Special Section Guest Editorial: The SKA Observatory

Anna Bonaldi,[a] Stefan J. Wijnholds,[b] Luca Stringhetti,[a,c] and Justin Jonas[d,e]

[a]SKA Observatory, United Kingdom
[b]ASTRON, The Netherlands and University of Stellenbosch, South Africa
[c]INAF IASF, Milano, Italy
[d]Rhodes University, South Africa
[e]South African Radio Astronomy Observatory, South Africa

The Square Kilometre Array (SKA) Observatory, comprising the SKA-Low telescope in Australia and the SKA-Mid telescope in South Africa, will ultimately cover a continuous frequency range from 50 MHz to 15 GHz with two antenna technologies and 6 frequency bands. It will be a world-leading radio facility. With the observatory now just established and the two telescopes in construction, the aim of this special section is to provide an up-to-date overview of the planned SKA as well as designs for its future.

The design of the SKA was driven by a very broad and ambitious set of science goals. The SKA science book[1] provides a comprehensive and detailed description of these science goals. Here, we give only a brief summary:

1. Penetrating the earliest stages of the Universe (Cosmic Dawn) as it transformed from a sea of neutral hydrogen to the first stars and galaxies (Epoch of Reionization);
2. Mapping the evolution of galaxies from their earliest formation until the present day using high-sensitivity observations of huge samples of galaxies;
3. Strong testing of Einstein's theory of gravity in the regions around black holes;
4. Discovering long-period gravitational waves, which have emanated from the Big Bang itself;
5. Understanding how cosmic magnetism has shaped the Universe;
6. Tracing the star-formation history of the Universe;
7. Discovering the earliest stages of the formation of disks around stars before planet formation;
8. Finding the astronomical origin of mysterious bursts of radio emission.

The SKA design posed several technological challenges, such as large-N radio interferometry, resilience to radio frequency interference (RFI), high sensitivity, high system complexity, a harsh operating environment, and large data volumes. A systems engineering approach, based on best practices, has been adopted throughout the design to meet the scientific requirements within cost and time constraints. (See Kusel for a description of how this methodology was applied to the design of the MeerKAT radio telescope, an SKA precursor in South Africa.)

The necessary development was informed and assisted along the way by SKA precursors like the Australian SKA Pathfinder,[2] MeerKAT,[3] the Murchison Widefield Array,[4] and the Hydrogen Epoch of Reionization Array[5] and pathfinder instruments.[6] Such instruments not only are acting as technology demonstrators for components of the SKA but also are pioneering some of its planned observations. Amongst several upcoming projects of interest is the Hydrogen Intensity and Real-time Analysis eXperiment, or HIRAX (Crichton et al.), to be deployed at the SKA site in South Africa.

Labate et al. present an overview of the design of SKA-Low, covering the 50–350 MHz frequency range. Some of the most stringent requirements for SKA-Low derive from the Cosmic Dawn/Epoch of Reionization science case. This very challenging measurement (Barry et al.) is currently being attempted by several experiments, like EDGES[7] and SARAS[8] and telescopes, such as MWA[4] and LOFAR.[9] An accurate characterization of all instrumental effects is needed to reach the desired calibration accuracy. This includes the effect of the antenna radiation patterns (Virone et al.) Some effects, such as the impact of the far sidelobes of the SKA-Low stations (Trott) and mutual coupling (Bolli et al.) on Cosmic Dawn/Epoch of Reionization science, are very hard to calibrate and need to be minimized as much as possible by design. Significant prototyping activity has been undertaken for the SKA-Low station, as discussed in Bolli et al., Macario et al., and Wayth et al.

An overview of the design of SKA-Mid, covering the 350 MHz–15 GHz frequency range in 5 different bands, is presented in Swart et al. Lehmensiek et al. give a detailed description of the design of the Band 2 (L-band, 950 MHz–1760 MHz) cryogenic receiver front-end. In Phase I, which is the current construction project, SKA-Mid will comprise a total of 197 dishes, 64 of which will be integrated from the currently operational MeerKAT telescope.

After completing the construction and commissioning of the planned SKA Phase I, the SKA Observatory development program will ensure the longevity of the SKA Observatory by means of several upgrades. One of the possible extensions that are envisioned for SKA Phase II is the Mid-Frequency Aperture Array (MFAA), which will operate in the 450 to 1450 MHz range. Wilke et al. discuss the challenges involved in the calibration of the very large number of analog receive paths involved and possible solutions to that problem.

The SKA design has many engineering and programmatic challenges. Two examples are data transport and accurate time keeping. To overcome the data transport challenge for the SKA-Low telescope, RF-over-fiber systems are selected to transport the analog signals from the antennas to the analog-to-digital converters located in a central facility that is miles away from many stations. The details of the SKA-Low design choices are discussed in Perini et al. Time and frequency synchronization across the array are discussed in Hendre et al. and Naldi et al. for the SKA, and Burger et al. for MeerKAT.

Surely, SKA is recognized as one of the "Big Data" challenges for the next decade. By the time the SKA is in steady-state operation, SKA-Low and SKA-Mid will produce, respectively, a raw data rate of ~ 2 Pb/s and ~ 20 Tb/s. The Correlator and Beam former Facility (CBF) is at the heart of the signal processing. Hampson et al. address the SKA-Low CBF, while the one adopted by MeerKAT is described in van der Byl et al. Due to the large data volumes, data calibration and imaging will be the responsibility of the observatory and will happen at the Science Data Processor (SDP). The SDP will reduce the data rates out of each telescope to ~ 300 PB a year. Ambitious capabilities for calibration of instrumental and atmospheric contributions as functions of time, frequency, and position are required to achieve the scientific goals of the SKA. A general description of direction-independent corrupting effects is given in Alachkar et al. Calibration of direction-dependent ionospheric effects, particularly relevant for SKA-Low, is addressed in Rioja et al. The issue of RFI is discussed and applied to the MeerKAT radio telescope in Sihlangu, Oozeer, and Bassett Calibrated SKA data will finally reach a network of SKA Regional Centers (SRCs). Prototyping is now under way for the SRC network as well as the individual nodes. Garrido et al. describe one of those efforts.

The guest editors would like to thank all authors and referees who have contributed to this special section, as well as all researchers, engineers, and professionals around the world who are making the SKAO a reality.

References

1. R. Braun et al., "Advancing astrophysics with the square kilometre array," Vol. 1–2 (2015).
2. A. W. Hotan et al., "Australian square kilometre array pathfinder: I. system description," *Publ. Astron. Soc. Aust.* **38**, e009 (2021).
3. J. L. Jonas, "The MeerKAT radio telescope," in *MeerKAT Sci.: Pathway SKA, Proc. Sci.* (2016).
4. R.B. Wayth et al., "The Phase II Murchison widefield array: design overview," *Publ. Astron. Soc. Aust.* **35**, e033 (2018).
5. D. R. DeBoer et al., "Hydrogen epoch of reionization array (HERA)," *Publ. Astron. Soc. Pac.* **129**, 045001 (2017).

6. Square Kilometre Array Observatory, "Precursors and Pathfinders," https://www.skatelescope.org/precursors-pathfinders-design-studies/ (2022).
7. J. D. Bowman, A. E. E. Rogers, and J. N. Hewitt, "Toward empirical constraints on the global redshifted 21 cm brightness temperature during the epoch of reionization," *Astrophys. J.* **676**(1), 1 (2008).
8. S. Singh et al., "SARAS 2: a spectral radiometer for probing cosmic dawn and the epoch of reionization through detection of the global 21-cm signal," *Exp. Astron.* **45**, 269–314 (2018).
9. M. P. van Haarlem et al., "LOFAR: the low-frequency array," *Astron. Astrophys.* **556**, A2 (2013).