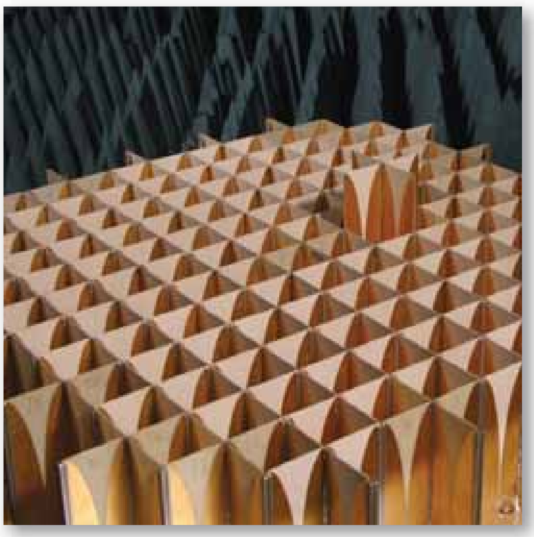
Discovery of pulsars by Bell & Hewish in 1967.



According to Moore's law, computer power doubles about every eighteen months, By the time of completion of the SKA, computers should be 1000 times more powerful than today.

SKA Engineering





The SKA - a technological and engineering challenge

The SKA demands new approaches to designing radio telescopes. The path to SKA involves producing cheap antennas and using programmable signal processing engines, or even general-purpose computers, within the instrument's signal path. Pushing the instrument in the direction of a "software telescope" allows designers to take advantage of Moore's law for digital hardware - processing power doubles every 18 months.

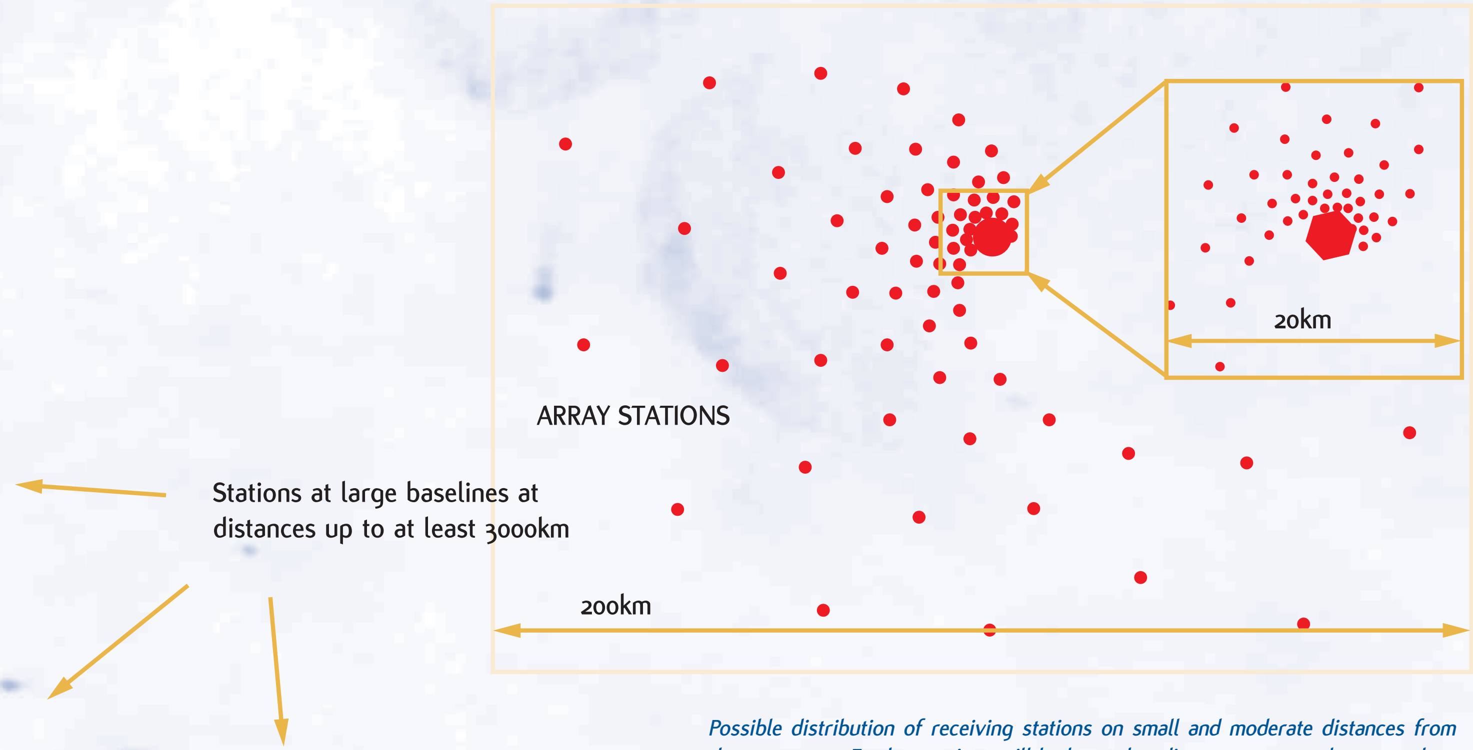
Even with the expertise of a multi-national collaboration, the scale of the SKA makes it challenging to translate the SKA concept into the world's foremost radio astronomical facility. New technology, and progress in fundamental engineering science are both required. These breakthroughs can only happen with the collaboration of industrial partners offering expertise in fields such as information and communication technology, high performance computing and mass production manufacturing techniques.

Areas of particular relevance include:

- Low-cost collecting area
- Low-noise, highly integrated, receivers
- Phased-array antenna technology
- Wideband optical-fibre signal transport systems
- Fast, high resolution, analogue-to-digital converters
- High-performance computing engines
- Data storage and innovative retrieval technologies

SKA Engineering

In order to achieve both high brightness sensitivity and high-fidelity images of the radio sky, the elements of the SKA will be distributed in an inner array and in groups of receiving elements located further away from the core. The signals of the "stations" will be transported back to a central processing engine where the data are manipulated to form images and time series, and to combat the effects of harmful radio frequency interference (RFI) signals.



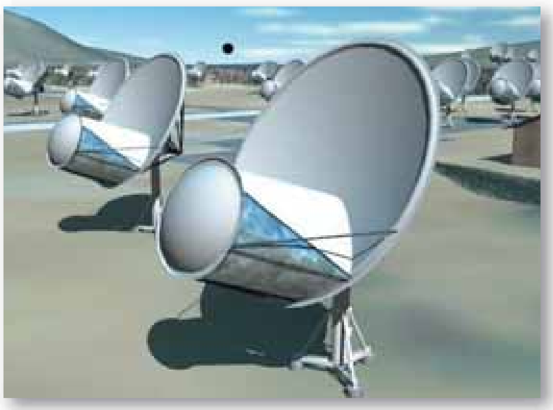
Possible distribution of receiving stations on small and moderate distances from the array core. Further stations will be located at distances up to at least 3000km.

Antenna Engineering

Overcoming the cost barrier

The key feature of the SKA - its enormous collecting area - can only be realised by moving away from traditional telescope designs and by constructing efficient, broadband, low-cost antennas capable of multiple beam operation. This goes hand-in-hand with the development of low-cost, low-noise radio frequency amplifiers and highly-integrated receivers.

Several innovative approaches are being investigated to find an optimum enabling technology solution for the key science projects. To meet the reqiuirements for the wide frequency range, and to enable multiple fields-of-view at low frequencies, it is likely that two antenna concepts will need to be combined.

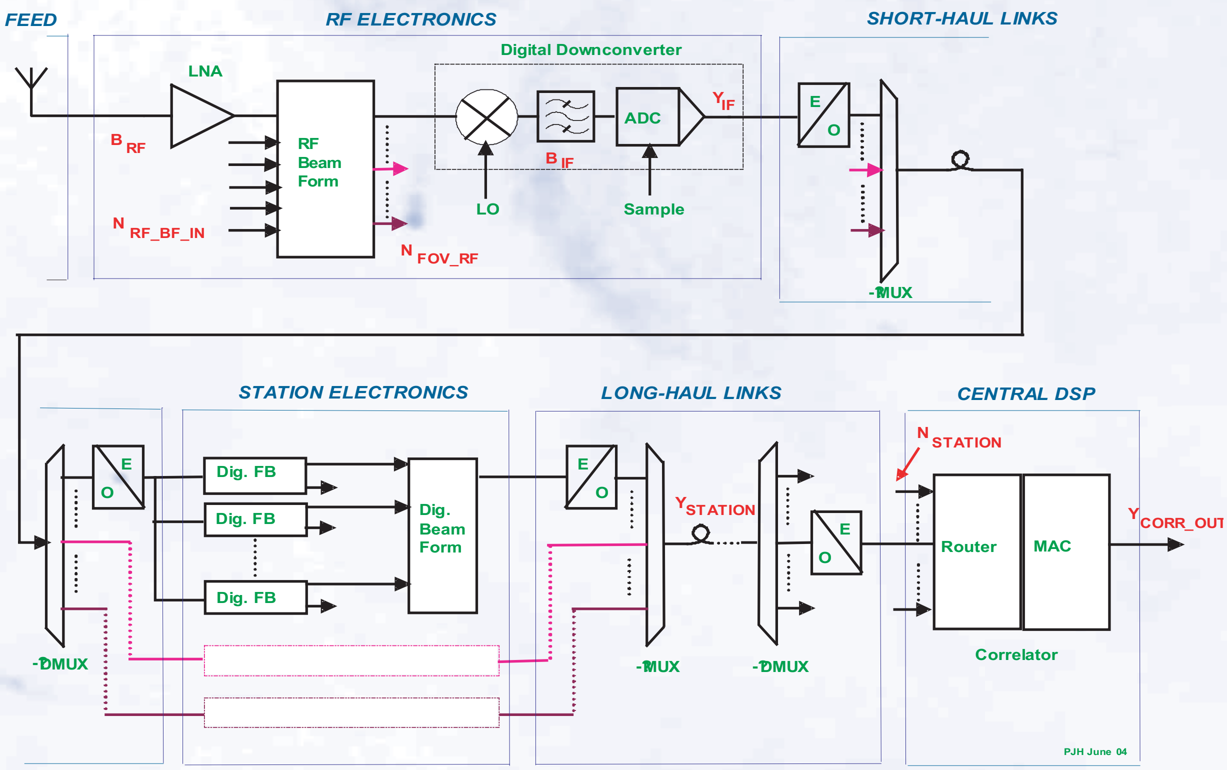


Artist's impressions of some of the antenna concepts under investigation for the SKA. Top right: aperture arrays observing much of the whole sky at once; Middle: high frequency dishes; Bottom: small dishes with phased arrays at their foci.

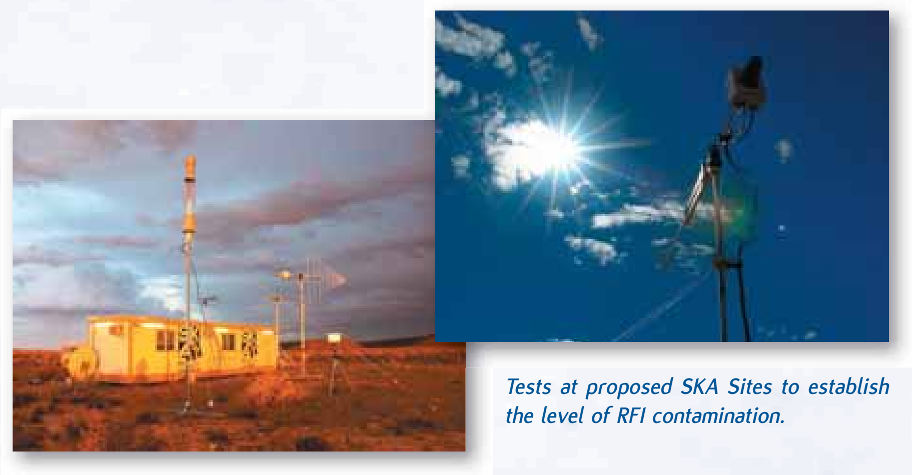
System Design Engineering

Overall design

A great deal of the SKA design challenge lies in transporting high data rates across large distances and then processing that data in well defined ways. Antenna prototypes are now being built and tested, and there is an international system design and costing process also underway. This includes the development of interference mitigation techniques to enable broad bands of the radio spectrum to be utilised to give high sensitivity.



One SKA system concept



Tests at proposed SKA Sites to establish the level of RFI contamination.

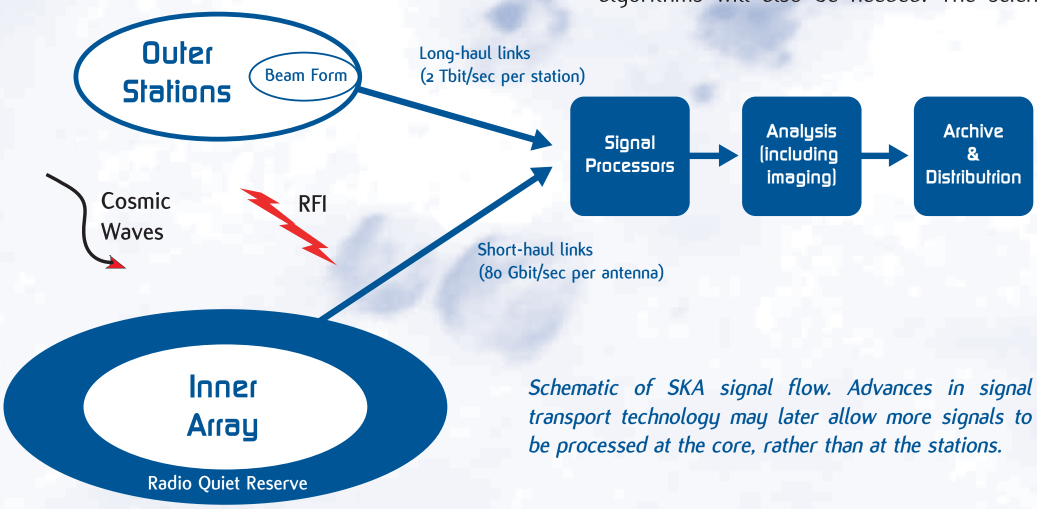
Digital Engineering

Data transport and signal processing

After undergoing fast, high resolution sampling (several GBit/sec), data will be transported to a central processor. Short-haul links in the inner array will transfer 80 GBit/sec per antenna, and long-haul links will need a capacity of 2 TBit/sec per station - more than the current internet traffic of Europe!

Processing and post-processing will rely on the extension of Moore's Law beyond 2015, as very high-performance central computing engines (10^{15} operations per second) will be required. Furthermore, transfers of 1TByte images world-wide will be needed every minute and extensive station-based data processing will be required for calibration.

Hardware is important but the SKA will also stretch algorithm development in two vital areas. Faster and better ways will be needed to make the high dynamic range (10^6:1) images central to SKA science drivers. Effective radio interference (RFI) mitigation algorithms will also be needed. The science goals of the SKA require observations across wide segments of the radio spectrum. This means that active mitigation schemes must be implemented to allow radio astronomy and other services to co-exist, even at relatively radio-quiet SKA sites.



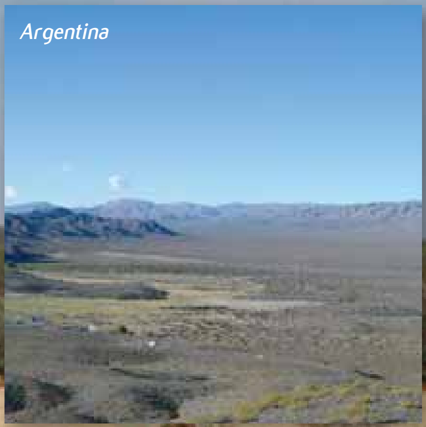
Schematic of SKA signal flow. Advances in signal transport technology may later allow more signals to be processed at the core, rather than at the stations.

Various examples of pathfinder and technology demonstrators

Engineering Demonstrators

Engineering paths to the SKA

After a first stage of concept exposition and review, intensive prototyping and demonstration of key aspects of SKA technology is nowunderway. In parallel with the demonstration work, international studies of the various concepts are being done to establish accurate costing and to simulate the expected astronomical performance. Final selection of component technologies will be made in 2009.


Argentina


China


Australia


South Africa

SKA Location

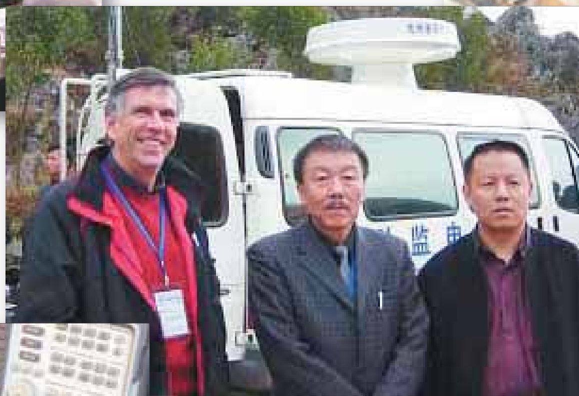
Finding the best site for transformational science

Siting proposals are being prepared in four countries: Argentina, Australia, China and South Africa. Final proposals are due at the end of 2005, and a ranking on siting will be made by the International SKA Steering Committee in 2006. Factors influencing the decision include: land availability, radio quietness, infrastructure development costs, and ionospheric and tropospheric characteristics. SKA infrastructure is estimated at around 25% of the project budget, including the dedicated optical fibre network needed to support the inner 200 km or so of the array. Wherever the telescope is built, innovative infrastructure solutions will be needed including in fields such as low-cost energy supply to remote stations.

Two particularly important attributes affecting the site selection are the suitability of the site for the Key Science Projects and its exposure to radio interference. Prior to the site decision, an independent assessment of the radio frequency environments of candidate sites will be done for the International SKA Project Office.

- 20% of total collecting area within 1 km diameter
- 50% of total collecting area within 5 km diameter
- 75% of total collecting area within 150 km diameter
- maximum baselines at least 3000 km from array core

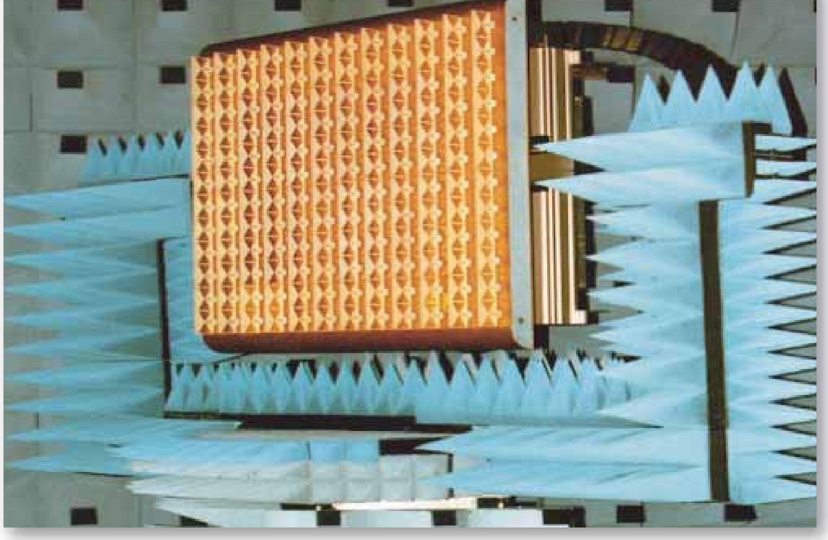












SKA & Industry

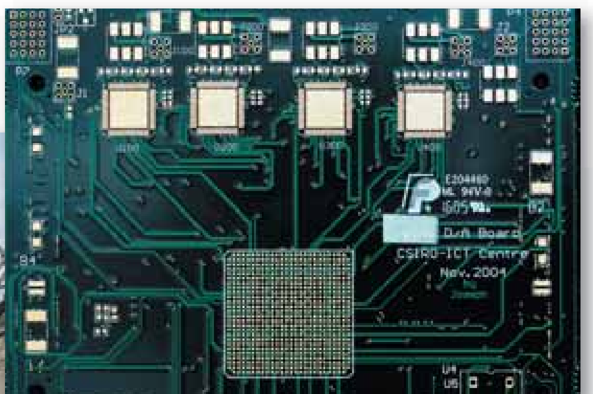
The SKA: a science and engineering partnership

Radio astronomy provides a demanding yet benign, development and test environment for state-of-the-art devices, systems and algorithms. Construction of the SKA over a 6-year period is equivalent to building and commissioning a 100 m radio telescope every 20 days - a task far beyond the world's astronomy community. Large industry contracts will therefore be necessary to build the telescope. Even before the construction phase, many of the R&D programs needed for SKA demonstrators require industry know-how, especially in crucial areas such as reduction of production cost.

The international SKA project, and its associated national programs, welcome interest from potential industry collaborators. Joint research and development is viewed as a shared-risk endeavour, with SKA consortia and industry each contributing to defined activities.

Advantages of collaboration for industry participants include:

- the opportunity to harness the creative energies of the best professionals in a highly imaginative project
- the ability to perfect leading-edge techniques and products in a demanding application, with technologically sophisticated users
- the ability to generate and share information with R&D partners in a benign commercial environment
- high visibility flowing from association with an innovative international mega-science project
- potential for early involvement in a 1 billion Euro project spanning a range of engineering and computing disciplines



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For further information, visit www.skatelescope.org

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