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The Square Kilometre Array Project

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ABSTRACT

The Square Kilometre Array is a global research infrastructure project to construct and operate a radio telescope observatory of unprecedented scale. The first stage of the project's implementation (SKA1) has concluded its design phase and is about to begin construction in 2021. Composed of two interferometric arrays covering a frequency range of 50-350 MHz in Australia (SKA-LOW) and 350 MHz to 15.4 GHz in South Africa (SKA-MID), the observatory provides sensitivity and resolution which advance the currently available research infrastructure capabilities across a range of scientific frontiers.

We describe the design development process for the SKA1, the antenna design and specifications, and the current construction planning and schedule.

Keywords: SKA, Array, Astronomy, Interferometry, Telescope

1. INTRODUCTION

The Square Kilometre Array is an international effort to solve the technical challenges toward the construction of a radio observatory with the ambition of achieving at least one square kilometre of effective collecting area (e.g., [1], [2], etc.). The SKA1 will be the first phase in the realization of this technical and scientific ambition.

The design of the Observatory flows from the high-level performance required to address a range of key science drivers.

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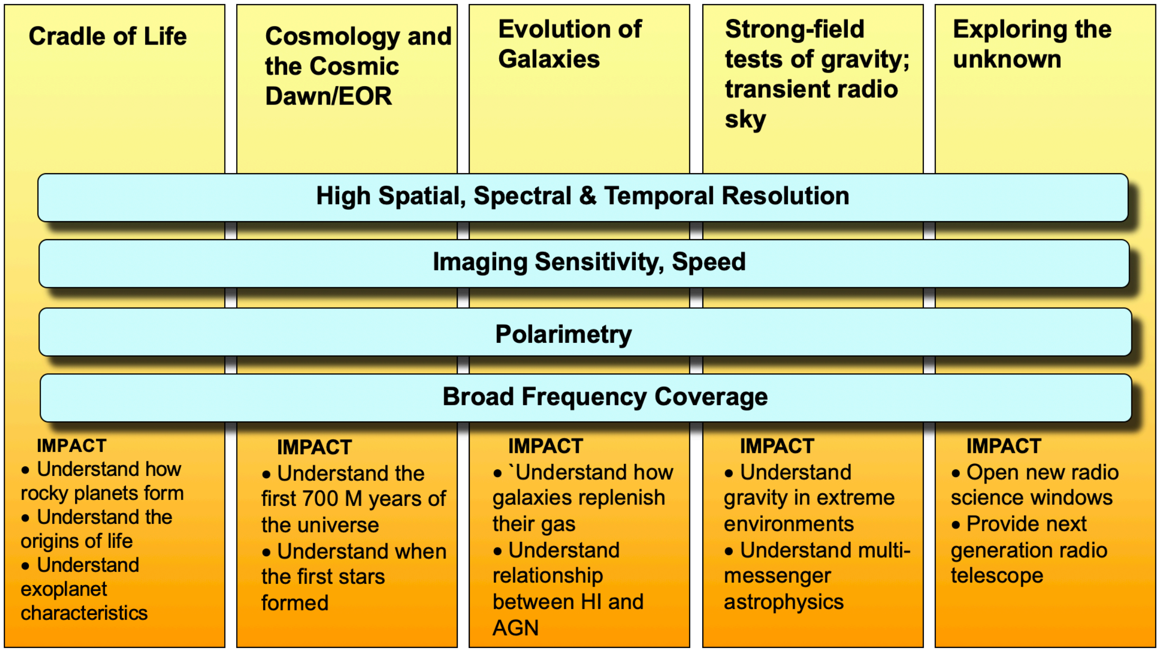

Figure 1. Subset of Key Science Drivers (Top) noting the potential impacts from discoveries in these areas (bottom) with the common engineering design drivers shown in blue (middle).

To develop the design, a multi-stage approach was adopted to leverage the efforts across the member country partners. This included an extended design development phase to capture the broad range of elements required for the observatory, followed by a design adoption phase and finally a system design review.

2. SKA1 DESIGN

The SKA Observatory global headquarters 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 functions, engineering and project management processes, science planning and execution, Observatory operations, a telescope development programme, and public outreach and broader societal impact programme ownership. The project has been designed with facilities capable of managing two remote telescopes, where parts of the organisation are spread across multiple time zones.

The overall architecture is characterized by a 3-2-1 composition (see Figure 2):

- 3 Host Countries: Australia (SKA1-Low), South Africa (SKA1-Mid) and the United Kingdom (SKA Headquarters)
- 2 Facilities: SKA1-Low, SKA1-Mid
- 1 Observatory: A coherent single observatory facing the astronomical community

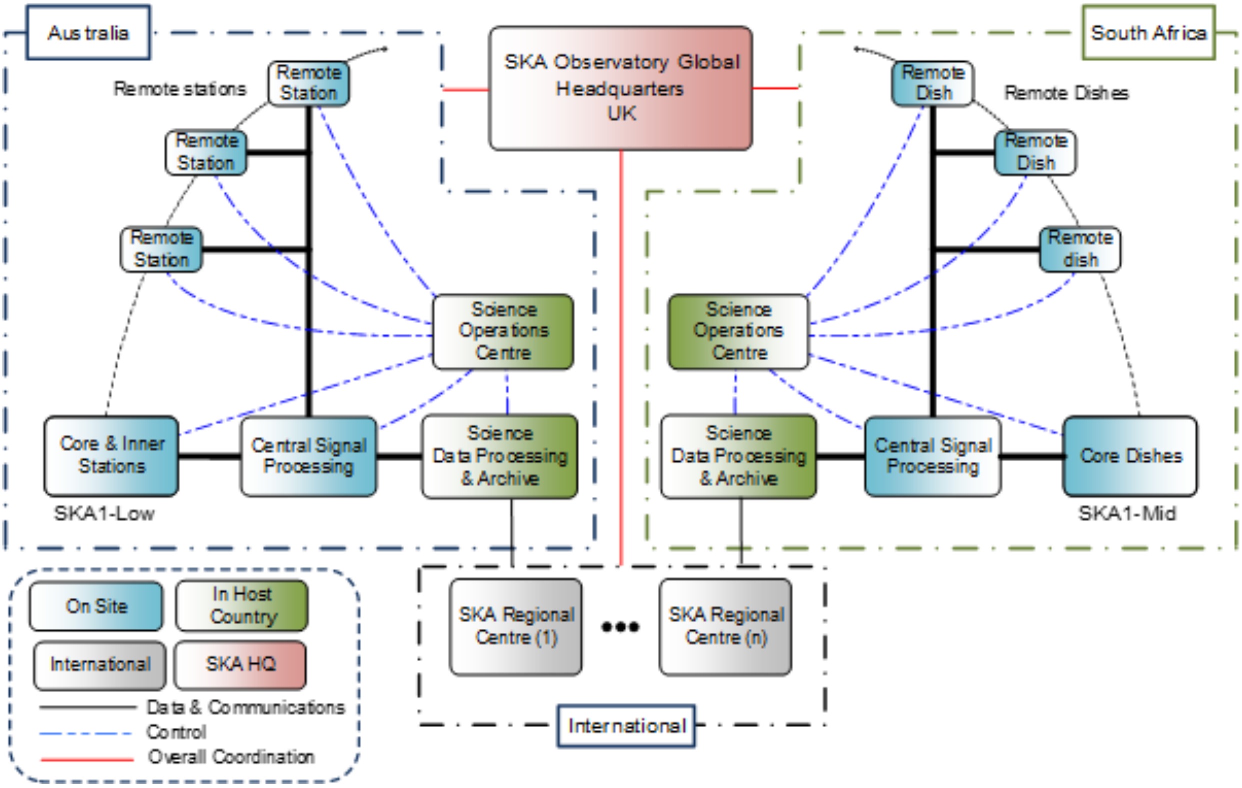

Figure 2. Schematic diagram of the SKA Observatory.

In Figure 2, the thick black lines show the unidirectional transport of digitised data from the antennas to the central processing facilities on the telescope sites (housing the correlators, beamformers, pulsar search and timing engines and timing/power distribution equipment), and from there to the science data processing centres and archives in Perth, Australia and Cape Town, South Africa. The Observatory is driven by a large body of interconnected software systems which can be functionally summarised as:

- Science Management (proposal handling, observation design, observation scheduling, execution and tracking)
- Monitor and Control (real-time coordination of hardware and software systems to collect the science data and operational support data)
- Science Data Processing (calibration, imaging, time-domain analysis of science data as well as maintenance of Sky models and quality assessment) and,
- The enterprise systems which ensure the smooth functioning of non-science aspects of the Observatory.

The Telescope Sites will produce immense amounts of data (see Figure 3), driven by both the astronomical specifications as well as the radio frequency interference environment which requires high precision data for decoupling from the science data.

The next sections outline the design development process followed by summary descriptions and attributes of the SKA1-Low and SKA1-Mid facilities.

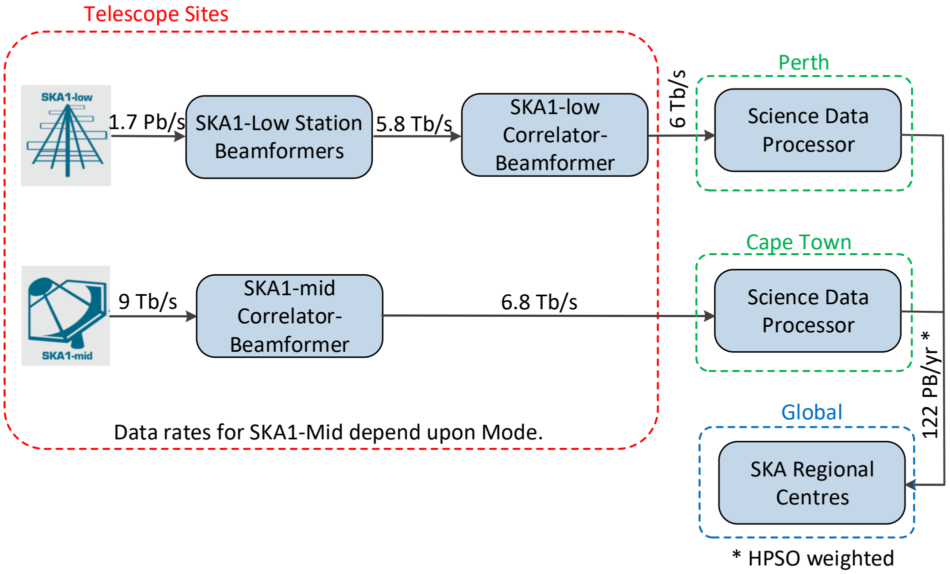

Figure 3. Telescope and Observatory data flow volumes. The rate of dataflow to the SKA Regional Centres is the current estimate, based on the weighting of expected High Priority Science Objectives.

2.1 Design Development – Element Design

During the Pre-construction phase the SKA design and development was a global effort by 12 international engineering consortia (9 within the construction project and 3 for development) representing approximately 600 engineers and scientists in 20 organizations. 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 (Figure 2). The 9 consortia each 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. Eight consortia focused on Elements (component sets) of the telescope, each critical to the overall success of the project.

- Central Signal Processor (CSP, Canada)
- Dish (DSH, China)
- Infrastructure South Africa (INSA, South Africa)
- Infrastructure Australia (INAU, Australia)
- Aperture Array Design and Construction (LFAA, Netherlands)
- Signal and Data Transport (SaDT, United Kingdom)
- Science Data Processor (SDP, United Kingdom)
- Telescope Manager (TM, India)

The ninth consortium worked to define the Assembly, Integration and Verification (AIV; South Africa) of the arrays.

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 formed in 2013, the design of the SKA has evolved in response to available funding and to take account of scientific advances. In December 2014, the process reached its first milestone, with the start of the Elements' Preliminary Design Reviews (PDRs). Each consortium presented its detailed proposal for assessment by an expert panel from the SKA and external organizations, and the results were fed back into the ongoing design work.

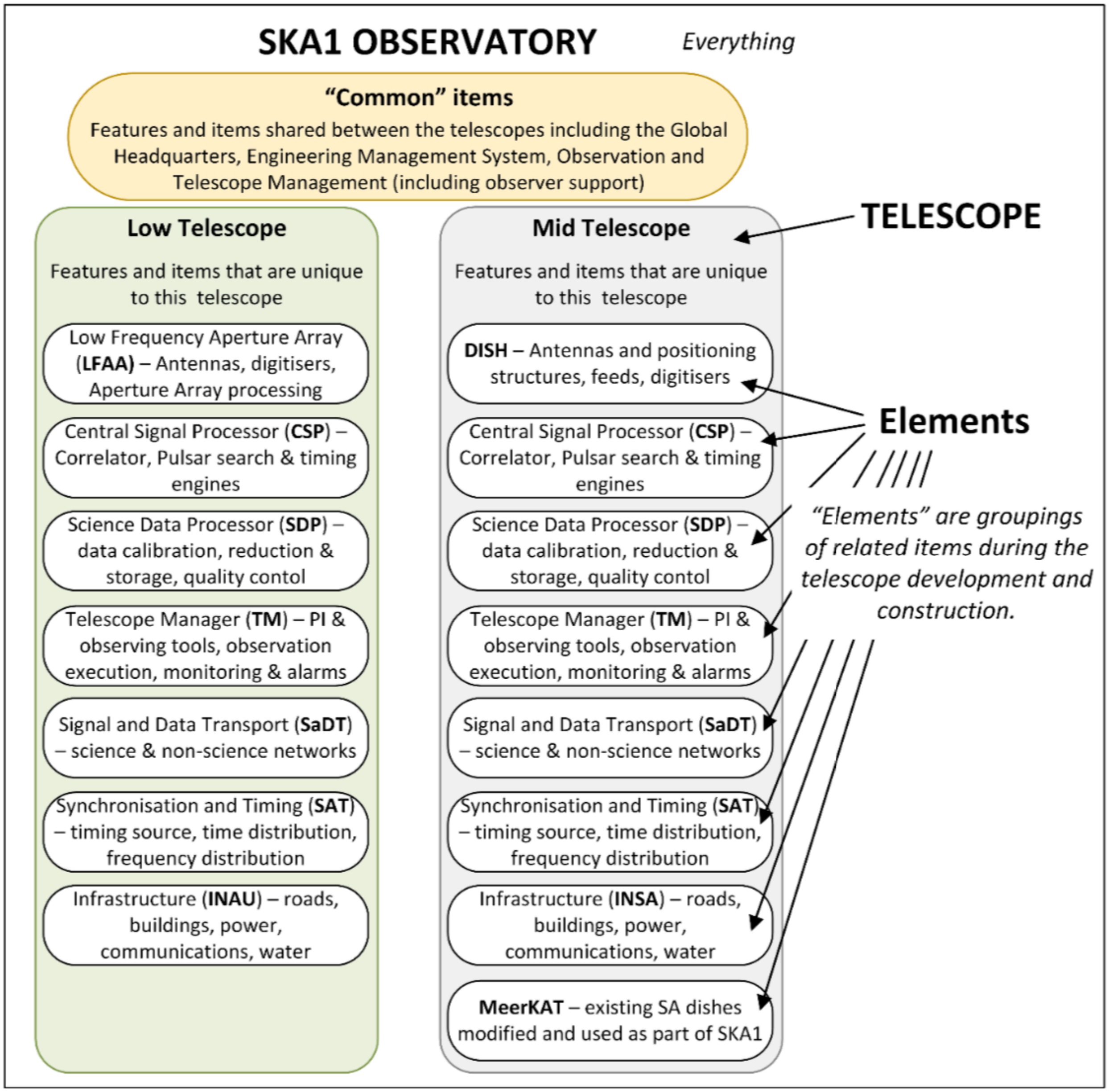

Figure 4. Representation of the Element Design groups during the Pre-Construction phase of the Project.

There followed several years of effort by the international consortia to arrive at the Element Critical Design Reviews (CDR). The Element CDR period began in 2018 and provided an assessment of the design completeness/readiness, a demonstration that the remaining risks were acceptable, and established an Element-level design baseline for subsequent integration.

2.2 Design Development – Design Adoption

Following the Element design completion, it was necessary to align and integrate the designs to verify that the system requirements were met and to identify any issues or gaps. This process provided a system-level view of the individual designs within the broader context of the observatory performance, iterating the design and providing a final assessment of the residual risk. Further, it advanced the detailed technical requirements for the procurement, development, manufacture and delivery of the telescope products. The design adoption was completed over Q2-Q3 2019.

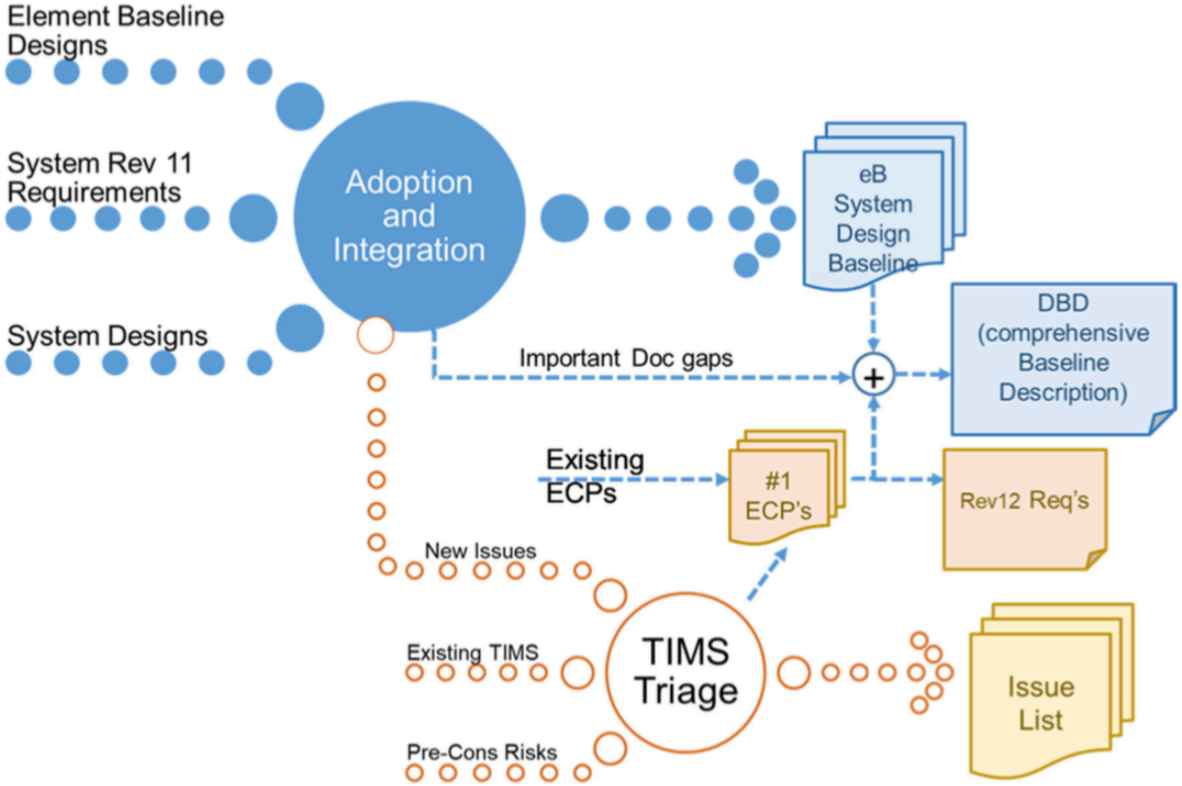

Figure 5. Design Adoption process. Starting from the left, the products of the Pre-construction design phase are integrated and reviewed. Issues are recorded and managed through a Telescope Issue Management tracking System (TIMS) with design changes passing through a formal change control process (ECP=Engineering Change Proposal). All documents are stored in eB, the document management system with the process culminating in the SKA1 Design Baseline (DBD = Design Baseline Document).

2.3 Design Development – System Critical Design Review

Following these design phases, a System Critical Design Review (CDR) was developed to reconcile the 'bottom-up' development with the 'top-down' understanding of the system and its operations. The objective of the System CDR was to assess the design at the system level, and to test the understanding of the design and confirm that the remaining risk to construction and operations is acceptable for the start of construction. The review further focused on the detailed execution planning, including the full construction cost, schedule, scope and risk management for the baseline design

The benchmark criteria were:

- A design qualified at system and subsystem level by test or advanced analysis;
- Manufacturing, assembly and integration and test plans at an advanced stage;
- Remaining lifecycle costs determined with high confidence;
- Remaining development risks at low level.

The System CDR process began in October 2019, with multiple external panel meetings, culminating in a face-to-face meeting to review specific design/programmatic details. It concluded successfully in March 2020.

The resulting designs for the antenna systems for both SKA1-Low and SKA1-Mid and the key performance measures are summarized below.

2.4 SKA1-Low

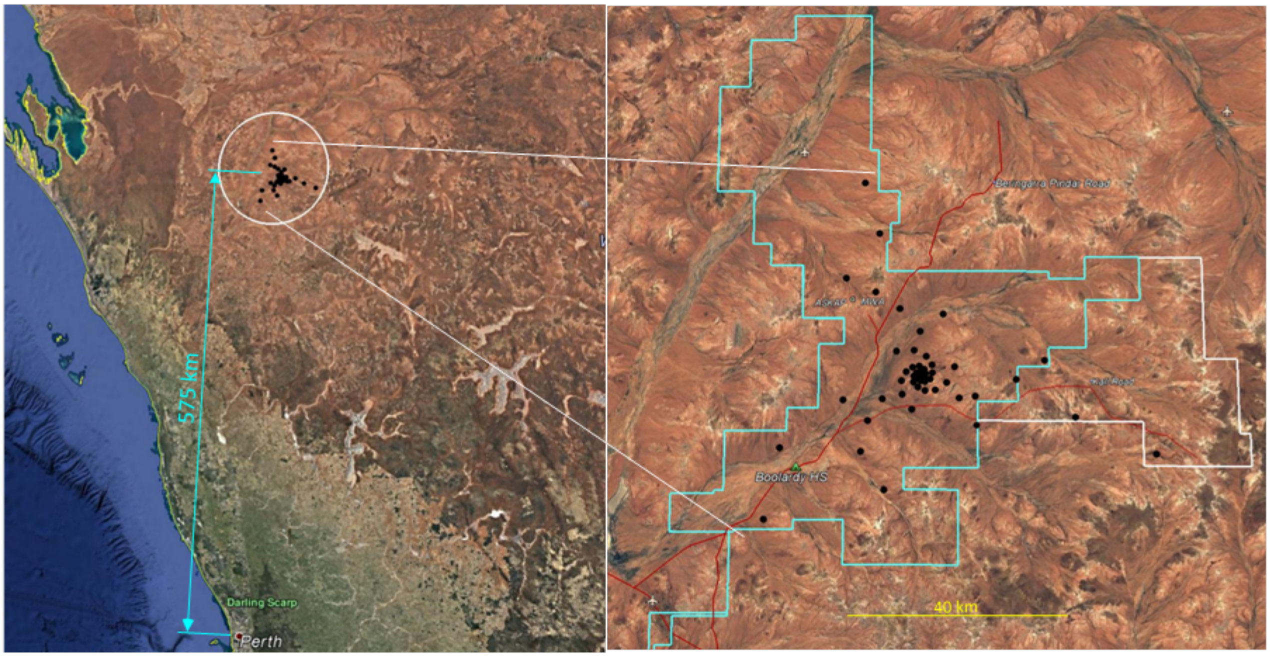

Figure 6. The geographic location of SKA1-Low in Western Australia. The blue outline shows the approximate boundary of the currently acquired property.

At low frequencies ‘wideband antennas’are much more efficient than reflectors. A challenge in the SKA 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.

The log-periodic 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 (e.g., [3]). The SKA1- Low telescope will consist of an array of ~130,000 dual-polarised, log-periodic antenna elements, designed for sensitivity from 50 to 350 MHz [4]. Like all quasi-resonant structures, effective area falls off as λ^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.

The antenna elements will be combined in circular antenna arrays (‘stations’), distributed across a ~65 km diameter area, each containing 256 antenna elements. Each station, having a diameter of about 40 meters, acts like a phased array antenna capable of forming multiple independent steered ‘beams’ on the sky.

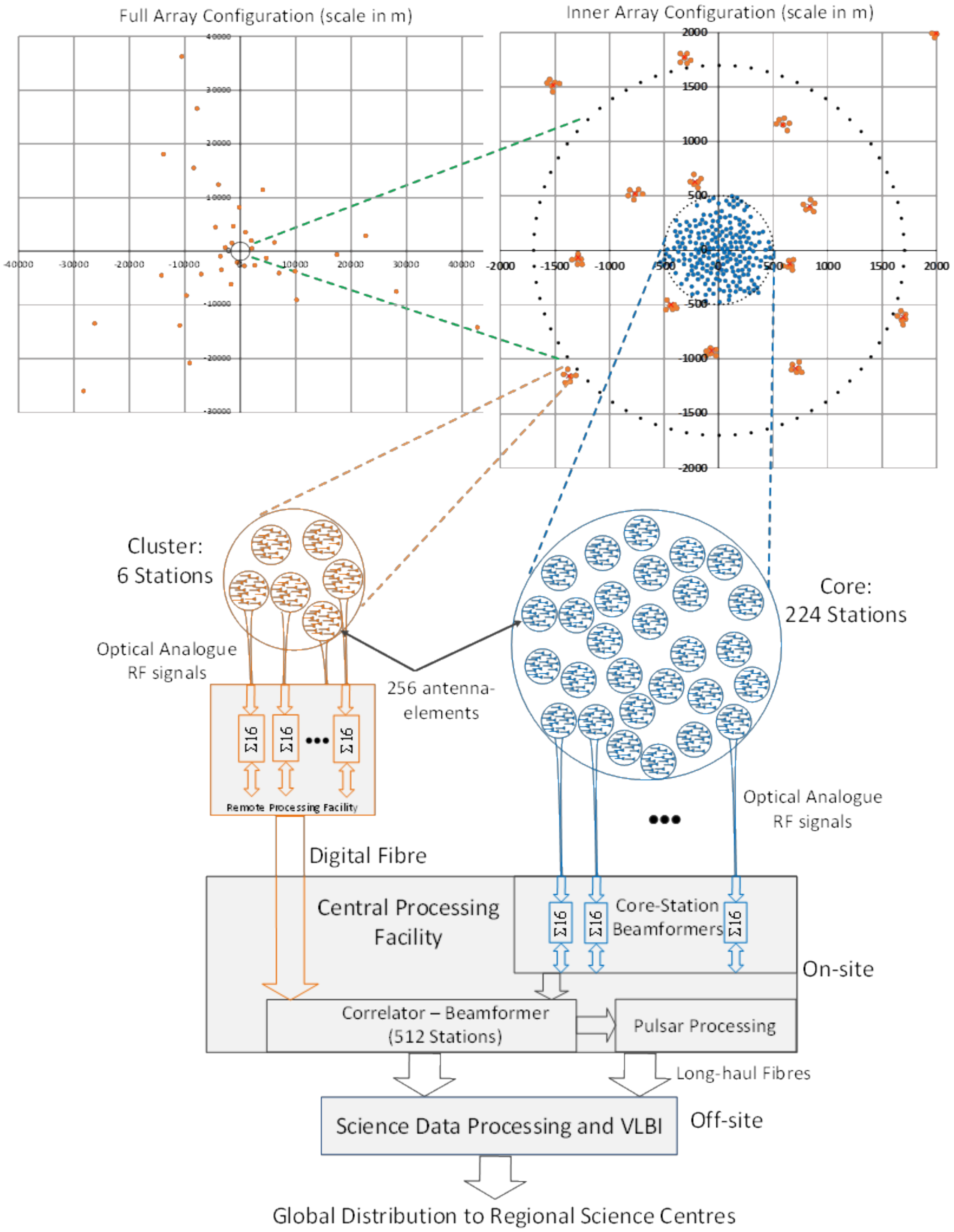

Figure 7. Schematic illustration of the SKA1-Low system, showing the details of the array architecture.

The stations are arranged in a very compact core with a diameter of ~1 km, and three quasi-spiral arms.

Table 1. Selected SKA1-Low performance parameters.

Aperture Arrays		
Lower Frequency	50 MHz	Each antenna element covering full range
Upper Frequency	350 MHz	Dual pol'n
Number of antennas per station	256	Log-Periodic-Dipole antennas
Station Effective Diameter [1]	38 m	
Number of stations	512	
Total physical aperture	5.8 x 10^5 m^2	
Dense/Sparse Transition [2]	~94 MHz	
Array Configuration		
Core (radius <500 m)	224 stations	See Figure C-1
Inner (radius <1700 m)	278 stations	″
Spiral Arms	234 stations	″
Station Beam Forming		
Number of beams [3]	1-384	Each with dual polarisation.
Max. bandwidth per beam	300 MHz	Each polarisation.
Max. no. of antennas per beam	256	
Signal Processing System		
Max. no. frequency channels	55296	
Standard Frequency Resolution	5.4 kHz	300 MHz/55296 = 5.4 kHz
Max. Frequency Resolution	226 Hz	Zoom mode
Complex Correlations [4]	2.9 x 10^{10}	(512·513/2) baselines x (1) beams x 4 pol'n prod's x 55296 chans
Integration Time	0.9 s	Reduceable to 0.3 s for a limited number of sub-stations
Array Beam Former		
Full beamformer	512 stations	
Within 20-km Array Diameter	404 stations	
Pulsar Search	500	Independently steerable; 2 pol'n
Pulsar Timing	16	″
VLBI	4	″
Max. bandwidth per beam	300 MHz	300 MHz; 2 pol'n
Pulsar Search	118 MHz	Per beam; 2 pol'n
Pulsar Timing	300	″
VLBI	300	″

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[1] The effective diameter of a station is a best-fit circle, centered 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.

[2] Dense: Station A_e is equal to the station physical area, assuming no losses. Sparse: Station $A_e = A_{e\_ant}$ x N_{ant} (effective area per antenna times the number of antennas); this is always less than the station physical area).

[3] No. of beams, bandwidth per beam, and number of antennas included in the beam can be traded to maintain a constant data-output from the beamformer to the correlator.

[4] Includes autocorrelations.

Figure 8. The SKALA (SKA Log-Periodic Antenna) 4.1 shown amidst a prototype station deployed at the Murchison Radio Astronomy site.

2.5 SKA1-Mid

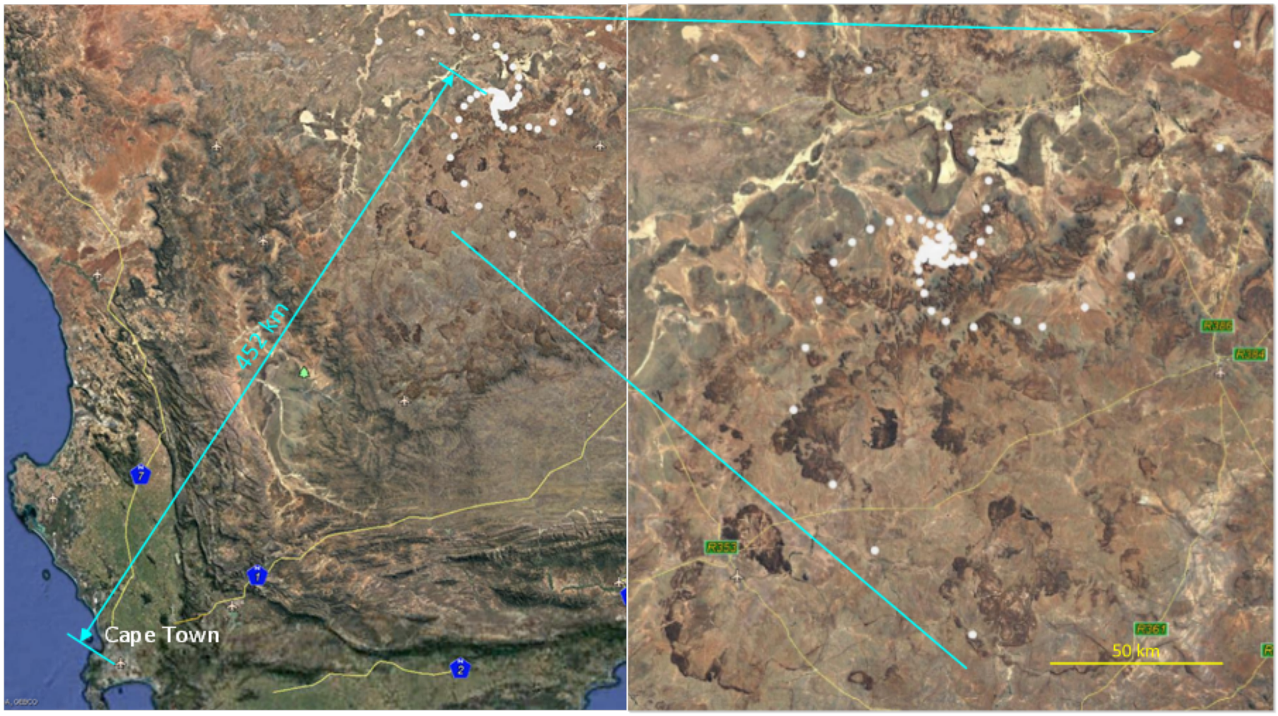

Figure 9. The geographic location of the SKA1-Mid in South Africa. Each grey dot represents an Antenna. The dense core contains MeerKAT and SKA1 antennas.

The SKA1-Mid telescope will consist of a 150-km diameter array of reflector antennas ('dishes'). It will be a mixed array of 133 15-m SKA1 dishes and 64 13.5-m diameter dishes from the existing MeerKAT telescope [5]. The telescopes are equipped with a package of 4 single-pixel feeds (see [6]).

The antennas for SKA1-Mid are a critical component of the system; in effect these are what 'couples' the telescope to the sky. There are many compromises in designing the antenna; SKA1 has selected a 15-m projected-diameter, offset Gregorian optical arrangement 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);
5. Space at the focus for multiple independent receivers;
6. Very low second and higher order sidelobes;
7. Excellent dual polarization performance;
8. Excellent performance down to ~450 MHz, good performance to 350 MHz;
9. Excellent performance up to 15 GHz, good performance at 20 GHz (gradually falling off thereafter);
10. Beam as circular as possible.

As for SKA1-Low, 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. 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.

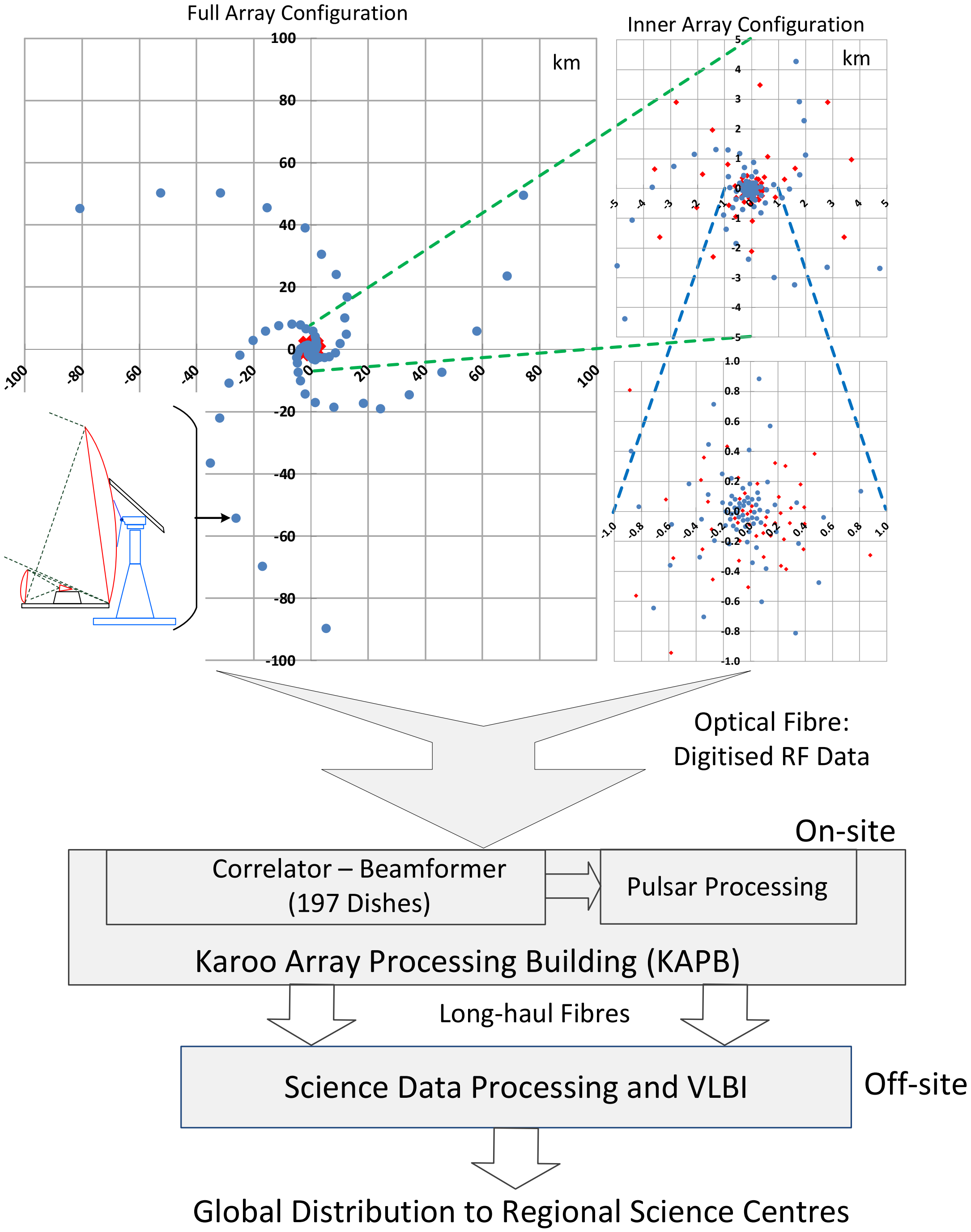

Figure 10. Schematic illustration of the SKA1-Mid system, showing the details of the array configurations and architecture.

Table 2 Selected SKA1-Mid performance parameters.

Aperture	m^2	133 x 15-m (equiv. dia.) offset Gregorian reflectors Plus 64 x 13.5-m (equiv. dia.) offset Gregorian reflectors
Total physical aperture	33306	
Total Available aperture	31641	Availability 95%
Minimum Elevation Angle	15 deg	All Azimuths – 270° wrap
Array Configuration	Antenna	Filling factor %
radius <~400 m	80 (41%)	2.67
~400 m < radius < ~1000 m	35 (18%)	0.22
~1000 m < radius < 2500 m	23 (12%)	0.023
~2500 m < radius < 4000 m	13 (6.6%)	7.04E-03
~4000 m < radius < 10000 m	13(6.6%)	8.53E-04
10000 m < radius < 30000 m	15 (7.6%)	1.05E-04
~30000 m < radius < 100000 m	18 (9.1%)	1.11E-05
Antenna RF System		
Frequency Range	GHz	
Band 1 (high) + UHF Band	0.58 – 1.015	Dual pol'n. Shared Frequency Range
Band 2 + L-band	0.95 – 1.67	"
Band 3 [5]	1.65 – 3.05	Dual pol'n. SKA antennas only
Band 4 [5]	2.80 – 5.18	"
Band 5a	4.60 – 8.50	"
Band 5b	8.30 – 15.4	"
Band 5c [5]	15.0 – 26	"
Continuum Sensitivity		
SEFD (available antennas, Stokes I)	Jy	Equivalent A_e/T_{sys} (m^2/K)
Band 1 (high) + UHF Band	2.85	967
Band 2 + L-band	1.55	1784
Band 3	2.50	1102
Band 4	3.49	792
Band 5a	2.38	1161 (Max. Sampled Bandwidth 2 x 2.5 GHz)
Band 5b	2.77	998 (Max. Sampled Bandwidth 2 x 2.5 GHz)
Min. detectable flux (rms) (ΔS_{min})	µJy s$^{-1/2}$	
Band 1 (high) + UHF Band	99.8	Average over RF bands
Band 2 + L-band	42.1	"
Band 3	48.9	"
Band 4	53.1	"
Band 5a	25.3	"
Band 5b	29.4	"
Signal Processing System		
Correlator		
Freq. chans (widest sampled BW)	65536	
Full Bandwidth Velocity Resolution	km-s^{-1}	
Band 1 (high) + UHF Band	~5	Non-Zoom, all available frequency channels
Band 2 + L-band	~5	"
Max. Frequency Resolution	0.21 kHz	$\boxed{13.440 \cdot 2^{-n}}$ $\boxed{n \in (0,..,6)}$ kHz in Zoom mode
Standard Frequency Resolution	13.44 kHz	220.200960 / 16384
Complex Correlations	5.1 x 10^9	(197^2/2) baselines x 4 pol'n prod's x 65536 chans

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[5] 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 upper end of the frequency range is to be decided at a later date.

Minimum Integration Time	0.14 s	Interface Control Document
Transient Capture Buffer Size	72 – 288 s	For 330 MHz BW, scaling with 2-8 bits sample width
Pulsar Search Array Beam Former		
Full beamformer	197 antennas	Any Front-end band.
No. Antennas in 20 km array diameter	164	Typical Beam-forming Sub-array
Available Bandwidth	300 MHz	Each polarisation
Beam Area at 1 GHz	12.7 arcsec^2	$\pi/4(1.3\ \lambda_{1GHz}/\ D_{array})^2$ 13 arcsec
Available No. of IQUV Stokes power beams	1500	Pol'n corrected on output.
Available No. of Frequency Channels	3720	Resolution 80.64 kHz
Channel tuning resolution	1.26 kHz	
Impulse Response Bands 1-3	30 dB/sample	Decay rate with no oversampling
Impulse Response Bands 4-5	40 dB/sample	″
Pulsar Timing Array Beam Former		
Full beamformer	197 antennas	Any Front-end band.
Available number of 'voltage' beams	16	
Available Total Bandwidth	20 GHz	Each pol'n; aggregate over 16 beams
Available No. dual pol'n Freq. Chans.	3720	Resolution 53.76 kHz
Impulse Response Bands 1-3	30 dB/sample	Decay rate with no over-sampling
Impulse Response Bands 4-5	40 dB/sample	″
VLBI Beam Former		
Full beamformer	197 antennas	Any Front-end band.
Available Bandwidth	2 x 2.5 GHz	Per beam; 2 pol'n; Band 5, full BW for other bands.
Available No. of real-valued voltage beams	4	Pol'n corrected on output.
No. of frequency-chan bandwidths	9	1, 2, 8,16, 32, 64, 128, 224 MHz

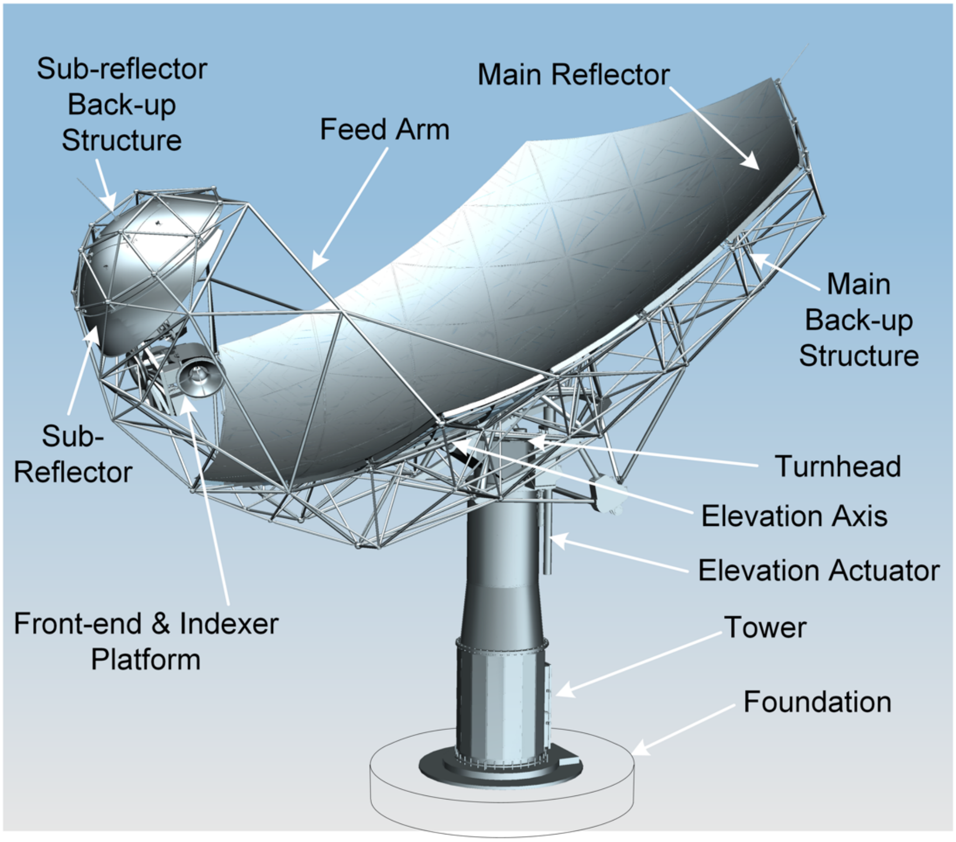

Figure 11. The SKA-MID Antenna utilising a Gregoria-offset design.

3. CONSTRUCTION SCHEDULE

Based on a mid-2021 start date for SKA1, the construction phase extends approximately 8 years to 2029. The following table lists the high-level project milestones.

Table 3 Level 1 Milestone projection completion dates.

Key project milestone	**Identifier**	**Low Telescope**	**Mid Telescope**
Start of construction	T0	1st July 2021	1st July 2021
Earliest start of major contracts	C0	August 2021	August 2021
Array Assembly 0.5 finish	AA0.5	February 2024	March 2024
Array Assembly 1 finish	AA1	February 2025	February 2025
Array Assembly 2 finish	AA2	February 2026	December 2025
Array Assembly 3 finish	AA3	January 2027	September 2026

Array Assembly 4 finish	AA4	November 2027	June 2027
Operations Readiness Review	ORR	January 2028	December 2027
End of Construction		July 2029	July 2029

In Table 3, the Array Assemblies (AA) represent the completion of incremental subsets of the full array in the number of stations (Low) or dishes (Mid) along with an increasing set of observing mode capabilities. AA0.5 is the earliest incarnation of a working array. AA1 begins with 18 stations/8 dishes and basic continuum and spectral line imaging capabilities. Construction culminates with the full 512 station/197 dish facilities with imaging, pulsar timing and search, dynamic spectra, transient capture and VLBI functionality.

Engagement with the community will begin through data releases during the Array Assembly roll-outs.

3.1 Milestones for the End of each Array Assembly – SKA1-Low

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

- AA0.5
    - 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
    - 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
    - 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
    - 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
    - Full SKA1-Low array
        - Demonstrate imaging with optimized 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 centers.

3.2 Milestones for the End of each Array Assembly – SKA1-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
    - 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
    - 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
    - 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
    - Full SKA1-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 centers

CONCLUSION

The SKA1 Project is concluding its Pre-Construction Phase through the efforts of the Member Country engineers and scientists. We anticipate the start of construction in 2021.

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