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OBSERVATIONAL FACILITIES

The Square Kilometre Array: current status and India's role in this upcoming facility

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Abstract. The Square Kilometre Array (SKA) observatory is a next-generation radio astronomy facility, which is just started its construction, after successful completion of the design and early prototyping phases. With more than 12 countries currently participating in the international consortium to build this facility, the SKA is expected to revolutionize radio astronomy, while driving the growth of many important new state of the art technologies. Once completed and fully operational by the turn of this decade, the SKA observatory will offer cutting edge science capabilities in an extremely broad range of topics in astrophysics. Indian scientists and engineers have played a significant role in the definition of the SKA concept and its science case as well as in the design of the instrument. India is now getting ready to join the construction phase of the SKA, and Indian astronomers are preparing to engage in front line science with the facility as and when it is ready. This paper describes the current status of this global project with a focus on India's role in the collaboration.

Keywords. Radio astronomy—facilities—GMRT—SKA.

1. Background, early history and current status

The Square Kilometre Array (SKA) observatory (see www.skatelescope.org for details and Figure 1 for illustration of an artist's view) is a global project that aims to build the next generation state of the art radio telescope, for addressing a wide variety of cutting edge science goals, ranging from the birth of the Universe to the origins of life. At present, 12 nations, including India, are participating in this mega-science project, and some more nations are expected to join shortly. The SKA is expected to revolutionize radio astronomy, while driving the growth of many important new state of the art technologies. Given the scale of the SKA, participation from industry will be an important ingredient in the building of the SKA.

Though the first ideas to build a large radio astronomy facility like the SKA were put forward in the early 1990s, the concept gained traction only during the late 1990s and early 2000s (see, e.g., Ekers 2012; Noordam 2012, for some historical viewpoints), and formal project work started around 2012 with the setting up of the SKA Organisation in November 2011. The name SKA derives from the concept that proposes to build an array of total collecting area of one square kilometre to meet the cutting edge science goals (e.g., Wilkinson 1999).

Given the size and complexity of the full SKA, a decision was taken around 2005 that the SKA should be built in two phases. The first, SKA1, would comprise $\sim 10\%$ of the final collecting area of the array, but would still be significantly better than any existing facility (see Figure 2); and the second phase, SKA2, comprising the remainder, would follow once the first phase had established the sites and the technical feasibility of the project.

Around the same time, the process was started to decide the location, where the SKA observatory would be built. Several possible options in regions of the

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Figure 1. An artist's illustration of how SKA1 antennas will look like, showing SKA1-Mid dish antennas on the left and the SKA1-Low dipole antenna array stations on the right (credit: SKA Observatory).

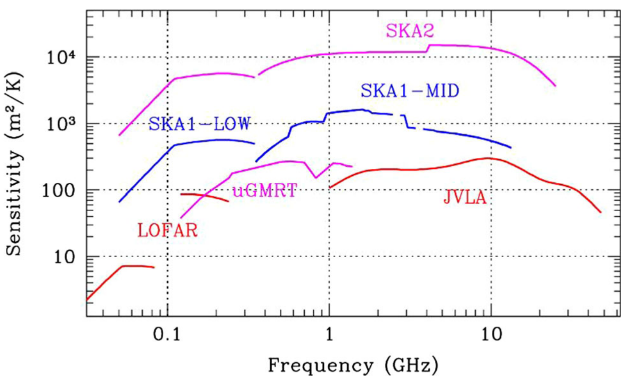

Figure 2. Illustrating the sensitivity of the SKA1-Low and SKA1-Mid telescopes, along with that of some of the prominent currently operational facilities, as well as of the futuristic SKA2. As can be seen, SKA1 will be a significant improvement over all existing facilities, over its entire proposed frequency coverage from about 50 MHz to about 14 GHz.

world which provide remote, radio-quiet sites were proposed around 2004. The two best sites were found to be Australia and South Africa. Finally, after a thorough evaluation and detailed discussions, it was decided to utilise both these sites and locate the low-frequency component of the observatory (SKA1-Low) in Australia, and the higher-frequency component (SKA1-Mid) in South Africa. SKA1-Low will be centered at the Murchison Radio Observatory at Boolardy in Western Australia, about 800 km north of Perth; SKA1-Mid will be centered in the Karoo of the Northern Cape province of South Africa, about 800 km NNW of Cape Town. Further, around 2015, it was decided to have the operational headquarters of the SKA in the UK at Jodrell Bank, near Manchester.

Both Australia and South Africa have established precursor telescopes on the two SKA telescope sites. In Australia, we have the Australian SKA Pathfinder (ASKAP) project with 36 antennas (Hotan *et al.* 2021) and the Murchison Widefield Array (MWA) project with 128 low frequency dipole antenna stations (Tingay *et al.* 2013), which have been delivering scientific results for some time. In South Africa, we have the 64 antenna MeerKAT array (Jonas & MeerKAT Team 2016) which has recently become operational. MeerKAT will eventually be fully integrated into SKA1-Mid.

More recently, in 2020, the project completed the detailed design of SKA1, and after a bridging phase, where useful prototyping activities have been carried out, it is now set to transition into full fledged construction by the end of 2021. A new governance vehicle—an Inter-Governmental Organisation (IGO), called the 'SKA observatory (SKAO)'—that came into being from March 2021, has replaced the SKA organisation, and will oversee the construction of SKA1 and the subsequent operations and possible further expansions of the project over the next few decades.

The design of SKA1 was carried out during 2014–2020 by a set of 9 core design consortia authorised by the Board of the SKA organisation. Each consortium reflected the international nature of the SKA partnership with institutes from around the world contributing to the design effort. A total of over 600 scientists and engineers were involved in the entire exercise, whose cost was estimated to be around 200 million Euros over the 6 year period.

2. Science potential of the SKA

Since the initial definition of the SKA, the science case for the SKA has developed and evolved significantly in several steps, with the two volume compendium 'Advancing Astrophysics with the SKA' (Braun *et al.* 2015) providing the latest and most comprehensive coverage of the vast range of science that the SKA will be capable of. The main science drivers for the SKA are summarized below (and also illustrated in Figure 3), and these provide crucial inputs for deriving the technical specifications for what is to be built for the SKA1. The science case for the SKA covers a truly vast and diverse range:

1. Physics of the early Universe and cosmic dawn: the SKA will be able to detect and image the first stars and galaxies that formed as the Universe evolved from being a sea of neutral hydrogen gas to a more complex, highly ionized state.

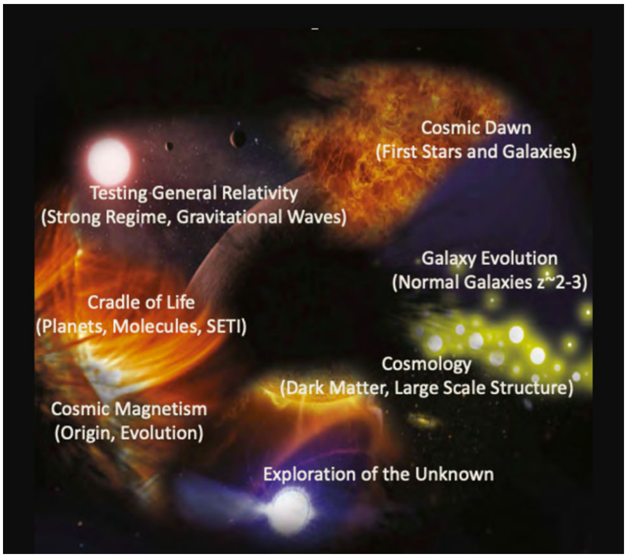

Figure 3. A mosaic illustrating the main science drivers for the SKA—a vast and diverse set of goals will make the SKA one of the most powerful and versatile next generation astronomy facility (credit: SKA Observatory).

2. Tracing the evolution of galaxies from their earliest formation to the current stage: the SKA will be able to study millions of galaxies spanning eight billion years of evolution, which will greatly advance our understanding of the life-cycle of galaxies, as well as provide unprecedented details about dark energy.
3. Understanding cosmic magnetism and its influence on the evolution of the Universe: magnetic fields permeate the Universe from the smallest (stellar system) to the largest scales (galaxy superclusters and beyond). The SKA will enable the first three-dimensional magnetic map of the Universe to be created.
4. Strong field tests of existing theories of gravitation: discovery of pulsars in exotic environments, such as close orbits around black holes will allow to check the validity of Einstein's theory of gravitation in the most extreme conditions.
5. Detection of low-frequency gravitational waves: by studying the fluctuation in arrival times of a dense grid of millisecond pulsars spread out over our Milky Way galaxy, the SKA will be able to detect and study long-period gravitational waves, complementary to the short-period gravitational waves detected by LIGO type observatories.
6. Study of the 'cradle of life': the SKA will probe planet formation via studies of centimeter to meter scale structures coalescing within planetary disks, as well as be able to detect spectral lines from complex molecules that are precursors to life. It will also give a major boost to the Search for Extra-Terrestrial Intelligence (SETI) from sources within about 100 parsecs around us.
7. Finally, last but not least many new and unexpected results and findings will also come from the SKA, as serendipitous discoveries are always made whenever a new facility is realized, what is significantly more powerful, sensitive and versatile than any existing facility.

3. Technical specifications and design for the SKA

As mentioned above, the science drivers, most important ones of which are described in the previous section, are used to derive the technical specifications and the baseline design for the SKA1 (e.g., Dewdney *et al.* 2015). One such key parameter is the frequency range that the SKA1 needs to operate over. To meet the key science targets, this range is roughly 50 MHz–14 GHz. This is a very large frequency range—much larger than that of any existing radio observatory—and it cannot easily be achieved by a single type of telescope. Consequently, it was found advantageous to split the SKA1 observatory into two separate telescopes, one covering the low frequency end of the range (50–350 MHz) called SKA1-Low, and the other covering the rest (350 MHz–14 GHz) called SKA1-Mid. Furthermore, given that the low-frequency range is better covered with dipole antenna arrays (rather than dish antenna arrays), the SKA1-Low design is based on the use of stations of log-periodic dipole antennas, while the SKA1-Mid design utilises the more traditional dish antennas, though of a special type called offset paraboloid that provides an unblocked aperture. Sample illustrations of these two kinds of antennas are shown in Figure 4.

Next, the total number of antennas required in SKA1-Mid (and their layout and configuration) and the total number of dipole antenna stations in SKA1-Low (and their layout and configuration) as well as the number of dipole antennas in each station, are designed to meet the requirements of the sensitivity, the angular resolution and the quality of the images required by the key science drivers. This leads to a configuration where there are a total of 197 dish antennas in SKA1-Mid, spread out over distances up to 150 km (Figure 5). Of these, 133 dishes will be the newly designed SKA1-Mid dishes (as shown in Figure 3) that are 15 m size antennas, each capable of supporting five receiver bands (to cover the frequency range of 300 MHz–14

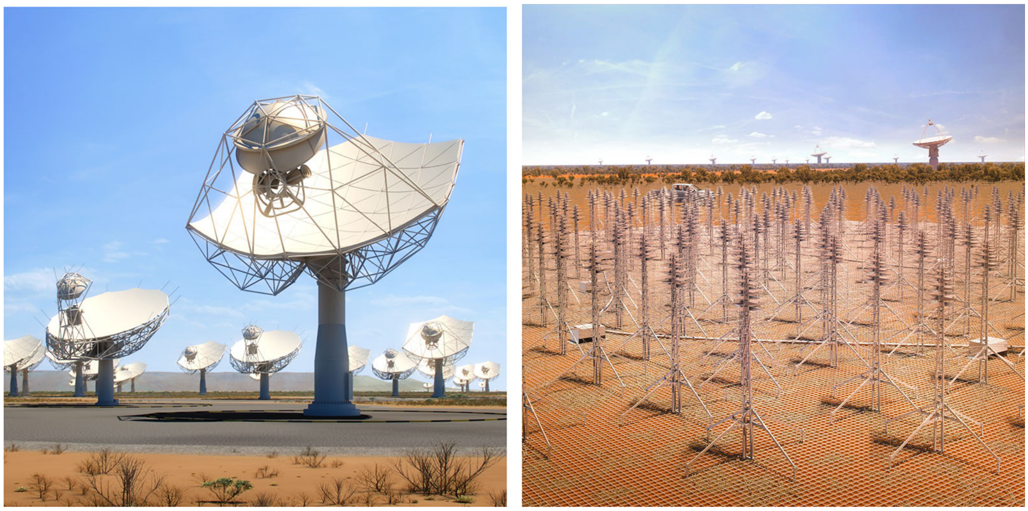

Figure 4. Artist's impressions of how the SKA1-Mid dish antennas (left) and SKA1-Low dipole antennas (right) will look like. The dish antennas in the background of the SKA1-Low station of dipoles depict the ASKAP array (credit: SKA Observatory).

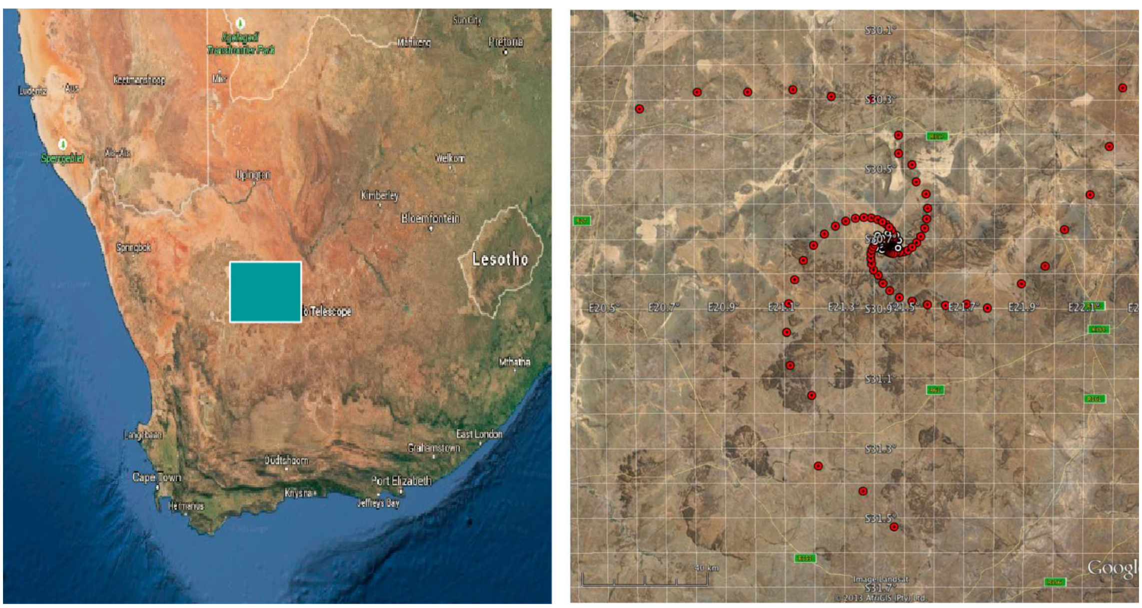

Figure 5. Location (left panel) and proposed configuration (right panel) of SKA1-Mid array which is coming up in the Northern Cape region in South Africa (credit: SKA Observatory).

GHz); the remaining 64 dishes will be antennas of the MeerKAT array, which will be incorporated into the SKA1. The SKA1-Mid configuration will have a centrally concentrated core (of radius about 3 km) and 3 spiral arms extending to about 80 km (Figure 5), located in the Karoo region of the Northern Cape of South Africa. For SKA1-Low, there will be as many as 131,072 low-frequency dipole antennas arranged in 512 stations, each having 256 dipoles. The SKA1-Low will also have a centrally concentrated core of radius <2 km, with the rest of the stations spread out on 3 spiral arms with maximum antenna separations of up to 65 km (Figure 6), located in the Murchinson shire region of Western Australia. Whereas SKA1-Low and SKA1-Mid will mostly operate as independent telescopes with observing plans driven by their respective science requirements, in principle it will be possible to observe the same source from both the telescopes simultaneously at their respective frequencies. However, given the separation in longitude between these two telescopes, the amount of common view time for most sources will be rather limited.

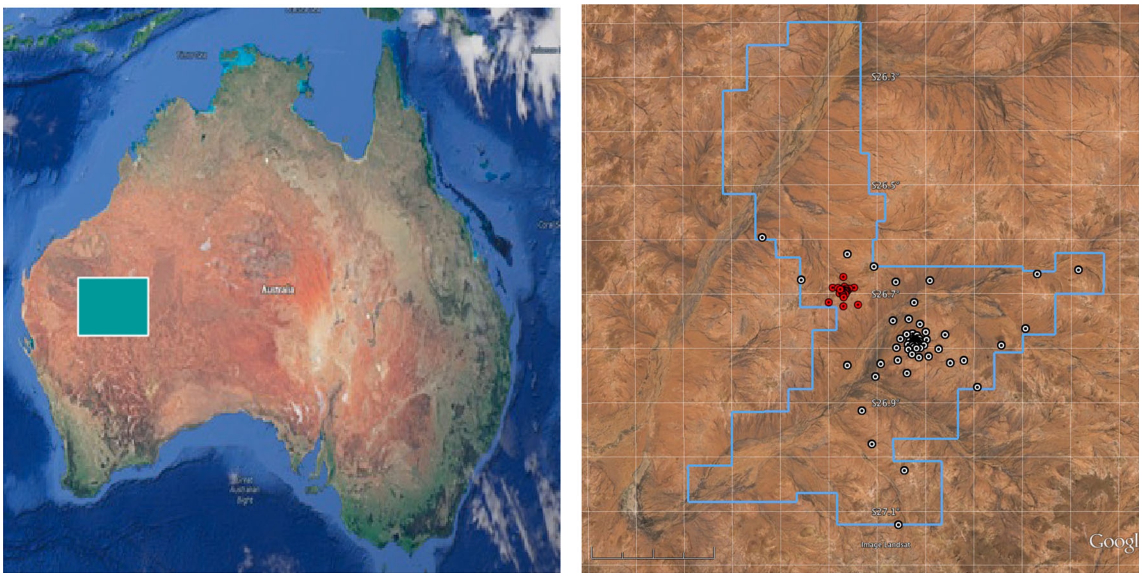

Figure 6. Location (left panel) and proposed configuration (right panel) of the SKA1-Low array which is coming up in the western part of Australia (credit: SKA Observatory).

The radio waves received by the antennas of SKA1-Low or SKA1-Mid are amplified and processed by sophisticated, low-noise electronics receiver systems, connected to the receiving elements (dipoles or dishes). In order to minimise the self noise from these electronics, they need to be cooled to cryogenic temperatures for SKA1-Mid receiver system. For SKA1-Low, the signals from the 256 dipoles in each station will be combined in special digital signal processing electronics to produce multiple station beams.

The signals generated from the distributed network of antennas of SKA1-Mid (dishes) and SKA1-Low (stations of dipole antenna arrays) need to be brought together to central locations, where the final correlation or beamformer outputs can be generated using dedicated signal processing hardware. Once again, the different science goals of the SKA require different kinds of signal processing and products to be generated, such as the correlation outputs required to carry out the high resolution imaging results, and the beamformer outputs required for observations of time varying sources like pulsars and fast transients. To bring the signals together from the distributed antennas, an extensive network of optical fiber connections has been designed. As shown in Figure 7, the total data flow over this network is going to be 5.8 Tbits s^{-1} for SKA1-Low (from the stations to the SKA1-Low correlator and beamformer at the central facility) and 9.0 Tbits s^{-1} SKA1-Mid (from the antennas to the SKA1-Mid correlator and beamformer at the central station). Furthermore, as Figure 7 shows, the data from the above correlators and beamformers for SKA1-Low and SKA1-Mid will go to the science data

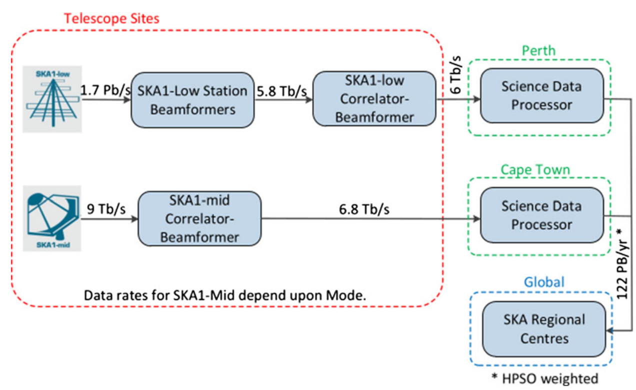

Figure 7. Block diagram showing the data flow patterns and data rates in the SKA1-Low and SKA1-Mid telescopes, as well as to the regional centers located in different member countries of the SKA (credit: SKA Observatory).

processors (located at Perth in Australia and Capetown in South Africa, respectively), and from there, the relevant data products are to be distributed to the SKA regional centers located globally in different SKA member countries. The aggregated data rate in these regional data centers is expected to be a phenomenal 122 PBytes yr^{-1}!

The cost of building the above description of the SKA1 is nothing less than astronomical: as per detailed estimates coming from the design exercise and a thorough cost review conducted by an external professional agency, the capital cost of construction for building the SKA1 is pegged at 1200 million Euros over a 10 year period extending till 2030. In addition, as the SKA1 observatory starts becoming functional, operational costs will start building up and are

Figure 8. India joins the SKA as a full member—signing ceremony at Mumbai, India, on 5 October 2015, with Prof. Philip Diamond (SKA) and Dr R. K. Sinha (DAE).

estimated to be 700 million Euros over the same 10 year period. The full details of the plan to build the SKA1 can be found in the construction proposal, put up by the SKA organisation (SKA Phase-1 Construction Proposal 2020).

4. India's participation in the SKA

India, with its strong tradition in radio astronomy research and building of facilities, such as the GMRT near Pune (Swarup *et al.* 1999; Gupta *et al.* 2017), has been an active participant in the scientific, technical and administrative activities of the SKA project since the initial days. In fact, one of the earliest concepts for a large radio observatory of the class of the SKA came from the radio astronomy group in India, led by Prof. Govind Swarup, in the early 1990s (Swarup 1991). When the SKA Organisation was formed in 2012, India joined as an associate member, and became a full member in October 2015 (see Figure 8). India has contributed actively to the design phase of the SKA, including a leadership role in the Telescope Manager work package (see, e.g., Diamond & Gupta 2017). At present, India is awaiting final approval from the Government of India to join the international treaty organisation of the SKA observatory as a full member, for the construction phase of SKA1.

4.1 *Participation in technical activities*

During the design phase, India was involved in a few different areas, notably the Telescope Manger, the Signal and Data Transport and the Central Signal Processing work packages. Indian scientists from the National Centre for Radio Astrophysics (NCRA) led a consortium of seven SKA member countries for the design of the Telescope Manager system, which will be the controlling nerve center and brain behind the functioning of the entire SKA Observatory, as shown in Figure 9 (e.g., Natarajan *et al.* 2016). It was the first design consortium to complete and submit the final design, as early as mid-2018. In the ongoing bridging phase, India is continuing to build up on these activities with early prototyping efforts. This work has direct synergy with developments at the GMRT and a smaller, early version of the Telescope Manager design has been developed and deployed at the GMRT. Many of these SKA technical activities in India have been 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 of SKA1 as well.

In particular, India is poised to play a lead role in the production of the observatory monitor and control system, which is an expanded version of the Telescope Manager, with additional features and capabilities added to the scope. Further, India is going to play a significant role in building the digital electronics needed for the signal processing at the SKA1-Low stations, and will also be contributing to the construction of the radio frequency electronics for one of the bands of the SKA1-Mid antennas. In addition to these direct contributions to the SKA project, India will also be building a SKA regional data center in the country that can host a significant portion of the data products from the SKA1, for easy access of the SKA data by the Indian astronomy community.

Many of the above activities have synergy with the work ongoing at existing Indian facilities like the GMRT, which has 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 provide valuable feedback for the activities to build and use the SKA Observatory. Furthermore, any new technology and intellectual property developed by the SKA collaboration will be available for use in India for any domestic research and development work. This will greatly aid the spread of next generation technology within the country.

4.2 *Participation of the Indian Scientific Communities in the SKA*

Along with the above, science activities in India related to the SKA have also been making good progress. Already, several Indian Scientists are members of the International Science Working Groups for the

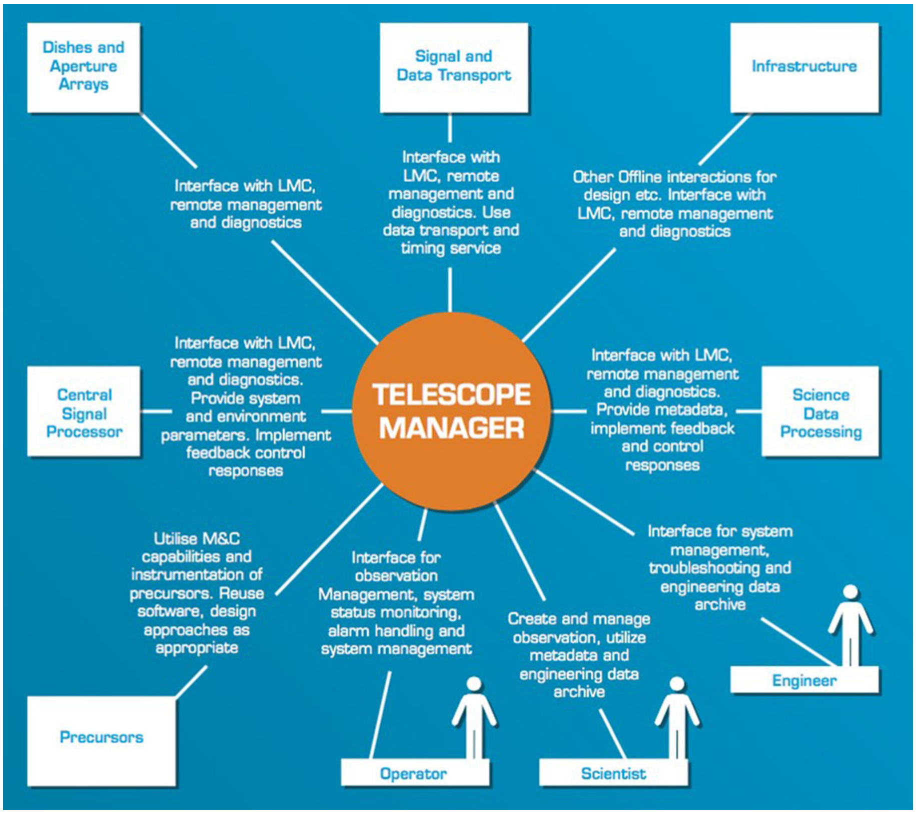

Figure 9. Illustrating the role of Telescope Manager in the SKA design. The Telescope Manager provides the 'nervous system' of the SKA, controlling and monitoring every aspect of the telescopes' performance.

SKA, including leadership roles in some of these groups. Furthermore, SKA India Science Working Groups which have been formed in 2014, 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 modeling, as well as using existing facilities like the GMRT for conducting research and investigations that will prepare the scientific community to make the best use of the SKA when it is ready. National level SKA workshops have been held in conjunction with the annual meeting of the Astronomical Society of India, for almost every year from 2014 onwards. India also hosted the International SKA Science Meeting in 2016 which was attended by a significant number of Indian scientists and students from a number of different organisations in the country, and provided a significant boost to SKA related science activities in the country.

The Indian astronomy community, guided by the SKA India Science Working Groups, has produced a series of papers describing their SKA science interests, which have been published in a special issue of the Journal of Astrophysics & Astronomy (Science with the SKA: An Indian Perspective 2016, see Figure 10). A refined and expanded version of these science case studies have been prepared as part of the supporting document for the proposal of Indian participation in the SKA1 that is currently under review by the Government of India. Some of the Indian working groups have also been making contributions to the international SKA science use cases, as documented in the SKA Science Books of 2015.

4.3 *SKA India Consortium*

To organise all the SKA related activities in India under a common umbrella consisting of all interested organisations within the country, the SKA India Consortium was formally launched in February 2015 at NCRA, Pune. Today, with more than 20 institutions from all over the country including colleges, universities and major research organisations signed up as members, and some others who are also engaged in SKA related activities (Figure 11), the SKA India Consortium is playing a major role in enhancing India's ability to participate effectively in the SKA project, in both science and technology. The overall guidance to the SKA activities in India is provided by the high-level SKA

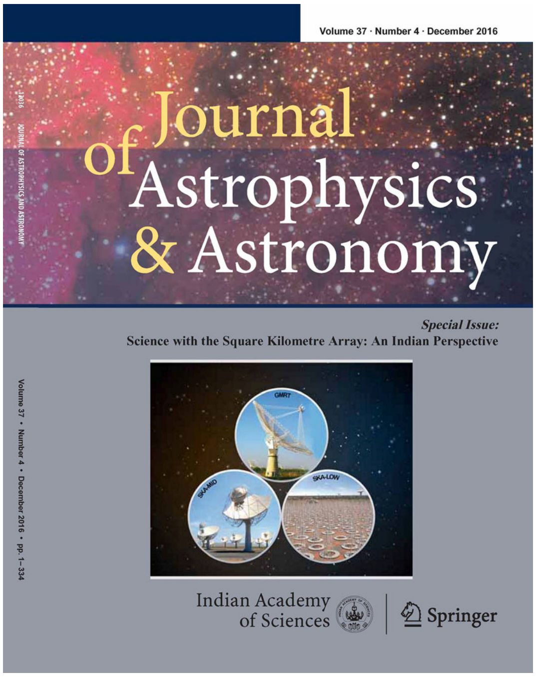

Figure 10. The first detailed version of the science case for the SKA by Indian astronomers was published in December 2016. Since then, more refined and updated versions have been produced as part of the main project proposal for India's participation in SKA1.

Figure 11. Map showing the country-wide distribution of institutions that are either members of the SKA India Consortium or otherwise involved in the SKA India activities.

India Steering Committee constituted by the Government of India.

4.4 *Benefits of Indian participation in SKA*

Benefits from India's participation in the SKA will be manifold. On the science front, it will allow Indian astronomers to have direct access to the best facility in the world in the future. On the technology front, it provides 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: antennas, 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 facilitate 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.

5. Summary

In summary, the SKA is a truly next generation project for astronomy as well as for science in general. It is also a major driver of several next generation technology developments. Having successfully completed the design phase, the governments, research organisations, scientists and engineers involved are now embarking on the construction of the SKA1 observatory, which is aimed to become fully operational towards the end of this decade, and expected to 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 to access to the best experimental radio astronomy facility of the future.

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