SKA Phase 1
Construction Proposal
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This document presents a 1.28 billion Euro (2020 €) project for the construction of the first phase of the Square Kilometre Array (SKA) Project, one of the most visionary and ambitious science projects of the 21st century. The project will establish the SKA Observatory as the leading infrastructure to promote global collaboration in radio astronomy, providing exceptional research capabilities to the worldwide astronomical community for the coming decades. Delivering the SKA will test the limits of engineering and scientific endeavour and allow participating countries to explore fundamental questions in astronomy and physics thanks to the SKA’s unique discovery potential.

Specifically, it is proposed to construct two telescopes: a mid-frequency array of 197 dishes in South Africa (133 15 m dishes and adding 64 13.5 m dishes from the MeerKAT Observatory) with a 150 km maximum separation between dishes, and a low-frequency array of 131,072 log-periodic antennas in Western Australia (512 stations with 256 individual antennas) with up to 65 km maximum separation between antennas. The two facilities will be operated separately, but will, along with the data processing centres and the global headquarters in the United Kingdom, form a single observatory. This proposal covers the initial phase of the SKA deployment, SKA1. Evolutions of the telescopes are planned with a long-term ambition to increase the number of mid-frequency dishes to 2000 and the low-frequency antennas well beyond current numbers.

Figure 1. View of MeerKAT antennas at the Karoo RSA site (lower) and prototype SKA1-LOW antennas at the MRO WA site (upper).
This Construction Proposal includes both the elements required to deliver the telescopes and instrumentation as well as the network of infrastructure and data processing required to support those facilities; it is one of the two paired documents, along with the Observatory establishment and development plan, which in combination represent the whole of the SKA Observatory.

The SKA will be constructed on already-operational radio observatory sites, which will be expanded and enhanced to accommodate the new infrastructure and all aspects of access to it. In addition, such powerful telescopes require significant processing both on and off-site to manage the quantity of data they will generate. This Construction Proposal includes a plan that will deliver significant data processing facilities and also the architecture to feed and coordinate the required regional centres which will act as windows to the observatory for the user community, enabling the world-leading science it promises.

The two sites have been chosen due to their relative radio quietness. This makes them ideal for radio astronomy, as MeerKAT (South Africa) and ASKAP (Australia) and the MWA (Australia) have already demonstrated. To ensure maximum benefit from the natural environment, a great deal of effort has been applied to the design of both telescopes to ensure that very little radio frequency interference is self-generated and that it is controlled by the infrastructure as much as possible. This has been taken into account within the overall architecture as well as the detailed design.

The scale and ambition of the SKA is a major endeavour in science, technology and engineering, demanding a global effort and long-term investment. Partnerships between institutes, universities and industry have formed to build and plan the exploitation of the telescopes, their systems and instruments. In addition, the technologies and innovations being developed to deliver the SKA have already found, and will continue to find, wider applications within industry and deliver broader benefit for society. It is clear that a project of the size and technological challenge of the SKA will require significant international cooperation across a wide range of partners and international bodies and have a significant economic, cultural, and scientific impact which from the outset will be implemented to ensure the maximum benefits outside astronomy in areas such as data science.

As the world’s largest radio-frequency interferometer, SKA will establish itself as the radio astronomy component of a suite of major facilities spanning the electromagnetic spectrum, on the ground and in space. In an era where multi-messenger, multi-wavelength astronomy will be accelerated by access to a new generation of highly-capable facilities, SKA will be in the prime position to provide targets of opportunity for follow up with the next generation of extremely large optical telescopes, and many other facilities, and to take full advantage of the discoveries made at other wavelengths/frequencies.

The work carried out to date, with industry involvement, has reduced the risks associated with both the technical demands and the management of the programme. Following successful technical and financial reviews, the programme is in an excellent position to move into construction, and the timing will ensure that SKA Observatory assumes a world-leading position amongst the largest astronomical facilities and the resulting research and discovery benefits.

This proposal is concerned mainly with the technological and management challenges of building the SKA; its main aim is to describe and promote a facility that will allow the scientific community to tackle some of the most exciting scientific questions of today (as addressed in the SKA Science Book) and bring what is perhaps the most compelling set of benefits of any large-scale research infrastructure to society through innovation, sustainability, jobs creation, skills training, education, outreach, tourism, culture, and strong local community relations. Should the governments of the SKA member states come to a timely decision regarding authorising the programme, their involvement and leadership in these discoveries and wider benefits for their economies and societies will be assured.
1 Proposal Introduction

The SKA Observatory will be delivered in phases. The first phase, called SKA1, is the subject of this proposal and represents a fraction of the long-term aspiration of the full SKA.

This proposal covers all aspects of the complete SKA1 design baseline, its procurement and construction.

To date, the project has completed the pre-construction phase and in so doing has been subjected to a series of major reviews to ensure that the project is ready for construction. These include:

- Element (subsystem) CDRs.
- System CDR carried out in December 2019 by an external international panel.
- External cost and management review carried out by an international construction consultancy in April 2020.

The outcome of these reviews demonstrates that the project is ready to start construction with sufficient funding, contingency and knowledge and control of the risks and opportunities.

This Construction Proposal describes, in general terms, the science requirements for the project, what the scope of the project is, how the project will be executed, monitored and controlled as well as the wider benefits of the project to society. Much more detail of the SKA1 construction phase is contained in a confederation of separate documents. Here we provide a simple map of the detailed project documentation to this Construction Proposal. The complete list of reference information and its organisation is provided in Annex D.
A high-level representation of the path through the project execution is shown in Figure 2 below.

Figure 2. Illustration of the high-level process for project execution and the associated products and guiding documents.
2 Scientific Motivation

The SKA1 design defines a pair of next-generation telescopes to enable transformational science and to complement other front-line telescopes in the emerging era of multi-messenger astronomy. The breadth of science that the SKA will address is truly remarkable:

- Penetration of the earliest stages of the Universe (Cosmic Dawn) as it transformed from a sea of neutral hydrogen to the first stars and galaxies.
- Mapping the evolution of galaxies from their earliest formation until the current day using high-sensitivity observations of huge samples of galaxies.
- Strong-field tests of Einstein’s theory of gravity in the regions around black holes.
- Discovering long-period gravitational waves, which have emanated from mergers of the most massive black holes and possibly even the big bang itself.
- Understanding how cosmic magnetism has shaped the Universe.
- Tracing the star-formation history of the Universe.
- Revealing the earliest stages of the formation of planets around stars.
- Utilising distant bursts of radio emission to probe the otherwise invisible intervening ionised gas and thereby study the evolution of the Universe.
- Exploring the origins of life itself through the study of radio emission from prebiotic molecules.
- Potential direct detection of the existence of intelligent life via technologically produced radio signals.

Some of the specific observations that would allow achievement of this scientific scope are listed in Table 1. This list of high priority science objectives (HPSOs) for the SKA was put forward by the science working groups (SWGs) that constitute the long-term community engagement in the SKAO design process [SKA1 Science Priority Outcomes].

Table 1. High priority science objectives, listed by science working group (SWG).

<table>
<thead>
<tr>
<th>SWG</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD/EoR</td>
<td>Physics of the early Universe IGM – I. Epoch of Reionisation Imaging</td>
</tr>
<tr>
<td>CD/EoR</td>
<td>Physics of the early Universe IGM – II. Epoch of Reionisation Power Spectrum</td>
</tr>
<tr>
<td>Pulsars</td>
<td>Reveal pulsar &amp; milli-second pulsar populations for gravity tests and Gravitational Wave detection.</td>
</tr>
<tr>
<td>Pulsars</td>
<td>High precision timing for testing gravity &amp; Gravitational Wave detection.</td>
</tr>
<tr>
<td>HI</td>
<td>Resolved HI kinematics &amp; morphology of gas-rich galaxies ($10^{10}$ M$_\odot$) out $z \sim 0.8$.</td>
</tr>
<tr>
<td>HI</td>
<td>High spatial resolution studies of the ISM in the nearby Universe.</td>
</tr>
<tr>
<td>HI</td>
<td>Multi-resolution mapping studies of the ISM in our Galaxy.</td>
</tr>
<tr>
<td>Transients</td>
<td>Solve the “missing baryon problem” at $z \sim 2$ &amp; determine the Dark Energy Equation of State.</td>
</tr>
<tr>
<td>Cradle of Life</td>
<td>Map dust grain growth in the terrestrial planet-forming zones at a distance of 100 pc.</td>
</tr>
<tr>
<td>Magnetism</td>
<td>The resolved all-sky characterisation of the interstellar &amp; intergalactic magnetic fields.</td>
</tr>
<tr>
<td>Cosmology</td>
<td>Constraints on primordial non-Gaussianity &amp; tests of gravity on super-horizon scales.</td>
</tr>
<tr>
<td>Cosmology</td>
<td>Angular correlation functions to probe non-Gaussianity &amp; the matter dipole.</td>
</tr>
<tr>
<td>Continuum</td>
<td>Star formation history of the Universe – I &amp; II. Non-thermal &amp; Thermal processes.</td>
</tr>
</tbody>
</table>

The history of astronomy is replete with unexpected discoveries. Astronomy is not a laboratory science; it is an observational science in which observatories with very broad capabilities have delivered enormous scientific impact in ways that could not be foreseen when they were designed and built. Many of the most important discoveries in astronomy fall into this category of exploratory
science. Hence, a guiding design principle of the SKA has been to enable the broadest possible range of science, including even currently unanticipated observations. The SKA will monitor the sky in unrivalled detail and map it hundreds of times faster than any current radio facility.

2.1 Synopsis of Science Spanning the SKA1 Frequency Range

The proposal for the SKA arose from a demand from the science community for new capabilities to address fundamental questions in astronomy at the long-wavelength end of the electromagnetic spectrum. Through years of design and development, the project has evolved to the realisation of the observatory presented in this proposal. The mission of SKA1, presented in the following chapters, is to enable transformational science.

SKA1 is far more than two telescopes designed to carry out a few specific experiments. An open scientific consultation process, leading to a list of science drivers (key areas of science) has, over time, refined and driven the development of the design. A series of creative investigations, beginning with science assessment workshops, proceeding to a review of science priorities and culminating in the publication of a major review of millimetre-to-centimetre wave astronomy, the SKA Science Book “Advancing Astrophysics with the Square Kilometre Array”, has laid out decades of SKA research ahead, which will undoubtedly be bolstered by the SKA’s role in uncovering a range of unexpected phenomena throughout the Universe.

SKA1 comprises two complementary and quite different telescopes to address the high priority science cases: SKA1-LOW, with a frequency range of from 50 – 350 MHz and SKA1-MID, with a frequency range of 0.35 – 15.4 GHz in 5\(^1\) bands.

\(^1\) The feeds for bands 3 and 4 are not included in the initial deployment of SKA1.
Figure 3. A chart showing the major areas of observation and investigation for SKA1 in order of frequency. The SKA1-LOW frequency range is shown in green at the top of the figure, and SKA1-MID in red (bands 1–5). The vertical coloured stripes show the coverage of the observing bands, while darker grey shading shows overlaps. The numbers in brackets beside the labels on the science areas are the high priority science objective numbers [SKA1 Science Priority Outcomes].

Figure 3 shows the high and medium-priority observation categories derived from the SKA science prioritisation process to illustrate the mapping of science to the SKA frequency range. The list of categories is shown in order of increasing frequency to illustrate their correspondence with the planned observing bands, which are shown at the top of the figure. Blue horizontal bars are used to designate how the high priority science objectives (HPSOs) are distributed between the two telescopes and how they map to the SKA1-MID receiver bands. Their location in the plot illustrates why bands 2, 5, and 1 will have the highest priority for the initial deployment of SKA1-MID since they are essential for almost all the HPSOs for which SKA1-MID is relevant. Priorities for new receiver bands may change as a result of new discoveries or engineering breakthroughs.
2.2 Project Research Objectives

An indicative programme of “high priority science objectives” (HPSOs) was defined by the SKA science working groups [SKA1 Science Priority Outcomes] and the envelope of requirements for their successful completion has formed the basis for the SKA1 science requirements. The science requirements have in turn flowed down into all aspects of the system design. Some of the current key scientific objectives of the SKA are summarised below in order of their decreasing distance; these summaries provide a snapshot of the huge range of science possible with the SKA.

2.2.1 Cosmic Dawn and the Epoch of Reionisation

When did the first generations of galaxies form? What were their star-formation and AGN properties? How did they interact with each other? What is the structure of the intergalactic medium during the first billion years? What is the thermal and ionisation history of the baryons?

The footprint of all these processes is imprinted in the hydrogen gas, the major constituent of the intergalactic medium, and can be probed by observations of its hyperfine spectral line transition (occurring at the rest frequency of 21 cm). The SKA will carry out the deepest observations ever undertaken of the diffuse neutral hydrogen gas to trace the evolution of cosmic structure in the 6 < z < 30 range, unveiling the epoch when the very first luminous structures were born and how their growth ionized the intergalactic medium.

![Figure 4. A simulation of the brightness temperature fluctuations due to the redshifted 21 cm transition of neutral hydrogen in the early universe.](image)

**Cosmic dawn:**
Most models of structure formation predict the first stars to form at z ~ 30 and start to shine in an otherwise dark Universe. Their UV radiation excites the neutral Hydrogen gas which becomes a source of 21 cm radiation. As the intergalactic medium is colder than the cosmic microwave background (CMB), the 21 cm is expected to be seen in absorption.

**Heating era:**
As star formation is continuous in the first galaxies, X-ray emission is expected to be produced by accretion on the first stellar black holes (or mini-quasars). Eventually, this X-ray background heated the intergalactic medium above the CMB with the 21 cm signal seen in emission.

**Cosmic reionisation:**
Persistent star formation eventually generates a background of UV radiation that escapes the host galaxies and begins to ionise the surrounding medium as these first galaxies form and evolve. Deep observations with the SKA will measure the evolution of the 21 cm signal enabling an accurate timing...
of the various transitions, allowing us to learn the nature of the first luminous sources, the presence and properties of X-ray sources in the early Universe and the properties of the sources that were mostly responsible for cosmic reionisation.

2.2.1.1 Image Tomography of Reionisation

Cosmic reionisation is a complex physical process with a tight interplay between galaxies and the surrounding medium. An example is shown in Figure 5 which shows the matter distribution (green) inside a bubble of ionised hydrogen (dark regions) with the galaxy population highlighted (white circles, their size is proportional to the star formation rate). Hydrogen is still neutral in red regions. The most massive, actively star-forming galaxies are located at the peaks of the matter density field and generate regions of ionized gas around them. SKA observations will map the contrast between neutral and ionised regions as a function of redshift, measuring the three-dimensional structure of reionisation. Together with near-infrared observations that will reveal the galaxy population, SKA observations will map the interplay between the intergalactic medium and the ionising sources that will allow us to learn not just the physical properties of the high redshift sources, but also about the underlying dark matter halo distribution and the cosmological density field.

![Figure 5](image)

Figure 5. Simulations (left) of the intergalactic medium and the galaxy population at z = 7.6 (credit: Mutch & Geil). Simulated image (right) of the 21 cm signal at z = 8. The image was convolved to the expected SKA resolution. Largely ionised regions are in blue. SKA observations will be able to map the contrast between an ionised and neutral region in the 6 < z < 12 redshift range.

2.2.2 Cosmology

The SKA will enable pioneering cosmological surveys, probing immense volumes of the Universe which to date have been unexplored at radio wavelengths. This will be done by observing emission in both radio continuum and the 21 cm spectral line of neutral hydrogen (HI). The position in the radio sky of millions of galaxies, and intensity maps made by their collective HI emission, trace the large-scale structure of the Universe, which can reveal the form and growth of dark matter structures over time. Light travelling from distant galaxies is bent by the intervening dark matter, thus creating small shape distortions (weak gravitational lensing) that can be measured to detect this otherwise invisible component. These surveys will enhance our understanding of various aspects of cosmic history, including the faint imprints of the primordial period of inflation, the early stages of galaxy formation, as well as the nature of gravity, dark energy and dark matter which determine the growth of late time large-scale structure.
Proposed SKA1 cosmology surveys:

- Medium-deep survey of 5,000 deg$^2$ at 0.95-1.4 GHz for:
  - HI galaxy redshift survey with 3.5 million objects
  - Weak Lensing shape measurements with ~50 million objects
  - Continuum galaxy survey with ~60 million objects
- Wide survey of 20,000 deg$^2$ at 0.35-1.05 GHz for:
  - Continuum galaxy survey with ~100 million objects
  - HI intensity maps for 0.35<z<3
- Deep survey 100 deg$^2$ at 200-350 MHz for:
  - HI intensity maps for 3<z<6

Cosmology science goals

- **DARK ENERGY**: Investigate the nature of dark energy by measuring the expansion rate of the Universe at different times
- **MODIFIED GRAVITY**: Test for deviations from general relativity
- **NON-GAUSSIANITY**: Detect imprints of inflationary physics at ultra-large scales
- **DARK MATTER**: Probe the nature of dark matter through its gravitational interaction with normal matter
- **HI EVOLUTION**: Constrain the evolution of the abundance of neutral hydrogen in the Universe for 0<z<6
- **COSMOLOGICAL PRINCIPLE**: Test by measuring our motion relative to the Universal expansion

![Figure 6. Depiction of the expansion and evolution of the Universe. Image credit: NASA/WMAP science team.](image)

### 2.2.2.1 Weak Lensing

A statistical measurement of the shapes of millions of galaxies as a function of sky position and redshift enables us to measure the gravitational lensing effect of all matter – dark and baryonic – along the line of sight between us and those galaxies. This allows us to track the abundance of these structures and how they have grown. The combination of optical and radio weak lensing measurements will be crucial for the control of systematics within the data (cosmology science goals addressed: DARK ENERGY – DARK MATTER – MODIFIED GRAVITY).
2.2.2.2 HI Intensity Mapping

The mapping of the HI spectral line via integrating over multiple sources within a 3D pixel to create tomographic maps tracing the large-scale structure for $0 < z < 6$. For SKA1-MID, the HI intensity mapping survey will rely on the “single-dish mode” of observation, such that the maps are sensitive to the largest scales on the sky. Dark energy and neutrino mass constraints will be comparable with the ones from stage IV surveys like Euclid (cosmology science goals addressed: HI EVOLUTION – DARK ENERGY – NON GAUSSIANITY – MODIFIED GRAVITY).

Figure 8. From dark matter (left) to HI intensity maps (right) using the simulations from Wolz et al. (2016).
2.2.2.3 Radio Continuum Survey

The positions of many millions of distant radio galaxies over the southern sky will be used to measure the largest structures in the Universe, which act as cosmic fossils, first laid down during the Big Bang. We will also measure our motion relative to the universal expansion, testing the cosmological principle that is assumed in standard analyses (cosmology science goals addressed: DARK ENERGY – MODIFIED GRAVITY – COSMOLOGICAL PRINCIPLE).

![Figure 9. Dipole directions for a survey depth of 10 microJy, based on 500 simulations each, in Galactic coordinates and stereographic projection. Dots show CMB dipole (white), and the kinematic dipole with (red) and without (blue) local structure (from Bengaly et al. (2019)).](image)

2.2.2.4 HI Galaxy Redshift Survey

The unique clustering properties of HI-selected galaxies provide a measure of large-scale structure that is complementary to optical surveys, while accurate distance measures coupled with peculiar velocities along the line of sight enabled by the Tully-Fisher relation can probe modified gravitational physics and test General Relativity. The proposed medium-deep survey at \( \sim 1 \) GHz could be done in conjunction with the SKA HI SWG, maximising the scientific return for a single survey (cosmology science goals addressed: HI EVOLUTION – DARK ENERGY – NON GAUSSIANITY).

![Figure 10. Distribution of HI (blue open circles) and optical (red filled circles) sources. From Haynes et al. (2011).](image)
2.2.3 The Transient Universe

The SKA will revolutionise our understanding of topics ranging from stellar evolution and relativistic astrophysics to cosmology, via the study of variable and one-off astrophysical signals. Transient radio signals point to the sites of the most extreme phenomena in our Universe: e.g., supernovae, merging neutron stars, and the ultra-relativistic jets from accreting black holes. They give us unique insight into fundamental physics and through propagation effects on the radio signal they allow us to probe the intervening ionised and magnetised material that would otherwise be invisible to us. To name just a few examples of the astrophysical transients that the SKA will study:

2.2.3.1 Fast Radio Bursts

Discovered only a decade ago, fast radio bursts (FRBs) are a fascinating astrophysical puzzle. We now know that they originate in distant galaxies, but we have still not identified their physical origins. Dozens of theories have been proposed to explain these short but staggeringly luminous flashes of radio light. Are the FRBs that are seen to repeat created by exceptionally young, ultra-magnetised, neutron stars? Some FRBs appear to be one-off events, whose apparent lack of repetition suggests that they are created in cataclysmic explosions. However, whenever they can be accurately associated with an optical galaxy counterpart to yield a redshift, they allow a precision measurement of the baryonic density along that line of sight. With the anticipated large numbers (1000s) of precise localisations provided by the SKA, FRBs become a powerful cosmological tool for tracking the cosmic evolution of baryonic density (Macquart et al., 2020).

Figure 11. Artist’s conception of an FRB being localized to its host galaxy using geographically distributed radio dishes. Image credit: OzGrav, Swinburne University of Technology.
2.2.3.2  Gravitational Wave Events

With the discovery of the first gravitational wave sources, LIGO-Virgo has opened a new window on the Universe. We can use these gravitational waves to directly detect the mergers of neutron stars and black holes that spiral into each other as their orbits decay. Electromagnetic observations of these events are critical for understanding the resulting explosion and its aftermath. Radio observations, in particular, probe the relativistic outflows that are created. Low-frequency SKA observations will also probe sub-relativistic isotropic ejecta in surveys where the relativistic jets are missed.

Figure 12. Artist’s conception of two in-spiralling neutron stars, and their gravitational wave signature. Image credit: NASA.

2.2.3.3  Long Gamma-ray Bursts & Superluminous Supernovae

After exhausting their nuclear fuel, massive stars end their lives in supernovae and leave behind a neutron star or black hole. Long gamma-ray bursts and superluminous supernovae may be associated with even more extreme progenitor stars and explosions. Their relativistic jets and afterglows are well studied in radio bands, which can trace, e.g., the evolution of the outflow and its magnetisation, hence identify different channels of explosion.

Figure 13. Artist’s conception of a long gamma-ray burst. Image credit: NASA.
2.2.3.4 The SKA as a Transient Discovery and Follow-up Machine

The SKA will provide unprecedented sensitivity for detecting radio transients. Such observations will be triggered by the global suite of all-sky monitors spanning the electromagnetic spectrum, as well as multi-messenger alerts from, e.g., LIGO-Virgo and neutrino telescopes like IceCube. At the same time, the SKA will discover its own transients via the planned imaging and beam-formed (high-time-resolution) surveys. Critical to success is the ability to search for transients in parallel with other scientific use cases. Low latency for data access and the triggering of follow-up observations will also be key for delivering the science harvest. The SKA is poised to answer fundamental questions related to the origins and physics of known source classes like the examples above, and perhaps most excitingly: the SKA will discover astrophysical radio transients unlike any we have seen before, or perhaps even imagined.

2.2.4 The Evolving Energetic Universe

A powerful probe of our Universe is the continuum radio emission generated from the nearest star-forming galaxies to high-redshift clusters of galaxies, probing structure formation and evolution on all scales. Some specific focus areas in this realm are:

2.2.4.1 Cosmic Star Formation History

Understanding when, where, and how stars formed are key questions in astrophysics. Traditionally deep optical surveys are used to measure the star formation rate density at different epochs, but dust can obscure this emission leading to biases in our understanding of the cosmic star formation history. Unaffected by this, radio luminosity (powered by shocks from supernovae) is also a direct star formation tracer. Deep radio surveys now reach sensitivities where they are dominated not by powerful jets from black holes, but by star-forming galaxies. The SKA will probe deeper and wider, studying the star formation history as a function of many parameters, including galaxy mass, type, and environment as well as redshift.

Figure 14. Averaged 1.4 GHz image (left) of 445 star-forming galaxies at intermediate redshift contrasted with an averaged image of offset locations (right). Image credit: Bera et al. (2019).
2.2.4.2 Active Galactic Nuclei

AGN feedback processes have become a standard ingredient in models of galaxy evolution, but a clear understanding of these complex processes and their true role in shaping galaxy evolution remains elusive:

what is the relative importance of radiative winds and jet-driven feedback as a function of galaxy mass and epoch? Which role is played by the environment? What drives these processes? Sensitive SKA1 surveys up to ~2 GHz will probe the bulk of the AGN population over a wide range of redshift, environments and luminosities. At the same time, SKA1 surveys will be sensitive to the onset and earliest evolution of the radio-loud AGN phenomenon in the Universe, well into the epoch of formation of the earliest AGN (z > 7). SKA-LOW and MID multi-frequency surveys will provide the needed combination of spatial resolutions and spectral coverage for spectro-morphological AGN studies, aimed at a better understanding of their physics and life-cycles.

![Figure 15. This artist's concept depicts looking back in cosmic time to the quasar J1342+0928. The black hole resides in a mostly neutral universe, 690 million years after the Big Bang, at a time when the first galaxies were appearing and carving bubbles in the neutral hydrogen gas filling the universe. Image Credit: Robin Dienel / Carnegie Institution for Science.](image)

2.2.4.3 Galaxy Clusters

Galaxy clusters are the most massive objects in the Universe that have had the time to collapse under the influence of their own gravity. More than 80% of the huge cluster masses reside in dark matter. A hot and diffuse gas, permeating the space between cluster galaxies, dominates the baryonic component. Massive clusters can also “light up” at radio wavelengths due to the presence of non-thermal components, i.e., weak magnetic fields (~µG) and cosmic ray electrons in the ICM, giving rise to Mpc-scale synchrotron radiation. Observations show that this radiation is associated with dynamically disturbed systems suggesting that particle acceleration mechanisms related to turbulent motions and shock waves should be active in the ICM during the merging phase. SKA1 observations will be crucial for a complete census of diffuse emission in clusters and to investigate the presence of fainter emission associated to larger scales, from the outskirts of galaxy clusters to the cosmic web filaments.
2.2.4.4 Strong Gravitational Lensing

Gravitational lensing produces multiple images of distant radio sources, allowing the mass distribution of the foreground gravitational lensing galaxy to be modelled, whilst providing a high magnification view of the high redshift Universe. The SKA1-MID array will have an angular resolution of <0.5 arcsec, which is ideally suited for detecting gravitational lensing by galaxy-scale dark matter haloes. Shown in Figure 17 is a simulation (left and middle) of a gravitationally lensed extended star-forming galaxy and a point-like AGN with a total flux-density of 1 mJy when observed with SKA1-MID (McKean et al., 2015). The sensitivity and wide field-of-view of the SKA will permit the discovery of over $10^5$ new gravitationally lensed radio sources (at least 3 orders of magnitude more that are currently known) from a shallow all-sky survey over 1.65-3.05 GHz, which will be used to test models for dark matter and galaxy formation. Also shown is a simulation of HI in emission from a high redshift object when observed at ≈500 MHz (redshift 1.86; Deane et al., 2015). The large differential magnification preferentially boosts part of the HI rotation disk line profile, allowing the detection of intrinsically faint objects out to redshift 2.

Figure 16. The image is a composite of radio (in green), optical (white), and X-ray (purple) data of the cluster RX J0603.3+4214, known as the “Toothbrush Cluster” because of the morphology of the radio relic, which stretches over 6 million lightyears. Image credit: Credit: NASA/CXC/SAO/R. van Weeren et al; Radio: LOFAR/ASTRON; Optical: NAOJ/Subaru.

Figure 17. Shown is a simulation (left and middle) of a gravitationally lensed extended star-forming galaxy and a point-like AGN with a total flux-density of 1 mJy when observed with SKA1-MID (McKean et al., 2015) as well as the lensed HI emission (right) from a galaxy at z = 1.86 (Deane et al., 2015).
2.2.5 The Evolving Molecular Universe

With its unique sensitivity, the SKA opens up the study of many astrophysically important spectral lines in addition to the HI 21 cm line, both redshifted lines from distant galaxies or intrinsically faint lines from nearby galaxies and the Milky Way, allowing one to trace material and various environments from the local to the distant Universe. In a pan-chromatic multi-messenger astronomy era, the SKA will complement and be operated along with other existing facilities such as ALMA, or instruments being built like the ELT, matching their angular resolution in the radio domain. The science case for extragalactic spectral lines strongly advocates for an increase in coverage toward high frequencies (a SKA upgrade to >15 GHz [SKA Memo 20-01 “SKA1 beyond 15 GHz: The Science Case for Band 6”]).

The main science drivers are:

- the study of molecular gas, as the fuel for star-formation, is of primary importance for the evolution of galaxies in the distant Universe,
- unique diagnostics from masers and radio recombination lines, and
- absorption along the line of sight to background continuum sources.

![Plot showing the redshifted molecular species that can be detected by the SKA LOW and MID telescopes and a high frequency upgrade to MID.](image)

**Figure 18.** Plot showing the redshifted molecular species that can be detected by the SKA LOW and MID telescopes and a high frequency upgrade to MID.

2.2.5.1 Redshifted CO Lines and Dense Gas Tracers (HCN, HCO+, HNC, CS, ...)

High-redshift galaxy surveys with ALMA/NOEMA have shown that the gas fraction strongly increases with redshift and the depletion time slightly decreases (e.g., Tacconi et al., 2018; Combes, 2018). Most of these studies have not been able to observe the fundamental CO(J=1-0) line, which is the best proxy for molecular gas mass and kinematics and have mainly observed higher energy transitions (J=2-1, 3-2...) transitions. SKA at frequencies above 15 GHz will be able to probe the CO(J=1-0) line at z > 2, and SKA1-MID will cover this line for z > 7, offering an unprecedented tool to probe molecular gas in distant...
galaxies and study their evolution. Dense gas tracers are vital to trace locations of star formation (SF), and scaling relation between gas and SFR densities will be obtained at high-z with the SKA.

![Figure 19](image)

**Figure 19.** Galaxies on the main sequence (MS) have more gas at high-z and their star-forming efficiency $= 1/t_{\text{dep}}$ is higher (from Tacconi et al., 2018).

### 2.2.5.2 Masers as Tracers of AGN, Starbursts and Stars in the Local Group (H2O, OH, SiO, ...)

At sub-pc scales around AGN, water masers can be so intense that the resolution of VLBI can be used to measure the black hole mass, and distance with a precise and accurate estimate of $H_0$ (e.g., NGC 4258, Miyoshi et al., 1995; UGC 3789, Reid et al., 2013). The 22 GHz water line may be observed at redshift, $z = 0$ with an upgrade to SKA1-MID, and at $z > 0.5$ with band 5, providing a wealth of new H$_2$O maser sources from the local to distant Universe (e.g., Tarchi & Castangia, 2013). More than 100 OH megamasers have been detected in starbursts (e.g., Darling & Giovanelli, 2002), at $z = 0.1-0.23$. They are 2-4 orders of magnitude more luminous than OH galactic masers. With SKA1, a survey covering all redshifts up to $z = 5$ will allow the following of the cosmic starburst history. OH masers in the Galaxy trace regions where new stars are born as well as evolved stars. Observing with SKA1 at 18-cm, it will be possible to study such regions as far away as the Local Group of galaxies (e.g., Etoka et al., 2015).

![Figure 20](image)

**Figure 20.** Artist’s view of the nuclear disk around the NGC 4258 AGN, and at the bottom the H$_2$O maser spectrum. From Greenhill et al. (1996). Image credit: NRAO
2.2.5.3 Absorption Lines in Intervening Galaxies in Front of Quasars

SKA1 will give access to a plethora of bright background radio sources that could be used to probe molecular absorption from intervening galaxies along their line of sight. The absorption technique is extremely sensitive, and molecules can be used as an invaluable cosmological probe. Not only the chemical state of the absorbing gas can be explored in-depth (e.g., complex organic molecules, isotopologues), but molecules also reveal the ISM physics (e.g., cosmic-ray ionisation, molecular gas fraction) and gas excitation (measurement of the CMB temperature as a function of redshift). Rare isotopologues give us the possibility to track isotopic ratios and enrichment by nucleosynthesis products over cosmic times. Finally, some molecules (e.g., NH$_3$, CH$_3$OH, CH) are sensitive tracers to test possible cosmological variations of the fundamental constants (e.g., proton-to-electron mass ratio $\mu$, fine structure constant $\alpha$).

Figure 22. Excerpt of an ATCA spectrum toward PKS1830-211, showing the molecular richness of a z=0.89 absorber. From Muller et al. (2013).
2.2.6 The Gaseous Evolution of Galaxies

A key objective of the SKA is the study of the formation and evolution of galaxies by mapping the 21 cm spectral line of neutral atomic hydrogen (HI) in absorption and emission, over cosmic time. The SKA will conduct deep HI observations of millions of galaxies out to redshift \( z > 1 \). Some primary goals are to investigate the structure and dynamics of cold gas in and around galaxies, explore the gas-halo interface, discover plumes and streams of intergalactic gas, as well as map large-scale galaxy structures and their peculiar motions. Some of the key questions regarding galaxy formation and evolution are:

2.2.6.1 How do Galaxies Replenish their Gas?

Current models of galaxy evolution predict that galaxies are embedded in an extended cosmic web of gaseous filaments. For galaxies to continue forming stars over a Hubble time, they must continue to accrete new gas to form stars. With its high sensitivity and resolution, the SKA will enable for the first time the study of this very low-density gas to allow us to detect and image the gaseous interface between galaxies and the surrounding intergalactic medium.

![Figure 23. Artist’s impression of gas accretion from the cosmic web. Image credit: ESO/L. Calçada/ESA/AOES Medialab.](image)

2.2.6.2 How are Gas Accretion, Star Formation, & Feedback Related?

The gas cycle of galaxies involves the accretion of gas, star formation, and gas outflows (feedback). While observed global-scale relations link star formation and the molecular gas surface density, very little is known about the astrophysics contributing to star formation at sub-kpc scales. Stellar evolution processes such as supernovae expel gas from galaxy disks back into the halo creating holes and bubbles in galaxy disks. The resolution of the SKA will enable us to study the ISM structure and kinematics in nearby galaxies with unprecedented precision to better understand these fundamental processes.
NGC6822 is the closest gas-rich dwarf galaxy outside the Large and Small Magellanic Clouds. Image credit: E. de Blok. Optical background is a combination of B, V, R images (Massey et al., 2007), stars enhanced using near UV data (Hunter et al., 2010), red: H-alpha (de Blok, 2006), blue: VLA observations of HI (de Blok et al., 2000).

2.2.6.3 How is the HI in Galaxies Linked to AGN Activity?

Associated HI absorption around a radio source host galaxy can tell us about the structure of the central regions and feeding and feedback of AGN. The SKA will enable us to probe HI in absorption in AGN out to $z > 3$ and to trace neutral gas outflows over cosmic time to investigate the role of AGN feedback in galaxy evolution.

![Hi Outflow and Hi Disk](image)

Figure 25. HI absorption in 3C236 showing the integrated profile from WSRT (Morganti et al., 2005) and VLBI images (Schulz et al., 2018). Image credit R. Schulz. Broad, shallow HI absorption due to gas in a fast outflow of ~1000 km/s is detected along with a narrow deep component which is associated with the circumnuclear disk. The spatial distribution of the 2 components is shown in the VLBI images.
2.2.6.4 How is HI Affected by Galaxy Interactions, Environment, & Redshift?

Wide-field HI surveys to $z > 1$ with the SKA will provide statistical samples (in emission and absorption) to study the role of environment on the gas content of galaxies and to investigate the processes leading to the build-up of stellar mass (including galaxy mergers and interactions) and the quenching of star formation over cosmic time. High precision observations will also shed light on the 3D shapes of galaxy disks, their interface with the intergalactic medium, their dark matter content and the cuspy halo problem, and the formation of tidal dwarf galaxies.

Figure 26. HI imaging of late-type galaxies in the Virgo galaxy cluster overlaid on the ROSAT X-ray image (Böhringer et al., 1994). Image credit: Chung et al., 2009. The HI images have been enlarged by a factor of 10 for clarity. Statistical detection (right) of HI at red-shift 1 using the uGMRT (Chowdhury et al., 2020).

2.2.7 Galactic Baryon Ecology and Matter Cycle

The SKA will make major contributions to uncovering the ecology of baryons and understanding the cycle of matter between the different components of our Galaxy, from star formation in the densest regions of the interstellar medium (ISM) to the replenishment of the ISM with matter and energy released in the last phases of stellar evolution. Many details of this interplay can only be unveiled by using different radio diagnostics that are not limited by dust obscuration. This will allow us to use our Galaxy as a resolved template to understand how galaxies work. The SKA has the potential to make a tremendous impact on many key areas in galactic physics thanks to its transformative ability in wide-area, sensitive high angular resolution spectroscopy and its unparalleled astrometric measurements in line and continuum.

Figure 27. A multi-wavelength view of the galactic plane. Colours are 912 MHz-blue (ASKAP), 8 μm-green (Spitzer), and 70 μm-red (Herschel) (Umana et al., 2020).
2.2.7.1 From ISM to Stars

The star formation process is the driver of the evolution of ordinary matter in the Universe, from its primordial composition to the present-day chemical diversity necessary for the birth of life. The SKA will enable the detailed flow of mass and material through the atomic and ionised ISM to be studied, by creating sensitive and high dynamic range maps of the atomic, ionised, and molecular gas density across our Galaxy. Radio continuum images will pinpoint the location of intermediate and high-mass stars in proto-clusters, while proper motion and parallax information on all the young stellar objects in these clusters will allow us to make decisive steps toward a quantitative understanding of our Galaxy as a star formation engine. A first complete recipe for the Milky Way as a normal star-forming galaxy will be provided, that will be used as a $z = 0$ template for the accurate interpretation of star formation in distant galaxies.

![Figure 28. A VLA image of the Orion Cluster (Forbrich et al., 2016).](image)

2.2.7.2 Stars and their Neighbourhood

During their life, stars interact moderately with the surrounding medium, giving rise to phenomena that produce intense emissions in the radio band. These are the cases of stellar coronae, flares, coronal mass ejection, particle acceleration in stellar magnetospheres, interaction between stars and orbiting planets and interaction between expanding stellar winds. In the above cases, even if stars emit a negligible fraction of their total luminosity in the radio band, radio emission usually constitutes one of the best diagnostics to derive important physical parameters. The SKA will produce a real revolution in Stellar Physics since many classes of stars will be accessible over the entire Milky Way and their radio properties will be defined, allowing comparison with other stellar parameters, such as age, mass, magnetic field, chemical composition, and evolutionary stages over rather large samples of sources.

2.2.7.3 From Stars to the ISM

The chemical evolution of galaxies is mainly governed by the final stellar evolutionary stages when stars release part of their matter and kinetic energy to the ISM. The study of this process in the Milky Way is of great importance for the comprehension of the enrichment of the Universe itself, and, in
In this context, radio observations of stellar ejecta in post-main sequence evolution, are of fundamental importance to the comprehension of the origin and the full characteristics of mass-loss, since evolved stars constitute the major contributors of processed material (gas and dust) and kinetic energy (ejecta from massive stars) to the ISM.

Figure 29. This figure shows (a) spatial distribution, (b) internal proper motions, and (c) absolute values of the three-dimensional velocities of the water maser features around the evolved star (“water fountain”) IRAS 18113−2503 (Orosz et al., 2019).

2.2.7.4 The Galactic Centre

The centre of the Milky Way is a unique laboratory because it is the only galactic nucleus and the most extreme astrophysical environment that we can study in detail. The SKA will provide unique insights and breakthroughs through the study of intermediate-mass black holes, stellar winds, pulsars, stellar-mass black holes and neutron stars, magnetic fields, properties of the ISM, precision absolute astrometry of stars near the central black hole and throughout the GC, and the physics of massive YSOs.

Figure 30. The most detailed wide-field radio image of the centre of our Galaxy to date, obtained with MeerKAT.
2.2.8 Magnetism

Magnetic fields are a major agent of energetic processes in various cosmic objects, from star-forming regions and stellar remnants, through galaxies, including our own Milky Way, to the large-scale structure of the Universe. Magnetism has long been recognised as a crucial element in these problems, but new technology is required to make the observational progress needed for a full understanding of how these processes unfold in practice. Radio astronomy provides the most effective probes of cosmic magnetism. The SKA’s revolutionary capability promises to take our study of magnetic fields to a new level of precision and expand our horizon to distant objects that are not accessible in sufficient detail today. Specifically, its unrivalled sensitivity and resolving power, combined with wide frequency coverage, make the SKA ideal for probing magnetism across the Universe through the study of polarised synchrotron emission and its Faraday rotation, and Zeeman splitting.

2.2.8.1 A Dense Faraday Rotation Measure (RM) Grid

The SKA will produce a Faraday RM Grid, comprising polarimetric detections of 2-4 million radio galaxies, 60-120 times as many as the current state of the art. In addition to understanding the nature of the polarized sources themselves, the SKA’s RM Grid will be used to probe a wide range of extended, intervening foreground sources, including:

- Milky Way and sources within (HII regions, SNRs, HVCs, masers...)
- the Magellanic Clouds
- Nearby galaxies
- Galaxy Clusters
- Radio galaxies
- Cosmic web.

The extremely high density of background RMs will permit the study of individual objects as well as statistical investigations of source classes. SKA1-LOW will complement the dense SKA1-MID RM Grid by permitting very high-accuracy magnetic field measurements in some sources.

Figure 31. A visual impression of the projected source density as will be seen by SKA1-MID. Image credit: S.A. Mao, using data from Taylor et al. (2009) and Schnitzeler et al. (2019).
2.2.8.2 What is the Role of Magnetic Fields in the Evolution of Cosmic Objects?

The unmatched surface brightness sensitivity and angular resolution of the SKA will permit the imaging and detailed study of the diffuse magnetised media in nearby galaxies, galaxy clusters, and ultimately the magnetised cosmic web. This will allow us to uncover the role of magnetic fields in the star formation process, as well as determining the mechanisms that shaped and amplified the magnetic fields. Combined with the detailed view of the magnetised interstellar medium in our own Galaxy, the SKA will probe magnetic fields from the smallest to largest scales. The SKA’s dense RM Grid will also allow us to obtain information about the magnetic fields in foreground objects such as galaxies and clusters, averaged along the line of sight. In this way, we can find and understand magnetic fields on the largest possible scales.

Figure 32. The nearby galaxy M51 with magnetic field vectors overlaid. Image credit: G. Heald, using data from Fletcher et al. (2011) and background image: NASA, Hubble Heritage Team, (STScI/AURA), ESA, S. Beckwith (STScI). Additional processing: Robert Gendler.

Figure 33. The nearby galaxy M33 and the predicted density of background polarised sources. Image credit: S.A. Mao and G. Benintende (APOD, 2016/09/17).
2.2.8.3 What is the Structure of the Universe on the Largest Scales?

Our standard cosmology predicts that the majority of baryonic matter in the Universe exists as a cosmic web of diffuse, magnetised plasma. However, the distribution and properties of this extremely diffuse material are not yet well understood. The SKA’s dense grid of background RM s will shed light on the magnetised cosmic web and will unveil its overall form. Understanding the cosmic web will allow us to address longstanding questions of modern astrophysics such as the thermal and dynamical evolution of galaxy clusters, the origin of the ultrahigh-energy cosmic rays, and the inflationary theory of cosmology.

Figure 34. The cosmic RM background (Akahori & Ryu, 2011).

2.2.9 Fundamental Physics with Pulsars

Using both the LOW and MID arrays, astronomers will use SKA observations of pulsars to address some of the major unsolved problems of modern physics by tackling fundamental questions in ways that cannot be matched, or even attempted, by any other experiment:

- Is general relativity the ultimate theory of gravitation and, if not, at what point does it break down?
- What is the equation of state of matter beyond nuclear densities?
- How do supermassive black hole binary systems control galaxy evolution?

2.2.9.1 Strong-field Tests of Gravity

The SKA will allow discovery of all of the radio pulsars in the Milky Way that are beamed towards Earth. The wide tapestry of fundamental science that will be tackled through pulsars is all enabled by this. With such a complete galactic census, SKA will discover many new pulsars in highly relativistic binary systems. These are few-hour binaries where strong field gravitational effects are hugely magnified. Through the careful study of these systems, unprecedented tests of gravity in the strong field regime will be performed and compared to the predictions from general relativity and alternative theories of gravity. Some of the fundamental principles that will be tested include the strong equivalence principle, the existence of gravitational dipole radiation, and whether or not the true
description of the gravitational field involves extra components, scalar, vector or tensor, beyond the Einstein tensor of general relativity.

The SKA’s binary pulsar discoveries will likely include at least one pulsar in orbit around a black hole. This provides the ultimate laboratory for exploring and studying the physics of black holes which are thought to be governed by so-called black hole theorems. By timing the pulsar signal as it orbits one can trace out the properties of space-time in the region and determine the properties of the black hole. The mass, spin, and charge of the black hole impact the timing signature of the pulsar. This enables tests of the “cosmic censorship conjecture” which states that the laws of physics prohibit naked singularities and the “no-hair” theorem which states that black holes have mass, angular momentum, charge, and no further properties. Such observations will likely provide critical pointers towards a quantum theory of gravitation.

![Artistic depiction of a pulsar in orbit around a black hole. Image credit: SKA Organisation/Swinburne Astronomy Productions.](image)

**Figure 35.** Artistic depiction of a pulsar in orbit around a black hole. Image credit: SKA Organisation/Swinburne Astronomy Productions.

### 2.2.9.2 Dense Matter Equation of State

Neutron stars provide unique laboratories to study the physics of matter at densities greater than that of atomic nuclei. The surface of neutron stars is iron, and below that the crust consists of progressively heavier elements. The nuclei become so neutron heavy that they ‘drip’ out and below the level of the crust there is a superfluid of neutrons and a superconducting superfluid of protons. The exact distribution of where the crust ends, whether or not the superfluid interior progresses to deconfined quarks in the core, and in what way these components are coupled (rigidly like a golf ball or decouple like an eggshell and yolk) depends on the unknown details of high-density physics. Thus, the interior of pulsars are laboratories for understanding quantum chromodynamics. The physics at play in this realm decides the neutron star’s mass, radius, and spin properties. The spin properties can be seen with the SKA through the radio emission.

Timing pulsars via their radio emission allows us to solve for binary parameters and the masses of neutron stars. The SKA will yield an order of magnitude increase in the number of neutron star mass determinations. In tandem with these efforts, high-energy observations can determine their radii. Valuable independent estimates of radii will also be determined by measuring moments of inertia of the most relativistic binary systems. Furthermore, the SKA will be able to improve our understanding of neutron superfluidity through the detailed study of rotational irregularities in a wide range of pulsars. These regularities are due to fluid-crust interactions, and through measuring the associated...
angular momentum transfer, provide additional constraints on neutron star mass-radius parameters. In combination, this array of constraints on the mass-radius relationship of neutron stars, especially those provided by the fastest spinning and highest mass pulsars, will directly constrain the equation of state of cold dense matter.

![Image of a neutron star structure](credit: Nils Andersson)

**Figure 36.** A visualisation of the structure of a neutron star. Image credit: Nils Andersson.

### 2.2.9.3 Gravitational Waves

The SKA will substantially increase the number of millisecond pulsars known; these systems are the most precise of the pulsar clocks. After discovery, an intense programme of monitoring these sources will make the SKA into a low-frequency (microhertz to nanohertz) gravitational wave detector. The line joining the SKA to each pulsar is in effect a single Milky-Way-scale LIGO-like detector. By regularly observing an array of millisecond pulsars, well spread across the sky, the long-term behaviour of these cosmic clocks can be determined to high precision; the uncertainty in the arrival times is in some cases only a few tens of nanoseconds over timescales of decades. Any gravitational wave signal passing by a pulsar will affect the space-time in its vicinity, squeezing and stretching it (gravitational strain), and so causing the pulsar signal to arrive at Earth early or late as the wave passes. Distinct delay patterns occur for each ‘arm’ of the pulsar timing array, and this pattern can be used to identify the presence of gravitational waves. In the first instance, the SKA will aim to detect the stochastic background of gravitational waves generated by the cosmic merger history of supermassive black hole binary systems. The weak gravitational wave signals from these events all combine to a background ‘noise’ of gravitational waves. Depending on the strength of the stochastic background, the SKA may be able to characterise the shape of the strain spectrum and tell us about how supermassive black holes merge and thus how galaxies evolve. With more sensitivity, provided by more observations from continued monitoring and the addition of new pulsars as they are discovered, the SKA may be able to single out individual bright sources of gravitational waves above the stochastic background. Different theories of gravity also predict different characteristic pulsar correlations across the sky and if subtle differences like these could be discerned it would allow determination of the polarisation states of gravitational waves, anisotropies in cosmic structure, and even the mass of the graviton, the particle that mediates the gravitational force.
2.2.10 Cradle of Life

An essential goal of the SKA is understanding our origins as living beings on a rocky planet, and the origin and existence of life elsewhere in our Galaxy. SKA1 will explore the first steps of forming habitable planets and the presence of biologically important molecules during the formation of exoplanets, through studies of grain growth in planet-forming disks, and detection of heavy prebiotic molecules in planet-forming environments. SKA1 will characterise planets around nearby stars through the study of their magnetic fields via aurora emission at low radio frequencies. The potential for SKA to directly detect the existence of intelligent life via radio signals is immense; SKA1 has the potential to detect technology already present on Earth through leakage from advanced civilisations on planets around nearby stars and can draw meaningful conclusions on their prevalence from targeted searches.

2.2.10.1 Explaining Planet Formation

Rocky planets like Earth form through the growth of dust grains to pebbles to planetesimals in protoplanetary disks around very young stars (Hoare et al., 2015). These sub-micron dust grains incorporated into the disk at its formation epoch need to grow > 12 orders of magnitude in size within a few myr (Andrews, 2020). The growth of grains to cm-sized pebbles in this time frame is a challenge for theoretical models, so observations that reveal the location and temporal evolution of pebbles in disks are needed to solve the puzzle of how and where dust grains grow to form rocky planets. Only cm-wave instruments can track the growth of dust grains through this critical size regime, and only the SKA will provide the required resolution (a few astronomical units) and sensitivity at the appropriate wavelengths to do so in the foreseeable future (Hoare et al., 2015; Testi et al., 2015).

The only unambiguous way of detecting the presence of cm-sized pebbles is to measure the strength and the spectral index of the continuum emission at cm wavelengths. In principle, the longer the observing wavelength, the more sensitive the observations are to ever-larger grains, but the flux is...
falling off at least as fast as the inverse wavelength squared, so there is a significant trade-off with sensitivity, and non-thermal processes dominate at very long wavelengths. The size and location of the large grains in a proto-planetary disk are deduced from the shape of the spectral energy distribution at each location in the disk. This is best done across a broad spectral range all the way from mm through to cm wavelengths. At the resolution needed to resolve the terrestrial zone (a few au), this can be achieved with SKA1-MID operating at 2.5 cm in combination with the JVLA at 7 mm and ALMA at 3 mm as is illustrated in Figure 38.

![Figure 38. Opacities of various grain size distributions. The observing wavelengths of ALMA/JVLA/SKA1 are complementary, with SKA1 sensitive to the largest grains (a few cm).](image)

![Figure 39. Depiction (left) and image (right) of a planet-forming disk at sub-mm. wavelengths. SKA will offer similar resolution at cm wavelengths, observing larger dust grains forming planets (Credit: S. Andrews (CfA), ALMA (ESO/NAOJ/NRAO)).](image)

### 2.2.10.2 Detect and Image Biologically Important Molecules in Planet-Forming Regions

The detection of prebiotic molecules in the interstellar medium, and the search for biologically important molecules such as amino acids in the same environments, addresses the fundamental question of astrobiology; what is the origin of life and has it arisen beyond Earth? SKA1-MID will detect the presence of molecules that are of biological interest, including amino acids, in star-forming (and hence planet-forming) regions (Codella et al., 2015; Hoare et al., 2015; Testi et al., 2015; Jiménez-Serra...
et al., 2020). We know they can form in space as they have been found in meteorites and comets (Jiménez-Serra et al., 2020).

The amino acids, such as glycine (C₂H₅NO₂) and alanine (C₃H₇NO₂), sugars, and ribonucleotides, are heavy molecules that are the very building blocks of life and they have detectable transitions in the SKA Band 5b frequency range. The search for amino acids in the ISM has been attempted to date only in the millimetre (and submillimetre) wavelength regimes. The identification of such a large molecule at these wavelength ranges is non-trivial for several reasons. The regions in the ISM that present the highest level of chemical complexity are warm star-forming regions, with temperatures of ~100 K. At such high temperatures interstellar ices are sublimated, releasing all organic material into the gas phase. As a result, the sub-/millimetre spectra are populated by a myriad of molecular lines, leading to very high levels of line confusion. In addition, the line profiles show broad linewidths (~5-10 kms⁻¹), which leads to high levels of line blending (overlap) making line identification difficult.

The sensitivity and resolution of the core of SKA1-MID will enable searches for prebiotic molecules and amino acids in the outer regions of proto-planetary disks free from the line crowding and overlap present in millimetre wavebands. It is in these cold outer disk regions where their incorporation into comets could allow the possibility of delivery on to rocky inner region planets. The potential impact of SKA1-MID operating at Band 5 for the detection of prebiotic molecules in proto-planetary disks, pre-stellar outflows and pre-stellar cores is significant. The high sensitivity over a large range of angular scales of the SKA1-MID configuration is well suited to the search for these building blocks of life. The concentrated 1 km core results in the superb brightness temperature sensitivity on the several arcsecond scales necessary to detect molecules in the pre-stellar core sources. For the cold outer regions of proto-planetary disks, the resolution of around an arcsecond is well-matched to the 100-au spatial scale in nearby Sun-like star-forming regions. In this way, SKA1-MID can attempt to track the origin and evolution of prebiotic molecules and trace their journey from the interstellar medium into the regions where they could be incorporated into cometary material at the outer edges of young planet-forming systems (e.g., Ceccarelli et al., 2014; Hoare et al., 2015).

### 2.2.10.3 Search for Extra-Terrestrial Intelligence (SETI)

The potential for SKA to directly detect the existence of intelligent life via technologically produced radio signals is immense; SKA1 has the potential to detect technology such as that already present on Earth from planets around nearby stars through leakage from advanced civilisations and can draw meaningful conclusions on their prevalence from targeted searches, taking the search for extra-terrestrial intelligence to a whole new level. Such a discovery would of course be momentous in the history of humankind (Hoare et al., 2015; Siemion et al., 2015). SETI has formed part of the core science case for SKA since the project’s early days (Tarter et al., 2004), and since then SETI has transitioned from a niche area to the mainstream, due to advances in exoplanet discoveries. The Kepler mission has now shown that essentially every star has a planetary system (Dressing & Charbonneau, 2013), and the number of known Earth-like planets in habitable zones is increasing through missions such as TESS (e.g., Gilbert et al., 2020).

The unprecedented sensitivity of the SKA1 means that SETI searches can be central to its science programme. The fact that the SKA1 can detect the normal types of radio signals we on Earth emit as we go about our ‘everyday business’ means that well-defined questions regarding the probability of ETI can be addressed by observing every star within a set distance from Earth (a few 10s of parsecs; Siemion et al., 2015). For example, SKA1 will be capable of detecting emission sources analogous to high-power terrestrial transmitters such as airport radars at 10 pc distance in just 15 minutes. With longer observations unbiased surveys of all (>10,000) stars within 60 pc to such a brightness limit are feasible. The sensitivity of both SKA1-MID and SKA1-LOW also opens the possibility of detecting deliberate transmissions from radio transmitters of lower power (or at greater distances) than ever.
before. SKA1 will enable the most sensitive and exhaustive search for technologically produced radio emission from advanced extra-terrestrial intelligence ever performed. SKA1 will be a powerful SETI machine.

Figure 40. The number of stars in the solar neighbourhood from which narrow-band emission would be detectable for luminosities similar to our terrestrial aircraft radars (adapted from Siemion et al., 2015).

2.2.11 Solar, Heliospheric, and Ionospheric Physics

The Sun is a surprisingly challenging source to study – it has structures spanning a large range of angular scales, the intrinsic brightness of emissions from different mechanisms differs between them by many orders of magnitude, and the emission varies on very rapid time and frequency scales. Radio observations of the Sun carry a treasure trove of crucial information about solar magnetic fields and coronal processes not accessible by any other means. The SKA will provide the highest fidelity radio images of the Sun with very high time and frequency resolution – exactly what is needed to simultaneously track the details of solar emission across time, frequency, and morphology.
2.2.11.1 Solar Explosions and Solar Energetic Particles

Much of the time, the Sun shines steadily, as is our usual experience with the visible Sun, but occasionally it is home to extremely energetic burst-like phenomena. These solar flares take place in the atmosphere of the Sun and are usually associated with expulsions of large amounts of energetic plasma and accompanying magnetic field called coronal mass ejections (CMEs). These CMEs carry the solar influence to the terrestrial neighbourhood and are the primary carriers of space weather to the Earth. Their impacts include benign phenomena like the northern and southern lights (aurora) to more detrimental ones like electric supply blackouts, satellite damage, and disruption to radio communications, etc. Over the last decade, studying the Sun-Earth connection has become a key issue in space research and it is of enormous societal relevance.

The SKA will be able to image radio emission associated with active regions, solar flares, shocks, energetic particles, and CMEs in unprecedented detail and out to large distances in the heliosphere making remarkable new contributions to space weather studies, potentially enabling prediction of space weather events.

2.2.11.2 Coronal Heating

The solar corona has a temperature of a few million K, while the photosphere is only at about 6000 K. This apparent violation of principles of thermodynamics has been known since the early 1940s and is known as the coronal heating problem. With its extreme sensitivity and imaging fidelity, the SKA will explore the role and efficacy of both the leading contenders for explaining this mystery – nanoflares and wave-based heating mechanisms. A recent exciting development is that the very first observational evidence, based on radio observations, establishing contributions of "nanoflares" to coronal heating for the quiet Sun has recently been reported (Mondal et al., 2020).

2.2.11.3 Turbulence and Radio Wave Scattering

Though much of the radio emission from the active Sun is born deep inside the corona, it is heavily distorted and smeared as it propagates out of the very inhomogeneous and turbulent solar corona. On the one hand, this makes it challenging to disentangle the properties of the source of propagation effects, but on the other hand, it also provides a very useful probe of this otherwise very hard to study...
medium. SKA’s snapshot spectroscopic imaging capability will help us disentangle the propagation effects from intrinsic variations in the properties of radio sources.

2.2.11.4 Coronal Magnetometry

Though it is well known that the coronal magnetic field is responsible for the bulk of solar activity, it is notoriously hard to measure except at the solar surface. Radio observations provide the only known technique which can allow us to obtain quantitative estimates of coronal magnetic fields, the prime drivers of space weather. While these observations are very technically demanding, the SKA is expected to make vital contributions in this area with its unprecedented image quality and dynamic range.

![Image of solar eruptive event and simulated radio emission from energetic electrons in a flaring loop](image)

Figure 42. Top panel: Solar eruptive event (Image credit: SDO, NASA). Bottom panel: Simulated radio emission from energetic electrons in a flaring loop (Image credit: A.A. Kuznetsov).

2.2.12 High-Energy Cosmic Particles

Somewhere in the Universe, particles are being accelerated to energies up to ten million times higher than those achieved by particle accelerators like the Large Hadron Collider. These particles, known as cosmic rays, are the most energetic in nature, subject to laws of physics that are otherwise beyond our reach. When they collide with mundane matter, such as the Earth’s atmosphere or the surface of the Moon, they produce cascades of secondary particles that generate a burst of radio waves lasting only a few billionths of a second. The SKA will study these rare particles, to understand the physics of their interactions and the mystery of their origin.

2.2.12.1 The Cosmic-Ray Spectrum

Cosmic rays are composed of the same elements as interstellar gas: mostly protons and atomic nuclei. Their spectrum (see figure) extends over a huge energy range. It is thought that cosmic rays with lower
energies, up to perhaps $10^{17}$ eV, are being produced by sources in our own Galaxy: the remnants of supernovae, or the supermassive black hole at the Galactic Centre. At higher energies, only extragalactic objects, such as active galactic nuclei (AGN) or gamma-ray bursts (GRBs), are viable sources. When they impact Earth’s atmosphere or the Moon, they produce cascades of more than $10^{12}$ secondary particles. The equivalent energies of these collisions extend beyond those that can be studied with the Large Hadron Collider.

![Figure 43](image)

**Figure 43.** The cosmic-ray spectrum, extending over 8 orders of magnitude in energy and 24 orders of magnitude in flux. The energies probed by SKA-EAS and SKA-lunar are shown. These are compared to the centre-of-mass energies of the collisions (top axis). Image credit: T. Pierog et al. (2015); T. Huege, C.W. James.

2.2.12.2 *Radio Emission Mechanisms*

When a cosmic ray interacts, its energy is converted to mass, producing a range of exotic secondary particles. These collide to produce still more particles, and the process continues until the energy of the cascade has been exhausted.

**Askaryan effect:** As the cascade progresses, electrons in the surrounding medium are knocked loose from their atoms and entrained into the cascade. This leads to an excess negative charge that rapidly builds up and then disappears, producing a sub-microsecond burst of radio waves – Askaryan radiation.

**Geomagnetic effect:** If a cascade occurs in the Earth’s magnetic field, positive and negative particles – particularly the lighter ones; electrons and positrons – will be deflected in opposite directions. Due to their opposite charges, these particles also radiate coherently - geomagnetic radiation.

The two radiation mechanisms have different polarisation signatures, which can interfere to produce a unique pattern on the ground (see Figure 44).
2.2.12.3 Extreme Energies – Lunar

Cosmic rays at the very highest energies (above $10^{19}$ eV) will produce pulses of radiation so strong as to be visible from the distance of the Moon. The entire visible surface of the Moon will be used as a 20,000,000 km$^2$ particle detector to catch these rare ultrahigh-energy events. Observations with SKA1-LOW will cover the Moon with phased-array beams to search for these nanosecond-scale pulses.

![Figure 44](image1.png)

**Figure 44.** Diagram of the two radio emission mechanisms: the geomagnetic effect (dominant for cosmic ray interactions in the atmosphere) and the Askaryan effect (dominant for lunar interactions). Image credit: T. Huege.

**Advantages of radio detection:**
- No absorption
- Pure electromagnetic
- Observable for 24 h/d

by Oded Dooz, IHT

![Figure 45](image2.png)

**Figure 45.** Illustration of the Lunar and Extensive Air Shower radio-detection techniques (left). In the former, a cosmic-ray or neutrino impacts the Moon, generating radio emission in a cone. The radiation can escape the Moon and be detected on Earth as a few-nanosecond. Image credit left: J. Alvarez-Muniz, right: C. W. James.
Figure 46. The Galactic Centre revealed in TeV gamma rays by the High-Energy Stereoscopic System (HESS). Such gamma rays are expected from cosmic-ray interactions with the interstellar medium, which produce pions and, hence, gamma rays. Image credit: HESS Collaboration (2016).

2.2.12.4 High-Energy Particle Physics

The extreme energies of cosmic-ray collisions also allow the study of particle physics at energies unreachable by the Large Hadron Collider. Radiation patterns of particle cascades will be searched for signs of new physics beyond the Standard Model.

Figure 47. Simulation of a proton-proton collision at the LHC. The centre-of-mass energy – critical for creating new particles – is 13 TeV. The equivalent energy for cosmic-ray collisions can reach up to 500 TeV, allowing the study of new physics unreachable by terrestrial colliders. Image credit: CERN.

2.2.12.5 Extragalactic Sources

At the very highest energies, the paths of cosmic rays will be only slightly bent by cosmic magnetic fields, so their arrival directions will point to their origin. The measured properties of lunar events will be used to reconstruct these directions and point towards the source of extragalactic cosmic rays.

2.2.13 Ultra-High-Resolution Science

Figure 49. Depiction of observatories from around the world that will participate in very long baseline interferometry together with the SKA.
On its own, the SKA telescopes will considerably improve the sensitivity and angular resolution coverage over current standalone radio interferometer arrays. With VLBI it will be pushed to the extreme, to be able to study the faintest radio sources at the highest detail. With SKA sites located in Australia and Africa, there will be enhanced coverage of the Galactic Centre and the Southern Sky.

The SKA telescopes will provide multiple sensitive beams on the sky in VLBI mode while being able to produce standard SKA images at a lower resolution. Such unique capabilities will expand the view of studied regions of the sky, ensure superior calibration for SKA-VLBI images, and result in ultra-precise astrometry. Some of the science applications that most benefit from these capabilities are outlined below.

2.2.13.1 Contributions to Multi-Messenger Astronomy

Some of the most energetic phenomena in the Universe are transients. Revealing the true nature of these transient events requires a multi-messenger approach.

SKA-VLBI will be able to pinpoint the location of these (often) highly relativistic events and allow detailed studies of young, compact transients, which are fundamental to understand their physical processes. Possible targets for multi-messenger astronomy include gravitational wave events and repeating fast radio bursts (FRBs).
Figure 51. Artists impression of an energetic transient (top), together with radio imaging evidence for a jet signature in the binary neutron star merger event GW170817 (bottom left) and precise localisation of the repeating fast radio burst 121102 (bottom right). Image credits: Beabudai Design; Mooley et al. (2018); Marcote et al. (2017).

2.2.13.2 Continuum Surveys with VLBI Resolutions

Deep VLBI surveys will contribute to an understanding of the distinct roles of AGN versus star formation activity in galaxies. The surveys will make it possible to visualise the microJy radio source population at high angular resolution and will provide very detailed images of distant galaxies distorted by gravitational lensing.

Strong gravitational lensing provides an important tool to measure dark matter halo masses around galaxies in the early Universe. Models for galaxy formation can subsequently be tested, with VLBI required for high redshift studies.
2.2.13.3 High Precision Astrometry

Precise localisation provides a means to accurately measure tiny apparent motions of stellar sources, caused by the Earth orbiting the Sun (known as parallax), to establish their distances. Parallax measurements of interstellar masers will produce the most accurate measurements to date of basic Galactic parameters and distances to individual star-forming regions. Parallax distances of millisecond-pulsars will improve pulsar timing models for strong-field tests of gravity, the study of neutron star interiors, and will aid the detection of the long-wavelength gravitational-wave background in the Universe.

Figure 52. Illustration of ultrahigh-resolution imaging applied to strong gravitationally lensed systems (top) and very wide field surveys (bottom). From: McKean et al. (2018) and Radcliffe et al. (2018).
2.3 Key Measures of Scientific Success

The Observatory convention states (Article 5, paragraph 1):

*The SKA project shall be designed to be capable of transformational science, with a combination of sensitivity, angular resolution and survey speed far surpassing current state-of-the-art instruments at relevant radio frequencies.*

The primary success metric, as a measure of the SKA’s role in making fundamental scientific discoveries and facilitating overall scientific progress, will be the number of published, high-impact, peer-reviewed scientific papers using SKA data.

A suite of scientific and operational success metrics is needed to guide the management of an observatory, and there exists a wealth of literature on this subject. The following sections provide an illustrative and non-exclusive list of some of the metrics that will be used for the SKA. It is noted, however, that conventional observatory metrics require careful interpretation and tuning for the SKA due to the anticipated use of commensal observing, in which multiple science projects can be carried out simultaneously.

High scientific impact often results from the exploitation of unique observational capabilities. The SKA will offer such unique capabilities from the outset, primarily due to the large increase in collecting area over existing facilities, a superior imaging capability and the opportunity for multiplexing observations. In order to maintain this leading position, a vigorous SKA Observatory Development Programme (SODP) will be implemented. This programme will provide the Observatory with the designs of upgrades to existing capabilities and new capabilities, commensurate with the evolving ambitions of the SKA user community. The SODP will be described in the SKA Development Plan.

As part of a broader ongoing evaluation of the SKA’s impact as a research infrastructure, several scientific success metrics will be monitored once the Observatory becomes operational:

- the over-subscription of observing time is a measure of community demand for access to the facility. This metric will be determined during each time-allocation cycle;
- the number of publications featuring SKA observations and results or enabled by SKA resources. This metric will be subject to defined acceptance criteria including peer review and is a measure of the Observatory’s productivity. This metric will be tabulated at least annually through a combination of web searches and manual reviews of the literature;
- the number of citations to qualified SKA publications is a measure of scientific impact. This metric will be tabulated as required;
- the number of publications or citations per unit cost is a measure of value for money; and
- usage and reproducibility of SKA science data products. This metric will measure how often a data product is used by users other than the originating project team.

This list is not exhaustive and is expected to evolve over time; it nevertheless encapsulates the primary drivers for the operational model. A fundamental guiding principle of that model is that of “open science”, whereby both the basic Observatory data products as well as any added value enhanced data products are archived for widespread public access following any relevant proprietary period to stimulate further discoveries within existing data and promote straightforward verification of any published results.
2.4 Science Requirements

It is anticipated that during its 50-year operational lifetime the SKA Observatory will ultimately be equipped for observations at all radio frequencies between the ionospheric cut-off of about 20 MHz, to beyond 20 GHz, enabling the full range of scientific outcomes described in the SKA Science Book. It is widely understood and captured in the system requirements, that high performance will only be specified below 20 GHz. The expectation is that a graceful decline of performance will be available above that frequency. A staged deployment strategy has been adopted whereby a subset of the full capabilities, in terms of frequency coverage, sensitivity, and survey speed are delivered, consistent with the available resources and the scientific priorities. For the SKA1 deployment, the design has been guided by a specific set of scientific priorities [SKA1 Science Priority Outcomes]. The set of highest priority science objectives for SKA1 is shown in Table 1. An indicative observational strategy for their delivery within a time-constrained interval can be found in the Appendix of the science requirements document. Key specifications that must be met to enable these outcomes are also listed there and are linked by number designation to specific requirements.

It is acknowledged that while specific scientific objectives must be defined and enabled, it is also vital to provide the broader capabilities of a well-rounded observatory. History has demonstrated that it is often the unanticipated discoveries that have proven the most fundamental legacy of astronomical observatories.
3 The Broad Impacts of SKA

The SKA project has an unprecedented opportunity to position itself as the global research infrastructure with the broadest overall impact of any currently in planning or implementation.

Building on investments made by project partners over many years, and through the exploitation of policies and procedures under development now, the SKA is expected to deliver significant benefits for member states’ research landscape, economy, society, sustainability, and culture. These impacts span industry return and innovation, human capital development, inspiration and education, geopolitics and science diplomacy.

The SKA project’s partners have considered its impact on society as core to its mission since its inception. As early as 2010, a few years before the start of the design phase for the SKA, the European Cooperation in Science & Technology (COST) held a strategic workshop on the “Benefits of Research Infrastructures beyond Science – the example of the Square Kilometre Array (SKA)” in Rome, with sessions addressing information and communication technologies (ICT), green energy, global science-industry-government linkages, and human capital. The meeting, and its report, was a key driver in developing interest in the potential of the project globally.

3.1 Value of Large Research Infrastructures

Research infrastructures (RI) form an increasingly large component of national research investments. Although these facilities are primarily designed to support research needs, their impact goes beyond the production of scientific results and knowledge. Their conception, construction, and operation are almost always associated with unique technological developments, data management systems, and highly skilled staff.

“RIs offer opportunities for innovation and market development, can attract investments and contribute broadly to socio-economic development. In some cases, they can constitute a focal point for the development of an innovation ecosystem.”


Life-changing innovations born out of large-scale research infrastructures include:

- More than 100 spin-off technologies from NASA’s Space Shuttle program, including an artificial heart, bioreactor, infrared camera, and video stabilisation software.
- More than 150 technological innovations in the last decade alone from the European Space Agency, including baby-monitoring systems, anti-personnel mine detection, and software to ensure drinking water is free of contamination.
- Dozens of spin-offs technologies from CERN, including the introduction of the World Wide Web, grid computing (launching the era of cloud computing), and hadron cancer therapy.
- Specialist optical and telescope control technologies developed at the European Southern Observatory (ESO) have been pushed beyond customary limits or combined in novel ways, for enabling applications that support new high-technology and specialist industries, including new wavefront sensors for industrial optical testing, laser beam profiling and eye surgery³.

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³ European Southern Observatory. Novel technologies that have been developed by ESO. Retrieved from https://www.eso.org/public/industry/techtrans/develeso/
RIs provide access to unique equipment, data or services for a diverse user base, including businesses working with academic groups or carrying out their own proprietary research and innovation. They also provide a focal point for clusters of scientists and engineers, along with high-value, high-technology service companies. Large-scale facilities offer rare or unique research tools, which permit new research questions to be posed and increase the likelihood of breakthroughs in understanding, and such insight may have profound social benefits. The SKA in particular, as the foremost radio astronomy RI of its generation, is set to contribute in a major way to our understanding of fundamental physics and the evolution of the Universe and its constituents thanks to cutting-edge technology.

Arguably one of the critical contributions of large-scale RIs is their role in informing and educating the wider public. Major scientific projects appeal to people’s imagination, just as NASA’s Apollo programme did in its time to great national and international support. They are also ideal platforms to publicise science and fundamental research and its benefit to society. As an example, a study into the role and added value of large-scale RIs was commissioned by the Dutch Taskforce to promote large-scale research facilities and the Dutch Ministry of Education, Culture, and Science. Through a web survey of all such facilities in the Netherlands, the research found these infrastructures had profound economic, human capital, and social effects.

In terms of social effects, more than 90% of those surveyed agreed or strongly agreed that large-scale RI facilities help raise the profile of science among the general public and are necessary so that science can contribute to tackling social issues such as climate, health, energy, and ageing. In terms of human capital, close to 90% of respondents agreed or strongly agreed that large-scale RI facilities helped the country attract top researchers from abroad. In terms of economic effects, around 75% of respondents agreed or strongly agreed that large-scale RI facilities give a major boost to public-private collaboration in the field of R&D and are highly important for innovation in the commercial sector.

Figure 53. Economic effects of large-scale research facilities. Source: Technopolis Group (2011).

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3.1.1 Case Study: Large Hadron Collider ‘High-Luminosity’ Upgrade

A recent cost-benefit analysis of an upgrade to the Large Hadron Collider\(^6\) found that the socioeconomic and cultural benefits gained from the project – not including potential scientific discoveries – exceed the total monetary investment. The study found that in purely financial terms, every Swiss Franc invested in the ‘high-luminosity’ upgrade would pay back approximately 1.8 Swiss Francs in societal benefits.

figure 54. The identified benefits of the HL-LHC (1993-2038).

One of the most significant benefits, representing at least a third of the total, was the value of training for early-stage researchers. It was shown that the 2038 cohort of early-stage researchers will enjoy a ‘salary premium’ due to their experience at the HL-LHC or LHC until 2080.

The economic benefit from industrial spillovers, software and communication technologies is another major factor, together representing 40% of the project’s total benefits. Software and communication technology represent 24% of the total benefits within this category, while the rest comes from additional profits for high-tech companies involved in the HL-LHC.

Cultural effects, while hard to quantify because they depend on future announcements of discoveries and communication strategies, were estimated to contribute 13% to the benefits. More than half of this comes from on-site visitors to CERN and its travelling exhibitions.

3.2 Radio Astronomy as a Driver of Innovation

From its humble beginnings in the early 20th century, radio astronomy has grown in the space of 90 years into a major field of research, enabled by cutting-edge technology.

Radio astronomy has always had very strong industry links. Radio telescopes and their instrumentation are technically challenging, and very often employ solutions from other sectors that further improve the technology. Astronomers also have a long tradition of sharing technology through open platforms, making it available to other users.

This synergy is exemplified by pioneering British radio astronomer Sir Bernard Lovell, who employed an ex-military radar receiver unit to study cosmic rays. It led to the establishment of the Jodrell Bank Observatory and the construction of the 76 m Lovell telescope in 1957, which was able to track the Soviet rocket adapted from an intercontinental ballistic missile that launched the world’s first artificial satellite - Sputnik-1 later that year, thus immediately proving its broader impact beyond research at a time of heightened tensions.

This process of bringing technology into astronomy from industry, perfecting it in pursuit of demanding astronomical requirements and then pushing improved or developed technology back into other industrial and research sectors, can be regarded as a beneficial cycle of innovation.

In particular, radio astronomy is intimately linked to many technological breakthroughs, including:

- the invention of WiFi;
- magnetic resonance imaging (MRI);
- reference systems for space navigation and GPS;
- high-precision monitoring of tectonic plate movements;
- low-noise amplifiers for use in radar, telecommunications, and remote sensing;
- space tracking; and
- voluntary distributed computing for citizen-science.

Together, these developments have made an enormous contribution to daily life, global GDP, and social wellbeing. As the flagship international radio astronomy project of the coming decades, the SKA will fuel further technological advances with the potential to impact areas of society far removed from radio astronomy.
3.3 Impact of the SKA

*Beyond its significant contribution to academic research, the SKA will have an impact in four core areas; the economy, society, sustainability, and culture.*

The impact of the SKA is both direct and indirect, with visibility at local, regional, national, and international levels.

3.3.1 Contribution to the United Nations’ Sustainable Development Goals

The SKA project is helping to address global challenges by contributing to several of the United Nations’ Sustainable Development Goals (SDGs) to achieve a better and more sustainable future for all by 2030:

3. Good Health and Well-being  
4. Quality Education  
5. Gender Equality  
6. Clean Water and Sanitation  
7. Affordable and Clean Energy  
8. Decent Work and Economic Growth  
9. Industry, Innovation and Infrastructure  
10. Reduced Inequalities  
11. Sustainable Cities and Communities  
12. Responsible Consumption and Production  
13. Climate Action  
15. Life on Land  
16. Peace, Justice and Strong Institutions  
17. Partnerships for the Goals

Each SDG the SKA is contributing to is highlighted in the relevant section in this chapter.

*Figure 56. The United Nations’ sustainable development goals.*
Even before the official start of construction, the SKA has been delivering impact for member states. As outlined in this section, several positive impact stories have emerged from work linked to pre-construction efforts and SKA precursor and pathfinder facilities. These stories serve to demonstrate the nature of long-term potential benefits for SKA members.

### 3.3.2 Open Science

Open Science, based on the precept of making scientific research collaborative, transparent, and accessible to all, is rooted in SKA’s foundational principles. So is the related concept of scientific reproducibility, a fundamental aspect of the scientific method since the 17th century allowing independent teams to have access to methodology and tools to be able to confirm experiments and validate results.

Open Science and the application of the FAIR principles (findability, accessibility, interoperability, and reusability) is increasingly supported by funding agencies across the world. They offer a set of principles indicating how digital research objects (e.g. research data, tools, scientific workflows, configuration parameters, other digital resources and research processes) are published in a way that enables discovery, reuse and proper attribution, facilitating the reproducibility of the research and its underlying methods, hence boosting the exchange of scientific knowledge.

The SKA is already playing a major role in this sphere. As mentioned earlier in this document, data products produced by the SKA Observatory will be archived and made publicly accessible (after a proprietary period) to stimulate further discoveries and the verification of published results. Already Open Science principles are being adopted in the SKA’s set of data challenges for the scientific community. SKA partners are adopting Open Science principles in the development of a federated network of SKA Regional Centres, which will enable geographically distributed teams of researchers to collaborate. They will provide access to data, computational resources and analysis tools, while being equally accessible independent of user location and providing user support and training.

Ensuring data and methods are accessible can also increase productivity and research visibility, facilitate innovation, accelerate knowledge transfer and return on investment, while supporting human capital development and increasing trust in science. It also offers opportunities for governments, businesses, and entrepreneurs to harness it for economic, social, and scientific gains. For instance, UNESCO highlighted how Open Science can play a key role in democratising knowledge generation and ensuring every scientific challenge plays a part in addressing the UN SDGs. Making science more accessible increases collaboration and fosters partnerships. Accelerating knowledge transfer to society can support good health and wellbeing. Open Science speeds up skills building through training and citizen science, hence supporting quality education. It also reduces inequalities by equalising access to scientific knowledge and supporting gender equality, ensuring results produced by female researchers are accessible and not filtered out or anonymised.
3.3.3 Science Diplomacy and International Relations

3.3.3.1 Science Diplomacy

Collaboration is at the heart of the SKA Observatory. The scale of the SKA Project’s international collaboration is unique among major RIs, involving countries on five continents, representing 40% of the world’s population.

The SKA is an exciting step, moving astronomy collaboration from the national/regional level to a global level, and welcoming new actors and national communities into the field. It also bridges the traditional divide between developed and developing countries. This is exemplified by three of the five BRICS countries – the major emerging national economies – being full members of SKAO (India, China and South Africa). In 2014, all five BRICS science ministers visited the South African SKA site for the first BRICS Science, Technology and Innovation Ministerial Meeting, and the SKA is a regular agenda item at BRICS science ministers’ meetings.

The power of RIs as a tool for fostering international connections, government-level interaction and collaboration is well exemplified by CERN and ITER. The science and engineering collaborations required by world-leading international RIs have their own inherent value, in developing human capital, encouraging innovation and transferring that innovation internationally for the good of humanity. SKAO, as an organisation with a distributed infrastructure in Europe, Australasia, and Africa, offers iconic imagery with its physical scale, supported by a huge community presence around the world. It is the very definition of ‘international’.

Outside the direct return from the international nature of the SKA project, participation in the Observatory offers a new opportunity and framework for government-to-government interaction, using the SKA as the focal point and basis for international relations and dialogue in areas outside astronomy or science.

The SKA is already part of the dialogue at the global leadership level, with high-level diplomatic meetings, and state visits between member countries often featuring discussion of the project. SKAO will use its position to facilitate this cooperation further still, with greater engagement at regional (for example, the European Commission), multinational (for example, BRICS) and global (for example, the United Nations) levels to support these bodies’ aims and objectives.
Since 2012, high-level meetings have taken place annually between South Africa and SKA African partner countries Botswana, Ghana, Kenya, Madagascar, Mauritius, Mozambique, Namibia, and Zambia. These meetings discuss progress in astronomy cooperation and the SKA, as the countries work together to build national capacity and take advantage of research infrastructures. The co-hosting of the SKA project in Africa is supported by the African Union, with heads of state and government recognising the potential of investments in radio astronomy infrastructures and related projects to enhance the continent’s science and technology capacities.

“For the first time, Africa, Asia, Australasia, and Europe, commit at the inter-governmental level to collaborate on a large-scale science project as equal partners. This represents the start of a new era for global science governance. International cooperation in science plays a crucial role in fostering international friendship and solidarity and bolster commitment to multilateralism which will assist our world in addressing global challenges like poverty, inequality and climate change. The signing of the Convention puts science diplomacy into practice.”

Ms. Mmamoloko Kubayi-Ngubane, then Minister of Science and Technology, South Africa, on the occasion of the signing of the SKA convention (March 2019).

3.3.3.2 Relations with Other International Bodies
The SKA is increasingly part of important policy discussions in regional and international forums.

With nine European countries already formally involved in the SKA project, and its headquarters in the UK, relationships with Europe are strong. European Union investment in the development of the
SKA has been significant and influential. In 2018, the SKA was awarded Landmark status by the European Strategy Forum on Research Infrastructures (ESFRI)\(^7\), placing it among a select group of major RIs in Europe and facilitating its prioritisation on European member states’ national roadmaps.

This status has assisted in unlocking European Commission funding. Most recently, in 2015, the SKA project was awarded funding under the EU Research and Innovation programme Horizon2020 to support ongoing infrastructure work in Australia and South Africa.

The SKAO will continue to engage closely with the EU as one of the important stakeholders in the international arena.

![Figure 58. Carlos Moedas, then Commissioner of the European Commission for Research, Science, and Innovation, opening the ‘Shared Sky – the SKA’s indigenous art/astronomy exhibition’ at the European Commission Headquarters. Credit: European Union, 2018.](image)

“The success of the Square Kilometre Array has been really amazing. It’s one of those projects that really excites us here in the European Commission, and that’s why we’ve put more than 14 million euros so far to support it.”


The SKA is also building stronger ties with the United Nations, its agencies and other relevant international bodies. In particular, the SKA Organisation has been a sector member of the International Telecommunications Union – a United Nations agency – since 2014. This serves to protect radio astronomy operations from radio interference as use of the spectrum increases and to lobby on behalf of radio astronomy together with existing regional community bodies.

### 3.3.3.3 International Relations

As one of the major RIs of the coming decades and one of the great observatories of the 21\(^{st}\) century, the SKA is well placed to build links with other major facilities to jointly tackle areas of common interest.

The SKA Organisation has worked closely with CERN for several years, and in 2020 signed a Memorandum of Understanding (MoU) with CERN, GÉANT (the pan-European network and services provider for research and education), and the Partnership for Advanced Computing in Europe (PRACE), to overcome challenges related to high-performance computing in large, data-intensive science projects.

A similar agreement was signed with the Cherenkov Telescope Array Observatory (CTAO) to facilitate greater sharing of knowledge and expertise in engineering, science, technology and administration. Regular discussions are also taking place at the scientific, technical and policy level with other major observatories, including the European Southern Observatory (ESO), the US National Radio Astronomy Observatory (NRAO), the Vera Rubin Observatory (VRO) and ESA’s Athena X-Ray Observatory.

As SKAO comes into being, the opportunities to explore further relationships and participation with global research infrastructures and other appropriate organisations will be a focus for the Council.

“In this age of multi-messenger astronomy, building alliances with observatories across the spectrum are critical to achieving our common missions to expand our view and understanding of the Universe.”

Prof. Federico Ferrini, CTAO Managing Director.

3.3.4 Economy

The SKA will produce economic returns for member states through direct economic investment, indirect returns, through innovation and technological spin-offs, new high-tech jobs and boosted industrial capacity.

Astronomy return on investment in numbers – The Canadian example

2 to 1
Direct return received by Canada for every dollar invested in astronomy.

Up to 10 to 1
Indirect return received by Canada for every dollar invested in astronomy, since the knowledge gained working on astronomy projects leads to spin-off technology, and new and sometimes unforeseen business opportunities in sectors far removed from astronomy.

Source: Coalition for Canadian Astronomy (2008)\(^8\).

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**Case study: The Five-hundred-meter Aperture Spherical Telescope (FAST)**

FAST, in southern China, is the world’s largest filled-aperture radio telescope. The 1.148 B Chinese Yuan (~€140 M) telescope was completed in 2016 and is operated by the Chinese National Astronomical Observatory, part of the Chinese Academy of Sciences.

![Image](image1.png)

**Figure 59.** The FAST telescope is built in a natural depression in the Guizhou Province.

Although relatively new, the impact FAST has already had for the local area and China as a whole is, like the telescope itself, very impressive, cutting across a wide range of sectors. FAST has led to the creation of three joint research centres proposed and established by the FAST team, which evolved into new astronomy departments. Guizhou Normal University and QianNan Normal University for Nationalities, respectively, take 25 and 30 undergraduate students each year, and Guizhou University takes 6 graduate students in astronomy every year. The telescope boosted big data know-how through the creation of FAST data centres at Guizhou Normal University, Guiyang Computing Center and the Observatory. Industry engagement led to the involvement of 27 domestic companies who developed new patented technologies with other applications. The telescope is also showcased to visiting officials, ambassadors and politicians from around the world as well as domestic tourists.

FAST also boosted local job creation, including labourers for the construction of the telescope, staff for FAST operations and maintenance, and employees in newly established hotels, conference centres and restaurants in the nearby villages. The FAST Observatory now employs more than 100 employees directly.

### 3.3.4.1 Direct Economic Impact

The SKA will have a direct economic benefit to member states in terms of contracts to industry, commerce, and research institutes. Since 2013 more than €200 M has been spent in participating
countries for the design of the SKA, while construction spending is expected to exceed €900 M by the end of construction of the first phase of the SKA. These direct investments will be felt in the local, regional, and global impact, injecting cash into the local and national industry and are expected to create hundreds of jobs in a variety of sectors. This includes direct employment at SKAO and in partner agencies as well as associated employment related to SKAO business activities during construction and operations.

Before the COVID-19 pandemic, hundreds of professional visitors visited the SKA HQ in the UK each year, injecting cash into the local economy in housing, catering, transport, etc. Regular conferences organised by SKAO in member states have seen on average 250-300 international participants, attracting similar investment into the local economies.

Separately, around €290 M has already been invested in South Africa and around €250 M in Australia by their respective governments to pave the way for the SKA.

3.3.4.1.1 Impact Story: Hosting the SKA HQ – A Boost to the UK Economy

An independent review commissioned by the UK Science and Technology Facilities Council (STFC) in 2018 demonstrated that the UK is already seeing substantial benefits covering economic, scientific, and commercial skills and UK influence from the activities funded to date. In its final report, STFC concluded that the UK has benefited from contributing to three distinct aspects of the project: hosting the global headquarters, the design and technology work needed for the project, and the science carried out on the SKA and its precursors.

It is estimated the economic benefits up to 2018 included €64 M gross value added (GVA) – the measure of the value of goods and services produced – and 225 FTE jobs. Furthermore, UK expenditure to 2018 (€75 M) contributed to economic activities that included, for example, the construction of the SKA HQ. These generated additional economic benefits for the UK economy from 2016 to 2018 and into the future amounting to €87 M GVA and 211 FTE jobs. In total, therefore, and before the SKA project enters construction, the UK SKA investment up to 2018 delivered €151 M GVA and 436 jobs – many of which are high-paying skilled jobs – for the UK economy. These benefits are accrued in the UK as a direct result of the UK contribution to the SKA project funding.

Looking ahead, about 150 people will be hired by the SKA Observatory at the SKA HQ. The independent review stated that SKAO personnel and their families are expected to contribute £6.2 M (~€7 M) to the local economy every year and to invest an estimated £6 M (~€6.7 M) in the local property market.

Figure 60. Estimated contribution to the local economy and investment in the local property market by SKA HQ staff. Source: STFC & SKAO (2016).
3.3.4.1.2 Impact Story: Towards the SKA – The LOFAR Example

The Low-Frequency Array (LOFAR) is a radio telescope network with its core in the Netherlands and spread across Europe. Opened in 2010 and operated from 2012 by the Netherlands Institute for Radio Astronomy (ASTRON), the Dutch scientific partner in the SKA. LOFAR is a SKA pathfinder, where science of relevance for the SKA is being done and technologies are being tested.

Figure 61. Central area of the LOFAR core, the so-called ‘superterp’. 2011. Credit: TopFoto, Assen.

In 2016, using LOFAR as a reference scenario, the Technopolis Group\(^9\) issued a report about the expected gains of the Netherlands joining the SKA. The report, titled “Astronomical Prosperity?”, concluded the following:

“Dutch participation in the SKA will maintain or strengthen the Dutch top position in (radio) astronomy, depending on the size of the Dutch contribution. The SKA is considered a game-changing project in the field of Big Data, a technology field with great economic potential.”

In 2019, the Rathenau Institute, which researches the impact of science, innovation, and technology on society, conducted a review on the impact of large-scale research infrastructures, including LOFAR.

1.1 to 1
Direct return on investment to the Netherlands on LOFAR during the construction phase of the telescope.

1.24 to 1
Direct return on investment to the Netherlands on LOFAR during the operations phase of the telescope.

Source: Tjong Tjin Tai et al. (2019)\(^10\).

“The report [Tjong Tjin Tai et al., 2019] confirms with the Dutch example of LOFAR that returns in the country of establishment are relatively high when investing in a research infrastructure.”

Dutch Minister of Education, Culture, and Science Ingrid van Engelshoven (2019)\(^11\).

3.3.4.1.3 Impact Story: Precursor Construction Contracts in South Africa

The construction of the SKA precursor telescope MeerKAT and the optical telescope SALT enabled South Africa to develop capabilities in design and building of world-class telescopes, cost-effective supercomputing systems, multidisciplinary systems engineering protocols for large infrastructure and technology projects, development of a research investment hub, and technical skills.

Figure 62. The MeerKAT radio telescope in South Africa. Credit: South African Radio Astronomy Observatory (SARAO).

MeerKAT, designed entirely by South Africans, is now an iconic world-class scientific instrument and has already realised the following benefits locally in the Northern Cape and nationally.

8,785 Direct and indirect job opportunities created in the Karoo region.
364 Technicians trained from local communities.
R182 million (~€9.1 M) Spent with local Karoo suppliers, and R33 million spent on local emerging contractors.
90% Of Karoo-based staff originate from local communities.
56 Small, medium, and micro enterprises (SMMEs) from all local towns were identified and went through the Karoo Entrepreneurship Development Programme. These SMMEs have been mentored and trained on how to implement their newly acquired business skills in their own businesses.
R147-million (~€7.3 M) Awarded to 21 SMMEs nationally through a financial assistance programme. This has empowered local and national industry and institutions to acquire skills and expertise in advanced technologies and development programmes of SKA.
27 Locals employed from Carnarvon and surrounding communities, working in operations and maintenance of the infrastructure and telescopes, housekeeping, and security services. An accredited artisan training centre has also been established in town to train electrical engineers.
3 Patents were granted (in South Africa only) as part of the Commercialisation and Innovation Programme, alongside 6 trademarks, 1 assignment and 2 Open Source Softwares. The SANSA project, focusing on developing a data cube for the pre-processing of Earth observation data for ease of use by their customers was also developed as part of that programme.
3.3.4.2 Transfer of Advanced Knowledge and Skills to the Broader Workforce

“The SKA will expose Australian businesses to the high-level skills they need to be competitive because we know a highly skilled workforce is essential for an innovative and modern economy. This project is a great example of how science and technology can drive industry forward to grow the Australian economy and create the jobs of tomorrow.”


Among others, a sector in which SKA will make a valuable contribution is in developing skills in Data Science and Analytics (DSA), generally known as Big Data. While there is growing evidence that Big Data is and will be increasingly relevant to a variety of sectors, ranging from science, engineering and ICT, to healthcare, banking, and manufacturing, DSA skills are in critically low supply, with employers facing severe shortages.

In 2011, McKinsey & Co predicted there would be a deficit of 190,000 big data experts in the US by 2018. Similarly, a July 2017 Asia-Pacific Economic Cooperation report found as few as one-third of data science jobs are being filled.

How astronomy also broadens career horizons: The Australian case

Astronomy Australia Limited (AAL) has found that approximately half of Australian astronomy PhDs move into non-astronomy fields by 20 years after graduation. Many of these move into non-astronomy academic roles, government or the not-for-profit sector, but 15% move into the private sector. Finer-scale analysis by the Office of Australia’s Chief Scientist indicates that Australian Astronomy graduates apply their training to a wide range of professions, including design, engineering, science and transport (23%), education (14%) and information and communication technology (13%). In the United States, approximately 20% of astronomy PhDs were found to be employed in areas such as medical, computer hardware and software, engineering, earth sciences, business, and finance (from American Institute of Physics, 2014 survey of Astronomy PhDs).

“Partnering with the SKA has helped us by providing a publicly accessible case study for creating one of the world’s largest and most cutting-edge computing systems using Agile methods. Usually anything this cutting-edge is secret and under an NDA; but the public, open nature of the SKA has made it a favourite talking point on our courses, and at conferences and meetups within the SAFe community. This has not only benefited us and the SKA but the agile community as a whole.”

Ian Spence, Agile Coach to the SKA, Chief Scientist and SAFe Fellow @ Ivar Jacobson International.
3.3.4.3 Innovation and Technological Spin-offs

Creativity and Innovation is a foundational value of SKAO. The SKA will demand innovation in a number of fields, including electronics, communications, computing, and data management. It will push industry to the technological limit, requiring creativity and exploration. It is expected that technological developments in SKA member countries and/or the SKA itself will generate several by-products that will contribute to innovation in our society. The economic impact of this is expected to be many times the value of direct contracts.

The technological spin-offs that will arise from the SKA, and their impact on everyday life, by their very nature, can't be predicted in advance. However, SKA by-products are most likely to come in the following areas:

SKA dishes, antennas, and receivers
The steerable dishes, receivers and aperture array antennas represent one of the major costs in the construction of the SKA, and the design of these elements must be cost-efficient and deliver high performance.

Achieving the wide field of view required for SKA has driven the development of novel antenna arrays including focal-plane arrays at the focus of dishes and aperture arrays on the ground. The numbers of individual receivers required, in particular for the SKA-LOW telescope (131,072 receivers), is also stimulating the development of highly integrated receivers.

Radio signals from astronomical sources are incredibly faint and need to be amplified before being processed. This is done using low noise amplifiers (LNAs), whose main feature is to avoid adding lots of extra unwanted noise in the amplification process. During the design phase of the SKA, several companies and institutions have been enhancing further the LNA technology to meet SKA’s stringent requirements. For instance, the National Research Council of Canada’s (NRC) recently developed LNAs are already deployed on the MeerKAT telescope. They are several times better than previous such devices, with no cost increase, and introduce 10 to 1000 times less unwanted noise than commercial satellite-communication LNAs. Such LNAs also have exciting applications in areas as diverse as telecommunications and quantum computing.
Case study: From radio telescopes to the quantum computing boom – A Swedish example

In the construction phase, Sweden’s financial contribution will result in the company ‘Low Noise Factory’ delivering its world-leading Low Noise Amplifiers (LNAs) to several of the SKA’s receivers – key components for enabling new scientific discoveries.

Initially a spinoff from Chalmers University of Technology, the company has grown fast from its roots in the university’s nanofabrication laboratory. Driven by radio astronomy’s extreme requirements, ‘Low Noise Factory’ developed the capability to design and manufacture amplifiers of outstanding performance. For SKA, their amplifiers have to meet an unusual requirement: to operate optimally at room temperature. In industry, cooled amplifiers are the norm, and Low Noise Factory have become experts at both domains. Their products are now being bought in large quantities by tech giants like Google and IBM for building quantum computers.

“Developing and delivering amplifiers for the SKA has been important for us in many ways. We’ve been able to improve our product design, processes and our skills, making it possible for us to expand our business and product portfolio”.

Niklas Wadefalk, Low Noise Factory CEO.

Big data, high-performance computing, and low-power electronics

The SKA is often described as a Big Data endeavour, due to the fact that it will process and manage unprecedented amounts of information. The first phase of the SKA alone is expected to archive more than 700 PB of science data - the equivalent of 250 million high-definition movies every year, and will require two supercomputers, each of which would have been among the most powerful in the world if built in 2018. However, while such facilities would typically consume over 6 MW of power to deliver on the SKA requirements, SKA’s supercomputers will need to do the same with only about 2 MW. This corresponds to a factor of 3 improvement, demonstrating how the needs of a research facility can drive innovation that will then find market applications in low-power electronics.

Figure 63. Low noise amplifiers in the band 1 receiver for SKA. The Gothenburg company ‘Low Noise Factory’ developed the unique low noise amplifiers (LNA) for SKA band 1 that are visible in the middle of this image. They are specially designed for optimal performance without the need for cooling the feed. Credit: Chalmers/J. Bodell.
These data will be processed by high-performance computers in near-real-time, creating science products for distribution around the world on undersea fibre-optic cables to SKA regional centres in member countries. The need to manage information on this scale shows the importance for SKAO to keep forging collaborations with vendors before and during construction, to help drive innovation in energy-efficient computer designs which will, in turn, bring benefits to the ICT industry as a whole.

Preparationing the science community to the forthcoming deluge of data – the SKA data challenges

The SKA’s science data challenges are a prime example of enhancing skills and capacity, designed to not only help member countries to prepare their infrastructures in terms of data transfer, processing and storage, but also to ensure the community of users are prepared for how to handle and maximise the potential of SKA data. Importantly, the challenges are aimed not only at radio astronomers but the broader astronomy, physics, and computing spheres.

The first challenge in 2018/19 saw nine teams representing 12 institutions in eight countries take part. A second challenge is being launched in late 2020, this time also involving major computing facilities operated by partner institutions in several SKA member countries (e.g. Australia, China, and Portugal). The challenge aims to develop the techniques and skills required of both the users and the facilities for when SKA data begin to flow.

Signal processing and data transport
Aperture array stations require substantial digital signal processing to carry out beamforming and calibration. The LOFAR telescope in the Netherlands and the Murchison Widefield Array (MWA) in Australia have already pioneered the approach at low frequencies. The challenge for the SKA is to do this with much higher bandwidths, many more beams, and more than 100 times the number of elements while minimising the cost and power consumption.

The SKA telescope in South Africa will generate 8.8 Tb/s of data, and the telescope in Australia ~7.2 Tb/s. This will need to be transported over hundreds of kilometres. This is significantly larger than the total data flow through any of the world’s largest internet exchanges. This challenge represents a clear opportunity for innovation in new techniques for high bandwidths, as well as low cost and reliable installations, with applications that could extend well beyond radio astronomy.

High-performance digital acquisition backends
Radio astronomers make extensive use of signal processing techniques, similar to those employed in radio communication and radar applications. In particular, spatial beamforming is an emerging technique which is widely used in 5G telecommunication. In the SKA, these techniques will be pushed to their limits; SKA-LOW will employ massive beamforming, combining the signals from tens of
thousands of individual antennas. This will require cutting-edge technology, using field programmable gate arrays and analogue-to-digital converters, and efficient signal processing algorithms.

Figure 65. Work in Sweden at Onsala Space Observatory and the Netherlands at ASTRON to develop new instrumentation and electronics. Credit: SKAO, ASTRON.

3.3.4.3.1 Impact Story: Italian SKA Design Efforts Lead to High-Performance 4G-LTE Antenna

The challenge of delivering the SKA has enabled strong cooperation in Italy between industry and radio astronomical-technological research centres and driven the development of a new commercial high-performing antenna working at 4G-LTE frequencies.

The antenna was developed by Italian company Sirio Antenne, a contractor to the Italian National Institute for Astrophysics (INAF) in the SKA project, taking inspiration from their work, in collaboration with UK, Dutch and Australian teams, on the SKALA 4.1-AL antenna created for the SKA-LOW telescope and installed in the Australian outback.

Although the commercial and SKA antennas have very different purposes, the technical and electrical design of the commercial antenna has several common elements with SKALA 4.1-AL. The commercial antenna has generated good feedback from the European market and won a tender in France for the electrical network supplier (for ENEDIS/EDF FRANCE) for remote power consumption reading.

3.3.4.3.2 Impact Story: Technology Transfer in Spain

Critical industrial, financial and governmental applications increasingly require accurate, reliable, and traceable signals for time and synchronisation. SKA’s stringent requirements for signal timing and synchronisation have triggered technological developments from several partners that are already making their way to other fields beyond astronomy.

For example, work developed by the University of Granada and Seven Solutions as part of their involvement in the SKA signal and data transport design consortium, based on the White Rabbit Technology, has already found applications on the international market in sectors including aerospace, financial technology, smart grid, and more.
3.3.4.4 Building Capability in Industry

The scale of the SKA, and the inherent requirement to ‘productise’ and mass-produce many of its components, requires new and innovative levels of industry participation far exceeding that required in other astronomy projects.

The SKA will contract industry suppliers to manufacture and assemble components, systems and sub-systems. This commissioned work will allow industry to develop cutting-edge knowledge and expertise, and offer opportunities for R&D. This will generate economic benefits for member countries in the form of strengthened industrial capacity.

“Research infrastructures are a magnet for talent and knowledge-intensive companies. By collaborating with science on new technologies, industry can expand or improve its existing expertise to introduce new technologies to existing markets or enter new markets. Investing in RIs therefore also means investing in new key enabling technologies for future solutions to societal challenges and new prosperity.”

NL Minister of Education, Culture and Science Ingrid van Engelshoven (2019)

The construction of the SKA requires collaboration between researchers and manufacturers to produce new or improved instruments for specific products, which subsequently provide the platform for wider sales or even new product lines. This is an area of considerable business potential. The building and installation work will entail the purchase of various high-value instruments and software, some of which will likely involve technological innovation or other advances.

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Figure 66. A side-by-side view of the Gemini board (left) for the SKA-LOW central signal processor (CSP) and the TALON-DX board (right) for the SKA-MID CSP. TALON development was led by Canada’s National Research Council (NRC) in collaboration with industry partners Intel. The Gemini board is a joint effort between ASTRON in the Netherlands, CSIRO in Australia, and Auckland University of Technology in New Zealand, in collaboration with industry partner Xilinx.

The high-performance computing challenges of the SKA will also offer industry an opportunity to explore ways to work with unprecedented volumes of data. For instance, Australia’s contribution to the SKA supercomputing software has already exposed a range of companies to new capabilities, with both large (IBM, Cray, Asure Software, Amazon) and small (Think Bottom Up) companies involved in the development of the prototype software. Software engineers from industry have also been seconded to work on the SKA as a way of building capability and exposing them to large science projects, as has been the case with India-based Tata Consultancy Services and Persistent Systems.

“The SKA is the first project I’m involved in that’s given me an opportunity to work with various cultures. It gave me a lot of valuable input for my future work and really helps to improve myself.”

Snehal Nakave, Engineer, Tata Consultancy Services.
Case study: What next generation data centres could learn from SKA – the Canadian example

The SKA requires very fast processing of enormous amounts of data – a familiar challenge in today’s world but pushed to the extreme. The National Research Council of Canada (NRC) and MDA worked together to lead the design of the SKA1-MID correlator/beamformer (CBF). The CBF takes in wideband data from all 197 antennas and produces the visibilities needed to make astronomical images, as well as the data sums used to search for very fast astronomical transients and pulses. This is the equivalent of using millions of iPhones in tandem to download and process millions of high-resolution movies every second - but doing this at a fraction of the cost, using a fraction of the power, and generating much less heat in the process.

In a world that is increasingly dependent on using more data, faster, in everyday life, this sort of advanced high-efficiency processing is just what’s needed for next-generation data centres, and many other applications across the digital world.

“The SKA project provides an excellent opportunity for MDA and Canadian industry to collaborate with scientists, academics and leading industrial suppliers from around the world to explore innovative and cutting-edge solutions to world-class signal processing problems.”

David Stevens, Program Manager, MDA

In the UK, The University of Manchester’s Jodrell Bank Interferometry Centre of Excellence, IBM Research and the SKA Organisation are already researching how artificial intelligence and machine learning techniques can be adapted and extended for SKA science. Similar work is happening in other parts of the SKA partnership, including in China, where a collaboration between the Shanghai Astronomical Observatory and Huawei led to the development of new artificial intelligence approaches inspired by the challenges posed by the SKA. These approaches were then successfully tested on the Atlas 900 Huawei Cloud Ascend cluster service, processing over 200,000 radio galaxies in just 10.2 seconds as opposed to 169 days with an earlier system. The objective is to eventually apply machine learning solutions to seemingly routine tasks like identifying, classifying and cataloguing astronomical objects from SKA images to detect tens and hundreds of millions of astrophysical systems and use artificial intelligence to make sure that the classifications are unbiased.

In 2018 The University of Manchester entered into a collaboration agreement with the Chinese Engineering Group CETC to create a new joint laboratory for radio astronomy advanced instrumentation research, representing a multi-million-euro investment to develop new cutting-edge technologies for radio telescopes like the SKA.

In a 2019 report, a London-based independent economic forecasting and analysis consultancy centre for economics and business research found that increased capacity is likely to benefit physics-based industries and contributed significantly to the European economy. The report found physics-based industries generate more than 16% of Europe’s total turnover -more than the entire retail sector. It found physics also creates more than 17 million highly skilled jobs in Europe or 12% of Europe’s total business economy employment.

The activities of the physics-based sector also impact the wider economy through a ‘multiplier effect’, such as knock-on effects through the supply chain. For every €1 of physics-based output, a total of €2.49 output was generated throughout the economy as a whole. For every job in physics-based industries, a total of 3.34 jobs were supported.

3.3.4.4.1 Impact Story: From SKA Design Work to Construction - Enhancing Industry Capacity in the UK

In the UK, a review commissioned by the UK Science and Technology Facilities Council in 2018 found SKA design work represents a significant opportunity to benefit UK industry particularly in areas such as telecoms, computing, data storage, electronics, programme and project management, and civil and mechanical engineering. This includes the emergence of spin-off companies using the expertise acquired during this phase with the potential to find new market opportunities, such as CEMTL in the field of electromagnetic technology. As a result of the UK’s participation in SKA design work, the UK is leading on seven Tier 1 construction contracts, representing a total of ~£70 M (~€78 M) worth of construction work to the UK industry.

UK business engagement involves either collaborations, i.e., joint research with the scientific community to deliver specific elements of the work packages, or contracted arrangements to deliver fee-chargeable work. Consultations with businesses highlight that the main benefits arising to 2018 were not financial — instead, businesses greatly valued the opportunity to enhance their staff skills and credentials through their involvement in a high-profile global scientific endeavour. This is seen as providing a significant competitive advantage, particularly in competitive markets.

In 2020, for example, STFC funded two software engineers from the UK industry to join the SKA’s software development programme. Two companies, Observatory Sciences (developers of control software for large science systems and instruments) and ITDev (suppliers of software and electronic engineering services) were selected and their engineers are joining software engineers from The University of Manchester, STFC and CSIRO working on prototype monitoring software for SKA-Low.

“Our funding has provided an excellent opportunity for these companies to engage with the project, gaining new expertise across several domains and trialling the procurement practices that will be used during construction.”

George Madden, STFC Programme Lead for the SKA

As a matter of comparison with other investments in similar large-scale RIs, evaluation of the impact of CERN undertaken for STFC\(^ {15} \) found UK suppliers to CERN also realised wider benefits, beyond the value of the contracts themselves, including the development of innovative technologies and access to new market opportunities.

CERN contracts also bestowed a degree of prestige on suppliers that was not easily replicated elsewhere, which aids new sales. Involvement in the SKA is already showing signs of similar benefits, with a number of companies requesting to publish joint press releases with SKAO and case studies of their work with SKA, such as GitLab (software development), Unit4 (enterprise resource planning), Stratodynamics (aerial calibration) and Observatory Sciences mentioned above.

“Our involvement with the SKA has unquestionably contributed commercially and technically to us as a business. Our first SKA film won a European gold award, and as a direct result of that film, we were approached by CERN, who we continue to work with to this day. We have subsequently delivered films for other major international science projects including ITER, doors which would have been significantly harder – if not impossible - to open had we not worked with the SKA. The SKA’s strong presence in the global science community means the work we’ve produced for them has been foundational for us as a business in the science sector and continues to lead to new opportunities.”

Joe Kane, Director, Polar Media Production Company

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3.3.4.4.2 Impact Story: Industry and Academia Push Technological Boundaries in Australia

The construction of SKA precursor telescopes ASKAP and the MWA in Western Australia saw research organisations and firms undertaking problem-solving activities together, with knowledge exchange in both directions.

Figure 67. The Australian SKA site has been buzzing with activity the last few years, with work going on with the ASKAP, MWA, EDGES telescopes as well as the SKA prototype antennas being deployed. Credit: CSIRO.

The partnerships led to considerable benefits for local industry. Some examples are:

**Puzzle Precision**
This regionally located SME electronic assembly company partnered with CSIRO to jointly develop and produce 20,000 sophisticated electronic circuit boards, piecing together more than six million components to deliver receiver, beamformer and correlator systems for the ASKAP telescope, one of the SKA precursor facilities. It was crucial that Puzzle Precision met the stringent high yield and reliability requirements of ASKAP, as this telescope operates in the punishing environment of the Australian outback, and processes data at the rate of one Peta-operations-per-second, or a thousand-million-million operations per second, around the clock. The relationship between CSIRO and Puzzle was a true collaboration that enabled CSIRO’s innovative ideas to become manufacturable.

The ASKAP project led to new capability development for Puzzle – they doubled their workforce, employed and trained young locals, built a new state-of-the-art factory, and invested in cutting-edge machinery. Since ASKAP, Puzzle has expanded their reach into the space industry and Australian capability in the production of mission-critical, highly reliable electronics has also been enhanced.

**Innovation Composites**
This Australian composites and fibreglass manufacturer worked with CSIRO to develop radio insulated casings for ASKAP’s phased array feed (PAF) receivers. In addition to being lighter and more cost-effective than previous designs, the casings meet the requirements demanded by the harsh and remote working environment of ASKAP, while limiting radio frequency interference - a well-known obstacle in radio astronomy. Innovation Composites applied their specialist knowledge of marine composite technology, demonstrating how industrial skills can be applied to advanced science instruments. This collaboration has driven innovation and led to new applications of composite construction.

**Poseidon Scientific Instruments**
Poseidon Scientific Instruments (PSI), is a small Fremantle-based radio frequency specialist company, grown out of the University of Western Australia’s gravitational wave detection research. The company collaborated over a three-year period, to successfully configure and manufacture the MWA receivers and was subsequently acquired by major American multinational conglomerate Raytheon in the aerospace and defence sector. IBM and Cisco worked with PSI to create highly specialised hardware to process the vast amount of data created by the MWA.
The SKA’s distributed nature, with antennas spread over hundreds of kilometres, huge data flows and complicated signal and image processing, requires a sophisticated system for end-to-end monitoring, control, and management of the telescopes. India led the international consortium which designed this telescope manager (TM) system for the SKA.

India’s software industry has gone from strength to strength in recent decades, and some of the major players in this arena – including Tata Consultancy Services and Persistent Systems – engaged their R&D teams to work alongside experts from research organisations like the National Centre for Radio Astrophysics (NCRA). A good amount of this TM design work was done in a collaborative fashion, rather than as a purely commercial contract. This engagement has helped to build a strong and vibrant industry interaction model, which will benefit India and the SKA in the construction of the Observatory management and control work package (an expanded version of TM).

Indian industry has also found the experience enriching, with potential applications in other areas and large projects emerging from the experience gained in the SKA work. Some benefits from this synergistic activity are already visible, with experts from Indian industry playing and expected to play important roles in the SKAO software work.

"We have leveraged the strength of India’s software industry to work in a spirit of collaboration with us, and to build a partnership which is well placed to make significant contributions to the construction of the management and control software of the SKA."

Prof. Yashwant Gupta, Telescope Manager Consortium Lead and India’s science Director on the SKA Board.

In France, the national coordination of SKA-related scientific and technological activities is managed by a consortium of French partners from both industry and research sectors. The consortium, known as ‘Maison SKA-France’, includes universities and research organisations CNRS, Observatoire de Paris, Observatoire de la Côte d’Azur, University of Bordeaux, University of Orléans, INRIA and CEA/DRF as well as companies Air Liquide, ATOS-Bull, Callisto, CNIM, Kalray, FEDD and Thales. Such collaboration has played a key role in further positioning the SKA within industrial, scientific and political spheres in France. As a result, the SKA has been inscribed in the French Roadmap for Research Infrastructures, and in 2018 Maison SKA-France became the 12th member of the SKA Organisation. From the scientific point of view, French interest in the SKA has greatly increased in recent years, with French participation in the international SKA preparatory science meetings increasing from 2% in 2014 to 8% in 2019. The SKA France white paper, published in 2017, involved 178 authors from 40 institutes and six private companies.
Astrotourism or star tourism is now a major trend of a sustainable, high-quality tourism segment and became a central element in the protection of Dark skies across several SKA member countries such as Australia, Portugal, South Africa, and Spain, among others.

As an example of this growing appetite, every year, ESO’s Paranal Observatory in Chile welcomes 10,000 visitors alone. Chile, building on its strong support for such international observatories, has had much success in developing its astrotourism offer in particular in the north of the country, where major professional astronomy facilities are located. The government developed a national strategy for astrotourism across its regions, which is being promoted with national and international visitors alike. Professional observatories work with publications such as the Lonely Planet Guide to include information regarding their public tours. Local communities around those sites have developed their offers, including night sky viewing with trained guides, bed & breakfasts equipped with telescopes, etc.

The SKA offers a similar potential to its local communities. Already, guest houses have grown in Carnarvon (from 3 to 11 in nine years) to cater for the many workers coming to work on KAT-7 and then MeerKAT on the South African SKA site, providing a new source of income for the town. This is likely to be the case when SKA construction starts, with a number of SKA personnel and contractors who will require accommodation locally.

The South African Department of Tourism is developing an astrotourism route that includes the South African Large telescope in Sutherland and SKA in Carnarvon. As part of the concept, the department, together with SARAO and the Department of Science and Innovation, is in the process of developing a Science Exploratorium in Carnarvon.

Both CSIRO and SARAO have already trialled open days at the SKA sites attracting visitors from hundreds of kilometres away, and SKAO is considering the viability of such programmes for the SKA. There are also ongoing discussions to include exhibitions in existing museums and science centres but also to create entirely new spaces in regional communities near the sites like Geraldton and the Murchison in Australia, and Carnarvon in South Africa. Such developments are critical to support the interest of the public in SKA; due to the demand to maintain a radio-quiet environment at the Observatory, visits by the public will be strictly limited to organised events.
Astrotourism as a boost for local economy – the FAST example

The construction of the FAST telescope was associated with a number of infrastructure improvement works in the region to facilitate access to the facility. For instance, the project saw 100 km-long highways built in the region 20-30 years earlier than expected. This not only benefited local residents, it also boosted tourism locally.

An extensive Astronomy Town emerged out of a poor village with basic infrastructure, without paved road and nonexistent tourism offer. The Astronomy Town was co-designed by the FAST team and local governments and then built up by local governments to provide better living conditions in the remote area around the FAST site. It now enjoys a museum, park, and housing facilities, including two big hotels which employ more than 300 people (including associated services). FAST and the Astronomy Town welcomed 200,000 visitors in 2017 and over 400,000 in 2018, contributing enormously to the local economy by expenditure and job creation.
3.3.5 Society

Far from being in an ivory tower, science and astronomy in particular form an integral part of modern societies. As astronomy enjoys broad public appeal as an accessible science, it also plays a role in science, technology, engineering, and mathematics (STEM) education and encourages science literacy in the population as a whole.

Astronomy is well-known for its ability to attract young people to science and technology careers. It also drives education and training that can help solve major societal challenges involving science and technology.

“Astronomical research continues to offer significant benefits to the nation beyond astronomical discoveries. These benefits include its role in capturing the public’s attention and thereby promoting general science literacy and proficiency, its service as a gateway to science, technology, engineering, and mathematics careers, and a number of important and often unexpected technological spin-offs.”

New Worlds, New Horizons in Astronomy and Astrophysics, National Research Council of the National Academies (USA)

Because of its size, diversity, and high profile, the SKA can be a proactive and progressive voice in society, whether it is to address global challenges and emergencies, inspire the next generation or contribute to progressing the global agenda around equality, diversity, and inclusion.

3.3.5.1 Responding to Societal Emergencies

Skills honed on mega-science projects such as the SKA are readily transferable to meet immediate societal demands away from astronomy. In the recent past, SKA partner institutions played an active role in the COVID-19 pandemic response. For example, in South Africa, SARAO was appointed by the government to manage the design and production of respiratory ventilators in response to the COVID-19 pandemic thanks to its experience delivering the MeerKAT telescope. The skills they developed in engineering, project management, and systems engineering were utilised to great effect in the production of these much-needed medical instruments. Other examples include the UK’s STFC 3D printing of personal protective equipment, the development of educational online tools to support home-schooling or allocating computing resources to study the virus; the Institute of Astrophysics of Andalucía joining a Spanish effort to develop a portable detector capable of detecting the virus on surfaces; Australian astronomers at Swinburne University developing a symptom-tracking app; Italian’s Institute for Astrophysics (INAF) developing online educational tools for children; or India’s National Centre for Radio Astrophysics (NCRA) contributing to a public information campaign to combat misinformation. In Portugal, the ENGAGE SKA high-performance computing infrastructure was selected by the public administration to support Artificial Intelligence (AI) initiatives that aim to improve the response to pandemics such as COVID-19, while in Canada, a team of physicists, led by Dr Art McDonald (Nobel Prize in Physics for his work on solar neutrinos), was called in to design a ventilator to help in the treatment of the disease.
3.3.5.2 Inspiring the Next Generation

The SKA will enable astronomers to explore phenomena from planets around nearby stars (perhaps including planets where life may exist) to the most distant galaxies at the edge of the observable Universe. Astronomy and the wonder of space are particularly appealing to the general public and, as such, the SKA will be a beacon of inspiration for the next generation, leading some to careers in science, engineering, and technology.

SKA partners around the world already enthuse thousands and in some cases tens of thousands of children, students and adults alike every year through open day events at their facilities, public engagement initiatives such as talks or hands-on interactive activities, travelling exhibitions, etc.

Figure 70. National Science Day under the watchful eyes of the GMRT. Every year, over a hundred schools and colleges from the region exhibit their science activities and projects along with exhibits and live demonstrations from various research institutes and national labs. The 2-day event attracts an average of over 20,000 visitors each year. Credit: NCRA.
Every year, astronomy enthusiasts descend on the largest annual astronomy festival in Australia - Astrofest - to celebrate all things astronomy and the SKA through stargazing parties, talks and other activities. The event, coordinated by the International Centre for Radio Astronomy Research (ICRAR) on behalf of the collective Astronomy WA, began in 2009 in Perth and is now replicated around the state and the nation. In 2019, the festival won the Chevron Science Engagement Initiative of the Year at the WA Premier’s Science Awards. Over the years, it has attracted over 40,000 visitors. Credit: ICRAR.

SKAO is regularly involved in such public engagement events and solicited to take part in outreach opportunities. The SKA has been a permanent fixture at the Bluedot festival taking place each year at the Jodrell Bank Observatory, which sees some 15,000 members of the public attend and engage with scientists and engineers working on the project.

Figure 72. SKA stand at the popular Bluedot festival hosted at the Jodrell Bank Observatory. Every year the festival sees ~15,000 enthusiasts attend. Credit: SKAO.
SKAO and its partners also make full use of digital platforms such as websites and social media – with some campaigns like the signature of the SKA Treaty in Rome reaching up to 5 million users – as well as emerging technologies like Virtual Reality and Augmented Reality to develop applications that immerse viewers, most of whom will never have the opportunity to visit the sites (see inset image).

The emergence of citizen science in the past 20 years thanks to distributed computing is also offering opportunities to the SKA. Partners have already developed citizen science initiatives making use of data from SKA pathfinders such as Astron’s Radio Galaxy Zoo in the Netherlands which makes use of LOFAR data to help astronomers find black holes or the RAD@Home programme in India which uses GMRT data to train and teach students about galaxy evolution.

Experts working on the SKA at the HQ and around the world also regularly give public talks to popularise the science and engineering behind the project, such as in the popular TEDxTalks series in cities including Christchurch, Johannesburg, Manchester, Perth, and Sydney, as well as the Royal Institution’s popular Christmas Lectures in the UK, and even at science fiction conferences. Together, these talks made available online have reached tens of thousands of members of the public and help inspire new audiences with STEM.

SKAO is also developing close relationships with outreach experts internationally such as the IAU’s Office for Astronomy Outreach (OAO) and their global network of national coordinators to explore the possibility of jointly developing and delivering new radio astronomy outreach activities in SKA member states.
3.3.5.2.1 Impact story: The First Mega Science Exhibition in India

More than half a million people were inspired by Vigyan Samagam, a major travelling exhibition showcasing mega-science projects India is involved in, organised by India’s Department of Atomic Energy, Department of Science and Technology and National Centre for Science Museums. The exhibition – which means ‘Confluence of Scientific Ideas’ in Hindi – covered India’s participation in flagship mega-projects CERN, FAIR, INO, ITER, LIGO, SKA and TMT, and how participating in these projects is necessary to gain an exhaustive understanding of the Universe.

Between May 2019 and March 2020, the exhibition travelled across the country to Mumbai, Bengaluru, Kolkata and Delhi, featuring lectures, panel discussions, interactive stalls, competitions, and live demonstrations.

Along with huge crowds, the exhibition also received significant media coverage, popularising the SKA and other major fundamental research projects with students in India while building a coherent narrative in support of India’s participation in large-scale RIs.

![Figure 73. A glimpse of the SKA exhibition booth in Vigyan Samagam. The booth was visited by Dr Jitendra Singh (second from left), the Indian Minister in charge of the Department of Atomic Energy and Department of Space during the inauguration of the exhibition in Delhi.](image)

3.3.5.3 School programmes

By working closely with education authorities, building on the experience and success of existing efforts such as NASA/HST, Universe Awareness (UNAWE), and working together with international experts such as the newly launched IAU Office of Astronomy for Education, the SKA can make a substantial contribution to current efforts to bring astronomy onto the school curriculum. Initiatives are already underway in a number of member states to include radio astronomy and the SKA into...
curriculums and are set to grow over the coming years as the project gains visibility and the telescope starts delivering its first science results.

In the UK for example, education experts at the Jodrell Bank Discovery Centre received a grant from the Royal Academy of Engineering to develop classroom hands-on activities with support from SKAO to explain some of the complex engineering behind the SKA in a fun and engaging way. These resources were then made available for free on online platforms that are widely used by teachers and educators around the world.

Beyond member states, opportunities also exist to raise the SKA’s profile internationally. In 2017, SKAO worked with publishers Oxford University Press to appear in a new series of mathematics textbooks for students preparing the International Baccalaureate, which was sat by 170,000 students in 153 countries in 2019.

### 3.3.5.3.1 Impact Story: Radio Treasure Hunting in Italian Schools

The huge effort by the SKA worldwide community to select remote locations with a mostly uncontaminated radio frequency environment, and to protect the radio telescopes from radio interference has inspired the Italian National Institute of Astrophysics (INAF) to conceive an educational activity for high-school students, called “Radio treasure hunting”.

The activity aims to raise students' awareness of the problem of radio interference and therefore why the SKA, and more generally radio telescopes, need to be constructed and protected in remote locations. Moreover, it aims to highlight the long-standing work carried out by INAF to protect radio frequency bands in Italy in cooperation with the Ministry of Economic Development.

“Radio treasure hunting”, designed and tested within the game-based learning methodology, makes use of radio transmitters, antennas and receivers that allow students to practice concepts such as radio signal maximisation and searching, and localisation of a radio signal, all within a playful environment. The activity was first proposed at the games festival “Play” in early 2019 and later on at the Children’s Festival in Bologna.

### 3.3.5.3.2 Impact story: Improved Literacy, Mathematics, and Science Teaching in the Area Around the South African SKA Site

Since 2007, SARAO has been working with primary and high schools close to the SKA site to improve literacy, mathematics, and science teaching and learning. SARAO has seconded experienced mathematics and science educators to the schools, supported teachers and students, and offered a bursary programme for students to study at Carnarvon High School, the only school in the region offering mathematics and physical science to Grade 12. SARAO also coordinates and funds a Lego Robotics programme in schools in the Karoo, and in 2019 a team from a local high school won the International Lego Robotics Competition in Uruguay.

9 - Local schools supported in communities surrounding the South African SKA site, amounting to about 5,000 learners every year.

20 - Students from the Karoo region awarded scholarships to study science, engineering, or education at South African universities.

1 - Community computer lab, done in collaboration with Siyafunda organisation.
3.3.5.4 Tertiary Education and Training

Excellence is another of SKAO’s values. Building the SKA will produce a cohort of highly accomplished engineers and scientists, who will be capable of applying their talents to a broad range of areas of great benefit to the member state economies and societies.

The SKA member countries have education embedded in their development from the earliest stages, inspiring young people in time for them to become users of the telescope or engineers and scientists working with the SKA, and potentially encouraging more people to develop the STEM skills needed to maintain and grow the knowledge-based economy.

SKA summer schools have been organised in several member states to equip students with skills in key areas. In China, such week-long training sessions have been running since 2013 with the support of the Ministry of Science and Technology, the SKA China Office, and the Chinese Academy of Sciences, attracting about 100 students and junior researchers each time. In 2019 the school saw 70 BSc-level students from across China practise data processing techniques on the Chinese prototype SKA Regional Centre using data from SKA precursor and pathfinder telescopes, learning new techniques and providing valuable feedback to the data centre’s design in the process.

“The SKA requires continuous contributions from the community. Knowledge propagation and education of young scientists is a vital part of that.”

Dr Tao An, Shanghai Astronomical Observatory

As another example, the DOPPLER (DevelOpment of PaloP knowLEdge in Radioastronomy) project aims to improve quality of life in Mozambique using high-tech projects such as the SKA by fostering partnerships between institutions in Portugal and Mozambique, training students in areas of strategic relevance in order to enrich the local skilled labour force, promote digital literacy and help to prevent “brain drain”. Radioastronomy, Big Data, and earth observations training are complemented by initiatives for mutual capacity building in biodiversity, food security, and land management.

A number of skilled “blue-collar” jobs are also needed to make the SKA a reality. For instance, in preparation for the construction of the SKA in South Africa, the South African Radio Astronomy Observatory (SARAO) has created significant artisanal capacity to operate and maintain the MeerKAT and SKA facilities. Students from Karoo towns have trained as electricians, optical fibre technicians, fitters and turners, instrumentation technicians, diesel mechanics, IT, boilermakers, carpenters, plumbers, bricklayers, and welders. Of the 18 qualified artisans, 11 have been employed by SARAO. SARAO has also established a technical training centre in Carnarvon to train electrical-artisan students.
Figure 74. Workers in one of the shielded rooms of the Karoo Array Processing Building (KAPB) at the South African SKA site. Credit: SARAO.

### The value of training

£4.9 M

Value of free training returned to the UK economy through individuals participating in various formal CERN schemes in the past decade.

Source: Technopolis Group (2020)\(^\text{16}\).

#### 3.3.5.4.1 Impact Story: Human Capital Development in South Africa

When South Africa submitted its expression of interest to host the SKA in 2003, there were five radio astronomers in the country. Today there are more than 200 practising radio astronomers based at South African universities and national facilities, largely due to SARAO’s Human Capital Development Programme, established in 2005.

The programme creates upskilling and employment opportunities and attracts students to relevant STEM degrees with competitive grants to cover the cost of studying. Many of the programme’s graduates have been employed by SARAO, with others finding work in universities and industry.

1,279 - Grants provided since inception to 2019 to undergraduate students, postgraduate students, and postdoctoral fellows. Of these, 617 were awarded to Black South Africans and 275 to women.

5 - Research chairs supported at South African universities. The research chairs have further increased the number of researchers and supervisors able to supervise postgraduate students and manage SKA- and MeerKAT-related research.

44 - Young Professional graduates supported through SARAO’s Young Professionals Development Programme.

14 - Annual conferences organised since 2006 to bring together SARAO-supported fellows, students, astronomers, and engineers to share research and build international collaborations.

3.3.5.4.2 Impact Story: DARA Projects Build Radio Astronomy and Data Science Expertise in Africa

The DARA (Development in Africa with Radio Astronomy) and DARA Big Data projects are training young Africans to take advantage of the enormous opportunities radio astronomy and data science will bring. Together both projects have received £6.3 M (€7 M) from the Newton Fund as part of the UK’s overseas aid budget for scientific collaborations with developing countries, with matched resources from South Africa.

DARA was set up in 2015 and is training the first generation of radio astronomers in the eight SKA African partner countries - Botswana, Ghana, Kenya, Madagascar, Mauritius, Mozambique, Namibia, and Zambia - most of whom had few or no astronomers until recently. DARA has provided basic radio astronomy training to more than 250 graduates through four two-week training courses delivered by experts from the UK and South Africa over 12 months.

The DARA Big Data project was set up in 2017 and is training students in data science and machine learning. It has run hackathons and intensive workshops for almost 200 students.

DARA and DARA Big Data have also supported 50 students to study masters or PhD qualifications at UK and South African universities. These advanced programmes are highly competitive, receiving up to 10 times more applications than places available. The projects’ reach extends far beyond radio astronomy, with graduates finding work in areas as diverse as using big data to personalise breast cancer treatment and improving soybean breeding.

“Astronomy can contribute to the broader societal needs of the continent. The DARA partnership is equipping a new generation of entrepreneurs, scientists and professionals.”

Takalani Nemaungani, Acting Chief Director of Astronomy, South African Department of Science and Innovation.
Case Study: The International Centre for Radio Astronomy Research (ICRAR)

ICRAR was founded in September 2009 with the specific purpose of supporting Australia’s bid to host the SKA. The Centre is now home to a significant research community, with 120 staff and nearly 90 postgraduate students across two universities, Curtin University and The University of Western Australia. Since 2009 ICRAR staff have taught 6,952 undergraduate students, received 1,892 visitors, and had almost 600 seminars delivered by national and international speakers.

With more than 2,000 published papers and 60,000+ cumulative citations since 2009, ICRAR is considered a top radio astronomy research centre in the world.

Since November 2009, ICRAR has hosted 86 undergraduate students for 10-week summer studentships. Each year some studentship projects have been co-funded with the Pawsey Centre for Supercomputing for student projects that have a computational aspect or use Pawsey infrastructure as part of their studentship.

A 2017 Deloitte report found that for every dollar invested in ICRAR, $4.50 was created in income to Western Australia. For every job that was funded, the Centre created three jobs.

3.3.5.5 Indigenous relations

The land on which the SKA telescopes will be constructed, in both Australia and South Africa, has strong ties to indigenous heritage. Respecting indigenous cultures and the local populations and engaging positively with them has been a key consideration since the inception of the SKA project.

South Africa

In South Africa, the Karoo region was walked by the early ancestors of the San people, who are considered to be some of the most ancient people on Earth, having been around for the past 22,000 years. Today, there are still significant indicators of cultural heritage found on the land around the South African SKA site.
Figure 76. Statuesque dolerite rock formations can be found on hills close to the MeerKAT telescope site in South Africa, also the future site of the SKA. The Losberg Farm, now a construction camp, can be seen in the distance on the right. Credit: SKA Organisation, Rob Millenaar (ex-ASTRON).

In 2017, SARAO signed a Memorandum of Understanding with representatives of the San people that is structured around the protection and promotion of San culture and heritage, as well as the development of San youth. By taking the indigenous knowledge systems that focus on astronomy and cosmology seriously, SARAO aims to ensure that this knowledge is not portrayed as unscientific or dissimilar to Western science. SARAO engages in a variety of activities with the San to support these objectives, thus bridging the divide between ancient indigenous knowledge systems and some of the most advanced technology and astronomy projects in history.

The San were also involved in ecology and heritage studies conducted as part of the strategic environmental assessment required to construct the SKA. These studies entailed walking the land to identify cultural heritage, fauna, and flora then documenting and sharing the findings with the San Council.

Thanks to SARAO’s support, a whole indigenous culture is being revived helping South Africa safeguard a culture that is part of its heritage.

Figure 77. San leadership blessing the site for the future SKA in South Africa. Credit: SARAO.
Australia
The SKA in Australia will be located on the traditional lands of the Wajarri Yamaji in the Mid-West Region of Western Australia. It is an ancient landscape and geologists have identified some of the oldest rocks on Earth close to the SKA site. There is also evidence that the Wajarri Yamaji have lived on this land for tens of thousands of years.

In 2009, the Australian Government entered into an Indigenous Land Use Agreement (ILUA) with the Wajarri Yamaji. The ILUA provided a range of financial and non-financial benefits to the Wajarri Yamaji in exchange for their consent to establish the MRO on their traditional lands.

In addition to the requirements of the MRO ILUA, several additional activities have been undertaken aimed at building the relationship and recognising the critical part the Wajarri Yamaji will play in the successful implementation of the SKA Project. These activities have included:

- Balagardi Barnagardi – a Wajarri Art exhibition held over one week in Canberra. Five Wajarri artists travelled to Canberra for the exhibition to talk about their art and culture;
- a visit by the Pia Wadjari Remote Community School to Canberra (see Impact Story below); and
- a Wajarri language workshop held in Canberra and Sydney to provide learning and insight into one of the oldest languages on Earth.

Negotiations with the Wajarri Yamaji are currently underway for a new ILUA for the SKA. The existing relationship and the lessons learned from the MRO ILUA will enable an ILUA to be developed that will provide sustainable and intergenerational benefits to the Wajarri Yamaji in areas such as enterprise and training, education and culture. There will also be a requirement for all people working at the site to undertake cultural training to promote understanding and respect for traditions and culture and foster good relations between SKA personnel and the Wajarri Yamaji.

Wajarri Yamaji heritage and its protection at the SKA site is of critical importance. CSIRO has been working with the Wajarri Yamaji since April 2018 to survey (or walkover) the areas of land impacted by SKA infrastructure to record and protect heritage sites. The walkover team includes a group of Wajarri Elders as well as an archaeologist and anthropologist.

Figure 78. Members of the Heritage walkover team: From left Len Merry, Jimba Merry, Frank Merry, Kane Whitby, Daniel Puletama (Archaeologist), Quentin Simpson, Robert Ryan, Geoffrey Mongoo (front), Darry Hawkins (back), Jeremy Egan, Anthony Dann, Ted Ryan, Philip Haydock (Anthropologist), Dana Anaru (Assistant Archaeologist). Credit: CSIRO.
3.3.5.5.1 Impact Story: Pia Wadjarri Remote Community School Trip in Australia

The Pia Wadjarri Remote Community is the closest neighbour to Australia’s SKA site. In 2016, children from the Pia Wadjarri Remote Community School were supported by the SKA to travel to Canberra. The students were able to experience the nation’s capital and celebrate National Aboriginal and Torres Strait Islander Children’s Day at Questacon – the National Science and Technology Centre, with local indigenous Canberra schoolchildren. Their trip also included visits to the National Museum of Australia, the Australian War Memorial, and a visit to the Canberra Deep Space Communications Complex at Tidbinbilla before experiencing snow for the first time at Corin Forrest. The trip was the first time some of these children had been on an aeroplane and certainly the first time they had been to the nation’s capital.

![Image of teachers and children enjoying snow](image)

Figure 79. Teachers and children from the Pia Wadjarri Remote Community School enjoying snow for the first time at Corin Forest in Canberra.

3.3.5.6 Equality, Diversity, and Inclusion

Equality, diversity, and inclusion (EDI) are a fundamental part of the SKA as an international project involving countries on five continents and both hemispheres, and one of the foundational values of SKAO. The SKA is one of a few large-scale RIs that bridges the traditional geographical divides and includes both developed and developing countries as full stakeholders.

Quite uniquely among scientific intergovernmental organisations, signatories to the SKA convention – member states – also commit to “an organisation where diversity and equality are promoted and respected.”

SKAO takes this responsibility seriously and has developed an equality vision that aims to create an inclusive culture and environment that values all, is free from bias and which enables SKAO to:

- attract, retain and develop a diverse workforce, both now and in the future;
- benefit from the talents and different perspectives of all, with obstacles removed which impede development or limit opportunity. Through this, enabling equality of opportunity for all in an environment where everyone can be at their best;
• eliminate any form of discrimination within the scope of its activities, whether this be in relation to recruitment, development, pay, progression, or participation; and
• be recognised as a role model organisation, which embraces diversity and inclusion, both within the global SKA endeavour and also within the broader global scientific and engineering community.

This vision promotes equality, diversity and inclusion in all its forms. Its scope will extend from SKAO staff members through the SKAO board and its governing bodies to external SKAO related activities.

To deliver it, SKAO is committed to working pro-actively internally and externally with partners. A Code of Conduct, Code of Ethics, Ethical Champions, and EDI Working Group were put in place early on and an ambitious EDI action plan is being refreshed to improve EDI practices within the Observatory and across the entire partnership.

Working with the social media platform LinkedIn and building on other social platforms, SKAO is expanding and diversifying its recruitment to increase opportunities for underrepresented groups to apply for jobs at the SKA Observatory. As an influential voice in the field, SKAO actively supports and participates in the work of the International Astronomical Union (IAU) to develop an Equality and Diversity agenda, having sponsored and participated in the first IAU Symposium on EDI in 2019. Working with the IAU, European Space Agency and European Southern Observatory, it is also looking at issues of accessibility in astronomy, and how to develop inclusive practices and software for the benefit of all users.

On the topic of inclusion using astronomy, numerous initiatives have flourished in recent years. For instance, as part of the International Inspiring Stars exhibition, promoted by IAU, INAF has developed the exhibit “Sense the Universe”, exploiting radio data to highlight the concept of the ‘invisible’ sky, in the form of a multi-sensorial map of radio data accessible to anyone, both with and without sensory impairments. SKAO is planning to work closely with the IAU’s Offices of Astronomy for Development and for Education to support initiatives aiming at making radio astronomy more widely accessible.

SKAO also regularly profiles scientists and engineers from diverse backgrounds to give them more visibility as well as marking major UN-approved International Days like International Day of Women and Girls in Science.

![Figure 80. Members of Team SKA at SKA HQ wearing Science is for Everyone T-shirts prior to Bluedot Festival 2019. Credit: SKAO.](image)
“The SKA partner countries are inherently diverse, and as a result, the SKA could be a model for how world observatories tackle issues related to EDI. That stems not only from engaging with Indigenous and local populations where the SKA will be built but also from using the SKA as a vehicle for addressing systemic inequalities in all of the partner countries.”

Prof. Kristine Spekkens, Royal Military College of Canada and Queen’s University, Canadian’s Science Director on the SKA Board.

3.3.6 Sustainability

Sustainability is a foundational value of the Observatory, underpinning all other activities.

The SKA is designed to deliver transformational science for at least 50 years. The organisation aims to build and operate a sustainable observatory and work to minimise negative environmental impacts of the construction and operation of the telescope over its entire lifetime. To this effect, the SKA has included sustainability as a requirement within its procurement policy.

The observatory’s goal is consistent with the definition of sustainability from the UN World Commission on Environment and Development:

“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”

The following sustainability goals have been identified for the Observatory:

- minimise carbon emissions associated with the construction of the SKA, with an aspirational benchmark of 50% of materials delivered to site by sustainable means;
- minimise waste generation and maximise reuse and recycling (measured through factors including the percentage of waste diverted from landfill, and volume of remediated soil/demolition material reused);
- minimise the use of potable water during construction;
- source and use environmentally and socially responsible materials, with an aspirational benchmark of 20%, by value, of construction materials to be of a reused or recycled source (and 25% recycled aggregate for permanent works); and
- all timber to be sustainably sourced.

3.3.6.1 Environment

In South Africa, the 130,000 hectares of land acquired for the SKA is a protected area which has been declared a new national park (Meerkat National Park), under management from SANParks. The Meerkat National Park allows for the creation of multi-disciplinary research platforms. It will enhance heritage, archaeological, ecological, aquatic, flora and fauna conservation and promote resource management through the removal of alien invasive trees. A number of tertiary and research institutions are already undertaking environmental research on the SKA site.
In Australia, the SKA telescope will be constructed on the Murchison Radio-Astronomy Observatory, located primarily on a 3,500km² destocked cattle station known as Boolardy Station. The Murchison district and Boolardy station have a rich and diverse flora and fauna heritage. CSIRO, in conjunction with the Western Australian Government, has commenced collating and analysing decades of data on the flora in the region. This research will be used to provide advice to a multitude of agencies and working groups on the impact of grazing activities and climate change in the broader region, as well as with a specific view on assisting with future activities on land and water management, including principles of rehabilitation for Boolardy Station. In the coming years, a new ranger programme will employ the service of the Wajarri Yamaji to protect and preserve the heritage of Boolardy and to help educate all involved with the management of the site.

3.3.6.2 Renewable Energy

The SKA has put the use of renewable energy at the core of its ambitions from the early stages and has now identified opportunities to use renewable energy on both SKA sites and reduce the Observatory’s reliance on fossil fuels. Having considered environmental impact during design, it is estimated that the projected power consumption of the Observatory has already been halved through innovative design solutions.

The highest priority, and the best opportunity to further reduce the environmental impact, is to use electricity generated by solar photovoltaic panels at the SKA sites in Australia and South Africa. SKAO is preparing to engage with companies that could implement renewables-based power systems at the telescope sites under likely long-term power purchase agreements. The Observatory is also exploring ways to maximise the use of sustainably generated power for the computing facilities.

Electricity for the SKA’s global headquarters in the UK is provided by the University of Manchester and already comes from 100% renewable sources. The SKA HQ was designed with sustainability as a guiding principle and features a number of environmentally friendly elements, such as natural daylight and ventilation, dark sky compliant lighting around the building, and electric vehicle charging points.
3.3.6.2.1 Impact Story: Photovoltaics at the Australian SKA Precursor

CSIRO, Australia’s national science agency, partnered with Horizon Power and a Perth-based small business to deliver astronomy’s first hybrid solar-diesel power system.

An array of 5280 silicon solar panels, covering an area of three hectares, generates up to 1.6 MW of renewable power. An additional 250 kW solar array is built into the base diesel power station, to deliver a total peak solar generation of 1.85 MW - enough to power the telescopes without any input from the diesel generators for many hours each day.

A bank of lithium-ion batteries with a total storage capacity of 2.5 MWh stores excess power generated by the solar array during the day and uses this power to supplement the diesel generation at night. Modelling suggests, this saves up to 840,000 litres of diesel, and reduces the carbon emissions by up to 2,200 tonnes, per year. The battery’s discharge capacity is more than enough to power the entire MRO electrical load and modelling also indicates that the battery will enable the PV system to provide up to 40% of the MRO’s total power needs.

A major challenge was to protect the telescopes from the high-power electrical equipment in the power system. The low-cost solution design is based on standard shipping containers which were modified by adding sealed steel floors, and by installing specialist RFI shielded doors for personnel and equipment access. The external air-conditioning and cooling equipment is housed in steel mesh cages to shield any interference.

3.3.6.2.2 Impact Story: ENGAGE SKA in Portugal

ENGAGE SKA or Enabling Green E-Science for the square kilometre array, is part of the Portuguese National Roadmap for Research Infrastructures. The initiative is a public-private partnership that brought together universities and industry in the SKA design consortia to bring green ICT concepts like those used in Green Smart Data Centres (such as Altice Covilhã) to radio astronomy. Amongst other initiatives, ENGAGE SKA took part in BIOSTIRLING - 4SKA (B4SKA), a €5 M demonstration project supported by the EU for the implementation of a cost-effective and efficient new generation of solar dish – Stirling plants based on hybridisation and efficient storage at the industrial scale. ENGAGE SKA also investigated with industry how photovoltaic power and smart grids can improve overall SKA power efficiency and help to cut operational costs.
3.3.6.3 Dark and Quiet Skies

The SKA sites are located within areas of extremely low population density with an almost pristine radio frequency environment. Protection from terrestrial sources of interference that could disturb the astronomical observations is provided by the site location together with strict laws to regulate the use and installation of equipment in radio-quiet zones around the radio telescopes.

![Figure 82. MeerKAT antenna at night. Credit: SARAO.](image)

However, satellites and aircrafts will still pass over the sites, potentially producing interference in the SKA frequency bands. This is especially true because the SKA aims to observe the sky over a much wider frequency range than allocated by the international radio regulations to the radio astronomy service. The recent and forthcoming rise of satellite mega-constellations poses additional challenges and SKAO will keep undertaking spectrum management to coordinate and negotiate special agreements with industry to ensure satisfactory solutions are sought to mitigate the impact of these constellations. The SKA community is establishing contacts with the national administrations of the stakeholder countries to seek their support in discussions with the major public and private telecommunications agencies.

SKAO is working closely with other organisations such as the International Astronomical Union, European Southern Observatory, Royal Astronomical Society, as well as industry and international bodies like the International Telecommunications Union, the United Nations’ Committee for the Peaceful Uses of Outer Space (UNCOPUS) and UNESCO.

By interacting directly with industry, government and international bodies, the SKA has the potential to play a key role in the protection of the night sky and the development of a sustainable way for industry and radio astronomy observatories to work together.
3.3.7 Culture

Science and culture can be intimately connected and throughout history, many illustrious scientists have also thrived and left an imprint thanks to their creative thinking. Many have documented how their passion and interest for all things art and science intimately nurtured one another, sometimes leading to disruptive innovations or majestic artworks.

As an integral part of society and its deep aspirations to understand the Universe, the SKA is bound to develop strong links with culture, whether it is art, poetry, writing, pop culture, or otherwise.

In South Africa for example, SARAO has been supporting local artists who design and produce souvenirs and artefacts that are typical of the region and promoting their work during open days and major visits to the site. Some of these artists are now selling their artefacts at the Waterfront in Cape Town, a popular tourist destination, providing great exposure of their work and sales opportunities.

In Australia, CSIRO is working with the local community in the Murchison Shire to create a SKA interpretive centre; an interactive station that allows the local community and visitors to learn about the SKA without seeking to visit the Murchison Radio-astronomy Observatory. The interpretive centre seeks to bring business to the settlement whilst still protecting the radio-quiet nature of the MRO.

In cooperation with SARAO and CSIRO, SKAO will be working closely with the local communities around the telescope sites on this cultural aspect as well, strengthening existing initiatives and developing new ones that help link them to the SKA in a meaningful way and create a sense of pride and ownership in the project. This could include bespoke projects such as art and craft projects, featuring traditional techniques or local materials.

3.3.7.1 Art

The SKA project and its precursors and pathfinders have already inspired artists all over the world, generating several artistic projects and exhibitions, including the Ilgarijiri art exhibition in Australia, the international Shared Sky exhibition featuring artwork from indigenous artists from South Africa and Australia, the Dôme art project in France and the MeerKAT Creative Community Initiative in South Africa, among others.

It is anticipated that this synergy between art and science will continue through the construction and operational phases of the SKA and as the project’s visibility grows.
3.3.7.1.1 Impact Story: Shared Sky Indigenous Art-Astronomy Exhibition

Shared Sky stems from a vision by the SKA to bring together under one sky Indigenous Australian and South African artists in a collaborative exhibition celebrating humanity’s ancient cultural wisdom. This vision embodies the spirit of the international science and engineering collaboration that is the SKA project itself, bringing together nations around two sites in Australia and South Africa to study the same sky.

It reflects the richness of the artists’ ancestors understanding of the world developed across countless generations observing the movements of the night sky. Shared Sky explores how this sophisticated understanding of celestial mechanics resonates in the work of living artists that are sharing their insights with scientists working to unlock the secrets of the Universe.
Shared Sky was developed in 2014 and has since been used as a fantastic science diplomacy and education tool to engage with high-level audiences and bring awareness about the SKA among decision-makers, funders and more generally art enthusiasts and the general public.

Shared Sky has been touring the world, having travelled to six countries in both hemispheres, and has been exhibited in prestigious places including the European Commission Headquarters in Brussels, the John Curtin Gallery in Perth and the Iziko South African National Gallery in Cape Town, but also in educational and public centres such as the Manchester Library, Jodrell Bank Discovery Centre and the Genoa Science Festival in Italy. Workshops with the artists have been conducted and collaborative artworks created while teaching the public painting techniques such as aboriginal dot-painting.

Shared Sky continues to travel internationally and is estimated to have been seen by tens of thousands of visitors already, helping to raise awareness of the rich heritage and culture of indigenous peoples around the SKA sites.

3.3.7.2 Media and Pop Culture

The SKA and precursor telescopes generate thousands of media articles a year, extending the reach of astronomy research and science around the globe and inspiring audiences and readers. Coverage of the SKA in the media has included prestigious broadcasters such as the BBC, CNN, and Euronews but also publications such as Nature and Science regularly and print media all over the world. In 2019 alone, the SKA was mentioned in close to 5,000 press articles and reached on average 1 billion readers every month.

The scale of the SKA and its growing profile has also led to its inclusion in elements of pop culture, such as SKA posters appearing in episodes of the popular TV sitcom The Big Bang Theory, or the telescopes featuring in music videos from popular bands, TV ads for cars in South Africa, in political cartoons as part of the national conversation, and even in fantasy books, showing how the project is gradually becoming embedded in society.

Figure 85. The SKA appears in this fiction novel by writer Matthew Reilly as a secret facility already operating that has detected a galaxy hurtling towards Earth. Credit: Matthew Reilly.
Figure 86. The SKA’s prototype low frequency antennas as well as the SKA precursor telescope ASKAP and SKA pathfinder Parkes appeared in this music video by Australian rock band Voyager. Credit: Voyager.

Telescopes and in particular radio telescopes have long created a fascination with film directors and producers, appearing in TV shows and movies such as “The Dish” with Sam Neill, James Bond (Paranal Observatory, Arecibo), Dr Who (Lovell Telescope), or science-fiction movies like Contact or Independence Day (VLA).

It is reasonable to assume that as the profile of the SKA grows, as the construction of the telescope progresses and as science results start to be delivered, due to the breathtaking nature of the telescope sites, appearances in mainstream media, broadcasts, documentaries and elements of international pop culture will dramatically increase, helping to cement the SKA’s position in the popular consciousness.

3.3.7.2.1 Impact Story: The Sky at Night

In 2018, the BBC filmed an episode of long-running science show ‘The Sky at Night’ at the Murchison Radio-astronomy Observatory (MRO). Initially, the producers planned to film only part of the programme in Western Australia, but when they saw the video assets captured on site by CSIRO, ICRAR, and a local production company, the BBC producers chose to film an entire episode.

This opportunity put the MRO’s telescopes (ASKAP, MWA, and EDGES), the future SKA telescope, its cutting-edge infrastructure, and the relationship with the site’s traditional landowners in front of a mainstream UK audience of half a million people. SKA Australia also established a working relationship with the BBC in London. The 30-minute show, titled ‘Outback Astronomy’ aired in the UK in July 2018, and was available online through BBC iPlayer.
3.4 Measuring impact

The impact of the SKA and its return to member states will be monitored continuously, assessed regularly and presented through periodic reports.

Recent years have seen an increased focus on the tools and techniques that may be used to monitor and quantify impact, moving the field from a purely case-study based approach to something more routine and meaningful.

SKAO intends to develop a framework for assessing the impact of the Observatory, and its economic, social, sustainability, and cultural returns to member states. These data will be collected and reported on periodically.

Already SKAO has been working with STFC and the OECD to establish a standard set of metrics to measure impact. The OECD approached the SKA as an exemplar of large-scale distributed research infrastructure.

The SKA is also a landmark project in the European Strategy Forum on Research Infrastructures (ESFRI) Roadmap. ESFRI intends to undertake periodic review activities for its landmark/roadmap projects to ensure their competitiveness in the field as well as wide impact of the projects to social, economic, and innovative benefits.
4 The SKA Observatory

The outcome of this proposal is the SKA Observatory (see Figure 87), a research infrastructure which will consist of a global headquarters, two SKA telescopes to cover the observing frequency range necessary for the science cases described above, and the activities necessary for their construction and a start of operations.

4.1 Observatory Design

While the Global Headquarters facility is located at the Jodrell Bank Observatory site, in Cheshire, UK, the SKA telescopes will be located within radio quiet zones provided by the host countries of Australia and South Africa, eventually including several Southern African countries and expanding across the west of Australia in SKA2. In particular, the Murchison Radio-astronomy Observatory in Western Australia will host the “SKA1-LOW” telescope, operating in the 50 MHz - 350 MHz frequency range, while the “SKA1-MID” telescope will be centred in the Karoo Central Astronomy Advantage Area in the Northern Cape province and operate between 350 MHz and, initially, 15.35 GHz.

In order to reach the sensitivity necessary for SKA1, the two Telescopes use the interferometer concept in which multiple connected “receptors” work together as a single antenna. For both SKA1-LOW and SKA1-MID configurations, the receptors are arranged in a core with a diameter of ~1 km, and three spiral arms. The maximum baseline is 65 km and 150 km, respectively for SKA1-LOW and SKA1-MID.

Due to the different frequency ranges, the SKA1-MID “receptors” will be 133 15 m projected-diameter offset Gregorian dishes integrated with the existing 64 13.5 m MeerKAT dishes, while in SKA1-LOW “receptors” will be “aperture arrays” composed of 256 dual-polarised log-periodic antennas randomly distributed in 512 38 m diameter circular stations.
Data captured by each dish and each aperture array station will be processed, after digitisation, to form up to 48 independently steerable “station beams”. These data will be sent to the central processing facility located near the core of each telescope in order to be correlated as well as beamformed to generate multiple tied-array beams which will be further processed by the pulsar timing and pulsar search engines. Visibility data, pulsar search candidates and heuristics, and pulsar timing results will be sent to the signal data processor (SDP), located in high-performance computing centres in Perth and Cape Town for SKA1-LOW and SKA1-MID, respectively. SDP software will further process the visibility and pulsar/single-pulse data and archive science-ready data.

In addition to conventional imaging and pulsar observations, the telescopes will also include substantial support for transient and time-domain science. Each telescope will provide transient buffers storing up to 510 seconds (SKA1-LOW) or 22 seconds (SKA1-MID) of channelized voltage data for each “receptor”, triggerable from internal or external sources. The SKA1-LOW system will also provide raw voltage-capture for a subset of the antennas in each station. Both SKA telescopes will also provide VLBI capabilities and participate as stations in the global VLBI network.

### 4.2 Organisation

The scale of new, transformational research facilities generally requires funding, resources, and experience beyond the capabilities of a single institution or even a single country or region. The SKA Observatory is achieved through the committed collaboration of its participating member countries and institutions. Only through this combined capacity in resources, knowledge, and experience (industrial, technical and scientific) can SKA be realised.

#### 4.2.1 Governance

SKA Organisation was established as a UK limited company in 2011 to act on behalf of its membership to facilitate international collaboration to undertake the pre-construction phase of the SKA. The shareholders, or members, of the Organisation have appointed a board of directors which acts as the primary governing body for the pursuit of the company’s aims.
In 2013, after various initiatives to determine a preferred legal structure, the member governments with an interest in SKA decided to establish an international government organisation (IGO), the SKA Observatory, governed by intergovernmental convention, to construct and operate the SKA.

The SKA Observatory convention is an international treaty that establishes and governs the SKA Observatory as a legal entity. Multi-lateral negotiations between the various governments with an interest in participating in the IGO began in 2015 and concluded in 2017. On 12 March 2019, the SKA Observatory convention was signed by seven founding member countries - Australia, China, Italy, The Netherlands, Portugal, South Africa, and the United Kingdom. India and Sweden, who participated in the negotiations, are expected to sign the convention at a later stage, with other countries to follow, by acceding to the convention.

Each signatory has its own government approval process to ratify the convention. Once five countries, including the three host countries, have ratified the Observatory convention, it will enter into force. This means that, from this point, the SKA Observatory will exist as a legal entity. The SKA Observatory Council, the governing body of the organisation, will then be convened. However, at this stage, the SKA Observatory will have no assets or employees. To ensure business continuity towards the start of construction, the current company, the SKA Organisation, will transition its business, assets and employees, to the SKA Observatory under the UK’s TUPE (Transfer of Undertakings (Protection of Employment)) regulations. This process can only take place after the Council is established and will require approval from both the SKA Board and the SKA Council.

The Council will be the governing body of the SKA Observatory with each member represented by up to two representatives. The Council is responsible for the overall strategic and scientific direction of the SKA Observatory, good governance, and attainment of purpose.

The Director-General of the SKA Observatory will be appointed by the Council for a fixed period. The Director-General will report to the Council and will act as the Chief Executive of the SKA Observatory as well as its legal representative. Key responsibilities include exercise of project, operational and financial authority as provided by the Council and General Management of the SKA Observatory. The Director-General will be assisted in the execution of their duties by appointed staff.

4.2.2 External Organisations and Partnerships

The SKA Observatory relies upon sets of agreements with external organisations to fulfil the full scope of the construction. There are two key sets of agreements built into the observatory structure during construction (and into operations):

- Host Agreements.
- Construction Phase Host Country Cooperation Agreements.

4.2.2.1 Host Agreements

The host agreements describe the arrangements for hosting the infrastructures associated with the Observatory; namely the two telescopes, and the headquarters. Each specifies the mutual responsibilities and obligations between the SKA Observatory and a host country through the construction, operations and decommissioning/site restoration of the observatory facilities. There are three such agreements:

- Agreement between the Government of the United Kingdom and the SKA Observatory on hosting the headquarters of the Observatory.
Agreement between the Commonwealth of Australia, represented by the Department of Industry, Science, Energy and Resources and the Square Kilometre Array Observatory concerning the hosting of the square kilometre array.

Agreement between the Republic of South Africa represented by the Department of Science and Innovation and the Square Kilometre Array, concerning the installation and operation of the square kilometre array.

The two telescope host agreements broadly outline the host country responsibilities:

- Provision of access to the site, assets, and infrastructure (granted through licenses, permits, leases, or property instruments).
- Securing necessary rights to enable a grant of licenses or leases.
- Provision of the required registers of environment and heritage.
- Provision of radiofrequency protection in respect to the site.
- Coordination of interaction with all concurrent users of the site, including indigenous land users.
- Coordination of construction and operation of other radio facilities on-site to ensure construction and operations according to the convention.
- Maintenance stakeholder relationships with national and local governments and other local actors.

And the SKA Observatory responsibilities:

- Execution of the construction, operations, and maintenance of SKA1 in compliance with local regulations.
- Responsibility for all aspects of the SKA1 project, that are not the responsibility of AUS/RSA, including management and governance, compliance with regulatory processes, recruitment/management/administration of SKAO staff and contractors, decommissioning/demolition and restoration of the site, outreach/communication/promotion activities within the host country.
- Operation and maintenance of all equipment required for the implementation of the SKA1 project.
- Compliance with relevant state and federal laws and regulations.
- Support for host country stakeholder relationships.

Both agreements also outline the specification, schedule and valuation of assets contributed by the host country to be accepted and/or used by the SKA Observatory.

Additionally, for the Republic of South Africa, there are additional agreements on ensuring mutual benefit from the contribution of the MeerKAT antennas to SKA1-MID (agreement on joint development and performance activities, parallel operations agreement, handover management agreement).

The headquarters hosting agreement is somewhat different in nature to the telescope hosting documents. In the HQ agreement, the focus is on the legal implementation of the convention in the UK, and the obligations, privileges, and immunities afforded to the Observatory as an organisation (for example provision of immunity from legal suit, exemptions from taxation for Observatory official activities). It also considers the provisions for the Director-General and staff, and for other categories of personnel interacting with the HQ in the UK, and (for example) how movement of those people in and out of the UK will be facilitated. The agreement also describes the local governance oversight arrangements on the site. The agreement also links to the lease arrangements that enable the availability of the land on which the HQ sits.
4.2.2.2 Construction Phase Host Country Cooperation Agreement

The SKA1 construction project acquisitions are organised into contracted/procured areas and self-performed work (i.e., SKAO staff performed activity). The contracted/procured areas are organised into ‘Tier 1’ contracts between the SKA Observatory and member country institutions (see Section 10: Acquisitions).

In the operations phase, a suite of roles and responsibilities have been identified which can best be filled/implemented through host country institution execution. During construction, a potential earlier expansion of this partnership model is possible enabling construction support roles to be similarly realised.

It was recognised during the construction planning stage that areas within the construction scope will benefit from the continuity of design phase and SKA precursor staff and experience within the host countries. This continuity can be secured through the early allocation of this work scope and can be implemented either through the acquisitions phase planning (e.g., NEC4 Professional Services Contracts) or through a broader cooperation agreement (a.k.a., the partnership model) to enable flexible access to specific key skills and experience.

4.3 Observatory Organisation and Structure

The SKA Observatory requires a long-term structure to support the range of operational responsibilities. This structure is fully realised at the end of the construction phase and so will commence during that phase.

4.3.1 Observatory Level

The high-level Observatory organisation is represented in Figure 89. The overall structure is relatively static throughout the construction phase and into operations, with the relative sizes of divisions scaling according to the needs of the observatory; for example, programmes is the largest division during construction, but is smaller in operations, at the conclusion of the SKA1 construction phase, when its responsibility shifts to the SKA Observatory Development Program and observatory support. In addition, as operations begins and the Telescope Directors are appointed, the operations (AU) and operations (RSA) functions will be represented in the evolving organisational chart; similar functions will be established under the Science Directorate.
The responsibilities of the high-level divisions and the roles for their leads within the observatory are described in detail in the Observatory Establishment and Delivery Plan, the sister document to this one, and may be summarised as:

- **Director-General**: The Director-General is responsible to the SKA Observatory Council for effective leadership of the SKA Observatory. The role is delegated authority to assume the responsibility of all areas of management and has responsibility for all personnel, HSE and financial matters within the Observatory. In addition, the Director-General is responsible to the Council for the management of relationships within the SKA Observatory membership and will engage with all member countries and their representatives.

- **Director-General’s Office**: The Director-General’s office is focused on all activities that support the strategy and development of SKA. It supports the Director-General in all external activities as well as being responsible for governance activities that ensure the organisation is meeting its legal and strategic commitments. In delivering this, it brings together those activities where especially close contact with the Director-General is important to achieve this aim.

- **Assurance**: The assurance function is focused internally, providing assurance to the Director-General/Deputy Director-General that all processes and procedures are carried out in line with
Quality and HSE (Health, Safety and Environment) standards. The assurance function is also responsible for the management of business risk and spectrum management.

- **Science**: The Science Directorate leads the scientific direction of the Observatory, being the guardians of the delivery of science in line with the Observatory’s mission. This includes developing SKA’s science strategy and working with stakeholders and the science community in defining science priorities, in order to lead the way in scientific discovery. The Science Directorate will also run the time allocation process.

- **Operations**: The Operations Directorate is ultimately responsible for coordinating and managing Observatory operations across host sites in such a way as to meet stakeholder needs whilst delivering the Observatory’s mission. This Directorate ensures the effective preparation and planning of observing programmes, the operation and maintenance of state-of-the-art high-tech observing instruments and ensures the management of data through the SRGs (SKA Regional Centres). Ahead of full operations, the Directorate is responsible for the development of the operations plan for the Observatory and works closely with the Programmes Directorate in the effective commissioning of the telescopes and delivery of early science.

- **Programmes**: The Programmes Directorate is responsible for leading the delivery of project construction and for ensuring the establishment of the necessary computing and software capabilities. This Directorate will work closely with both science and Operations Directorates as well as the broader science and engineering communities to ensure the design and build of the telescopes meets both the science needs and the practical requirements of effective operations. This group also coordinates externally with the host countries on the delivery of joint host agreement obligations as well as with the existing, operating facilities on-site during construction. Beyond construction and into operations the Programme Directorate will continue to be responsible for the ongoing construction associated with planned operational development to continue to meet the needs of science.

- **Human Resources**: The HR function is responsible for defining and delivering a people strategy that meets the current and future business needs where people are integral to the success of the organisation. This covers all aspects from resource and capability planning, diversity and inclusion, recruitment and relocation, individual and leadership development, performance and succession management, reward, staff engagement, employee relations, and HR policy development. Core to the function of HR is also supporting the management of staff time away from work, dealing with staff issues and managing all associated administration and system management.

- **Finance**: The finance function is responsible for leading all financial and commercial related matters at both the strategic level and operational level. This includes the management of all financial policies and procedures, financial planning, budget, cash flow, and accounts management as well as banking and treasury. The finance function will work with internal and external audit to ensure compliance with taxation and accounting standards, as applicable. With responsibility for the organisation’s commercial matters, finance has responsibility for procurement. In addition, the finance function will have responsibility for general services of the headquarters, including logistics and facilities management.

### 4.3.2 Programme Level

The high-level programme organisation designed to deliver SKA1 is represented in Figure 90. The Programme Directorate is composed of the senior staff in each branch of the Directorate along with the Site Construction Directors. Following construction, the Site Construction Directors’ responsibilities are transferred to the operations division.
The responsibilities of the high-level programme divisions and the roles for their leads within the observatory may be summarised as:

- **Head of Project Management**: The role guides the programme in the use of project management processes and resources to provide guidance to achieve the project mission and to provide necessary project tracking and stakeholder communications and reporting. The Head of Project Management is also a ‘Head of Profession’ role and Team Leader, responsible for PM training, support and development.

- **Head of Engineering, Project Engineer**: The role guides the use of engineering processes and resources to provide guidance and to achieve the project mission. He/she is the final authority on engineering design and verification. The Head of Engineering is also a ‘Head of Profession’ role and Team Leader, responsible for engineering training, support, and development within the observatory.

- **Head of Computing and Software**: The role guides the use of computing and software resources to achieve the project mission. This role also leads the observatory IT responsibilities. The Head of Computing & Software is also a ‘Head of Profession’ role and Team Leader, responsible for computing and software training, support and development within the observatory.

- **System Scientist**: The System Scientist provides scientific advice and guidance for all elements of the SKA1 construction project implementation and assures that the system design and development are consistent with the science requirements and objectives. The role supports further development of science requirements, goals and objectives, and leads the identification of science-engineering trades required to achieve project objectives within the schedule and resources available. In addition, the role is responsible for leading scientific aspects of commissioning and system verification to ensure that the SKA meets its level 1 requirements. The System Scientist also leads the definition of the science verification process, in collaboration with science operations team to demonstrate that the system meets science (level 0) requirements.

- **Site Construction Directors**: The Site Construction Directors are responsible for the facilitation of the planned telescope site activities in each host country. The role supports the relevant Senior Project Manager (LOW or MID) planning, providing real-time information for the strategic construction execution. The role also provides integration/coordination with existing facilities on-
site (e.g., MeerKAT, ASKAP, guest instruments, etc; other things at the site), power outages, and handover activities. They act as a conduit for host country stakeholder engagement and relations and local communications. The Site Construction Directors are responsible for monitoring and controlling all host country agreement obligations and providing reports and updates on these areas, as well as monitoring, controlling, and reporting all site permitting and compliance issues.

4.3.3 Interactions with Observatory Divisions

The programme team relies upon the whole of the observatory during the project execution. In particular, the Director-General’s Office, HR, and finance divisions provide critical support to the activities of the programme (e.g., Director-General’s Office: strategy and communications with member countries, HR: recruitment and training, finance: procurement and contract support, etc.). In addition, assurance, operations and science directly participate with the programme staff in the execution of construction activities (e.g., assurance: provides configuration management, reviews verification execution and process, staffs the health, safety and environment functions and provides product quality assurance; operations: provides staff to maintain accepted components and scientists for science verification; science: provides analyses of science verification data to ensure final compliance, etc.).

4.3.4 Construction Programme Divisions

During construction, the programme is organised as in Figure 91. The line management representation of these divisions will be summarised in the following sections along with the core roles of each division.

4.3.4.1 Project Management

The project management division holds the project management and control expertise within the observatory. During construction, they provide the contractual guidance for the procured deliveries as well as supporting the self-performed and overall integration of the facility. Figure 91 illustrates the line management organisation for the project management division.

Figure 91. Project management staff and line management relationships.
• **Senior Project Manager (LOW, MID):** The Senior Project Manager is the construction role responsible for the overall delivery of a telescope facility (LOW, MID), establishing the priorities of work and driving the delivery of products, systems, and ultimately, the facility.

• **Project Manager (infrastructure, dish, field node, LOW digitisation, MID digitisation, networks & computing, software, AIV):** The Project Manager is a named position within NEC4 contracts and is responsible for the delivery of specified contracts containing work packages and their corresponding products.

• **Solution Train Engineer:** The Solution Train Engineer is a SAFe program/ART level role responsible for the successful operation of the teams on the train. The STE is accountable for the agility of the trains, the successful application of the SAFe framework and the removal of any and all impediments beyond the capability of the teams.

• **Project Controls Manager and Team:** The Project Controls Manager is responsible for maintenance of the project management control systems including scheduling, earned value management, budgeting, risk and change control. The three roles within the team are analysts responsible for specific controls.

4.3.4.2 Engineering

The engineering division maintains the technical expertise across the core disciplines within the observatory (e.g., antenna, RF, RFI, digital systems, time and frequency, etc.). These staff provide supervisory roles during the construction phase for contracted services within the field and, in the longer-term operation of the observatory, support the maintenance and enhancement of the facilities. Figure 92 illustrates the line management organisation for the engineering division.

![Figure 92. Engineering line management organisation.](image-url)
• **Senior Systems Engineer:** The Senior Systems Engineer is responsible for managing the observatory technical definition and compliance along with analysis for change control. The Senior Systems Engineer is the custodian of the systems engineering processes in the SKAO and the L1 requirement baseline.

• **Systems Engineer:** The Systems Engineer is responsible for managing the requirements at the telescope level for the L1 requirement baseline. The Systems Engineer also support the PDTs to manage the product requirements and product interfaces.

• **Telescope Engineer:** The Telescope Engineer is responsible for the execution of the engineering best practice within the assigned telescope in collaboration with the Project Engineer and the SKA Domain Specialists. The role reports to the Senior Project Manager on technical risks and performance compliance.

• **<LOW, MID> Domain Specialist:** The Telescope Domain Specialist is responsible for the performance of a telescope in collaboration with the System Scientist.

• **<Specialisation> Domain Specialist:** The Domain Specialist develops and manages the technical budgets within their area. The role identifies and resolves domain-specific technical issues and monitors and controls compliance for the specific domain.

• **<LOW, MID> AIV Lead Engineer:** The <LOW, MID> AIV Lead Engineer leads the development of <LOW, MID> ITF establishment and preparation for AIV process. This activity is independently overseen by Assurance to ensure the quality and adherence to process.

### 4.3.4.3 Computing and Software

The computing and software staff are responsible to manage the evolution of the software used within the observatory during both the construction and operations. The staffing level is planned to ramp up during construction. It is also anticipated that there may be a significant transfer of construction staff to operational staff, and this will have to be actively managed.

Since the three largest bodies of software (deriving from the TM, SDP, and CSP.PSS pre-construction consortia) plan a large shared codebase with different configurations for the two telescopes, for the purposes of planning it is assumed that support for common codebase items will be located at SKA HQ in the UK, and telescope specific roles located at the Perth and Cape Town Science Operations Centres.

At the moment it is assumed that the teams in the three sites are not directly connected through line management chains because line management is planned to be local, but they form a senior planning and management leadership structure as shown in Figure 93.
Figure 93. Computing and software leadership roles at end of construction. Dashed lines indicate the relationship is not directly line-managed.

The proposed SKA HQ line management structure under the Lead Architect at the end of construction is shown in Figure 94.

Figure 94. SKA HQ project-related computing and software line management organisation.

This differs slightly from the current line management structure, but the evolution is manageable and is inevitable given the timescale.

The proposed South African and Australian line management structure for project-related roles in the computing and software area is shown in Figure 95.
Figure 95. SA and AU project-related computing and software line management organisation.

A description of the key roles is below.

- **Head of Computing and Software**: This role is responsible for all SKA Observatory computing and software activities in a particular SKA host country. In addition to project-related responsibilities, they may also be responsible for other functions, such as IT services, data management, computing aspects of the SRCs and the development of the operations capabilities.

- **Lead Software Architect**: The Lead Software Architect is responsible for the overall SKA software high-level design choices, technical standards, coding standards, tools, and platforms.

- **Software Quality Engineer**: The Software Quality Engineer acts as the Technical Lead in the SAFe system team.

- **DevOps Engineers**: The DevOps Development Engineers report to the Software Quality Engineer and develop and support the continuous integration, testing, and deployment systems.

- **Head of Controls**: The Head of controls manages a team of Controls Engineers in a SKA host country. They are both a Management and a Technical Lead and in SKA HQ, also acts as the Lead Controls Architect, reporting to the Lead Software Architect.

- **Controls Engineer**: These are Software Engineers specialising in control systems.

- **Platform Architect**: The Platform Architect Leads the platform development to define computing platforms that are suitable for the needs of the SKA.
• **Network and Security Architect:** The Network Architect is responsible for the high-level design choices for network and security.

### 4.3.4.4 System Science

System science provides the linkage between the engineering and science disciplines and leads the science commissioning activity. The System Scientist provides guidance to the engineering teams, particularly the AIV teams, to ensure that the verification process leads to the necessary science performance. The commissioning scientists, both in the host countries and at SKA HQ, will understand the system as a whole and work with the engineers to diagnose any faults in the hardware or software, working directly with the engineering teams and the operations scientists. The line management structure is shown in Figure 96.

![Figure 96. Line management within the system science team.](image)

- **Lead Commissioning Scientist:** The Lead Commissioning Scientist for LOW, MID, work with the System Scientist to develop the program of activities and to manage the Commissioning Scientist resources to meet the verification/commissioning schedules.

- **Commissioning Scientist:** The Commissioning Scientist works with the AIV Engineers to develop tests, identify faults, diagnose faults and provide analysis of the system as a whole, building toward end-to-end Science Verification activities.

- The SAFe Solution Manager and Product Managers are described in the computing and software areas but will work directly for the System Scientist.

### 4.4 Construction Project Delivery Organisation

The previous section outlines the profession line management relationships within the organisation, both at HQ and any of the member institutions. However, the observatory is initially driven by the construction phase of SKA1 which requires project-oriented structure and roles to secure the successful execution of the work.
4.4.1 Project Delivery Structure, Roles, and Responsibilities

The preceding section outlined the core divisions and line management responsibilities, however, the driving organisation (priority setting, work tracking, and management) is driven by the delivery team structure. This is a matrix structure and is composed of three tiers:

- **Observatory**: Highest level, intended to ensure an integrated and coherent set of observatory capabilities which can be presented to the community.
- **Telescope**: Facility level capabilities reflecting the geographically split telescopes in Australia and South Africa which provide specific capabilities across a determined frequency range and set of observing modes through the integration of components and sub-systems.
- **Product**: Component or sub-system capabilities which provide subsets of functionality to their telescopes.

The SKA1 construction organises the acceptance, integration, and delivery according to this representation with matching groups and individuals having responsibility and ownership. The following subsections describe these groups and their roles and responsibilities.

4.4.1.1 Observatory Delivery Team

The Observatory Delivery Team is composed of the Programme Directorate leads plus assurance, specifically:

- Programme Director
- System Scientist
- Project Engineer
- Head of Project Management
- Head of Computing and Software
- Head of Assurance
- Site Construction Directors, AUS, RSA
- (Senior Project Manager, LOW, MID)

The roles and responsibilities of these individuals are described in para 4.3.2; both the Site Construction Directors and the Senior Project Managers drive on the telescope delivery level but are incorporated into the Observatory team to ensure strong vertical communication. As the Observatory Delivery Team, they are ultimately accountable for the final delivery of all observatory facilities and meeting the performance, budget, schedule and other constraints. They are advised by the Programme Board which is an SKAO-internal board composed of the Programme Directorate alongside the Divisional Leads from operations and science.

4.4.1.2 Telescope Delivery Teams

The Telescope Delivery Teams are the highest facility-level authority and are responsible for the LOW and MID telescope deliveries. The Telescope Delivery Team is composed of:

- <LOW, MID> Senior Project Manager
- <LOW, MID> Telescope Engineer
- <LOW, MID> Domain Specialist
- <LOW, MID> Systems Engineer
- <LOW, MID> AIV Lead Engineer
- Lead Product Manager (sits on both teams)
- Lead Software Architect (sits on both teams)
- (<LOW, MID> Site Construction Director)
The Telescope Delivery Teams are responsible for the overall delivery of the LOW or MID facilities to the Observatory, leading the Product Delivery Teams to assemble and demonstrate the components and subsystems, managing the overall system integration and the schedule, budget and risks throughout the construction phase.

The Telescope Delivery Team is led by the Senior Project Manager at the SKAO HQ and supported by the Site Construction Director who manages the Site Management Team (section 4.4.1.4) at the SKA1-LOW and MID sites.

4.4.1.3 Product Delivery Teams

A product delivery team is composed of a Project Manager/Domain Specialist pair who together have responsibility for managing one or more Tier 1 contracts and/or self-delivery work and are the only individuals authorised to communicate directly with the contractor.

4.4.1.4 Site Management

The roles and responsibilities on-site (in each host country) are complicated by a range of overlapping jurisdictions and the need to acknowledge the ongoing operations of existing facilities adjacent to/overlapping with the SKA1 construction. The site management work is governed by the agreed site information documents.

The Site Management Team in each country is an aspect of the telescope delivery teams, reporting directly to the Site Construction Director. The Site Manager role is expected to be on-site during construction activities to support the coordination of activities and to provide necessary decision making on priorities under the dynamic situations on-site. The Site Management Team is composed of:

- Site Manager [2 per country; 1 Senior, 1 deputy to provide continuous on-site coverage]
- RFI/EMC Engineer [skills/capabilities provided through product assurance staff]
- Administrator/Logistics [1 per country].

The Site Manager is expected to liaise with the host country observatory Site Management Team for the subset of the area under construction by SKAO. The host country observatory Site Management Team is responsible for maintaining their compliance aspects but provides access to the SKA1 construction areas based on maintenance of the agreed-upon compliance.

The HSE team is composed of:

- Health, Safety, and Environment Manager [1 budgeted per country]
- Health & Safety Officers [up to 3 budgeted per country]
- Environmental Officer [1 budgeted per country]

The HSE Manager, working under the direction of SKA Head of HSE, ensure that all HSE considerations are included in the construction phase HSE plan and monitors and support their implementation during construction. This role is supported by site-based Safety and Environmental Officers who support the site reviews.

4.4.1.5 Scaled-Agile Framework Development

The scaled-agile framework development is the chosen methodology for software development within the observatory. It shares a common approach with lean and agile engineering practices but has a different lexicon and specific sets of best practices that need to be integrated and reconciled with the
overall project execution. These approaches will be tuned to the needs of the SKA1 project execution and their details reconciled to represent a coherent set of roles, responsibilities and processes, for example:

- SKA1 construction aligns the software development construction work by developing a common roadmap where priorities are aligned.
- SKA1 construction adopts a project-level synchronisation cadence of 3 months, following from the SAFe practice. This synchronisation enforces an alignment in priorities between all development areas.
- SKA1 construction adopts a project-level reporting cadence of 1 month (aligned with the program increment 3-month cadence) for review and communication of status and KPIs (earned value, risk exposure, estimate-to-complete, etc.).
- SAFe agile teams work with the product delivery teams to ensure the successful integration of component/subsystem hardware and software, often delivering to the product delivery teams.
- SAFe agile release trains work with the product delivery teams and the telescope delivery teams to ensure integration across the different SAFe teams at all levels.
- Observatory level integration will occur through the Observatory delivery team.

The distinction between work packages in which SAFe is applied versus lean engineering will be apparent through:

- Management process incorporates SAFe roles and responsibilities for their management (i.e., release train engineer, product management, architect guidance vs. product delivery team guidance alone) but with many common review and reporting needs.
- Contracting structure (time and materials with elaborated work priorities vs. SOW referencing specifications, etc.; see section 9 for details) coordinated through the project-level alignment meetings.
Figure 97. Illustration of the interplay between the project organisation and the SKAO SAFe implementation organisation.
4.5 Staffing

Staffing resources are required for the execution of work within the SKA. If these resources are a part of the SKAO, roles have been established with descriptions (as in the last sections); this effort is designated as a part of the construction support and is a part of the project labour. If these resources are part of a contracted delivery, they do not explicitly appear as labour but are counted alongside all the other costs within the contract which is designated as materials; the basis-of-estimate for these areas was built on a detailed staffing plan provided during the pre-construction stage.

The time-phased representation of the projected construction phase roles is illustrated below; we note the full observatory portrait of staffing is contained within the Observatory Establishment and Delivery Plan.

Table 2. Staffing profile of the Observatory for a 10-year period from the start of construction through to the operations phase.

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5 Baseline Design

5.1 Pre-Construction Development

During the pre-construction design and development phase, the SKA design was a global effort by 12 international engineering consortia representing approximately 500 engineers and scientists in 20 countries. The effort and investment from the organisation members in this period were significant and has set the foundations for the current proposal. The consortia were responsible for working out the look and functionality of the different elements of the SKA and ensuring that they will all perform together. The 12 consortia had a designated lead institution that coordinated the work. They operated in conjunction with a Specialist Project Manager along with the Domain Specialists based at SKA Headquarters in the UK. Nine of the consortia focused on a component of the telescope, each critical to the overall success of the project, while three others have focused on developing advanced instrumentation for the telescopes and future systems.

- Assembly, integration, and verification (AIV)
- Central signal processor (CSP)
- Dish (DSH)
- Infrastructure South Africa (INSA)
- Infrastructure Australia (INAU)
- LOW-frequency aperture array (LFAA)
- Signal and data transport (SaDT)
- Science data processor (SDP)
- Telescope Manager (TM)

Advanced instrumentation programme (AIP):

- Wideband single pixel feeds (WBSPF)
- MID-frequency aperture array (MFAA)
- Phased array feed (PAF)

During this phase (2013-2019), it is estimated that an overall budget of approximately €200 M was used in the development of the designs. The table below shows the temporal progression of the core nine consortia providing designs for SKA1.

An essential part of each consortium’s role was to ensure that their design ultimately enables the SKA to achieve its science goals. This means scientists and engineers have worked closely together to ensure that the final design meets the science community’s requirements. To that end, the SKA formed the Science working groups (SWGs) to feed into the process.

Since the consortia were first formed in 2013, the design of the SKA has evolved in response to available funding and to take account of both scientific advances and the critical information provided by SKA precursor telescopes (MeerKAT in South Africa and ASKAP and MWA in Western Australia). In December 2014, the process reached its first milestone, with the start of the elements’ preliminary design reviews (PDRs). Each consortium presented its detailed proposals for assessment by an expert panel from the SKA and external organisations, and the results were fed back into the ongoing design work.

There followed several years of effort by the international consortia to arrive at the element critical design reviews (CDR); the critical design review definition is governed by document SKA-TEL-SKO-0000652 Critical Design Review Definition. This document describes the design process during the pre-
construction. The CDR period began in 2018 and continued through the overall system CDR in late 2019 (See section 5.1.2).

Table 3. Pre-construction design consortia timelines to baseline.

<table>
<thead>
<tr>
<th>Element</th>
<th>RRN Submission*</th>
<th>CDR Submission</th>
<th>CDR Meeting</th>
<th>CDR Close</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SKA1-MID Specific</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DSH</td>
<td>07 Sep 2018</td>
<td>28 Sep 2018</td>
<td>Jun 2020</td>
<td>Feb 2022¹⁷</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>26-27 Nov 2018 (Pre-CDR)</td>
<td>DS Pre-CDR: Jul 2019</td>
</tr>
<tr>
<td></td>
<td>23 Jul 2018</td>
<td>NA</td>
<td></td>
<td>Apr 2019</td>
</tr>
<tr>
<td>MeerKAT Integration</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>19 Mar 2018</td>
<td>30 Apr 2018</td>
<td>02-04 Jul 2018</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Feb 2019</td>
</tr>
<tr>
<td><strong>SKA1-LOW Specific</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INAU</td>
<td>19 Mar 2018</td>
<td>30 Apr 2018</td>
<td>27-29 Jun 2018</td>
<td>Dec 2018</td>
</tr>
<tr>
<td><strong>Common to or covered by both Telescopes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TM</td>
<td>29 Jan 2018</td>
<td>28 Feb 2018</td>
<td>17-20 Apr 2018</td>
<td>Jul 2018</td>
</tr>
<tr>
<td>SDP</td>
<td>17 Sep 2018</td>
<td>31 Oct 2018</td>
<td>15-18 Jan 2019</td>
<td>Apr 2019</td>
</tr>
</tbody>
</table>

5.1.1 System Adoption Design Review

The pre-construction work of the SKA delivered the element design baselines through their element CDRs, or in some cases, Pre-CDRs. Although this development work was guided by a set of system baselines delivered through their element CDRs, or in some cases, Pre-CDRs. Although this development work was guided by a set of system baselines delivered through their element CDRs, or in some cases, Pre-CDRs. Although this development work was guided by a set of system baselines delivered through their element CDRs, or in some cases, Pre-CDRs. Although this development work was guided by a set of system baselines delivered through their element CDRs, or in some cases, Pre-CDRs. Although this development work was guided by a set of system baselines delivered through their element CDRs, or in some cases, Pre-CDRs. Although this development work was guided by a set of system baselines delivered through their element CDRs, or in some cases, Pre-CDRs. Although this development work was guided by a set of system baselines delivered through their element CDRs, or in some cases, Pre-CDRs. Although this development work was guided by a set of system

¹⁷ This date is for the full dish element systems. The dish structure CDR is schedule for Apr 2021 which is the proximal contracting need.
requirements (Level 1). As the work progressed, many opportunities, gaps, issues, and risks were also highlighted. Some design optimisation was also required to reduce the overall cost of the project.

In heading to System CDR, it was necessary for the SKAO to integrate the element designs to establish their alignment with each other and with the overall system design and requirements. During this process further issues, gaps and risks were exposed, and decisions made to resolve these. To achieve this, the SKAO reaffirmed ownership of the complete SKA1 design, to be able to procure what is required during the construction phase. This process of taking ownership, integrating the designs and fully assessing them, is design adoption. This was a key preparatory step towards the system CDR.

The adoption design review was captured in a report (SKA-TEL-SKO-0001069 System Adoption Design Review Report) which detail the two-week review and its follow-up leading to the system CDR readiness.

5.1.2 System Critical Design Review

The system critical design review was held from the 9-12 December 2019 at the SKA GHQ at Jodrell Bank. The panel, including 11 distinguished members with significant and broad experience, had received a comprehensive documentation package together with a reading list. A series of presentations were also given over video link to give the context for the review. The review itself was a series of in-depth discussions to address issues arising from comments (OARs) plus other areas that came up during the review itself. All issues were tracked on the SKA JIRA system including all agreed actions and outcomes.

The panel recommended that the SKA system CDR had been passed, with actions. The panel provided a set of findings, assessments, and recommendations. The panel's evaluation of the SKA1 system resulted in a number of additional recommendations, as detailed in the body of their report, covering both design, management, and safety aspects of the project.

Regarding the overall design of SKA1, the panel found that it is comprehensive, complete, and well documented. There are nevertheless residual inconsistencies, gaps in traceability, and non-compliances between the design and requirements. These recommendations were actioned and were completed in a series of documentation updates and engineering change proposals to complete the system requirements and design description (updated system-level requirements and design baseline document).

Regarding management, the panel found that rigorous processes and controls are in place to ensure successful completion of construction on schedule and within budget, but the panel had recommendations for some improvements. For example, they recommend that the SKA project should consider having an additional management reserve to deal with the unknown unknowns. Such a reserve should be held at Council level and be of order 5-10% depending on the Council’s appetite for risk. Additionally, the SKA noted that the representation of risk for the project was based on a projection of activity to conclude outstanding subsystem CDR work which would be updated up to the submission of the proposal to ensure accurate tracking.

Regarding safety, the panel found the overall SKA health, safety, and environmental management system and approach to be mature and appropriate at this stage in the project. The project would nevertheless benefit from further developing the SKA hazard analysis process, by establishing a methodology to verify hazard mitigations and determine a hierarchy for who is responsible for the verification of mitigations.

The required actions for the system CDR were completed on 6 April 2020, concluding this process.
5.1.3 Independent Cost Review

Additionally, a further check of the robustness of programmatic and particularly cost estimation aspects was targeted to give the SKA Council the confidence that the project was able to proceed to construction. In addition to the technical and costing aspects of the system CDR, it was the intention that this review would act as a ‘Ready to Invest’ Gate Review. To achieve this, following the CDR, an invitation to tender was distributed to 11 companies deemed competent to carry out such a task. Arup was selected and contracted to carry out the review.

The reviewers concluded that:

“Overall, the schedule and approach to construction follows logic and evidences good practice across both LOW and MID telescopes. There has been a significant level of planning work completed to date regarding both sites and this is evidenced in the detail shown throughout the reviewable documentation. The project appears to be in a very good place in advance of receiving funding and any competent contractor should be able to pick up and develop the delivery programme and schedule information as it currently stands. The internal SKA project management have proved to be a knowledgeable panel of experts and collaboration with this team has been beneficial for Arup during this programme review, it should also ensure a smooth transition into the delivery phase of this project with the appointed delivery partners.” (Square Kilometre Array Independent Cost Review, ARUP REP/273948/01).

The office has reviewed all issues and advice and has responded accordingly (SKA-TEL-SKO-0001701 Independent Cost Review Report Response). Having passed this review and incorporated the Arup advice into project planning, the SKAO is in a strong position to deliver the project.

5.2 The SKA Observatory Design Baseline

Several major assumptions and constraints have been adopted by the project, mainly as decisions of the SKA Board of Directors and/or the SKA members.

- The SKA Board has required the integration of as much of the MeerKAT telescope as possible into SKA1-MID.
- The SKA Board has urged the re-use of the investment in infrastructure and telescope equipment, developed for the precursor telescopes (ASKAP and MeerKAT) as possible for both sites, based on a feasibility and cost-benefit analysis.
- The ‘funded boundary’ of the two telescopes includes all the capital equipment described in this document, not including infrastructure that will exist on the two sites at the time of construction. In particular, archives in each site country, containing the accumulated data products, are included but facilities or equipment required to provide global access to data products or to science analysis are not included.
The SKA Observatory GHQ is located in the United Kingdom (UK), at the University of Manchester’s Jodrell Bank Observatory and will have overall responsibility for the SKA Observatory. Coordination of the overall project includes business enabling, engineering, project management, science, Observatory operations, a telescope development programme, and public outreach. It has been designed with facilities capable of managing two remote telescopes, where parts of the organisation are spread across multiple time zones. Figure 99 illustrates the overall architecture of one distributed Observatory with two telescopes on two sites: SKA1-LOW in Australia, SKA1-MID in South Africa and the SKA GHQ in the United Kingdom (UK). The thick flowlines show the unidirectional transport of large amounts of digitised data from the receptors to the central signal processing facilities on the telescope sites, and from there to the science data processing centres and archives (in Perth and Cape Town). The thin dash-dot lines show the bi-directional transport of system monitor and control data.

The science data processors will be supercomputing facilities with enough off-line storage to house one copy of the science-ready data. The science data processors are where calibration of the data takes place, images of sky brightness are formed, and further analysis of time-domain observations are carried out.

The archives that science users will interact with are the responsibility of the SKA regional centres (SRCs) and data will be transferred from the telescopes to these archives continuously over dedicated international network links. Data in these archives will be kept for an indefinite time. The SRCs are also where science analysis will take place and are funded separately from the SKA project (see Section 5.3.4), in a similar way to the Conseil Européen pour la Recherche Nucléaire (CERN) Tier 1 centres. The SKA project has established a group to liaise with external organisations on the nature and structure of SRCs, but apart from general descriptions and specific interfaces, their number and precise scope are undefined at this point. The SRCs are outside the scope of this proposal.
5.2.1 Location of Major Entities

SKA1-LOW and SKA1-MID telescopes (see Sections 5.2.5.2.5 and 5.2.6, respectively) will be located on remote sites at Boolardy Station in the Murchison Shire of Western Australia.

Figure 99. The geographic location of the SKA1-MID site.

Figure 100. The geographic location of SKA1-LOW in Western Australia. The blue contour shows the approximate boundary of the currently acquired property.
The SKA1-MID telescope will be about 150 km in extent; the SKA1-LOW telescope will be about 65 km in extent. In addition, there will be establishments elsewhere in Australia and South Africa that will provide scientific and technical support for SKA1 operations.

Also, on each site will be large central signal processing facilities which house:

- Correlators that process the raw signals from the SKA1-MID antennas or SKA1-LOW stations to form astronomical imaging visibilities at low time resolution (approximately every second).
- Beamformers that combine the outputs from the antennas/stations to produce a stream of data that can be used for pulsar/transient observations and VLBI.
- Pulsar search and timing engines.
- Timing and power-distribution equipment.

The science processing centres will not be housed on-site but will be established at Perth and Cape Town. This has been designed to reduce power consumption on-site and to reduce the possibility of additional RFI.

Figure 101 is a simplified diagram of the major centres of SKA activity. In each host country there will be three facilities external to the telescope sites and provided by the host country entities (see Figure 98).

- Science operations centre (SOC).
- Engineering operations centre (EOC).
- Science processing centre (SPC).

![Figure 101. Functional and operational depiction of the SKA centres of activity.](image-url)

The SOCs will be in Cape Town and Perth, for SKA1-MID and SKA1-LOW, respectively. This is where telescope-specific (as opposed to telescope-common) science operations will be based. The EOCs will be in Klerefontein and Geraldton, respectively. These locations are sufficiently far from the sites that
there are some services available and some radio frequency emission can be tolerated. These will be the home base for the people maintaining the on-site facilities.

The telescope operators will sit in operations control centres for each telescope. The location of these will be either at the EOC or the SOC in each case, both are designed to provide the functionality required.

The GHQ will contain an operations monitoring centre for monitoring telescope operations. The regional centres will be globally distributed and interfaced to the SPCs to provide science data access to the users of the telescopes.

5.2.2 SKA Telescope Environments

5.2.2.1 Noise Environment

Irreducible ‘sky noise’, a determining factor in sensitivity, varies over 3 orders of magnitude in the SKA frequency range. This greatly influences the design of the telescopes (Figure 102 shows the variation of sky noise with frequency and the relationship to receiver bands). Sky noise dominates the signal-to-noise ratio over most of the SKA1-LOW frequency range, whereas reducing instrumental noise to levels below sky noise requires the use of cryogenic receivers for most of the SKA1-MID frequency range.

![Figure 102. The positioning of receiver bands for both SKA1-LOW and SKA1-MID. Superimposed on a plot of sky brightness temperature on a log scale over the entire SKA frequency range. The bump in sky temperature on the right side is the influence of the 22 GHz water line.](image)

5.2.2.2 RFI Environment

Now and in the future, the design of radio telescopes will be constrained by their radio frequency interference (RFI) environment. From the perspective of radio astronomy, RFI encompasses all human-generated radio frequency signals, much of which is far stronger than natural signals. It now occupies much of the radio spectrum and is strong enough to create false detections of astronomy signals or to reduce the available observing time. Its control is the main reason for the remote,
protected SKA locations provided by the site countries. This protection goes well beyond the allocation of radio frequency agreed under the auspices of the International Telecommunications Union (ITU).\(^{18}\) RFI emanates from the following:

- **Ground-based external**: This class of sources includes emissions from nearby transmitters and electromagnetic interference (EMI) from devices deployed on or near the sites, but not under the direct control of the SKA. Low-frequency RFI on the Australian site can also be received from distant transmitters.

- **Internally generated**: Sources of emissions from devices under the control of the SKA. A SKA standard has been put in place to ensure that internally generated RFI is controlled.

- **Aircraft and satellite-based**: Aircraft transmit in a variety of bands that affect the SKA, and some of the transmissions are exceedingly powerful. Satellite transmissions occur throughout the SKA frequency range, but with prominent exceptions, tend to be much weaker than aircraft. The number of satellites transmitting in the SKA bands is destined to explode in the next decade with the growth in international commercial projects to enable satellite-borne communication and internet capability to remote areas. SKA endeavours to collaborate with satellite companies and the ITU to manage this and secure mitigation approaches (directly on the interfering system and through legislative and regulatory processes) so as to not significantly degrade science capability.

Notwithstanding the selection of RFI-quiet sites, SKA telescopes will be equipped with additional design features to reduce the impact of RFI:

- Antennas designed to reject signals as much as possible from unimportant directions.

- Signal processing processes the mixture of RFI and astronomical signals without creating distortions of the astronomical components.

- Sophisticated software techniques for identifying and excluding non-astronomical signals.

### 5.2.2.3 Physical Environment

The physical environment is the primary influence on the design of the telescope and its supporting infrastructure. It includes the climate, with special emphasis on extremes of temperature, rainfall, wind, and electrical storms. Other considerations are altitude, seismic activity, population density, ionospheric conditions, and distance from potential support bases.

- Both sites are characterised as “hot arid desert”. Both are likely to be stable over the long term, perhaps getting hotter.

- The population density in the region around the Australian site is extremely low; around the South African site is moderately low.

- Altitude\(^{19}\): South African site: 900 to 1100 m; Australian site: 460 m.

- Ionospheric conditions\(^{20}\): Neither site is near any ionospheric anomaly.

- Neither site is seismically active.

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\(^{18}\) See https://www.itu.int/en/Pages/default.aspx.

\(^{19}\) Altitude is important for high-frequency observations, for which the troposphere is a significant source of noise.

\(^{20}\) Ionospheric conditions are important for low-frequency observations, where they can significantly distort the apparent positions of radio sources.
In summary, both sites are arguably as good as any sites that can be found for ground-based radio telescopes for this frequency range.

5.2.3 Infrastructure

Infrastructure covers the design of foundational support facilities for the SKA Observatory.

5.2.3.1 Offsite

Off-site infrastructure covers office/conference buildings, high-performance computer buildings (SPC SRC), maintenance buildings, parts of the mains power supply and associated communication infrastructure (optical fibre). Section 5.2.1 and Figure 101 describe the off-site facilities in the host countries. The SKA HQ building, at Jodrell Bank Observatory in the UK, contains offices for ~160 persons, meeting rooms and a large conference facility.

Figure 103. The SKA HQ building at Jodrell Bank Observatory in the UK.

5.2.3.2 Onsite

The remote site-locations originally contained little infrastructure. However, the two precursor telescopes, MeerKAT, ASKAP, and the MWA have now provided much basic infrastructure. The SKA will expand this, and in the case of MeerKAT absorb most of into the SKA1-MID. Nevertheless, the on-site infrastructure covers an extensive list of facilities:

- Power supply: SKA1-LOW: this will be a mixture of solar generation, with a battery energy storage system, and back-up diesel generation. The power station will be constructed, owned, and operated by an external supplier. SKA1-MID: grid power is available, and the supply is sufficient for the telescope. However, a small power margin and significant losses due to the long transmission line lengths have prompted investigations into supplementing the grid supply with solar generation and a battery energy storage system. In addition, for the majority of power on the spiral arms of both telescopes, local solar generation with the associated battery systems will form part of the design and be provided by an independent power producer. Power generation scope is a part of the Observatory Establishment and Delivery Plan which contains details on the cost basis and strategy for approaches to the market for long-term power purchase agreements.

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21 Off-site here indicates not on the actual telescope sites.
Figure 104. Grid power in SKA-MID (left) and existing Meerkat power distribution (right).

Figure 105. The SKA1-LOW power location (left). Power distribution in core area (right).

- Power distribution: SKA1-LOW: Power will be an underground distribution from the CPF to both the array core and the spiral arms. SKA1-MID: The same underground distribution plan will be used in the core area. The inner dishes in the spiral arms will be supplied via overhead transmission lines, with short underground feeders to each dish, while the outermost 7 dishes on each spiral arm will be supplied by local photovoltaic power generation.

- Access roads: For both SKA1-LOW and SKA1-MID, existing roads will be used wherever possible and upgraded as necessary. Road construction standards will be based on anticipated usage.
Figure 106. Layout of new and existing roads for SKA1-LOW.
Buildings: SKA1-LOW: there will be a large central processing facility and 36 remote processing facilities. SKA1-MID: the Karoo Array Processing Building (KAPB) will house all the primary computing and electronic sub-systems on-site.

Figure 108. 3D perspectives of building upgrades SKA1-MID.
- Dish foundations: SKA1-MID: The foundation designs consist of piled and pad foundations tailored to suit the soil conditions at each location.
Station ground preparation: SKA1-LOW: An area for the core array has been selected to be very flat and not subject to flooding. The positions of the station clusters have been similarly selected within constraints imposed by the array design. Hence minimal ground disturbance will be necessary.

Data transport: Both SKA1-LOW and SKA1-MID will use buried optical fibre where necessary for data transport from dishes or stations, and from the site to other host-country facilities. For SKA1-MID, fibre is also strung on poles in the spiral arms to reduce the cost.

Other facilities: Infrastructure on both sites also covers RFI and security monitoring, weather monitoring, water and sanitation, site access (security) and vehicles.

All infrastructure, especially buildings, that are capable of emitting electromagnetic interference (EMI) are shielded to meet an agreed SKA EMI Standard, suitable for a radio observatory site.

5.2.4 Telescope Capabilities and Performance

Scientific performance is determined mainly by the capabilities and performance characteristics which are defined in Annex A. The specific requirements of the two telescopes are contained, from a scientific viewpoint in the Science Requirements document (SKA-TEL-SKA-0000007) and a technical point of view in the Systems Requirements document (SKA-TEL-SKA0_0000008, Rev 12).

The requirements have been developed down several levels to ensure that verification of the performance can be tested at each level to help build confidence that the complex observatory will meet the scientific requirements or level 0 requirements.

It is vital to design the Observatory to be as flexible as possible in ways not fully captured in the Requirements documents; flexibility will be emphasized except in cases where it results in significant unavoidable cost.

A key system design feature to improve flexibility is sub-arrays: the ability to allocate and configure a subset of telescope resources (antennas, beamformers, correlators, processing resources), just sufficient for the observation. Once the configuration is done, the observation is executed on the sub-array. In addition, some observations may be identified as candidates for commensal observing, where
data from a single sub-array is shared between projects; clearly, the configuration will need to support this capability.

The performance requirements for SKA-MID are found in Annex B, those for SKA-LOW in Annex C.

5.2.5 SKA1-MID

The SKA1-MID telescope will consist of an array of reflector antennas (‘dishes’), 150-km in total extent. It will be a mixed array of 133 15 m SKA1 dishes and 64 13.5 m diameter dishes from the MeerKAT telescope. The outer part of the array is a 3-arm spiral configuration which is known to provide excellent instantaneous coverage of the $u$-$v$ plane\textsuperscript{22}. The antennas are approximately equally spaced in radius on a log scale, to provide a ‘scale-free’ distribution of baselines, except for the central core. The dense core provides excellent sensitivity to extended regions of low brightness and a sensitive (single-dish-like) sub-array for pulsar and transient astronomy.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure111.png}
\caption{Left: The entire MID array configuration; Middle: the inner 2 x 2 km region of the array (blue dots are the MeerKAT dishes). Right: A simulated view of the inner part of the array.}
\end{figure}

\textsuperscript{22} The $u$-$v$ plane is a 2-dimensional space where interferometer data is placed before Fourier transforming to make an image of the sky. Each pair of dishes (baselines) will generate a data-point (visibility) on this plane every second or so, based on the distance between the dishes and the orientation of the line between them.
Figure 112. Major sub-systems of the SKA1-MID telescope. The black or red lines indicate signal or data flow; the dash-dot lines, timing and synchronisation signals; the dashed green lines, control and monitoring flow. The text under each block indicates the underlying technology. The green-shaded regions are part of the overall architecture but outside of the SKA1 specified components.
Figure 112 illustrates the flow of astronomy signals, data, and synchronisation signals through the major sub-systems of SKA1-MID. The black or red lines indicate signal or data flow; the dash-dot lines, timing and synchronisation signals; the dashed green lines, control and monitoring flow. The text under each block indicates the underlying technology.

5.2.5.1 Reflector Antennas, Feeds, and Front-ends (Dishes)

The antennas for SKA1-MID are a critical component of the system as they ‘couple’ the telescope to the sky. There are compromises in designing the antenna; SKA1 has selected a 15 m projected diameter, offset Gregorian optics with the feed on the low side of the reflector. The following qualitative characteristics have guided this choice:

1. Lowest possible instrumental noise, commensurate with the level of sky noise.
2. High aperture efficiency.
3. Sufficient control and stability of the beam-shape, particularly pointing, to enable wide-field, high dynamic range imaging at low frequencies and good control of performance at high frequencies.
4. Smoothness of response in spatial and spectral dimensions, as limited by fundamental physics (e.g., edge diffraction)\(^{23}\).
5. Space at the focus for multiple independent receivers.
6. Very low sidelobes beyond the first one.
7. Excellent dual polarisation performance.
8. Excellent performance down to ~450 MHz, good performance to 350 MHz.
9. Excellent performance to 15 GHz, good performance at 20 GHz (gradually falling off thereafter).
10. Beam as circular as possible.

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23 Minimal scattering: Scattering objects, such as feed supports in the optical path, tend to generate low-level resonances, which will have relatively fine frequency structure and/or chromatic sidelobes.
The relative simplicity of an unblocked aperture will enable accurate modelling of the main beam response and the near-in sidelobes. The lowest spill-over noise and highest aperture efficiency are achieved with feeds that have a ratio of 1.85:1 between the highest and lowest frequencies. This determines the number of feeds. The design principle guiding the choice of receiver bands is to minimise total noise and maximise antenna efficiency at frequencies where sky noise is lowest, and to relax these slightly at the low end of the frequency range in a trade for more frequency coverage. Although cryo-cooling of low-noise amplifiers is essential to reach the required system temperatures, the cost is significant for such a large telescope. However, a cost-benefit study concluded that cryo-cooling is unconditionally cost-efficient for SKA1-MID, except for the lowest frequency band. The bands are:

Table 4. Summary of frequency range and sensitivity for the SPF sub-element.

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency (GHz)</th>
<th>Sensitivity requirement$^{24}$ (m²/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Array (L1)</td>
</tr>
<tr>
<td>1</td>
<td>0.35 – 0.650</td>
<td>272 – 545$^{25}$</td>
</tr>
<tr>
<td>UHF</td>
<td>0.65 – 1.050</td>
<td>545</td>
</tr>
<tr>
<td>2</td>
<td>0.95 – 1.760</td>
<td>337</td>
</tr>
<tr>
<td>L-Band</td>
<td>0.90 – 1.670</td>
<td>916</td>
</tr>
<tr>
<td>3</td>
<td>1.65 – 3.050</td>
<td>170</td>
</tr>
<tr>
<td>4</td>
<td>2.80 – 5.180</td>
<td>916</td>
</tr>
<tr>
<td>5a</td>
<td>4.60 – 8.500</td>
<td>833</td>
</tr>
<tr>
<td>5b</td>
<td>8.30 – 15.40</td>
<td>1110</td>
</tr>
</tbody>
</table>

$^{24}$ Requirements and compliance are for the full RF frequency range specified.
$^{25}$ Requirement based on a line interpolated linearly between lower (left) and higher values (right).
$^{26}$ Allocated requirement for an individual dish (L2) based on analysis (see DBD).
$^{27}$ Allocated requirement for an individual dish Single Pixel Feed (L3) based on analysis (see DBD).
Figure 114. Schematics for SPF band 1 (left) and band 2 (right).
Data from the dishes is transmitted to the correlator-beamformer system over optical fibres.

Figure 116. Connectivity between telescope systems and fibre routes.

5.2.5.2 Correlator-Beamformer (CBF)

Several of the functions of the telescope capabilities are performed by the CBF sub-system, whose outputs can be rendered into images and other data products. An efficient design will have a high
utilisation-factor; in other words, there will be many ways to schedule observations so that the whole telescope is engaged in high-priority observations while using a high fraction of the processing equipment.

A desirable attribute is also scalability. Correlators are typically difficult to scale because the number of operations depends on the square of the number of inputs (array baselines). However, both bandwidth and the number of dishes scale linearly; hence scaling in these dimensions is an avenue for creating an efficient design. While this does not linearise the scaling, it does provide a solution for a large number of antennas. This approach is adopted for SKA1-MID, resulting in the frequency slice processor illustrated in Figure 118. Each frequency slice of ~200 MHz can be processed independently of the others and can carry out one of a selection of tasks, depending on the type of observation. The tasks always include channelisation and transient capture, and can also be correlation, pulsar beamforming, or VLBI beamforming (Figure 118, Appendix B). Beam data is passed on to pulsar processors and VLBI terminal systems. This equipment will be contained in the MID CPF (Karoo Array Processing Building; KAPB) at Losberg, near the centre of the site.

Figure 117. TALON-DX signal processing board with FPGA air-cooled heatsink.
Figure 118. Left: A simplified version of the frequency slice CBF architecture. Right: An illustration of how the RF band is split into slices, where each slice is processed independently of the others. There are many frequency slice processors (FSP) in the system. Each FSP is capable of being programmed to carry out various functions, including channelisation.
5.2.5.3 Synchronisation and Timing

All interferometer systems like the SKA telescopes must be able to combine the signals from different antennas coherently\(^{28}\). Among other measures that are taken for SKA1-MID, the ‘clock-signals’ that feed the analogue-to-digital converters in each antenna must be synchronised across the array. This is accomplished by converting a reference signal from the central Observatory clock into an optical signal, which is transmitted over a fibre link to each antenna. The fibre is subject to changes in length due to temperature changes and noise due to environmental disturbances on the link, which degrades the phase-stability and thus the coherence of the reference signals.

Figure 119. SKA1-MID synchronisation and timing architecture.

SKA1-MID will employ actively stabilised frequency-transfer technology to suppress the environmental effects and ensure phase coherence across the array. This is done by sending the reference signal to the antenna and back and then using a feed-back system to stabilise the round-trip phase. If the ‘out’ and ‘return’ paths are sufficiently similar (a key part of the design) then the delivered phase is also stabilised. Variations on this technique have been used for decades in radio telescopes; SKA1-MID implements it, using the latest optical technology.

\(^{28}\) A stable relationship of the mutual phase differences of the radio signals across the bandwidth among all the antennas in the array. Without coherence, correlation will fail.
5.2.6 SKA1-LOW

The SKA1-LOW telescope will consist of 512 aperture array stations, each comprised of 256 dual-polarised log-periodic antennas randomly distributed in a 38 m diameter circular area (131,072 antennas in total). The inner aperture array stations are arranged in a compact core with a diameter of ~1 km with three spiral arms with a maximum baseline (maximum distance between receptors) of 65 km.

Figure 120 illustrates the flow of astronomy signals, data and synchronisation signals through the sub-systems of SKA1-LOW. The black or red lines indicate signal or data flow; the dash-dot lines, timing and synchronisation signals; the dashed green lines, control and monitoring flow. The text under each block indicates the underlying technology.
Figure 120. Major sub-systems of the SKA1-LOW telescope. The black or red lines indicate signal or data flow; the dash-dot lines, timing and synchronisation signals; the dashed green lines, control and monitoring flow. The text under each block indicates the underlying technology. The green-shaded regions are part of the overall architecture but outside of the SKA1 Specified Components.
5.2.6.1 Antennas

Because at low frequencies ‘wire antennas’, such as dipoles, are much more efficient than reflectors, SKA1-LOW is constructed using such antennas. A challenge is to cover the frequency range from 50 – 350 MHz in one band (7:1 frequency ratio), which constrains the choice to only a few designs (See Table 6 for the main performance characteristics). Although methods exist to increase their bandwidth somewhat, single dipoles and their derivatives tend to be narrower band than required.

The log-periodic dipole antenna has overcome this problem by coupling many dipole antennas, each tuned to a specific frequency range, to a single transmission line in a ladder formation. The SKA1-LOW telescope will consist of an array of 131,072 dual-polarised, log-periodic antenna elements, designed for sensitivity from 50 to 350 MHz. Like all quasi-resonant structures, effective area falls off as $\lambda^2$, but log-periodic antennas have higher directivity than simple dipoles over a wide range of frequencies. Because approximately three dipoles at a given frequency are involved in beamforming, the directivity is higher overall.

![Figure 121. SKALA 4.1 log-periodic antenna.](image)

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29 Invented by D. Isbell and R. DuHamel at the University of Illinois in 1958.
30 This number has been ab-initio fixed to constrain cost.
Table 5. Main performance of the Isolated antenna element at four different frequencies.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>50</th>
<th>110</th>
<th>230</th>
<th>350</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directivity at zenith (dBi)</td>
<td>8.1</td>
<td>7.4</td>
<td>7.4</td>
<td>8.1</td>
</tr>
<tr>
<td>Directivity at 45 deg (E-plane) (dBi)</td>
<td>3.5</td>
<td>2.1</td>
<td>0.4</td>
<td>1.9</td>
</tr>
<tr>
<td>Directivity at 45 deg (H-plane) (dBi)</td>
<td>5.3</td>
<td>6.3</td>
<td>5.0</td>
<td>5.4</td>
</tr>
<tr>
<td>Reflection coefficient (dB)</td>
<td>-0.2</td>
<td>-13.4</td>
<td>-11.2</td>
<td>-10.6</td>
</tr>
<tr>
<td>Average IXR in the FoV (dB)</td>
<td>41.2</td>
<td>32.5</td>
<td>33.7</td>
<td>27.2</td>
</tr>
<tr>
<td>Minimum IXR in the FoV (dB)</td>
<td>19.3</td>
<td>12.3</td>
<td>11.4</td>
<td>12.3</td>
</tr>
<tr>
<td>Noise Figure LNA (dB)</td>
<td>7.54</td>
<td>0.51</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>Transducer gain LNA (dB)</td>
<td>29.6</td>
<td>45.4</td>
<td>45.7</td>
<td>44.0</td>
</tr>
</tbody>
</table>

The antenna elements will be combined in circular ‘stations’, each containing 256 antenna elements to act like single 38 m diameter antennas, capable of forming one or more ‘beams’ on the sky (See Annex C: SKA-LOW Performance Parameters).

5.2.6.2 Stations

The following considerations interact strongly with the array configuration, and affect sensitivity, correlations and analysis:

- Sufficient diameter in wavelengths to reduce far-out sidelobes to an acceptable level.
- An acceptable level of near-in sidelobes.
- Sufficient collecting area for on-sky calibration and to enable characterisation of the ionospheric phase-screen.
- Sufficient field-of-view for EoR/CD imaging.
- Smooth spatial and spectral responses over the field-of-view in a single beam or in a mosaic of beams.
- Polarisation response that can be accurately modelled and/or measured.

A feature of aperture arrays (i.e., antenna elements assembled into a station) is the so-called sparse-dense transition: within a station, when the antenna elements are farther apart than about one wavelength (sparse), they act independently and the effective collecting area is proportional to the square of the wavelength (λ²). When the separation is closer than about a 1/2 wavelength (dense), the antenna elements strongly interact in such a way as to force the effective collecting area to be constant with frequency. A complex series of trade-offs has led to a choice of the sparse-dense transition frequency of ~94 MHz. This means that the considerations noted above are sufficiently well met.

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31 A beam is an area of reception inversely proportional to the size of the array in wavelengths (e.g., at a wavelength of 2 m, a 38 m station will have a beam with an angular diameter of approximately 2/38 radians).
32 Separation here refers to average separation. The distance between antenna elements is randomised to prevent the build-up of resonant interactions between antennas that can greatly affect beam performance.
Figure 122. Top Left: Full array configuration. Each dot is a cluster of 6 stations. Top Right: Inner 4 km diameter array configuration. Each dot is a station. Bottom: Station beamformers, the correlator-array beamformer and the pulsar processors which transmit output data to the science data processors and VLBI terminals in Perth.
5.2.6.3 The Array, Station Beamformers, and Correlator-Beamformer

Figure 122 is a combination schematic showing the SKA1-LOW array configuration at the top, and the on and off-site processing facilities at the bottom. The outer part of the array is a 3-arm spiral configuration which is known to provide excellent coverage of the \( u-v \) plane.

Each point in Figure 122 (left) represents a cluster of six stations. This arrangement has been chosen to provide high sensitivity (more collecting area) in the outer part of the array; it represents a cost-effective method of doing so that reduces \( u-v \) coverage only slightly.

The inner-circle on the left of Figure 122 explodes into the inner configuration (shown on the right), where there is also a heavy concentration of stations in the core of the array. This configuration provides excellent sensitivity to extended regions of low brightness and provides a sensitive sub-array for pulsar and transient astronomy.

RF signals are amplified at each antenna and transmitted as analogue signals over optical fibre (RF-over-Fibre (RoF)) to nearby processing enclosures. The received optical signals are digitised and added to the other antennas in a station in groups of 16\(^{33}\); the groups are then summed to form up to eight station-beams from all 256 antennas (two polarisations each).

Figure 122 shows that this occurs for outer stations in small enclosures adjacent to a cluster (remote processing facilities (RPF)); for the core and a few of the nearby clusters, this occurs in the much larger central processing facility (CPF).

\(^{33}\) The granularity of 16 is because the circuits that receive these signals (Tile Processing Modules – TPMs) can handle 16 dual-polarised signals each.
The CPF also contains the correlator-beamformer for the array, which carries out channelisation, transient capture, correlation, pulsar beamforming, and VLBI beamforming. Beam data is passed on to pulsar processors and VLBI terminal systems\(^{34}\). Correlator data is sent to the science data processor.

5.2.6.4 Observatory Clock and Synchronisation and Timing

The synchronisation and timing (SAT) system for each telescope is responsible for the implementation and distribution of a local time and frequency standard across the array. Figure 125 shows the overall common architecture used in the SKA1-MID and SKA1-LOW telescopes. There are three sub-systems in the SAT system with four different functionalities: the observatory timescale subsystem (clock), the reference frequency distribution subsystem, and the time distribution subsystem. In addition, there is a monitoring and control subsystem for the previous three sub-systems.

![Figure 125. The Synchronisation and timing architecture. FRQ: Frequency distribution sub-system, UTC: Time generation and distribution sub-system, NTP/PTP: Network time protocol/precision time protocol time distribution, SAT-LMC: Monitor and control, NSDN: Non-science data network (used for monitor and control).](image)

5.2.6.4.1 SAT.CLOCK: Observatory Clock Sub-System

The SAT.CLOCK sub-system in each telescope is responsible to implement a local time and frequency standard for the telescope. The fundamental purpose of the observatory clock at each telescope site is to keep accurate time (SKA timescale). Using satellite time-transfer, the SKA timescales are closely synchronised with coordinated universal time (UTC), the official worldwide time standard maintained by BIPM\(^1\). To achieve the required level of long-term time accuracy demands, the SKA will participate in the group of organisations that contribute to BIPM by implementing a time-keeping node (UTC(SKA)) for each telescope. The required synchronisation accuracy with UTC is 5 ns for SKA1-MID and 9 ns for SKA1-LOW over a time-duration of at least 10 years. Figure 126 illustrates the architecture of the SAT.CLOCK, which is similar for both telescopes.

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\(^{34}\) These operations can be carried out for all 512 stations or sub-arrays of stations, including multiple beams. Stations, themselves, can be sub-arrayed to increase field-of-view or provide coverage of the central u-v plane. However, there are restrictions on the combinations that can occur simultaneously to retain a reasonable cost.
Figure 126. Architecture of SAT.CLOCK sub-system for both telescopes.

Accurate timekeeping at each receptor is needed to know the (geodetic) position of each antenna on a rotating Earth. This enables the determination of the position of the antenna-array in the celestial frame as well as the angular positions of radio sources in the Earth-based frame. This allows dishes/stations to point in the desired directions and the calculation of the time taken for a wavefront to travel from one dish or station to another (geometrical delay). Over timescales up to years, accurate timekeeping at receptors is also needed to conduct pulsar search and timing observations. The Observatory clock sub-system not only provides time to receptors, but it also provides less accurate network time services for each device looking for time information on the network.

Over timescales of hours, the phase and frequency stability of the output reference frequency from the observatory clock subsystem is an important driving parameter for very long baseline (VLBI) related observation.

5.2.6.4.2 Reference Frequency Distribution Subsystems

The capacity of the interferometric radio telescope to capture the maximum possible power from an astronomical signal depends, among other factors, on the frequency stability at the antenna locations used for the digitisation process. As described above, the SKA centrally generates an accurate, reliable, frequency source separately for each telescope which is tightly synchronized with coordinated Universal Time (UTC). These frequency sources must be replicated at each station or dish, to be used as sampling clocks for the analogue-to-digital converters. The reference frequency from the SAT.CLOCK is distributed over fibre to the receptors. Changes in environmental conditions, especially temperature, affect the travel time of the reference signal through the fibre, altering its phase, which can badly affect sensitivity. Although a variety of options were explored, the systems that have been chosen are based on the widely-used round-trip feedback system, updated to utilise the latest optical techniques. This method measures and tracks the delay variations in the fibre links and mitigates them by taking appropriate actuation steps to compensate.

The architecture of the reference frequency distribution systems used in SKA1-MID and SKA1-LOW are quite different.

The basic requirements for SKA-MID and SKA1-LOW telescopes differ markedly, leading to a different architecture for each:
The distances from the centre of the array to the outermost dish/station are ~100 km for SKA1-MID and only about ~30 km for SKA1-LOW. Actual distances in both cases are longer in practice.

The maximum observing frequency for SKA1-MID is ~15 GHz, whereas for SKA1-LOW is ~350 MHz. As coherence depends on phase at the observing frequency, the fluctuations in terms of phase are inherently much higher for SKA1-MID.

SKA1-MID: The reference frequency distribution system used in the SKA1-MID is a photonic round-trip phase compensation system, that measures the photonic length variations on the fibre link and corrects it, for keeping the reference frequency as stable as possible. All the measurements and corrections are performed at the transmitter side inside the CPF. It also delivers slightly offset reference frequency at each dish than the nominal to implement sampling clock frequency offset (SCFO) scheme to mitigate self-generated radio frequency interference (RFI).

![Figure 127. A simplified diagram of the SKA1-MID reference frequency round-trip distribution system.](image)

Figure 127 is a simplified view of the round-trip feedback method for one antenna. The entire system comprises a Michaelson interferometer. The optical signal from one laser is split into two arms of an MZI (Mach-Zehnder Interferometer). In one arm, a static microwave frequency shift is applied to the optical signal. When the two arms are recombined at the output of the MZI, this results in two optical signals on a single fibre with the microwave-frequency separation. This signal is transmitted over the optical fibre link to the remote telescope site where it is translated into the electronic domain by a photodetector, recovering the microwave signal. Part of the optical signal is reflected back to the transmitter site, where it is mixed with a copy of the transmitted optical signals, and the frequency modulation is extracted with a local photodetector. This electronic signal is then mixed with a copy of the microwave signal, to produce an error signal that has encoded the fluctuations of the link. Applying this to the drive signal of an AOM (acousto-optic modulator) closes the servo loop and effectively cancels the link error for the remote site. The reference frequency is 7.92 GHz. This frequency is replicated at the output, whereupon it is divided by two to produce 3.96 GHz.

SKA1-LOW: The reference frequency distribution subsystem used in SKA1-LOW is a non-harmonic precision reference frequency synchronisation scheme. It compares the one-way phase fluctuations of 2f signal with two-way (round trip accumulated) fluctuations of 1f signal and mitigates the phase fluctuations at the receiver side to deliver a stable reference frequency signal. In contrast with the SKA1-MID system, the SKA1-LOW system does the correction at the remote end. Hence the expansion of the system is easier because the central end contains so little hardware. This makes the system simpler at the expense of a somewhat larger remote system.
Figure 128. A high-level description of the design in SKA1-LOW.

Figure 128 provides a high-level description of the design in SKA1-LOW. For each RPF, a central transmitter modulates a laser with a 2-GHz signal that is sent to the remote end via the fibre link. The remote end contains the feedback electronics. A voltage-controlled oscillator at the remote end generates a laser-modulated 1-GHz signal that is sent to the central end and reflected back to the remote end. The 1-GHz and 2-GHz signals are mixed to produce another 1-GHz signal in which the phase fluctuation introduced by the fibre link has been eliminated.

5.2.6.4.3 Time Distribution Sub-system

The goal of the UTC distribution is to precisely timestamp the signals at the receptors to achieve the science goals noted above and to enable time-stamping of the received signals with sufficient accuracy to allow real-time fringe finding during calibration. In both SKA1-LOW and SKA1-MID, the required accuracy for the UTC distribution is 2 ns (rms) compared to SKA-timescale.

Each telescope uses a similar white rabbit based time distribution system. White rabbit is a robust open protocol available in many COTS implementations and hence reliable. It uses a master-slave topology where slave adjusts its clock to synchronise with the master. The white rabbit master will be located at the CPF and receives a 1-PPS and a reference-frequency signal from the observatory clock subsystem. The white rabbit slave at each receptor communicates continuously with the master to mitigate fibre delays. The white rabbit slave retards its physical clock as to synchronise with master and then generates a synchronous time signal at the receptors.

5.2.7 Time-Domain Capabilities (Pulsars and Transients)

SKA1 will deploy dedicated equipment to enable the time-domain astronomy capabilities. A characteristic of all pulsed or fast-transient astrophysical emissions is dispersion, the effect of encountering electrons along the path to the Earth. Depending upon the total column density of electrons along the path, dispersion delays the emissions in proportion to \( f^{-2} \), the inverse square of frequency. This is illustrated in, Figure 129, where a pulse follows a curved path in the time-frequency plane.
Figure 129. Left: The time-frequency signature of a dispersed pulsar pulse or an astronomical transient. The red solid curve suggests trials of unsuccessful lower dispersion measures until the correct value has been reached. Right: Time-alignment after a matched de-dispersion operation has been applied. Bottom: The red plot shows the increase in signal-to-noise of the pulse after the de-dispersion operation and a summation over frequency has been applied.

5.2.7.1 Pulsar Search (PSS) and Transients

The correlator-beamformers can generate streams of digital data (PSS-beams) by summing the outputs of a sub-array of antennas or stations – 1500 beams for SKA1-MID; 500 beams for SKA1-LOW (see Annexes B and C for basic parameters). Each of these beams can be searched in parallel for pulsars or transients. The search is carried out by trialling a series of dispersion measures as shown in Figure 129.

Transients (single pulse events) are detected when a single pulse is strong enough to exceed a pre-determined signal-to-noise ratio (SNR). For SKA1-MID, when this happens a trigger-signal is sent to the CBF to freeze the contents of a buffer to capture the signal from each antenna. For SKA1-LOW, the trigger is sent to the TPMs, where the freeze-buffer is located (see section 5.2.6.3). In both cases, this permits the observer to ‘go back in time’ to carry out further analysis of the transient signal.

The search for pulsars continues by trialling a series of pulse periods, using a ‘folding’ method. Folding entails dividing the time series into chunks of varying length and summing all the chunks together. A detection is found when a pulse period is detected above a pre-determined signal-to-noise ratio.

In addition, the PSS system can also search in a restricted way for pulsars in a binary system whose period changes with orbital motion. This capability adds another compute-intensive dimension to the search.

5.2.7.2 Pulsar Timing (PST)

The correlator-beamformers can also generate up to 16 PST-beams for each of SKA1-MID and SKA1-LOW. In principle, these are like the PSS-beams, but the details are different; owing to the precision required, they are formed separately. For pulsar timing, the pulsars are characterised in advance, and the goal is to accurately measure and track the time-of-arrival of each pulsar for durations up to a decade. The underlying method (Figure 129) is the same as for pulse searching except that trials are not required, and the detailed implementation is more precise.
5.2.8 VLBI Capability

Very long baseline interferometry (VLBI) is a technique for assembling arrays of antennas whose locations span the globe into a single high-resolution telescope. Data from each antenna in a VLBI array is delivered to a central site where it is correlated in a manner like that for the SKA.

Because the antennas in a VLBI array are usually different from each other, standardised interfaces, setups, metadata and file formats are required. Also, standardised equipment is used to either record data from a given antenna or to send it in ‘packets’ to the correlator, which is typically at one of the major VLBI observatories (e.g., the European VLBI Network).

The SKA will support VLBI capability on both SKA1-MID and SKA1-LOW

Note that VLBI can observe concurrently with other types of observations; for SKA1-MID, VLBI observations can be performed concurrently with SKA imaging from the same sub-array and transient search; for SKA1-LOW, there is additional flexibility available, as all types of observations can be performed simultaneously in the same sub-array, and from the different station beams.

5.2.9 Data Flow

The SKA telescopes will be prodigious generators of data (see Figure 130). SKA1-LOW, in particular, generates data from each of the 130,000 antennas. Part of the reason is that the modern radio frequency interference (RFI) environment requires much higher precision of data values than required purely to handle astronomy signals. Also, the output data-rates from correlators must be high to support very wide-field imaging.

These data-rates are a driving factor in the system design to operate the science data processors in quasi-real-time. Otherwise, approximately 19,000 PB of data (visibilities) would need to be stored per year, which would require the construction of a small data-centre each year, well beyond reasonable expectations.

![Figure 130. Telescope and Observatory data flow volumes. The rate of dataflow to the SKA regional centres is the current estimate, based on the weighting of expected science objectives. Maximum capacity is ~600 PB/year.](image-url)
5.2.10 Specialised Software Design

As already alluded to, the SKA Observatory is driven by software technology. There are specialised software categories that underpin the design of the telescopes. From a functional perspective they are:

1. Manage the science (proposals, observations, communicating with observers).
2. Monitor and control the telescopes in near real-time (including science data processing).
3. Process science data.

The SKA software is intended to match the approximate 50-year lifetime of the observatory, hence considerable effort is being taken to design it with longevity in mind. Although the details are voluminous, the software design has utilised up-to-date techniques to ensure availability, scalability, maintainability, portability and other features.

5.2.10.1 Telescope Manager

The first two functions in the previous section are closely intertwined and have been designed together under the heading Telescope Manager (TM). TM supports teams of observers (see section 5.3.2), SKA operations (see section 5.3 and provides central coordination of each telescope). In more detail TM manages the following:

- **Observations**: TM accepts science proposals, designs observations, schedules them and prepares the system for executing the observations.
- **Observation execution**: TM orchestrates the hardware and software systems to control observations through well-defined interfaces. It also provides alarm management and handles faults.
- **Operational support data**: TM facilitates maintenance of telescope systems through continuous logging of parameters to monitor telescope health and evaluates conditions that may impact observations. It provides support for performing diagnostics based on archived data and delivers data to operators, maintainers, engineers and science users through user-interfaces.

The SKA has adopted the TANGO controls framework on which to implement these functions. This mature, open-source software architecture was first used to control particle accelerators and its large library of modules are relatively easily adapted to the needs of the SKA. Every software module directly involved in the management of the Telescope will be built on top of this common framework.

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35 There is a large body of software needed to manage and carry out the design (e.g., office software, design tools, simulation tools, communication tools, etc.). Although they are mainly commercially available, they also require significant effort to select, configure, and manage.
5.2.10.2 Science Data Processing (SDP)

Figure 132 shows the functions performed by the science data processors. The data shown in the top box originates on the telescope sites and is transmitted over optical fibres to the high-performance computer (HPC) in Cape Town and Perth. Because SDP must process data at the same average rate that it is produced, it is under the overall control of the Telescope Manager.

Most data are ingested at a high rate, stored temporarily in a buffer and passed to batch mode processors. However, some data, such as pointing calibration data for dishes, ionospheric calibrations and responses to transient events, must be processed in a time-critical manner and fed back to Telescope Manager. As shown at the bottom of Figure 132, batch-mode data products are provided to the various SKA regional centres.

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36 At the level of detail shown in Figure 132. SDP dataflow, architecture and functions.
The SDP receives two types of observational data. These are visibility data (correlator outputs), received as a continuous flow to be imaged and non-imaging data (transient buffer, pulsar and transient search candidates, and pulsar timing data) received as discrete chunks. In cases where there are commensal observations, the same data may be processed as both imaging and non-imaging data.

In addition to science data products, the SDP computes calibration data, generates metadata, generates alerts and maintains Local/Global Sky Models\(^{37}\). Additional information is generated to track and assess the efficacy, throughput and quality of the data production.

Figure 132 also depicts many pipeline processors running in parallel. This technique is highly effective and easily applicable to visibility data. Without this capability, processing SKA data in this volume would probably be impossible.

\(^{37}\) The Global Sky Model contains a collection of sources and components covering the entire sky visible to the SKA stored as a searchable database.
5.2.11 Design for Availability

Critical to scientific success, the SKA telescopes and support systems are designed to be highly available\textsuperscript{38}, within the constraints of accessible resources. Engineering analysis indicates that the SKA telescopes design should offer an inherent availability\textsuperscript{39} of >95%. From the perspective of observatory operations, however, operational availability is the relevant figure of merit. Both telescopes are required to have an operational availability\textsuperscript{40} of at least 95%, which means that it can perform astronomical observations, including signal processing and data reduction, with at least 95% of its collecting area, including associated signal and data processing.\textsuperscript{41}

This level of availability is because aperture synthesis telescopes are inherently redundant and robust to failures, especially in a system which has many contributing antennas. The loss of a few antennas, frontends or even segments of the signal path is likely to only slightly degrade performance. Flexible scheduling and sub-arrays provide an effective mitigation strategy to prevent failures from adversely affecting a scientific project. Where feasible, redundancy has been employed at critical failure points. As many items as possible have been designed as line replaceable units (LRUs).

The telescope systems have been analysed extensively: the design process for each telescope sub-system includes failure modes, effects, and criticality analysis (FMECA). FMECA analysis has led to a system reliability analysis that identifies the critical sub-systems and probabilities of failures for all sub-systems. The results have been fed back to the sub-system designers in the form of an availability allocation. For most sub-systems, these allocations have been met and included in a reliability, maintainability, and maintenance (RAM) report as illustrated in Figure 133.

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\textsuperscript{38} Technically, availability is the probability that a system is operating satisfactorily at any point in time under stated conditions. It is a measure of how often an item fails (reliability) and how quickly it can be restored to operation (maintainability).

\textsuperscript{39} Inherent availability is the probability that a system is operationally capable at any point in time when used in an ideal support environment, i.e., one in which repair commences instantaneously upon failure.

\textsuperscript{40} Operational availability is the probability that a system is operationally capable at any point in time when used in a realistic support environment. It is thus a measure of not only reliability and maintainability, but also of the response time of the support system.

\textsuperscript{41} This definition is strictly for the purpose of defining availability. It is clearly possible to carry out science observations with less than 95% of the full array.
On-going availability will be supported by a SKA maintenance plan that will include both preventive maintenance and corrective maintenance, varying from system to system, depending on the known failures.

5.2.12 Assembly, Integration and Verification (AIV)

The SKA adheres as much as possible to a classic system-engineering approach to design and implementation (Figure 134). Although the telescope sub-systems have been designed in many locations, each design contains interface control documents (ICDs) that will ensure smooth assembly into a full working telescope system in the field. A roll-out strategy has defined verification through a series of tests (e.g., factory acceptance, pre-installation tests at an integration test facility, and finally after assembly in the field) as illustrated in Figure 135.
The roll-out itself, illustrated in Figure 136, will be sequential so that the system can be verified in stages (i.e., stopping points defined by the number of dishes or stations installed); the very nature of a synthesis telescope system allows it to be scaled in this way. This procedure will mitigate many of the up-front risks, as early as possible when shortcomings can be dealt with less expensively than if they were discovered after production or in the field.
5.3 Synopsis of Telescope Operations

5.3.1 Principles and Capabilities

There are two key principles behind SKA operations:

1. The SKA will be operated as a single, integrated observatory running two telescopes: SKA1-LOW and SKA1-MID.
2. The SKA will run as efficiently as possible to maximise the output of scientifically valuable data.

Based on these principles, the capabilities embedded in the design and physical constraints (access to right ascensions, weather, maintenance) the following operational capabilities will be provided:

- Continuous operation, including data processing.
- Multi-queue observation scheduling – to ensure dynamic response and to maximise output:
  - Observations controlled by the SKA Observatory (observers not present).
  - Capability to multiplex observing programmes to take advantage of sub-arrays and commensal observing.
- Close coupling of science programmes to maximise complementarity over the full SKA frequency range.
A practical implication from the size of the telescopes and the breadth of the science is that the flow of raw data (e.g., the output from correlators and/or beamformers) will be too large to store in any foreseeable storage system. This means that significant science data processing will be done in quasi-real-time as part of the telescope, and observers will receive data products such as images and pulsar detections, which require much less storage\textsuperscript{42}. The science data processor is the telescope resource whose scheduling ensures that data reduction never hampers or obstructs data acquisition. Calibration of raw data is the responsibility of the SKAO. These data in most cases will be accessible to observers through SKA regional centres (SRCs).

5.3.2 Proposal and Observation Cycle

The SKAO will use conventional, periodic calls for proposals and ranking methods for assigning observing time and associated resources. However, the SKA telescopes contain additional capabilities that increase scheduling complexity:

- Multiple sub-arrays are independently scheduled.
- Observations that are running at the same time on the same sub-array can be scheduled independently.
- Time-domain response to fast transients and targets of opportunity\textsuperscript{43} will interrupt queues and require re-scheduling.
- Continuous observing may be interrupted by breakdowns.

Nevertheless, as illustrated in Figure 137, the SKAO will present to the observer a relatively simple linear process from proposal preparation to data-product delivery. A suite of tools will be available to support observers and the SKAO staff through the sequence of stages, and each data product will be accompanied by an extensive meta-dataset.

This will ultimately be an extensive software development task. However, not all of it is needed at the beginning; those parts required for acceptance, verification, and commissioning will be rolled out as needed.

![Figure 137. Top: Proposal and observation flow. Middle: Suite of software tools that support the entire process from proposal submission to data-product delivery.](image)

\textsuperscript{42} This is a departure from the previous generation of large telescopes (e.g., the very large array), for which the observer is responsible for calibration and all data processing.

\textsuperscript{43} Targets of opportunity are pre-arranged observations that can only take place once an event happens. Other aspects, such as optimal observing frequencies, cadence, decay time, exact position in the sky, etc. may not be predictable.
5.3.3 Access to SKAO Data & Resources

Access to SKAO data and resources refers to telescope time on the sky plus the computational resources needed to produce a calibrated Observatory data product (ODP). This is much more than many currently available telescopes provide.

Proposals for SKA projects can be categorised approximately as:

- Standard proposal (PI): A project typically led by a principal investigator (PI) to target a specific scientific objective (usually a small group of investigators).
- Key science project (KSP): A large scale project designed to cover an area of astrophysics, usually associated with one of the high priority science objectives and carried out by a team of investigators.
- Open time (OT): There will be a small fraction of time available to PIs from non-member countries.
- Director-General discretionary time (DDT): proposals requiring a timely response needing only the approval of the SKAO Director-General.
- VLBI proposal (VLBI): Very long baseline interferometry projects for which a sub-array is used as part of a globally distributed array of antennas.

For the purposes of this proposal, access policy can be summarised as:

- Access will be proportional to members’ shares in the project. The actual fraction is to be agreed among the member countries.
- Subject to the preceding constraint, access will be based on scientific merit and technical feasibility.
- Time will be made available for key science projects, PI projects, Director-General’s discretionary time and open time, at proportions to be determined by the Council’s overall scientific strategy for the Observatory.
- The Director-General will be responsible for time allocation, advised by a time allocation committee.
- Observatory data products will be openly available after a suitable proprietary period but will remain the property of the SKAO.

---

44 The actual fraction is to be agreed among the member countries.
45 A member is a member country or an associate member country as defined in the convention (see section 3.5).
46 Subject to unanimous vote of the IGO Council.
5.3.4 SKA Regional Centres (SRCs)

The SRCs are not part of the SKAO but will be established separately as a global network of centres in member countries or regions. Their main tasks are to provide portals to Observatory data products, platforms/forums for advanced scientific analysis, user support for SKA observers and training; these are detailed in the SKA Observatory Establishment and Delivery Plan.

The main factors that lead to this model are:

- SKAO data processing must maintain throughput matched to input data rate and data volumes will be too large to directly deliver to end-users.
- Science data products that emerge from the SKAO will not be in the final state required for science analysis and does not account for future discovery archives.
- The community of scientists working on SKA science data products will be geographically distributed.
- The SKA will require the development of new methods, algorithms and techniques. As these will be driven by the community, they need a platform for this work.

As depicted in Figure 139, there will be significant collaboration among the SRCs to ensure that all SKA users should be able to access their data products, irrespective of whether their country or region hosts a regional centre.

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47 Because the SRCs are still under development, detailed structure is not yet available.

48 There will be no direct access to the SKAO for ODPs.
5.3.5 Maintenance and On-going Support

A challenge for any observatory is to achieve the optimal balance between science operations and engineering operations. The SKA poses unique challenges in this respect due to its scale and geographic extent. This tension arises because maintenance activities will, in general, compromise availability and therefore scientific productivity. Maintenance is nevertheless essential, not only to repair faults but also to ensure the long-term condition of the telescope facilities.

A detailed maintenance plan, encompassing both hardware and software components, is being developed as part of the system design LOW and MID. It will include both preventive and corrective maintenance, varying from system to system, depending on accumulated failure data.

A major aspect of the maintenance plan is to acquire an engineering management system (EMS), a software package required to support the telescopes during operation. The EMS will provide services such as configuration management, tracking service level agreements, availability management, problem reporting and tracking, and other general support planning.

5.4 Comparative Performance

Part of the telescope design process is to ensure that astronomical performance will be a major step over currently available telescopes. The driving concept for the SKA has been sensitivity\(^49\), where the goal is a major step in collecting area and where system noise is determined by sky noise, not instrumental noise.

Resolution is almost as important as sensitivity and for many types of observations (e.g., studies of weak, distant radio sources) resolution and sensitivity must be matched\(^50\). The array configurations of the two telescopes have been designed to meet the SKA science goals, while in the spirit of minimizing bias, does not favour particular angular scales, except for the cores. The 3-arm spiral configuration provides excellent instantaneous coverage of the \(u\)-\(v\) plane. The antennas also are approximately equally spaced in radius on a log-scale which provides a ‘scale-free’ distribution of baselines, except for the cores.

\(^{49}\) Note that imaging and spectral dynamic range are also required in order to utilise the sensitivity.

\(^{50}\) Otherwise, weak radio sources cannot be separated from one another, a phenomenon known as the ‘confusion limit’.

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Figure 139. Expected flow and access to data (ODPs) and processing among SRCs.
The dense cores provide excellent sensitivity to extended regions of low brightness and a sensitive (single-dish-like) sub-array for pulsar and transient astronomy. For SKA1-LOW the core also provides the highest possible sensitivity to extended emission from the highly redshifted HI-line, expected to present at the epoch of the Cosmic Dawn. A full analysis of the sensitivity of the SKA1 telescopes as a function of angular scale has been completed.

The sensitivities of radio telescopes, both those currently available and those that are under construction or planned have been estimated in Figure 140 is a plot on a log-log scale of the most fundamental measure of sensitivity ($A_e/T_{sys}$) for these telescopes. $A_e$ is the effective area of the telescope, accounting for all the inefficiencies of the design. $T_{sys}$ is the total noise, a determining factor in the detection of weak radio sources; it includes instrument noise, noise picked up from the ground, and noise-opacity of the atmosphere and sky background. The latter two are irreducible (not under the control of the designer) and are very frequency-dependent.

**Figure 140. The sensitivity of existing radio telescopes that cover similar frequency range to the SKA.**

In the decimetre range of wavelengths, which includes the 21 cm HI-line of atomic hydrogen, SKA1-MID provides a major advance over existing instruments. Resolution, sensitivity and survey speed are an order of magnitude better in most cases and, in combination, occupy a new region of performance.

SKA1-LOW covers a similar frequency to the low-frequency array (LOFAR) and the Murchison Widefield array (MWA) but provides an overall sensitivity increase of more than an order of magnitude albeit being optimised for brightness temperature sensitivity – much of the collecting area in a very compact array.

SKA1-MID antennas will be capable of contiguous frequency coverage from 350 MHz to 20 GHz, although initially they may not be equipped with all the receivers. This is a scientifically critical capability for a modern general-purpose radio telescope.

Figure 141 shows simulated images, based on simulated short integrations (snapshots), from SKA1-MID (left, M83) at 1.4 GHz and SKA1-LOW (right, Crab Nebula) at 140 MHz, respectively (see SKA-TEL-SKO-0000818 for more details). The original Hubble images have been rescaled in dynamic range, pixel size, and FoV to approximately simulate SKA observations. The resultant images have been multiplied by the appropriate Gaussian primary beam then convolved with the dirty PSF of the relevant
telescope. Although system errors and noise have not been included in the simulation, the simulations illustrate the potentially superb imaging capability of these two telescopes.

In summary, the SKA1 designs outlined in this document will be a major step forward in astronomical performance, and their location in the Southern hemisphere will complement similar telescopes in the North, as well as the very large optical/infrared (IR) telescopes and the Atacama Large Millimeter/submillimeter Array (ALMA) in the South.

Figure 141. Simulated continuum transit snap-shot dirty noiseless images with SKA1-MID at 1.4 GHz (right) and SKA1-LOW at 140 MHz (left). The original images of M83 (left) and the Crab Nebula (right) are optical Hubble images, modified for radio simulations as described in the text.

5.5 Background to Telescope Sites

The SKA1-LOW and MID facilities will be realised in Australia and South Africa, respectively. Each site offers unique opportunities for the planned research facilities as well as unique challenges in environmental, cultural, regulatory, safety and health compliance.

5.5.1 Australia

The Murchison Radio-astronomy Observatory is an observatory established in 2009 on a portion of land excised from Boolardy pastoral station. The MRO is in the process of being expanded, and the intention is that it will occupy the entire contiguous area of the current Boolardy Station and the neighbouring Kalli Station.

The SKA LOW project features 512 field stations located in a central core and along 3 spiral arms with outer spiral elements approximately 65 km apart. Each field station will include 256 antenna and so the total number of antennas installed will be 131,072.

The field stations will be located on land where Wajarri Yamaji people have been present for thousands of years. In recent years pastoral activities were conducted on the area of land that became known as Boolardy pastoral station. Heritage surveys are being conducted and have led to some alterations of the Low configuration; additional minor alterations may be necessary, pending the results of the final surveys.

The land will be designated diversified use, with radio-astronomy having primacy. The MRO currently covers approximately 3,500 sq km and will extend over approximately 4,310 sq km in its final form.
To provide context, the Boolardy boundary and the site’s location and scale is illustrated below in Figure 142 and Figure 143.

Figure 142. Geographic context for the planned location of SKA1 LOW within the Murchison Radio Observatory (MRO) located within the Boolardy pastoral station.

Figure 143. Boolardy Station outline with the projected layout of the SKA1-LOW station configuration (blue dots).

The detailed site information is contained in SKA-TEL-SKO-0001041 Australian Site Information.
5.5.2 South Africa

The Radio Astronomy Observatory in the Karoo was established in 2007. The KAT 7, MeerKAT and HERA radio telescopes are located on the farms Meysdam and Losberg. Meysdam and Losberg have been declared as the Core Astronomy Advantage Area in terms of the Astronomy Geographic Advantage Act, 2007 (Act No. 21 of 2007) (Government Gazette Notice 33462, 20 August 2010).

The Observatory has been expanded in 2017 to host the SKA radio telescope. This expansion includes the acquisition of an additional 36 land portions in the Karoo; taking the total land size up to 135,000 hectares. This land is owned by the National Research Foundation (NRF). The NRF has entered into a Management Agreement with SANParks to undertake the land management responsibility of the NRF-owned land and has declared it a National Park in terms of the National Environmental Management: Protected Areas Act, 2003 (Act No. 57 of 2003).

The 3 SKA1_MID spiral arms are located on 72 land portions which are currently being secured through Servitude Agreements with 59 landowners. This equates to approximately 1200 hectares of land which will accommodate access roads, overhead and buried optic fibre cable, standalone photovoltaic plants, transformers and buried electrical cable, antenna foundations and the surrounding platform at each antenna location.

The Klerefontein Support Base is located approximately 75 km from the Site and 10km from Carnarvon and is also deemed as part of the Observatory.

A detailed breakdown is illustrated in Figure 144 and Table 7. A total of 176 dishes are located on the NRF-owned land (National Park) and 21 dishes on servitudes secured with landowners.

Figure 144. Figure from SKA-TEL-SKO-0001040 showing map of South Africa with provinces and distances to SKA site from key areas.
Figure 145. Figure from SKA-TEL-SKO-0001040 showing map of SKA1 antenna locations with regard to land jurisdictions.
Table 6. Summary of SKA1_MID.

<table>
<thead>
<tr>
<th>Geographic Location</th>
<th>Description</th>
</tr>
</thead>
</table>
| MeerKAT/SKA core – 5 km diameter on Meysdam and Losberg farms | 91 SKA1 MID dishes  
74 SKA1 MID dishes  
4 SKA1 MID dishes (AA0.5)  
13 SKA1 MID dishes (MeerKAT+)  
64 MeerKAT dishes |
|                                                          | **SUB TOTAL: 155 dishes (77% of array)**         |
| NRF-owned land (National Park) – 135,000 hectares.       | 21 SKA1 MID dishes  
18 SKA1 MID dishes  
3 SKA1 MID dishes (MeerKAT+) |
|                                                          | **SUB TOTAL: 21 dishes (89% of array)**           |
| 3 Spiral Arms (up to 120 km baseline from core) – 1200-hectare extent | 21 SKA1 MID dishes |
|                                                          | **SUB TOTAL: 21 dishes (100% of array)**          |
| TOTAL                                                   | 197 Dishes                                       |

The detailed site information is contained in *SKA-TEL-SKO-0001040 South African Site Information*. 
6 Construction Project Definition

The components of the project definition are:

- **Work breakdown structure** which establishes management points for planning and control using work packages with defined scope and deliverables which can be represented with one or more activities/milestones.
- **Product breakdown structure** which defines the combined components and systems which together represent the Observatory.
- **Total project cost (budget) and schedule**
- **Specifications** tracing the high-level requirements down to the component levels (covered in section 7)
- **Project plans and processes** (covered in sections 7, 9, and 11).

We note that all aspects of the construction project definition (a.k.a. project baseline) are subject to modification according to the project’s change control process (summarised in section 11.7 SKA1 Change Control and detailed in SKA-TEL-SKO-0001100 SKA1 Project Management Control Systems). At the time of the submission, change control is an active aspect of the project and was utilised in the development of the design and programmatic aspects for this Construction Proposal. Approved engineering change proposals were integrated into the planning and budgeting; further engineering change proposals which were (and will be) undergoing analysis after this submission will be assessed based on their impact on the constraints of the project baseline.

6.1 Work Breakdown Structure and Product Breakdown Structure

This Section presents the work breakdown structure (WBS) at a summary level for the construction of the SKA1 design baseline. The WBS includes work packages for SKA organisation “construction support” activities including engineering and project management, product assurance, HSE management and management of contracts and in-kind contributions. The majority of the work packages are those for the construction of the Observatory products by contractors.

The WBS is a product-oriented hierarchy that includes all elements of the SKA1 project and their relationships as represented and maintained in the work breakdown structure dictionary.

- The cost estimates for each WBS element are based on the scope of work defined in the dictionary. These are described in the cost book (SKA-TEL-SKO-0001102 SKA1 Project Management Baseline Cost Book).
- The logic and schedule based on the durations and interdependencies of the work scope are described in the schedule (SKA-TEL-SKO-0001103 SKA1 Integrated Project Schedule).

A graphical representation of the WBS is shown in Figure 146.
In Figure 146, blue boxes represent work scope covered under the capital cost of construction (see Acquisitions) while orange boxes represent work scope performed under the construction support budget; the orange tabbed boxes are led by the SKAO and so have components of both budgets.

The WBS is the basis for all project controls related systems and reports.
6.1.1 WBS Dictionary
To define all aspects of the SKA project, a WBS dictionary has been generated (SKA-TEL-SKO-00011101).

6.1.2 Product Breakdown Structure
The product breakdown structure is established and maintained through Observatory configuration management (SKA-TEL-SKO-0000120). A graphical representation from the eB configuration management tool is shown in.
Figure 147. SKA1 high-level product breakdown structure (derived from eB).

Additionally, a multi-thousand-line spreadsheet provides the detailed mapping between the WBS and PBS elements.
6.2 Baseline Budget

6.2.1 Summary

This section presents cost estimates for the construction of the SKA1 design baseline, work package by work package. The costs include SKA Organisation “construction support” activities including engineering and project management, product assurance, HSE management and management of contracts and in-kind contributions. The majority of the estimated cost is that of construction of the Observatory, labelled “capital cost”.

6.2.2 Cost Basis

All costs are in 2020 Euros using 12-month rolling average exchange rates as of June 2020 with the exception of those technology costs likely to be (de-)escalated and those are estimated for the time of purchase.

6.2.3 Scope

Cost estimates in this document are for the duration of the construction phase of the project from T0, start of SKA1 construction, to the end of construction (T0 + 8 years) and include:

- Labour
- Travel
- Materials
- Spares sufficient for up to and including the product handover to System AIV and 1 additional year's supply per RAM analysis
- Lifetime spares in the case of custom manufactured products
- Warranty
- Plant and equipment (including emulators and simulators where needed to qualify designs)
- Sub-contracts
- Management
- Shipping
- Contractor’s design, overhead and administration
- Fees including licenses for use of IP
- Contingency

Excluded from the construction cost estimates are:

- Pre-construction activities (design, development and prototyping necessary for CDR and procurement preparation, i.e., procurement data packs).
- SKA Organisation activities in the “business enabling” budget, i.e., those for Finance, HR, Legal, Admin, Comms, Science, Director-General’s Office, Operations & IT and part of Assurance.
- SKA Organisation activities in the “development” budget, i.e., the SODP including MFAA, WBSPF and PAF development activities and upgrades.
- SKA Organisation activities in the “operations” budget such as maintenance and repair of accepted products, including those in the construction period.
- Adopting or adapting hosting agreement Annex 3 items at both telescope sites.
- Providing hosting agreement Annex 4 items in Australia: Science operations and engineering operations centres (SOC and EOC - both new build or lease) and science processing centre (SPC) (expansion of existing facility) and a new power station - these are subject to negotiation.
- Providing hosting agreement Annex 4 items in South Africa: SOC (new build or lease), EOC (expansion of existing facility) and SPC (new build) - these are subject to negotiation.
• MeerKAT precursor asset value.
• Taxation and duties.

Host country costs are excluded as above but do appear in the WBS and cost book (in the latter as placeholders with nominal 1 Euro values) in order to capture the full scope in planning and in execution, to track associated dependencies. Similarly, a small number of infrastructure-related work packages do deliver functionality in construction but will be paid for as a service via the operations budget: these appear in the WBS but in the costs only as nominal placeholders.

6.2.4 Contract Structure

The topmost contract structure is assumed to take the form of approximately 50 Tier 1 contracts as listed within the procurement section. SKAO will be the client for all Tier 1 contracts. The majority of the Tier 1s are collections of related work packages. The WBS has been designed such that the majority of work packages are mapped to a single contract and dependencies between Tier 1s are minimised. The exception to this is software.

6.2.5 Labour, Travel, and Exchange Rates

Element level costs include items for which the labour amounts were calculated according to local conditions. Most of the planned contracts will be for deliverables and so these are categorized as materials without having the labour element broken out; in cases where the work scope is a professional services contract, the labour elements are broken out to reflect the time and materials estimates. Similarly, for internal SKAO labour, including secondees, the labour estimates are broken down by resource. For these purposes, a set of day rates were calculated for the 3 host countries where SKAO staff will be based, and for contractor software, which is not linked to a particular country. These day rates are modelled using relevant pay benchmark data for June 2020 (in GBP and converted to Euros) and include overheads using the calculators shown. As a guide, currently the specialist rate has been used for Project Managers and Engineers, the Senior Specialist rate for Senior Project Managers and Senior Engineers and the Senior Manager rate for Heads of Group and Directors. These are not fully allocated labour costs so other staff-related costs such as IT on-costs, travel, and training have been added separately in Dash 360 – see Table 8 for the standard rates used there, based on actuals from the end of 2017 in GBP, inflated to 2020 and converted to Euros.

Table 7. Labour calculators.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Working hours per annum</td>
<td>1760</td>
</tr>
<tr>
<td>Working days per annum</td>
<td>220</td>
</tr>
<tr>
<td>SKAO UK overhead rate</td>
<td>0.45</td>
</tr>
<tr>
<td>SKAO AUS overhead rate</td>
<td>0.45</td>
</tr>
<tr>
<td>SKAO RSA overhead rate</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Table 8. Non-labour rates.

<table>
<thead>
<tr>
<th></th>
<th>Cost in Euros</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training cost per person per annum</td>
<td>1,208</td>
</tr>
<tr>
<td>IT on-costs per person per annum</td>
<td>1,208</td>
</tr>
</tbody>
</table>
It was accepted that other staff-related costs such as professional subscriptions vary between different skill groups so these weren’t standardised. Specialist tools including software required by staff were also added separately and not standardised.

In estimating travel costs for SKAO staff, whether for project purposes or training, a set of rates for trips were used based on the known average trip costs for travelling between member countries as at the end of 2017 and inflated to 2020. The rates include economy flights, accommodation, meals and taxis and are based on a trip of up to 5 days (Table 9). We note that the COVID-19 pandemic may have significant consequences for travel estimation; this issue is carried as a risk until more clarity is established on how to update this costing.

<table>
<thead>
<tr>
<th>Trip (TP or TT)</th>
<th>Destinations</th>
<th>Cost in GBP</th>
<th>Cost in Euros</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>Within country or region, e.g., within Europe, within Western Australia, within South Africa</td>
<td>1,000</td>
<td>1,208</td>
</tr>
<tr>
<td>Medium</td>
<td>Between Europe and Canada/South Africa/India/China</td>
<td>2,000</td>
<td>2,416</td>
</tr>
<tr>
<td>Large</td>
<td>Between Europe/South Africa and Australia/New Zealand</td>
<td>3,000</td>
<td>3,624</td>
</tr>
</tbody>
</table>

Table 10. Exchange rates against the Euro (12-month average as of 25th June 2020).

<table>
<thead>
<tr>
<th>Currency</th>
<th>Exchange Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>USD</td>
<td>1.12</td>
</tr>
<tr>
<td>GBP</td>
<td>0.87813</td>
</tr>
<tr>
<td>SEK</td>
<td>10.6589</td>
</tr>
<tr>
<td>AUD</td>
<td>1.6486</td>
</tr>
<tr>
<td>CAD</td>
<td>1.4833</td>
</tr>
<tr>
<td>CNY</td>
<td>7.7749</td>
</tr>
<tr>
<td>INR</td>
<td>80.0292</td>
</tr>
<tr>
<td>NZD</td>
<td>1.7376</td>
</tr>
<tr>
<td>ZAR</td>
<td>17.2495</td>
</tr>
</tbody>
</table>


It is expected that some of the Tier 1 contractors will sub-contract some of the work packages as Tier 2 contracts. A full list of Tier 1 contracts is found in section 10.2.

6.2.6 Cost Summaries

The total project cost for the SKA1 is €1282 M (Jun 2020).

- Table 11 summarises the budgeting information by resource type and cost type. For the resource type categories (labour, non-labour, travel and contingency), it should be noted that the labour category includes only that from SKAO and key professional service contracts, for example software development and System AIV; labour in other areas is generally shown as non-labour. The cost types are construction support, capital cost, and contingency; these data were derived at the work package level, as work packages are of only one type. Capital cost are the main product delivery work packages which will be contracted out.
Table 11. SKA1 Annual budgets by resource type and cost type.

<table>
<thead>
<tr>
<th>Time Phased Cost by Resource Type (Euro)</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
<th>2027</th>
<th>2028</th>
<th>Total (Euro)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labour</td>
<td>6,680,458</td>
<td>32,629,317</td>
<td>34,485,173</td>
<td>37,297,554</td>
<td>40,343,075</td>
<td>41,776,086</td>
<td>40,129,456</td>
<td>17,037,821</td>
<td>250,378,940</td>
</tr>
<tr>
<td>Non-Labour</td>
<td>7,666,066</td>
<td>165,591,072</td>
<td>218,779,857</td>
<td>175,132,027</td>
<td>100,009,267</td>
<td>52,970,777</td>
<td>13,919,803</td>
<td>637,347</td>
<td>734,706,217</td>
</tr>
<tr>
<td>Travel</td>
<td>1,171,360</td>
<td>3,292,407</td>
<td>3,570,392</td>
<td>3,681,954</td>
<td>3,709,391</td>
<td>3,690,066</td>
<td>3,565,068</td>
<td>1,527,618</td>
<td>24,208,257</td>
</tr>
<tr>
<td>Contingency</td>
<td>51,813,845</td>
<td>27,266,376</td>
<td>19,331,904</td>
<td>41,290,144</td>
<td>25,648,085</td>
<td>30,947,249</td>
<td>19,918,504</td>
<td>56,293,114</td>
<td>272,509,221</td>
</tr>
<tr>
<td>Total</td>
<td>67,331,729</td>
<td>228,779,173</td>
<td>276,167,326</td>
<td>257,401,680</td>
<td>169,709,818</td>
<td>129,384,178</td>
<td>77,532,831</td>
<td>75,495,901</td>
<td>1,281,802,635</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time Phased Cost by Cost Type (Euro)</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
<th>2027</th>
<th>2028</th>
<th>Total (Euro)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost</td>
<td>7,832,124</td>
<td>184,345,290</td>
<td>240,109,744</td>
<td>196,865,117</td>
<td>122,318,980</td>
<td>74,929,563</td>
<td>33,954,085</td>
<td>7,539,076</td>
<td>867,893,979</td>
</tr>
<tr>
<td>Contingency</td>
<td>51,813,845</td>
<td>27,266,376</td>
<td>19,331,904</td>
<td>41,290,144</td>
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<td>228,779,172</td>
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<td>257,401,680</td>
<td>169,709,817</td>
<td>129,384,179</td>
<td>77,532,831</td>
<td>75,495,900</td>
<td>1,281,802,635</td>
</tr>
</tbody>
</table>
This information is summarised in Figure 148 below:

- The pie chart shows the breakdown of the total cost estimate by estimating methodology.
- The bar chart shows the total cost estimate by calendar year and by the cost type.
- The line chart shows the cumulative cost by calendar year and by cost type.
- The doughnut chart shows the breakdown of the total cost estimate by cost type.

Figure 148. SKA1 budget breakdowns: Cost by estimate type, time phased cost by cost type, cumulative cost by cost type and cost by cost type.

6.2.7 Commitment Profile

The contracting model is discussed in section 10.3. The information from section 6.3 (baseline schedule) provides the logical schedule for the work activities which must be preceded by the acquisitions of products or services needed for those activities. As such, each contract has a ‘C0’ or anticipated award date which is set by the time required to advertise and select a contractor in order to meet those scheduled dates.

The SKA1 work plan is heavily front-loaded with the C0 award dates for the contracts. As an example, essentially all of the contracts are needed to be both awarded and performed in time for the first realisation of the SKA1-LOW and MID arrays which begin approximately 18 months after the start of construction.

The simplest representation of the commitment profile would therefore be to support the full contract prices on each of their C0 dates. In this model, 75% of the funding (approximately €800 M) would need to be available to the Observatory for deployment in the early (12 months) period of acquisition following the start of construction. We note this is not a viable funding plan and so a staged or constrained approach to the commitment profile is being planned.
In this model, we work within the contracting structure to secure the full production run of supplies or services for each work package but include an appropriate ‘termination for convenience’ clause and potentially additional stage gates, to enable management of those elements to adjust to a potentially dynamic funding situation. The anticipated commitment profile with these constraints is illustrated in Figure 149. This profile represents the quantified commitments anticipated toward and around the key Array Assembly milestones in the project delivery (see section 9.2 for details). We note that the flexibility of slowing a planned delivery due to shortfalls in anticipated funding will potentially increase the cost of each Tier 1 (and underlying Tier 2) contract to which it is applied. The profiles below do not yet impose the additional costs of these conditions (from the contractor perspective these have additional cost risk for them) as they will be negotiated individually.

The cumulative total profile indicates the minimum funding profile, with as yet undetermined costs imposed due to the premium/fees required for the staging/flexibility to be added, which is required to enable the project to advance according to this plan; without this funding profile, the project will incur immediate delays and consequent costs.
Figure 149. SKA1 commitment profile based on staged Tier 1 deliveries (cumulative T1 value), the anticipated risk contingency burn profile (SKARR cumulative), the construction support cumulative profile and the totals of each of these (cumulative total).
6.3 Baseline Schedule

This section presents the schedule estimate for the construction of SKA1 by WBS. The schedule is based on the integration work done for the adoption process.

This schedule covers the construction phase of the project from T0, start of SKA1 construction, to the end of construction (T0 + 6.5 years + 18 months of schedule contingency).

The end of construction has been defined as successful operations readiness review.

6.3.1 Level 1 Milestones and Critical Path

A tabular view of the high-level schedule illustrated by the Level 1 milestones is shown below. Each of the milestone dates indicates the completion date for that activity. The schedule contingency is represented as an additional level 1 milestone (end of construction) 18 months after the completion of the currently scheduled activities (based on statistical modelling of the best-case, worst-case and most likely duration scenarios for the integrated project schedule).

Table 12. Level 1 milestone completion dates.

<table>
<thead>
<tr>
<th>Key project milestone</th>
<th>Identifier</th>
<th>LOW Telescope</th>
<th>MID Telescope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start of construction</td>
<td>T0</td>
<td>1st July 2021</td>
<td>1st July 2021</td>
</tr>
<tr>
<td>Earliest start of major contracts</td>
<td>C0</td>
<td>August 2021</td>
<td>August 2021</td>
</tr>
<tr>
<td>Array Assembly 0.5 finish</td>
<td>AA0.5</td>
<td>February 2024</td>
<td>March 2024</td>
</tr>
<tr>
<td>Array Assembly 1 finish</td>
<td>AA1</td>
<td>February 2025</td>
<td>February 2025</td>
</tr>
<tr>
<td>Array Assembly 2 finish</td>
<td>AA2</td>
<td>February 2026</td>
<td>December 2025</td>
</tr>
<tr>
<td>Array Assembly 3 finish</td>
<td>AA3</td>
<td>January 2027</td>
<td>September 2026</td>
</tr>
<tr>
<td>Array Assembly 4 finish</td>
<td>AA4</td>
<td>November 2027</td>
<td>June 2027</td>
</tr>
<tr>
<td>Operations Readiness Review</td>
<td>ORR</td>
<td>January 2028</td>
<td>December 2027</td>
</tr>
<tr>
<td>End of Construction</td>
<td></td>
<td>July 2029</td>
<td>July 2029</td>
</tr>
</tbody>
</table>

6.3.1.1 Milestones for the End of each AA - MID

Milestones for science commissioning, expected to be achieved within 1 month of the engineering milestones are defined as follows:

- AA0.5
  - 4-dish array
    - Basic array element calibration demonstrated
    - Observation calibration demonstrated
    - Basic imaging
    - Data reduction expected to be off-line. No science verification in AA0.5.
• **AA1**  
  o 8-dish array  
    ▪ Basic array element calibration demonstrated  
    ▪ Observation calibration demonstrated  
    ▪ Basic imaging  
    ▪ Data reduction expected to be off-line. No science verification in AA1.

• **AA2**  
  o 64-dish array; baselines mostly <20 km  
    ▪ Demonstrate ability to form at least one, steerable tied-array beam  
    ▪ Show that known pulsars can be detected and timed  
    ▪ Demonstrate imaging of a quality comparable to that of Extended MeerKAT in bands 1 and 2  
    ▪ Refinement of calibration  
    ▪ Demonstrate ability to operate two independent subarrays  
    ▪ Data reduction expected to be off-line.  
    ▪ Demonstrations performed as science verification observations; data released publicly.

• **AA3**  
  o 133-dish array, including long baselines  
    ▪ Demonstrate imaging including at least one zoom mode.  
    ▪ Demonstrate simultaneous use of three subarrays  
    ▪ Complete initial calibrator survey.  
    ▪ Data reduction by SDP operational system pipeline.

• **AA4/Operations readiness review**  
  o Full MID array including MeerKAT dishes  
    ▪ Demonstrate imaging in bands 1 and 2 and with SKA1 dishes in band 5.  
    ▪ Demonstrate pulsar search, pulsar timing, and dynamic spectrum with multiple beams.  
    ▪ Demonstrate commensal imaging and transient search.  
    ▪ Demonstrate full end-to-end operation, including data processing at full scale and data delivery to regional centres.

6.3.1.2 **Milestones for the End of each AA – LOW**

Milestones for science commissioning, expected to be achieved within 1 month of the engineering milestones are defined as follows:

• **AA0.5**  
  o 6-station array  
    ▪ Basic array element calibration demonstrated  
    ▪ Observation calibration demonstrated  
    ▪ Imaging validated by comparison with results from MWA  
    ▪ Data reduction expected to be offline
• AA1
  o 18-station array
    ▪ Basic array element calibration demonstrated
    ▪ Observation calibration demonstrated
    ▪ Imaging validated by comparison with results from MWA
    ▪ Data reduction expected to be offline

• AA2
  o 64 stations
    ▪ Demonstrate ability to form multiple beams
    ▪ Demonstrate timing of pulsars
    ▪ Demonstrate imaging
    ▪ Refinement of array element and observation calibration
    ▪ Demonstrate ability to operate two independent subarrays
    ▪ Data reduction expected to be offline
    ▪ Demonstrations performed as science verification observations; data released publicly

• AA3
  o 256-station array including long baselines
    ▪ Demonstrate imaging
    ▪ Demonstrate simultaneous use of three subarrays
    ▪ Deliver initial Global Sky Model
    ▪ Data reduction by SDP operational system pipeline

• AA4/Operations readiness review
  o Full LOW array
    ▪ Demonstrate imaging with optimised direction-dependent calibration
    ▪ Demonstrate pulsar search, pulsar timing and dynamic spectrum with multiple beams
    ▪ Demonstrate commensal imaging and transient search
    ▪ Demonstrate full end-to-end operation, including data processing at full scale and data delivery to regional centres

6.3.2 Integrated Project Schedule

The integrated project schedule is maintained in Primavera (see SKA-TEL-SKO-0001200 SKA1 Project Management Controls System). A snapshot of the projected schedule at the start of construction is provided in SKA-TEL-SKO-0001103 SKA1 Integrated Project Schedule.
7 Project Engineering

This section summarises the planning and methodology (processes, procedures) and overall approach for the delivery of the engineering project scope to the observatory (fully described in SKA-TEL-SKO-0001201 SKA1 Engineering Management Plan). In other words, this plan defines the “what” or which processes and methodology are in place in the SKAO during the construction phase. The higher-level organisational aspects including configuration management, scope/requirements management etc. are referenced here but covered in detail in SKA-TEL-SKO-0001200 SKA1 Project Management Controls System [RD11]. It is part of the federation of documents within the Project Execution Plan [AD3].

How these processes are implemented (the “how”) will largely be determined by the “builder” of a system/sub-system/product and the relevant development life cycle methodology (within the scope of what they are building). For example:

- SKAO will build the SKA software by acquiring effort to do software development using professional services contracts. This will closely resemble an “in house” development, and therefore SKAO will define how these processes are implemented in the context of SAFe (the chosen development life cycle methodology);
- the dish contractor will build the SKA dishes and therefore the dish contractor will define how these processes are implemented in the context of the chosen development life cycle methodology.

Where the “builder” is a 3rd party, the implementation of these processes is reviewed, negotiated and accepted by SKAO as part of the acquisition process described below.

7.1 Project Engineering Processes

The engineering processes planned for the delivery of SKA1 incorporates best practices from Lean and Agile product development. This is made very explicit in the adoption of the SAFe framework in the software area, but the underlying principles are applied to the larger set of engineering areas.

The processes follow the typical representation as per IEC15288 life cycle processes, but in this document, only the processes that will be managed by the engineering and software groups are shown. Some other processes will see the support of the engineering group, but where they belong to different departments of the SKAO organization, the reference to the correct document is presented.

7.2 Technical Management Processes

7.2.1 Risk Management Process

SKA1 project management control system defines the project level risk management plan including the maintenance and regular (monthly) review of the project risk register.

The project needed an ability to explore the emergence of new risks (aspect of risk identification) as well as direct work on identified risks for which additional technical analysis is required. The result is a system process called the telescope issue management system which has been implemented as a Jira project for tracking these issues. The outcomes can be the proposal of new risks or mitigations for the project risk register or the update of risks within the project risk register.

The SAFe framework adopts a standard ROAM based approach to risk, where risks are logged during PI planning and continuously assessed during the program increment. These risks are the
decomposition/detailing of the high-level risks in the project risk register. ROAM is also implemented as a Jira project to enable tracking and linkages between the various systems.

7.2.2 Configuration Management Process

The engineering processes adopt and rely upon the configuration management process described in [AD3]. This process encompasses not only document configuration management but also the management of software, engineering models, and physical items that will be used throughout the project life cycle. The SKAO will provide a central repository for the configured items through the configuration management office, as part of the assurance department.

Baselines of the system configuration will be defined as a minimum for the following events:

- Development baseline at system CDR.
- Design baseline for Construction Proposal.
- Baseline for sub-systems that are manufactured, i.e., dish, correlator hardware, etc.
- System-level baseline at the end of each array assembly activity.

While the software and firmware development and deployment effort will form a continuous flow of changes and it will be carried out with the common cadence provided by the SAFe heartbeat of team sprints and solution PIs, the release process can be decoupled from this timeline.

Software will be released and versioned according to a semantic versioning scheme. Software products will not be released and versioned as a whole across the project, but different software components will be released according to independent life cycles.

In particular, it will be possible to have a view of the software currently deployed in each production environment at any given point in time with the associated versions. This capability can be used to realise a baseline of the software system. All software releases will be traceable to an element of the PBS at the appropriate level, most likely grouping different software components with L3 and L2 elements of the PBS.

A common nomenclature will be adopted for software releases and their tracking in the configuration management system.

7.2.3 Information Management Process

The project will manage the information held on the project in a variety of ways, depending on the type and nature of the information. The following will be managed:

<table>
<thead>
<tr>
<th>Table 13. Information to be managed.</th>
</tr>
</thead>
<tbody>
<tr>
<td>System requirements</td>
</tr>
<tr>
<td>Formal project documents &amp; artefacts</td>
</tr>
<tr>
<td>PMCS artefacts</td>
</tr>
<tr>
<td>Architecture documentation</td>
</tr>
<tr>
<td>Design artefacts &amp; documentation</td>
</tr>
</tbody>
</table>
A test management platform will be centrally provided and managed by SKAO. Contractors and builders will make use of this platform to report and document the testing activity.

There will be times in the life cycle of the project where information must be shared among a larger group (e.g., during reviews). SKAO will manage the repositories and the authorisation so that the larger group may access the required material in time. If there is a specific need with a limited duration, authorisations can be withdrawn as per plan. For example, for external or internal reviews SKAO will grant access to Confluence, Dropbox, JIRA and Jama.

### 7.2.4 Measurement Process

The main KPIs to be monitored for engineering artefacts are:

- Budget maturity levels
- System Readiness level

The verification control document informs the status of the system readiness, which ultimately informs the maturity of the budgets and therefore of the main performance metric. The SAFe process will make available a series of quality metrics for all software and firmware products and development processes. Other metrics will be developed as leading indicators of customer value during the SKA1 development process.

### 7.2.5 Quality Assurance Process

The SKA product quality assurance plan (PQA) defines product quality assurance requirements and management activities to be performed during the SKA1 construction phase. All contractors shall respond to quality requirements defined in the PQA with a quality plan.

The PQA describes how products developed using the SAFe framework will be constructed in a continuous and iterative way, and also describes how the SAFe framework contributes to the implementation of quality requirements.
7.3 Technical Processes

In modern scientific complex projects, it is very difficult to disentangle the requirements, the architecture, and the design processes, or indeed any of the technical processes. Notably, the technical processes are happening concurrently and iteratively for the whole life cycle of the project.

7.3.1 System Requirements

The SKA has brought together requirements statements into a document and database referred to as the SKA1 L1 system requirements (Rev 12; SyRD); this set was baselined at the system CDR and updated. To change any of these requirements, a change request must be approved by the SKAO project. The correct adoption of this set, including the organisational standard, will be the contractual binding set that will define the construction.

The L1 requirements are baselined at system CDR. These requirements are the base to derive the technical specifications that will be built during the preparation for tenders and will be the base for Tier 1 contracts. For this document, the Tier1 level is synonymous of L2. There is a further down level of contracts, the Tier2, managed by the Tier 1 contractors, for the scope of this document Tier2 is synonymous of L3. Any changes during contract execution will be managed through change control. In addition, the traceability of the requirements will always be maintained and managed through the Jama tool.

The invocation of standards in the SKA, including both industrial and SKA standards, will be explicit with regard to the completeness of compliance, detailing the clauses that are not complied with where necessary. SKA standards will be developed and subsequently treated as parent documents, which means that they appear in the specification tree, and are applicable document for Tier1 contracts.

7.3.2 Architecture Definition Process

The architecture consists of elements (the parts that compose the structures of the architecture, i.e., components, products, modules, functions, data, etc.), relations among the elements, and important properties of both.

Architecture is not necessarily concerned with all requirements, but rather only with those that drive the architecture itself. On the other hand, the design definition process takes into account all the requirements and is driven by requirements that have been vetted through the architecture and more detailed analyses of feasibility. An effective architecture is as design-agnostic as possible to allow for maximum flexibility in the design trade space.

The architecture for the SKA1 system (including sub-systems) has been designed and baselined at the system CDR. Although the majority of the architecture design activity has been completed at system CDR, the architecture definition process will continue to be used during the life cycle of the project as things change.

7.3.3 System Budget Analysis

The development of the system budgets is an iterative process where the budget allocations are used to derive low-level requirements that are then verified through design, analysis and verification in the construction phase. If the budget allocation requirement is found to be non-compliant or overly conservative during the design or verification process, the budget is rebalanced, and the process repeated to meet the system-level requirements. The TDTs will manage and will keep the budgets updated in order
to capture the most updated information and manage margin internally in the budget. To do that a budget control figure is used.

- **LEVEL 1** requirement: The contribution is based on the requirement that has been allocated to describe that specific property. This is the entry point to generate the first simulation of the assessment or of the budget allocation.
- **LEVEL 2** Draft analysis: The contribution has been verified by analysis, but the analysis is not completed yet and it is in draft. More work is expected to refine the contribution.
- **LEVEL 3** Verified by analysis: The verification by analysis has been completed and the analysis work is sound. This is the level expected for CDR where a verification by analysis of the specific requirement is requested. The analysis can be fed also by measurement of prototypes, engineering breadboard, or demonstrators that can support a more reliable evidence.
- **LEVEL 4** Measurement: if possible (it is not always the case) the contributor is measured by a dedicated test. The HW/SW used for this test must be in "form and fit" configuration. This is the latest level and the most preferable option.

The final output of the budget work is the budget maturity table. An example of this table is shown below:

**Table 14. Budget maturity table.**

<table>
<thead>
<tr>
<th>Product</th>
<th>Allocation Value</th>
<th>Margin</th>
<th>Actual Value (Analysis, Test)</th>
<th>Budget Control Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product #1</td>
<td>20</td>
<td>± 10%</td>
<td>22</td>
<td>2 (Analysis)</td>
</tr>
<tr>
<td>Product #2</td>
<td>30</td>
<td>± 10%</td>
<td>28</td>
<td>4 (Test Available)</td>
</tr>
<tr>
<td>Product #3</td>
<td>40</td>
<td>± 10%</td>
<td>NA</td>
<td>1 (Only Allocation is Available)</td>
</tr>
</tbody>
</table>

The responsibility to compile and update different components of the budget can be assigned to different parties to manage. In this case, the responsible party will inform the TDT of any change in the budget.

The concept of maturity is essential to estimate the level of the system readiness level. The lower the maturity level is, the bigger the margin (and vice versa).

The budget document and the budget maturity table are live documents. They shall be updated whenever a more precise analysis or test is conducted on the specific product. The budget documents will be maintained up to site integration and test by the TDTs.
7.3.4 Implementation process

The implementation process is managed entirely by the PDTs. Each PDT is responsible for the delivery of a number of sub-systems (in relation to the number of contracts the PDT is managing). The PDT itself will follow the delivery in accordance with the quality assurance plan as described in the Quality Assurance Process.

A completely virtual software test environment will be developed to test full system integration and perform system-level demos before hardware is available. Development teams will have access to the common testing harness to define and perform tests in different environments.

Software development practices will be defined and maintained in more detail, with reference to specific technologies and programming languages, as part of the SKA developer portal\(^{51}\) under the supervision of the SKA Software Quality Engineer and the SKAO staff collaborating with the SAFe solution and program level.

7.3.5 Integration process

It is difficult to separate the integration process from the verification process, especially in complex projects. In the SKA environment integration does not only mean the integration of two sub-systems (e.g., the feed system in the antenna) but also the integration of SW and FW in a sub-system. In the SKA definition, the integration is done also at product level, addressing this particular concern.

During this process of continuous integration, parts involving the ITF, features will be accepted as done, according to the “definition of done”, only after being demonstrated as part of the integrated system. System demonstrations will happen regularly during the development lifecycle, possibly occurring every

\(^{51}\) https://developer.skatelescope.org
development iteration. This will be the moment where a new feature can be demonstrated as part of the working system. PI demonstrations will happen for every program increment, demonstrating the larger development of the system in an integrated way to all relevant stakeholders.

The responsibility of integrating a new module or feature into the system is of the team developing the software. A dedicated system team will support this effort aiding the provisioning of integration environments and providing a central infrastructure used to manage integration tests.

7.3.6 Verification process

Large scale radio-astronomy technology, at the level of the system, is immature and complex. This means that some high-level requirements are impossible to verify with certainty until the full system exists in an integrated form. It is critical to plan for as much design qualification as possible at as low a level of integration as is appropriate – this means that design qualification takes place incrementally and partially. In this context, partial qualification may involve the use of simulators or emulators. Where products are developed in element work-packages managed by consortia, and where design qualification requires integration with products from other elements, careful planning and the judicious use of simulators and emulators will retire risk as early as possible. Plans may include the integrated testing of subsets of interfacing hardware and software at an early stage, away from the telescope sites. As per the integration process, the PSI can provide support for the verification at early stages.

The two basic principles are:

- The preferable verification methodology is test (This means that we want to test early).
- The test shall be repeated. (This means we want to test often).

These two basic principles are fundamental to the SKA verification process and are one of the main advantages of the SAFe methodology and the test-driven development (TDD) and behaviour-driven development (BDD) processes, wherein short we define the tests and we develop the code to pass that test, continuously refactoring the source code in iterative cycles.

There are different levels of verification and in some instances, verification can be very formal and explicitly requested according to the contracts. As a general rule for Tier1 contracts, we can foresee the process as set out below.

### Inputs
- SKA Requirement specifications
- SKA Verification Plan
- SKA-specific test descriptions

### Process
- Verification

### Output
- Tier 1 VCD
- Tier 1 Verification Plan
- Tier 1 Verification Reports
- NCR, RFW, ECPs

![Figure 151. Verification process.](image)

The verification needs to be requested by SKAO to the contractors is not always completely defined by a requirement specification. In some cases, SKAO will request the execution of specific verification tests, or even more detailed test procedures, to be executed in a very specific way. This is generally done because
of the lessons learnt during the pre-construction phase. In other words, the entire process is not based only on requirements but also on the knowledge resident in the community and SKAO.

Through the continuous improvement process and supported by the NEC4 contracts, continuous refinement of these plans within the verification process can be foreseen. The tailoring process will be used and the PDTs (supported by the TDTs and by the AIV Lead Engineer) will manage the entire process, which will be iterative and recursive.

7.3.7 Verification Process at Tier 1 Level

During the execution of the Tier 1 contracts, there will be different points where verification is requested. It is very difficult to describe a flow that covers all the contracts’ approaches in one single picture, therefore once again the tailoring process will be heavily used in the PDTs to drive the verification process to the SKA quality standards.

The SKAO will be involved in many if not all the verification steps. Quality Managers, PDT Engineers, and AIV Engineers will follow especially the test readiness review (TRR) and the test review board (TRB) when results will be assessed. It is foreseen that also Domain Specialists can be involved in specific tests (e.g., the RFI Domain Specialist during RFI tests).

7.3.8 Verification at System Level

The system-level verification is managed entirely by the SKAO. The plans are described in the AIV plan and in the roll-out plan which describes the full processes. The flow and the work are described in the roll-out and verification plans.

7.3.9 SW Verification Program

One of the main principles of the SAFe methodology is that the technical processes are recursive and iterative, but they are repeated in a time scale that is very short (2 weeks), which is defined as an iteration or sprint. This agility allows the SW development to be continuously tested, at a minimum every two weeks. This concept is aligned with the principle expressed in the introduction of the SKA verification process, that is, testing early and testing often:

- The preferable verification methodology is to test (this means that we want to test early).
- The test shall be performed as soon as possible (this means we want to test often).

The continuous integration process shown in the following picture includes a test of the SW. Obviously, this test can vary in terms of capabilities tested in relation to the moment the test is executed in the life cycle of the project.
All the technical processes are always active, and this iteration is repeated every two weeks for SW. The verification plan is driven by the availability of the HW (at PSI, at ITF, and eventually on-site), and this availability can be seen as milestones in the project. Since the whole project is aligned to the 3 months SAFe cadence, the roadmap can be derived by examining what is expected by the future milestones and what has been learned during the previous verification activity. The composition of these two factors will plan the future activity for the subsequent PI and will inform the SW team on what the telescope needs in terms of capabilities.

The workflow is guaranteed because the SW architect is a member of each TDT, and the SW engineering discipline is always present in the integrated teams.

7.3.10 Reliability

The SKA failure recording analysis and corrective action system (FRACAS) will be operational from the start of construction to capture failure data and to assess the diagnostic performance. The engineering management system (EMS) will interface with TM for equipment maintenance-related operating parameter and status information. Telescope FMECA data will be continuously updated in the EMS, as references for fault-finding, status aggregation, and condition-based maintenance.

Reliability test candidates will be identified, and special reliability and accelerated life test will be done on selected items. These tests will be set up to identify possible weak areas and to ensure reliability growth.

All problems identified during the construction and operational phases will be reported, logged, and tracked by means of an operational problem reporting and tracking system (PRTS) as a measure to effectively assign and track problem resolution. The PRTS shall provide in-progress tracking information for open issues and shall provide access to process records of all open and closed-out issues.

The maintenance management system (MMS) will support the operations in accepting maintenance-related issues assigned to the maintenance teams. The maintenance management function will provide problem resolution maintenance in-progress and close-out status to the related problems.

Problems related to telescope failures will be assessed for root cause and corrective action requirements, making use of the FRACAS. The PRTS, MMS, and FRACAS form part of the engineering management system.


8 Computing

This section covers the observatory computing IT and security policies and processes during construction. The software development planning information is contained within the engineering management plan.

8.1 Cyber Security

The SKA Observatory has chosen to adopt an Information security management system (ISMS) based on the ISO 27001:2013 standard. The ISO 27001:2013 standard was chosen as it integrates information security throughout all aspects of the organisation. It outlines the need to attain management support, perform risk assessments, and lists the controls that should be implemented. As the SKA Observatory will not seek formal ISO 27001 certification, it can determine which controls to implement, based on legislative requirements and its risk appetite.

The policy documents that comprise the SKA Observatory ISMS are largely complete and are under review but waiting for the establishment of the Observatory before being formally approved and implemented.

Figure 153 illustrates the current ISMS document structure and the continuous improvement lifecycle.

![SKA Observatory Information Security Management System Document Structure](image)

Figure 153. The SKA ISMS document structure.
There are three high-level policy documents that define the security governance of SKA Observatory. These documents are explained below:

- Information security policy – this document states that an information security policy is in place, provides a high-level overview of the security practices and states that security policies must be adhered to.
- Scope – this document defines what is bound by the security policies. This includes physical SKA Observatory assets and the information contained on them, plus SKA Observatory information stored by third parties such as that hosted in the cloud or at regional centres.
- Statement of applicability – this document lists all controls defined in the ISO 27001:2013 standard and states which controls will be implemented by the SKA Observatory.

Individual policy documents have been created, based on the controls listed within the statement of applicability document and define how these controls must be executed.

As the SKA Observatory transitions to an intergovernmental organisation, it is envisaged that these policy documents will be reviewed and approved according to the Council’s schedule of delegation.

### 8.2 Code Development

Software and firmware development processes, along with data management aspects are described in *SKA-TEL-SKO-0001201 Engineering Management Plan.*
9 Verification and Commissioning

9.1 Introduction

This section outlines the processes of science commissioning and science verification. These are the activities required to perform astronomical tests of the SKA prior to the start of scheduled observing. Planning of the activities of assembly, integration, and verification (AIV) are documented in detail in the documents listed below. The relationships between AIV, science commissioning and science verification are close and important, as are the interactions between the corresponding teams. These interfaces are described here.

9.1.1 Core Documentation

The planning for systems integration, verification, and commissioning, including acceptance procedures is covered under a set of key documents, the core of which are represented below:

- SKA-TEL-SKO-0001201 SKA1 Project Engineering Management Plan
- SKA-TEL-SKO-0001350 SKA1 Science Commissioning and Verification Plan
- SKA-TEL-AIV-4430001-SE-DIVP-PLN-Rev2-Integration and Verification Plan for SKA1 Low
- SKA-TEL-AIV-2430001-SE-DIVP-PLN-Rev2-Integration and Verification Plan for SKA1 Mid

9.1.2 Overview

The classical (but oversimplified) view of the respective roles of science verification, AIV and product contractors in system verification for the SKA is as follows:

- The science verification team validates the user requirements, which are listed in the level-0 (science) requirements and the operations plan.
- The system AIV team verifies the (Level-1) engineering requirements.
- The product contractors verify the lower-level requirements (Level-2 and below).

In practice, however, much of the work is in what we call “commissioning”. In the SKA context, commissioning is the process that includes all activities necessary to arrive at a working end-to-end system. These activities include setting-to-work, integration testing, system testing, as well as the execution and analysis of test observations, with the aim of debugging the overall system. This is a collaborative, interdisciplinary activity, requiring skills in astronomy/interferometry, signal processing, control and data analysis software, as well as hardware engineering. It is almost always a highly iterative process, usually involving several repetitions of each test, and is a necessary prerequisite for system verification. "science commissioning" is the specific subset of commissioning that requires the extensive use and interpretation of astronomical observations and therefore a specific skill set. For SKA1, there is a distinct science commissioning team.

In practice, however, the jobs of the science commissioning and AIV teams are not cleanly delineated. Science commissioning includes a significant amount of level-1 requirement verification because many of the level-1 requirements are actually science requirements, and some can only be fully tested after the end of construction. Conversely, the AIV team will use science observations in their tests. The two teams must therefore work very closely together, as described further below.
Science verification will be carried out as a set of end-to-end tests of individual observing modes, from proposal submission to data delivery, essentially to demonstrate that the SKA can provide high-quality science to its users (section 9.4). It, therefore, follows science commissioning and is executed by a different team, again in close collaboration.

9.1.3 Definitions

Here, we summarise the definitions introduced above and used in the remainder of this section.

**Array assembly (AA):** A package of hardware and software, characterised by the number of dishes/stations included in the array and by its capability as an end-to-end telescope system with predefined functionality.

**Assembly (A).** The activities required to physically establish a product of the SKA1 telescope system on-site. This will likely include connecting interfaces to other systems such as electrical, computer, or security systems, and may include software interfaces as well. The installed product may be verified against simulators and/or emulators.

**Commissioning (C):** All activities necessary to arrive at a working end-to-end system that can be used to perform system verification.

**Integration (I):** The activities required to incorporate a product into the SKA1 telescope system. Any simulators and/or emulators that might have been used during the installation process are replaced with real hardware and/or software, and the associated tests repeated, perhaps in abbreviated form.

**Observing mode:** A distinct type of observation applicable to a range of astronomical targets.

**Science commissioning (SC):** The subset of commissioning which requires specification, execution, and analysis of astronomical observations.

**Science verification (SV):** All activities that are executed to verify the telescope system against its Level-0 Requirements, i.e., to ensure that the telescope system meets the needs of the science and operational users.

**Verification (V):** All activities that are executed to formally verify the telescope system against its level-1 requirements.

9.1.4 AIV, Commissioning, and Science Verification: Process

A simple view of the AIVCSVO (= Assembly, Integration, Verification, Commissioning, Science Verification and Operations handover) process is a linear sequence for the entire system:

AIV › commissioning › science verification › operations.

In principle, there might only be one cycle of commissioning. In fact, there will be many iterative cycles of AIV, commissioning, and SV throughout the construction, and phases will overlap. The need for planning flexibility means that a more detailed sequence of events cannot be specified here.
<table>
<thead>
<tr>
<th>Description</th>
<th>Mission Assurance (SKAO)</th>
<th>Product Supplier (incl. SW products)</th>
<th>Integrated Team Lead = decision on Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance at IF of delivered Products, through checking of supplier documents and witnessing their repeat tests, where needed. This also applies to a new build of SW arriving.</td>
<td>Inspect arriving product and documents. Witness acceptance tests.</td>
<td>Provide Product &amp; documents according to contract. Provide evidence of Product compliance to requirements.</td>
<td></td>
</tr>
<tr>
<td>Installation of the Product in the IF or Telescope. Checking workmanship and installation correctness.</td>
<td>Interface inspections to confirm workmanship and installation correctness.</td>
<td>Install product into required location and provide necessary inspection reports.</td>
<td></td>
</tr>
<tr>
<td>AIGC</td>
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</tbody>
</table>

**Figure 154. Integrated team for AIV, science commissioning, and science verification.**
The context for AIV, science commissioning and verification teams is summarised in Figure 154. All are elements of integrated product teams (IPT) for LOW and MID (located in the respective host countries), each of which has several distinct elements:

1. **Engineering (hardware and software)**
   These are Domain Specialists (HW and SW) and can be SKAO or contractors’ personnel. They will follow and support specific tests.

2. **Verification**
   Typically, Systems Engineers with verification experience. This team will use the resources presented in 9.5.1.

3. **Science commissioning**
   These are the Telescope Experts and Scientists that can analyse the data and support the IPT Lead as requested. This team will use the resources presented in 9.5.2.

4. **Science Verification**
   Astronomers from operations who carry out and analyse science verification observations.

5. **Operations Support**
   Staff from operations who will operate the telescope to support testing.

Assurance will independently monitor the execution of the full AIVCSVO

The Engineering Lead leads the coordination of work on-site on a weekly basis and that there are also daily planning/fault triage meetings with delegated responsibilities. Longer-term planning is expected to be done on a three-monthly cycle, synchronised with SAFe programme increments.

![Figure 155. Integrated team for AIV (IPT).](image-url)

The IPT Lead will change during the different phases of the verification, commissioning, and science verification as indicated in Figure 155. The responsibilities of the engineering, science commissioning, and operations team leaders at different stages of the process are as follows:

1. **Engineering Lead** (hardware, software, verification, assurance and systems engineering; AIV) is the authority for product acceptance, installation, integration and engineering commissioning/verification, co-leads science commissioning, and supports science verification.

2. **Science Commissioning Lead** supports product acceptance and installation; co-leads engineering commissioning; is the authority for science commissioning and co-leads science verification.
3. **Science Operations Lead** supports product acceptance, installation, integration, engineering commissioning/verification and science commissioning and is the authority for science verification.

9.1.5 **Science Commissioning and Verification**

Although the skills needed for science commissioning and science verification overlap, the roles are distinct. Science verification is in many ways a rehearsal for normal operations and is therefore logically performed by the operations group. The respective roles are summarised in Table 15 and Table 16.

**Table 15. Responsibilities during science commissioning.**

<table>
<thead>
<tr>
<th>Commissioning Scientist</th>
<th>Operations Scientist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead integration testing</td>
<td>Support astronomical observations</td>
</tr>
<tr>
<td>Lead system testing</td>
<td>Review and edit operational documentation</td>
</tr>
<tr>
<td>Execute and analyse test science observations with the aim of debugging the system</td>
<td></td>
</tr>
<tr>
<td>Optimise the system efficiency</td>
<td></td>
</tr>
<tr>
<td>Develop initial documentation</td>
<td></td>
</tr>
<tr>
<td>Train Operations Scientists</td>
<td></td>
</tr>
</tbody>
</table>

**Table 16: Responsibilities during science verification (following successful commissioning).**

<table>
<thead>
<tr>
<th>Commissioning Scientist</th>
<th>Operations (SV) Scientist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify and resolve faults</td>
<td>Develop and pre-select SV projects for defined observing models with the aid of an outside advisory group</td>
</tr>
<tr>
<td>Optimise observing modes</td>
<td>Prepare, verify and execute scheduling blocks</td>
</tr>
<tr>
<td></td>
<td>Maintain SV documentation (e.g., web pages) which describe all plans and activities including availability of observations</td>
</tr>
<tr>
<td></td>
<td>Reduce (or monitor pipeline reduction of) data and perform quality checks</td>
</tr>
<tr>
<td></td>
<td>Deliver the data to Science Data Centres (and individual users)</td>
</tr>
<tr>
<td></td>
<td>Provide information about and assist users in exploitation of the data</td>
</tr>
</tbody>
</table>

9.1.6 **Operations and Technical Support**

Operator and technical support are required for science commissioning. Depending on the time available, either 1 or 2 operator shifts per day will be required on weekdays and 3 shifts per day on weekends (working potentially full 24-hour periods). On-call technical and software support are also needed, from some combination of AIV, software, and operations teams.
9.2 Assembly, Integration and Verification

9.2.1 Responsibilities

The responsibilities of the AIV team include:

- Coordination and execution of integration and verification activities on-site and at the Integration test facility.
- Assistance with site logistics and site management.
- Assistance provided to the SKAO in establishing and maintaining the system configuration.
- Assistance with the Product Hand-Over Process (under the authority of the SKAO).
- Integration of level-2 products into the SKA1 telescope system.
- Resolution of level-1 integration issues.
- Development of detailed verification test procedures.
- Performance of verification testing and reviews.
- Support of the science commissioning and verification teams.
- Verification of the integration of MeerKAT into SKA1-MID.

9.2.2 Roll-Out Overview

High-level AIV roll-out plans have been developed for each of:

- SKA1-MID (including MeerKAT integration).
- SKA1-LOW.

These describe the sequential assembly of new hardware, firmware, and software. For both arrays, the roll-out plans are divided into five phases, namely array assemblies 0.5 though to 4, already introduced in section 6.3. Their capabilities are listed in more detail in Table 17 and Table 18, below.

In addition, the concept of an integration test facility (ITF) has been introduced. This tests as much as possible of the system in a laboratory environment.

The array assemblies (with the exception of AA 0.5) are construction phases on-site of roughly equal duration. Each array assembly is characterised by a number of dishes (MID) or stations (LOW), the key functionalities of the array and the resulting scientific capability. Science commissioning and verification are tied to the roll-out plans, as they depend on the capabilities thus deployed. The schedule for the array assemblies is given in section 6.3.

The official end of construction, at the end of AA4, is defined by an operational readiness review (ORR).

9.2.3 Preparation for System AIV

The integration and verification processes start in the facility where products are tested in a stand-alone configuration before the factory acceptance tests are executed and continue through several different phases of integration even before reaching the site.

There are different times where personnel of the IPT will be involved:

- Qualification tests of the products (i.e., environmental tests).
- Integration test of prototypes (i.e., through the prototype system integration).
- Integration of production hardware in the ITF.
- Factory acceptance tests.
- Site acceptance tests.
For each event, the IPT, along with Assurance, will be involved with different roles. This activity is paramount to prepare and train the AIV team on the performance, functionality, and operability of the products.

9.2.4 Integration Test Facility (ITF)

The System ITF is a laboratory environment designed to test as much of the system as possible before assembly on-site, with the aim of reducing risk during the site deployment. It will not be possible or convenient to test all the products in the ITF before shipment, for instance, the activities of the ITF will not include the dish structure or a LOW station, but the ITF will test most of the interfaces before related products will reach the site. To the stable and controlled laboratory environment of such a facility, verification and qualification testing will provide test results that are more consistent and reliable. Such a facility also enables early feedback and interfaces between products can be tested against real hardware and not against simulators or emulators. The principal aims of the ITF are:

- System-level design qualification
- Product development
- Troubleshooting
- Testing and debugging of interfaces
- Introduction of standard operating procedures, such as the product hand-over process
- Functional and performance testing
- Product qualification and verification against level-2 and level-3 requirements
- Signal chain line-up of pre-production items to demonstrate data flow, control and monitoring
- Limited control and monitoring
- Limited interferometric testing
- Quality gate to give manufacturers the go-ahead for full-steam production
- Gain confidence in product performance prior to on-site installation

There will be separate ITFs for SKA1-LOW and MID, located in Geraldton and Cape Town, respectively.

9.2.5 Production Hardware FAT and SAT

Once the production HW is ready to leave the contractor a factory acceptance test is organised. This test will be witnessed by AIV along with assurance. Such a test will also define the procedure to accept the product at the site and it will be based on the experience gained in the ITF. This procedure will be repeated many times during the life cycle of the product: at FAT, at site acceptance test (SAT) and it will be replicated by the AIV team during the first integration of the product in the array. Such step ensures a clear benchmarking of functionality and performance of the product in its final environment before any handover.

---

52 Dish structure interfaces will be tested through the dish prototype system and the LOW station through the AAVS system, so these interfaces are already de-risked elsewhere.
9.2.6 SKA1-MID Roll-out

Table 17. SKA1-MID roll-out plan.

<table>
<thead>
<tr>
<th># Dishes</th>
<th>Frequency Bands</th>
<th>Imaging</th>
<th>Pulsar Timing</th>
<th>Dynamic Spectrum</th>
<th>Pulsar Search</th>
<th>Transient Capture</th>
<th>VLBI</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0.5</td>
<td>4</td>
<td>Band 1</td>
<td>✓</td>
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<td>✓</td>
<td>✓</td>
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<tr>
<td></td>
<td></td>
<td>Band 2</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Band 5:</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>goal on 4</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dishes, but may not be supported by correlator</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td></td>
<td></td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
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<tr>
<td></td>
<td></td>
<td>1k channels</td>
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<td>✓</td>
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<tr>
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<td>✓</td>
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<td></td>
<td>on 64</td>
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</tr>
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<td></td>
<td>6k channels</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Zoom mode</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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</tr>
<tr>
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<td></td>
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<td>✓</td>
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<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>Full Continuum and Spectral Line imaging pipelines</td>
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</tr>
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<td></td>
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<td>✓</td>
<td>✓</td>
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</tr>
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<td>✓</td>
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<td>Real time operation</td>
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</tr>
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<td></td>
<td>Full bandwidth</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
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</tr>
</tbody>
</table>

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9.2.7 SKA1-LOW Roll-Out

Table 18. SKA1-LOW roll-out plan.

<table>
<thead>
<tr>
<th># Stations</th>
<th>Imaging</th>
<th>Pulsar Timing</th>
<th>Pulsar Search</th>
<th>Dynamic Spectrum</th>
<th>Transient Capture</th>
<th>VLBI</th>
</tr>
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<tbody>
<tr>
<td>AA0.5</td>
<td>6</td>
<td>Yes</td>
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<tr>
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<td>• Basic Continuum and Spectral Line Imaging</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Standard Channellisation</td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>• 75 MHz bandwidth</td>
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<td>• 75 MHz bandwidth</td>
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<td>AA2</td>
<td>64</td>
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<td>Yes</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>• 0.5 and 1.8KHz zooms</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>• 75 MHz bandwidth</td>
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<tr>
<td>AA3</td>
<td>256</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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</tr>
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<td>• Basic Continuum and Spectral Line Imaging</td>
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<tr>
<td></td>
<td>• Standard Channellisation</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>• 0.2, 0.45, 0.9, 1.8KHz zooms</td>
<td></td>
<td></td>
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<td>AA4</td>
<td>512</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>• All zooms</td>
<td></td>
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<td>• 300 MHz bandwidth</td>
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<td>125 beams</td>
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<td>500 beams</td>
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<td>• Supported by PST</td>
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<td>• Supported by PST</td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>• Transient response and commensal observing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Full capabilities</td>
<td></td>
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</tr>
</tbody>
</table>

9.3 SKA1 Science Commissioning

Science commissioning for both SKA1-LOW and MID is divided into a number of key areas, as follows:

- **Basic functional tests.** These are needed primarily in AA0.5 and AA1 and cover the commissioning of an interferometric imaging array with a small number of dishes or stations and basic calibration. There is significant overlap with the AIV test programme.

- **Array element calibration.** The individual elements of the array (dishes or stations for MID and LOW, respectively) are tested, characterised and calibrated (e.g., pointing and beam models).

- **Array calibration.** Standard interferometric calibrations include element location, static delays, complex gain, bandpass and polarisation leakage. These will be tested, refined and monitored for stability.

- **Interferometric imaging.** This covers broad and narrow-band imaging, self-calibration and correction for direction-dependent (e.g., ionospheric) effects in all polarisations. Key metrics are noise and dynamic range (image, polarisation, and spectral).

- **Beam-forming and non-imaging modes.** These include pulsar search and timing, transient detection and VLBI.

- **Regression tests.** These are observations of standard fields, run at approximately weekly intervals to monitor the stability of the system and the improvement in performance with time.

- **Calibrator and sky model surveys.** Both arrays will require calibration sources and fields to be identified and characterised.

These areas require specialisation on the part of the commissioning team, reflected in the staffing profile.
The amount of time required to complete the commissioning programme (and science verification for AA2-3; see below) is approximately 75% of night-time and weekends.

9.4 SKA1 Science Verification

9.4.1 Purpose and Overview

The purpose of science verification (SV) is to demonstrate the scientific performance of SKA to the astronomical community and hence to verify against the majority of the level 0 (Science) requirements. This implies the distribution of SKA data to the community in a timely manner well before the start of scheduled observing. There are several specific aims, as follows:

1. An SV observation provides an end-to-end test of the entire SKA for a specific mode of observation. Once the array is complete, this will include proposal submission, scheduling, execution, data reduction and delivery. SV is therefore the way in which level 0 requirements can be formally validated.
2. The SV process also provides access to SKA data for the community during construction, enabling data quality to be assessed by a wider group of astronomers outside the immediate commissioning team. We stress that this is a substantial commitment of time: about 1600 hr in total are allocated for each of MID and LOW SV over the course of construction. Even factoring in a significant failure rate, this should enable major early science returns.
3. The process is effectively a dress rehearsal for full science operations.

Science verification has the following steps:

1. An announcement to the community inviting short proposals to utilise specific modes and capabilities of the SKA.
2. Internal technical appraisal of the proposals received by the Observatory to ensure that they meet the stated objectives.
3. Light-touch priority assessment, which could be by an external group (e.g., ALMA uses its science advisory committee) or internal to the Observatory. The intention would be to generate a pool of proposals suitable for ranges of conditions and times rather than a rigorous scientific ranking. The emphasis will be more on selecting proposals that span the range of different types of observation (e.g., duration, target angular size, frequency range, spectral resolution, surface brightness, closeness to bright confusing sources, ...). Comparison with observations of the same targets with other arrays will be important to validate performance in the early stages, although they become less valuable when the capabilities of the SKA substantially exceed those of any other facility.
4. Execution of a full end-to-end test, starting with a mock proposal and ending with QA and data delivery. During earlier phases of construction, only parts of this process would be supported by the available hardware and software, but the full process must be validated before formal handover to operations.
5. Data releases will be public and announced in advance. They will be made by the regional centres. They will normally consist of full processed data products (e.g., image cubes, averaged visibilities) rather than raw data, following the SKA model, section 5.3.4). It may be that exceptions will be made to this rule, particularly in the early phases of commissioning, to allow independent processing.
6. Each SV observation generates a report which can be used to assess the status of the associated observing mode.
9.4.2 Stages of Science Verification

9.4.2.1 Early Science Verification

Observing modes will be verified with progressively improving functionality, in particular numbers of antennas/stations, subarrays, channels or beams, increasing bandwidth and improving pipeline support. It is likely that the first data releases will become worthwhile towards the end of AA2 for both arrays, when at least some of the capabilities meet or exceed those of similar facilities. At that stage, it is unlikely that full pipeline support will be available, so at least some of the processing will be manual.

Science Verification before AA4 will be interspersed with commissioning and will share use of available time during nights and weekends.

9.4.2.2 Preparation for Cycle 0

The transition to scheduled observing has implications for the SV process, which are discussed in this subsection. The need to describe anticipated capabilities in the Call for Proposals constrains the dates for observing modes reviews and the Science Verification activities which inform them.

Open science observing is anticipated to start immediately after the end of construction and roughly coincident with the operations readiness review (ORR). Given the need to issue a call for, review and allocate proposals, the decision on what modes to offer in the first cycle will have to be taken (roughly) six months before the end of AA4, i.e., well before the formal end of construction. There are two implications for Science Verification:

1. There will be an Observing Modes Review to decide what capabilities to offer in the first Call for Proposals. It is likely that some modes will be specified with a minimum guaranteed capability, but with the recognition that capability is likely to have increased by the time the observations are scheduled and will be made available. Examples are numbers of MeerKAT dishes or LOW stations, since their integration and commissioning will not be complete at the time of the Review.

2. In turn, this will require a dedicated block of SV observations designed to complete end-to-end tests of the currently commissioned modes (as already noted above) and to check that the Observatory can sustain science operations over an extended period.

The first Cycle ("Cycle 0") is expected to be "shared risk” science, defined to imply that should a scheduled observation be unsuccessful for any reason, there would be no guarantee that the proposal would be rescheduled. The duration of Cycle 0 is not yet decided but is indicated as 9 months. Note that the start of Cycle 0 coincides (approximately) with the ORR. The timetable leading up to Cycle 0 is given in Table 19.

<table>
<thead>
<tr>
<th>Event</th>
<th>Start Date (months)</th>
<th>Duration (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dedicated SV block</td>
<td>end AA4-9</td>
<td>0.5</td>
</tr>
<tr>
<td>Observing Modes Review</td>
<td>end AA4-7</td>
<td>0.25</td>
</tr>
<tr>
<td>Proposal Call</td>
<td>end AA4-6</td>
<td>2</td>
</tr>
<tr>
<td>Proposal review</td>
<td>end AA4-4</td>
<td>3</td>
</tr>
<tr>
<td>Proposal allocation</td>
<td>end AA4-1</td>
<td>1</td>
</tr>
<tr>
<td>Cycle 0 observing</td>
<td>end AA4/ORR complete</td>
<td>9 + ORR conclusion</td>
</tr>
</tbody>
</table>
9.4.2.3 Handover to Operations

The formal definition of the end of construction is as follows:

The formal end of construction is signified by a successful Operations Readiness Review (ORR). This will demonstrate the ability of the Observatory to execute a set of key observing modes, illustrated by end-to-end tests of representative Science Verification projects from proposal preparation to (public) data delivery. This process confirms compliance to Level 0 requirements and the ability to execute high-priority science cases. System Verification against the majority of the applicable Level 1 (engineering) requirements is an essential prerequisite.

The operations readiness review will take place at the end of AA4 and is informed by a second extended block of SV observations. At this point, AIV should be complete for the whole system and all of the high-priority modes should have been through the commissioning process (in many cases also preliminary SV).

Handover of the commissioned and verified system to operations for scheduled observing is, however, a gradual one. It is expected that specific modes will be released in sequence, starting with basic (and commonly used) modes and leaving difficult and esoteric ones for later. For that reason, we have divided the observing modes given in the next section into three groups:

1. High-priority modes for cycle 0. These must undergo SV before the first call for proposals is issued.
2. High-priority modes for the end of construction and cycle 1. These undergo SV before the ORR and the resulting reports form part of the input to that review.
3. Additional modes which may be tested and verified after the formal end of construction (although the process will start earlier). These include challenging and esoteric modes as well as the full variety of multiplexed commensal modes.

Decisions on what modes to offer at a particular time will obviously be made based on the actual results of commissioning and science verification: the lists given below are very preliminary. We note an additional complexity in the handover for the MID case, where coordination of the ramp down of MeerKAT science to migrate to SKA-1 MID science will need to be clearly communicated; we anticipate this planning occurring alongside the indicative timeline for Cycle 0 (Table 19).

9.4.2.4 Cycle 1

As well as marking the formal end of construction, the ORR is at a suitable time to act as the decision-making forum for modes to be offered in cycle 1. An indicative timeline is given in Table 20.

<table>
<thead>
<tr>
<th>Event</th>
<th>Start date (months)</th>
<th>Duration (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dedicated SV block</td>
<td>end ORR-2</td>
<td>1</td>
</tr>
<tr>
<td>Operations Readiness Review</td>
<td>end ORR+1</td>
<td>0.5</td>
</tr>
<tr>
<td>Proposal Call</td>
<td>end ORR+3</td>
<td>2</td>
</tr>
<tr>
<td>Proposal review</td>
<td>end ORR+5</td>
<td>3</td>
</tr>
<tr>
<td>Proposal allocation</td>
<td>end ORR+8</td>
<td>1</td>
</tr>
<tr>
<td>Cycle 1</td>
<td>end ORR+9</td>
<td>12</td>
</tr>
</tbody>
</table>

9.4.3 Science Milestones

In this sub-section, we give a set of science (commissioning and SV) milestones for the five array assemblies. These should be read together with the engineering milestones in the AIV roll-out plans (see
Table 17 and Table 18). The criteria for AA4 apply to the formal end of construction and the handover to operations (part of the operations readiness review).

**Table 21. Science milestones for SKA1-MID array assemblies.**

<table>
<thead>
<tr>
<th>Array Assembly</th>
<th>Key objectives to be achieved by the end (acceptance) of the array assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>Basic array element calibration demonstrated (pointing, antenna location and delays, holography).</td>
</tr>
<tr>
<td></td>
<td>Observation calibration demonstrated (delay, bandpass, complex gain, polarization leakage and phase, direction-independent self-calibration, initial RFI flagging).</td>
</tr>
<tr>
<td></td>
<td>Basic imaging of a range of target fields in bands 1 and 2 (band 5 if available) with up to 4-dish array, validated by comparison with results from existing instruments - MeerKAT, ATCA, Jansky VLA (fields around bright calibrators and sparse extragalactic).</td>
</tr>
<tr>
<td></td>
<td>Data reduction on-line through SDP and offline (baseline CASA).</td>
</tr>
<tr>
<td></td>
<td>No SV.</td>
</tr>
<tr>
<td>1</td>
<td>Similar to AA0.5 but with improved imaging, production, and equipment.</td>
</tr>
<tr>
<td></td>
<td>Basic array element calibration demonstrated (pointing, antenna location and delays, holography).</td>
</tr>
<tr>
<td></td>
<td>Observation calibration demonstrated (delay, bandpass, complex gain, polarisation leakage and phase, direction-independent self-calibration, initial RFI flagging).</td>
</tr>
<tr>
<td></td>
<td>Basic imaging of a range of target fields in bands 1 and 2 (band 5 if available) with up to 4-dish array, validated by comparison with results from existing instruments - MeerKAT, ATCA, Jansky VLA (fields around bright calibrators and sparse extragalactic).</td>
</tr>
<tr>
<td></td>
<td>Data reduction on-line through SDP and offline (baseline CASA).</td>
</tr>
<tr>
<td></td>
<td>No SV.</td>
</tr>
<tr>
<td>2</td>
<td>Demonstrate ability to form at least one, steerable tied array beam with the required phasing efficiency in bands 1, 2 and 5 for use by pulsar search and timing, dynamic spectrum and VLBI (accurate polarization calibration boresight only). Show that known pulsars can be detected and timed accurately using PSS and PST.</td>
</tr>
<tr>
<td></td>
<td>Demonstrate imaging (wide and narrowband) of a quality comparable to that of Extended MeerKAT (up to 64 dishes; baselines mostly &lt;20 km) in bands 1 and 2 (band 5 if possible). Range of targets, spectral resolutions. Full polarisation.</td>
</tr>
<tr>
<td></td>
<td>Refinement of array element and observation calibration (add reference pointing and initial direction-dependent calibration).</td>
</tr>
</tbody>
</table>
|                | Demonstrate the ability to operate two independent subarrays for
engineering and science.

Data reduction expected to be on-line through SDP.

Demonstrations performed as SV observations, but not fully automated/pipelined; data released publicly.

3

Demonstrate imaging with up to 128-station array, including long baselines. bands 1, 2 and 5; 5200 MHz bandwidth. Range of targets, spectral resolutions, including at least one zoom mode. Full polarisation.

Demonstrate simultaneous use of three subarrays (2 commensals for science + 1 for engineering).

Complete initial calibrator survey.

Data reduction by SDP operational system pipeline. Demonstrate consistency with earlier off-line reduction and ability to operate at AA3 scale.

4/ORR

Demonstrate imaging with full MID array including MeerKAT dishes in bands 1 and 2 and with all SKA1 dishes in band 5, including zoom modes.

Demonstrate pulsar search, pulsar timing and dynamic spectrum with multiple beams.

Demonstrate commensal imaging and transient search.

Demonstrate full end-to-end operation, including proposal submission, scheduling block generation, scheduling array and data processing, data processing at full scale, data delivery to regional centres.

Table 22. Science milestones for SKA1-LOW array assemblies.

<table>
<thead>
<tr>
<th>Array Assembly</th>
<th>Key objectives to be achieved by the end (acceptance) of the array assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>Basic array element calibration demonstrated (station calibration, location, and delays).</td>
</tr>
<tr>
<td></td>
<td>Observation calibration demonstrated (delay, bandpass, complex gain, polarization leakage and phase, direction-independent self-calibration, initial RFI flagging).</td>
</tr>
<tr>
<td></td>
<td>Imaging of a range of target fields with up to 6-station array, validated by comparison with results from MWA; range of fields and frequencies covering the full RFI-free band.</td>
</tr>
<tr>
<td></td>
<td>Data reduction online through SDP and offline (baseline CASA).</td>
</tr>
</tbody>
</table>
No Science Verification.

1
Similar to 0.5 but with improved imaging and expanded equipment.

Basic array element calibration demonstrated (station calibration, location and delays)

Observation calibration demonstrated (delay, bandpass, complex gain, polarization leakage and phase, direction-independent self-calibration, initial RFI flagging)

Imaging of a range of target fields with up to 18-station array, validated by comparison with results from MWA; range of fields and frequencies covering the full RFI-free band.
Data reduction expected to be through SDP.

2
Demonstrate ability to form multiple, steerable beams.

Demonstrate timing of known pulsar.

Demonstrate imaging (wide and narrowband; up to 64 stations; full range of centre frequencies; range of targets fields; full polarization). Validate by comparison with MWA.

Refinement of array element and observation calibration (add direction-dependent calibration).

Demonstrate ability to operate two independent subarrays for engineering and science.

Data reduction expected to use SDP; off-line as a check.

Demonstrations performed as Science Verification observations, but not fully automated/pipelined; data released publicly.

3
Demonstrate imaging with up to 256-station array, including long baselines. Range of targets, spectral resolutions, including at least one zoom mode. Full polarization.

Demonstrate simultaneous use of three subarrays (2 commensal for science + 1 for engineering)

Deliver initial Global Sky Model.

Data reduction by SDP operational system pipeline. Demonstrate consistency with earlier off-line reduction and ability to operate at AA3 scale.

4/ORR
Demonstrate imaging with full LOW array; optimised direction-dependent calibration; wide and narrow bands, including zoom modes.

Demonstrate pulsar search, pulsar timing and dynamic spectrum with multiple beams.
Demonstrate commensal imaging and transient search

Demonstrate full end-to-end operation, including proposal submission, scheduling block generation, scheduling array and data processing, data processing at full scale, data delivery to regional centres.

9.5 Staffing and Management

AIV, science commissioning and science verification will all be managed directly by SKAO. This section describes the structure of the individual teams.

9.5.1 AIV

The AIV responsibility for each telescope is managed by an AIV Lead Engineer. This person will be located on site but will continue to be integrated in the telescope TDT so frequent travels to GHQ can be envisaged. The AIV Lead reports directly to the SKA Project Engineer.

A simplified view of the AIV team can be shown in the following diagram:

![Diagram of AIV team structure](image)

Figure 156. AIV team for the MID telescope. Full lines denote line and functional responsibility; dashed lines functional only. The LOW telescope will have a very similar team organisation with the exclusion of the MeerKAT integration box.

The MID and LOW AIV teams will be based in Cape Town and in Geraldton respectively, very close to the system ITF. The AIV Lead will be supported by a team (Figure 156). It can be described in more details by the following:

- An AIV Deputy Engineer. This person will be an SKAO employee and will act as deputy for the AIV Lead Engineer and will take the responsibility of the ITF and its team.
- System AIV: this team is made up of engineers, systems engineers, and technicians that will support the integration and the verification. These persons will be managed by the AIV Lead Engineer through a professional service contract (or a combination of secondments to the SKAO).
• SW support: these persons will act as the natural link between the SW developers and the AIV team. They will be integrated into the SW development force, but they will be working for the AIV Lead directly.
• ITF: A few engineers and technicians are envisaged to support and run the ITF. This small group of people will report directly to the AIV deputy that will act as ITF responsible person.
• In the case of SKAO-MID, the AIV will need to be supported by an additional team to ensure the integration of the MeerKAT system. This team will be managed directly by the AIV Lead through a second professional service contract (or a combination of secondments).

9.5.2 Science Commissioning

9.5.2.1 GHQ
The SKA System Scientist is based at GHQ and has overall responsibility for science commissioning of the Observatory. A small group, also located at GHQ, provides direct support. The SKAO science team is also expected to contribute effort to commissioning.

9.5.2.2 MID and LOW
The majority of science commissioning effort is located in the two host countries. The MID and LOW teams have the same structure. Each is managed by a Lead Commissioning Scientist (who reports to the System Scientist and is an SKAO staff member). The core commissioning team is composed of a combination of SKAO staff alongside host and member country staff (on secondment, or as part of professional services contracts with host-country organisations).

It is anticipated that the science commissioning teams in the host countries will work almost exclusively in Cape Town and Perth, with very limited reason to travel to site (except possibly in the very early phases).

The work of the science commissioning teams can be subdivided into broad functional roles, although the balance between them will evolve with time and it is important to retain the ability to switch resources between the individual areas at short notice.

Figure 157. Functional and line management of science commissioning. Full lines denote line and functional responsibility; dashed lines functional only. For clarity, the LOW structure (identical to that for MID) is not shown.
9.5.3 Science Verification

The management structure for science verification is shown in Figure 158. The Science Verification Team reports to the Head of Science Operations in the host country.

Figure 158. Functional and line management structure for science verification. Full lines denote line management and functional responsibility; dashed lines functional only. For clarity, the LOW structure (identical to that for MID) is not shown.
10 Acquisitions

10.1 SKA Observatory Business Enabling Functions

The development of the initial funding schedule will include a component describing the funding required for the overall operation of the Observatory, which is referred to as a business-enabling plan. Detailed plans for these functions are in development to support the business case for funding the initial period of the Observatory (i.e., 2021-2022).

Business enabling functions include:

- The Director-General’s Office and Corporate Governance,
- Human Resources,
- Strategy,
- International Relations,
- Finance,
- IT,
- Communications & Outreach,
- Other enterprise supporting functions.

Critical to the success of many of these functions is investment in a modern and fit for purpose enterprise resource planning (ERP) system. Significant progress has already been made in this area during 2020 with the development of core components for finance, procurement, and HR which are being progressively rolled out. Further development will take place during Phase II to accommodate construction era-specific requirements.

10.2 Procurement

The SKA1 construction procurement plan is fully aligned with the SKA Observatory procurement policies. The plan seeks, as far as reasonable, to:

A. Facilitate members’ industrial and fair work return (“FWR”) aspirations by allocating the leadership of, and participation in, a significant number of SKA1 work-packages.
B. Broadly achieve a minimum 70% FWR (as defined within Appendix 1 of the procurement policy) at the outset of SKA1 construction for members.
C. Best manage and mitigate commercial and contractual risks.
D. Provide opportunities for competitive procurement wherever possible.
E. Enable both cash-procurement and in-kind contributions to co-exist without materially disadvantaging members seeking to apply either procurement methodology.

Overall procurement activity for SKA1 construction can be considered as a two-stage business process that starts with pre-procurement activity during the SKA Organisation era and ends when the final SKA1 construction contract enters into force. Stage 1 describes the historical, strategic/tactical pre-procurement activity carried out during the SKA Organisation era; stage 2 describes the transactional procurement activities to be carried out after the Observatory is a fully operational legal entity.

10.2.1 Overview

The overall SKA1 procurement plan is a 2-stage process for acquiring the significant goods, services and works contracts required to construct the SKA1. Stage 1 takes place during the SKA Organisation era and stage 2 is then initiated during the SKA Observatory era.
The SKA1 procurement plan can be considered as a ‘hybrid model’, i.e., there is a significant percentage of work allocated to members during stage 1 but, wherever possible, scope for competitive procurement is maintained during stage 2. However, sole or single source procurement is possible insofar as this is supported by a robust business case and the appropriate justifications are in place.

Procurement activities during stage 1 were developed to provide members with a structured and transparent opportunity to identify and secure their interest in performing specific SKA1 contracts, either as the nominated Tier 1 Lead, a participant or as part of a consortium. Oversight during stage 1 procurement activity was provided by the CPTF. Stage 1 started with a request for information to all members and ended within a significant number of SKA1 construction contracts being conditionally allocated (both the lead and participating roles) to member countries by the CPTF.

All allocations to members were first endorsed by CPTF on a provisional basis, i.e., the allocation was endorsed by CPTF on the understanding that an agreement in principle could be agreed between the SKA office, the provisional Tier 1 Lead and all other participants.

For each of the provisional allocations, this agreement in principle was captured within a delivery plan and an outline procurement plan. These documents were developed collaboratively ‘in the spirit of mutual trust and cooperation’ between the SKA office and each of the provisional Tier 1 leads. Each of these delivery plans and outline procurement plans were developed and negotiated in order to reasonably satisfy:

- the member leading the Tier 1 contract;
- members participating in the delivery of the contract;
- members who had expressed an interest in participating in the delivery of the contract that could not reasonably be accommodated;
- the SKA Office.

When an outline procurement plan was deemed acceptable to all of the parties noted above it was presented to the CPTF for endorsement by the SKA office with a recommendation that the status of the allocation should be changed from ‘provisional’ to ‘conditional’, i.e., there is a reasonable delivery plan and outline procurement plan in place, the allocation is strengthened and it is now only conditional upon A) pre-qualification by the SKA office of the final contractor(s) that will perform the contract(s) and B) the appropriate level of funding being made available by the members in order to reasonably perform the contract(s) and satisfy fair work return requirements.

In the event of a failure to develop an acceptable outline procurement plan the SKA office will not endorse the provisional allocation and will recommend to the CPTF that the contract is competitively sourced from the membership as per the procurement policy.

At the time of writing of the Construction Proposal, draft delivery plans and outline procurement plans have been successfully developed; the CPTF has approved the change in status from ‘provisional’ to ‘conditional’ as appropriate.

At the conclusion of stage 1 of the procurement planning process (in other words, in time for construction start and procurement commencement) all SKA1 contracts will either be conditionally allocated or unallocated and in the competitive workstream. At that point, the status of allocations will be updated to reflect the final status of allocations before procurement activity transitions into stage 2.
All procurement activities during Stage 1 should be considered as ‘pre-procurement’, i.e., development of overarching procurement strategy (the hybrid procurement model, provisional allocations, development of individual delivery plans and outline procurement plans).

Stage 2 covers the transactional business process of procuring contracts in accordance with the approved policy and can only take place when: the SKA Observatory legally exists; all procurement-related policies have been approved by the Council and sufficient funding is available to enter into binding financial commitments with contractors.

During Stage 2 all SKA1 contracts (cash and in-kind) will be developed, tendered, negotiated, and entered into with successful contractors in accordance with each of the outline procurement plans developed during stage 1.

The SKA Observatory stage 2 procurement process is well aligned with processes applied by similar IGOs also engaged in large science infrastructure projects (ITER, ESS, ESO). The SKA Observatory procurement process cannot therefore be described as either ‘novel’ or ‘innovative’. Adopting a relatively ‘traditional’ procurement approach should:

- Generate more interest from potential suppliers by making SKA1 contract opportunities more attractive (suppliers never appreciate ‘novel’ or ‘untested’ procurement methods).
- Reduce the risk of inadvertent non-compliance (SKA Observatory procurement procedures have been developed to be simple and easy to apply, practical, transparent, and fair).

As previously noted, stage 2 can only be initiated after the completion of stage 1 and:

- the SKA Observatory exists as a legal entity;
- procurement policies and procedures are approved;
- governance structures are approved;
- funding considerations have been finalised;
- The SKA1 Construction Proposal has been approved.

10.2.2 Core Procurement Principles for SKA1 Construction

The approach to procurement embodies the following core procurement principles set out in the SKA Observatory procurement policy:

- Fair work return
- Equity
- Transparency
- Competitiveness

The procurement policy sets out a minimum fair work return (FWR) target as follows:

“Members shall receive at least 70% fair work return on their contribution to the capital cost of SKA1 construction, excluding contingency; there will be a target of at least 70% fair work return on the contribution to the capital cost of construction inclusive of contingency. Further opportunities for members to achieve a return on investment through procurement of elements outside of the capital cost of construction will be pursued.”
The two-stage ‘hybrid’ SKA1 construction procurement strategy developed by the SKA office has broadly been successful insofar as it has enabled members to secure an economic interest in the work-packages most aligned with their individual strategic industrial aspirations and achieve a reasonable percentage financial work-return on investment from the outset of the project (i.e., the moment funds are committed to SKA1 construction) – the two-stage strategy aimed to leverage FWR to achieve ‘significant continued engagement’ from members during stage 1 and this objective has largely been achieved.

The final record of the SKA convention established the principle of an undefined FWR weighting for infrastructure work, a ‘weighting’ of 50% for defined infrastructure work was included within the draft SKA Observatory procurement policy and this was subsequently endorsed by the CPTF. The weighting means that work to deliver the SKA LOW Infrastructure and SKA MID infrastructure work packages will be counted at 50% of actual value for the purposes of assessing FWR.

10.2.3 Description of Individual Steps Within the 2 Stage Procurement Process

As previously discussed, the end-to-end SKA1 procurement process is a two-stage process comprising 10 individual steps. The end-to-end process is outlined in Figure 159 below:

![Figure 159. Procurement Process.](image)

**Stage 1 – Steps 1 to 5**

- Step 1 – Discovery & facilitated discussions (completed)
- Step 2 – Initial report to CPTF (completed)
- Step 3 – Develop in-principle of procurement agreements (completed)
- Step 4 – Final report to CPTF (partially completed and still ongoing at issue of the first draft of this Construction Proposal).
- Step 5 – SKA1 issue procurement plan (partially completed – to be updated as and when the status of further allocations change from ‘provisional’ to ‘conditional’).
Stage 2 – Procurement - SKA Observatory era procurement

Step 6 – SKA Construction Proposal to Council.
Step 7 – Provisional work return adjusted following discussions with members and SKA Council
Step 8 – IGO era procurement process as per approved procurement procedures.
Step 9 – Recommendations will be made to the finance committee for deliberation and approval in full compliance with approved SKA Observatory procurement procedures.
Step 10 – Contracts will be awarded, and final fair work return adjusted accordingly.

10.2.4 Roles and responsibilities

10.2.4.1 CPTF / SKA Observatory Council

Stage 1 of the SKA1 Procurement Plan process outlined above (the process of developing the provisional/conditional contract allocations) has been carried out in the era before the SKA Observatory comes into force and was overseen by the CPTF. Stage 2 will occur under the auspices of the SKA Observatory and will therefore be overseen by the SKA Observatory Council.

10.2.4.2 CPTF Observer Countries

CPTF Observer countries (i.e., countries with a stated interest in signing the SKA convention and joining the SKA Observatory as full or associate members) have been able to fully contribute to procurement during stage 1 of the process, including taking part in requests for information, endorsement of provisional allocations by CPTF, development of Outline procurement plans, and inclusion of contract allocations within this SKA1 Construction Proposal after review and change of status (from ‘provisional’ to ‘conditional’) by CPTF. As with other parties, their continued participation in the procurement phase once construction begins relies on a financial commitment and engagement with the Observatory being confirmed.

10.2.4.3 The SKA Office

Whilst the main oversight of this process lies with the AGANE CPTF and later, the SKA Observatory Council, the SKA Organisation staff have had a significant role to play providing advice and guidance to CPTF, and facilitating the allocative process during stage 1. SKAO’s Procurement Team will manage all procurement activity in accordance with approved policies under delegated authority from the Council during stage 2.

10.3 Processing Individual Procurement Actions

Regardless, of the type of acquisition (cash vs. in-kind, competition vs. allocation) a procurement documentation pack will be assembled according to the guidance in SKA-TEL-SKO-0000710 Technical Preparation for SKA1 Procurement:

- Statement of work,
- Technical specifications
- Interface definitions including all relevant ICDs
- Applicable contract drawings (if any)
- Verification plan
- Reference design
- Applicable SKA Observatory organisational standards
- Applicable National/International standards (also see section 10 on-site information).
If the contract has been conditionally allocated the SKA office will invite interest from potential contractors within the conditionally allocated member country only. All potential contractors expressing an interest in tendering for the contract will, without exception, need to be pre-qualified by the SKA office to take part.

Unless there is a compelling single or sole source justification all conditionally allocated contracts will be competitively tendered. However, the tender will be restricted to potential contractors within the member country with the conditional allocation only. All tenderers will be also required to source certain pre-defined Tier 2 sub-contracts from other member countries in accordance with the tender documentation (so as to broadly maintain the work-return arrangements as agreed within the outline procurement plans).

Contracts that have not been conditionally allocated will be competitively tendered amongst all member countries.

All transactional aspects advertising of contract opportunities, the end to end tender process and the evaluation and awarding of contracts and in-kind contribution agreements are detailed within the SKA Observatory procurement manual and the SKA Observatory procedures covering the acquisition of in-kind contributions.

The management of these deliverables is built upon the management model of the SKAO as the ‘client’ interacting directly with the Tier 1 contractors in the delivery to the observatory. These descriptions and diagrams come directly from the NEC4 “Establishing a Procurement and Contract Strategy” document.

**Use of NEC Contract Templates**

The application of the right contract is central to the successful delivery of any large infrastructure project. The NEC suite of contracts has been in existence for nearly 30 years and has linked projects, people and processes together to create the best possible contractual environment for delivering successful projects. The NEC is a suite of standard contracts, each of which has the following attractive characteristics for the SKA1 construction project:

- Use stimulates good management of the relationship between the two parties to the contract, and hence the work covered by the contract.
- It can be used in a wide variety of commercial situations, for a wide variety of types of work and in any location.
- An NEC contract is a clear and simple document – contracts are written in easy language and in a structure that is straightforward and easily understood.
- Unlike most ‘standard terms and conditions’ the NEC4 terms and conditions have not been developed to advantage the client organisation – rather they have been developed to encourage positive contractual behaviours that have been shown to result in the best possible outcome for both client and contractor equally.

For the above reasons the SKA Observatory intends to apply one the various NEC contract templates to every SKA1 commercial relationship, i.e. when procuring goods, services and/or works from contractors. The NEC4 engineering and construction (ECC) will be used when scope includes complex engineering and design activities, delivery of tangible goods and/or civil works. The NEC4 professional services contract (PSC) will be used for intangible services such as engineering consultancy and the NEC4 supply contract (SC) will be used when tangible goods requiring minimal engineering or design activity are being procured.
Whenever goods, services and or works are being acquired as in-kind contributions the contributor is expected to enter into an in-kind contribution agreement with the SKA Observatory. A template approach for these in-kind agreements is under development at present, based on the format of the NEC contract approach; its aim will be to ensure good contractual management and positive behaviours.

The basic model for infrastructure contracting is:

Figure 160. Basic Tier 1 contract management model for SKA1.

Where the “client” is the SKAO (SKAO roles are coloured green), represented by the Product Delivery Team Project Manager and domain specialist who directly fulfil the Project Manager and supervisory roles (see below). However, the breadth of Supervisory discipline support is fully represented by the engineering domain specialists, systems engineers and assurance product assurance staff within SKAO. The grey boxes are those areas not anticipated to be needed in general while the blue boxes are the Tier 1 contactors (dark blue) under different circumstances (e.g., working with sets of subcontractors, suppliers, etc.).

In this general, model the Tier 1 deliveries are made to SKAO and are then integrated through the execution of the AIV, commissioning, and science verification activities which are themselves an integrated team of SKAO staff and professional services contracted staff from the member countries.

Overall, the SKAO manages the SKA1 construction through a mix of SKAO staff (e.g., SKAO Site Construction Director, SKAO Site Manager) supported by professional service providers contributing essential additional skills and effort. SKAO remains the employer and pays invoices based on their advice (see SKA-TEL-SKO-0000740 SKAO Health, Safety, and Environmental Plan for specific HSE duties and responsibilities).

10.4 Insurance

SKAO intends to work with a broker to develop an overall SKA1 construction insurance programme. This will provide high-grade insurance policies that can be relied upon across the project rather than relying upon insurance products provided by individual contractors; our existing insurance provider and their principle underwriter have informed us that this strategy is common for large infrastructure projects and it should result in better value for money overall, greater transparency and a better ability to manage
insurable risks. The SKA1 insurance programme over the next 12 months overall is being developed alongside the current SKA Organisation insurance broker; some insurance estimates are included within areas of the SKA1 cost book but in general, these costs will be shared across the observatory (i.e., some costs will be outside of the construction project estimation). For insurance purposes, the following assumptions are made:

- The premises, infrastructure and assets available for use by the SKA Observatory (SKAO) may be owned or leased by, or licensed to, the SKAO. The assets will include a fleet of motor vehicles.
- Persons coming into contact with those premises, infrastructure and assets may be SKAO employees; secondees to the SKAO; invitees, agents, contractors, and partners of the SKAO; trespassers.
- Insured risks include (without limitation) fire, explosion, lightning, earthquake, storm, flood, bursting and overflowing of water pipes, impact by aircraft and articles dropped from them, impact by vehicles, riot and civil commotion, wind including cyclones; vicarious liability; liability arising under applicable partnership law; strict liability, where relevant; liability arising through ownership or under relevant leasing and licencing arrangements; liability arising under contract and under indemnities; and any other risks as reasonably determined from time to time.
- Reinstatement costs should take into account (inter alia) inflation; costs of demolition, site clearance, site protection and shoring up; professional fees and expenses; work required by law; value-added or similar taxes.
- It should be assumed that title and risk to any asset will have passed to the SKAO before it is transported or shipped to the SKAO.
- Power solutions for the sites in Australia and RSA will largely be provided by third parties.
11 Project Management Controls

This section covers the SKA1 project management controls system (PMCS). It covers processes, tools, roles, and responsibilities and how SKA will use these to inform decisions and to satisfy stakeholders and their respective requirements.

11.1 Overview of the PMCS

The PMCS comprises a number of tools, some commercial-off-the-shelf (Primavera, Cobra, Confluence, CEMAR, and JIRA), some commercial and tailored specifically for SKA (Business World On! and Dash360) and some in-house (SKARR), and the processes by which we use them. These tools will be integrated to varying degrees. The key field linking all the databases is the work package identifier. All data is loaded at the work package level and all actual expenditures are also at the work package level. Figure 161 above summarises the scope of each tool. The next few sub-sections will give more detail on each one.

11.2 Work Breakdown Structure (WBS) and Cost Book

The core component of the PMCS is the SKA1 WBS. A fuller description of each work package of the WBS together with its cost estimate is held in the cost book [RD2] and the schedule for each work package is shown in [RD3].

The WBS is thus the basis for all project controls related systems and reports. It has been developed over many years, using as inputs the project scope as progressively set out in SKA Board papers, the pre-construction statement of work, element and system preliminary design review baselines, element critical design review baselines and the SKA design baseline.

SKA has procured the Dash360 web-based tool for storing and reporting on the WBS and cost book.

The screen shot in Figure 162 capture a single product delivery work package, 02.02.02 – band 02 SPF: delivery. This is an external work package to be contracted out and is covered by the capital cost (of construction) budget.
The Dash 360 tool’s reporting function enables the download of all work packages with a summary analysis of each one in terms of annual cash flow and estimate type, and this is contained in [RD2].

The costs in Dash 360, whilst appearing at a summary level, are thus supported by a multitude of spreadsheets, vendor quotes, and BoEs.

[RD2] gives more detail on the cost guidance and how Dash 360 was populated.

11.3 Management Roles and Responsibilities

Roles and responsibilities within the context of the PMCS are as follows:

- Programme Director (PD) – accountable on behalf of the Director-General for programme delivery. Also, the Chair of the change control board and, as the Line Mrdoananger of the programme Directorate, the Chair of the Observatory delivery team.
- Head of Project Management Group (HPMG) - responsible for programme budget, schedule, earned value, contingency, risk management, PM training, support and development. Guides the use of PM processes and resources to deliver the project and to provide necessary stakeholder communications and reporting.
- Senior Project Manager (SPM) - responsible for telescope schedule, budget, scope, earned value and monthly reporting. Additionally, the senior project managers support the contingency and risk management at the Observatory level. Also chair the appropriate telescope delivery team.
- Project Manager (PM) - point of ownership for planning, coordination and delivery of work packages for which they are designated as the PM. Where these are contracted out work
packages, the PM chairs the appropriate product delivery team and as such is supported by the relevant domain specialist(s). Key responsibilities include management, execution, and reporting of:
- Schedule development including detailed inputs for activities, logic, and durations
- Schedule updates
- Delivery of milestones
- Budget estimating and management
- Actual costs
- Earned value and variance analysis/reporting
- Risk management
- Change management
- Monthly report inputs
- Contract management
- Issue resolution including managing early warnings and compensation events under NEC.
- Project Controls Manager (PCM) and team - responsible for maintenance of the project management control system including scheduling, earned value management, actual costs, budgeting, risk and change control. Ensures storage and retrieval of schedules, cost and related planning data. Produces monthly report.
- Change Control Board (CCB) - responsible for reviewing, approving or rejecting all change requests that impact technical, cost and schedule performance.
- SKAO Finance (Fin) - responsible for all accounting related functions and providing the necessary data exports for import into the SKA1 earned value tool (Cobra). Responsible for coordinating the establishment of new work packages (as needed) and the processing of invoices.
- Telescope and Product Delivery Teams (TDT and PDTs) - provide subject matter expertise and key inputs to the management team.

11.3.1 SKA1 PMCS RASCI Matrix

The responsibility, accountability, support, consultation and information (RASCI) matrix for SKA project management is shown in Table 23. Role acronyms are given in the preceding section. NA means not applicable.

**Table 23. RASCI for PMCS.**

<table>
<thead>
<tr>
<th>Activity</th>
<th>PD</th>
<th>HPMG</th>
<th>SPM</th>
<th>PCM</th>
<th>PM</th>
<th>CCB</th>
<th>Fin</th>
<th>DS</th>
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<tbody>
<tr>
<td>Observatory budget, schedule, scope, EV, contingency, risk management</td>
<td>A</td>
<td>R</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>C</td>
<td>S</td>
<td>C</td>
</tr>
<tr>
<td>Telescope budget, schedule, scope, EV, risk management</td>
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<td>C</td>
<td>R</td>
<td>S</td>
<td>S</td>
<td>C</td>
<td>S</td>
<td>C</td>
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<td>C</td>
<td>A</td>
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<td>A</td>
<td>C</td>
<td>C</td>
<td>R</td>
<td>NA</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>Monthly progress updates (work performed, actual cost, schedule)</td>
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<td>A</td>
<td>C</td>
<td>C</td>
<td>R</td>
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<td>C</td>
<td>C</td>
<td>R</td>
<td>NA</td>
<td>NA</td>
<td>C</td>
</tr>
</tbody>
</table>
11.4 Risk and Opportunity Management

11.4.1 Risk Management Plan

SKA1 maintains a standard ISO 21500 risk management plan.

11.4.1.1 Introduction

The objective of risk management is to affect the results of uncertainties in future events, with the goal of maximising outcomes favourable to execution of the project. In this case, the project is the design and construction of the Square Kilometre Array phase 1. Design and construction of this dual facility observatory is a complex undertaking, one that benefits from the application of risk management. The risk management plan supports the project by:

- providing methods to identify risks;
- providing criteria to evaluate risks in terms of probability and consequence;
- outlining the process of risk handling or mitigating potential adverse events;
- providing a methodology for risk monitoring in terms of review and reporting; and
- providing a format for documenting the process and results of risk management.

Risk management is a proactive management approach to meeting project objectives and keeping risk at an acceptable level. There are three types of risk associated with a project such as SKA1:
1) technical risk consisting of the risk of not meeting performance requirements;
2) programmatic risk which consists of the risk of project failure due to cost or schedule overruns; and
3) risk of harm which consists of risk to personal safety (“hazards”).

The last risk is covered under the project safety plan. The first two are covered here.

11.4.1.2 Definitions
The project employs the following definitions for risk and contingency.

Risk: “An uncertain event or condition that, if it occurs, has a positive (opportunity) or negative effect on at least one project objective.”

Contingency: “A planned amount of money or time which is added to a baseline estimate to address specific, identified risks”.

- An amount of the total project cost reserved for those initially unknown tasks which when identified in the future are within the scope of the project but may not have been included in the scope of the work package.

  Contingency is considered part of the total project cost, where total project cost = sum of the performance baseline and the budgeted contingency.

  Contingency is held by the programme and managed as elaborated below.

Management reserve:

- Covers unforeseen risks to the project ("unknown unknowns"), such as natural disasters.
- Management reserve is not considered a part of the total project cost.
- Also known as provisions: time, money or other resources that are made available to cover variation from target value or estimate, not arising from a specific risk event. [APM]
- If the management reserve is available, it is held at the highest level of the organisation (IGO, member countries). If it is not available, a likely response to an unforeseen risk occurrence which gives rise to a cost is, therefore, de-scoping to stay within budget.

It is important to stress that contingency does not provide for costs outside of the approved project scope. Should change requests of this nature arise that are considered to be scope-creep they will be rejected unless they are clearly within the realms of value-engineering, e.g., changes that will reduce whole-life costs for the Observatory [need to be careful with this].

Given the two highlighted points above it is, therefore, necessary to have a mechanism to seek guidance or funds from members when additional costs may be incurred outside of the contingency budget.

11.4.1.3 Risk Identification – Risk Register

11.4.1.3.1 Risk Register
The sub-system/intra-sub-system risks have then been evaluated based on their probability of occurrence and the associated exposure in labours and materials. In addition, the ‘trigger date’ or ‘end date’ for
encountering the risk has been noted to better support modelling of the contingency burn rate throughout the project.

The identified construction project risks are then be reviewed by the Programme Directorate and used for contingency estimation and monitoring.

The risk tool (SKARR) provides a web-based interface for risk data entry and review as well as providing basic reporting functions on changes over specified periods. The web-interface connects to a locally served SQL database where the risk information is stored. The database is managed through a phpMyAdmin web interface that allows flexible manipulation of the database fields and content.

At the highest level, the risk may be characterised as illustrated in Table 24; we note that the impact of COVID-19 is distributed across several risks, impacting most substantially the near-term schedule of the project and driving the updated schedule contingency calculations (See 11.5.3) as well as in the projected completion of pre-construction activities (high-level programme risk).

Table 24. Highest level risk classification.

<table>
<thead>
<tr>
<th>Risk Type</th>
<th>Risk Title</th>
<th>Risk Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>Product deliveries fail to meet performance or quality requirements.</td>
<td>There are a range of technical/performance risks associated with the construction development/deliveries across the WBS.</td>
</tr>
<tr>
<td>Performance</td>
<td>Missing or inadequate requirements identified during integration/verification</td>
<td>The SKAO has utilised a strong systems engineering approach to requirement elaboration and flow down. However, the complexity of the facilities argues that there could be remaining gaps and misinterpretations which will challenge the project as it does final integration and verification. This risk captures the additional effort/equipment required to correct this possibility.</td>
</tr>
<tr>
<td>Budget</td>
<td>Uncertainties in MID costing</td>
<td>This risk summarises the range of budgetary uncertainties across the MID deliveries through to system integration.</td>
</tr>
<tr>
<td>Budget</td>
<td>Uncertainties in LOW costing</td>
<td>This risk summarises the range of budgetary uncertainties across the LOW deliveries through to system integration.</td>
</tr>
<tr>
<td>Budget</td>
<td>Uncertainties in SAFe resourcing implementation.</td>
<td>The scaled agile framework development method is a best practice but is culturally new within the organisation. The observatory has only the Bridging period in pre-construction to test and commission its application within the realm of SKA1. Additional skills, agile teams or release trains, may be required to best realise the necessary performance.</td>
</tr>
<tr>
<td>Schedule</td>
<td>Procurement complexity (delay to start of construction).</td>
<td>The SKAO is planning for a 6-month period following the initial funding to release and award the initial contracts (conservative estimate; many contracts will be ready shortly after T0). The organisational complexity (e.g., Fair Work Return, alliance model for Tier 1 contract delivery, minimum cash requirements, in-kind deliveries, etc) may challenge this timeline. Additionally, with the selection of NEC4, we have a framework for the contracting, but this</td>
</tr>
</tbody>
</table>
must be tuned to the organisational constraints as well as be introduced into a range of institutions with more familiar, artisanal contracting schemes. This risk area captures the potential delay in the early contract awards which affects the project schedule.

<table>
<thead>
<tr>
<th>#</th>
<th>Risk ID</th>
<th>Risk Title</th>
<th>Probability of occurrence %</th>
<th>Exposure (€M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PO-380</td>
<td>Uncertainty in Cost Estimate</td>
<td>50%</td>
<td>€ 31,500,000</td>
</tr>
<tr>
<td>2</td>
<td>PO-274</td>
<td>Contractor Delay Due to Insufficient Coordination with Other Contractors</td>
<td>50%</td>
<td>€ 28,750,000</td>
</tr>
<tr>
<td>3</td>
<td>PO-303</td>
<td>In-Kind Contributions Are Not Compliant With Technical, Quality Or Programme Requirements</td>
<td>50%</td>
<td>€ 24,500,000</td>
</tr>
<tr>
<td>4</td>
<td>LOW-307</td>
<td>Low Stations Cannot be Calibrated to Meet Requirements</td>
<td>25%</td>
<td>€ 14,055,000</td>
</tr>
<tr>
<td>5</td>
<td>PO-281</td>
<td>Adverse Exchange Rates</td>
<td>50%</td>
<td>€ 11,705,000</td>
</tr>
<tr>
<td>6</td>
<td>MID-312</td>
<td>Qualification of the Dish Prototype is Delayed</td>
<td>50%</td>
<td>€ 10,152,500</td>
</tr>
<tr>
<td>7</td>
<td>PO-387</td>
<td>Incomplete Product Level Acceptance Testing</td>
<td>80%</td>
<td>€ 8,938,720</td>
</tr>
<tr>
<td>8</td>
<td>PO-300</td>
<td>Procurement Phase Duration</td>
<td>50%</td>
<td>€ 7,500,000</td>
</tr>
</tbody>
</table>
and Complexity Under-Estimated in Project Schedule

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>PO-382</td>
<td>Missing L1 Requirements 80% € 6,055,200</td>
</tr>
<tr>
<td>10</td>
<td>MID-162</td>
<td>Permits, Licenses and Land Access not in place in time for Spiral Arm Construction 50% € 5,026,525</td>
</tr>
</tbody>
</table>

Risk will be managed through using a risk register during project execution; the risk register projected at the start of construction is detailed in SKA-TEL-SKO-0001104 SKA1 Risk Register. Currently, there are 84 high-level risks which encompass the overall project exposure. The risk exposures given in these 2 tables are probability-weighted numbers; the total risk exposure calculated by the Monte Carlo analysis is higher than this (see 11.5.2).

<table>
<thead>
<tr>
<th>WBS Area</th>
<th>No. of Risks</th>
<th>Risk exposure €M</th>
</tr>
</thead>
<tbody>
<tr>
<td>01 SKA1</td>
<td>20</td>
<td>122</td>
</tr>
<tr>
<td>01.01 Project Office</td>
<td>9</td>
<td>14</td>
</tr>
<tr>
<td>01.02 MID Telescope</td>
<td>22</td>
<td>40</td>
</tr>
<tr>
<td>01.03 LOW Telescope</td>
<td>17</td>
<td>31</td>
</tr>
<tr>
<td>01.04 Observatory Computing &amp; Software</td>
<td>16</td>
<td>13</td>
</tr>
<tr>
<td>Totals</td>
<td>84</td>
<td>221</td>
</tr>
</tbody>
</table>

11.4.1.4 Risk Handling

Responses to risks generally fall into one of four categories; mitigate, accept, avoid or transfer. The selected strategy is documented in the applicable risk assessment form. Cost and schedule impacts related to the scope of the related risk handling strategies are thereby included in the project baseline cost and schedule independent of any cost contingency or schedule contingency.

11.4.1.5 Risk Monitoring

A primary criterion for successful management is formally monitoring and documenting the on-going risk management process as it:

- provides the basis for program assessments and updates as the project progresses;
- provides the framework for a more comprehensive assessment;
- provides a basis for assessment of risk handling success;
- provides project background for new personnel; and
- provides a history of the rationale for project decisions.

The risk register and JIRA issue tracking (for capturing and reviewing potential risks/issues/opportunities) when combined with the project’s budget, schedule, WBS and ICDs form a comprehensive risk management toolbox and are employed as essential tools and guides in our risk management process.
They allow the project team to easily record and track risk management issues, quickly assess the technical status of the designs in the context of risk assessment and proactively manage risk-related issues. A regular monthly review during construction provides the forum which allows the telescope delivery Teams to identify, assess and track risks, risk mitigation effectiveness and form the associated risk mitigation plans and actions. The detailed technical readiness of the various assemblies and sub-systems is considered and updated as they evolve, and issues raised are recorded and reviewed, all in the context of the overall budget and schedule. This process extends throughout construction including the assembly, integration, and test, commissioning phase, and science verification phases.

The risk register review has several monitoring components:

- It is a part of the monthly programme & telescope delivery team meetings. On this time cadence, the risks associated with the ongoing/future efforts are reassessed (along with any newly identified or proposed risks). The mitigations are reviewed (along with exploration of opportunities). The probabilities are reviewed and adjustment as well as the cost basis of estimate if there is new information. Trigger dates are also updated as new information in the execution is obtained.
- It is an aspect of the bi-weekly telescope delivery team meetings which review product delivery status and between-sub-system issues (first alert to potential risks).
- The risk register itself evolves over time. As information is obtained risks can be elaborated potentially splitting into multiple, better-defined components.
- The overall burnout of the contingency over time is monitored and compared to the 80% probability of success exposure.

Risk change logs will enable easy summary of changes over specified time ranges for easy reporting and historical review.

### 11.5 Contingency Management

#### 11.5.1 Contingency

The establishment of the project contingency is described in detail in SKA-TEL-SKO-0001200 SKA1 Project Management Controls System.

The project employs the following definitions for risk and contingency.

- **Risk**: “An uncertain event or condition that, if it occurs, has a positive (opportunity) or negative effect on at least one project objective.”. See section 5 for more on risks.
- **Contingency**: “A planned amount of money or time which is added to a baseline estimate to address specific, identified risks”.
- **Management reserve**: A reserve held at the highest level of the organisation (Observatory Council, member countries). If it is not made available, a likely response to an unforeseen risk occurrence which gives rise to a cost is a de-scoping to stay within budget.

Contingency is considered part of the total project cost, where total project cost = sum of the performance baseline and the budgeted contingency.

Contingency is held by the programme and managed through a change control process (SKA-TEL-SKO-0001200).
There are additional risks that the project faces, but which are not considered appropriate to include within the total project cost, particularly those for which the risks cannot be clearly identified and estimated. For these areas, there should be a management reserve established.

The management reserves:

- Covers unforeseen risks to the project (“unknown unknowns”).
- Is not considered a part of the total project cost.

It is important to stress that contingency does not provide for costs outside of the approved project scope. Should change requests of this nature arise that are considered to be scope-creep they will be rejected unless they are clearly within the realms of value-engineering, e.g., changes that will reduce whole-life costs for the Observatory.

If the programme and costing were completely accurate, all contingency funds will have been allocated to work package areas and spent by the end of the project.

If the programme underestimated the risk exposure in realising the construction, the project will need to provide descopes to stay within the total project cost.

If the programme overestimated the risk need, funds can be returned to the IGO general fund and hence back to the member countries unless some other agreement can be made.

11.5.2 Budget Contingency

As described in detail in SKA-TEL-SKO-0001200 SKA1 Project Management Controls System, we employ three techniques for estimating the project exposure to risk:

- Reference case evaluation of the SKA1 project compared to other comparable, successful projects with similar levels of uncertainty. Using principally large research facility projects, a range of 20-30% can be applied to assure successful completion within the constraints of budget and schedule.
  - This indicates a contingency valuation of €200 M-€300 M.
- Work package level evaluation of the technical, cost and schedule risks for the individual, isolated work activities (represented in SKA-TEL-SKO-0001102) estimated on the basis of design maturity and work content by a standard method. We note that this estimation does not consider dependencies between work packages.
  - This indicates a contingency valuation of €224 M (22%)
- Risk register evaluation organised by WBS, subjected to Monte Carlo simulation. The risk identification process is elaborated in SKA-TEL-SKO-0001104.
  - This indicates a contingency valuation of:
    - Probability weighted: €221 M (22%)
    - 50% probability of success: €216 M (21%)
    - 80% probability of success: €273 M (27%)

Overall, the contingency estimation is consistent across these techniques. We propose the 80% probability of success from the Risk Register Monte Carlo modelling as the ‘best’ estimate, resulting in a €273 M (27%) contingency value.
This value represents the initial contingency pool to allow the project to manage the represented uncertainties and still deliver the project scope within budget and schedule. This value and its time phasing, derived from the modelling, will be integrated into the funding profile for the project.

There are additional risks outside of this estimation, in particular, the “unknown-unknowns”, which cannot be readily identified (i.e., quantified in time or impact) or factored into the existing risk management framework. This includes force majeure events during the period of execution. If such events occur during the construction phase, the SKA Observatory expectation is that the measurable consequences will need to be jointly managed by the IGO member countries alongside the construction project management; this expectation was confirmed by the SKA Board of Directors Executive Committee.

Table 25. Contingency estimates.

<table>
<thead>
<tr>
<th>Method</th>
<th>Overall contingency % estimated</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference case</td>
<td>26</td>
<td>DKIST, on track</td>
</tr>
<tr>
<td>Work package</td>
<td>23</td>
<td>Dash 360, 231 M</td>
</tr>
<tr>
<td>Quantified risk register</td>
<td>22</td>
<td>SKA, 221M probability-weighted risk exposure</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>SKA, 273 M at 80% success probability</td>
</tr>
</tbody>
</table>

During project execution, the contingency will be held at the project level by the programme and allocated as needed via the formal change control process. For the avoidance of doubt, it will not be held at the work package or contract level. The contingency needs to be held in cash and cannot be provided in-kind.

11.5.3 Schedule Contingency

Schedule contingency, as with budget contingency, represents the known unknowns in task duration for the various WBS components that will contribute to the overall duration of the project but that are not deterministic at the outset of the project.

Each work package has an assessed best-case and worst-case schedule scenario for completion. A Monte Carlo simulation of the project with these ranges indicated an 18-month schedule contingency was required for the 80% likelihood of success; we note this number has increased in the context of the COVID-19 pandemic, which has added significant uncertainty to the near-term (initial years) of the project due to schedule impacts for travel and manufacturing availability.

- July 2029: The requested baseline completion date; there are 18 months of schedule contingency remaining between the current IPS end date and this date.
- January 2028: The current IPS end date; this schedule will be reviewed monthly.

The estimated schedule contingency is converted into a cost exposure at the work package level and is therefore included as a part of the budget contingency.

11.5.4 Scope Contingency

The project has no in-built scope contingency within the plan, that is, all viable reductions in scope correspond to an impact on the overall project performance in technical or programmatic areas. This indicates that we rely strongly on the initial projections and risk assessment performed at the beginning of the project along with the risk management process to deliver the project over its projected eight-year execution.
If the contingency funds are insufficient to manage the risks encountered during the execution of the project or if there are issues with funding availability (whether due to a short-term deficit that emerges during the programme timeline or a more significant challenge to funding, for example, the withdrawal of commitment from a member), there may be some need to consider de-scopes during the execution. There are essentially two types: 1) temporary descope (e.g., a pause in production to manage across a short-term funding situation) 2) a permanent descope (e.g., a reduction in capability due to a persistent funding shortfall). In the former case, the project would apply this as a part of the approved contract management and recover at the earliest opportunity with information highlighted in the planned monthly reports; in the latter case, the project would solicit review and approval for scenarios from the Observatory Council (or its delegated body) with a rapid suspense for decision-making from the available de-scope options.

At the time of preparation of this proposal, looking to the start of the construction phase, it is understood that the full funding commitment for the SKA1 design baseline is not yet identified. This provides challenges in the execution, particularly in the acquisitions functioning. However, the array-concept of the observatory naturally leads to working systems at early stages and as such holds little risk for even permanent funding shortfalls in providing a functioning observatory, albeit with reduced performance. The following section outlines a high-level set of scenarios which exploit the planned array assembly roll-out of capability. As noted, this model provides a persistent, working facility at an early stage with full extensibility to the design baseline, as funding allows, given the early full implementations of the infrastructure scope.

11.5.4.1 Scientific Scenario Planning

As the construction of SKA1 proceeds, there is a continuous growth in its hardware and software scope that is paired with continuous enhancement of its scientific capabilities. The system roll-out has been organised into a sequence of delivery milestones, termed “array assemblies” (abbreviated AA). These occur at roughly yearly intervals. A summary of the scope of these Array Assemblies is listed in Table 17 and Table 18 (Section 9; taken from the roll-out plans for the two arrays and the “Science Commissioning and Verification Plan”, SKA-TEL-SKO-0000315), together with an indication of the capabilities that are currently planned to be delivered at each stage. After science commissioning, the capabilities enabled by the array assemblies will be made available to the astronomical community through regular public science verification (SV) data releases for individual observing modes. An SV observation provides an end-to-end test of the entire SKA for a specific mode of observation and demonstrates the performance of the system to the wider community.

Some context for how the scientific capability increases with AA roll-out is given in Figure 163 and Figure 164, where the array sensitivity and survey speed as a function of frequency are contrasted with existing facilities. What is apparent from this comparison is that competitive scientific performance is available from about AA2 (64 LOW stations, 64 MID dishes) onward at essentially all frequencies for both SKA1-LOW and SKA1-MID. At about this point, both the sensitivity and survey speed performance begin to exceed that of the best existing facilities operating at these frequencies. For this reason, the first science verification data releases are planned towards the end of AA2 and will continue at regular intervals through construction as new modes are commissioned, and capabilities improve. However, it is clear that the transformational science of which SKA is capable will only begin to be available at AA3 and the truly unique capabilities of AA4 remain the goal of the entire partnership.

To briefly summarise the scope and scientific capabilities by AA:
• AA1 (18 LOW stations, 8 MID dishes): Basic continuum and spectral line imaging with some restrictions on total bandwidth and spectral sampling, CASA software.
  o Continuum and spectral line (below 2 GHz) imaging studies, for example, to characterise star formation and atomic hydrogen kinematics within nearby galaxies, to confirm basic telescope operation and calibration, but with non-competitive sensitivity.

• AA2 (64 LOW stations, 64 MID dishes): As above plus wider bandwidths and pulsar timing with limited beams
  o Continuum and spectral line (partially equipped up to 15 GHz) imaging studies, for example, to provide imaging of complex galactic and extragalactic fields and wide-area surveys of the polarised continuum sky with competitive sensitivity.

• AA3 (256 LOW stations, 128 MID dishes): As above plus full bandwidth, full pulsar timing, partial pulsar survey, partial transient capture and SDP software
  o Continuum and spectral line (half equipped up to 15 GHz) imaging studies, for example, to achieve statistical detection of the Epoch of Reionisation and obtain deep neutral hydrogen imaging of low redshift galaxies with state-of-the-art sensitivity.

• AA4 (512 LOW stations, 197 dishes; 133 MID + 64 MeerKAT): As above plus full pulsar search, transient capture and VLBI
  o The complete science programme of the SKA is now accessible, including extremely fast and complete pulsar surveys, fast transient source localisation, direct imaging of Epoch of Reionisation structures and proto-planetary disks, etc. Sensitivity and survey speed are matched to delivery of an indicative core programme of scientific deliverables (the so-called high priority science objectives) within a five-year timeframe.

Figure 163. Sensitivity as a function of frequency for AA1 through AA4, contrasted with existing facilities.
11.5.5 Contingency Management

Contingency management is a formal process that provides the ability and flexibility to solve issues that may impact the project’s budget, schedule and technical performance, including activity-based and event-based uncertainties. It is a part of the SKA1 change control process and risk management processes.

As noted in 6.3, the programme will review risk exposure vs. contingency envelope on a monthly basis and recalculate the remaining risk exposure. The Euro value exposure of the 80% confidence level in risk is then compared to the project’s contingency pool and profile to ensure that the project maintains at least that level of success.

11.5.6 Contingency at the End of Construction

If the programme was completely accurate, all contingency funds will have been allocated to work package areas and spent.

If the programme underestimated the risk exposure in realising the construction, the project will need to provide de-scopes to stay within the total project cost established by the committed cost cap funding plus the internal work package budget.

If the programme overestimated the risk need, funds can be returned to the IGO and back to the member countries.
11.6 Risk and Contingency Management

SKA1 has a change control board which convenes and supports the risk management and contingency management processes. These processes are a component of the project’s PMCS.

The change control board is composed of four voting members:

- SKA1 Programme Director (Chair)
- SKA1 Director of Science
- SKA1 Director of Operations
- SKA1 Head of Assurance (Deputy Chair)

It is intended that decisions will be unanimous. If an agreement cannot be reached it will be escalated by the chair to the Director-General.

The Programme Director in their role in the CCB is supported by:

- SKA1 Head of Project Management Group (further supported by relevant PMs)
- SKA1 Project Engineer (further supported by relevant telescope and system engineers)
- SKA1 Head of Computing and Software (further supported by relevant software engineers)
- SKA1 System Scientist
- SKA1 Site Construction Director (LOW, MID)

The Observatory delivery team members (being the Programme Director, their direct reports and the 2 senior PMs) will review the risk and contingency information monthly, assessing the following KPIs:

- Overall project risk exposure (in €M)
- Risk exposure trend (first derivative over time)
- Risk confidence level (assuming 80% probability of success at the start of the project, review whether this metric is being maintained).
- Critical milestone date (track the current planned project end date vs. the baseline forecast)
- Budget contingency
- % Budget contingency of estimate to complete (use both ETC equations)
- Schedule contingency (schedule expenses maintained in the overall budget contingency)
- Contingency burn down profile as compared to funding profile

11.6.1 Risk and Contingency Planning

This risk management and contingency management planning within this document will be updated as our processes/procedures change. It will be reviewed annually.

11.6.2 Resource Implications of the Plan

As noted in 6.3, there is at least a monthly tracking within the project at the subsystem and integration level. In addition, external risk experts will be used periodically to help improve our processes and enhance the visibility and accuracy of the information.
11.6.3 Schedule Implications of the Plan

As above, at least monthly review is required. Documented updates are expected within the risk register at least quarterly (the risks are colour coded to indicate their time of last modification). Similarly, mitigation status and notes are documented through the web interface. All KPI metrics will be updated and reported monthly (internally).

11.7 SKA1 Change Control

Changes will inevitably occur, and the change management process ensures these changes are captured and incorporated into the baseline in a controlled and timely manner. The change process is initiated by the need to modify the design baseline, the cost baseline and/or the baseline dates or resource allocations in the integrated project schedule (IPS). These databases collectively compose the SKA1 “baseline”. The change control process is designed to ensure all changes to the project are controlled, documented and managed in a consistent manner. The process is fully documented in [AD3].

Change requests are generally driven by risks or opportunities identified in the risk register and the “risk ID” is entered on the change request form when available.

The change control process in the context of the PMCS focuses on the management and maintenance associated with handling the baseline data within the earned value management system (Cobra) and the integrated project schedule (Primavera). Additionally, both of these databases are driven by any changes that may occur to the technical scope of the project. Once changes are implemented in the respective PMCS databases, budget changes are implemented in the SKA1 ERP system and documented in JIRA.

11.8 Project Management Controls

11.8.1 Cost Management

The baseline budget is produced by work package in Dash 360 and once approved by the Council is entered into the Business World On! accounting tool. The budget will be amended via formal change control as described previously. Actual costs are recorded at the work package level as they are received, whether by invoice (for cash contracts, internal non-labour and travel), by value allocation (for in-kind contracts) or by time-recording (for internal labour). Project Managers will review actual costs against the budget for each of their work packages on a monthly basis, correct any errors and then investigate and address any variances. The cost status and variances will be reported in the monthly report.

Actual costs vs budget for each work package is communicated on a monthly basis from Business World On! to Cobra for the earned value analysis.

11.8.2 Schedule Management

The baseline schedule is produced and maintained in Primavera at and below work package level. Progress against the schedule is reported on a monthly basis by Project Managers to the Project Controls Manager, based on inputs they receive under the NEC contracts and other agreements. Depending on the work package type, progress may be reported as % complete, by milestone or level of effort. Project Managers will review progress against schedule for each of their work packages on a monthly basis, correct any errors and then investigate and address any variances. The schedule status including that of key milestones, critical path and near critical path activities and variances will be reported in the monthly report.
Progress vs. schedule for each work package is communicated on a monthly basis from Primavera to Cobra for the earned value analysis.

11.8.3 Earned Value Management

The earned value of the project will be the sum of the earned value of all of its constituent workpackages. Each workpackage will be assigned an earned value technique in Cobra that will be used to calculate its earned value on a monthly basis.

Cobra contains the latest approved budget by work package and receives monthly updates from Business World On! and Primavera as to the actual costs and progress of each work package. Reports are then produced on a monthly basis of the earned value (budgeted cost of the work performed) at the work package level. Other performance indicators are also produced, namely, cost performance index, schedule performance index, estimate at completion and rolling trends of schedule and cost variance. These reports are used by Project Managers and the Programme Directorate to identify and address areas of concern.

In general, the internal construction support work packages will use the level of effort technique. For the contracted-out work packages these will generally use milestone or % complete. For software, in particular that delivered using the agile methodology, this is not as straightforward as the scope is more flexible and plans at the work package level are subject to more frequent change as resources are allocated to where they are likely to deliver the greatest value at that time. An earned value method for the agile work will use an assessment of the proportion of the committed resources actually engaged for each three monthly program increment (PI) together with the proportion of the objectives actually achieved in that PI.

11.8.4 Issue Management

The monthly review of risks by Project Managers will maintain an up to date view of the probability and exposure associated with each risk and therefore assess whether it has materialised into an issue.

Other issues that weren’t foreseen and listed as risks may also arise. Technical issues are logged in the TIMS/JIRA tool by anyone with access to the tool and allocated to the appropriate owner (currently done by the telescope engineers). Programmatic issues may also arise (also logged in TIMS/JIRA - TBC). The progress of these is reviewed at the appropriate level, which may be the PDT, TDT, or PB/PD. Should the treatment of these issues require a change to the budget, schedule or specification, a change request will be raised.

Contract issues (early warnings, compensation events, queries) are likely to be first identified in CEMAR (see below) and notified to the Project Manager in that way. Depending on the nature of the issue the Project Manager may raise a change request, a TIMS/JIRA issue ticket or take no action (if the so-called issue is simply a question of clarification or is deemed invalid).

Issues that are identified as non-conformances have a specific treatment – this will be more properly described in [AD3] however is summarised below as a placeholder. These are not dealt with as change requests because they are temporary situations.
11.8.5 Contract Management

CEMAR is the tool used to manage contract data and communications. Monthly reporting data including progress against schedule (the “programme”), early warnings and compensation events will be raised by contractors in this tool and Project Managers will inform the contractors of their decisions using the same mechanism.

11.9 Reporting

The Project Controls Manager will be responsible for collating monthly reports with the support of their team, the Project Managers, and Finance. It will be used by internal stakeholders to inform decision-making. Whilst it is recognised that the IGO Council will meet only 2 or 3 times per year, the report will be made available to them and other key stakeholders on a monthly basis. The monthly report will be used in aggregate form to support meetings occurring on a lower frequency.

11.10 Stakeholder Management and Communications

The communications, outreach, & education team in SKA provide communication to both internal and external stakeholders in the form of newsletters, the public website and social media, and provide outreach and education support to enable the ambitions of the Observatory by providing a SKA presence at relevant local and international conferences, exhibitions, and other events. The aim of this section is not to describe all of these, rather to focus on the project level stakeholder needs and communication flows that are managed or supported by the programmes team during construction such that the requirements for the PMCS can be set in context. This section thus ignores the Board of Directors, the transition to the IGO and the Council preparatory task force (as they will have been superseded/completed), the wider science community (managed by the science team) and public engagement (managed by the comms team).

Table 26. Key project stakeholder groups and their planned communications and owners (draft).

<table>
<thead>
<tr>
<th>Stakeholder group</th>
<th>Interest area</th>
<th>Communications Channels</th>
<th>SKAO Owner</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGO Council</td>
<td>Governance</td>
<td>Monthly Report, Council meetings</td>
<td>Programme Director</td>
</tr>
<tr>
<td>Science Working Groups</td>
<td>Users</td>
<td>TBC</td>
<td>Science Director</td>
</tr>
<tr>
<td>Science &amp; Engineering Advisory Committee</td>
<td>Advice</td>
<td>Monthly Report, SEAC meetings, Council meetings</td>
<td>Director-General</td>
</tr>
<tr>
<td>Finance Committee</td>
<td>Financial</td>
<td>FC meetings</td>
<td>Chief Finance</td>
</tr>
<tr>
<td>SKAO Members and Observatory Partners (e.g., government, funding agencies, industrial liaisons)</td>
<td>Financial/Fair Work Return, publicity</td>
<td>TBC, ad-hoc visits</td>
<td>Head of DG’s Office</td>
</tr>
<tr>
<td>Member Contributing Institutions</td>
<td>Financial, published papers</td>
<td>(As Tier 1 or 2 contractors or Construction Consultancy or via IGO Council members)</td>
<td>Programme Director</td>
</tr>
<tr>
<td>Host Countries</td>
<td>Long term continuity of facilities, financial, SKAO presence in-country</td>
<td>Monthly Report, Council meetings</td>
<td>Programme Director</td>
</tr>
<tr>
<td>Stakeholder group</td>
<td>Interest area</td>
<td>Communications Channels</td>
<td>SKAO Owner</td>
</tr>
<tr>
<td>-------------------------------------------------------</td>
<td>----------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------</td>
<td>------------------------------------------------</td>
</tr>
<tr>
<td>Telescope site local communities</td>
<td>Preventing disruption, employment opportunities</td>
<td>(Local communications plan and stakeholder engagement plan)</td>
<td>Construction Site Directors</td>
</tr>
<tr>
<td>Science Regional Centres</td>
<td>Users</td>
<td>TBC</td>
<td>Operations Director</td>
</tr>
<tr>
<td>National Regulatory Organisations (e.g., ITU for radio frequency interference; health, safety and environmental)</td>
<td>Compliance</td>
<td>TBC</td>
<td>Head of Assurance; Spectrum Management</td>
</tr>
<tr>
<td>Senior Leadership Team</td>
<td>Governance</td>
<td>Monthly Report, SLT meetings</td>
<td>Director-General</td>
</tr>
<tr>
<td>SKAO programme staff (project management, engineering, software, product assurance, configuration management, HSE)</td>
<td>Personal fulfilment, coordination, employment</td>
<td>Monthly Report, TDTs, PDTs, Engineering Forum, Q&amp;A, team meetings, CCB, Program Increment Planning events</td>
<td>Programme Director/delegates</td>
</tr>
<tr>
<td>Other SKAO staff outside the programme team (Operations, Science, Finance, Comms, HR)</td>
<td>Users and supporters, employment</td>
<td>Monthly Report, SLT, weekly briefing</td>
<td>SLT members</td>
</tr>
<tr>
<td>Tier 1 contractors</td>
<td>Financial</td>
<td>Contract meetings, CEMAR</td>
<td>Project Managers</td>
</tr>
<tr>
<td>Tier 2 contractors</td>
<td>Financial</td>
<td>Contract meetings, CEMAR</td>
<td>(Project Managers)</td>
</tr>
<tr>
<td>Wider engineering community (e.g., other observatories or science infrastructure projects)</td>
<td>Collaboration/mutual benefits in exchanging reviewers, employees, lessons learned etc.</td>
<td>Peer to peer</td>
<td>Programme Director/delegates</td>
</tr>
</tbody>
</table>

**11.11 Review and Reporting**

The key performance indicators measured to monitor and control the project execution are represented in the following table (and further elaboration in SKA-TEL-SKO-0001200 SKA1 Project Management Controls System).
Table 27. Projected key performance indicator reporting for the project management control system.

<table>
<thead>
<tr>
<th>EVM Status Report</th>
<th>€ M</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVM Reporting Date</td>
<td></td>
<td>Date of the report</td>
</tr>
<tr>
<td>Total Project Cost (TPC)</td>
<td>€1282 M</td>
<td>Performance Baseline+Contingency</td>
</tr>
<tr>
<td>Member Funding To-Date</td>
<td>€0</td>
<td>Amount of funding received to date</td>
</tr>
<tr>
<td>Budget at Completion (BAC)</td>
<td>€</td>
<td>Approved Budget</td>
</tr>
<tr>
<td>Planned Value ($M)</td>
<td>€</td>
<td>Planned value for date of report</td>
</tr>
<tr>
<td>Earned Value ($M)</td>
<td>€</td>
<td>Earned value for date of report</td>
</tr>
<tr>
<td>Actual Costs ($M)</td>
<td>€</td>
<td>Actual costs at date of report</td>
</tr>
<tr>
<td>% Complete (Planned)</td>
<td>0%</td>
<td>PV/BAC*100%</td>
</tr>
<tr>
<td>% Complete (Actual)</td>
<td>0%</td>
<td>EV/BAC*100%</td>
</tr>
<tr>
<td>% Complete (Spent)</td>
<td>0%</td>
<td>AC/BAC*100%</td>
</tr>
<tr>
<td>Cost Variance (CV)</td>
<td>€0.0</td>
<td>EV-AC</td>
</tr>
<tr>
<td>Schedule Variance (SV)</td>
<td>€0.0</td>
<td>EV-PV</td>
</tr>
</tbody>
</table>

Forecast

| Estimate at Completion (EAC - €M) | €1282 | Latest updated budget estimate |
| EAC1: AC+(BAC-EV) | | Date of last update of the EAC |
| EAC2: AC+(BAC-EV)/(CPI*SPI) | €1282 | |
| Date of last EAC update | Jun 2020 | |
| Unencumbered Funds | € | TPC-BAC |
| Liens | Known costs, variances not in BAC |
| Budget Contingency | € | Unencumbered Funds - Liens |
| Estimate to Complete (ETC) | €1282 | EAC1-AC |
| Estimate to Complete (ETC) | €1282 | EAC2-AC |

A high-level tabular representation of the SKA1 Stakeholders is shown below in Table 28:

Table 28. Coarse stakeholder taxonomy for stakeholder management.

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Interest</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGO</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Science Community</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>(e.g., member radio astronomy communities, broader astronomical communities, etc)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Member Countries</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>(e.g., funding agencies, industrial liaisons, etc)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Member Contributing Institutions</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Host Countries</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>National Regulatory Organisations (e.g., telecommunications for radio frequency interference, etc)</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>General Public</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

The SKA1 project stakeholder management entails the development of monthly reports built on summary status updates as well as tracking according to the KPIs as noted above; these will be provided to the IGO and flow from there through the member country communities. This is intended to handle the high Interest/high power organisations which need to have direct and detailed insights into the project execution.

Further stakeholder management, in particular with regard to the general public, will be directed through the SKA Observatory’s communications office.
12 Health, Safety, and Environmental

SKAO HSE philosophy is to integrate good health, and environmental performance as a core element in every planning, design and construction operation to achieve our aim of being safe and secure. The details of the planning in this area are contained with SKA-TEL-SKO-0000740 SKA Organisation Health, Safety, & Environmental Management Plan.

12.1 HSE Policy

The SKAO HSE Policy (SKA-GOV-000063) sets out our general approach to health and safety and environmental issues. It explains how we, as an employer, will manage health and safety in our business.

This policy applies to all aspects of the SKAO programme, including implementation within the SKAO (through this SKAO project execution plan) and suppliers/industry partners (through contracts and agreements developed by the SKAO in accordance with the construction and operations plans).

The SKAO senior leadership team will ensure the availability of resources needed to implement this policy and ensure that it remains effective and relevant through regular reviews and updates.

This policy will be reviewed annually and communicated to all employees, users, and stakeholders.

12.2 HSE Planning

SKAO shall engage with all our staff, partners and suppliers to confirm that everyone is enthusiastically involved in managing risk, securing success and acting as an ambassador for our realistic and practical vision.

Current planning mainly draws on requirements from occupational health and safety management Standard ISO 45001:2017, environmental management standard 14001:2015 and is also inspired by similar plans from other major telescope projects.

Key national legislation includes (but is not limited to):

- South Africa - Occupational Health and Safety Act 1993,
- South Africa - Construction Regulations 2014,
- Australia - Work Health and Safety Act 2011,
- Australia - Work Health and Safety Regulation 2011,
- United Kingdom – Health & Safety at Work Act 1974,
- United Kingdom - Management of Health and Safety at Work Regulations 1999
- South Africa - National Environmental Management Act (NEMA) 1998 and amendments,
- Australia - Environmental Protection and Biodiversity Conservation Act (EPBA Act) 1999,
- Australia - Environmental Protection Act 1986 (WA) (EP Act),

The existing work of the SKA precursor and pathfinder telescope sites (e.g., ASKAP, MeerKAT, etc.) in the area of operational safety management are acknowledged and referenced with a view to incorporating best practice, lessons learned and coordination.

Health, safety, and environment management roles and responsibilities are described in SKA-TEL-SKO-0000740.
12.3 Safety in Design

The Design Safety Compliance Report (SKA-TEL-SKO-0001059) reviews design safety for phase 1 of the SKA Observatory, encompassing both SKA-LOW and SKA-MID. It does not consider construction or operation of SKA phase 2, the scope of which is not yet defined, although it is anticipated that the concepts defined there should be easily extensible to expanded versions of SKA-MID and SKA-LOW.

A design safety review was completed and focused on unusual aspects of the design which may involve unusual hazards that may require unusual risk controls to eliminate or minimise the risk (e.g., a working at height hazard involved in the maintenance of light fittings in a building atrium). Hazards that can be adequately addressed by applying solutions/guidelines in existing standards, e.g., building code requirements, standards, specific industry guidelines will be addressed via the adoption of the relevant solutions/guidelines (e.g., slips/trips/fall hazard associated with a stairway are addressed by compliance to the relevant building code and referenced standards).

The review included a process of consolidating consortia health and safety analyses data (from element CDR). Where appropriate, additional safe design options have been incorporated in the design to eliminate or mitigate identified hazards. The results are included in the hazard safety register.

Derived risk levels are an estimation, utilising relevant information available at the time of the design safety review. Any assumptions made at the time of the review may need to be confirmed at a later stage. It is strongly advised to confirm, so far as is reasonably practicable, that risks associated with the construction of the design, and use and maintenance of the design as a workplace, have been identified, that any estimated risk levels are appropriate, and that additional control measures (e.g., safe work instructions) instituted where required.

The design safety review sought, so far as reasonably practicable, to involve the participation of relevant project participants, including operations, to identify unusual hazards and controls associated with any unusual design aspects.

12.4 Security

The SKA1 construction project is maintained across several sites each with distinct physical security. The physical security measures are intended to address vulnerabilities to project staff, resources and information, in particular handling the threats of:

- Theft
- Physical damage
- Interruption of services/utilities
- Unauthorized disclosure of information

This is distinct from the safety arena which addresses the protection of life and assets against accidents, natural disasters, fire, etc. Physical security encompasses principally vandalism, theft and attacks by individuals while cybersecurity addresses aspects of electronic interference and theft.

For the project sites, this information is noted in:

- MID Site: SKA-TEL-SKO-000040 South African Site Information
- LOW Site: SKA-TEL-SKO-000041 Australian Site Information
13 Product Quality Assurance

The SKA1 Product Quality Assurance Plan is contained within SKA-TEL-SKO-0000739. This document defines the requirements and management activities for the SKA1 project, taking into account ISO 9001 standards, to ensure the characteristics of products and systems will fulfil the overall SKA1 requirements.

Quality assurance/product assurance is performed independently of the project under the Observatory assurance division. The project maintains responsibility for the acceptance and verification activities while quality assurance monitors and reviews the execution of those activities against the project standards and processes.

The approach to be taken is a system of inspections and acceptance events tailored to the technological and scale risks inherent in the construction of the SKA. The surveillance of parts, materials and processes focusses on those deemed critical, where criticality is determined by a number of factors such as lack of standards, historical manufacturing difficulties, and the vulnerability of the schedule to delays caused by supply. As is usual with product assurance activities, the more record-keeping, inspections and staff involved, the more costly the exercise. The SKA1 product quality assurance plan is the result of a trade-off against manufacturing risk as perceived from the production plans produced during pre-construction; hence the pattern of proposed inspections has led to the specification of a quality organisation suited to the specific task of ensuring quality in SKA1 construction whilst not overburdening resources and the schedule.

To illustrate the scope and completeness of the plan, the key sections extracted from the table of contents is reproduced below.

Table 29: Key sections from the table of contents for the SKA1 product quality assurance plan.

<table>
<thead>
<tr>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Quality Assurance Management</td>
</tr>
<tr>
<td>Quality Objectives</td>
</tr>
<tr>
<td>SKAO quality policy</td>
</tr>
<tr>
<td>Roles and responsibilities</td>
</tr>
<tr>
<td>SKAO PQA tasks</td>
</tr>
<tr>
<td>PQA Requirements</td>
</tr>
<tr>
<td>PQA management requirements</td>
</tr>
<tr>
<td>PQA general requirements</td>
</tr>
<tr>
<td>QA requirements for procurement</td>
</tr>
<tr>
<td>QA requirements for design, manufacturing and verification</td>
</tr>
<tr>
<td>QA requirements for testing</td>
</tr>
<tr>
<td>QA requirements for acceptance and delivery</td>
</tr>
<tr>
<td>QA requirements for learning from experience</td>
</tr>
<tr>
<td>Annexes</td>
</tr>
<tr>
<td>Quality Objectives Measurements Checklist</td>
</tr>
<tr>
<td>Checklist of Key PQA Activities</td>
</tr>
<tr>
<td>Quality Performance Indicators (QPI)</td>
</tr>
<tr>
<td>Nonconformance Report (NCR) Template</td>
</tr>
<tr>
<td>PQA Review Record Sheet</td>
</tr>
</tbody>
</table>
14 Project Close-Out

The project concludes with the completion of the hardware and software deployments, their successful verification and acceptance and the observatory science commissioning and science verification completion according to SKA-TEL-SKO-0000315. These milestones are reviewed and closed-out at an operations readiness review described in the SKA Product Quality Assurance guidelines (SKA-TEL-SKO-0000739):

“Following the system verification and science verification, SKAO will organise an ORR to review and evaluate their respective verification evidence in order to determine whether the telescope system and all its support hardware, software, personnel, procedures, and user documentation accurately reflect the deployed state of the telescope. A successful ORR at AA4 will be used to formally declare the telescope as fully operational.”

At the time of the ORR, the SKA1 project will demonstrate compliance with the subset of level 1 requirements possible at that time and based on the available observing modes outlined for AA4 in the verification and commissioning plans. The SKA1 project schedule has the level 1 milestone for this ORR in September 2027; as described in section 9, our modelling indicates that 12 months of contingency are required to assure completion of this milestone given the uncertainties in the duration of the activities and their logic. The level 1 milestone for the end of construction is September 2028.

In addition, to the above, there are additional areas for the project close-out:

- **Contractual**
  - The Head of Procurement reviews and identifies any open contracts and contacts remaining contractors for any relevant actions necessary to close the contract, as designated in the associated contract clauses and per SKA Observatory’s procedures and policies.
- **Observatory acceptance**
  - The Director-General/Director of Operations issue a formal acceptance receipt noting that the terms of the project have been met according to plan (noting any waivers or considerations).
- **Host country**
  - The host country organisations conclude all asset transfers required for the start of observatory operations.

Further, subsequent to the project Close-out, the SKA Observatory maintains obligations for the decommissioning and deconstruction of the SKA1 at the end of its lifetime (approximately 50 years, pending other agreements). The SKA Observatory will develop a fund over its lifetime to ensure this capability.
15 Acknowledgements

These documents are the culmination of years of effort by a diverse, global group of experts from a wide range of organisations, including present and former staff of the SKA Organisation, the many partner institutions, industry collaborators, the construction consortia, advisory and review committees, science working groups and SKA governance structures. We hope that all contributors are proud of the result and we sincerely thank them for their excellent input. Their involvement has been instrumental in shaping the Project as we prepare to move now from planning to implementation and to set up the SKA Observatory as an Intergovernmental Organisation.
Annex A: Telescope Capabilities and Performance Definitions

Scientific performance is determined mainly by the following capabilities and performance characteristics:

- **Frequency range**: The range of frequencies or wavelengths over which the telescope has significant sensitivity.

- **Sensitivity**: The sensitivity can be defined in a variety of ways. A customary way to specify sensitivity is $A_e/T_{sys}$, where $A_e$ is the effective collecting area, considering inefficiencies and losses, and $T_{sys}$ is the total system noise, including sky noise and instrumental noise. This normally does not include systematic effects, which limit sensitivity through noise-like errors that cannot be removed. A second measure of sensitivity is ‘survey speed’, a measure of the time taken to reach a specified noise level on an image over a large area of sky. The customary parameterisation of this is $(A_e/T_{sys})^2\Omega$, where $\Omega$ is the noise effective field-of-view of the telescope. Neither of these sensitivity measures takes into account bandwidth.

- **Bandwidth**: The radio frequency (RF) bandwidth that is available to the telescope at any one time. Sensitivity for wide-band (continuum) observations is proportional to $\sqrt{B}$, where $B$ is the bandwidth. Bandwidth does not confer additional sensitivity for spectral line observations but does assist searches for spectral-line emission at unknown frequencies.

- **Polarisation capability**: The capability to measure and image polarisation characteristics of radio emission.

- **Distribution of collecting area**: At a given frequency, the sensitivity of the telescope to components of the spatial spectrum. This is determined by the array configuration.

- **Maximum baseline**: This determines the ultimate spatial resolution of the telescope, although the detailed distribution of collecting area determines the sensitivity at maximum resolution. The resolution is given approximately by the inverse of the maximum baseline, measured in wavelengths.

- **Temporal resolution**: The ability to resolve temporal variations limited only by bandwidths and noise.

- **Specialised pulsar capabilities to**:
  - Carry out searches for new pulsars over the entire visible sky.
  - Carry out extremely precise pulsar timing observations over a decade of elapsed time.

- **Very long baseline interferometry (VLBI)**: A capability to participate in observations with VLBI networks for which there are mutual sky visibility and frequency range compatibility.

- **Processing capability of the telescope along three dimensions over large fields**:
  - Spatial processing: the capability to make images of the sky in a given frequency band in all four Stokes parameters (IQUV).
  - Spectral processing: the capability to make spectra over a defined area of sky.
  - Mosaicked and on-fly-maps of large fields (SKA1-MID): the previous two capabilities over fields larger than the field-of-views of dishes.

- **Observing flexibility and response time temporal processing capabilities to**:
  - Divide the telescope arrays into sub-arrays.
  - Support multiple scientific uses of the same observations from the same sub-arrays (Commensal data collection, e.g., pulsar searches and imaging observations).
- Form multiple beams as well as multiple sub-arrays (SKA1-LOW).
- Detect and respond to fast (ms) astronomical transient events (e.g., fast radio bursts).
- Take images on sub-second time scales (slow astronomical events).
- Rapidly change observing programs as a result of an external or internal trigger (e.g., super-nova event detected by another telescope).

It is vital to design the Observatory to be as flexible as possible in ways not described above. Flexibility is only abandoned when it results in a significant, unavoidable cost. A key system design feature is sub-arrays: the ability to allocate and configure a subset of telescope resources (antennas, beamformers, correlators, processing resources), just sufficient for the observation. Once the configuration is done, the observation is executed on the sub-array. In addition, some observations may be identified as candidates for commensal observing, where data from a single sub-array is shared between projects; clearly, the configuration will need to support this capability.
Annex B: SKA1-MID Performance Parameters

Figure B-1 shows the array configuration and its relationship to the entire system. See also Figure 112 which illustrates the major sub-systems of the SKA1-MID telescope in block diagram form, including the signal chain.

Table B-1 contains selected performance parameters for SKA1-MID. In the frequency ranges where the MeerKAT antenna and the SKA1 antenna frontends overlap the common frequency range is shown. This provides the maximum collecting area for the array in those ranges.

More detail is provided in SKA-TEL-SKO-0001075 SKA1, design baseline description.

Figure B-1. A schematic illustration of the entire SKA1-MID system, showing the details of the array configuration.
Table B-1. Selected SKA1-MID performance parameters

<table>
<thead>
<tr>
<th>Aperture</th>
<th>m²</th>
<th>133 x 15-m (equiv. dia.) offset Gregorian reflectors Plus 64 x 13.5-m (equiv. dia.) offset Gregorian reflectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total physical aperture</td>
<td>33306</td>
<td></td>
</tr>
<tr>
<td>Total Available aperture</td>
<td>31641</td>
<td>Availability 95%</td>
</tr>
<tr>
<td>Minimum Elevation Angle</td>
<td>15 deg</td>
<td>All Azimuths – 270° wrap</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Array Configuration</th>
<th>Antenna</th>
<th>Filling factor %</th>
</tr>
</thead>
<tbody>
<tr>
<td>radius &lt;~400 m</td>
<td>80 (41%)</td>
<td>2.67</td>
</tr>
<tr>
<td>~400 m &lt; radius &lt; ~1000 m</td>
<td>35 (18%)</td>
<td>0.22</td>
</tr>
<tr>
<td>~1000 m &lt; radius &lt; 2500 m</td>
<td>23 (12%)</td>
<td>0.023</td>
</tr>
<tr>
<td>~2500 m &lt; radius &lt; 4000 m</td>
<td>13 (6.6%)</td>
<td>7.04E-03</td>
</tr>
<tr>
<td>~4000 m &lt; radius &lt; 10000 m</td>
<td>13(6.6%)</td>
<td>8.53E-04</td>
</tr>
<tr>
<td>~10000 m &lt; radius &lt; 30000 m</td>
<td>15 (7.6%)</td>
<td>1.05E-04</td>
</tr>
<tr>
<td>~30000 m &lt; radius &lt; 100000 m</td>
<td>18 (9.1%)</td>
<td>1.11E-05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Antenna RF System</th>
<th>Frequency Range</th>
<th>GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1 (high) + UHF Band</td>
<td>0.58 – 1.015</td>
<td>Dual pol’n. Shared Frequency Range</td>
</tr>
<tr>
<td>Band 2 + L-band</td>
<td>0.95 – 1.67</td>
<td></td>
</tr>
<tr>
<td>Band 3 (Note 1)</td>
<td>1.65 – 3.05</td>
<td>Dual pol’n. SKA antennas only</td>
</tr>
<tr>
<td>Band 4 (Note 1)</td>
<td>2.80 – 5.18</td>
<td></td>
</tr>
<tr>
<td>Band 5a</td>
<td>4.60 – 8.50</td>
<td></td>
</tr>
<tr>
<td>Band 5b</td>
<td>8.30 – 15.4</td>
<td></td>
</tr>
<tr>
<td>Band 5c (Note 1)</td>
<td>15.0 – 26</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Continuum Sensitivity</th>
<th>Jy</th>
<th>Equivalent $A_e/T_{sys}$ (m²/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1 (high) + UHF Band</td>
<td>2.85</td>
<td>967</td>
</tr>
<tr>
<td>Band 2 + L-band</td>
<td>1.55</td>
<td>1784</td>
</tr>
<tr>
<td>Band 3</td>
<td>2.50</td>
<td>1102</td>
</tr>
<tr>
<td>Band 4</td>
<td>3.49</td>
<td>792</td>
</tr>
<tr>
<td>Band 5a</td>
<td>2.38</td>
<td>1161 (Max. Sampled Bandwidth 2 x 2.5 GHz)</td>
</tr>
<tr>
<td>Band 5b</td>
<td>2.77</td>
<td>998 (Max. Sampled Bandwidth 2 x 2.5 GHz)</td>
</tr>
<tr>
<td>Min. detectable flux (rms) ($\Delta S_{min}$)</td>
<td>µJy s⁻¹/²</td>
<td></td>
</tr>
<tr>
<td>Band 1 (high) + UHF Band</td>
<td>99.8</td>
<td>Average over RF bands</td>
</tr>
<tr>
<td>Band 2 + L-band</td>
<td>42.1</td>
<td></td>
</tr>
<tr>
<td>Band 3</td>
<td>48.9</td>
<td></td>
</tr>
<tr>
<td>Band 4</td>
<td>53.1</td>
<td></td>
</tr>
<tr>
<td>Band 5a</td>
<td>25.3</td>
<td></td>
</tr>
<tr>
<td>Band 5b</td>
<td>29.4</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signal Processing System</th>
<th>Correlator</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq. chans (widest sampled BW)</td>
<td>65536</td>
<td></td>
</tr>
<tr>
<td>Full Bandwidth Velocity Resolution</td>
<td>km-s⁻¹</td>
<td></td>
</tr>
<tr>
<td>Band 1 (high) + UHF Band</td>
<td>~5</td>
<td>Non-Zoom, all available frequency channels</td>
</tr>
<tr>
<td>Band 2 + L-band</td>
<td>~5</td>
<td></td>
</tr>
<tr>
<td>Max. Frequency Resolution</td>
<td>0.21 kHz</td>
<td>13.440 • 2⁻ⁿn E (0,..,6) kHz in Zoom mode</td>
</tr>
<tr>
<td>Standard Frequency Resolution</td>
<td>13.44 kHz</td>
<td>220.200960 / 16384</td>
</tr>
<tr>
<td>Complex Correlations</td>
<td>5.1 x 10⁹</td>
<td>(197²/2) baselines x 4 pol’n prod’s x 65536 chans</td>
</tr>
<tr>
<td>Minimum Integration Time</td>
<td>0.14 s</td>
<td>Interface Control Document</td>
</tr>
<tr>
<td>Transient Capture Buffer Size</td>
<td>72 – 288 s</td>
<td>For 330 MHz BW, scaling with 2-8 bits sample width</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pulsar Search Array Beam Former</th>
<th>Full beamformer</th>
<th>197 antennas</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Antennas in 20 km array diameter</td>
<td>164</td>
<td>Any Front-end band.</td>
</tr>
<tr>
<td>Available Bandwidth</td>
<td>300 MHz</td>
<td>Each polarisation</td>
</tr>
</tbody>
</table>

---

Notes:
53 This table reflects based on the best available performance information as of March 2020. In some cases, they are based on actual sub-system designs and in others on requirements. The table will be updated in further releases.
<table>
<thead>
<tr>
<th>Beam Area at 1 GHz</th>
<th>$12.7 \text{ arcsec}^2$</th>
<th>$\frac{\pi}{4} (1.3 \lambda_{1\text{GHz}} / D_{\text{array}})^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available No. of IQUV Stokes power beams</td>
<td>1500</td>
<td>Pol’n corrected on output.</td>
</tr>
<tr>
<td>Available No. of Frequency Channels</td>
<td>3720</td>
<td>Resolution 80.64 kHz</td>
</tr>
<tr>
<td>Channel tuning resolution</td>
<td>1.26 kHz</td>
<td></td>
</tr>
<tr>
<td>Impulse Response Bands 1-3</td>
<td>30 dB/sample</td>
<td>Decay rate with no oversampling</td>
</tr>
<tr>
<td>Impulse Response Bands 4-5</td>
<td>40 dB/sample</td>
<td></td>
</tr>
</tbody>
</table>

**Pulsar Timing Array Beam Former**

<table>
<thead>
<tr>
<th>Full beamformer</th>
<th>197 antennas</th>
<th>Any Front-end band.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available number of ‘voltage’ beams</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Available Total Bandwidth</td>
<td>20 GHz</td>
<td>Each pol’n; aggregate over 16 beams</td>
</tr>
<tr>
<td>Available No. dual pol’n Freq. Chans.</td>
<td>3720</td>
<td>Resolution 53.76 kHz</td>
</tr>
<tr>
<td>Impulse Response Bands 1-3</td>
<td>30 dB/sample</td>
<td>Decay rate with no over-sampling</td>
</tr>
<tr>
<td>Impulse Response Bands 4-5</td>
<td>40 dB/sample</td>
<td></td>
</tr>
</tbody>
</table>

**VLBI Beam Former**

<table>
<thead>
<tr>
<th>Full beamformer</th>
<th>197 antennas</th>
<th>Any Front-end band.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available Bandwidth</td>
<td>2 x 2.5 GHz</td>
<td>Per beam; 2 pol’n; Band 5, full BW for other bands.</td>
</tr>
<tr>
<td>Available No. of real-valued voltage beams</td>
<td>4</td>
<td>Pol’n corrected on output.</td>
</tr>
<tr>
<td>No. of frequency-chann bandwidths</td>
<td>9</td>
<td>1, 2, 8, 16, 32, 64, 128, 224 MHz</td>
</tr>
</tbody>
</table>

Note 1: While bands 3, 4 and 5c are not formally part of the design baseline, the design will support these bands when LNAs are installed on the single cryostat that contains bands 3, 4, and 5. For bands 3 and 4, the entire signal-chain is present except the feeds and LNA components. For band 5c, the RF design is less mature, and the upper end of the frequency range is to be decided at a later date.
Annex C: SKA1-LOW Performance Parameters

Figure C-1 shows the array configuration and its relationship to the entire system. See also Figure 120, which illustrates the major sub-systems of the SKA1-LOW telescope in block diagram form, including the signal chain.

Table C-1 contains selected performance parameters for SKA1-LOW. More detail is provided in SKA-TEL-SKO-0001075 SKA1, design baseline description.

Figure C1: Top left: Full array configuration. Each dot is a cluster of 6 stations. Top right: Inner 4 km diameter array configuration. Each dot is a station. Bottom: Station beamformers, the correlator-(array) beamformer and the pulsar processors which transmit output data to the science data processors and VLBI terminals in Perth.
Table C.1. Selected SKA1-LOW performance parameters.

<table>
<thead>
<tr>
<th>Aperture Arrays</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Frequency</td>
<td>50 MHz</td>
</tr>
<tr>
<td>Upper Frequency</td>
<td>350 MHz</td>
</tr>
<tr>
<td>Number of antennas per station</td>
<td>256</td>
</tr>
<tr>
<td>Station Effective Diameter*</td>
<td>38 m</td>
</tr>
<tr>
<td>Number of stations</td>
<td>512</td>
</tr>
<tr>
<td>Total physical aperture</td>
<td>$5.8 \times 10^5 \text{ m}^2$</td>
</tr>
<tr>
<td>Dense/Sparse Transition**</td>
<td>~94 MHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Array Configuration</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Core (radius &lt;500 m)</td>
<td>224 stations</td>
</tr>
<tr>
<td>Inner (radius &lt;1700 m)</td>
<td>278 stations</td>
</tr>
<tr>
<td>Spiral Arms</td>
<td>234 stations</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Station Beam Forming</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of beams***</td>
<td>1 – 384</td>
</tr>
<tr>
<td>Max. bandwidth per beam</td>
<td>300 MHz</td>
</tr>
<tr>
<td>Max. no. of antennas per beam</td>
<td>256</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signal Processing System</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. no. frequency channels</td>
<td>55296</td>
</tr>
<tr>
<td>Standard Frequency Resolution</td>
<td>5.4 kHz</td>
</tr>
<tr>
<td>Max. Frequency Resolution</td>
<td>226 Hz</td>
</tr>
<tr>
<td>Complex Correlations****</td>
<td>$2.9 \times 10^{10}$ (512-513/2) baselines x (1) beams x 4 pol'n prod's x 55296 chans</td>
</tr>
<tr>
<td>Integration Time</td>
<td>0.9 s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Array Beam Former</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Full beamformer</td>
<td>512 stations</td>
</tr>
<tr>
<td>Within 20-km Array Diameter</td>
<td>404 stations</td>
</tr>
<tr>
<td>Pulsar Search</td>
<td>500</td>
</tr>
<tr>
<td>Pulsar Timing</td>
<td>16</td>
</tr>
<tr>
<td>VLBI</td>
<td>4</td>
</tr>
<tr>
<td>Max. Total Bandwidth</td>
<td>118 MHz</td>
</tr>
<tr>
<td>Pulsar Search</td>
<td>300</td>
</tr>
<tr>
<td>Pulsar Timing</td>
<td>300</td>
</tr>
<tr>
<td>VLBI</td>
<td>300</td>
</tr>
</tbody>
</table>

* The effective diameter of a station is a best-fit circle, centred at the station location, to the centres of symmetry of the antenna elements in a station. The inverse of this diameter in wavelengths will approximate the width of the unweighted station beam on the sky in units of radians.

** Dense: Station $A_e$ is equal to the station physical area, assuming no losses. Sparse: Station $A_e = A_{e\text{, ant}} \times N_{\text{ant}}$ (effective area per antenna times the number of antennas. This is always less than the station physical area).

*** No. of beams, bandwidth per beam, and no. of antennas included in the beam can be traded, so as to maintain a constant data-output from the beamformer to the correlator.

**** Includes autocorrelations.
Annex D: Project Execution Plan Content Summary with Navigational Pointers to Detailed Document Areas

Table D-30. Project execution plan content summary.

<table>
<thead>
<tr>
<th>Document Component</th>
<th>Project Document Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Introduction</td>
<td>SKA-TEL-SKO-0001100 SKA1 Project Execution Plan</td>
</tr>
</tbody>
</table>
| 2 Science Motivation | SKA-TEL-SKO-0000007 SKA1 Science Requirements (Lvl 0)  
SKA-TEL-SKO-0000307 SKA1 Operational Concept Document (Lvl 0)  
Description of scientific objectives and impacts motivating the proposal. |
| 3 The SKA Observatory | SKA-TEL-SKO-0001100 SKA1 Project Execution Plan  
Description of internal and external organisation, governance and communications (including key roles and responsibilities) as well as staffing plans and hiring/staff transition plans.  
SKA-TEL-SKO-0001075 SKA1 Design Baseline Description  
Brief summary of pre-construction design development phase; link to design baseline description. |
| 4 Baseline Design   | SKA-TEL-SKO-0001100 SKA1 Project Execution Plan  
Ref: SKA-TEL-SKO-0001075 SKA1 Design Baseline Description  
Brief summary of pre-construction design development phase; link to design baseline description. |
| 5 Construction Project Definition | SKA-TEL-SKO-0001100 SKA1 Project Execution Plan  
SKA-TEL-SKO-0001101 SKA1 WBS Dictionary  
SKA-TEL-SKO-0001102 SKA1 Project Management Baseline Cost Book  
SKA-TEL-SKO-0001103 SKA1 Integrated Project Schedule  
SKA-TEL-SKO-0001104 SKA1 Risk Register  
SKA-TEL-SKO-0001200 SKA1 Project Management Controls System  
Description of WBS, scope management plans, cost estimating plans, cost reports and baseline budget, funding profile, baseline schedule risk management and all contingencies. |
| 6 Project Engineering | SKA-TEL-SKO-0001201 SKA1 Engineering Management Plan  
Description of systems engineering plan, requirements, and interface management plans. |
| 7 Verification and Commissioning | SKA-TEL-SKO-0001100 SKA1 Project Execution Plan  
Ref: SKA-TEL-SKO-0001201 SKA1 Engineering Management Plan  
SKA-TEL-SKO-0001350 SKA1 Commissioning Plan  
SKA-TEL-AIV-4430001-SE-DIVP-PLN Integration and Verification Plan for SKA1 Low  
### Integration and Verification Plan for SKA1 Mid

**SKA-TEL-AIV-2430001-SE-DIVP-PLN**

Detailed planning and procedures to perform and verify the system performance against both the level 1 and the level 0 requirements (for a subset of identified observing modes).

<table>
<thead>
<tr>
<th>8 Acquisitions</th>
<th>SKA-TEL-SKO-0001100 SKA1 Project Execution Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SKA-GOV-0000069 SKAO Procurement Policy</td>
</tr>
<tr>
<td></td>
<td>SKA-GOV-0000070 SKAO Procurement Procedures</td>
</tr>
<tr>
<td></td>
<td>SKA-GOV-0000071 Framework for the Administration of In-Kind Contributions</td>
</tr>
<tr>
<td></td>
<td>SKA-GOV-0000072 Framework for the Administration of Fair Work Return</td>
</tr>
</tbody>
</table>

Description of procurement plans, processes, and contracting strategy, including time-phased list of procurement actions and assumed contract approval governance process. We note this points directly to the Observatory procurement policy & associated procurement procedures.

<table>
<thead>
<tr>
<th>9 Project Management Controls</th>
<th>SKA-TEL-SKO-0001200 SKA1 Project Management Controls System</th>
</tr>
</thead>
</table>

Description of project management control organisation and processes including EVMS, change control and risk management.

<table>
<thead>
<tr>
<th>10 Site</th>
<th>SKA-TEL-SKO-0001100 SKA1 Project Execution Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SKA-TEL-SKO-0001040 South African Site Information and Instructions: SKA1 MID</td>
</tr>
<tr>
<td></td>
<td>SKA-TEL-SKO-0001041 Australian Site Information and Instructions: SKA1 LOW</td>
</tr>
</tbody>
</table>

Summary of site environments and all permitting and compliance management aspects.

<table>
<thead>
<tr>
<th>11 Computing and Software</th>
<th>SKA-TEL-SKO-0001100 SKA1 Project Execution Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SKA-TEL-SKO-0001201 SKA1 Engineering Management Plan</td>
</tr>
</tbody>
</table>

Plan for maintaining security of data, hardware and networks during all stages of the project life cycle; plans for writing, testing and verifying, deploying and documenting software including configuration control during the stages of development.

<table>
<thead>
<tr>
<th>12 Health, Safety and Environment</th>
<th>SKA-TEL-SKO-0001100 SKA1 Project Execution Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SKA-TEL-SKO-0000740 SKAO Health, Safety and Environmental Management Plan</td>
</tr>
</tbody>
</table>

Description of health, safety, and environmental strategy during all stages of observatory life cycle; includes context of SKAO, leadership, worker participation, planning, support, competence, operational planning and control, performance evaluation, improvement, software and safety, functional safety, construction, AIV and HSE culture.

<table>
<thead>
<tr>
<th>13 Quality/Product Assurance</th>
<th>SKA-TEL-SKO-0001100 SKA1 Project Execution Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SKA-TEL-SKO-0000739 SKA Product Quality Assurance Plan</td>
</tr>
</tbody>
</table>

Description of the PQA requirements and management activities during construction.
| 14 Review and Reporting | **SKA-TEL-SKO-0001100 SKA1 Project Execution Plan**  
Ref **SKA-TEL-SKO-0001200 Project Management Control System**  
Description of the planned reporting from the project to its oversight/stakeholders as well as regular planned reviews. |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>15 Broader Social Impact</td>
<td></td>
</tr>
</tbody>
</table>
| 16 Project Close-out | **SKA-TEL-SKO-0001100 SKA1 Project Execution Plan**  
Note the handling of the observatory decommissioning phase and responsibilities as currently understood. |
Annex E: List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Actual Costs</td>
</tr>
<tr>
<td>AD</td>
<td>Applicable Document</td>
</tr>
<tr>
<td>ADR</td>
<td>Adoption Design Review</td>
</tr>
<tr>
<td>AGN</td>
<td>Active Galactic Nuclei</td>
</tr>
<tr>
<td>AIP</td>
<td>Advanced Instrumentation Programme</td>
</tr>
<tr>
<td>AIV</td>
<td>Assembly, Integration and Verification</td>
</tr>
<tr>
<td>AIVCSVO</td>
<td>Assembly, Integration, Verification, Commissioning, Science Verification and Operations</td>
</tr>
<tr>
<td>ALMA</td>
<td>Atacama Large Millimetrewave Array</td>
</tr>
<tr>
<td>APM</td>
<td>Association for Project Management</td>
</tr>
<tr>
<td>APOD</td>
<td>Astronomy Picture of the Day</td>
</tr>
<tr>
<td>ART</td>
<td>Agile Release Train</td>
</tr>
<tr>
<td>ASKAP</td>
<td>Australia Square Kilometre Array Pathfinder</td>
</tr>
<tr>
<td>ATCA</td>
<td>Australia Telescope Compact Array</td>
</tr>
<tr>
<td>au</td>
<td>Astronomical Unit</td>
</tr>
<tr>
<td>AUS</td>
<td>Australia</td>
</tr>
<tr>
<td>AURA</td>
<td>Association of Universities for Research in Astronomy</td>
</tr>
<tr>
<td>AVN</td>
<td>Africa Very Large Baseline Interferometry Array</td>
</tr>
<tr>
<td>BAC</td>
<td>Budget at Completion</td>
</tr>
<tr>
<td>BDD</td>
<td>Baseline Design Document</td>
</tr>
<tr>
<td>BIPM</td>
<td>Bureau International des Poids et Mesures</td>
</tr>
<tr>
<td>CASA</td>
<td>Common Astronomy Software Applications</td>
</tr>
<tr>
<td>CBF</td>
<td>Correlator Beam Former</td>
</tr>
<tr>
<td>CCB</td>
<td>Change Control Board</td>
</tr>
<tr>
<td>CD</td>
<td>Cosmic Dawn</td>
</tr>
<tr>
<td>CDR</td>
<td>Critical Design Review</td>
</tr>
<tr>
<td>CEMAR</td>
<td>Contract Event Management And Reporting (software)</td>
</tr>
<tr>
<td>CERN</td>
<td>Conseil Européen pour la Recherche Nucléaire</td>
</tr>
<tr>
<td>CME</td>
<td>Coronal Mass Ejection</td>
</tr>
<tr>
<td>CON</td>
<td>Consultant</td>
</tr>
<tr>
<td>COVID</td>
<td>Coronavirus Disease</td>
</tr>
<tr>
<td>CPF</td>
<td>Central Processing Facility</td>
</tr>
<tr>
<td>CPI</td>
<td>Cost Performance Index</td>
</tr>
<tr>
<td>CPTF</td>
<td>Council Preparatory Task Force</td>
</tr>
<tr>
<td>CRRL</td>
<td>Carbon Radio Recombination Line</td>
</tr>
<tr>
<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation</td>
</tr>
<tr>
<td>CSP</td>
<td>Central Signal Processing</td>
</tr>
<tr>
<td>DBD</td>
<td>Design Baseline Document (SKA-TEL-SKO-0001075-01A_DBD)</td>
</tr>
<tr>
<td>DDT</td>
<td>Director General’s Discretionary Time</td>
</tr>
<tr>
<td>DG</td>
<td>Director General</td>
</tr>
<tr>
<td>DKIST</td>
<td>Daniel K. Inouye Solar Telescope</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy (US)</td>
</tr>
<tr>
<td>EAC</td>
<td>Estimate at Completion</td>
</tr>
<tr>
<td>ELT</td>
<td>Extra Large Telescope</td>
</tr>
<tr>
<td>EMC</td>
<td>Electromagnetic Compatibility</td>
</tr>
<tr>
<td>EMI</td>
<td>Electromagnetic Interference</td>
</tr>
<tr>
<td>EMS</td>
<td>Engineering Management System</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>ECC</td>
<td>Engineering Construction Contract</td>
</tr>
<tr>
<td>EMS</td>
<td>Engineering Management System</td>
</tr>
<tr>
<td>EOC</td>
<td>Engineering Operations Centre</td>
</tr>
<tr>
<td>EoR</td>
<td>Epoch of Reionisation</td>
</tr>
<tr>
<td>EPBA</td>
<td>Environmental Protection and Biodiversity Conservation Act (Australia)</td>
</tr>
<tr>
<td>ERP</td>
<td>Enterprise Resource Planning</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>ESO</td>
<td>European Southern Observatory</td>
</tr>
<tr>
<td>ESS</td>
<td>European Spallation Source</td>
</tr>
<tr>
<td>ETC</td>
<td>Estimate to Complete</td>
</tr>
<tr>
<td>EV</td>
<td>Earned Value</td>
</tr>
<tr>
<td>EVM</td>
<td>Earned Value Management</td>
</tr>
<tr>
<td>EVMS</td>
<td>Earned Value Management System</td>
</tr>
<tr>
<td>FM</td>
<td>Financial Management</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Model</td>
</tr>
<tr>
<td>FMECA</td>
<td>Failure Modes Effects and Criticality Analysis</td>
</tr>
<tr>
<td>FNDH</td>
<td>Field Node Distribution Hub</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field Programmable Gate Array</td>
</tr>
<tr>
<td>FRACAS</td>
<td>(SKA) Failure Recording Analysis and Corrective Action System</td>
</tr>
<tr>
<td>FRB</td>
<td>Fast Radio Burst</td>
</tr>
<tr>
<td>FSP</td>
<td>Frequency Slice Processor</td>
</tr>
<tr>
<td>FWR</td>
<td>Fair Work Return</td>
</tr>
<tr>
<td>GBP</td>
<td>Great Britain Pound</td>
</tr>
<tr>
<td>GC</td>
<td>Galactic Centre</td>
</tr>
<tr>
<td>GHQ</td>
<td>Global Head Quarters</td>
</tr>
<tr>
<td>GMRT</td>
<td>Giant Metrewave Radio Telescope</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>HERA</td>
<td>Hydrogen Epoch of Re-ionization Array</td>
</tr>
<tr>
<td>HI</td>
<td>Neutral Hydrogen</td>
</tr>
<tr>
<td>HPC</td>
<td>High Performance Computing</td>
</tr>
<tr>
<td>HPMG</td>
<td>Head of Project Management Group</td>
</tr>
<tr>
<td>HR</td>
<td>Human Resources</td>
</tr>
<tr>
<td>HRRRL</td>
<td>Hydrogen Radio Recombination Line</td>
</tr>
<tr>
<td>HSE</td>
<td>Health, Safety and Environmental</td>
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<tr>
<td>HSSE</td>
<td>Health Safety Security and Environment</td>
</tr>
<tr>
<td>HVC</td>
<td>High Velocity Cloud</td>
</tr>
<tr>
<td>IEMP</td>
<td>Integrated Environmental Management Plan</td>
</tr>
<tr>
<td>IGM</td>
<td>Inter Galactic Medium</td>
</tr>
<tr>
<td>IGO</td>
<td>Inter-Governmental Organisation</td>
</tr>
<tr>
<td>INAU</td>
<td>Infrastructure Australia</td>
</tr>
<tr>
<td>INSA</td>
<td>Infrastructure South Africa</td>
</tr>
<tr>
<td>IPS</td>
<td>Integrated Project Schedule</td>
</tr>
<tr>
<td>IRAS</td>
<td>Infra Red Astronomy Satellite</td>
</tr>
<tr>
<td>ISM</td>
<td>Inter stellar medium</td>
</tr>
<tr>
<td>ISMS</td>
<td>Information Security Management System</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standards Organisation</td>
</tr>
<tr>
<td>IT</td>
<td>Information Technology</td>
</tr>
<tr>
<td>ITER</td>
<td>International Thermonuclear Experimental Reactor</td>
</tr>
<tr>
<td>ITF</td>
<td>Integration Test Facility</td>
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</table>
**Abbreviation**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ITU</td>
<td>International Telecommunications Union</td>
</tr>
<tr>
<td>IXR</td>
<td>Intrinsic Cross polarisation Ratio</td>
</tr>
<tr>
<td>JSP</td>
<td>Junior Specialist</td>
</tr>
<tr>
<td>KAPB</td>
<td>Karoo Array Processor Building</td>
</tr>
<tr>
<td>KAT</td>
<td>Karoo Array Telescope</td>
</tr>
<tr>
<td>kpc</td>
<td>kiloparsec</td>
</tr>
<tr>
<td>KPI</td>
<td>Key Performance Indicator</td>
</tr>
<tr>
<td>KSP</td>
<td>Key Science Project</td>
</tr>
<tr>
<td>KUG</td>
<td>Key User Group</td>
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<tr>
<td>LFAA</td>
<td>Low Frequency Aperture Array</td>
</tr>
<tr>
<td>LHC</td>
<td>Large Hadron Collider</td>
</tr>
<tr>
<td>LIGO</td>
<td>Laser Interferometer Gravitational wave Observatory</td>
</tr>
<tr>
<td>LNA</td>
<td>Low Noise Amplifier</td>
</tr>
<tr>
<td>LOFAR</td>
<td>Low Frequency Array</td>
</tr>
<tr>
<td>LSR</td>
<td>Local Standard of Rest</td>
</tr>
<tr>
<td>LSST</td>
<td>Legacy Survey of Space and Time</td>
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<tr>
<td>MFAA</td>
<td>Mid Frequency Aperture Array</td>
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<tr>
<td>MKT</td>
<td>MeerKAT</td>
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<tr>
<td>MMS</td>
<td>Maintenance Management System</td>
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<tr>
<td>MRO</td>
<td>Murchison Radio Observatory</td>
</tr>
<tr>
<td>MSP</td>
<td>Milli Second Pulsar</td>
</tr>
<tr>
<td>M_sol</td>
<td>Solar Mass</td>
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<td>MWA</td>
<td>Murchison Widefield Array</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration (US)</td>
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<tr>
<td>NCR</td>
<td>Non Conformance Report</td>
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<tr>
<td>NEC</td>
<td>New Engineering Contract</td>
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<tr>
<td>NEMA</td>
<td>National Environmental Management Act (South Africa)</td>
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<tr>
<td>NMR</td>
<td>Nuclear Magnetic Resonance</td>
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<tr>
<td>NOEMA</td>
<td>NOrthern Extended Millimeter Array</td>
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<td>NRF</td>
<td>National Research Foundation (South Africa)</td>
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<tr>
<td>OAR</td>
<td>Observation Action Register</td>
</tr>
<tr>
<td>ODP</td>
<td>Observatory Data Products</td>
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<tr>
<td>ODT</td>
<td>Observatory Delivery Team</td>
</tr>
<tr>
<td>ORR</td>
<td>Operational Readiness Review</td>
</tr>
<tr>
<td>PAF</td>
<td>Phased Array Feed</td>
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<tr>
<td>PBS</td>
<td>Product Breakdown Structure</td>
</tr>
<tr>
<td>pc</td>
<td>parsec</td>
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<tr>
<td>PCM</td>
<td>Project Controls Manager</td>
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<tr>
<td>PDT</td>
<td>Product Delivery Team</td>
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<td>PI</td>
<td>Program Increment</td>
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<td>PM</td>
<td>Project Manager</td>
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<td>PMCS</td>
<td>Project Management Controls System</td>
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<td>PMI</td>
<td>Project Management Institute</td>
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<td>PQA</td>
<td>Product Quality Assurance</td>
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<td>PRTS</td>
<td>Problem Reporting and Tracking System</td>
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<tr>
<td>PSC</td>
<td>Professional Services Contract</td>
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<td>PSI</td>
<td>Prototype System Integration</td>
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<tr>
<td>PSS</td>
<td>Pulsar Search</td>
</tr>
<tr>
<td>PST</td>
<td>Pulsar Timing</td>
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<tr>
<td>PV</td>
<td>Planned Value</td>
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<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>QPI</td>
<td>Quality Performance Indicators</td>
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<tr>
<td>RD</td>
<td>Reference Document</td>
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<tr>
<td>RAM</td>
<td>Reliability Availability Maintainability</td>
</tr>
<tr>
<td>RAMS</td>
<td>Reliability Availability Maintainability and Safety</td>
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<tr>
<td>RASCI</td>
<td>Responsible, Accountable, Support, Consulted, Informed</td>
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<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RFI</td>
<td>Radio Frequency Interference</td>
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<tr>
<td>RM</td>
<td>Rotation Measure</td>
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<tr>
<td>ROAM</td>
<td>Resolved, Owned, Accepted, Mitigated</td>
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<tr>
<td>ROSE</td>
<td>Relevance of Science Education</td>
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<tr>
<td>RPF</td>
<td>Remote Processing Facility</td>
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<tr>
<td>RRL</td>
<td>Radio Recombination Line</td>
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<tr>
<td>RRN</td>
<td>Review Readiness Notice</td>
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<tr>
<td>RSA</td>
<td>Republic of South Africa</td>
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<tr>
<td>SAFe</td>
<td>Scaled Agile Framework</td>
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<tr>
<td>SALGA</td>
<td>South African Local Government Association</td>
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<tr>
<td>SAN</td>
<td>South African National (not San, the first nation group of South Africa)</td>
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<td>SARAO</td>
<td>South African Radio Astronomy Observatory</td>
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<td>SAT</td>
<td>Synchronisation and Timing</td>
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<td>Supply Contract</td>
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<td>SDO</td>
<td>Solar Dynamics Observatory</td>
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<td>SDP</td>
<td>Signal Data Processor</td>
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<tr>
<td>SEAC</td>
<td>Science Engineering Advisory Committee</td>
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<tr>
<td>SEFD</td>
<td>System Equivalent Flux Density</td>
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<tr>
<td>SETI</td>
<td>Search for Extra Terrestrial Intelligence</td>
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<tr>
<td>SF</td>
<td>Star Formation</td>
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<tr>
<td>SFE</td>
<td>Star Forming Efficiency</td>
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<tr>
<td>SFR</td>
<td>Star Formation Rate</td>
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<tr>
<td>SKA</td>
<td>Square Kilometre Array</td>
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<tr>
<td>SKAO</td>
<td>Square Kilometre Array Observatory/Organisation</td>
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<tr>
<td>SKARR</td>
<td>Square Kilometre Array Risk Register</td>
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<td>SMART</td>
<td>Small Modular Aggregation &amp; Radio Frequency over Fibre Trunk</td>
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<tr>
<td>SNR</td>
<td>Supernova Remnant, Signal to Noise Ratio</td>
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<tr>
<td>SOC</td>
<td>Science Operations Centre</td>
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<td>SODP</td>
<td>SKA Observatory Development Programme</td>
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<td>SOW</td>
<td>Statement of Work</td>
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<td>SPC</td>
<td>Science Processing Centre</td>
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<td>Science Processing Facility</td>
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<td>Schedule Performance Index</td>
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<td>Senior Project Manager</td>
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<tr>
<td>SQL</td>
<td>Structured Query Language</td>
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<td>SRC</td>
<td>SKA Regional Centre</td>
</tr>
<tr>
<td>STE</td>
<td>Solution Train Engineer</td>
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<tr>
<td>STEM</td>
<td>Science Technology Engineering Mathematics</td>
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<tr>
<td>STFC</td>
<td>Science and Technology Facilities Council</td>
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<tr>
<td>SV</td>
<td>Science Verification</td>
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<td>SWG</td>
<td>Science Working Group</td>
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<tr>
<td>TALON</td>
<td>National Research Council of Canada Correlator Beamformer Architecture</td>
</tr>
<tr>
<td>TANGO</td>
<td>An open source solution for supervisory control and data acquisition systems</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>TBC</td>
<td>To Be Confirmed</td>
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<td>Telescope Delivery Team</td>
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<td>TESS</td>
<td>Transiting Exoplanet Survey Satellite</td>
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<td>TIMS</td>
<td>Telescope Issues Management System</td>
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<tr>
<td>TPC</td>
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<td>Test Review Board</td>
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<tr>
<td>TUPE</td>
<td>Transfer of Undertakings (Protection of Employment)</td>
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<tr>
<td>UHF</td>
<td>Ultra High Frequency</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
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<tr>
<td>UTC</td>
<td>Coordinated Universal Time</td>
</tr>
<tr>
<td>UX</td>
<td>User Interface</td>
</tr>
<tr>
<td>VLA</td>
<td>Very Large Array</td>
</tr>
<tr>
<td>VLBI</td>
<td>Very Long Baseline Interferometry</td>
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<td>Work Breakdown Structure</td>
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<tr>
<td>WBSPF</td>
<td>Wideband Single Pixel Feed</td>
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<tr>
<td>YSO</td>
<td>Young Stellar Object</td>
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<tr>
<td>z</td>
<td>Redshift</td>
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