

India and the Square Kilometre Array

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The Square Kilometre Array (SKA), the world's next-generation radio telescope, is being designed by an international consortium. It will, once complete, deliver capability for a broader range of science than any other facility. Indian scientists and engineers have played a critical role in the definition of the SKA concept and its science case, in the design of the instrument and, hopefully, will do so in the construction and operation. This article describes the current status of the global project with a focus on India's role in the global collaboration.

Keywords: Global collaboration, international consortium, radio telescope.

Concept and history

THE Square Kilometre Array (SKA) will be the next-generation radio telescope; once fully constructed, it will be, by several measures, the largest scientific facility on Earth. The SKA is being designed by an international consortium of scientists and engineers to tackle some of the fundamental scientific questions of our time, ranging from the birth of the Universe to the origins of life.

As is the case with many scientific facilities, it is difficult to identify a single moment at which the concept for the facility crystallized. Ekers¹ and Noordam² have done an excellent job in describing the discussions and thinking that eventually led to the emergence of a telescope concept for what we now know as the SKA. To summarize: between 1988 and 1990 Braun, de Bruyn and Noordam (NFRA, now ASTRON) proposed a Dutch HI (neutral hydrogen) telescope with sufficient sensitivity to detect HI at high redshift. Independently, Govind Swarup in India, was developing a proposal for an International Radio Astronomy telescope consisting of one hundred 75 m dishes³ building on ideas developed in the construction of the Giant Metrewave Radio Telescope (GMRT) near Pune, India.

Now embedded in the SKA folklore is the VLA 10th Anniversary meeting (IAU 131: Radio Interferometry), held in Socorro, New Mexico, USA in October 1990. At this meeting, Wilkinson⁴, following discussions with

Dutch and other colleagues, proposed the Hydrogen Array, an array of 1 sq. km collecting area. Thus was born the concept of the SKA.

Science with the SKA

In the years since the initial definition of the SKA, several evolving science cases have been developed, each of increasing sophistication and range. The current detailed science case, with more than 1200 authors, and describing the science to be done with the first phase of the SKA and with the planned full array (up to 10 times larger than Phase 1) can be found in the two volumes *Advancing Astrophysics with the Square Kilometre Array*⁵. Phase 1, defined in more detail below, will, from this point be referred to as SKA1 and phase 2 as SKA2.

The principal science drivers for the SKA are briefly described below; these science drivers are used to derive and define the so-called level-1 requirements or technical specifications, for the SKA Observatory.

The science case for the SKA covers large range:

(1) The theme named 'The Cradle of Life' will address the origins of life in the Universe and the planetary systems which might support it. SKA1 will observe the formation of planets through the study of centimetre to metre scale structures coalescing within planetary disks. SKA2 will have the spatial resolution to observe the assembly of planets in earth-like orbits around their parent stars. SKA1 will have the sensitivity to detect the signatures of molecules such as the amino acid glycine.

(2) The Laser Interferometer Gravitational Wave Observatory (LIGO), in a spectacular observation, recently confirmed the existence of gravitational waves⁶. The SKA, using millisecond pulsars across the Milky Way, is being designed to observe and measure long-period gravitational waves, which are impossible to measure with Earth-based detectors.

(3) Magnetic fields permeate the Universe from the smallest scales (features on pulsars) to the largest (superclusters and larger); SKA will enable the first three-dimensional magnetic map of the Universe to be created. SKA1 will measure the individual magnetic components along the sightline toward large samples of sources distributed in all directions on the sky; SKA2 will be able to extend the measurements to sources at varying distances.

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SPECIAL SECTION:

(4) The SKA will for the first time allow galaxy evolution, as traced by atomic hydrogen, to be observed throughout cosmic time – one of its original goals. SKA1 will provide samples of 10 million galaxies spanning 8 billion years of evolution, which will greatly advance our understanding of the life cycle of galaxies. SKA2 will provide the most complete galaxy census ever contemplated, encompassing one billion galaxies and covering 12.5 billion years of cosmic history. These surveys will enable the most precise determination yet conceived of the properties of dark energy.

(5) Although the basic pattern of growth and decline of star formation with time has been established, there are still many unanswered questions. The SKA will play a key role in answering these questions, since it is likely that such events are so deeply enshrouded by material that they can only be seen at radio frequencies that can penetrate the obscuring material. With SKA1, it will be possible to make detections back to 1.5 billion years and image back to 6 billion years of age. When SKA2 is completed, it will be possible to probe star formation when the Universe was only 0.5 billion years old.

(6) The SKA will uniquely enable the measurement of a complete time sequence of images from the onset of cosmic dawn (using SKA2) to the end of reionization, when the Universe became transparent (already possible with SKA1), using the faint radio light coming directly from the hydrogen itself. The resulting movie of the first 700 million years of the Universe will answer a multitude of questions. When exactly did the first stars form? Were individual stars, large stellar clusters or even early black holes the most important source of heating and ionization of the Universe? How exactly did the process unfold? Was there a single progression from dark to light or were there multiple fits and starts, with different heating populations dominating at different times? This vital chapter in the history of the Universe was written long ago, but is now waiting to be read.

Baseline design of the SKA

As mentioned above, the science drivers, some of which are described in the previous section, are used to derive the technical specifications for the SKA. One key parameter that drives the major decision in the design of the SKA is the frequency range required to deliver all of the high-priority science. The science drives the SKA Observatory to enable observations over the frequency range 50 MHz to 14 GHz, with a strong preference to observe up to 25 GHz. This single requirement results in the need for two telescopes since dishes work best above 350 MHz and other forms of antenna design provide efficiency below that frequency. Figure 1 shows the frequency range associated with the major science drivers.

The science requirements have been translated into a baseline design. The design is formally represented by

the level-1 requirements, but is provided in narrative form in Dewdney *et al.*⁷. Table 1 gives the high-level summary of the SKA1 design.

A decision was taken in 2005/06 that SKA should be built in two phases. The first, SKA1, would comprise ~10% of the final collecting area of the telescopes; the second phase, SKA2, comprising the remainder, would follow once the first phase had established the sites and the technical feasibility of the project.

The SKA1-Mid specification will be delivered by constructing up to 133 SKA1-Mid dishes (15 m offset Cassegrain design), each capable of supporting five receiver bands and incorporation of the 64 antennas of MeerKAT (see below). The antennas will have a centrally concentrated core with a radius of ~3 km; and lying on three spiral arms extending to ~80 km from the centre, providing a maximum baseline length of ~150 km. SKA1-Mid will be constructed in South Africa (Figure 2).

The SKA1-Low specification will be delivered through the construction of up to 131,072 low-frequency antennas arranged in 512 stations, each of 256 antennas. The stations will be concentrated in a core of radius <2 km, with about 25% of the collecting area on baselines up to 65 km in three spiral arms. SKA1-Low will be constructed in Western Australia (Figure 3).

The SKA Board has set a cost-cap of €50M for the construction cost of SKA1. In July 2016, this was adjusted for inflation to €74.1M. Delivering a project of the scale of SKA1 to such a cost-cap is challenging and will require compromises in some system requirements and the possible deferral of some subsystems until new member countries join the project bringing additional funds.

SKA design (by) consortia

In July 2013, the SKA Board, following a Call for Proposals, authorized the formation of nine core design consortia for the SKA, and two consortia conducting R&D on advanced instrumentation which would likely be incorporated into SKA2. A third consortium of the latter designation is currently being formed. Each consortium reflects the international nature of the SKA partnership with institutes from around the world contributing to the design effort. Details of each consortium can be found on the SKA website (www.skatelescope.org). A list of design consortia, along with the lead institute for each, is provided below in alphabetical order:

- Assembly, Integration and Verification (SKA-SA, South Africa).
- Central Signal Processor (NRC-HAA, Canada).
- Dish (CSIRO, Australia).
- Infrastructure Australia (CSIRO, Australia).
- Infrastructure South Africa (SKA-SA, South Africa).

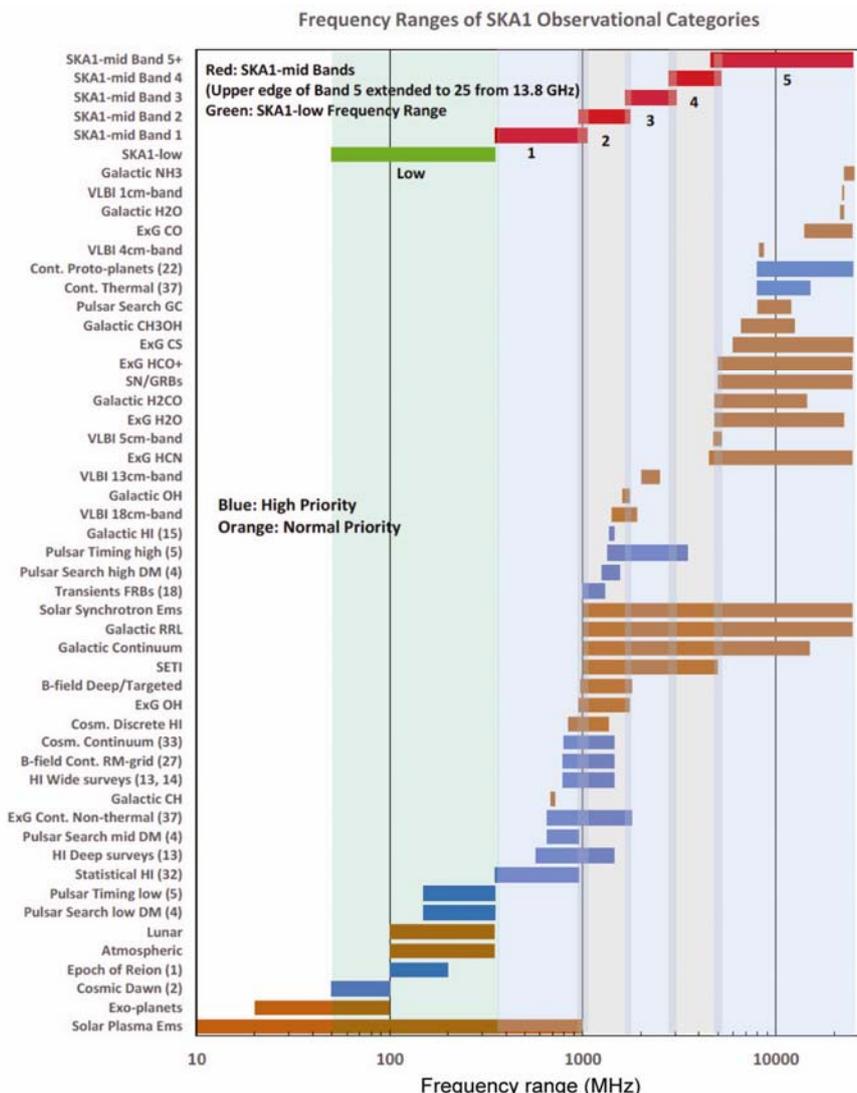


Figure 1. A chart showing the major areas of observation and investigation for SKA1 in order of frequency range. The bars at the top of the figure, the alternating green and grey shading show the coverage of the observing bands.

- Low Frequency Aperture Array (ASTRON, The Netherlands).
- Signal and Data Transport (University of Manchester, United Kingdom).
- Science and Data Processor (University of Cambridge, United Kingdom).
- Telescope Manager (NCRA, India).

The three advanced instrumentation consortia are:

- Mid-Frequency Aperture Arrays (ASTRON, The Netherlands).
- Phased-Array Feeds (currently forming; CSIRO, Australia).
- WideBand Single Pixel Feeds (Chalmers University of Technology, Sweden).

Approximately 600 scientists and engineers from around the world participate in the SKA design efforts.

Each consortium member receives funding from the respective national government or funding agency. They operate under the oversight of the SKA Office, the central office of SKA Organisation (SKAO); each consortium works to deliver a detailed design as specified by an agreed Statement of Work. As of the time of writing, all consortia have passed their preliminary design reviews and are working towards the critical design reviews, scheduled for the end of 2017 and early 2018.

Sites for SKA

The SKA Observatory will be located on three sites; the two telescopes will be located at remote, radio-quiet sites in the southern hemisphere. SKA1-Low will be centred at the Murchison Radio Observatory at Boolardy, Western Australia, ~800 km north of Perth; SKA1-Mid will be

SPECIAL SECTION:

Table 1. High-level specifications for SKA Phase 1, derived from the scientific requirements

Parameter	Unit	SKA1-low specification	SKA1-mid specification
Initial frequency range	GHz	0.05–0.35	0.35–1.8, 4.8–13.8
Fiducial frequency	GHz	0.11	1.67
$A_{\text{eff}}/T_{\text{sys}}$ (at Fiducial frequency)	m^2/K	550	1500
Field of view (at Fiducial frequency)	deg^2	14	0.33
Best resolution (at Fiducial frequency)	arcsec	7	0.25

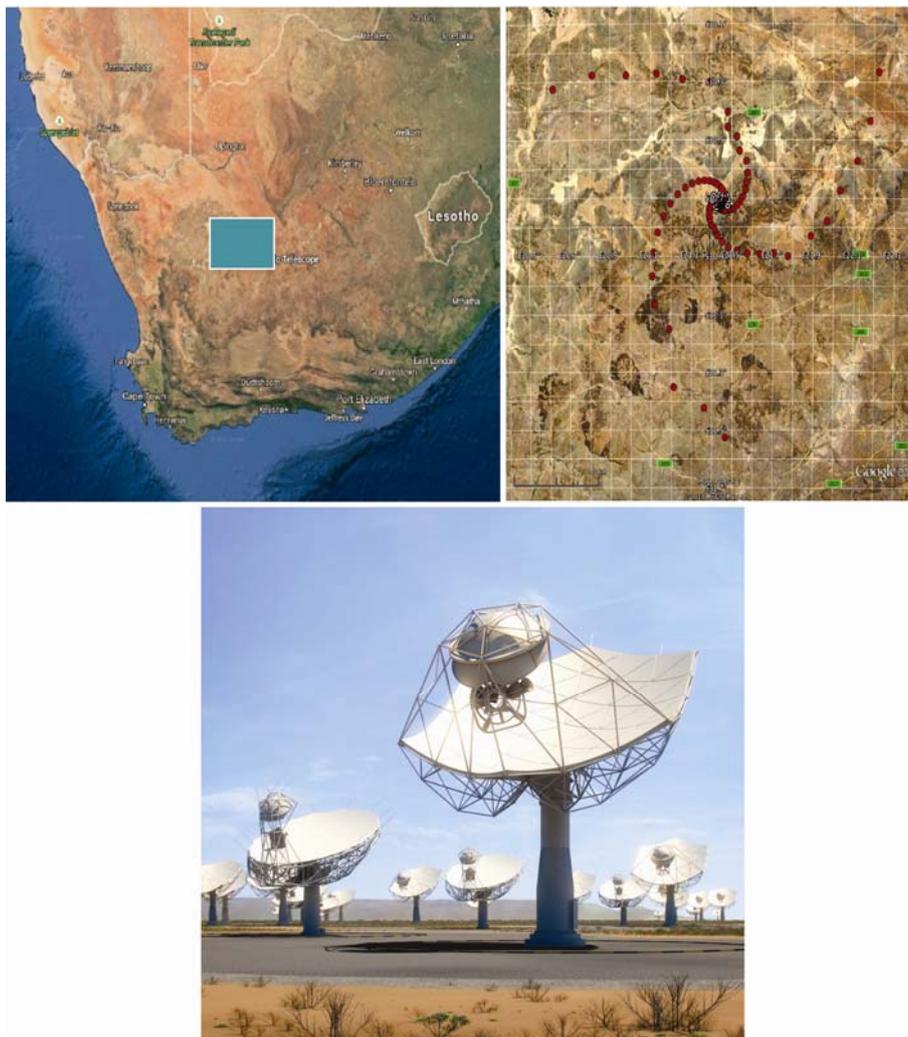


Figure 2. Location and proposed configuration of SKA-Mid array for SKA1 in South Africa (top panels), along with an artist's impression of the SKA-Mid array dishes (bottom panel), showing SKA1-Mid integrated with the South African MeerKAT array.

centred in the Karoo, Northern Cape, ~800 km NNW of Cape Town, South Africa. The SKA Observatory headquarters will be located in a purpose-built building at Jodrell Bank, near Manchester, United Kingdom.

The process of selecting the sites was lengthy and highly technical. In 2004, the then governing body of the SKA, the International SKA Steering Committee, issued a Call for Proposals for hosting the SKA, then envisaged to all be on one site. Four proposals were received; from Argentina/Brazil; Australia/New Zealand; China and South Africa (with eight partner countries across southern

Africa). Following a technical evaluation in 2005, a shortlist of two sites – Australia and South Africa – was made.

Detailed bids for the hosting of the SKA were then sought once the project was on a more secure footing, with governments forming the new SKAO, which was established in November 2011. Full details on the process and much of the documentation can be found in the SKA website (www.skatelescope.org/site-documentation/). As is now well known, it was eventually decided to take advantage of the special characteristics of both sites and

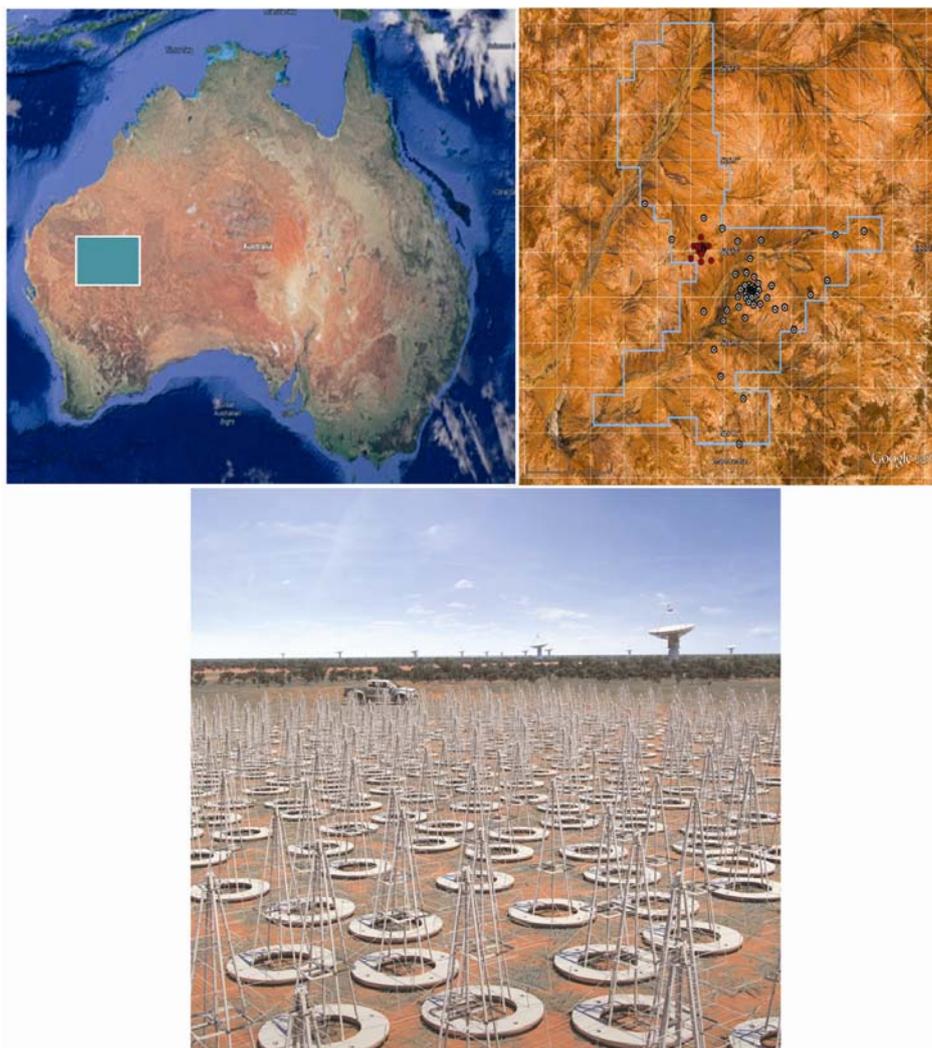


Figure 3. Location and proposed configuration of the SKA-Low array for SKA1 in Australia (top panels), along with an artist's impression of the SKA-Low array dipoles (bottom panel). The ASKAP dishes are visible at a distance.

locate the low-frequency component of SKA in Australia, and the higher-frequency dishes in South Africa. A key component of both sites is their excellent radio-quiet environment, a natural resource for astronomy protected by legislation and regulation.

Both Australia and South Africa have established precursor telescopes on the two sites. In Australia both the 36 dishes of the Australian SKA Pathfinder, and the 128 (soon to be 256) tiles of the Murchison Widefield Array have been delivering scientific results for some time. In South Africa, construction on the 64 antenna MeerKAT array is well-advanced, with first light achieved on 16 antennas, and routine operation expected towards the end of 2017. MeerKAT will eventually be fully integrated into SKA1-Mid. In a more recent development, a new precursor, the Hydrogen Epoch of Reionization Array, a US-led project, has been established on the MeerKAT site. It is currently under construction.

The location of the SKA HQ was decided in a separate process in April 2015, following two excellent bids from Italy and the UK.

Governance of the SKA

The governance of the SKA collaboration has gone through several evolutionary steps, from a scientific steering committee, to a Founding Board consisting of funding agencies and research organizations, through to its current structure of a not-for-profit UK Company Limited by Guarantee. The current organization has, as its top-level body, the Members, or shareholders. The Members provide the funding for the design effort, current ~€200M over 5 years. The Members have appointed a Board, on which each Member is represented by a voting Director and a science Director. The Chair of the Board

SPECIAL SECTION:

(currently Giovanni Bignami) is independent. The Board appoints a Director-General, who oversees the SKA pre-construction programme, with policy set by the Board.

As the project looks to construction and operations over a period of 50 years or more, it is recognized that the current structure is not optimum for such a mission. The governments participating in the SKA therefore decided to negotiate the establishment of a new Inter-Governmental Organisation (IGO) for the SKA, called the SKA Observatory. This IGO will be governed by a Convention and associated protocols. It is intended that the participating governments will appoint an SKA Observatory Council which will oversee the running of the Observatory and be responsible for the establishment of appropriate policies, which will then be implemented by a Director-General appointed by the Council.

At the time of writing (January 2017), the progress in establishing the IGO is excellent and there is a target date for the signing of the Convention of July 2017. The Convention must then be ratified in the national parliaments and legislatures, which is anticipated to take ~12 months. So, it is hoped that the SKA Observatory will enter into force in the middle of 2018, and the construction of SKA1 can start soon thereafter following approval from the Council.

India's participation in the SKA

India, with a rich history and tradition in radio astronomy, has been an active participant in the scientific, technical and administrative activities of the SKA project since the initial days. This association was further strengthened when the country became a Full Member of the present SKA Organisation, in October 2015 (Figure 4).

Participation in technical activities

India is currently involved in several of the design work packages of the SKA, notably the Telescope Manager, the



Figure 4. India joins the SKA as a full member – signing ceremony at Mumbai, India on 5 October 2015, with Philip Diamond (SKA) and R. K. Sinha (DAE).

Signal and Data Transport and the Central Signal Processing packages. Since October 2013, Indian scientists from the National Centre for Radio Astrophysics (NCRA), Pune, are leading a consortium of seven SKA member countries for the design of the Telescope Manager system (Figure 5), which will be the controlling nerve centre and brain behind the functioning of the entire SKA observatory. This work has direct synergy with developments at the GMRT, and a smaller, early version of the design is expected to be deployed at the GMRT. NCRA is also participating in the Central Signal Processing work package and the Signal and Data Transport work package. All these work packages have completed the preliminary design phase and are well into the detailed design phase.

Many of these SKA technical activities in India are being carried out in active collaboration with partners from Indian industry. It is expected that the involvement in these areas will extend into the construction phase as well.

In particular, it is expected that India will play a major role in the production of the Telescope Manager for the SKA, and will be involved in different aspects of the software for the entire SKA. NCRA is also exploring other possible options for Indian participation in the construction phase, that is expected to commence from 2018. Furthermore, there is Indian participation (via the Raman Research Institute), Bengaluru in the SKA precursor project called the Murchinson Widefield Array (MWA)⁸.

Many of the above activities have direct synergy with upgrade work ongoing at existing Indian facilities like the GMRT^{9,10}, which has recently been accorded the status of a SKA Pathfinder telescope, in recognition of the fact that important technical and scientific developments are being carried out at the GMRT which will provide valuable feedback to the teams designing the SKA facility.

Participation of the Indian scientific community in the SKA

Along with the above, science activities in India related to the SKA are also making good progress. Already, several Indian scientists are members of the International Science Working Groups for the SKA. Furthermore, SKA India Science Working Groups have been formed in March 2014, which have been working on developing the science case and enhancing the potential user base within the country. Their activities include carrying out theoretical studies and modelling, as well as using the existing facilities like the GMRT to conduct research and investigations that will prepare the scientific community to make the best use of the SKA when it is ready. National-level SKA science workshops have been held in conjunction with the Astronomical Society of India meetings of 2014 and 2015. More recently, the international SKA Science Meeting in 2016 was hosted by India and was attended by a significant number of Indian scientists and

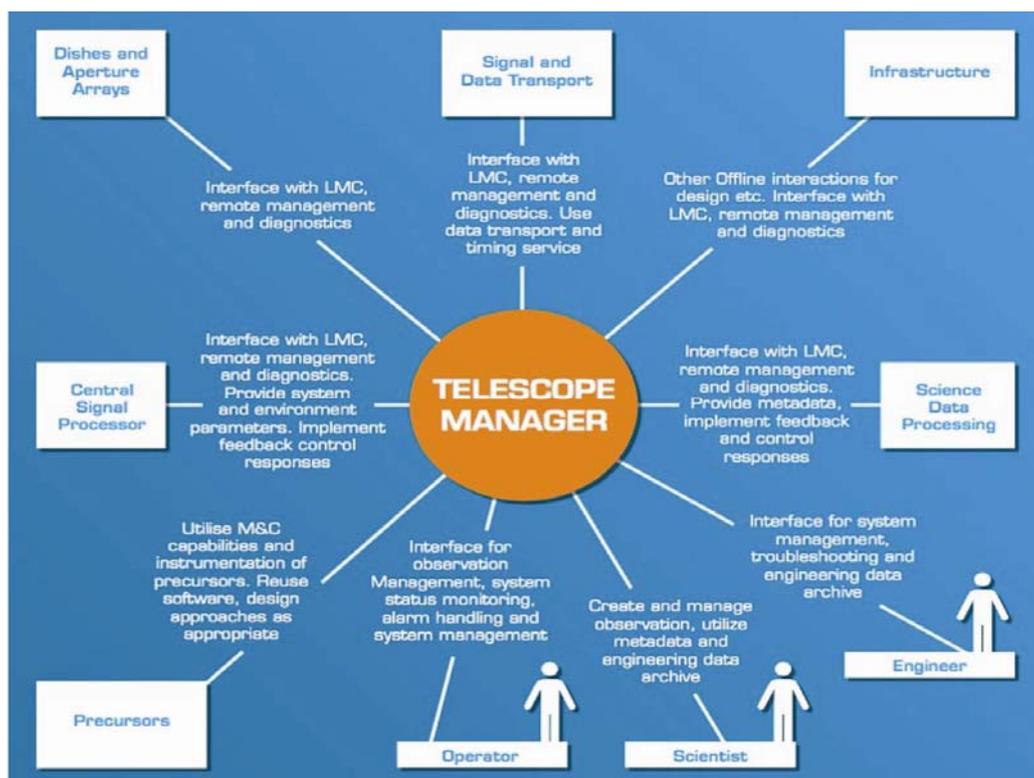


Figure 5. Flow chart illustrating the role of Telescope Manager in the SKA design. The Telescope Manager provides the 'nervous system' of the SKA, controlling and monitoring every aspect of its performance.

students from a number of different organizations in the country.

The Indian astronomy community, guided by the SKA India Science Working Groups, has recently produced a series of papers describing their SKA science interests, which have been published in a special issue of the *Journal of Astrophysics and Astronomy*¹¹. Some of the Indian working groups are also making contributions to the international SKA science use cases, as documented in the SKA Science Books (SKA Science Team, 2015).

The SKA India consortium

In order to organize all the SKA-related activities in India under a common umbrella consisting of all interested organizations within the country, the SKA India Consortium was formally launched in February 2015 at NCRA. With more than 15 institutions from all over the country (including colleges, universities and major research organizations) signed up as members, the SKA India Consortium is playing a major role in enhancing the country's ability to participate effectively in the SKA project, both in technical and scientific spheres. The overall guidance to the SKA activities in India is provided by the high-level SKA India Steering Committee constituted by the Government of India.

Benefits of Indian participation in the SKA

The benefits from Indian participation in the SKA are many fold. On the science front, it will allow Indian astronomers direct access to the best facility in the world in the future. On the technology front, it will provide an opportunity for research organisations and industry to contribute at (and learn from) the highest levels of technological development in the field. It will drive growth of technologies within the country in several areas: antennae, low-noise electronics, analogue and digital signal processing, high-speed computing, massive data storage, image processing, data mining, large software systems, etc. many of which will have direct societal benefits. It will also allow for the latest technological improvements to our own national facilities like the GMRT. It will lead to the development of a vibrant user community of researchers and astronomers within the country, and significantly improve the flow of students into the pure science areas. The SKA project can be used in a big way to spur interest in science, engineering and technology in the country, especially in the student population. Astronomy has a vast and popular appeal amongst all strata of society, and a large international project like the SKA with a significant Indian contribution is bound to capture the imagination of a large cross-section of people in the country.

SPECIAL SECTION:

Summary

The SKA is a truly next-generation project for astronomy and science in general. The technical, sociological, political and financial challenges that a global project such as the SKA faces are many and diverse. However, the governments, research organizations, scientists and engineers involved have the drive and enthusiasm to ensure that the SKA Observatory is built and will produce transformational science for decades to come.

Participation of India in the technical and scientific activities of the SKA mega-project provides an excellent opportunity for Indian science and technology to showcase its capabilities on the global stage, while at the same time giving ample scope to benefit from the development of next-generation technologies, and guaranteeing Indian astronomers the right of access to the best experimental radio astronomy facility of the future.

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