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Square Kilometer Array project status report

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ABSTRACT

This paper will describe the progress of the SKA-1 Telescope during the period from Preliminary Design Review to Critical Design Review. In addition to this, it will provide information on the management of the project with respect to managing cost and scope whilst working within a fixed cost cap. The paper will consider the balance between the technical choices made with the risk of delivering a large, distributed observatory across several continents. In addition, it will consider the challenges of carrying this out whilst developing the organisation towards an Inter-Governmental Organisation. It will consider, briefly, the key management tools used and the lessons learned.

Keywords: SKA, Array, Telescope, Astronomy

INTRODUCTION

The Square Kilometre Array (SKA) is an ambitious project to build a radio telescope that will enable breakthrough science and discoveries not possible with current facilities. Built over two sites in Australia and Africa it will, when both phases are complete (SKA1 and SKA2), provide over a million square metres of collecting area through many thousands of connected radio telescopes. Constructed in two phases: SKA1 is being designed now; SKA2 is planned to follow.

The SKA radio telescopes will provide continuous frequency coverage from 50 MHz (6 m wavelength) to 20 GHz (1.5 cm wavelength). SKA1 will cover most of this frequency range, while greater sensitivity at all frequencies and fast surveying will be added in SKA2. A project of this scale has perforce been developed from the very beginning as an international partnership that will draw on the scientific, technological, industrial and financial resources of its members. What will emerge is a new international observatory.

This paper describes an update of the SKA-1 Design, an update of the document issued in March 2013 (BD-v1), which outlined the design which would meet the, then, Level 0 Science Requirements. This update is a result of the Re-Baselining exercise which took place in 2016. At that time, it was realised that the complete vision of SKA-1 could not be met within the available cost cap and so a re-baselining was required. This was reported at the 2016 SPIE Conference. The outcome was:

"Taking into consideration the work undertaken by consortia and the SKA Office team, advice from the ad hoc Science Review Panel and the SEAC, it is my recommendation that the Board adopt the following components as the updated SKA1 Baseline Design to be built within the agreed cost cap of €650M (2013 Euros):

- *SKA1-Mid in South Africa should be built, incorporating MeerKAT. 70% of the planned 190 SKA1 dishes should be constructed with a target of delivering baseline lengths of 150km, but with a fallback of 120km if funding is constrained. Receiver bands 2, 5 and 1 should be constructed for all SKA1-Mid dishes, with their priority order as written. Capability to form and process 50% of the planned pulsar search beams should be delivered.*
- *SKA1-Low in Australia should be built. 50% of the planned 262,144 low frequency dipoles should be deployed. The array should cover the frequency range 50-350 MHz, as planned. The current planned baseline lengths of ~80km should be retained. The inclusion of a pulsar search capability for SKA1-Low (currently an Engineering Change Proposal on hold) should be actively explored.*
- *SKA1-Survey in Australia should be deferred.*

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CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2312438

In addition, an SKA Phased Array Feed (PAF) development programme should be initiated as part of a broader Advanced Instrumentation Programme.

It is also recommended that the Board approve funding, with Australia's agreement, for the operations of ASKAP as an integral component of SKA1; the start date to be negotiated with Australia. This would enable ASKAP to provide SKA1 with an early survey capability and also serve as a platform for the development of next-generation PAFs.

SKAO will immediately implement the variations in the design via a series of Engineering Change Proposals, which would require full documentation and review through our now standard processes. A new Baseline Design document will be generated for consideration at the July 2015 Board meeting."

Science

As a starting point, this will necessarily require reference to scientific priorities, which have matured to the point where clear linkages can be established between science goals and technical requirements. As described in the Level-0 science requirements, "The Level-0 requirements convey the scientific goals of the facility, while the Level 1 requirements convey the technical specifications that the project proposes to deliver to address those goals. Neither is formally 'applicable to', although both are 'informed by', the other." This document will provide general traceability to the Level 0 science document but will also reference specific requirements when necessary to motivate telescope individual design choices or capabilities.

Top-level Description of SKA1

The first version of the Baseline Design (BD-v1) has evolved at the top level primarily to take into account the results of the cost analysis of BD-v1 and subsequent 're-baselining' process. At the top level, the main change has been the deferral of the SKA-survey telescope. Much progress has been made in defining and designing the components of the telescopes.

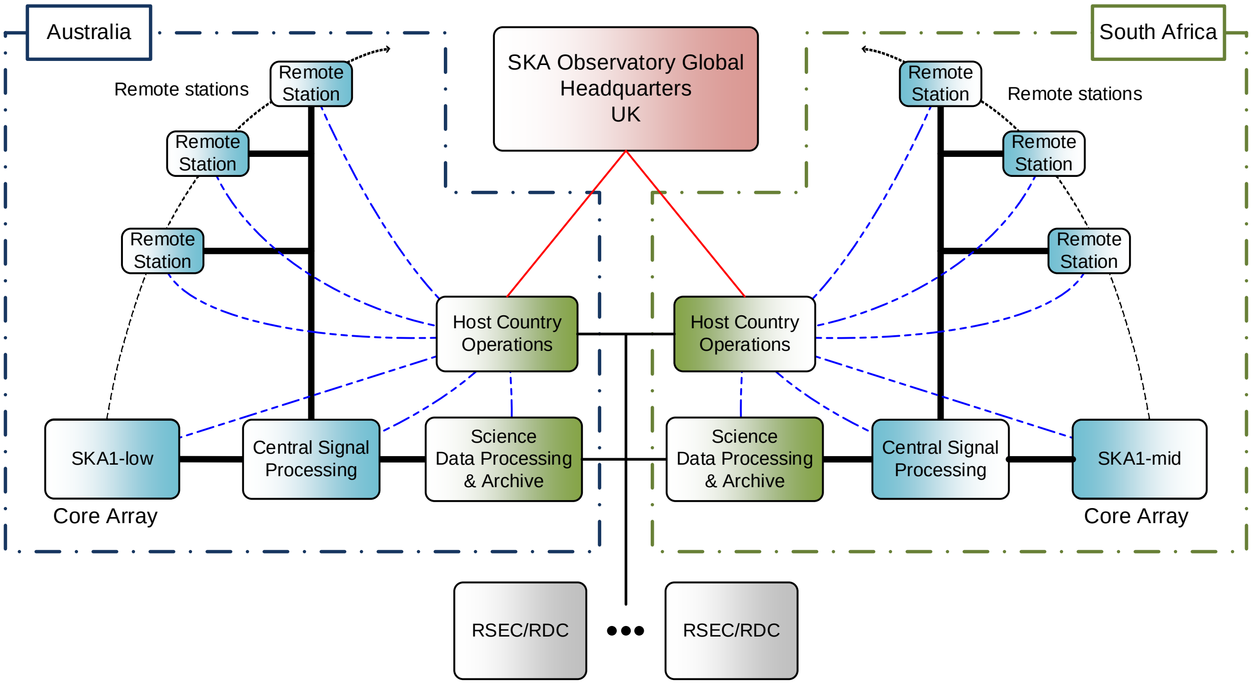


Figure 1: A schematic diagram of the SKA Observatory, showing the site entities (telescopes), the entities at Host Country centres (Host Country Operations, Science Data Processing & Archiving), and entities that are globally located (Global Headquarters and RSEC/RDCs[1]).

Figure 1 shows the major SKA Observatory entities: SKA1-low in Australia, SKA1-mid in South Africa and the SKA Global Headquarters in the UK. The thick flow-lines show the uni-directional transport of large amounts of digitised data from the receptors to the central signal processing facilities on the sites, and from the central signal processing facilities to the Science Data Processing Centres and Archives. The thin dash-dot lines show the bi-directional transport of system monitor and control data.

The Science Data Processor is envisaged to be a supercomputing facility with an attached or nearby archive to store science-ready data. The science data processor is where calibration of the data takes place, images of sky brightness are formed, and further analysis of time-domain observations are carried out. For current aperture synthesis arrays, algorithms for carrying out calibration and imaging are mature at higher frequencies. However, the SKA-mid is likely to require significant new developments in this area to handle the much larger amount of data, and to achieve the ambitious dynamic range targets without continuous human input. In addition for SKA1-low more fundamental advances are likely to be necessary in this area.

The Archives will store the outputs from the Science Data Processors in the site countries, where they will be kept for an indefinite time. The Science Regional Centres (SRCs) are the facilities where it is expected that actual science analysis will take place and/or science data will be stored. Engineering data will be stored and analysed at GHQ. Apart from very general descriptions, their number and precise scope is undefined at this point.

The design, construction and verification of all the entities shown in Figure 1 are part of the current capital funding-profile except for the SRCs and associated science data transmission facilities (Archives-to-SRCs).

Primary Telescope Performance Parameters

Scientific performance is determined mainly by seven 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 Ae is the effective collecting area, taking into account 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 an large area of sky. The customary parameterisation of this is $(A_e/T_{sys})^2\Omega$, where Ω is the instantaneous field-of-view of the telescope. Neither of these measures takes into account bandwidth.
- *Bandwidth*: The 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 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.
- *Processing capability of the telescope along three dimensions*:
    - 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.

  - Temporal processing: the capability to determine changes in the flux of emission from a defined area of sky over a given frequency band.
- *Very Long Baseline Interferometry (VLBI)*: A capability to participate in observations with VLBI networks for which there is mutual sky visibility and frequency range compatibility.

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 concepts for the SKA have been to develop high sensitivity telescopes. Table 1 contains a list of performance parameters for radio telescopes, both currently available and those that are under construction or planned, including the SKA1 telescopes.

Parameters for Comparable Telescopes														
		eMERLIN	JVLA	GBT	GMRT	Parkes MB	LOFAR	FAST	MeerKAT	WSRT	Arecibo	ASKAP	SKA1-low	SKA-mid
A_{eff}/T_{sys}	m^2/K	60	265	276	250	100	61	1250	321	124	1150	65	559	1560
FoV	deg^2	0.25	0.25	0.015	0.13	0.65	14	0.0017	0.86	0.25	0.003	30	20.77	0.49
Receptor Size	m	25	25	101	45	64	39	300	13.5	25	225	12	35	15
Fiducial frequency	GHz	1.4	1.4	1.4	1.4	1.4	0.12	1.4	1.4	1.4	1.4	1.4	0.11	1.67
Survey Speed FoM	$deg^2\ m^4\ K^{-2}$	9.00×10^2	1.76×10^4	1.14×10^3	8.13×10^3	6.50×10^3	5.21×10^4	2.66×10^3	8.86×10^4	3.84×10^3	3.97×10^3	1.27×10^5	6.49×10^6	1.19×10^6
Resolution	arcsec	$10\text{-}150 \times 10^{-3}$	1.4 - 44	420	2	660	5	88	11	16	192	7	7	0.25
Baseline or Size	km	217	1 - 35	0.1	27	0.064	100	0.5	4	2.7	225	6	80	150
Frequency Range	GHz	1.3-1.8, 4-8, 22-24	1 - 50	0.2 - 50+	0.15, 0.23, 0.33, 0.61, 1.4	0.44 to 24	0.03 – 0.22	0.1 – 3	0.7 - 2.5, 0.7 - 10	0.3 – 8.6	0.3 - 10	0.7-1.8	0.050 – 0.350	0.35-14
Bandwidth	MHz	400	1000	400	450	400	4	800	1000	160	1000	300	300	770
Cont. Sensitivity	$\mu Jy\text{-}hr^{-1/2}$	27.11	3.88	5.89	6.13	16.26	266.61	0.92	3.20	20.74	0.89	28.89	3.36	0.75
Sensitivity, 100 kHz	$\mu Jy\text{-}hr^{-1/2}$	1714	388	373	411	1029	1686	82	320	830	89	1582	184	66
SEFD	Jy	46.0	10.4	10.0	11.0	27.6	45.2	2.2	8.6	22.3	2.4	42.5	4.9	1.8

Table 1: A table of typical performance measures for a variety of radio telescopes (extant and under construction)

Notes to Table

eMERLIN	Frequencies non-contiguous			
JVLA	Multiple antenna configurations			
GBT	Single dish			
GMRT	Frequencies non-contiguous			
Parkes MB	Multi-beam (13)	Frequencies non-contiguous		
LOFAR	Parameters for all NL stations	Frequencies non-contiguous		
FAST	Single dish	Under construction		
MeerKAT	SKA Precursor	Under construction		
WSRT	Frequencies non-contiguous			
Arecibo	Single dish			
ASKAP	SKA Precursor	Multi-beam (36)	Under construction	
SKA1-low				Planned
SKA-mid		Mixed 13.5-m & 15-m dishes	FoV based on 15-m dishes	Planned
Notes: All	Fiducial frequency: Most Parameters	$\Omega_{FoV} = (\pi/4)(66\lambda/Ddish)^2$	Gray shading: <400 MHz capable	SEFD: System Equivalent Flux Density
(cont'd)	SEFD derived from A_{eff}/T_{sys}	Sensitivity derived from SEFD & BW	System efficiency assumed 100%.	

General Descripton

The Square Kilometre Array (SKA) will utilise a huge number of telescopes from two unique designs to attain its goal of matching a single instrument one kilometre in size. The three antenna types; dishes, mid frequency arrays and low frequency arrays, will be used to provide a continuous frequency coverage from 50MHz to 20 GHz. To achieve both high sensitivity and high resolution images of the sky the antennas will be densely distributed in the centre regions and more positioned in clusters along spiral arms becoming more widely spaced further from the centre. With an instrument of this size, sensitivity and capability, astronomers will have access to a radio telescope on a scale orders of magnitude greater than any previously built.

The SKA project is currently managed as an agreement between the participating countries. Currently, Australia, Canada, China, India, Italy, New Zealand, South Africa, Sweden, the Netherlands and the United Kingdom are full members. The project is funded by these members and currently managed through the Square Kilometer Array Organisation (SKAO) which is a non profit limited company incorporated in the UK. There are several other countries at present progressing towards membership.

In 2012 it was realised that the full project was too expensive to proceed with acceptable risk and so the project was split into 2 phases, SKA Phases 1 (SKA-1) and 2 (SKA-2). In addition a risk assessment of technologies was made and it was agreed which areas of technologies would be treated as technical development projects within the first phase and which areas would form part of the Baseline Design for Phase 1. The result was an agreement for SKA-1 to consist of a mid-frequency dish array in South Africa, a survey dish array and a low frequency aperture array in Western Australia. A capped budget for both procurement was agreed and the pre-construction phase initiated.

The pre-construction phase started in late 2013 with a group of 9 consortia from around the world developing the detailed design of the Elements of the project. The Elements are the top level ‘building blocks’ of the telescopes. In addition, two consortia were tasked to develop two areas of technology. The work is managed through the SKAO Office located at Jodrell Bank in the UK. Each consortium is made up of a series of institutes, universities and industry. The funding model for pre-construction is for each member country to make a contribution to the running of the SKAO and each institute to arrange funding nationally for the work being carried out with the consortia. The consortia deliverables thus become in-kind contributions. The phase is due to last 5 years culminating in a full construction proposal for SKA-1 and a development plan for SKA-2. The final milestone is a series of Critical Design Reviews in late 2018 leading to a System CDR in 2019.

To enable this phase to begin, the SKA Board agreed a budget for each element that sums to higher than the predicted budget for the construction phase. It is intended to address this by carrying out a re-baselining exercise later in 2014 to reduce the scope of SKA-1 to meet the available budget once more reliable costs are known.

It became obvious that all of the ambitions could not be attained for the target ceiling cost and so a re-baselining process was carried out to reduce the scope of the project to a solution that could be produced within the available cost cap. A process based on the key science objectives was developed and a rigorous assessment of all possible options was carried out to conclude with an affordable result.

Management

The SKAO Office in Jodrell Bank is responsible for the overall management of the SKA Project. This includes the creation and management of the Level 0 Science Requirements, the Level 1 System Requirements and the management through Memoranda of Understanding and Statements of Work of the detailed design activity being carried out within the consortia. To manage this, the office, ignoring the administration, is organised into:

- Science Office
- Engineering Group
- Mission Assurance Group
- Project Management Group

The Science Office is responsible to collate and manage the Science Requirements as well as engaging with the Scientific Community and progressing the scientific aims and ambitions. The Architecture Group owns and manages the System Requirements and provides technical expertise to the office. The Systems Engineers support the Project Managers by managing system aspects of the telescopes. The Project Managers manage the work carried out within the Elements. Project Control includes planning and control as well as configuration management. The Elements are managed by Integrated Element Teams which each consist of a project manager, systems engineer, scientist and member of the Architecture Group.

For the period of the Pre-Construction Phase, the work is separated into a series of work packages, known as Elements. These consist of:

Dish (DSH) The “Dish” Element of the SKA is probably what most people think of as a radio telescope. But for the Dish (DSH) consortium, it means all of the activities necessary to prepare for the procurement of the SKA dishes, including local monitoring & control of the individual dish in pointing and other functionality, their feeds and receivers, necessary electronics and local infrastructure. The Dish element of the SKA includes planning for manufacturing of all components, the shipment and installation on site of each dish (including feeds and other components) and the acceptance testing. The existing SKA dish precursors and pathfinders are a separate entity; DSH is about developing and building the future dish receptors of the SKA itself.

Low-Frequency Aperture Array (LFAA) The "Low-Frequency Aperture Array" (LFAA) Element consists of the array of antennas, low noise amplifiers, anaologue data transport and signal processing required for the Low-Frequency Aperture Array telescope of the SKA. LFAA includes the digital signal processing systems required to beamform the antenna signals as ~512 stations. Sophisticated calibration alogoritthms and antenna control systems are included to link to the overall SKA-low integration.

Signal and Data Transport (SaDT) The Signal and Data Transport Element includes all hardware and software necessary for the transmission of data and information between the Elements of the SKA. SADT also includes the provision of timing which is critical for interferometry.

Science Data Processor (SDP) The Science Data Processor Element will focus on the design of the computing hardware platforms, software, and algorithms needed to process science data from the correlator or non-imaging processor into science data products. The data rates involved in this will exceed that of the entire global internet traffic per day.

Telescope Manager (TM) The Telescope Manager Element includes all hardware and software necessary to control the telescope and associated infrastructure. The TM includes the co-ordination of the systems at observatory level and the software necessary for scheduling the telescope operations. It also includes the central monitoring of key performance metrics and the provision of central co-ordination of safety signals generated by Elements of the SKA. The TM provides physical and software access to, and at, remote locations for transmission of diagnostic data and local control. The TM does not include local control, whether hardware or embedded software, of units (e.g. individual dishes, beam formers, building control systems). It does not include either the generation of local metrics (e.g. tracking stability of dish, power consumption of LFAA).

Central Signal Processor (CSP) The Central Signal Processor Element includes design of the hardware and associated firmware/software necessary for the generation of visibilities, pulsar survey candidates and pulsar timing from the telescope arrays. CSP does not include the buildings, cooling, shielding or power supply to the building. CSP does include the distribution of data within the processor, diagnostic tools etc. necessary for the maintenance and operation of the system.

Assembly Integration & Verification (AIV) The Assembly Integration and Verification Element includes the planning for all activities at the remote sites that are necessary to incorporate the elements of the SKA into existing infrastructures whether these be precursors or new components of the SKA. AIV does not include design of new components of the SKA.

Infrastructure (INFRA) Infrastructure for the SKA requires two consortia, each managing their respective local sites in Australia and South Africa. INFRA-AU and INFRA-SA have the huge task of taking care of all SKA infrastructure on continent wide scales. The "Infrastructure" (INFRA) element as stated covers both the Infrastructure in South Africa and in Australia. It includes all work undertaken to deploy and be able to operate the SKA in both countries. Infrastructure includes roads, buildings, power generation and distribution, reticulation, vehicles, cranes and specialist equipment needed for maintenance that are not included in the supply of the other elements. Infrastructure does not include access rights to the land, environmental protection or monitoring. Infrastructure does not include protection from external sources of interference. Infrastructure includes the provision of any site wide safety systems necessary for personnel and equipment safety.

In addition, the project has two advanced instrumentation programmes aimed towards SKA-2. These are:

Mid-Frequency Aperture Array The "Mid-Frequency Aperture Array" (MFAA) Element, part of the SKA Advanced Instrumentation Programme, includes the activities necessary for the development of a set of antennas, on board amplifiers and local processing required for the Mid-Frequency Aperture Array telescope of the SKA. MFAA includes the development of local station signal processing and hardware required to combine the antennas and the transport of antenna data to the station processing.

Wide Band Single Pixel Feed The Wideband Single Pixel Feeds (WBSPF) Element, part of the SKA Advanced Instrumentation Programme, includes the activities necessary to develop a broad spectrum single pixel feed for the SKA. Specifically, WBSPF seeks to greatly expand the frequency range covered by radio astronomy receiver systems.

Systems Engineering

Context for Systems Engineering for SKA

The diverse environments and cultural backgrounds of contributors to the development of very large international research infrastructure projects make the establishment and maintenance of a fully specified and classical system engineering (SE) approach from the outset very difficult. In particular, tradition dictates that instruments and facilities used for research are built according to the ‘art of the possible’ rather than by imperative requirements and a few broad constraints. Highly advanced facilities necessarily incorporate immature technologies or mature technologies used in demanding ways. Furthermore, the performance ambitions that come with grand projects lead to the involvement of institutions adept at research and development at the technology level and the assembling of high-risk technologies into one-of-a-kind instruments where considerations of low cost manufacture, assembly, integration and verification rarely apply. Finally, the project cultures that are being brought together in SKA Phase 1 are highly diverse; there is no dominant, pre-existing and mature engineering culture that pervades the Project (such as that of ESO), which could be drawn upon to provide a tried and tested system engineering framework without debate or competition. However, the importance of system engineering and design integration for international megaprojects is emphasised in RD[1].

The absence of a pre-eminent and mature SE culture resulted in a protracted interchange of many months during 2011/12 regarding the SE approach to be followed. Underlying much of the debate was the erroneous idea that, for a large international collaboration of equals, major engineering decisions can be made based upon the opinions of a small group of co-located and like-minded individuals, and that this process could accommodate the pressures created by diverse national and institutional interests. The lack of a resolution in this debate prompted the Director-General to ask an external panel to conduct a review of System Engineering in the SKA in late 2012. The panel recommended that the SKA Office abandon the idea of creating and imposing a detailed and prescriptive system engineering framework on the Consortia at this stage, and to provide a simplified project baseline in order to allow development to commence. The baseline was comprised of:

- A Baseline Design document, reflecting the view of the project in design terms developed by the SKA Office Architecture group
- A Level 1 Requirements document comprised of requirements derived from the Baseline Design and some additional, key non-functional requirements.
- A Work Breakdown Structure of only 64 line items for the Pre-Construction Phase 1.
- A Statement of Work detailing deliverables for Preliminary Design Review and Critical Design Review.

These documents (with the exception of the Level 1 Requirements) formed a Request for Proposals (RfP) package, against which prospective Element Consortia bid. In their Bids, the RfP asked, amongst other things, for a System Engineering Management Plan (SEMP) to be provided. Upon negotiation with successful Consortia, these individual plans were deemed satisfactory and they are the basis upon which the Consortia carry out System Engineering to date. This means that there are considerable differences in approach and resourcing of SE across the Project.

It is within this environment that system engineering for the SKA operates. It is clear that system engineering at Project level must be pragmatic in the face of non-engineering and non-scientific pressures, and be highly capable of determining the impact of proposed change and the late emergence of new constraints, alongside its primary functions of rational design and system integration.

Architecture

As noted above, it has proved impossible, and perhaps unnecessary, to derive the architecture of the SKA1 Observatory from functional analyses alone. None of the major institutional contributors have allowed their contributions to be defined in this way. It is therefore pragmatic and sensible to 'assemble' the SKA from the intended technical contributions in the first instance and to adjust the boundaries and interfaces of these contributions during the early development phase using the tenets of System Engineering to guide the process.

The SE view of this process is straightforward. The limits of intended hardware and software deliverables and constituent technologies offered within the Elements are treated as constraints. The Baseline Design document can be seen as arising from an interpretation of these constraints ('bottom up' synthesis), and it is an initial attempt to do this whilst also meeting requirements derived from analysing a set of science use cases ('top down' synthesis). Owing to the presence of an extensive set of technical, managerial and programmatic constraints, functional analysis and partitioning carried out *ab initio* and *in vacuo* have very limited value. In particular, an architectural approach that strives to minimise the complexity and number of interfaces will fail where the project has already been partitioned by other, non-technical, processes.

Modelling

Any successful engineering development undertaken by a team requires a common understanding of objectives and solutions. For SKA, due to the sheer scale of the development and the complexity and dispersed nature of the contributions, this common understanding is critical and requires strenuous efforts to create and maintain. Hitherto, the necessary common understanding of the structure and behaviour of a system was achieved through the use of natural language documents, graphics, databases and isolated mathematical models.

Modern SE now provides us with a tool to harmonise and unify representations of the system whose usefulness extends well beyond visualisation and limited simulation; namely Model Based Systems Engineering (MBSE).

The project is now utilising a formal language of MBSE, SysML, to begin to represent SKA1 at the higher levels. SysML provides a means to model the structural and behavioural aspects of the system and, through parametric modelling, to support three important processes in system development:

- Requirements allocation, whereby such things as error budgets may be managed at successively lower levels of the design whilst controlling the overall budget
- Engineering resource management, where the utilisation of operating resources such as electrical power and maintenance assets can be determined
- Costing

Additionally, such a model can be used for the assessment of the technical impact of proposed change, including re-baselining.

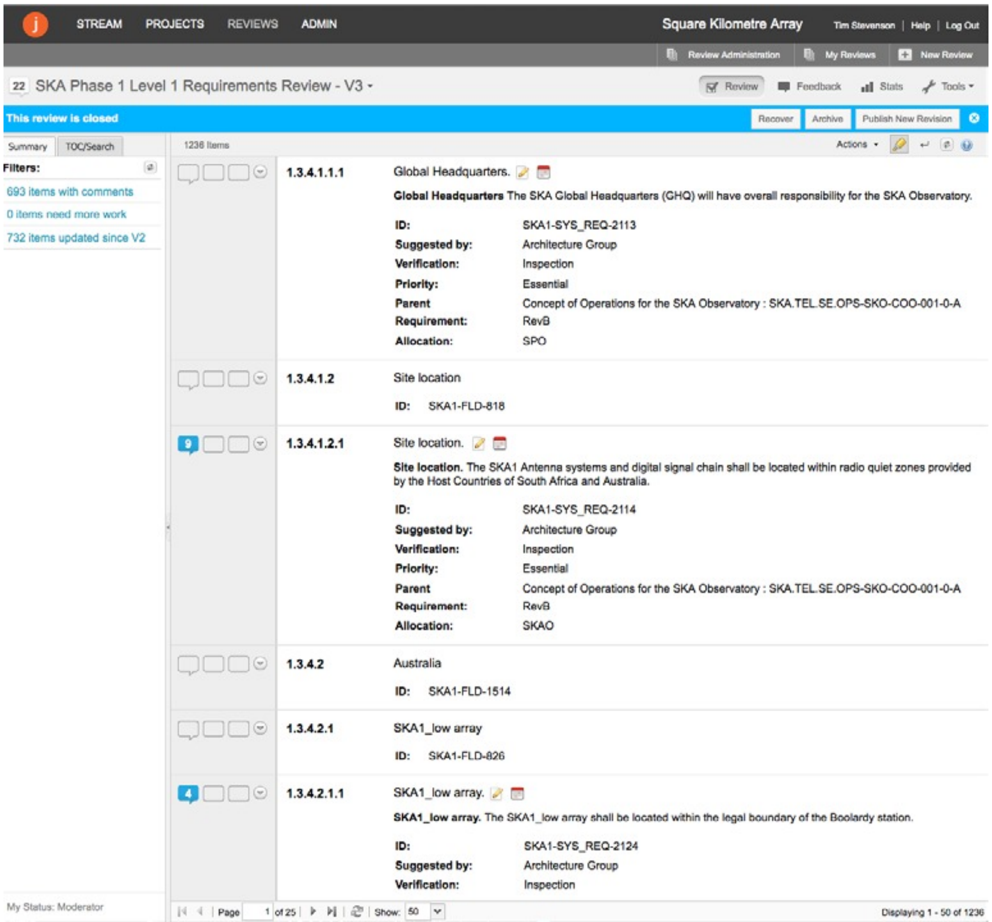
The SKA unified modelling effort is at an early stage.

Requirements and requirements traceability

As noted above, the SKA1 Pre-Construction Project is conducted by 11 Consortia, 8 of which are responsible for partitions of the Project known as Elements. The Elements are workshares – they do not correspond to branches of a product tree and cannot be represented easily on a hierarchical block diagram derived from a functional analysis driven purely by scientific and technical requirements. The workshares represented by the Elements are historically defined based upon the interests of the leading parties. The boundaries and the technical interfaces between the products that will be developed by them are currently being elaborated.

Where high-level requirements cannot be completely and unambiguously expressed, risk is taken along with many design decisions. The first class of risk relates to that of constructing a facility that does not meet expectations. The second class of risk is that the means to ensure that expectations have been met are absent, and that verification, testing, commissioning activities become unconstrained in cost and in time. The SKA project is actively managing these two classes of risk by undertaking requirements engineering as far as is possible. Historically, it proved impossible to converge on a pure and appropriately abstracted set of engineering requirements derived simply from a set of science requirements; amongst the reasons for this are disagreements regarding the likely scientific utilisation of the Observatory and misalignments between correctly derived requirements and the technical intentions of the likely contributors.

At present, the Consortia are working with a set of ‘Level 1’ Requirements extracted and derived from a baseline design description. The present status of these requirements are that they are baselined following extensive community review between December 2013 and March 2014. This review was conducted by invited access to a database running under the JAMA Contour requirements management tool. This wide review reflects the continuing need to obtain buy-in from a large number of stakeholders for whom convergence is historically difficult. The requirements review has contributed to the creation of a common purpose and a ‘bias for action’.



1.3.4.1.1.1 Global Headquarters.

Global Headquarters The SKA Global Headquarters (GHQ) will have overall responsibility for the SKA Observatory.

ID: SKA1-SYS_REQ-2113
Suggested by: Architecture Group
Verification: Inspection
Priority: Essential
Parent Requirement: Concept of Operations for the SKA Observatory : SKA.TEL.SE.OPS-SKO-COO-001-0-A RevB
Allocation: SPO

1.3.4.1.2 Site location

ID: SKA1-FLD-818

1.3.4.1.2.1 Site location.

Site location. The SKA1 Antenna systems and digital signal chain shall be located within radio quiet zones provided by the Host Countries of South Africa and Australia.

ID: SKA1-SYS_REQ-2114
Suggested by: Architecture Group
Verification: Inspection
Priority: Essential
Parent Requirement: Concept of Operations for the SKA Observatory : SKA.TEL.SE.OPS-SKO-COO-001-0-A RevB
Allocation: SKAO

1.3.4.2 Australia

ID: SKA1-FLD-1514

1.3.4.2.1 SKA1_low array

ID: SKA1-FLD-826

1.3.4.2.1.1 SKA1_low array.

SKA1_low array. The SKA1_low array shall be located within the legal boundary of the Boolardy station.

ID: SKA1-SYS_REQ-2124
Suggested by: Architecture Group
Verification: Inspection

Figure 2 A screenshot of a requirements database list view in JAMA Contour. Reviewers see a similar view, with the ability to comment, suggest amendments and to classify their input.

Review access was provided to 11 Consortia (8 product development Consortia, plus the AIV Consortium and two Advanced Instrumentation Programme Consortia). The Operations Working Group (OWG) and the leads of the Science Working Groups (SWGs) also participated. Reviewers were requested to act to improve requirements as written rather than comment on process or approach. This request was not heeded to a large extent – improvements to wording were offered only in a handful of cases.

Consortia co-ordinated comments generated within their numbers and input them to the database via one user account. OWG members participated on an individual basis, whilst SWG leads collected their respective groups’ comments.

Following review, there are 574 requirements from the 554 existing at the start of the review. 2215 comments were received in total, from a review team of 29. Bearing in mind the focus of the Consortia, 7 of them provided between 150 and 300 comments each.

At present, the Level 1 requirements owe their most direct heritage to the Baseline Design. Other requirements come from developing Supporting Documents such as the Concept of Operations, Configurations document, etc as shown in Figure 2. Currently, as the Operations Concept Review is completed, the Operations Requirements are currently being absorbed within the L1 Requirements.

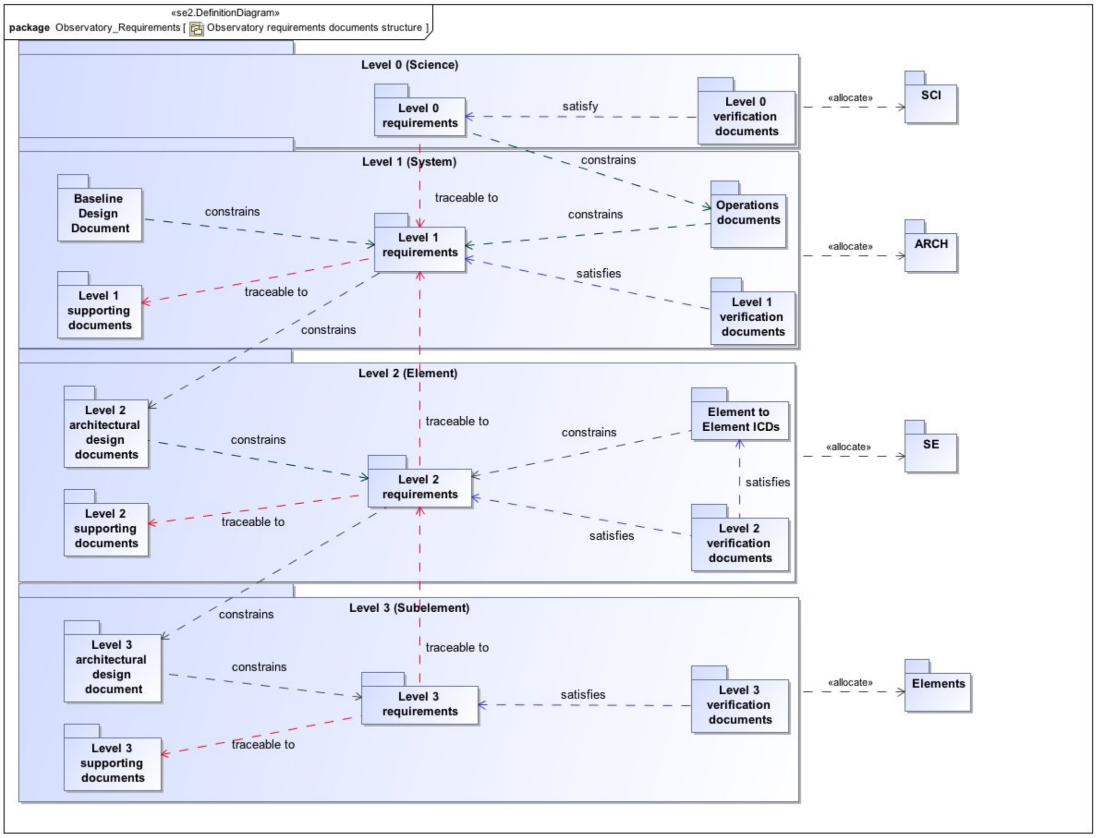


Figure 3 Observatory Requirements (SysML) Package Diagram showing the relationships between Requirements and documents at various levels and their ownership (allocation).

Interface Management

The RfP introduced a dramatically simplified Interface Management process (over standard practice) designed specifically to kick off the business of considering interfaces. The process has been initiated at Element level, whereby all interfaces between the products for which an Element Consortium is responsible and the products of a second Consortium are rolled into a single document. This is intended to address the natural inclination of R&D engineers to neglect interfaces with technical counterparts beyond their control and to avoid design activity affected by uncertainty. Uncertainty at interfaces (as well as elsewhere) is a fact of life for large ab-initio system development, and good engineering practice offers us a number of ways forward, such as the use of standards and known best practice.

The process has been both aided and hindered by some issues of ill-defined product boundaries:

- The lack of a firm product boundary has, in some cases, allowed us to specify a boundary between ‘subsystems’ that minimises complexity; the classical architectural derivation process. Interface definition has then proceeded with maximum buy-in.

- The lack of a pre-determined product boundary has allowed disparate views to persist and engineering at the respective boundaries to proceed in isolation. The late agreement or imposition of interfaces will render some of that work nugatory.

Change Management

The SKA1 Pre-Construction project operates a configuration management system that, whilst still under development, controls the baseline created by the RfP whose central document is the L1 Requirements. At the time of this writing, 17 Engineering Change Proposals are being considered. Prior to Re-Baselining, there was a strong emphasis on preventing scope creep, correcting errors and providing clarification.

Change management is classical – there is a workflow within which a Change Review Board (CRB) carries out the analysis and provides advice and a Change Control Board (CCB) that acts upon the advice and its own expertise. The CRB is an ad-hoc body appointed for its expertise and responsibilities within the project, and so has strong Consortium representation in many cases. The CCB is an expression of the Design Authority of the SKA Office and is staffed accordingly.

Change Management is traditionally an unpopular and painful process in the early stages of international research infrastructure development – the SKA is no different.

Verification

The project intends to follow a classical approach to verification as far as is possible and affordable. Previous 'sister' projects have met with varying success in this regard, and lessons have been learnt on the costs of not facilitating and planning verification from the very beginning; carrying it out in the hierarchical fashion that is the most cost effective approach.

Design Verification

Prototypes for various components of the Observatory are undergoing design, construction and testing, with those processes driven by SKA requirements. From the Office perspective the role of Technology Readiness Assessment is critical in the early stages, and later, System Readiness Assessment will also be applied in a formal way. In the immediate term, Technology Readiness Levels (TRLs) of at least 5 are to be met by PDR.

As intimated in the section on modelling above, the project is equipping itself with a configuration controlled MBSE model which will be used for many analytical verification tasks at system level.

As built verification

As the Telescopes are built up, verification tests will be carried out against requirements and in comparison with analytical and lower level test results. As is normal, both the costs and the criticality of tests are high and escalating as the degree of integration and the schedule proceeds. It is absolutely critical that:

- 'final' verification at each level is carried out as early as possible
- Verification is against requirements, and in that, 'verification' includes that mandatory parts of Commissioning where astronomical expertise is used to confirm compliance with the highest level science requirements which may require fine tuning and operational experience.

The Project is already planning Assembly, Integration and Verification (AIV) in accordance to these principles.

Re-Baselining

When the project entered its Pre-Construction Phase, it was foreseen that the complete Baseline Design would not be affordable and that a process would be required to reduce the project deliverables to maintain the cost cap. It was agreed that this would occur through a clear science driven process in late 2014, reporting the results to the SKA Board in March 2015.

The office designed a process which was agreed by the SKA Board and received Deign Descriptions and Costings from all the Consortia in October 2014. These costs were investigated and an understanding was reached.

The office then carried out a series of campaigns to generate suggestions on possible cuts. These came from consortia members, science group members and members of the SKAO staff. A workshop was also carried out at the 2014 Engineering Meeting in Fremantle WA to review some options.

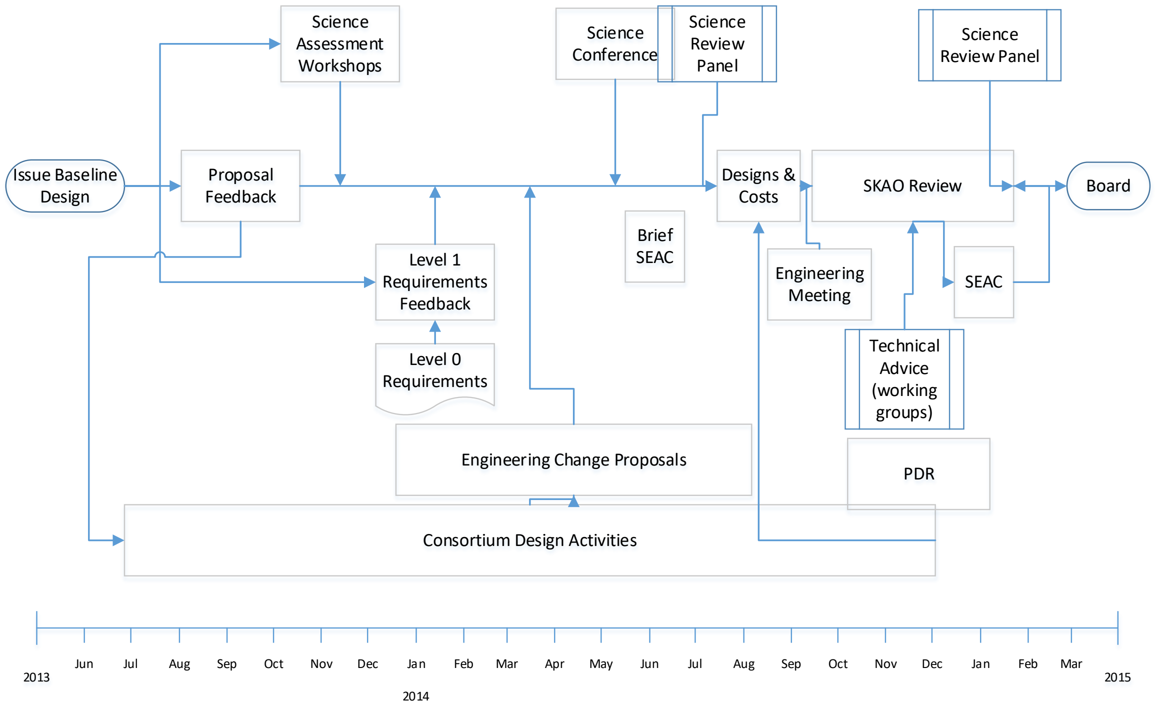


Figure 4: Re-Baselining Process

The options raised by the SKA Office were reviewed by a Science Review Panel, which set the project clear priorities of science to be achieved and also the Science and Engineering Advisory Committee which advises both the DG and the SKA Board.

The result was:

• SKA1-Mid in South Africa should be built, incorporating MeerKAT. 70% of the planned 190 SKA1 dishes should be constructed with a target of delivering baseline lengths of 150km, but with a fallback of 120km if funding is constrained. Receiver bands 2, 5 and 1 should be constructed for all SKA1-Mid dishes, with their priority order as written. Capability to form and process 50% of the planned pulsar search beams should be delivered.

• SKA1-Low in Australia should be built. 50% of the planned 262,144 low frequency dipoles should be deployed. The array should cover the frequency range 50-350 MHz, as planned. The current planned baseline lengths of ~80km should be retained. The inclusion of a pulsar search capability for SKA1-Low (currently an Engineering Change Proposal on hold) should be actively explored.

• SKA1-Survey in Australia should be deferred.

Cost Control Exercise

In 2016 it became clear that, following re-baselining, it was still difficult to control the costs to near the Cost Cap. It was therefore decided to carry out a Cost Control Project. This project built on the experience of Re-Baselineing and developed a process to manage costs.

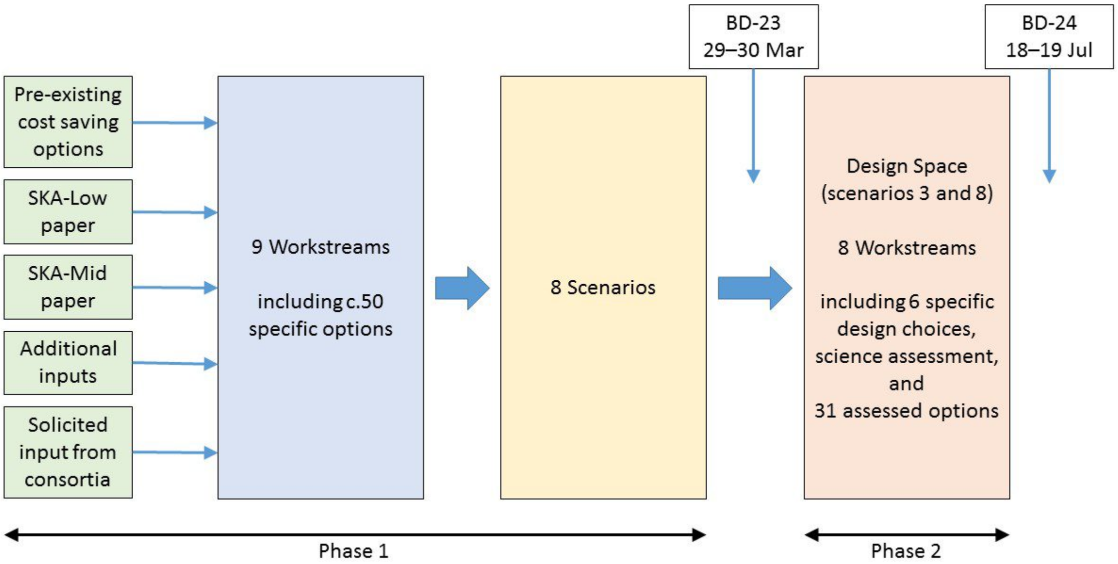


Figure 5: Cost Control Process

The Office conducted the CCP through two phases as shown above in Figure 1 and as described in the past to the Board. The initial Phase 1 was reported in full to the Board in March 2017. The plan for Phase 2 was described at an Interim Board Meeting in May. The plan has been translated into 8 Workstreams and 6 specific design choices. These Workstreams included 31 assessed individual options.

The work is being conducted under the following assumptions:

- The Office will deliver the most cost effective, compliant solution, other factors being equal.
- The proposal is based on the One Observatory; Two Telescope model
- The review is to be complete, fully transparent and auditable
- Construction and Operational costs have equal importance
- The Design Space includes the options that make up Scenarios 3 & 8 from the initial CCP work
- There should be a route identified to the re-instatement of capabilities that have been removed if and when additional funding becomes available.

In addition, some further assumptions were made by the Office:

- This work takes top priority in the Office. System PDR close-out takes second priority.
- The Consortia should continue to deliver to their CDR schedules, but when asked for input to the CCP work, that should take priority.
- Ongoing work and activities will need to be managed during this process.
- Where IP issues arise, those options will be noted and the risk assessed.

3.1

The top-level process for the Cost Control Project Phase 2 was to create a design space including both Scenarios 3 and 8 as described in. This translated into a menu of options shown in table 2:

WS / Origin	Description	LOW / MID / COMMON	Science Implication	Science Impact
5.39	INFRA_SA Renewable energy to outer dishes	MID	None	1
5.3	Maximise use of code produced during Pre-Construction	COMMON	None	1
5.38	Simplify DDBH LOW	LOW	None	1
5.38	Simplify DDBH MID	MID	None	1
5.25.2	Reduce PSS-MID: A, 750 nodes to 500 nodes	MID	Likely none, or small reduction of pulsar search parameter space.	1
5.25.2	Reduce PSS-LOW: A, 250 nodes to 167 nodes	LOW	Likely none, or small reduction of pulsar search parameter space.	1
5.35	Reduce CBF-MID: Freq. Slice variant of CSP design vs. MeerKAT-based design	MID	None	1
5.19	MID Frequency and Timing Standard: SaDT solution vs. MeerKAT-based solution	MID	None	1
5.36	MID SPF Digitisers: DSH solution vs. MeerKAT-based solution	MID	None	1
5.26 / 5.29	LOW RPF: Early Digital Beam Formation vs. Analogue Beam Formation	LOW	None	1
2	LOW Antenna: Log Periodic Design vs. Dipole Design	LOW	None of the current designs meet the L1 requirements	3
8	SDP- HPC: Deploy 200 Pflops (rather than 260 Pflops)	COMMON	Lower allowed duty cycle for HPC-intensive observations.	2

5.24.3	Reduce Bmax MID from 150 to 120 km: Case A, remove 3 dishes, but keep infra to 150km	MID	Reduction of maximum achievable resolution by 20%, although can be partially recovered with data weighting and longer integration times.	2
5.24.2	Reduce Bmax MID from 150 to 120 km: Case B, remove infra, but add dishes to core	MID	Reduction of maximum achievable resolution by 20%, although can be partially recovered with data weighting and longer integration times.	2
5.24.1	Reduce Bmax MID from 150 to 120 km: Case C, remove infra, remove dishes	MID	Reduction of maximum achievable resolution by 20%, although can be partially recovered with data weighting and longer integration times.	2
5.5.2	Reduce MID Band 5 feeds: A, from 130 to 67	MID	Placement to be determined based on full community consultation.	2
5.25.2	Reduce PSS-LOW: B, 167 nodes to 125 nodes	LOW	Likely reduction in processed PSS beam number (1.3x) or pulsar search parameter space	2
5.25.2	Reduce PSS-MID: B, 500 nodes to 375 nodes	MID	Likely reduction in processed PSS beam number (1.3x) or pulsar search parameter space	2
8	SDP- HPC: Deploy 150 Pflops (from 200 Pflops)	COMMON	Lower allowed duty cycle for HPC-intensive observations.	3
5.30.0	Reduce Bmax LOW to 50km: A, remove infra, add 18 stations to core	LOW	Science Risk to EoR: Bmax.	3
5.30.0	Reduce Bmax LOW to 50km: B, remove 18 stations	LOW	Science Risk to EoR: Bmax	3
5.30a	Reduce Bmax LOW to 40km: C, remove next 18 stations	LOW	Science Risk to EoR: Bmax	3
8	SDP- HPC: Deploy 100 Pflops (from 150 Pflops)	COMMON	Lower allowed duty cycle for HPC-intensive observations.	4

8	SDP- HPC: Deploy 50 Pflops (from 100 Pflops)	COMMON	Lower allowed duty cycle for HPC-intensive observations.	4
5.31	Reduce CBF-LOW BW: A, 300 to 200 MHz	LOW	Longer observing times for continuum applications (1.5x)	4
5.25.2 / Deeper Savings	Reduce PSS-LOW: C, 125 nodes to 83 nodes	LOW	Likely reduction in processed PSS beam number (2x) or pulsar search parameter space	4
5.25.2 / Deeper Savings	Reduce PSS-MID: B, 375 nodes to 250 nodes	MID	Likely reduction in processed PSS beam number (2x) or pulsar search parameter space	4
5.13.2	Reduce Bandwidth output of band 5 to 2.5GHz	MID	Longer Band 5 observing times for some applications (2x)	4
5.35	Reduce MID CBF and DSH BW: 5 to 1.4 GHz	MID	Longer observing times to achieve continuum sensitivity in Band 5 (3.6x)	4
5.24 / Deeper Savings	Remove 11 MID Dishes from core	MID	10% Array sensitivity loss in core	4
5.30 / Deeper Savings	Remove 54 LOW stations from core	LOW	10% Array sensitivity loss in core	4
5.24 / Deeper Savings	Remove additional 11 MID Dishes from core	MID	20% Array sensitivity loss in core	4
5.30 / Deeper Savings	Remove additional 54 LOW stations from core	LOW	20% Array sensitivity loss in core	4
5.24.2	Reduce Bmax MID from 120 to 100 km: D, remove infra, remove next 3 dishes	MID	Lose Science (Planetary disks, High resolution Star Formation)	4
5.5.1	Remove MID Band 1 feeds: 105 to 0	MID	Lose Science (Cosmology, Galaxy Evolution)	4
5.5.2	Reduce MID Band 5 feeds: B, from 67 to 0	MID	Lose Science (Planetary disks, Star Formation)	4

Table 2: Cost Control Project Phase 2 Design Space

Notes:

1. The colours shown within the Science Impact relate to their score
2. The green highlighted in the Description column indicate a work-stream
3. The pink highlighting indicate issues for which science input has led to an adjustment of the plan

CURRENT STATUS

KEY SCIENCE GOALS for SKA1-LOW and SKA1-MID

The scientific demand from the science community for new capabilities to address fundamental questions in astronomy has led to the definition of key science goals for the SKA1-Low and SKA1-Mid telescopes, each of which will re-define our understanding of space as we know it [1].

The SKA1-Low science goals are various, and the High-Priority Science Objectives (HPSOs) for SKA1-Low include the observations of the highly red shifted 21-cm hyperfine line of neutral hydrogen from the Epoch of Reionization and earlier (Cosmic Dawn), as well as pulsar (search) surveys, and timing observations. Others major areas of observation and investigation, as shown in Figure 1, include the study of magnetized plasmas both in the Galaxy and intergalactic space, radio recombination lines, potentially extrasolar planets, VLBI, etc.

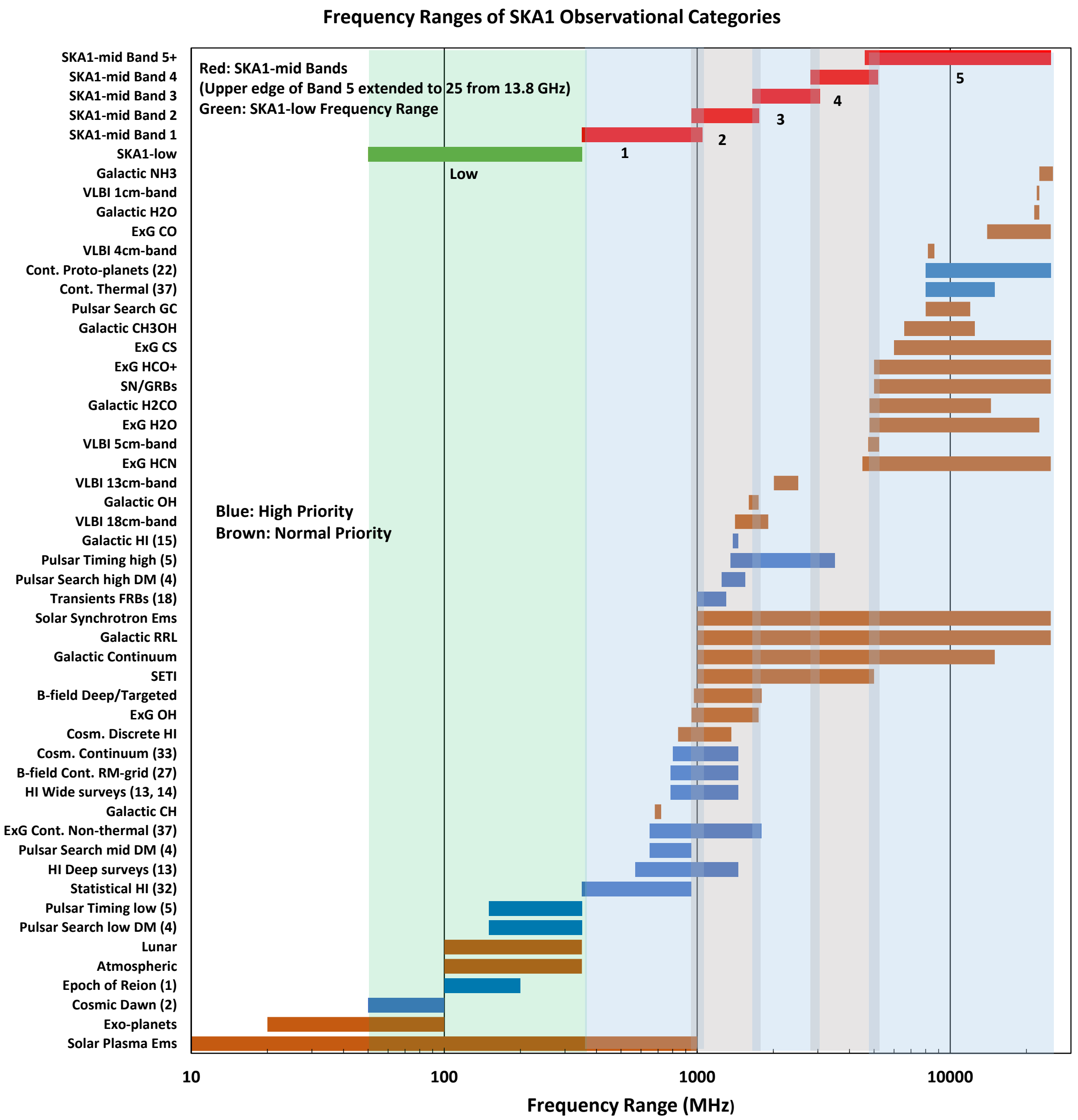


Figure 6: SKA1-Low and SKA1-MID major areas of observation and investigation. Frequency coverage of SKA1 on top, High Priority Science Objective are indicated as blue bars [2].

To achieve the high science expectations, the SKA1-Low has been designed to be an excellent imaging instrument for both deep and wide-field continuum surveys and characterization of the Epoch of Reionization and Cosmic Dawn (EoR/CD) galactic and extragalactic foregrounds, as well as to enable measurement the power spectrum of 21cm brightness temperature fluctuations during the EoR (ν = 100 to 240 MHz) and CD (ν <100 MHz), and to image HII regions (bubbles) during the EoR. From this data one can derive a wealth of information about the sources responsible for heating and ionizing the Universe at early cosmic times and cosmological information such as the density of baryons. Imaging of HII regions would be truly ground-breaking as it would result in a three-dimensional view of the formation of structure and evolution of ionized zones throughout the EoR period, which can then be compared to the locations of galaxies and AGN to infer their impact on the surrounding intergalactic medium.

While pulsar surveys and pulsar timing within the Galactic plane would be conducted with SKA1-MID, the SKA1-LOW will provide complementary searches of the Milky Way halo due to the steep spectrum synchrotron nature of the emission processes means, as per the surveys described in Kramer and Stappers [3] and models that predict that these SKA1-LOW surveys would identify 7000 normal and 900 millisecond pulsars (Keane et al.) [4]. The detection of fast-transient events through SKA1-LOW will include the provisioning of single station-beam data for further post-processing too.

The SKA1-Mid telescope will primarily address observations of radio pulsars and observations of the 21-cm hyperfine line of neutral hydrogen from the local Universe, to moderate redshifts, as well as high sensitivity observations of continuum emitting objects at all frequencies, including proto-planetary disks at high frequencies. It will also be well suited for conducting observations of various spectral lines in addition to the 21-cm hydrogen line (e.g. OH-lines), many classes of radio transients, magnetized plasmas both in the Galaxy and intergalactic space. Bands 2, 5, and 1 will be the highest priority for the initial deployment of SKA1-Mid, although priorities for new bands may change as discoveries are made or engineering breakthroughs, such as the development of highly efficient WBSPFs, take place.

Major elements of the telescopes

Although the two telescopes (SKA1-LOW and SKA1-MID) will have different characteristics due to the different frequency bands, science objectives and main requirements, however the high-level architecture and major components which allow to capture the signal from the sky and generate the desired science-ready data to be further analyzed by the scientific community shows strong communality, as shown is Figure 2.

Major components of the two telescopes, having similar high-level functionalities are:

The Telescope Manager, which is orchestrates the control of each telescope and provides the user interfaces to the scientific and operational staff.

The Signal and Data Transport, providing the interconnection between the telescope systems and the very accurate Synchronisation and Timing signals that are required to achieved signal coherence.

The Correlator, Beam-Former, Puslar Search Engine and Pulsar Timing Engine, which process the sampled data from the Dish and Low-Frequency Aperture Arrays in real-time.

The Science Data Processing system which further calibrates, analyses and stores the partially processed data to prepare it for scientific use.

The site infrastructure, including power supply, roads, buildings and environmental monitoring.

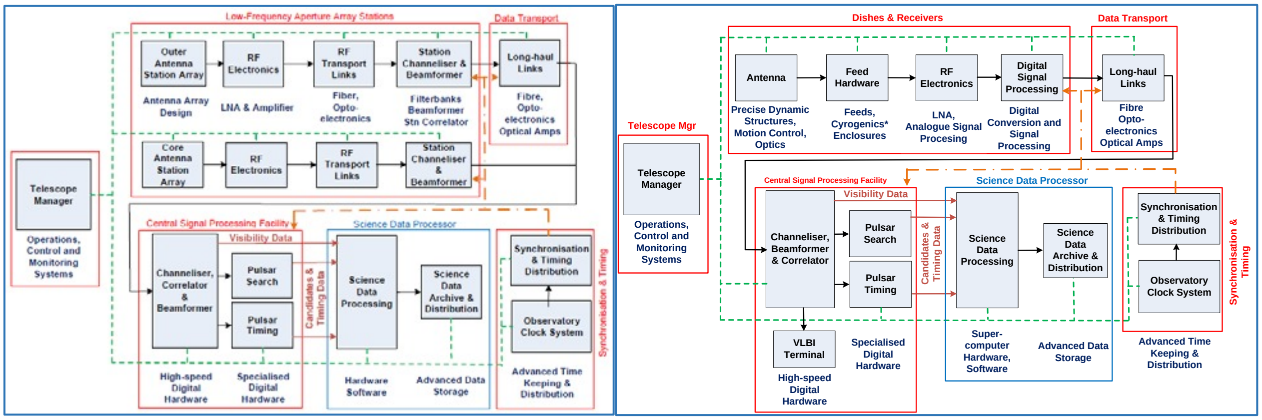


Figure 7. Major components of SKA1-Low (upper) and SKA1-Mid (lower) through the signal flow, areas of consortia responsibility (red boxes) and the key technologies needed. The green dashed line shows the bi-directional flow of monitor, control and operational data, and the dot-dashed line shows the distribution of synchronization and timing signals [1].

The signals from the sky are received by the SKA1-Low antennas/stations and SKA1-Mid dish antennas, conditioned and digitized and then, if the conditioning happened in the Remote Processing Facilities (RPF) (see section on layout for Low) carried on the long-haul networks to the Central Processing Facility (CPF) to be correlated and/or beamformed. The correlator and array beam-former component receives indeed data from each station/dish from which it generates full cross-correlation in four Stokes parameters, while simultaneously forming a number of tied-array beams (narrow 'beams' within the field of view of a station/dish) which will then be distributed to specialized pulsar search and timing equipment. This equipment can also detect de-dispersed transients (rare or one-off, potentially extra-terrestrial radio-burst signals), and do continuum spectra.

Data output from the correlator and time-domain processors will be transmitted by a high-volume, long-haul data link to an off-site location for science data processing including calibration, imaging and archiving. The required processing of the science data will be varied and elaborate, and will likely include several calibration steps, image-cube formation (i.e., spatial plus spectral data) on various scales, and statistical analysis. Initial data assessment, calibration, and reduction processes will take place at the primary Science Data Processing center, while further analysis specific to science projects will be done at Regional Science centers located in member countries.

The overall coordination and control of the system is provided by a software telescope management system, consisting of software sub-systems which handle tasks from preparation of observations through scheduling and monitoring of operations, processing, and quality assurance. Monitor and control of the telescope components will be provided by a hierarchical, distributed software system enabling automated operation, minimal on-site staffing and supporting as far as possible automated quality assessment and fault diagnosis of the system. A comprehensive Telescope Model will contain information on the configuration, status and history of the array as well as calibration models and data.

Timing reference for all of the stations/dishes will be derived from a set of MASER master clocks tied to both TAI and UTC by appropriate software and GPS references. The sample-clock reference and a 1 pulse-per-second tick will be then distributed within the central processing facility to the individual racks as well as over a phase-corrected fiber-optic link to the remote processing facilities in the case of the SKA1-Low telescope.

The design and reliability of infrastructure to cope with the hot remote sites will underpin the scientific success of the telescopes. This will include the supply and on-site distribution of electrical power, which in the actual design consists of a hybrid solar/diesel power system located near the building containing most of the on-site digital signal processing, but far enough away from the antennas to provide some EMI protection.

THE MANAGEMENT OF OBSERVATIONS WITH SKA

The scale of SKA requires careful consideration of its operating and maintenance principles. The Telescope Manager is the high-level controlling software that orchestrates the whole observation process under the guidance of the operations staff. As seen in Figure 3 below, there will be a Proposal Submission Tool with which the PI can interact to prepare and submit an observing proposal. The Time Assignment Committee reviews each proposal through the Proposal Management Tool establishes a longer term observing plan.

For approved proposals, the PI and co-PI's will next define the observation details through the interactive Observation Design Tool which also provides a limited simulation of the planned observation. The required telescope resources and system settings are defined for each Scheduling Block (SB) and recorded as an execution script.

The operations team of each telescope will, on a frequent basis (e.g. every two weeks), define the short term observing schedule from the long term one, based on the available telescope resources and planned maintenance activities. This is done using the Observation Planning Tool.

The Telescope Operator will use the Observation Scheduling Tool to extract SB's from the short-term plan, based on the immediate weather and telescope status. The actual SB execution is triggered and managed through the Observation Execution Tool, which also allows an override of ongoing work to support Targets of Opportunity and response to local events.

During the execution of an observation the Telescope Manager will be implementing scripts and commands from the Observation Execution Tool to control the telescope resources accordingly. It will also be monitoring the status of each telescope system and displaying any alarms and the observation progress to the Operator.

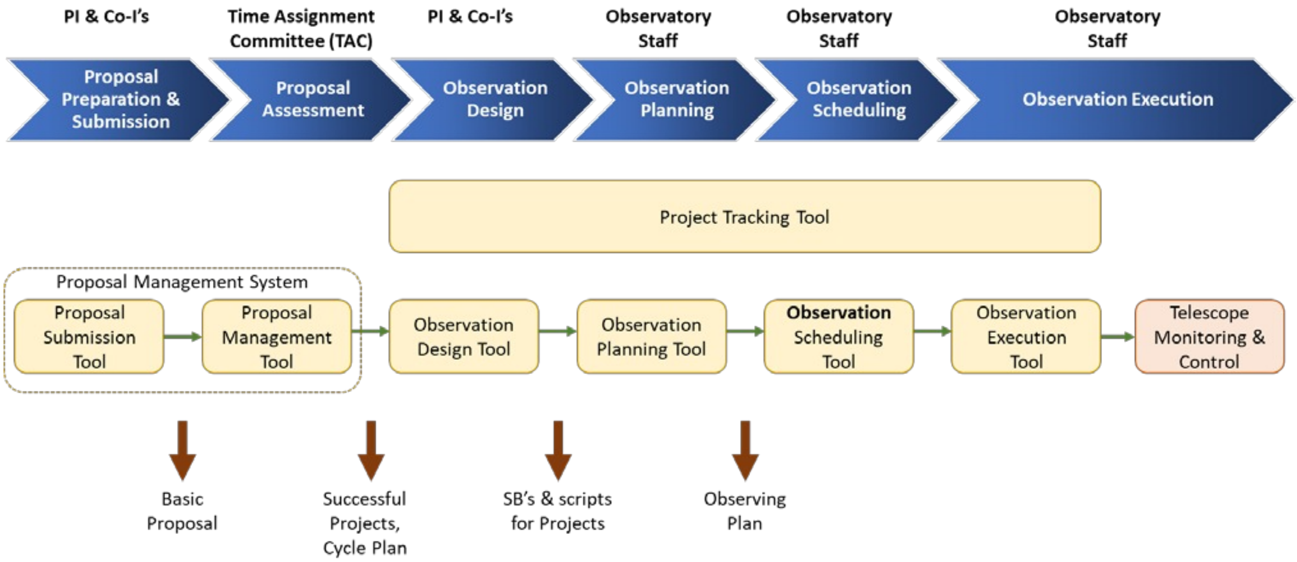


Figure 7. The observing life-cycle and the SKA software tools that will be used to manage each step.

THE SKA1-LOW Telescope

To achieve the high-demanding scientific performance and do transformational science, the SKA1-Low telescope has to fulfill challenging requirements, in terms of sensitivity, resolution, dynamic range, polarization purity, spectral and spatial stability, and so on, as per [5], on a wide frequency range between 50 MHz and 350 MHz.

Parameter	Value
Frequency range	50 MHz – 350 MHz
Collecting area (effective)	465,500 m2 (@ 100 MHz)
Maximum baseline	~ 65 km
Instantaneous bandwidth	300 MHz
Brightness dynamic range	≥ 50 dB
Station FoV (half-power beam)	20 deg2 @ 100 MHz
Core synthesized-beam resolution	~5 to 10 arcmin (mid-frequency)

Table 3: some SKA1-Low technical specifications

As shown in Table 1 and in [5], the scientific objectives of the EoR/CD experiments translate into a requirement for high brightness temperature sensitivity (~1-2 mK over the same frequency range) for arcminute to degree angular scales, while long baselines, providing much higher resolution, will be required to lower the confusion limit of low frequency continuum surveys.

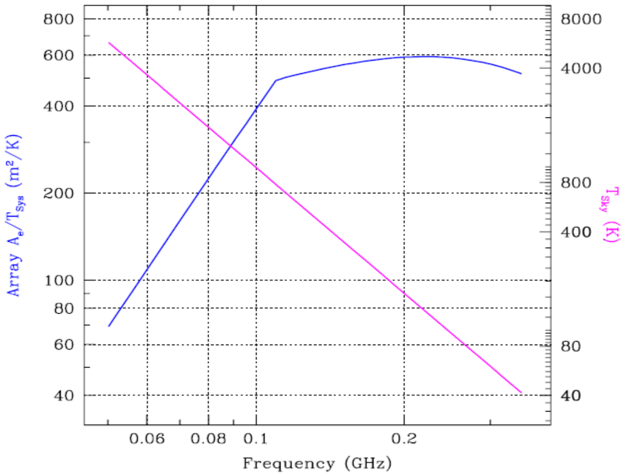


Figure 8: Sensitivity of SKA1-LOW Telescope. Note that the complete requirement (and the Tsys actually assumed) are described more accurately in SKA1-SYS_REQ-2135 and Sect. 26.2 of the SKA1 System Requirements Specification [5]).

To do transformational science and achieve the performance shown in Figure 4 and Table 1, the SKA1-LOW will consist of 131,072 wideband dual-polarized antennas, having a 7:1 frequency range (50 – 350 MHz). These antennas will be grouped in aperture arrays, named "stations". These will allow to use the array technology and generate station beams, through a first-stage beamforming of the antenna signals, and scan these them electronically and generate multi-beams too within a single station. A sub-set of antennas within a single station can be also be processed, generating, in this way, sub-station beams which will allow to have further flexibility in case larger beams (smaller than antenna beams but larger than station beams) are required.

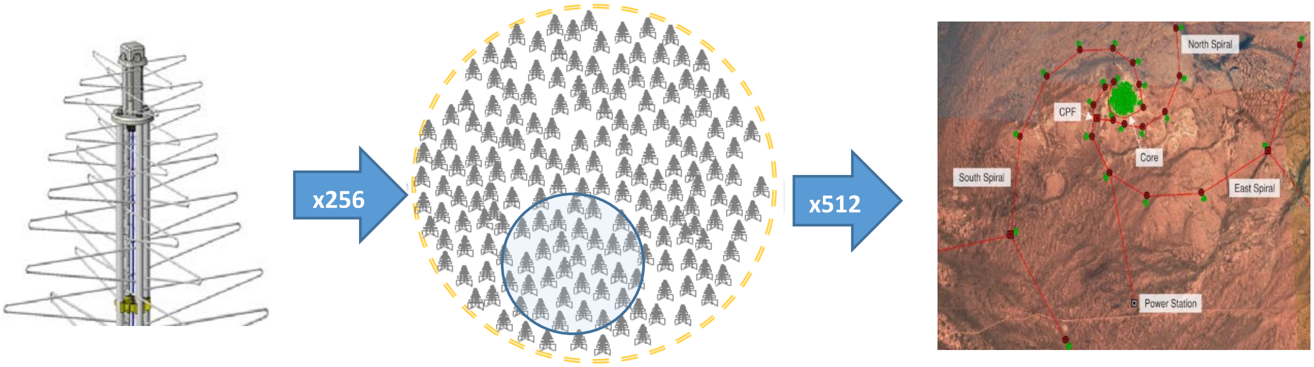


Figure 9: Conceptual grouping of the single antennas (left) in stations (centre), which will form the SKA1-Low array (right). The blue circle within the station shows the sub-station concept.

As shown in Figure 9, a station is formed by 256 log-periodic dual-polarized antennas; the 512 stations, located accordingly to the SKA1-Low telescope configuration (see next section), will constitute the SKA1-Low Telescope. The signal from each antenna are carried through Radio Frequency over Fiber (RFoF) up to the processing facilities. While the stations nearby the Core Area (see Figure 11) are connected directly to the Central Processing Facility (CPF), the signals from outer stations are sent to Remote Processing Facilities (RPFs). Within the RPF and CPF the signal is conditioned and digitized. The digitized signals are then processed in the Tile Processing Modules (TPMs) in order to form the station beams. These station beams are then sent to the Correlator and Signal processor (CSP). If these beams are generated in the RPF, then the signal will be transported to the CPF (hosting the CSP) through long-haul links.

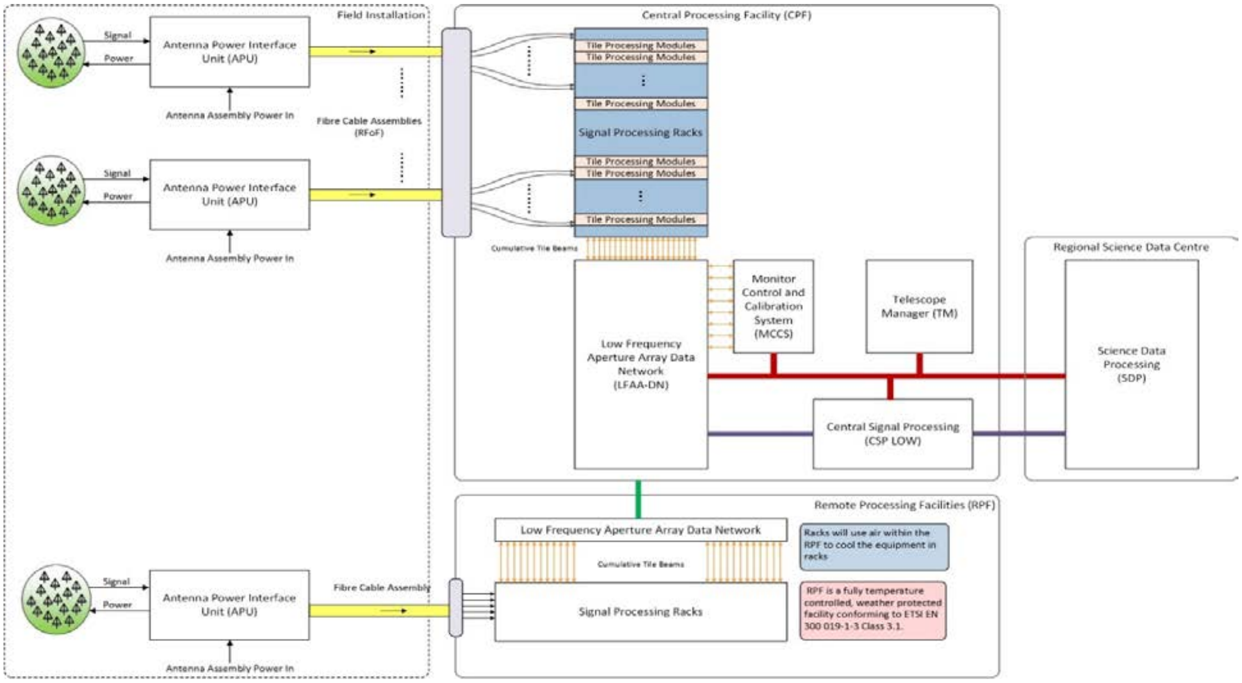


Figure 10: High-level conceptual representation of the SKA1 LOW Telescope Architecture [5]

The CSP is responsible to correlate the stations-beams and/or beamform these beams in order to obtain narrower beams called tided-array beams. These tided-array beams are further processed to search for pulsars and single pulses, and/or perform pulsar timing and dynamic spectrum.

The outputs from the correlator and time-domain processors are then sent to the Signal Data Processor (SDP) located off-site where the science-ready data products (output of the SKA1-Low telescope) are be generated and make available to the science community.

In order to achieve the demanding performance targets, significant levels of calibration and modelling accuracy will be required. The design of the array and the sub-system elements has taken into account the need for design for calibration from the outset. Two concurrent calibration loops running during operation of the telescope will be performed: a station calibration concerned with correcting the gain and phase drifts of each individual antenna signal path and applying the station pointing model, and a global calibration which corrects for array geometry effects and Ionospheric distortion. The station calibration corrections will be calculated within the Monitor Control and Calibration System (MCCS) and applied in the Tile Processing Modules (TPMs), while the array-level calibration will mostly be responsibility of SDP, and CSP will apply some of the corrections accordingly.

As detailed in the previous sections, the overall coordination, monitoring and control of the overall telescope is provided by the Telescope Manager (TM), but the sub-system will participate accordingly to a hierarchical distribution enabling automated operation, minimal on-site staffing and supporting as far as possible automated quality assessment and fault diagnosis of the system.

Timing reference for all of the stations will be derived from a set of MASER master clocks and the sample-clock reference and a 1 pulse-per-second tick will be distributed within the CPS to the individual racks as well as over a phase-corrected fiber-optic link to the remote.

The networks part of the SKA1-LOW telescope includes the LFAA Data Network (LFAA-DN) which transport the signal from the RPFs to the CPF, and moreover provides local links between the station processing hardware, the monitoring, calibration and control system, and the correlator/tied-array beamformer sub-systems. Moreover, a separate high-speed link will transport the final data off of the Murchison Radio Observatory site to the Science Data Processing center. In addition to these, dedicated network services for management, control, and timing will be provided to separate traffic according to security and priority.

The design and reliability of infrastructure to cope with the hot remote sites will underpin the scientific success of the telescopes. This will include the supply and on-site distribution of electrical power.

The overall architecture of the SKA1-Low telescope will enable the maximum utilization of science capabilities through a built-in flexibility which allows to trade across parameter space in order to optimize the system operation for specific science cases. This includes the capability to form multiple station and sub-station beams within the available 300 MHz processed bandwidth, support for up to 16 independently-scheduled and steered sub-arrays, support for commensal image, spectral, and time-domain pulsar and transient data processing.

The location of the stations in the area on the Murchison Radio Observatory site, located at Boolardy Station, Western Australia Marchison, will be accordingly to the SKA1-Low configuration defined in [7]. The SKA1-Low configuration, has been chosen in order to provide the best compromise between performance requirements, costs and environmental constraints, consists of 512 aperture arrays ("Stations") distributed in a very compact "Core" (area with a diameter of ~1 km), and then, outside the Core, arranged in groups of 6 Stations, named "Clusters", as shown in Figure 11. While the "Core" is characterized by a high filling factor and provides roughly half of the effective collecting area, the rest of the configuration shows a logarithmic decline out to maximum baselines of roughly 65 km along the three modified spiral arms within the Boolardy Station boundary.

The Stations and Clusters within the core and central area respectively are randomly distributed, in order to avoid regular spatial structure and achieve, in this way, better performance. Also the antenna within each 38 meter station (center to center of the antennas) are randomly distributes to avoid greeting lobes and randomize unwanted effects such as mutual coupling, etc.

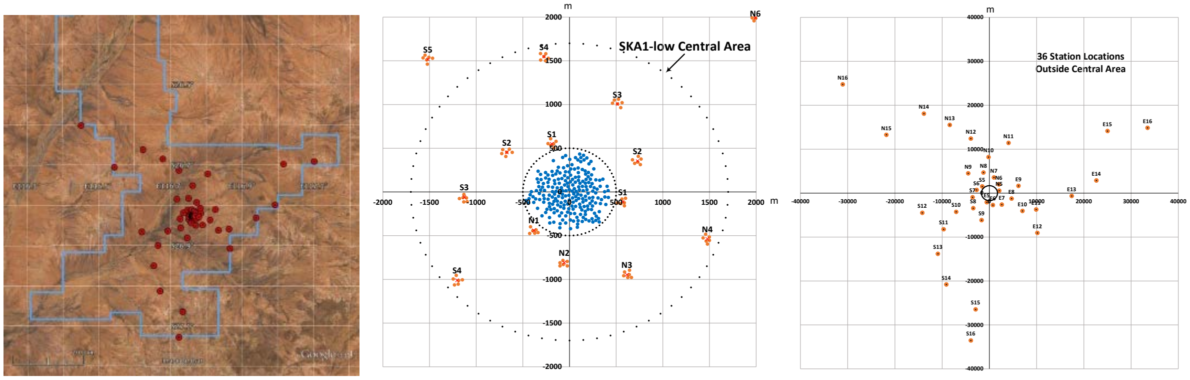


Figure 11. Configuration of the SKA1-LOW cluster locations.

Such a compact "Core" allows to achieve a high brightness sensitivity and also the pulsar searches, which involve tied-array beamforming out to stations (grouping of dual-polarized antennas) as far apart as 20 km for timing, will benefit from it. The modified-log-spiral design of the arms is intended to minimize infrastructure costs (primarily the length of power and fiber trenching required) while maintaining a logarithmic fall-off of sensitivity with radial distance and reasonable U-V coverage of the aperture plane.

The SKA1-MID Telescope

As seen in Figure 1, the SKA-1 Mid Telescope is designed to cover higher-frequencies than the Low Telescope, covering the range from 350MHz to 15.4 GHz split across 5 Bands. The design will allow this to be extended to 20GHz at a later stage [5]. 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 MeerKAT Telescope. Table 4 below summarises some of the important specifications of the telescope.

Parameter	Value
Frequency range	350 MHz – 15.4 GHz
Collecting area (effective)	26,500 m2 (@ 3 GHz)
Maximum baseline	~ 150 km
Instantaneous bandwidth	2.5GHz per polarisation (Band 5)
Brightness dynamic range	≥ 60 dB
Dish FoV (half-power beam)	0.49 deg2
Sensitivity (excl. MeerKAT)	916m2/K (@ 0.95 to 3.05 GHz)

Table 4: Key SKA1-MID technical specifications

Telescope performance has so many dimensions that only a cursory treatment is within the scope of this paper. Figure 9 is a plot of the ratio of effective area to system temperature (Ae/Tsys) for an individual SKA antenna. For reflector antennas, effective area is the product of the physical area and an efficiency factor. [2][5]

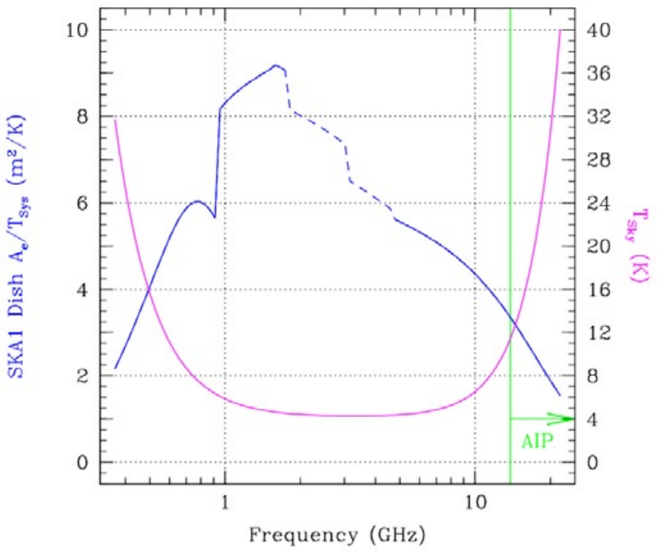


Figure 12. The Ae/Tsys sensitivity of an SKA1-mid antenna over its frequency range.

SKA1-mid requires 5 receiver bands to cover from 0.35 to 15.4 GHz . The dashed part of the curve is for bands 3 and 4, which are not expected to be fitted initially. [2]
For SKA antennas, the efficiency is 80-90% from ~1-15 GHz. It drops off at the low-frequency end because the sub-reflector becomes electrically small, and at the high end when reflector surface errors become larger than ~λ/30. Noise at the extreme ends of the frequency range arises mainly from sky background. Between 1 and 20 GHz, noise arises from the front-end amplifiers and increases with frequency.

Because it is difficult to design very high-efficiency feeds over bandwidths greater than 2:1 (upper-to-lower frequency ratio), the frequency range is covered by a series of feeds, in most cases a version of corrugated horns, except for Band 1, which is a quadridge feed.

As seen in Figure 13 below, the SKA-1 Mid Array will be arranged in three spiral arms 150km in extent with increasing density towards the centre.

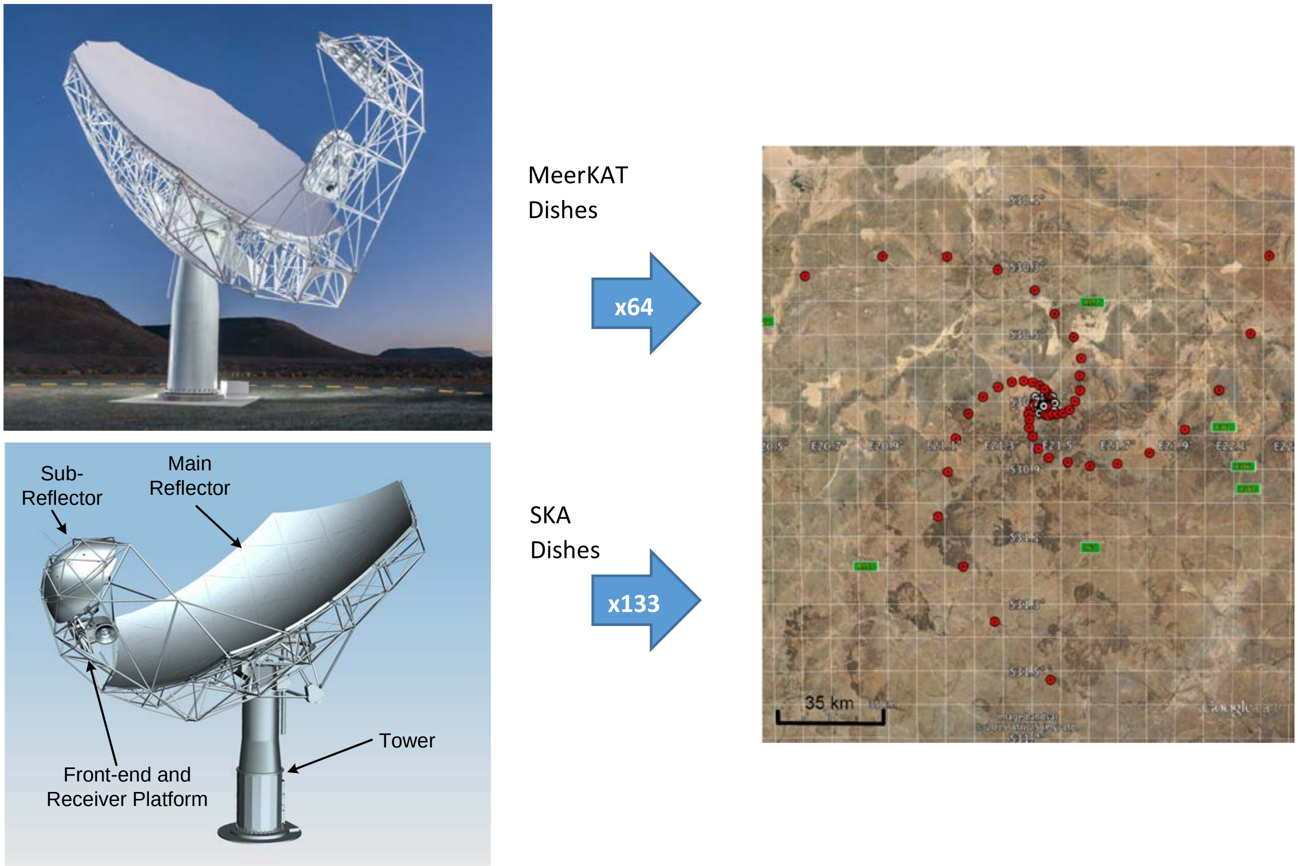


Figure 13. SKA1-MID integrates the 64 existing MeerKAT (top left) dishes with 133 new SKA-1 dishes (bottom left).

SKA dishes have increased performance and wider band coverage but the data from both dish types will be combined to form a 197-dish, 150km array placed in the Karoo, South Africa. The black and white circles show the locations of the MeerKAT antennas. The background is from Google Earth. [11]

Figure 11 shows the digital signal processing part of the system. The correlator beam-former (CBF) compensates for geometric and instrumental delays, divides the wide-band input data (up to 2 x 2.5 GHz) into narrow frequency channels (‘channelises’), and correlates the signals (cross and auto) from each of the antenna pairs. Separately for pulsar search applications and for the inner 20 km of the array, the CBF provides channelized output data-streams for 1500 pulsar search beams each with 300 MHz of bandwidth, individually ‘steerable’ within the primary beam of the antenna. For pulsar timing applications, 16 ‘high-specification’ beams can be formed so that polarization and time-domain artefacts are minimised. In addition, there is a beam-former that provides a data stream to a VLBI recording or e-VLBI interface.

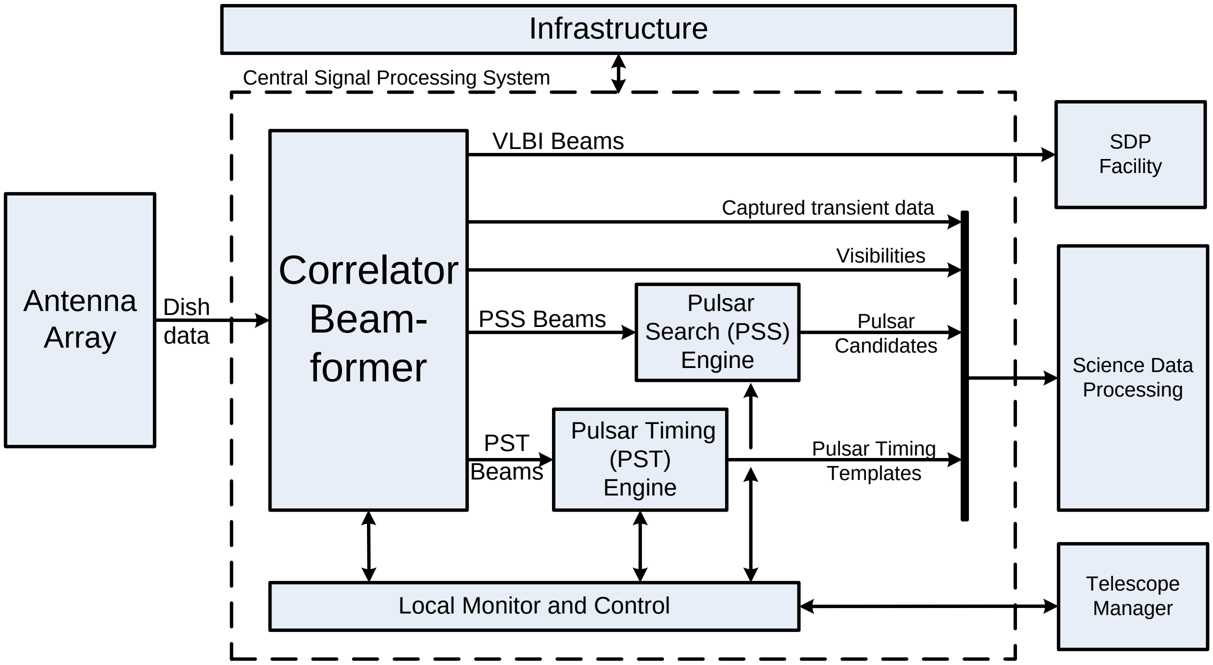


Figure 14: The functional context and flow diagram of Central Signal Processing (CSP) and Science Data Processing (SDP) systems [11].

Pulsar Search (PSS) consists of many processing steps that must be carried out on each beam. Time series lasting 100's of seconds are processed in sequence. An outline of basic steps is: de-dispersion (progressively delaying the signal with decreasing frequency to compensate for the dispersion of the interstellar medium), Fourier transform (FFT), folding and 'acceleration search'. The goal is to search a multi-dimensional space for weak repetitive signals with periods between a few ms and a few seconds, and with pulse widths from a few μs to a 10's of ms. In cases where a pulsar is orbiting a massive object, its period can change rapidly; hence the need for 'acceleration' as an extra search dimension.
The goal of pulsar timing is to monitor the 'arrival time' of pulsar signals over periods of up to 10 years. The means of doing this is described in the previous section.

Science Data Processing (Figure 14) is a major component of the telescope system. Its primary functions include:

Ingest of data from the CSP and the Telescope Manager.
Processing of input data into science data products:
Spectral data cube imaging and spectral extraction,
Continuum data cube imaging,
Final qualification of Pulsar Search candidates,
Transient detection,
Single-dish intensity mapping,
Rotation-Measure mapping.
Processing of input data into calibration products:
Telescope signature removal,
Removal of atmospheric and ionospheric effects.
Archiving of the science data products.
Access to the long-term science data archive.

The problem size and the amount of data to be generated by the correlator, and the pulsar search and timing engines requires high-performance-computing (HPC) infrastructure, much of which is being developed specifically for SKA.

Future Planning

The project is moving towards the conclusion of the Pre-Construction Phase with Critical Design Reviews (CDRs) planned for the remainder of 2018 and into 2019. This will conclude with a System CDR in the first half of 2019. In parallel, the organisation is in the final part of preparation to become an Inter Government Organisation. This should come into being in late 2019. From that date, full construction can begin as the IGO Council will have the authority to authorise Construction and, later, Operations. The current CDR schedule is shown at Figure X below:

Consortium	Consortium Agreement End Dates	Consortium CDR Closeout Date
AIV	Dec 2018	System
CSP	Oct 2018	Oct 2018
DSH	Dec 2018	TBC
INFRA-AUS	Jul 2018	Jul 2018
INFRA-SA	Jul 2018	Jul 2018
LFAA	Sep 2018	Sep 2018
SaDT	Jun 2018	Jun 2018
SDP	Dec 2018	Dec 2018
TM	Jul 2018	Jul 2018

Table 5 List of Element Consortia along with their respective agreement end dates and CDR dates.

The planned in Figure X shows several issues that are being faced by the Office at the moment. Although most consortia will survive in some form or other up until System CDR, they all complete following that and before Construction begins in the IGO era. To mitigate this, the Project is planning a Bridging Phase to ensure that expertise is not lost and that essential work can continue between the completion of System CDR and construction formally beginning.

The early planning between 2018 and operations is currently looking like Figure 15

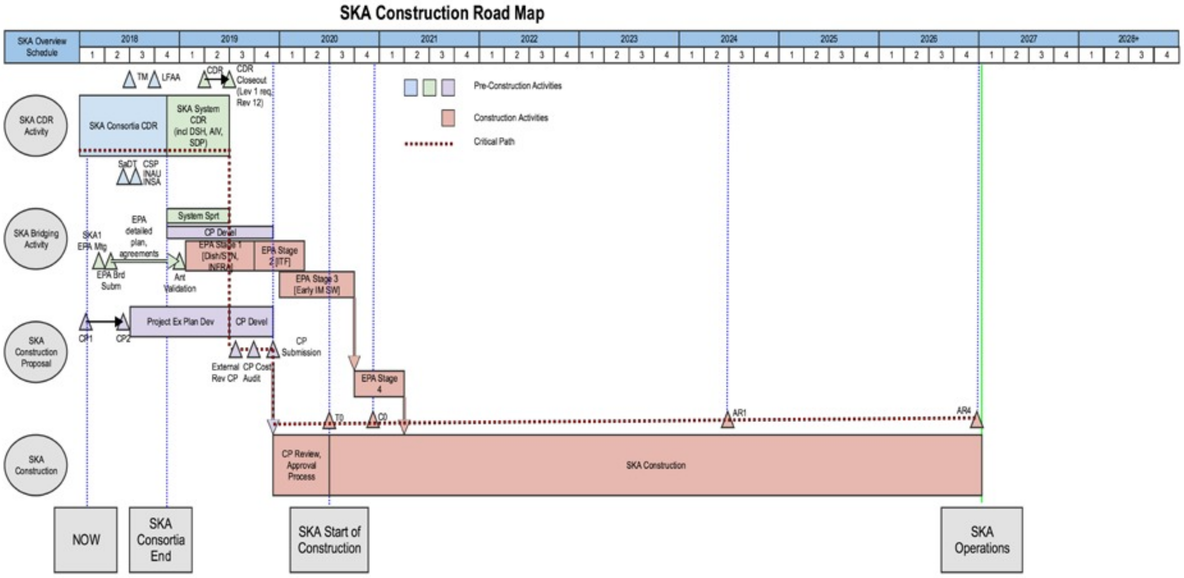


Figure 15: Outline Construction Road Map

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