SKA1 OPERATIONS PLAN

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ADP .... Advanced Data Product
ALMA............................. Atacama Large Millimetre/submillimetre Array
ASKAP .... Australian SKA Pathfinder
Az .... Azimuth
CBF .... Correlator-Beamformer
CMMS .... Computerised Maintenance Management System
Co-I................................ Co-Investigator
CP .... Coordinated Proposal
CPF .... Central Processing Facility
CSP .... Central Signal Processor
DDT .... Director-General's Discretionary Time
Dec .... Declination
El .... Elevation
EMC .... Electromagnetic Compatibility
EMI .... Electromagnetic Interference
EMS............................... Engineering Management System
EOC............................... Engineering Operations Centre
FAQ .... Frequently-Asked Question
FFT................................ Fast Fourier Transform
FMECA.......................... Failure Modes, Effects and Criticality Analysis
FoP................................ Friend of Project
FOV .... Field of View
FPGA............................. Field-Programmable Gate Array
FRACAS........................ Failure Reporting, Analysis and Corrective Action System
GHQ .... Global Headquarters
GSM .... Global Sky Model
HPC............................... High-Performance Computing
HSE .... Health, Safety and Environment
IETM/P .... Interactive Electronic Technical Manual/Publication
ISO .... International Organisation for Standardisation
IVOA.............................. International Virtual Observatory Alliance
JSP................................ Joint SKA Proposal
KSP .... Key Science Project
LFAA .... Low-Frequency Aperture Array
LMC............................... Local Monitoring and Control
LRU .... Line-Replaceable Unit
LSA................................ Logistic Support Analysis
LSM .... Local Sky Model

LTP................................Long-Term Proposal
MCCS...........................Monitoring, Control and Calibration System
ODA...............................Observation Data Archive
ODP...............................Observatory Data Product
OEM ....Original Equipment Manufacturer
OHS...............................Occupational Health and Safety
OLDP.............................Observation-Level Data Product
OT ....Open Time
PBS ....Product Breakdown Structure
PDF ....Portable Document Format
PI ....Principal Investigator
PLDP ....Project-Level Data Product
PRTS.............................Problem Reporting and Tracking System
PSS ....Pulsar Search
PST ....Pulsar Timing
QA ....Quality Assessment
RA ....Right Ascension
RAM ....Reliability, Availability, Maintainability
RFI.................................Radio-Frequency Interference
S&TE ....Support & Test Equipment
SARAO..........................South African Radio Astronomy Observatory
SB..................................Scheduling Block
SDP ....Science Data Processor
SEAC.............................Science and Engineering Advisory Committee
SED ....Spectral Energy Distribution
SKA ....Square Kilometre Array
SKA1 ....SKA Phase 1
SKA2 ....SKA Phase 2
SKAO ....SKA Observatory
SLA................................Service-Level Agreement
SOC...............................Science Operations Centre
SODP ....SKA Observatory Development Programme
SPC ....Science Processing Centre
SRC...............................SKA Regional Centre
SRU...............................Shop Replaceable Unit
SWG..............................Science Working Group
TAC ....Time Allocation Committee
TAI.................................International Atomic Time
TBD ....To Be Determined
TM ....Telescope Manager

ToA................................Time of Arrival

ToO ....Target of Opportunity

UK ....United Kingdom

UTC...............................Coordinated Universal Time

VDIF ....VLBI Data Interchange Format

VEX ....VLBI Experiment

VLBI...............................Very-Long Baseline Interferometry

VO ....Virtual Observatory

XML...............................Extensible Markup Language

1 Introduction

1.1 Purpose of the Document

This document is the Operations Plan for Phase 1 of the SKA Observatory (SKA1). Its purposes are:

a) to define how the SKA Observatory will be operated, including (and emphasising) the operation of its two telescopes; and
b) to define the required resources to implement this Plan.

The document focusses on all aspects of operating the two telescopes, SKA1-LOW and SKA1-MID. In this respect it represents the implementation plan for the Operational Concept defined in [RD1], which it will supersede. The operation of other aspects of the Observatory, as well as the provision of business-enabling functions, is described elsewhere.

1.2 Scope of the Document

The overall Observatory budget received from the Council will be split into four budgetary areas:

- Construction Support. This includes all Office and non-Office costs to build, deploy, integrate, verify and commission the SKA telescopes. The Construction Proposal will contain the full justification of this budget. This Construction Support budget complements the capital cost for construction.
- Observatory Development. This includes all Office and non-Office costs to develop new techniques and technologies for upgrades to SKA1 or as input to the design of SKA Phase 2 (SKA2). The Development Plan will contain the full justification of this budget.
- Observatory Operations. This includes all costs encompassing all functions of the Observatory that are essential for the operation and maintenance of the SKA telescopes, defining and executing the SKA science programme, generating science data products and delivering them to SKA Regional Centres for release to the community. This document contains the full justification of this budget.
- Business Enabling. This includes the Director-General's office and corporate governance, Human Resources, Strategy, International Relations, Finance, IT, Communications and Outreach, and other enterprise supporting functions. These functions provide essential services to the global organisation as a whole. The Business-enabling Plan will contain the full justification of this budget.

1.2.1 Exemptions

This Plan describes the Observatory Operations activities in some detail, and the staffing tables and budget includes Observatory Operations, Construction Support and Business Enabling resourcing and activities. It does not address the Capital Cost of Construction or Observatory Development Programme, nor does it consider SKA2.

1.3 Verb Convention

The verb *shall* is used whenever a statement is intended to be binding. The verb *will* is used to express an intention. The verbs *should* and *may* express non-mandatory provisions.

2 References

2.1 Applicable Documents

The following documents are applicable to the extent stated herein. In the event of conflict between the contents of the applicable documents and this document, **the applicable documents** shall take precedence.

[AD1] SKA-TEL-SKO-0000740, SKA Project Safety Management Plan, Rev02
[AD2] SKA-TEL-SKO-0000202, SKA EMI/EMC Standards, Related Procedures and Guidelines
[AD3] SKA-TEL-SKO-0000120, SKA Configuration Management Plan

2.2 Reference Documents

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, **this document** shall take precedence.

[RD1] SKA-TEL-SKO-0000307, SKA1 Operational Concept Document
[RD2] SKA-BD-26-13, Operations Model Review
[RD3] SKA-TEL-SKO-0000122, SKA1 Science Priority Outcomes
[RD4] SKA-TEL-SKO-0000941, Anticipated SKA1 HPC Requirements
[RD5] SKA-TEL-SKO-0000951, Anticipated SKA1 Archive Requirements
[RD6] SKA-TEL-SKO-0000116, SKA1 External VLBI ICD
[RD7] SKA-TEL-SKO-0000102, SKA RAM Allocation
[RD8] SKA-TEL-SKO-0000103, SKA Support Concept
[RD9] SKA-TEL-SKO-0000104, SKA Integrated Logistic Support Plan
[RD10] SKA-TEL-SKO-0000949, Low Telescope RAM and Logistic Support Report
[RD11] SKA-TEL-SKO-0000590, Mid Telescope RAM and Logistic Support Report
[RD12] MIL-STD-1388-2B, Department of Defence Requirements for a Logistic Support Analysis Record
[RD13] S1000D, International Specification for Technical Publications using a Common Source Database
[RD14] 602-000000-001, Engineering Management System Architecture
[RD15] 602-000000-002, Engineering Management System to Observation and Telescope Management ICD
[RD16] ISO 45001:2018, Occupational Health and Safety (OHS) Management Standard
[RD17] SKA-TEL-SKO-0001083, SKA Computing Hardware Risk Mitigation Plan
[RD18] SKA-TEL-SKO-0000315, Science Commissioning and Verification Plan, Rev01
[RD19] SKA-TEL-SKO-0000735, SKA Regional Centre Requirements, Rev03
[RD20] SKA-TEL-SKO-0001640, Calibration Plan

3 Objectives and Key Performance Indicators

3.1 Delivery of transformational science

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

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

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

A suite of scientific and operational success metrics is needed to guide the management of an observatory, and there exists a wealth of literature on this subject. The following sections provide an illustrative and non-exclusive list of some of the metrics that will be used for the SKA. It is noted, however, that conventional observatory metrics require careful interpretation and tuning for the SKA due to the anticipated use of commensal observing, in which multiple science projects can be carried out simultaneously (§6.4.2.6).

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

3.2 Scientific success metrics

Several scientific success metrics will be monitored once the Observatory becomes operational:

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

This list is not exhaustive and is expected to evolve over time; it nevertheless encapsulates the primary drivers for the operational model. The SKA will adopt values of Open Science currently being discussed and formulated in the community.

These metrics can be analysed with different amounts of granularity: e.g., over-subscription per Member state, or number of publications per telescope (SKA1-LOW/SKA1-MID) or per science mode. In particular, the number of papers published in high-impact journals (e.g., Nature, Science) and the number of high-impact papers (e.g., those with citation rates in the top 1% of all refereed papers world-wide) are measures of the Observatory's delivery of transformational science.

3.3 Operational success metrics

Scientific success and operational success are intimately linked: a highly efficient observatory, for example, will enable more science time on sky.

The following operational success metrics will be monitored once the Observatory becomes operational:

- system down time due to faults;
- system down time due to unavailability of computational resources;
- system down time due to planned maintenance;
- operational availability;
- operational availability of specific capabilities (specific bands and specific observing modes);
- observing efficiency (integration time per unit available time);
- observing project completion; and
- safety record.

This list encapsulates the primary drivers for the operational model. However, it is not exhaustive and will certainly be added to and will evolve over time.

3.4 Accountability and Reporting

The Observatory Convention states:

- *The Chairperson shall convene the meetings of the Council in accordance with its Rules of Procedure. The Council shall meet as and when required, but not less than once per year. (Article 8, paragraph 12)*
- *The Director-General shall report to the Council. (Article 9, paragraph 1)*
- *The functions of the Director-General shall be to … submit an annual report to the Council… (Article 9, paragraph 2b)*
- *… the Council shall … approve and publish annual reports … (Article 8, paragraph 3f)*

The annual reports submitted by the Director-General, and the papers provided to the Council for its meetings, will report on progress against the objectives of the Observatory. A set of key performance indicators will be developed and reported to enable monitoring and oversight of the Observatory's performance.

4 Constraints and Assumptions

4.1 Operating Constraints

In this section, several factors that limit or constrain the operation of the SKA Observatory are presented. Operation of the SKA telescopes will be carried out in the host countries and in accordance with a collaborative operational model being developed between the SKA Observatory and the organisations representing each of the two site host nations, guided initially by Memoranda of Understanding. SKAO will collaborate with CSIRO in Australia and SARAO in South Africa. As Engineering and Science Operations will be carried out under the auspices of these agreements, the term SKAO shall be understood to refer to operations or maintenance staff working within this partnership, regardless of their specific employer. Any change to this assumption will be agreed separately.

4.2 Host Country Agreements

The SKA Observatory will consist of the following physical infrastructure components:

- a Global Headquarters (GHQ) situated at Jodrell Bank, UK;
- SKA1-LOW, an array of dipole antennas at the Murchison Radio Observatory in Western Australia; and
- SKA1-MID, an array of dishes in the Karoo region of South Africa.

In addition, there will be establishments elsewhere in Australia and South Africa that will provide scientific and technical support for SKA1 operations. In particular, the main establishments in each country will be:

- a Science Operations Centre;
- an Engineering Operations Centre; and
- a Science Processing Centre.

As per the Hosting Agreements between SKAO and the Governments of Australia and of South Africa, these establishments will be made available to the SKA in support of its construction and long-term operations. The SKA Observatory will engage in a leasing arrangement to pay for the use of these centres. The functional structure of the observatory, showing these centres, is described in §5.

A Host Country Agreement document covers a broad range of agreements that together specify the mutual responsibilities and obligations between the SKA Observatory and a Host Country through the construction, operations and ultimately the decommissioning and site restoration of the Observatory facilities. Broadly, the host country and SKA Observatory responsibilities are outlined in Table 1.

Table 1: Host Country and SKA Observatory responsibilities as outlined in the Host Country Agreements.

Host Country Responsibility	SKA Observatory Responsibility
• Provision of access to the telescope sites, assets and infrastructure (granted through licenses, permits, leases, or property instruments). • Secure necessary rights to enable a grant of licenses or leases. • Provide required registers of environment and heritage. • Provide radiofrequency protection in respect to the telescope sites.	• Execution of construction, operation and maintenance of SKA1 in compliance with local regulations. • Be responsible for all aspects of the SKA1 Project that are not the responsibility of the host country, including management and governance, compliance with regulatory processes, recruitment/management/ administration of SKA Observatory staff and contractors, decommissioning/demolition

• Coordinate interaction with all concurrent users of the site, including indigenous land users. • Coordinate construction and operation of other radio facilities on site to ensure construction and operations according to the Convention. • Maintain stakeholder relationships with national and local governments.	and restoration of the telescope site, outreach/communication/promotion activities within the host country. • Operate and maintain all equipment required for the implementation of the SKA1 Project. • Comply with relevant state and federal laws and regulations. • Compliance with the terms for access to the sites, including any radio frequency interference standards and protection protocols. • Provision of adequate insurance cover for the telescopes, works, staff, contractors, assets and infrastructure. • Support host country stakeholder relationships.

The provisions of the Hosting Agreements are binding on SKA1 Operations.

4.2.1 Operations Policy

An Operations Policy has been negotiated by the Members as a Tier-2 document under the Observatory Convention. This policy will, when approved, specify the functional structure of the Observatory from the perspective of telescope operations.

As noted above (§4.1), a new operational collaborative model is currently being developed. It is anticipated that, when agreement is reached, the Operations Policy will be revised.

4.2.2 Access Policy

An Access Policy has been negotiated by the Members as a Tier-2 document under the Observatory Convention. This policy will, when approved by the Observatory Council, constitute a governing document for the operation of SKA1.

The elements of the Access Policy that are salient for this document are as follows:

- Access will be proportional to Members' shares in the project, as determined by their contributions.
- Subject to the preceding constraint, Access will be based on scientific merit and technical feasibility, evaluated through a common time allocation process.
- Time will be made available for Key Science Projects (§6.3), PI projects, Director-General's Discretionary Time and Open Time, at proportions to be determined by the Council's overall scientific strategy for the Observatory.
- The Director-General will be responsible for time allocation, advised by a Time Allocation Committee (TAC).
- Science data products are to be made openly available after a suitable proprietary period as determined by the Council.
- Associate Members will be treated in the same way as Members for the purposes of Access. Thus, throughout this document, reference to "Members" should be interpreted as "Members and Associate Members".

- All science data products will be owned by the SKA Observatory.

The detailed implementation of the Access Policy is being developed in a Tier-3 document, the Access Rules and Regulations.

4.2.3 Safety, Health and Environment

The SKAO and its staff are committed to being leaders in health, safety and environmental (HSE) management. The Observatory shall integrate good Health, Safety & Environmental performance as a core element in every planning, design, construction and operations activity to achieve our aim of being safe, secure and sustainable.

The protection of the health and safety of everyone involved in or affected by our work, and the protection of the local and global environment is important to us. HSE performance will be given the highest priority at all times by systematically identifying, assessing and managing HSE risks, monitoring our performance against targets and publishing the results.

Our vision is to go beyond eliminating preventable illnesses, injuries, business losses and environmental harm due to unplanned events in our premises and on our sites. This includes improving the wellbeing of all involved in the project work by addressing our impact on climate change and waste, preventing pollution, enhancing biodiversity and encouraging inclusion and healthy living during the design and construction phases and beyond.

To this effect, the SKAO will issue an HSE policy statement and associated management plans. The policy will, in general, set out our intent to integrate good HSE performance as a core element in every operational activity to ensure our aim of being safe and secure. Our management plans will ensure that the SKAO policy commitments are met and that our activities exceed the statutory HSE requirements of the three host jurisdictions.

At time of writing, a SKA Project Safety Management Plan [AD1] has been published. The Plan mainly draws on requirements from Occupational Health and Safety (OHS) Management Standard ISO 45001:2018 [RD16] and is also inspired by similar plans from other major telescope projects. The existing work of the SKA precursor and pathfinder telescope sites in the area of operational safety management are also acknowledged and referenced with a view to incorporating best practice, lessons learned and coordination.

The SKA Project Safety Management Plan specifies requirements for the OHS management systems, and gives guidance for their use, to enable organisations to provide safe and healthy workplaces by preventing work-related injury and ill health, as well as by proactively improving OHS performance. It is, and will be, applicable to any organisation that wishes to establish, implement and maintain an OHS management system to improve occupational health and safety, eliminate hazards and minimize OHS risks (including system deficiencies), take advantage of OHS opportunities, and address OHS management system nonconformities associated with its activities.

A SKA Project Environmental Plan is being drafted for inclusion in [AD1]. It will set out the criteria for an environmental management system and maps out a framework that a company or organisation can follow to set up an effective environmental management system.

Drawing upon requirements from OHS Standard ISO 14001:2015 will provide assurance to SKAO management and employees as well as external stakeholders that environmental impact is being measured and improved.

All relevant SKAO health, safety and environmental policies and rules shall be specifically mentioned with all procurement specifications. As a general rule, all conditions affecting safety, either with respect to the design and testing of equipment, or for work on SKAO sites, shall always be presented in SKAO technical requirements.

Compliance with the SKAO's HSE policy and mandatory plans will be required for all SKAO staff and its agents, contractors and visitors.

4.2.4 Radio-Quiet Environment

The SKA1 Telescopes will be located within radio-quiet zones in Australia and South Africa. These zones are globally unique resources. Both countries have obligations through the Hosting Agreements (§4.2) to protect the sites from radio-frequency interference arising from external influences within their jurisdiction and from other facilities on the sites. The SKAO will be responsible for controlling self-interference arising from the operation and maintenance of the SKA telescopes, and for limiting radio pollution of the sites by the SKA equipment or activities that may affect other facilities.

An EMI/EMC standard for the SKA, including details of implementation and enforcement, has been developed and agreed [AD2]. This standard is binding upon SKA1 Operations.

4.2.5 Data Flow

One of the unique challenges of the SKA is its extremely high data rate: it is currently estimated that each SKA telescope could produce 300 PB of science data each year in routine operations.

In July 2013, the SKA Board imposed a cap on the construction cost of SKA1, and in so doing defined the scope of the project to include the generation and storage of data products by the Science Data Processor (SDP). No provision was made at that time for the archiving of these data, their distribution to users, nor for computational facilities to enable users to undertake further data analysis, both of which are mission-critical if the SKA is to deliver on its scientific promise. Full scientific exploitation of the SKA requires that a research ecosystem be in place for efficiently translating the large data volume into science results. This research ecosystem must have three components that are not within the scope of the SKA1 Observatory:

- computational capacity for processing and science analysis;
- storage capacity for archiving Observatory and Advanced data products; and
- local user support.

In April 2016, the SKA Board determined that these functions should be provided by a set of SKA Regional Centres (SRCs). The SRCs are to be funded and operated by the regions[1] in which they reside, and they are therefore not formally within scope of the project: the relationship between the SKAO and the SRCs is to be collaborative in nature, based on Memoranda of Understanding and an accreditation framework. The advantages of this approach are:

- it recognises the understandable preference of any region to invest in infrastructure within its own borders;
- resources can be tailored to the local needs of the regions, which are diverse across the SKA partnership;

[1] The term "region" is used here generically to refer to an SKA Member State, a jurisdiction within a State, or a grouping of States; thus, "regional" could be replaced by "national" in the case of a single State.

- it offers the opportunity for early community engagement with the SKA, not only for astronomers but also for data scientists and software and computing experts;
- it offers the opportunity to leverage existing computational infrastructure across the SKA partnership; and
- it widens the pool of potential funding sources.

The essential functions of the SRCs are:

- to give SKA users access to SKA data, in compliance with the SKA data access policy;
- to provide the computational and data management resources for the archiving of SKA data;
- to provide SKA users with processing infrastructure to enable the science analysis of SKA data;
- to form a federated environment which allows transparent data access across the SRC network, giving access to data products across the global science archive to all members of the SKA community; and to provide
- users with local user support.

Some regions may wish to provide additional, non-essential functions through their local SRC (e.g., regional point of contact; outreach and publicity; development activities). Such additional functions are optional and at the discretion of the regions.

Development and implementation of the SRC concept is the responsibility of the SRC Steering Committee. For the purposes of this Plan, it is assumed that an ensemble of SRCs will be in place as currently envisaged (see §6.5). Resources are identified for coordination of this activity. The SRC Steering Committee has developed a draft White Paper describing its vision for the structure, functions and scope of the network of SRCs.

4.3 High-Level Assumptions

High-level assumptions that have been made in the development of this Plan are listed in Table 2. These assumptions are distinct from design choices, which are presented in the following chapters.

Table 2: High-level assumptions.

No.	Assumption	Ref.
A1	SKA Phase 1 will be delivered, in compliance with the SKA1 Construction Proposal.	N/A
A2	An ensemble of SRCs will be provided by the SKA Members, in compliance with governance arrangements and technical interfaces to be determined.	§4.2.5
A3	The SKA Telescopes will be capable of 24-hour operation.	§6.4
A4	The proprietary period will be 1 year from the date of notification to the user that data products are available.	§6.4.1
A5	It is assumed, for the current version of this Plan, that the Design Baseline will be implemented. Adoption of the Deployment Baseline will affect the resource requirements, and potentially also the observing modes to be made available. These impacts will be evaluated when the Deployment Baseline is defined as part of construction planning.	§6.4.2.2 §8
A6	The existing working patterns for the precursor telescopes ASKAP and MeerKAT will be adopted. Routine, on-site operational support will be provided on a 5-day working week.	§6.6.6
A7	The SOCs, SPCs and EOCs will be delivered by the Host Countries in compliance with SKA requirements. They will be leased at a not-for-profit rate, and the SKA will not own these facilities at the end of any lease.	§4.2

5 Observatory Functional Structure

As noted in §4.2, the SKA Observatory will be comprised of three infrastructure components: the Global Headquarters in the United Kingdom, the SKA1-LOW telescope at the Murchison Radio Observatory in Western Australia, and the SKA1-MID telescope in the Karoo region of South Africa. The operation of both telescopes is supported by activities at several facilities in the two site Host Countries. The functional structure of the Observatory is shown in Figure 1.

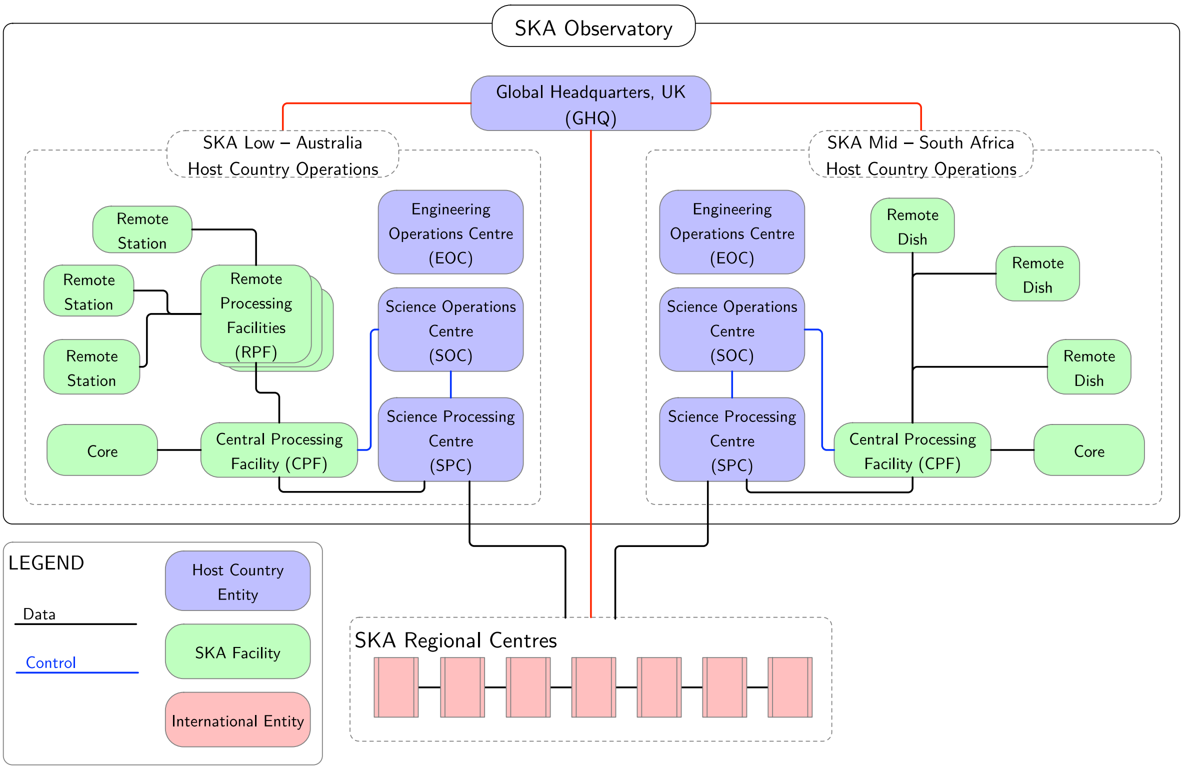

Figure 1: Functional structure of the SKA Observatory.

The SRCs are included in this structure because even though they are outside the scope of the Observatory construction project, they are an important functional component of the Observatory. As discussed in §4.2.5, a collaborative operational partnership will be set up between the Observatory and the ensemble of SRCs.

A list of the functions to be carried out by the Observatory, and the allocation of those functions to the GHQ and the two Telescopes, is presented in Table 3. The functions have been assigned to three categories as follows:

- Business-enabling functions: those functions that are essential for operating the Observatory as an organisation;
- Observatory Operations: those functions that are directly connected with operating the two SKA Telescopes and generating science data products for release to the community; and
- Development Support: those functions that are required to run the SODP.

Table 3: Functional allocations between the GHQ and the two SKA telescopes.

Category	Function	LOW	GHQ	MID
Business-Enabling Functions	D-G office		x	
	Senior leadership	x	x	x
	Long-term policy		x	
	Relationship management	x	x	x
	IGO Legal and business affairs	x	x	x
	Communications, public outreach, branding	x	x	x
	Spectrum management, RFI policy & standards, ITU		x	
	Corporate services (finance, HR, IT, audit, etc.)	x	x	x
	Procurement	x	x	x
	Health, safety & environment	x	x	x
	Secretariat for external bodies		x	
Observatory Operations	Engineering policy & standards		x	
	Engineering support (spares, logistics, configuration, etc.)	x	x	x
	Hardware support (mechanical, electronic, instrumentation)	x		x
	Computing and software management & strategy	x	x	x
	Software engineering (architecture, quality, toolset, observation management)		x	
	Software engineering (controls, data acquisition, scientific computing)	x	x	x
	Computing infrastructure (operational systems)	x	x	x
	Science operations (telescope-specific)	x		x
	Science operations (observatory-wide)		x	
	Helpdesk	x	x	x
	Interface to SKA Regional Centres	x	x	x
	Scientific research	x	x	x
	Site operations (land management, infrastructure maintenance, RFI monitoring, etc.)	x		x
Development Support	Scientific strategy		x	
	Upgrade programme management		x	
	Interface to SKA Development Centres		x	

For each Telescope, the operational activities will be carried out at a number of facilities, as indicated above in Table 3. These facilities are as follows:

- Science Operations Centre (SOC): These will be located in Perth and Cape Town (exact locations TBD). It is expected that the SOC in Australia will be in the Australian Resources Research Centre building and the SOC in South Africa will be in a new building on the site where the NRF iThemba LABS is located. All telescope-specific science operations activities will be based here: this includes executing the observations, carrying out quality assessment, and ensuring data are of sufficient quality for delivery to the SRCs. Software support and most administrative functions will also be based here.
- Science Processing Centre (SPC): These will also be located in Perth and Cape Town (exact locations TBD). In Australia it is anticipated that this will be the Pawsey Centre, under some form of contract. In South Africa no such data centre presently exists, and SARAO are planning to construct one to meet SKA requirements adjacent to the SOC at the iThemba LABS site. The SPCs are high-performance computing centres that will host the Science Data Processors.

- Engineering Operations Centre (EOC): These will be located in Geraldton in Australia and Klerefontein in South Africa. They will function as the administrative bases for on-site activities and host mechanical/electrical/instrument workshops and RFI chambers.

These centres are identified in the Hosting Agreements as Host Country deliverables. For the purposes of this Plan, it is assumed that these centres will be provided and will be compliant with SKAO requirements.

The allocation of in-country functions to these three centres is indicated in Table 4.

Table 4: Functional allocations within each SKA Telescope.

Category	Function	SOC	SPC	EOC/Site
Business-Enabling Functions	Senior leadership	x		
	Relationship management	x		
	IGO Legal and business affairs	x		
	Communications, public outreach, branding	x		
	Corporate services (finance, HR, IT, audit, etc.)	x		x
	Procurement	x		x
	Health, safety & environment	x	x	x
Telescope Operations	Engineering support (spares, logistics, configuration, etc.)			x
	Hardware support (mechanical, electronic, instrumentation)			x
	Computing and software management & strategy	x		
	Software engineering (controls, data acquisition, scientific computing)	x		
	Computing infrastructure (operational systems)	x	x	x
	Science operations (telescope-specific)	x		
	Scientific research	x		
	Site operations (land management, infrastructure maintenance, RFI monitoring, etc.)			x

6 Observatory Operations

6.1 Principles of Operation as an Observatory

On 25th July 2013, the SKA Board approved a set of top-level operational principles. These principles were amended slightly on 29th October 2013, and then more substantially on 14th July 2016 to reflect the ongoing evolution of the operational concept.

The principles were developed during the pre-construction phase of the project and include references to SKA Organisation and the SKA Board that are not applicable for the construction and operations phases of the project. Some minor modifications have therefore been introduced to the principles in this Plan to provide consistency. Explanatory comments are provided in the footnotes.

These principles govern the design of SKA operations. It is anticipated that they will be superseded by the Operations Policy (§4.2.1) and the Access Policy (§4.2.2). The current set of principles, and references to their implementation in this document, is provided in Table 5.

Table 5: Approved operational principles and references to their implementation.

No.	Principle	Ref.
The SKA Observatory		
1	The SKA Observatory will consist of SKA Telescopes[2], local activities necessary for their operation, data processing and archive facilities and a Global Headquarters.	§5
2	The SKA Observatory will be operated as a single organisation.	§5
3	The purpose of the SKA Observatory will be to enable scientists to pursue world-leading scientific programmes, to organise and conduct improvements and upgrades of the SKA telescopes in order to provide and maintain facilities that are at the forefront of science and technology and to ensure the protection of the SKA sites for the SKA and future radio telescopes.	§3
4	The scope of the SKA Observatory will be to provide, commission, operate, maintain, and upgrade the SKA Telescopes, and to produce scientifically viable data products from the telescopes.	§6
5	The SKA Telescopes will be located within radio-quiet zones provided by the Host Countries of South and Southern Africa and Australia.	§6.7.1.1
6	The expected lifetime of the SKA Observatory is 50 years.	§8.4.2.2
7	The SKA Observatory will be the technical design authority for the SKA Telescopes.	N/A
8	The primary success metric for the SKA Observatory will be the significance of its role in making fundamental scientific discoveries and facilitating overall scientific progress, expressed as high impact, peer-reviewed scientific papers using SKA data.	§3
Structure of the SKA Observatory		
10	The SKA Observatory shall be led by a Director-General, who will report to the SKA Observatory Council.	N/A
11	The SKA Observatory shall operate a Global Headquarters (GHQ), which will have overall responsibility for the SKA Observatory.	§5
12	The SKA Observatory shall establish a presence in the two Host Countries for the purpose of controlling SKA infrastructure and conducting SKA Operations in the Host Countries.	§5
13	The SKA Observatory shall appoint an external body to provide independent advice to the Director-General on the planning and conduct of SKA operations and science. The members will be appointed on the basis of their scientific expertise and experience.[3]	§3.4
14	The SKA Observatory Council will control the SKA brand and the GHQ will implement policies on such branding.	N/A
SKA Operations		
15	SKA Operations is the sum of all SKA activities that are centrally managed, and which are neither part of the SKA Construction Project[4], nor Planning Activities[5].	§6

[2] SKA Telescope: A single scientific instrument of the SKA that can operate as a coherent system independently of other telescopes, but which may share resources, including software, with other telescopes. In practical terms, SKA1-LOW and SKA1-MID are both considered SKA Telescopes.

[3] This is currently the Science and Engineering Advisory Committee (SEAC). Its remit, as defined in its Terms of Reference, is in fact much wider than indicated here.

[4] SKA Construction Project: Everything defined in the capital project plan. Anything not explicitly in the capital project plan is not part of Construction.

[5] SKA Planning Activities: The activities leading to the definition of the capital project plan (or a major phase of the plan), and the operations plan. Planning includes project definition, system engineering and design. It includes the Preparatory and Pre-Construction phases of the project schedule, and any of the planning activities that are required for SKA2.

	For this purpose, managed activities include those contracted out, provided in kind by agreement, or similar.	
16	The Host Countries will have an obligation to protect the radio-quiet zones for the SKA and future telescopes from outside transmissions and other telescopes on site to agreed standards. The SKA Observatory will have responsibility for control of self-interference from SKA Telescopes.	§4.2.4
17	The SKA Observatory Council will define a SKA Access Policy governing the right to propose for observations and to have access to data.	§4.2.2
18	The Director-General will retain the final authority for time allocation, within the policy framework set by the Council.	§4.2.2
19	The SKA Observatory will be designed to accommodate a mix of large co-ordinated observations proposed by large teams and PI-driven programmes.	§6.3
20	The SKA Observatory will calibrate SKA data and make science data products and ancillary data products available to the users.	§6.4
21	The SKA Observatory will coordinate a network of SKA Regional Centres that will provide the data access, data analysis, data archive and user support interfaces with the user community.	§4.2.5

6.2 SKA Observatory Operations organisational structure

The organisational structure of the SKA Operations group is shown in Figure 2. It shows how the reporting structure flows down from the Director-General through the Director of Operations. The relation between staff at the GHQ and the two telescope sites is also shown. All staff at each of the SKA1-LOW and SKA1-MID telescopes report up through to the Telescope Director, who in turn reports directly to the Director of Operations.

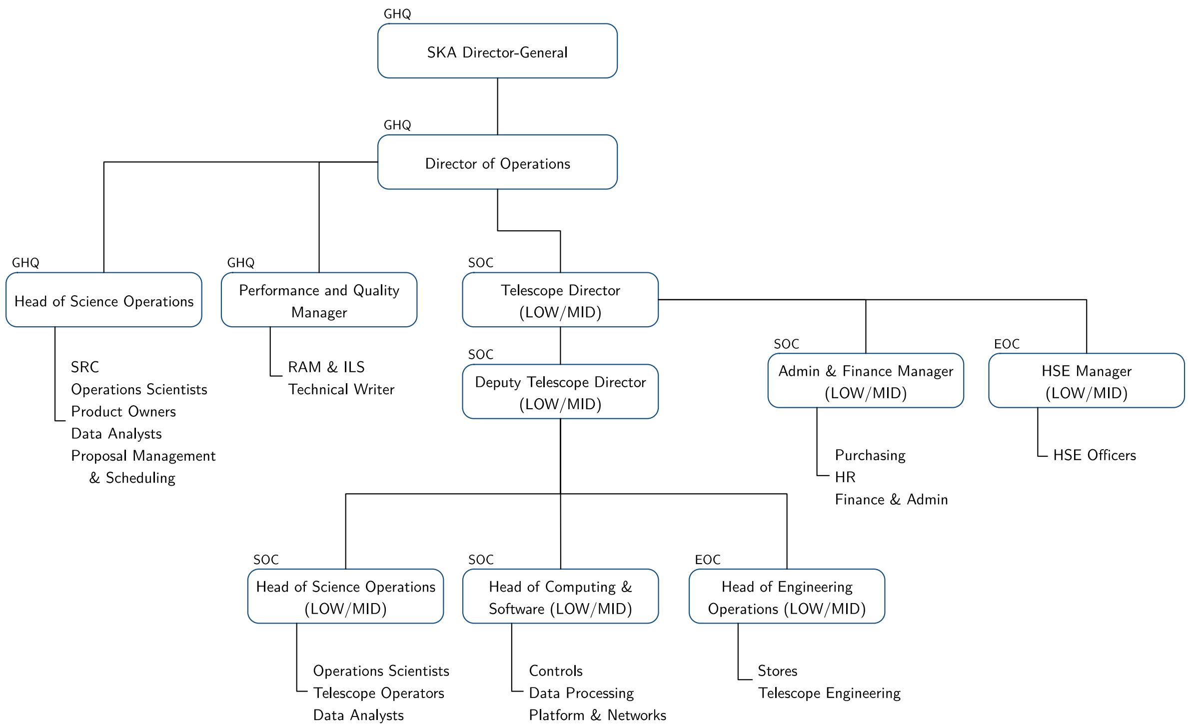

Figure 2: Organisational structure for the SKA Operations group. The location (GHQ, SOC or EOC) for each lead role and their functional area is also depicted.

6.3 Science Programmes

The SKA will undertake science observations that enable generation of science data products (§6.4.6) in accordance with the Access Policy outlined in §4.2.2.

6.3.1 Scientific Scope

A wide range of scientific programmes that utilise the capabilities of the SKA have been identified that will lead to fundamental advances in our understanding of the Universe. An indication of the breadth and depth of that Science Programme is given in [RD3] and is summarised in the list of science goals in Table 6. Within each science area, the entries are ordered in the rank provided by the SKA Science Working Group (SWG) Chairs. The eight different groups of SWG contributions are listed in the Table in an arbitrary sequence.

The scientific motivation for each of these research topics, together with the observational strategy that will be used to address them is given in [RD3]. *This table of research topics should be viewed as indicative only*, since the scientific landscape within which the SKA will operate continues to evolve and diversify, as demonstrated by the fact that since publication of [RD3] the number of distinct SKA Science Working Groups has increased from eight to thirteen, while the total membership within these bodies has increased from about 300 to 800 individuals.

As noted within the Access Policy, it is foreseen that a wide range of science programmes will be supported, both in terms of observing time requirements on the two SKA telescopes as well as high performance computing (HPC) requirements to generate the associated Observatory Data Products (§6.4.6).

The relevant range of total observing time needed for any particular programme will vary from less than 1 hour to several thousand hours. The programmes requiring the largest observing time allocations will be classified as Key Science Projects (KSPs), while those with smaller time allocation needs (exact number of hours is still TBD, but 100-hours is often used as a guide) will be classified as standard Principal Investigator (PI) projects (§6.4.4.2). The guidelines for proposal preparation and submission in both categories will be distributed within a regular Call for Proposals prior to each observing cycle (§6.4.4), although it is anticipated that KSPs and PI projects will have different cycles.

Table 6: Collated list of SKA science goals.

Science Goal	SWG	Objective	SWG Rank
1	*CD/EoR*	Physics of the early universe IGM - I. Imaging	1/3
2		Physics of the early universe IGM - II. Power spectrum	2/3
3		Physics of the early universe IGM - III. HI absorption line spectra (21cm forest)	3/3
4	*Pulsars*	Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection	1/3
5		High precision timing for testing gravity and GW detection	1/3
6		Characterising the pulsar population	2/3
7		Finding and using (Millisecond) Pulsars in Globular Clusters and External Galaxies	2/3
8		Finding pulsars in the Galactic Centre	2/3
9		Astrometric measurements of pulsars to enable improved tests of GR	2/3
10		Mapping the pulsar beam	3/3
11		Understanding pulsars and their environments through their interactions	3/3
12		Mapping the Galactic Structure	3/3
13	*HI*	Resolved HI kinematics and morphology of ~10^10 M_sol mass galaxies out to z~0.8	1/5
14		High spatial resolution studies of the ISM in the nearby Universe.	2/5
15		Multi-resolution mapping studies of the ISM in our Galaxy	3/5
16		HI absorption studies out to the highest redshifts.	4/5
17		The gaseous interface and accretion physics between galaxies and the IGM	5/5
18	*Transients*	Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State	=1/4
19		Accessing New Physics using Ultra-Luminous Cosmic Explosions	=1/4

20		Galaxy growth through measurements of Black Hole accretion, growth and feedback	3/4
21		Detect the Electromagnetic Counterparts to Gravitational Wave Events	4/4
22		Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc	1/5
23		Characterise exo-planet magnetic fields and rotational periods	2/5
24	*Cradle of Life*	Survey all nearby (~100 pc) stars for radio emission from technological civilizations.	3/5
25		The detection of pre-biotic molecules in pre-stellar cores at distance of 100 pc.	4/5
26		Mapping of the sub-structure and dynamics of nearby clusters using maser emission.	5/5
27		The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields	1/5
28		Determine origin, maintenance and amplification of magnetic fields at high redshifts - I.	2/5
29	*Magnetism*	Detection of polarised emission in Cosmic Web filaments	3/5
30		Determine origin, maintenance and amplification of magnetic fields at high redshifts - II.	4/5
31		Intrinsic properties of polarised sources	5/5
32		Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales.	1/5
33		Angular correlation functions to probe non-Gaussianity and the matter dipole	2/5
34	*Cosmology*	Map the dark Universe with a completely new kind of weak lensing survey - in the radio.	3/5
35		Dark energy & GR via power spectrum, BAO, redshift-space distortions and topology.	4/5
36		Test dark energy & general relativity with fore-runner of the 'billion galaxy' survey.	5/5
37		Measure the Star formation history of the Universe (SFHU) - I. Non-thermal processes	1/8
38		Measure the Star formation history of the Universe (SFHU) - II. Thermal processes	2/8
39		Probe the role of black holes in galaxy evolution - I.	3/8
40	*Continuum*	Probe the role of black holes in galaxy evolution - II.	4/8
41		Probe cosmic rays and magnetic fields in ICM and cosmic filaments.	5/8
42		Study the detailed astrophysics of star-formation and accretion processes - I.	6/8
43		Probing dark matter and the high redshift Universe with strong gravitational lensing.	7/8
44		Legacy/Serendipity/Rare.	8/8

6.3.2 Joint SKA Programmes relying on both SKA1-LOW and SKA1-MID

The review of high priority science objectives for the SKA (documented in [RD3]) led to the identification of a wide range of science programmes that would benefit from observations undertaken with both the SKA1-LOW and SKA1-MID telescopes. Together such programmes may account for up to about 50% of the total SKA science time. The science categories currently identified for which this capability is most important are:

(a) Transients, to track in real-time the evolution of highly time variable source properties;
(b) Pulsars, to most effectively detect new pulsar populations in complementary portions of the sky (with different dispersive characteristics);
(c) Continuum, to fully characterise the Spectral Energy Distributions (SED) of different source classes;
(d) Magnetism, to measure the polarised SED and reliably recover intervening Faraday depth features; and
(e) Physics of the Sun-Earth system including imaging of shock waves, Coronal Mass Ejections, and resolved magnetohydrodynamic waves.

The proposal submission and time allocation process described in §6.4.4 will support successful completion of such joint programmes.

6.4 Science Operations

The SKA will be the world's largest observatory in the centimetre to metre wavelength range, greatly surpassing the current generation of telescopes in sensitivity, field of view and survey speed. As discussed above, the SKA is intended to be a high-impact and transformative observatory, commensurate with the scale of investment by the Members. The science operations element of the Observatory has been designed to enable these ambitions. The SKA will operate for 24 hours every day to maximise its scientific productivity and provide access to as much of the southern sky as possible throughout the year. The SKA will be operated as a single, integrated Observatory running two telescopes, SKA1-LOW and SKA1-MID, without observers present at the telescopes. Although the telescopes operate over different frequency ranges using different technologies, there will be opportunities for joint observing programmes. To drive efficiency up and overhead down, the SKA Observatory will run a flexible observing programme to allow it to continue to be scientifically productive in the face of adverse circumstances (e.g. weather, faults, etc.), and to multiplex its observing programmes as much as possible.

6.4.1 Access to data and resources

Access to the SKA Observatory and its resources shall be guided by the Access Policy (§4.2.2) and the Access Rules and Regulations (currently being developed). These broadly follow the basic principles that:

- time allocation shall be a fair process driven by the scientific excellence of proposals and will be robust against, and be able to resolve, conflicts of interest wherever they may arise;
- the priority for the time allocation process is to ensure that the science programme of the SKA is of the highest quality, undertaking high-impact science projects;
- access will be proportional to Members' contributions to the SKA Observatory.

A traditional allocation of "telescope time" is misleading in the SKA context, since what is really allocated to projects are observatory resources. For the SKA Observatory, an allocation of "telescope time" alone does not accurately or proportionately reflect the investment that is necessary to arrive at a calibrated Observatory Data Product. The computational resources throughout the signal chain will also need to be allocated to ensure sufficient processing time and capability to deliver the required Observatory Data Products (ODPs). In other words, proposals will need to justify not only the telescope time required but also their use of other resources, especially the computing resources of the SDP and SKA Regional Centres.

Throughout their lifetime, the ODPs will remain the property of the SKA Observatory. All scientists of the Member nations of the SKA Observatory shall have access via the SRC network to ODPs they are authorised to. Each ODP will be subject to a proprietary period wherein access to that ODP will be limited to the PI and Co-Is of the originating project. The proprietary period will be specified in the Access Rules & Regulations but is currently assumed to be 1-year from the date that the PI is informed the ODPs are available.[6] Following the expiration of the proprietary period, the ODPs will be publicly available. The SKA Director-General will have the discretion to alter the proprietary period for any ODP on a case-by-case basis.

There will be no direct access for users to science data products at the SKA Observatory itself. Access to all science data products (Observatory and Advanced Data Products) will be via the SRCs.

6.4.2 Observing

Observations will be executed out within subarrays (see §6.4.2.7) which are a subdivision of an SKA telescope that can be scheduled and operated independently.

6.4.2.1 Scans, Scheduling Blocks and Observing Blocks

The SKA will utilise three execution concepts in its operations: Scans, Scheduling Blocks (SBs), and Observing Blocks. The definitions for these, and how they relate to each other, are provided below.

[6] Some ODPs, for example arising from commissioning or calibration observations, will have no proprietary period.

Scan:
- the scan is the atomic unit of execution; e.g., a 10-minute track on a target is an executable scan;
- a scan is a period during which astronomical data are being continuously acquired;
- the configuration of the subarray is fixed during a scan.

Scheduling Block (SB):
- the SB is a concept that provides a user's view of the system;
- the SB is utilised as the atomic unit of observation planning and contains all information needed for that purpose, i.e., telescope, instrument, correlator and SDP configurations;
- an SB consists of more than one scan, and long integrations can be built up by repeating a number of sequential scans within SB Instances, drawn from the parent SB;
- users interact with their project and observation design at the SB level, e.g., target lists, calibration choices, frequency and bandwidth configurations, SDP pipeline parameters;
- an SB should include all information necessary for it to be executed successfully (i.e., without error) at the telescope and to produce observatory data products (i.e., they must include calibration information);
- SBs may have a range of durations and may be executed many times;
- an SB executes on a subarray, which may include the whole available array.

Observing Block:
- Observing Blocks can act as containers of SBs that are necessary to achieve the science goals of the project;
- the SBs in an Observing Block can be related by certain scheduling constraints or breakpoints in the observing, such as:
  - SBs that need to be observed in a specific order;
  - SBs with very specific scheduling constraints (e.g., observe the SKA1-LOW SBs before those on SKA1-MID);
  - repeat the SB at a range of hour angles;
  - observe a given number of SBs from the Observing Block and then move to observing from another Observing Block.

Scheduling Blocks are generated using the Observation Design Tool (§6.4.5.1) based on the contents of the submitted proposal if that proposal is successful and becomes a project. A proposal may have a number of different Science Programmes (e.g., continuum survey and spectral imaging). During SB generation, each Programme is mapped to an Observing Block which contains the set of observations required to achieve its goals. Each observation is represented by a single SB.

All observations that generate data on the SKA telescopes will have a project and SBs associated with them. This includes data taken using a slice of the system for Engineering purposes.

6.4.2.2 Observing modes

A number of observing modes will be supported by the SKA to enable the scientific goals of the Observatory and its community to be realised. These observing modes can be differentiated between imaging and non-imaging modes. The observing modes shall be:

- Continuum Imaging
- Spectral/Zoom window imaging
- Pulsar Search

- Pulsar Timing
- Dynamic Spectrum
- Transient Search
- Very-Long Baseline Interferometry (VLBI)

Independently of the observing modes, there are different ways in which the telescope carries out observations, i.e., tracking modes (§6.4.2.2.3). Furthermore, there will be special observing modes to allow fast reaction to Targets of Opportunity, triggered events, etc.

6.4.2.2.1 Imaging modes

There will be two imaging modes available. In each case, phase corrections will be applied to the visibilities for those objects whose distance places them in the near field for the largest baselines in the subarray.

Continuum imaging: Designed for imaging areas of the sky over a broad bandwidth. The bandwidth chosen is configurable and for SKA1-MID it is limited by the receiver chosen. Spectral resolutions can be configured from 5.4 kHz for SKA1-LOW and from 13.4 kHz for SKA1-MID. As well as the correlated visibilities, this mode is able to deliver the autocorrelations to support intensity mapping observations. All four Stokes parameters can be imaged.

A dedicated fast-imaging pipeline will produce snapshot images, at low latency and high time resolution, to search for radio transients with variability ranging from seconds to hours. Detections are recorded in a Transient Source Catalogue. The detection of a transient may trigger an International Virtual Observatory Alliance (IVOA) alert, dependent on its parameters.

Spectral line/Zoom window imaging: Spectral line imaging provides between 52,500 and 65,536 linearly-spaced channels across the frequency band. Zoom windows allow for higher spectral resolution images to be obtained, down to several hundreds of Hz. The number of simultaneously available zoom windows available for SKA1-MID will depend on the available processing and data transfer resource available. These windows contain between 14,000 and 16,384 linearly-spaced channels that can be configured across the available bandwidth. SKA1-LOW can have up to four zoom windows with bandwidths ranging between 4 and 256 MHz. This mode is able to deliver the autocorrelation as well as the correlated visibilities. All four Stokes parameters can be imaged.

6.4.2.2.2 Non-imaging modes

Pulsar and transient search: This mode searches for periodic pulses over a range of possible dispersion measure values, including acceleration searches for highly relativistic pulsars. It is also capable of searching for single pulses. The Pulsar Search pipeline sifts through and identifies candidates and generates a catalogue of those as a science data product. Detections of new single pulses and new pulsars may produce IVOA alerts and may trigger the dump of the transient buffer.

This mode is capable of searching the visible sky from each SKA1 telescope by means of using a large number of tied-array beams (500 for SKA1-LOW and 1500 for SKA1-MID) to achieve high sensitivity and survey speed.

Pulsar timing: This mode converts tied-array dual-polarisation voltage beams into folded integrated pulse profiles of pulsars to accurately measure the time-of-arrival (ToA) at which a fiducial phase of a pulsar's periodic signal arrives at the phase centre of SKA1. The ToA is used to generate the timing model for a given pulsar. This mode processes up to 16 dual-polarisation, beamformed voltage streams simultaneously and independently. They can be formed from up to 16 different sub-arrays.

Flow-through: This mode is designed to record raw tied-array beam data for offline analysis (e.g., at SRCs), to allow for testing of specialist techniques and algorithms that require full phase information in the incident signal. The output product is a configurable portion of the total bandwidth of the dual-polarisation voltage beam signal.

Dynamic spectrum: This mode produces a generic, high time-resolution, dynamic spectrum that may be used for a broad range of scientific applications. The resultant data product is a time-versus-frequency spectrum with configurable time and frequency resolutions, that may contain all or a subset of the Stokes parameters.

VLBI: This mode provides independently steerable tied-array beams to participate in VLBI imaging and non-imaging observations, with other radio astronomy observatories located around the globe. This mode provides ultra-sensitive elements (at µJy noise level) to the VLBI networks, at milli-arcsecond angular resolutions. At least four dual-polarisation VLBI beams can be formed from one or more subarrays, including up to the full array. Polarisation corrected and RFI masked tied-array beam voltage data is recorded in VDIF format compatible with external VLBI correlators, for inclusion in either real-time or post-observation correlation.

For SKA1-LOW, VLBI beams can be formed with a maximum bandwidth of 256 MHz per polarisation, per beam. For SKA1-MID, visibility data are produced simultaneously within each VLBI-mode subarray to provide calibration solutions to establish beam coherence and to enable standard imaging with the subarray in interferometric mode. The standard VLBI bandwidths are available up to 200 MHz per polarisation, per beam. For increased bandwidth, the appropriate number of VLBI beams should be configured with the same pointing.

Transient Buffer: A buffer continuously records a certain bandwidth of raw voltage data, in dual polarisation, from all the antennas/stations to capture transient events. The characteristics of the buffer (e.g., bandwidth and size) depends on the upstream configuration of the SKA1 telescope. The buffer dump is triggered when a Virtual Observatory (VO) Alert is received, either internally from the SKA1 telescope (e.g., following the detection of a single pulse), or externally from other observatories across the electromagnetic spectrum and/or multi-messenger facilities (e.g. gravitational waves, neutrino experiments). The data that are dumped by the buffer start a few seconds before the event was detected and lasts for 900 seconds or 60 seconds, for SKA1-LOW and SKA1-MID, respectively.

6.4.2.2.3 Telescope tracking modes

Data for each observing mode can be collected using different telescope tracking modes. The tracking mode should be chosen depending on the characteristics of the scientific project, providing the highest observing efficiency for the depth required. There will be four tracking modes available.

Sidereal Tracking: In this mode, antennas/stations from a subarray observe a target position by tracking it at sidereal speed.

Non-Sidereal Tracking: In this mode, antennas/stations from a subarray observe a target position, tracking it at a speed that is different to the sidereal rate, e.g., for objects in the Solar System.

Wide Area Scanning: This mode is for observing large areas of the sky with shallow integrations. This mode will be used when the overheads of using other observing modes to obtain a large map are significant. The region to observe is scanned at higher than sidereal speed, performing parallel scans (i.e., raster scans). The scan area can be defined (within the SB) in either (RA, Dec), (Az, El) or Galactic coordinates.

Drift Scanning: In this mode, the antennas/stations in a subarray do not track the sky but are fixed relative to the Earth, i.e., they point to a fixed position defined in (Az, El) coordinates, while the sky moves across the beam at the sidereal rate.

6.4.2.3 Targets of Opportunity, triggered events and overrides

The ability to acquire new objects quickly, in response to alerts that have been triggered by events either externally or internally to the SKA (e.g., Targets of Opportunity (ToOs), transients, etc.), is an important science driver for the SKA. Follow up on potential SKA discoveries by other observatories will be crucial for multi-wavelength and multi-messenger studies. The SKAO will use the VOEvent protocol to communicate alerts between SKA1-LOW and SKA1-MID telescopes, to publish alerts externally, and to subscribe to VOEvent announcements from other observatories or researchers in the science community.

For approved projects, the response to different triggered events will be dependent on the scientific ranking of those projects as assigned in advance during the proposal review process, a judgment that will be based on the proposal's scientific merit, impact and urgency. These projects will have pre-defined SBs to allow their observation with minimal delay. Once triggered, the SB for that project will have any late-binding information (typically target position and name) added to it and will be available for observing. The SB will be scheduled for execution according to its ranking at an appropriate time commensurate with its scheduling priority, just as any other project. Projects that may result in trigger events will need to include rules for issuing VOEvents.

A project may have override status due to its importance and urgency (an evaluation that will emerge from the proposal review process), e.g., a supernova explosion in a nearby galaxy. It is anticipated that the majority of trigger events will not have override status. A project that is triggered with override status will immediately enter the top of the currently executing schedule (with maximum 1 second latency), displacing other projects. If the environmental constraints are satisfied, then the SB will begin executing immediately, aborting currently executing SBs if necessary, to obtain the required resources. Decisions on which SBs to abort will be based on their scientific priority and the amount of resource that will be freed. The override status may differentiate between immediately aborting and stopping the currently executing SBs at the end of the current scan.

For the majority of cases any late-binding information will be in the form of a target's position and name, or a late update to the ephemerides where the orbit of a body is not well known at the time the proposal was written (or when the SB was last updated). All pertinent information will need to be included in the VOEvent that triggered the SB.

VO alerts may also be received as requests from researchers in the community. As there is no existing project, that request for observing will go directly to the Director-General, or their delegate, and if approved for execution a Project and SBs will be created for it. In most cases, such an event will likely be of very high importance and override status may be assigned at the Director-General's discretion. A response system will be put in place to ensure decision and implementation within 12 hours of receiving the request.

6.4.2.4 Calibration

Calibration [RD20] is a specific activity needed to render raw data into science data products that may then undergo further scientific analysis. The basic framework for calibration is the Hamaker-Bregman-Sault measurement equation, including direction-dependent effects and making use of frequency-dependent Global and Local Sky Models. The calibrations can be broadly classified as follows:

A priori calibrations	• Flagging for non-operational equipment, antenna not on source, RFI in known bad channels or above defined thresholds, antenna shadowing, etc. • Ionospheric Faraday rotation (determined from Total Electron Content and a model of the geomagnetic field) • Gain-pointing direction curves (gain-elevation for Mid) • Antenna/Station voltage patterns • Application of pointing models • Application of delay models
External calibrations (using pre-determined sky models):	• Delay (parallel and cross-hand) • Bandpass • Polarization leakage • Absolute flux-density scale • Complex gain • Calibration transfer between bands, beams, spectral configurations • Autocorrelation spectra from interferometric observations Note that RFI flagging will be performed iteratively during the calibration loop.
Self-Calibration:	Applied iteratively to refine both amplitude and phase (or delay) calibration and sky model during the imaging process (again interleaved with RFI flagging). • Direction-independent phase and amplitude • Direction-dependent (correcting for non-isoplanatism in the ionosphere, inaccuracies in the beam or station model, residual pointing errors) o A and AW-projection o Facet-based imaging o Peeling o Pointing self-calibration
Real-time calibrations:	These require analysis and feedback on-line and are applied by sub-systems other than SDP. • Station calibration (SKA1-LOW), applied by LFAA/MCCS • Reference pointing (SKA1-MID), applied to the dishes • Complex gain calibration to be applied in the beam-formers • Polarization leakage calibration (to determine Jones matrices for PST, PSS or VLBI beam-forming), also applied in the beam-formers • Gain monitoring using noise diode (SKA1-MID); applied in the correlator

Array Calibrations: These require significant blocks of observing time and are executed periodically by the Observatory to determine parameters required for every element of the array and applied in the a priori calibrations described above.

- Dish Pointing (SKA1-MID)
- Dish Gain-Elevation (SKA1-MID)
- Antenna locations and cable delays
- Beam models (SKA1-MID: holography; SKA1-LOW: raster scans)

Many calibrations are determined and applied off-line by the Science Data Processor ICAL pipeline; others are executed infrequently or, conversely, applied on-line. The Observatory will maintain an ongoing calibration programme that will periodically undertake routine calibration observations (see *Array Calibrations* above, for instance) at various cadences. The details of and policies for this calibration programme are under development.

The strategy for carrying out these calibrations is discussed in detail in §6.4.5.5. Calibration data will be public and shareable between projects and Scheduling Blocks, if appropriate.

6.4.2.5 Timing Conventions

The SKA Observatory will base its timing convention on the use of active hydrogen masers as reference clocks. Two timescale realisations are calculated in parallel, master and back-up, with the ability to switch between the two in case of failures. This solution applies to both telescopes, SKA1- LOW and SKA1- MID.

The SKA timescale will be traceable to Coordinated Universal Time (UTC) using Global Navigation Satellite System receivers to accurately determine the time offsets with respect to UTC. From the observer's perspective, any timing constraints in Scheduling Blocks will be expressed in UTC, Local Sidereal Time and/or in local time for the telescope site in question.

The SKA timescale will need to apply leap second corrections to its Network Clocks and Caesium Clock. Leap seconds are announced six months before the event and can be applied at 23:59:59 on the last day of June or December of the year as required, whenever UTC has drifted more than 0.6 seconds behind the mean solar time. The leap second correction could be an automatic process or be manually commanded. The addition of the leap second means that UTC will read 23:59:60 before reaching midnight. Implementing the leap second shall not interrupt SKA Operations, and the Observatory will keep monitoring the integer difference between UTC and International Atomic Time (TAI).

6.4.2.6 Commensal observing

Commensal observing will have a significant impact on the scientific productivity of the SKA. Three different types of commensal observing are defined:

- <u>Data Commensality</u>: multiple projects can use the same Observatory Data Products but for different science goals, as recommended by the TAC and approved by the D-G.

- <u>Observing Commensality</u>: multiple projects can use the same field of sky, and telescope/instrument configuration, but they each need different observatory data products;

  - the commensal projects would result in different observatory data products from the same SB, e.g., two different pipelines acting on the same set of visibilities, or, non-image processing and spectral line imaging products.

- Multiplexed Commensality: the ability to use multiple subarrays and/or tied-array beams to concurrently observe different fields of the sky.

There is no sharing of time between commensal projects. Each commensal project will be charged the execution time used (see §6.4.2.10), up to the limit of the time awarded by the TAC, e.g., if 6 hours of time is used executing an observation for two commensal projects, they are each charged 6 hours (not 3 hours).

Whether Observing and Multiplexed commensality are feasible at any instant in time is dependent on the availability of the signal and data processing resources needed to generate the desired number of observatory data products for each of the commensal projects.

At the proposal submission or observation design stage, it is not possible to know with certainty whether a particular project can be executed commensally or not[7], and as such PIs are not required to identify or label their proposals or projects as commensal[8]. The nature and number of commensal projects at any point in time will always depend on the telescope resources available, as well as the relative scheduling priorities of other potentially commensal projects. All decisions with regard to commensal projects will be taken at the Cycle Planning and Observation Planning stages (§6.4.5.2) by SKA operations staff.

6.4.2.7 Subarrays

There will be projects for which the science goals do not require the entire telescope array, e.g., observing a very bright target or multiple objects across the sky. The SKA will be able to configure into subarrays and/or tied-array beams to enable this multiplicity of observing. The general definition of a subarray is:

> A subarray is a subdivision of an SKA telescope that can be scheduled and operated independently of other subarrays. A subarray constitutes a set of resources and can be as large as the whole telescope array, or a single constituent item. A subarray is only prevented from being created by resource constraints.

Resources are capable of being controlled to perform certain tasks. In the context of the SKA, a resource could be a dish, a beam, or a slice of the correlator. Resources are schedulable entities. As such, the number of subarrays that the SKA can support is resource limited. The control and configuration of subarrays will be via the Telescope Manager.

In practice, subarrays will fall into two operational categories: engineering subarrays and astronomy (or science) subarrays. An engineering subarray will generally be used for maintenance, repair, test and commissioning purposes, and may not need an entire system “slice” with end-to-end functionality, but this is not precluded. For instance, a set of dishes without the need of signal or data processing may be configured into an engineering subarray. Conversely, an astronomy subarray requires end-to-end capability.

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[7] However, the KSP science programme will be designed to maximise commensality amongst the different projects.

[8] Although, clearly, a PI will be able to flag SBs within their own project as commensal.

Subarray templates will be developed from which users will select when writing their proposals and designing their SBs. These templates will continue to evolve to reflect array usage patterns and scientific demand, and to increase commensal opportunities. For example, pulsar search subarrays might only use inner receptors and pulsar astronomers will want as many inner receptors as possible, but the overall scientific throughput will be higher if another subarray is made available containing (possibly) a small number of inner receptors with spiral arm receptors to allow high-resolution work to be carried out commensally (§6.4.2.6). Having subarray templates rather than a 'free-for-all' approach will constrain the complexity and simplify the scheduling.

6.4.2.7.1 Independent and dependent subarrays

It will be possible for subarrays to be operated independently of each other. This allows different types of science programmes to run concurrently on the telescope and brings operational advantages, e.g., testing software or firmware updates on a live system slice of the telescope without impact on the ongoing science programme.

The architectures of the SKA1-LOW and SKA1-MID correlators/beamformers are significantly different such that the behaviour of subarrays in the two telescopes will differ in detail. For instance, the SKA1-MID correlator with its Frequency Slice Architecture allows the sharing of correlator resources between subarrays. This leads to concepts of independent and dependent subarrays, as illustrated in Figure 3.

The upper panel of the figure depicts conceptually what may be a typical commensal (multiplexed) configuration of the SKA1-MID telescope with independent subarrays. Subarray 1 is allocated with dish resources configured to observe in Band 1, while Subarray 2 is allocated dishes configured for Band 2. Two Scheduling Blocks will be executed on Subarray 1 (observing commensality), SB1 for imaging and SB2 for non-imaging (Pulsar Search, in this instance). Subarray 2 is observing in Band 2 using, for example, spectral zoom windows as defined by SB3. The SDP, as a formal part of the signal chain, not only produces the observatory data products (defined in each SB), but also provides calibration solutions in real time. All observing details are defined within the SBs, and the scheduling tool (§6.4.5.4) ensures that all resources are available before configuring any subarrays and executing the observations. These Scheduling Blocks do not need to be from the same project.

In the SKA1-MID correlator, two different subarrays can be utilising the same set of Frequency Slice Processors as long as they are both using the same observing mode (e.g., imaging or pulsar timing), irrespective of the receiver band upstream. This presents a situation where two subarrays have a dependency between them as shown in the lower panel in Figure 3. Subarray 1 is allocated dish resources configured for Band 1 observing for two SBs: SB1 for continuum imaging and SB2 for Pulsar Search. Subarray 2 is allocated dish resources configured for Band 2 observing by the two SBs selected (SB3 and SB4). In the CBF, SB1 and SB3 can use the same set of resources for imaging, while SB2 and SB4 will use the same beam forming resources (in the CBF) for Pulsar Search. Once more, none of the Scheduling Blocks need to originate from the same project, and the scheduling tool ensures that all resources are available before configuring the subarrays and executing any observations.

In general, it is anticipated that a mixture of dependent and independent subarrays will be in operation, e.g., two dependent subarrays sharing resources in the CSP, with a third subarray allocated resources that are independent of those in the other subarrays. Operationally, this allows the observatory to utilise an engineering subarray for testing or maintenance while the rest of the telescope is still following the observatory's science programme with astronomy subarrays.

SKA1-LOW uses different technology, and allocated resources are shared between separate subarrays (Figure 4). For any particular subarray (up to a maximum of 16), all observing modes can be processed simultaneously, and each active subarray is processed in parallel. All Field Programmable Gate Arrays (FPGAs) in the correlator are used simultaneously to ingest the data and process the different sub-arrays and observing modes. For SKA1-LOW, a subarray is configured with beams rather than stations (or sub-stations).

Every FPGA in the SKA1-LOW correlator processes a certain bandwidth. As such, although it is possible to select a subset of FPGAs to be used as part of an engineering subarray, this will be at the cost of some bandwidth to other active subarrays.

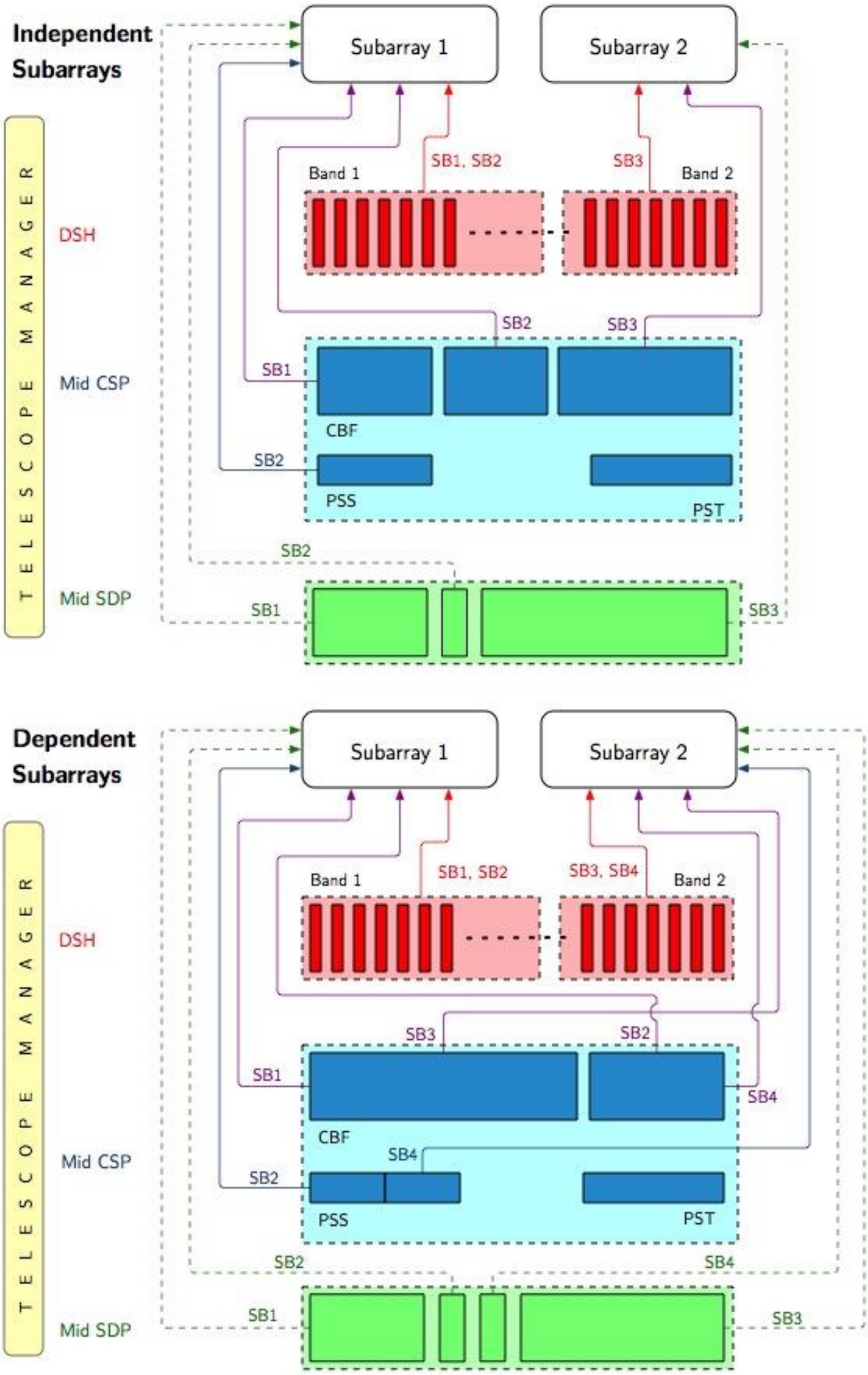

Figure 3: Resource allocations for independent (top) and dependent (bottom) subarrays on SKA1-MID. For the independent subarrays, Subarray 1 is executing imaging and pulsar search SBs commensally, while Subarray 2 is executing an imaging project. For dependent subarrays, both are executing imaging and pulsar search SBs, sharing the same resources in the CBF for imaging (SB1, SB3) and beam forming for pulsar search (SB2, SB4). The Telescope Manager handles the resource allocations to the subarrays based on the information within each SB. The SDP (dashed lines) is an exception as it handles its resource management internally, although the Telescope Manager is informed by SDP that resources are available to complete the data processing before it sends any SB for execution.

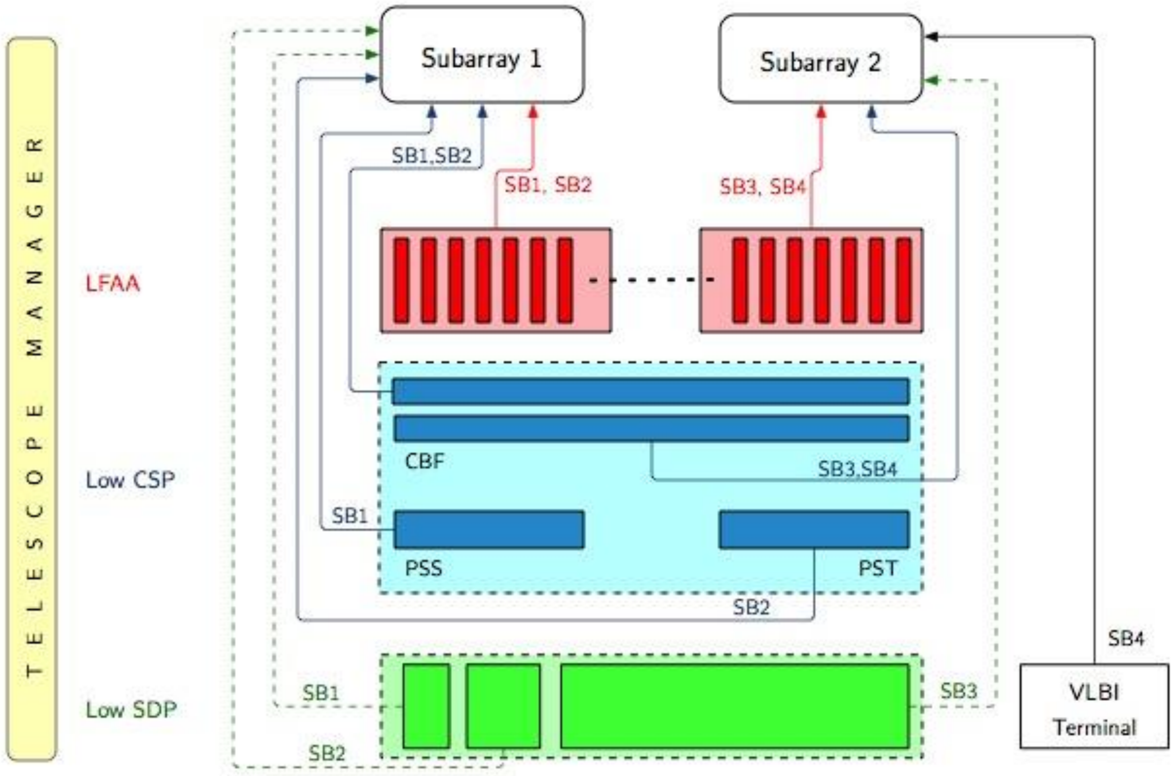

Figure 4: Resource allocations to SKA1-LOW subarrays. Two subarrays are being configured. Subarray 1 is undertaking Pulsar Search (SB1) and Pulsar Timing (SB2) commensally, while Subarray 2 is configured for an imaging observation (SB3) and VLBI (SB4). The Telescope Manager handles all resource allocations based on the information within each SB. The SDP (dashed lines) is an exception as it handles its resource management internally, although the Telescope Manager is informed by SDP that resources are available to complete the data processing before it sends any SB for execution.

6.4.2.8 Tied-array beams

It is possible to operate the SKA1 array as a single element (i.e., a virtual single dish) rather than as an interferometer. The full array or any subarray can operate as a single element through coherent summation of the signals from the individual antennas or stations in the array/subarray. As a result, one or more (up to 500 for SKA1-LOW and 1500 for SKA1-MID) tied-array beams of improved sensitivity can be produced from the same or different subarrays, each with independent pointings on the sky, and configured and operated independently of each other. Tied-array beams are used for many scientific applications, such as observations of transients and pulsars, and allows SKA1 to participate in VLBI observations, providing a very sensitive element to VLBI networks.

Beamforming makes use of real-time calibration to minimise efficiency losses caused by misaligned signal phases, atmospheric effects and polarisation impurity, as well as state-of-the-art RFI detection and excision algorithms.

6.4.2.9 Custom experiments

It is the SKA's principal aim to undertake transformative science of the highest possible impact. This may present itself in the form of an experiment that is not directly supported by the design of the SKA, or that requires a higher level of support and expertise than is provided under normal operations. Custom Experiments provide a framework within which unique and innovative ideas can be performed on the SKA.

Custom experiments will normally require an extension of existing SKA functionality or performance by the addition of hardware or software. Custom hardware may be used for data acquisition and bespoke software for pipeline data reduction may be made available via the SDP as long as they interface appropriately with the SKA while adhering to Health, Safety & Environmental, and network security policies of the SKA.

Custom experiments will be subject to the same review process as other proposals, with the TAC assessing the scientific impact, urgency and priority of the proposed experiment. This will be supported by a technical review of the custom experiment proposal to provide a statement as to the impact that the experiment will have on normal operations of the SKA Observatory, assessing the observatory resource required to support it. The review process will consider any risk or inefficiency (e.g., wasted or unscheduled telescope time) that may be inherent in scheduling custom experiments and ensure that any equipment meets established standards. This technical review will normally be undertaken by SKA staff, or external experts if necessary.

Supporting custom experiments can be costly, thus the technical review process will only consider recommending a custom experiment if the necessary observatory resources are available and if the subsequent impact on observatory operations is negligible and/or warranted. The custom experiment team are responsible for conforming to existing SKA interfaces and will provide, and test, any additional hardware and software necessary for the success of the experiment. All custom experiment teams will be responsible for providing data products (not raw data) suitable for archiving and must abide by the same proprietary period policy as other SKA data. This requirement to archive data products will be waived only in exceptional circumstances.

6.4.2.10 Time accounting

The execution time to observe scheduling blocks shall define the time charged to projects. This time shall be tracked and then subtracted from the remaining allocated time on that project. The total elapsed time will also need to be accounted for with the Telescope Operator responsible for ensuring that the elapsed time recorded tallies with the actual time available (e.g., 24 hours) during an observing period/shift. The elapsed time will be accounted for against various categories. These times will be recorded in the shift log and reported in the observing report filed at the end of an observing period.

Definitions of elapsed and execution time are:

Elapsed Time:	the ‘wall clock’ time that has passed during any operational activity.
Execution Time:	the elapsed time to carry out an executable action (e.g. a scan, a pointing, a slew).
Chargeable Time:	the sum of execution times that go towards the observation of an SB and is charged to the project.

Due to commensality and subarrays, the total chargeable and execution time in a single 24-hour period, say, can be greater than 24 hours as there will be more than one project being executed at the same time. The elapsed time will still be 24 hours.

For the purposes of tracking the observatory's activity and observing efficiency, the following time accounting categories will be used:

- Configure,
- Calibration,
- Science,
- Engineering,
- Commissioning,
- Fault,
- Weather,
- Other.

This establishes a clear demarcation of activities during a typical observing period. For instance, the Engineering category is to identify any data that are taken specifically for the purposes of engineering or maintenance and the time elapsed for these should be accounted for separately from that for obtaining Science or Calibration data. There are activities that may not result in data on disks (e.g., fault finding) but the time elapsed for those activities still needs to be accounted for. It is important that all time periods and gaps are appropriately labelled and tagged in the observatory's Shift Log Tool (see §6.4.5.4). The Other category is to be used for activities that do not easily or clearly fall into one of the standard categories – a clear description in the Shift Log Tool will be required to describe what did occur.

At the end of each observing period an observing report will be generated, archived and automatically shared with operations staff. This report should contain a log of all observations carried out or attempted, whether successfully or otherwise. The report should also contain any narrative from the Operator(s) on events that occurred during the observing period and reports on any faults encountered and remedial action taken (if at all). Links to the tickets giving detailed description of the faults will be included in the report and the log. The Telescope Operator will ensure that the total elapsed time reported tallies with the total available time (e.g., 24 hours for a daily report).

6.4.3 VLBI

VLBI projects will be allocated through the SKA's normal proposal review process, as Coordinated Proposals. Furthermore, by the time SKA1 becomes operational it is anticipated that proposals to use the SKA as part of a VLBI network may also be peer-reviewed for scientific merit and assessed for technical feasibility by a separate body as part of procedures that are yet to be established. At the time of writing discussions of this separate body, which will have a global perspective, are in their infancy. The SKA Director-General will determine how the SKA Observatory will be represented in this body, which will need to establish a policy with the SKA with regard to data rights.

The SKA-VLBI capability provides ultra-sensitive elements (at µJy noise level) in the form of tied-array beams to the VLBI networks, at milli-arcsecond angular resolutions. Standard interferometer imaging to enhance the calibration, and/or complement the science return will be available. As for other observing modes, VLBI can be performed commensally with other observing modes (e.g. PSS, PST, imaging) as long as the resources exist to support these modes.

6.4.3.1 VLBI Technical considerations

SKA-VLBI projects will make use of at least four independently steerable VLBI beams formed from a core subarray, with a concentric layout; most science cases will use the inner core (8 km baselines with 70-80% total sensitivity) but in principle SKA-MID can beamform the whole array (up to 150 km baselines) while SKA1-LOW is limited to 20 km baselines. The core subarray size selection is based on a trade-off between the field of view (FoV) and the sensitivity in the beams but will be ultimately limited by the beamforming stability. A higher number of VLBI beams in each subarray (e.g. 8 or 10) could enhance the astrometry products to an order of magnitude better than currently achievable (up to 1 microarcsec) and observing a field with a high density of targets will be more efficient. A standard set of VLBI specific subarray templates will be made available to cover the range of sensitivities and FoV required.

For projects requiring broadband or simultaneous bands observations, VLBI beams may be utilised from several core subarrays (i.e. core partitions) with similar resolution and sensitivity. To better utilise the SKA resources for some configurations, it may also be advantageous for VLBI experiments to use a core subarray providing the beams plus several SKA antennas at larger baselines as individual elements to provide short uv-spacings. The subarray phase centre's position and time is referred to ITRF and UTC, respectively. The SKA will need to track positions and velocities of the subarray centres due to continental drift.

Polarisation-corrected and RFI-masked tied-array beam voltage data is recorded in VDIF format compatible with external VLBI correlators, for inclusion in either real-time or post-observation VLBI correlation. The standard VLBI channel bandwidths are available up to 64 MHz for SKA1-LOW and 128 MHz (and 200 MHz) for SKA1-MID. The total bandwidth of the LOW beams is 256 MHz per polarisation, covering most of the band, while for SKA1-MID the maximum bandwidth is 5 GHz per polarisation, for 2 beams, (or 2.5 GHz for 4 beams). SKA1-MID is able to provide more beams but with decreasing sensitivity, up to a maximum of 52 beams per subarray with 200 MHz bandwidth, per polarisation. The external data network usage to transfer data from the SKA to the VLBI correlators will depend on whether the SKA-VLBI observation is performed in real-time (e-VLBI) or not.

In order to successfully participate in VLBI experiments, the SKA needs compatible VLBI equipment and the VLBI correlators need to be upgraded to support multi-beam instruments with broad bandwidths (out of scope of the SKA project). It is currently anticipated that an SKA-VLBI Consortium will be able to attract the funding to provide the VLBI Element (including appropriate hardware and software) for the SKA Observatory, for both SKA1-MID and SKA1-LOW telescopes. This element will be integrated into the SKA Observatory for Monitor and Control functions using the Tango framework [RD6]. It will operate in standard record/playback mode or in e-VLBI mode (streaming of VLBI data to the external correlator, for real-time correlation). This equipment will be located at the Science Processing Centres in Perth and Cape Town.

A VLBI observing project will contain the necessary timing constraints as to when the observation needs to be executed with other stations in the VLBI network. The PI initially generates a standard VLBI VEX (VLBI Experiment) file[9], which is common for all the participating observatories and contains a complete description of the observation, including:

- observatory characteristics (e.g. geographical coordinates, wrap limits, etc.);
- target and calibrator information (e.g. coordinates, flux density, etc.);
- technical information about the observation design (e.g. type of VLBI data acquisition terminal, bandwidth, channels, etc.); and,
- the detailed observing schedule specifying the observing and calibration scan times in UTC.

[9] It is anticipated that version VEX2.0 will be available when SKA1 becomes operational and will support multi-beam instruments such as the SKA1 and will detail the intent of every scan (i.e., target vs calibrator).

This VEX file will be attached to the SKA VLBI observing project submitted to the observatory, ingested and parsed to extract the necessary technical details needed to generate the associated SBs. The original VEX file will remain associated with the SB so that it is accessible by the Observation Design Tool (§6.4.5.1). The SKA will be able to accept changes to observing details if users submit an updated VEX file (e.g., change of calibrator) up to a few hours before the observation starts, an action that will automatically update the associated SB accordingly.

6.4.4 Observatory operations – Phase 1

Telescope time is conventionally awarded to PIs via a multi-phase process (see Figure 5). In Phase 1, a proposal is prepared and submitted by a PI and their Co-Is, followed by a peer review process undertaken by an independent TAC. If the proposal obtains an award of telescope time, it enters Phase 2 as a Project where scheduling blocks and technical details can be refined (perhaps following feedback, recommendations or restrictions from the TAC). PIs will, through a common, central utility, be able to prepare and edit draft proposals, and to track their active and past projects. In Phase 3 the observed data from the correlators/beamformers are processed to generate Observatory Data Products (§6.4.6.1) that are delivered to SKA Regional Centres for users to access for science extraction and exploitation.

This section outlines the key features of a proposal submission system covering all activities up to and including the recommendation of awards of time and resources by the TAC, with the final confirmation of those recommendations made by the Director-General. The system is designed to implement the terms of the Access Policy (§4.2.2); the detailed implementation rules are in the draft Access Rules and Regulations (currently being developed).

The Observatory will accommodate both large programmes and conventional PI-driven programmes (§6.3). In addition, the process will allow for future new and innovative schemes and campaigns. For the first few years of operations, the SKA will be focussed on Key Science Projects (KSPs) and PI observing programmes.

The process for proposal submission and time allocation for PI projects is described below. It is anticipated that proposals for KSPs will follow similar principles.

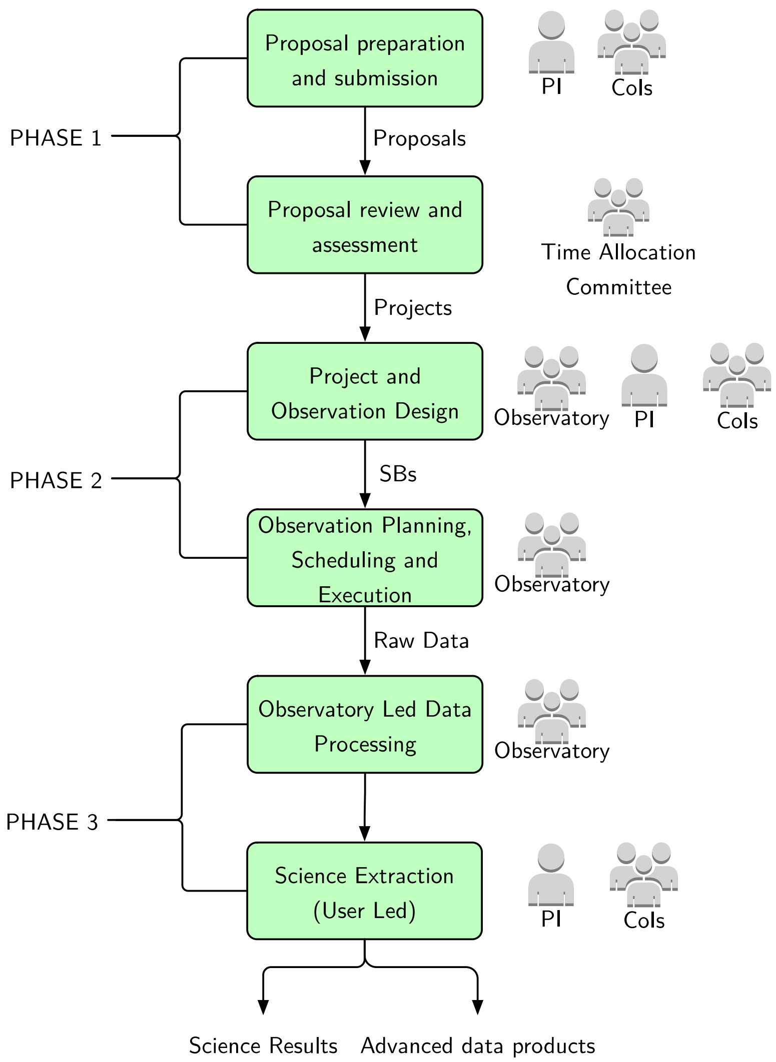

Figure 5: Three-phase science operations workflow for proposal and project preparation, observation design, scheduling and execution, and data processing and science extraction. The primary actors involved at each stage are indicated. The Observatory provides support in all stages of these phases.

6.4.4.1 Proposal preparation and submission

A central project database will store all current and historical proposals (PIs and Co-Is will be able to access only their own proposals). A Proposal Handling Tool will provide access to this repository as well as allowing all potential users of the SKA Telescopes to prepare a feasible scientific proposal without the need for specialist radio interferometry knowledge (although some radio astronomy knowledge must be assumed).

This will be achieved by allowing the PI to choose from a selection of templates from a library that they can use to construct the technical elements of their proposals. This template library will include examples that cater for a breadth of science goals – with different spatial and spectral resolutions and varying sensitivity chartacteristics – for the observing modes available for the cycle and incorporating the appropriate subarray configurations for those science goals. It is anticipated that this library will grow with time and experience of operating the SKA telescopes.

The basic constituents of a proposal will include: title, author list, abstract, scientific and technical justifications, data product pipeline requirements, the total integration time estimated using a sensitivity calculator, calibration needs, and access to astronomical databases to resolve names of specific objects and/or their coordinates. An estimate of the resources required at SKA Regional Centres will also be needed. To aid in the design of observations, the PI shall be able to access a library of standard template configurations (e.g., pulsar timing, deep imaging, wide-area mosaic) that can be inserted into a proposal and tailored to specific user needs. To facilitate collaboration across globally distributed teams, a PI will be able to delegate editing privileges to co-investigators.

If the science goals of a proposal require the use of both SKA1-LOW and SKA1-MID, then it will be possible to request and justify the use of both telescopes within a single proposal. A separate technical section for each telescope will be required.

6.4.4.2 Proposal types

Any potential user of the SKA will be able to apply for a variety of proposal types. The main categories of proposal are as specified in the Access Policy (§4.2.2):

Standard Principal Investigator Proposal (PI)	A standard PI proposal is an observing proposal initiated following a Call for Proposals and is typically completed within a single time allocation cycle. Standard proposals are typically submitted by a small team led by a Principal Investigator.
Key Science Project (KSP)	Proposals for Key Science Projects will be for relatively large resources allocations (time and compute) for observing programmes that cannot be completed within a single time allocation cycle. Proposals for KSPs will (most likely)[10] be received and reviewed at a time and cadence that differs from the regular call for proposals.
Open time (OT)	There will be a fraction of time available to PIs from member and non-member countries
Director-General Discretionary Time (DDT)	DDT proposals (that could not reasonably have been submitted in the normal cycle) can be submitted at any time needing only the approval of the Director-General

There will also be the following subcategories of proposal:

Target of Opportunity (ToO)	These are proposals that require rapid response to alerts that have been triggered by events either externally or internally to the SKA.
Long-term proposal (LTP)	These are for projects that require more than one time allocation cycle to complete (e.g., long-term monitoring campaigns) but are too short in overall observing time to qualify as a KSP
Joint SKA Proposal (JSP)	A proposal that requires both SKA1-LOW and SKA1-MID telescopes to achieve the science goals. Such proposals may be linked so that observations can be executed contemporaneously.
Coordinated Proposal (CP)	A proposal requiring observing to be coordinated with another facility (either ground- or space-based) with user-specified scheduling constraints provided. The SKA Observatory will seek to establish relationships with key, complementary facilities (e.g.,

[10] At the time of writing, a full policy for KSPs has not been determined.

ALMA) to facilitate CPs. Proposals for VLBI will be considered as Coordinated Proposals.

Clearly, some of these categories may apply to more than one proposal. For instance, it may be possible to have a proposal which is both ToO and JSP, or LTP and CP.

6.4.4.3 Proposal review and time allocation

The time allocation process will be managed, coordinated and supported from the GHQ by the Science group. Full details of the time allocation policy and review process are yet to be fully defined, but here we outline the expected process.

Given the expectation of a high volume of proposals from across the SKA member nations, it is likely that the time allocation process will utilise separate panels to review proposals addressing different science themes. The use of templates and proposal validation described in §6.4.4.1, should ensure that all submitted proposals are technically feasible. Following a triage of proposals, SKA Operations staff will technically assess the remaining proposals to ensure that observing and calibration strategies, for instance, are sound. Of course, the review panels will have the opportunity to request a further or more detailed/specific technical assessment on any proposal.

Grades assigned to proposals will require normalisation so that direct comparisons can be made across the science themes, and so that a final merged ranking of all proposals can be constructed. This will also allow comparisons to be made between distinct proposal cycles and as different personnel rotate on and off the panels.

The TAC, with support from the SKA Operations team, will be able to use a cycle planning tool to assess how the proposals they are recommending for awards are distributed across the sky for the whole observing cycle. This will help to minimise underutilised areas of the sky, while applying a degree of oversubscription to provide some tensioning to the observing programme so that the telescope is always occupied doing the best possible science projects. The tool will also look to the available computing resources at the SDP, as well as in the global network of SRCs. There will be sufficient information in each proposal to allow the cycle planning tool to do this, and to identify opportunities for commensality between different projects.

The cycle planning tool will also be designed to ascertain how observing time is being distributed amongst the Members and the likelihood that the appropriate fractions go to each, by modelling the likely completion statistic for each project subject to estimates of fault and weather losses.

The cycle planning tool will have the requisite sophistication and access to information (e.g., schedules of known maintenance/engineering events) to explore different strategies to craft the best possible science programme for the observing cycle that satisfies the national and scientific interests of the SKA Members and is commensurate, over a time period to be defined, with their contributions to the SKA Observatory.

6.4.4.4 Proposal lifecycle and states

Figure 6 illustrates the lifecycle of a proposal from when the Call for Proposals is issued to the point where a proposal is accepted or rejected. Once authenticated, a PI is able to create a new proposal or continue working on an existing one.

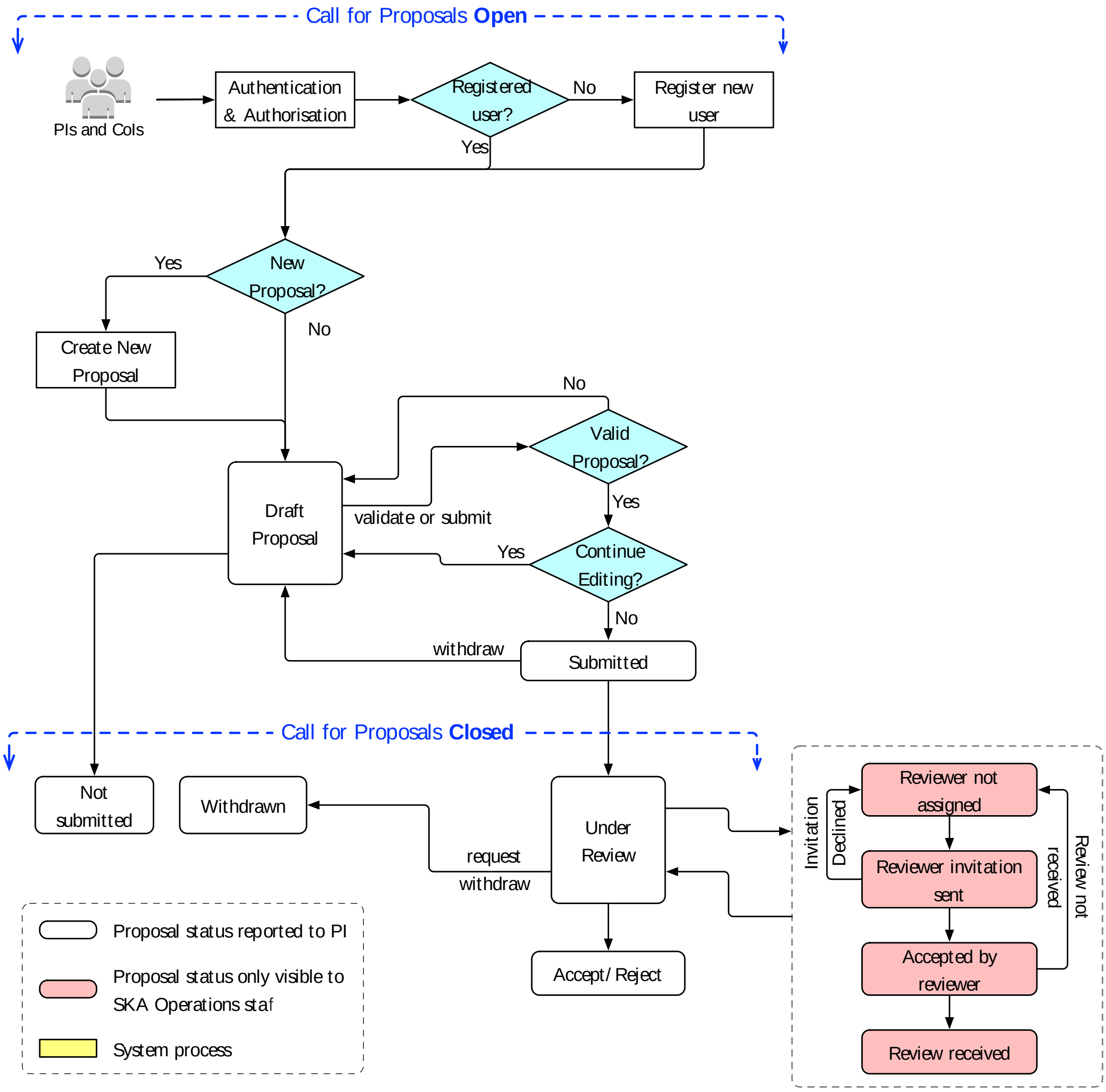

Figure 6: Overview of the lifetime of a proposal. The process starts when the Call for Proposals is opened and then a proposal is prepared as a draft, submitted and then reviewed. Green boxes indicate the proposal status as reported to PIs and Co-Is. The proposal status while under review is only visible to SKA staff supporting the review process.

The states of a proposal are:

Draft:

- on creation of a new draft proposal, the PI is notified;
- only proposals in the *Draft* state can be edited;
- a draft proposal may be validated (to check for technical correctness) at any time, and always when it is submitted;
- if validation finds errors in the proposal these are reported to the user and the proposal is returned to *Draft*;
- a proposal that is in the *Draft* state will not be considered for review.

Submitted:

- a proposal that has passed validation and can be considered for review once the call for proposals has closed;

- a unique identifier code is assigned to the submitted proposal that reflects the proposal cycle that it is being submitted into;
- a notification is sent to the PI and Co-Is acknowledging successful submission of the proposal (quoting the proposal's unique identifier code).

Not submitted:
- any proposal that is still in a *Draft* state once the Call for Proposals has closed is flagged as *Not submitted*.

Under Review:
- the proposal is currently in the process of being reviewed and assessed.

Withdrawn:
- a proposal may be withdrawn from the *Submitted* state at any time before the Call for Proposals has closed, and returned to the *Draft* state;
- a proposal may be withdrawn from being reviewed via a request to SKA Operations;
- only the PI or SKA Operations may withdraw a proposal that is currently *Under Review*;
- DDT proposals, with no formal submission deadline, can only be withdrawn by the PI or SKA Operations.

Accept/Reject:
- the result and final output of the time allocation process;
- notification is sent to the PI and Co-Is reporting the outcome of the review of their proposal, including the official feedback and ranking to emerge from the review process.

While a proposal is under review by the TAC, it will enter and exit from states that are only viewable to SKA personnel supporting the review process. The PI or Co-I of the proposal continue to see their proposal as Under Review. These 'hidden' states are:

Reviewer not assigned:
- once the call for proposals is closed all proposals enter this state

Reviewer invitation sent:
- a reviewer for a proposal has been identified and an invitation has been sent requesting their assistance in reviewing the proposal within a given timeframe;
- if the invitation is declined, the proposal returns to *Reviewer not assigned* until a new reviewer is identified.

Accepted by reviewer:
- the invitation to provide an evaluation of the proposal has been accepted by the reviewer by the agreed date;
- for reviews not received in time an extension can be offered, otherwise the proposal returns to *Reviewer not assigned* and a new reviewer is sought.

Review received:
- the final review and evaluation has been received.

6.4.5 Observatory operations – Phase 2

Successful proposals that have been allocated and approved time and resources on the SKA Observatory and SKA Regional Centres become projects. As projects, they become the containers for all pertinent information related to them including, *inter alia*, scheduling blocks, observing logs, quality assessment (QA) records, project progress against allocation, associated calibrations, faults encountered and the environmental conditions during observations. There will also be a record of all communications to and from the PI and the SKA observatory regarding the project.

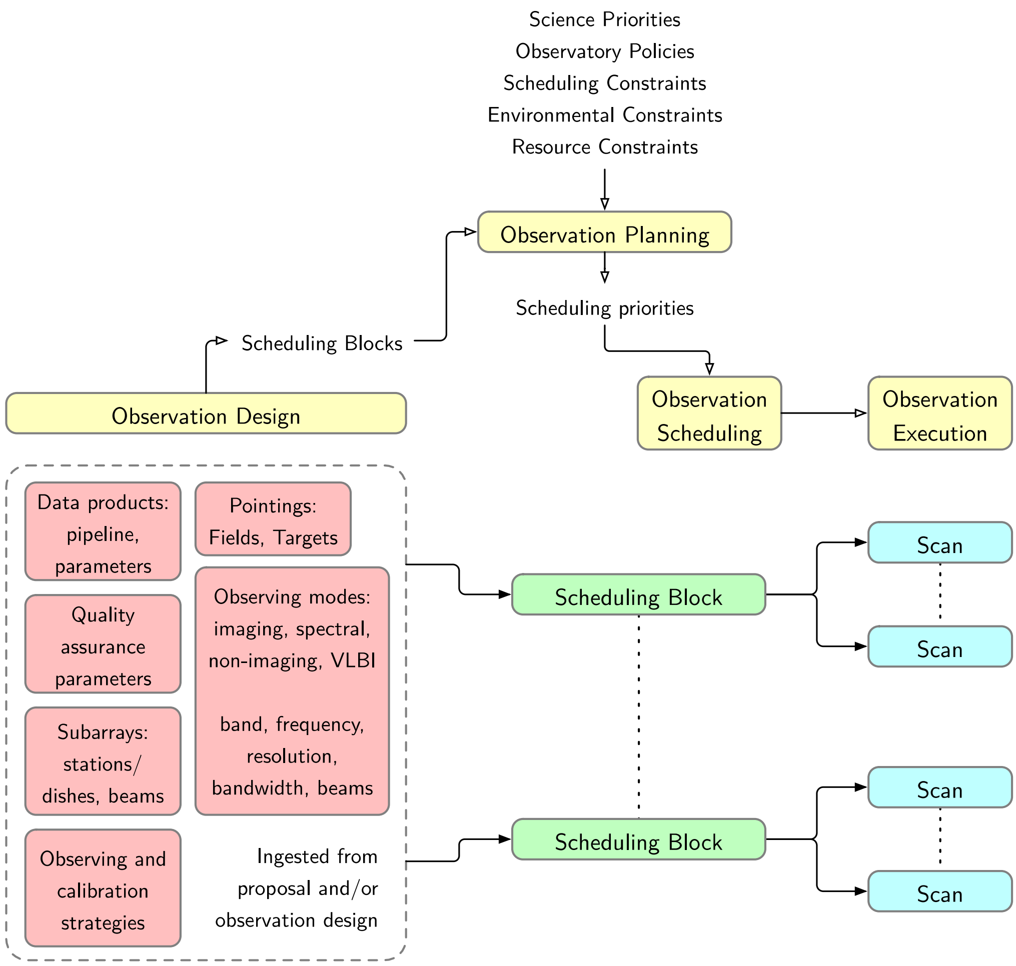

Figure 7: Phase 2 of observatory operations. In Observation Design, the PI defines the details of spectral, telescope and data reduction parameters, including observing and calibration strategies. This generates SBs that are used for observation planning that generate the scheduling priority for each SB. At the telescope, these scheduling priorities are used to select individual SBs from which the relevant scans are then executed for the project.

Phase 2 of observatory operations is traditionally related to those functions pertinent to projects and preparing them for execution. This includes the detailed design of the observations through to their scheduling and execution on the telescope, as illustrated in Figure 7.

6.4.5.1 Observation design

Scheduling Blocks are initially generated through the automated extraction of the relevant technical details from the original proposal. The PI, or their designate(s), can, if necessary or required (e.g., by the TAC), further develop the detailed instrument and telescope configurations for each SB in their project. Similar to proposal preparation (§6.4.4.1), PIs will be able to select from a library of templates to refine their observation designs if needed, permissible or appropriate.

As well as a detailed prescription of the instrument and telescope configurations, the PI will also be able to specify how the data will be processed by selecting the data reduction workflow(s) that will be associated with the observed data.

Note that it is expected that PIs will carry out the majority of the observation design for their projects during proposal preparation with help from support staff as and when it is required. It is anticipated that the required level of support for this will decrease over time as the SKA community become familiar with SKA science operations, including the observation preparation and design tools.

PIs will be encouraged to complete their observation designs as soon as possible. The sooner they do, the sooner their SBs will be included in observation planning and execution. Observation design of projects will be possible throughout the observing cycle.

6.4.5.2 Observation planning

For observation planning to proceed, SBs need to be available in the Observation Data Archive (ODA). Observation planning for each telescope can then be executed considering all known constraints. These constraints can include any scheduled maintenance or commissioning work, observations that need to be observed contemporaneously between the two SKA telescopes, or other known scheduling constraints (e.g., coordinated observations with other facilities). Clearly, the observability of targets in the sky is another constraint. Observation planning can be exercised over any user-defined timescale.

The scheduling priorities of SBs that emerge from observation planning are driven by the scientific priority assigned by the time allocation process. Scheduling priorities are generated from these for each SB based on the expected environmental and resource constraints. Scheduling priorities can be updated as determined by operational needs and priorities. Observation planning will include a simulation mode whereby operations staff can "execute" the observing programme over the planning period, look for discrepancies, errors or inefficiencies, and refine and repeat the planning process if necessary, before the resulting scheduling priorities are made available to the telescopes.

In the same way, "fake constraints" can be used to simulate an observing programme and investigate the impact to the productivity of the telescope under various scenarios; for example, losing half an array due to some unforeseen event, or for some known major engineering work that needs to be undertaken in the future. This allows the operations staff to plan appropriate remedial action. This will also be an important tool for managing, and predicting, the SKA Members' completion statistics.

Observation planning is an activity that necessarily reflects overall observatory-wide science priorities, Members' shares, and telescope operations. As the scheduling priorities of SBs will be dependent on a number of factors that bridge the activity across both telescopes, observation planning will be conducted at the GHQ as this provides an observatory-wide view of telescope operations. SBs and their resultant scheduling priorities are then replicated to the telescope sites where the science programme is executed according to those priorities.

6.4.5.3 Identifying commensality

Commensality between SBs of different (or the same) projects will be identified during the observation planning stage. In particular, instances of data and observing commensality (see §6.4.2.6) will need to be identified and the SBs appropriately packaged for execution into a Compound Scheduling Block. A Compound SB is a scheduling construct that contains a set of SBs to be executed in parallel. The SBs share the same front end (stations or dishes) resources, but not necessarily the same back end (i.e.

compute) resources. The Compound SB is scheduled as a whole, but the contained scheduling blocks are executed in parallel.

The scheduling priority of the commensal group of SBs in the compound SB will be determined by the highest-ranked SB in that group. This is simply to avoid the highest-ranked project being penalised by other lower ranked projects that it happens to be commensal with. Of course, this is a boon for those lower ranked SBs in the compound SB.

6.4.5.4 Flexible observing, scheduling and execution

The SKAO will execute its science programme using flexible scheduling (also known as dynamic scheduling). This is a mode of operation that allows the observatory to react quickly and efficiently to changing environmental conditions, availability of resources and capabilities, and other operational or scientific needs. Flexible observing aims to drive efficiency upwards by allowing the Observatory to continue to be scientifically productive in the face of adverse circumstances (e.g., weather, faults, etc.), and to multiplex its observing programmes as much as feasibly possible. Observations will be executed according to scheduling priorities that emerge from observation planning (see §6.4.5.2). An automated decision is made at the "point of execution" on whether the resources and capabilities required by the next scheduled observation are available and sufficient to execute. As changes occur in real time at the telescope, science operations can continue with high efficiency if and when these constraints and/or priorities change. Flexible observing decisions are informed by:

- dish/station availability,
- availability of receiver bands and observing modes,
- data transport capacity,
- compute availability in the correlator and beamformer,
- processing capacity of the Pulsar Search and Timing engines,
- ingest and processing capacity of the SDP,
- capacity of the VLBI buffer,
- observability of the target(s),
- environmental constraints (wind speed, ionosphere, RFI, etc.), and
- scheduling priorities of the SBs.

Telescope management for SKA1-LOW and SKA1-MID will be aware of the most up-to-date local maintenance schedule through an interface with the Engineering Management System (§6.6.10). If the observation cannot be executed within these constraints, the scheduling tool will automatically search for and select the next-highest priority SB (or compound SB) and repeat the decision-making process before sending any observation for execution (see Figure 8).

In determining whether an SB can be executed within operational constraints, the scheduling tool will be able to look forward in time. For example, if there is maintenance planned and scheduled of particular dishes/stations a few hours in the future, the scheduling tool will ensure that no scheduling blocks that require those resources shall be sent for execution.

Flexible scheduling will also allow the Observatory to quickly respond to internal or external triggers and events and change the observing schedule depending on the priority and urgency of the triggered event. Triggered projects with override status (see §6.4.2.3) will be executed on the telescopes as soon as possible, aborting currently executing observations if necessary. Once a scan has been executed the system will update the shift log (and thus the database) as well as the specific project and Members' completion statistics.

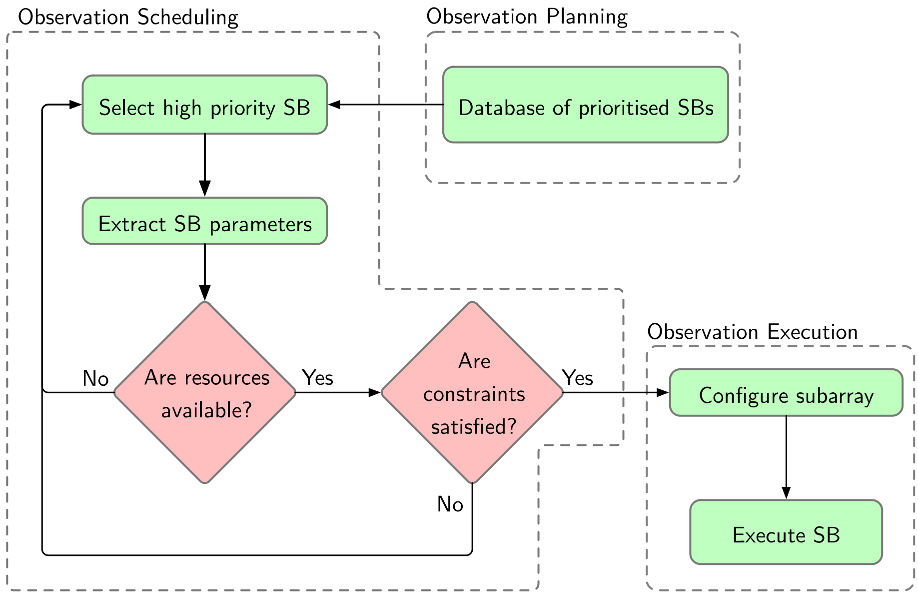

Figure 8: Block diagram illustrating the basic decision workflow for flexible scheduling.

6.4.5.5 Calibration strategy

To produce fully calibrated data products, each observation requires a set of calibration data associated with it. It is the responsibility of the Observatory to ensure that data from each SB that is observed can be processed and fully calibrated before it is made available to the PI.

To ensure this, every SB shall be associated with a calibration *schema* that describes and specifies the calibration data required for each observation. The calibration data may:

a) be included as part of the same SB as the observation;
b) have already been observed, either as part of another science observation or as an observatory calibration; or,
c) be observed at some time in the future.

In the case of c), the calibrations will need to be observed within a certain time limit (which will vary depending on the type of observation and calibration, and calibration target) and will have to be allocated a sufficiently high priority to ensure that the calibration data are obtained within that time limit. Setting this priority will be a task for the Scheduling tool once the original SB is sent for execution. The Scheduling tool (and indeed the Planning tool) will ensure that the calibration can be feasibly observed before scheduling the original SB for execution.

A consequence of this policy is that it allows for calibration observations to be shared between projects, i.e. more than one SB from different projects may be associated to an observed, or future, calibration. This clearly will increase the observing efficiency/productivity of the SKA telescopes. The chargeable time for a calibration will be attributed to an Observatory calibration project rather than to the science project. As such, it is the Observatory's responsibility to provide the appropriate calibration data for each observation, and the PI will not be required to specify these, or estimate the time for them, in their proposal. This does not preclude a PI from defining a bespoke calibration requirement/strategy in the proposal and SB.

Table 7 lists those calibrations that can be, and those that should not be, shared between different observations and projects.

Table 7: Shared and non-shared calibrations

Calibrations that can be shared	Calibrations that should not be shared
Bandpass Delay Phase Polarisation leakage Amplitude Antenna voltage pattern Gain-elevation curve	Complex gain Reference pointing

6.4.5.6 Manual operation and control

For safety and/or engineering requirements, it will always be possible for an Operator to take manual control of the telescope, its subarrays, components and instrumentation. Furthermore, it will be possible to secure manual control at several levels:

- by manually requesting inclusion of an engineering, or related, operation within the schedule;
- by manually editing the execution schedule to insert an automated operation at a future point in time (by either sending an SB or engineering operation for execution); or
- by performing manual low-level control of the telescope.

Other manual operation controls may be identified through the course of operating the telescopes and will be added accordingly.

6.4.6 Science data products – Phase 3

6.4.6.1 Observatory and Advanced Data Products

Science data products are those that have been calibrated into useful astronomical units and can be used in scientific analysis. In general, the SKA defines three types of science data products split between two categories:

Observatory Data Products (ODPs):	Observation-level Data Products (OLDPs) are calibrated data products generated by SDP workflows and are based on data obtained from one or more Scheduling Blocks. Project-level Data Products (PLDPs) are calibrated data products generated by combining several, related, observation-level data products, delivering the requirements of the PI as outlined in their original proposal.
Advanced Data Products (ADPs):	These are the user-generated products, produced through the detailed and rigorous analysis and modelling of Observatory Data Products (either at the Observation or Project level).

The generation of ADPs will usually require some level of interactive visualisation and examination of data, as well as comparison to data from other SKA observations or other facilities. Conversely, generating ODPs will not require any interaction by the science users, and the execution of workflows to generate these will be performed by the Observatory.

6.4.6.2 Pipelines and data products

Observatory data products will be generated by the SDP using workflows and pipelines specified within the SB. The complete list of ODPs that SDP will be capable of producing, each of which will have an associated processing and quality assessment, is reproduced below. The log file associated with each ODP generated will show the pipelines and parameters used as well as the resultant QA data.

Image products 1: Image cubes	• Imaging data for Continuum, as cleaned restored Taylor term images (no image products for Slow Transients detection have been specified – maps are made, searched and discarded). • Residual image (i.e. residuals after applying CLEAN) in continuum. • Clean component image (or a table, which could be smaller). • Spectral line cube after (optional) continuum subtraction. • Residual spectral line image (i.e. residuals after applying CLEAN). • Representative Point Spread Function for observations (cut-out, small in size compared to the field of view (FOV)).
Image products 2: UV grids	• Calibrated visibilities gridded at the spatial and frequency resolution required by the experiment. One grid per facet (so this grid is the FFT of the dirty map of each facet). • Accumulated Weights for each uv cell in each grid (without additional weighting applied).
Calibrated visibilities	Calibrated visibility data and direction dependent calibration information, with time and frequency averaging performed as requested.
LSM Catalogue	Catalogue of a subset of the Global Sky Model (GSM) containing the sources relevant for the data being processed. These are the sources in the FOV, as well as, potentially, strong sources outside of the current FOV. Initially, the Local Sky Model (LSM) is filled from the GSM. During data processing, the sources found in the images are added to the LSM.
Imaging Transient Source Catalogue	Time-ordered catalogue of candidate transient objects pertaining to each detection alert from the real-time, fast imaging pipeline.
Pulsar Timing Solutions	For each observed pulsar, the output data from the pulsar timing section will include the original input data as well as averaged versions of these data products (either averaged in polarisation, frequency or time) in PSRFITS format. The arrival time of the pulse. The residuals from the current best-fit timing model for the pulsar.
Transient Buffer Data	Voltage data passed through from the CSP when the transient buffer is triggered.
Sieved Pulsar and Transient Candidates	A data cube which will be folded and de-dispersed at the best Dispersion Measure, period and period derivative determined from the search. A single ranked list of non-imaging transient candidates from each SB. For those transients deemed of sufficient interest, the associated “filterbank” data will also be archived. A set of diagnostics/heuristics that will include metadata associated with the scheduling block and observation. Discovery of

	sufficiently interesting pulsars will generate an alert as well as being recorded in a log.
Science Alerts Catalogue	Catalogue of Science Alerts produced and communicated by the SDP. The alerts themselves are IVOA alerts. This catalogue provides a searchable and retrievable record of past alerts.
Science Product Catalogue	A database relating to all science data products processed by the SDP. It includes associated scientific metadata that can be queried and searched and includes all information so that the result of a query can lead to the delivery of data.

Different products can be generated commensally, but only those products required for the project(s) requested with a specific SB will be produced, since resources will be limited. SDP's pipelines will be tuned to the specific requirements of each SB to deliver the required calibration solutions and ODPs.

6.4.6.3 Quality assessment

Quality Assessment (QA) occurs within each element of the observatory that undertakes data processing – principally in the SDP but also in the CSP (specifically in the PSS and PST) and in the LFAA Monitoring, Control and Calibration System (MCCS).

Within the SDP, quality assessment is undertaken as part of the real-time and off-line processing pipelines. Its purpose is to check whether the observations are proceeding or have proceeded as planned. In the real-time case, QA can give useful feedback that might affect whether the current SB should be continued or aborted (e.g. from the impact of the ionosphere on the data), and in the off-line case measure the performance of the telescope system and determine whether the SDP pipelines themselves are appropriately tuned.

SDP QA will be performed on:

- data astrometry (source positions),
- photometry (comparison of source fluxes with known standards),
- radiometry (overall image statistics),
- polarimetry (comparison of polarisation fluxes and angles with known standards), and
- spectrometry (measurement and characterisation of emission line fluxes and moments).

The PSS and PST facilities within the CSP will produce QA artefacts as timing data are passed through the various analysis algorithms. The LFAA MCCS servers will have access to station-level calibration and monitoring data, so can report on station health and calibration solution behaviour. Details of the specific metrics are TBD.

In all cases, QA information is passed to TM. Aggregated information will be entered into a QA log that is preserved and delivered with (and linked to) the ODPs, and stored in the project log, ensuring that it is accessible to the operations staff at the Observatory and to science users. The non-aggregated, live system health information will be accessible to SKAO operators and staff.

6.4.6.4 Lifecycle of data products

Observatory data products, i.e. those generated within each SDP, will be delivered to SKA Regional Centres where users will access them (§6.5). Once all planned SDP pipelines needing a particular set of raw data have been completed, those data can be deleted when necessary to free space in the

SDP's buffer. This applies to the hot buffer, where data are stored only whilst batch processing is being run and from which an almost immediate deletion of raw data is anticipated once a batch pipeline completes, and to the cold buffer.

Deletion of unprocessed data from the cold buffer is also possible and might be required if the buffer has insufficient space to take in data from a ToO observation that has been triggered with override status. In that case, data will be deleted in accordance to their differing science prioritisation values, with the most valuable data deleted last.

In addition to being delivered to SRCs, all ODPs will be stored in a long-term preservation system for both telescopes. This long-term preservation is capable of restoring data products to SRCs but should be seen as an option of last resort since this storage will be off-line and slow to extract data from (so that it is as inexpensive as possible). Requests to restore data from the SDP long-term preservation system will come from SRCs to the Observatory, not directly from individual users. Note that there are no direct interfaces to the SDP for non-staff users. If a user discovers that some of their data is missing, they can then file a Helpdesk ticket (§6.10.1) and the data product will be re-delivered to the SRCs, if necessary. For the majority of cases where data products are lost from an SRC, it will be faster and more efficient to copy missing products from another SRC than to use the observatory's staging and delivery platform and data link (which will be needed for ongoing campaigns).

Once delivered to the SRCs, users will be able to access these data products if they have appropriate permissions. As products move out of their proprietary periods, user access will be opened up to the general public. Some products may be public from the outset.

6.4.7 Science operations workflow

The SKA science operations workflow starts with the submission of a proposal and ends with users accessing data products in SKA Regional Centres around the world (Figure 9). The SKA Observatory first engages with its community with the issue of a Call for Proposals and then with proposal preparation (§6.4.4.1). Successful proposals then enter the workflow as SKA projects. Observation design (§6.4.5.1) ensures that the SBs for each project are sufficiently well defined such that users' only interaction with the SKA thereafter is after the resultant ODPs have been delivered to the collaborative network of SRCs (§6.5).

All relevant observational details pertaining to SKA observing projects are kept within the Observatory Data Archive (ODA), including the SBs. Observation planning (§6.4.5.2) will take SBs from each project and given the set of known constraints, which includes maintenance schedules for each telescope, the science priorities for each project to emerge from the proposal review process, and the requirement to provide a return for the Members of the SKA Observatory, and maps out the science programme to observe. Scheduling priorities are assigned to each SB in the ODA over a given timeframe, which could be the whole observing cycle. Commensality between SBs is also identified at this stage and the corresponding SBs packaged into a Compound SB (§6.4.5.3).

The ODA is replicated between the three Observatory sites, allowing the scheduling priorities to be used by telescope management at the SKA1-LOW and SKA1-MID telescope sites to guide and execute the observing programme in a flexible manner. The availability of telescope resources and capabilities, constrained by short-term engineering schedules and environmental conditions, inform whether any single SB can be expected to be feasibly executed. Each telescope will adapt its schedule flexibly in response to any perturbing events that are triggered during the observing period, e.g., ToO events or faults that interrupt observing (§6.4.5.4). VO Alerts may originate either internal or external[11] to the Observatory (see §6.4.2.3). In this way, telescope management ensures that only SBs that will result in ODPs will enter the signal chain (blue arrows in Figure 9).

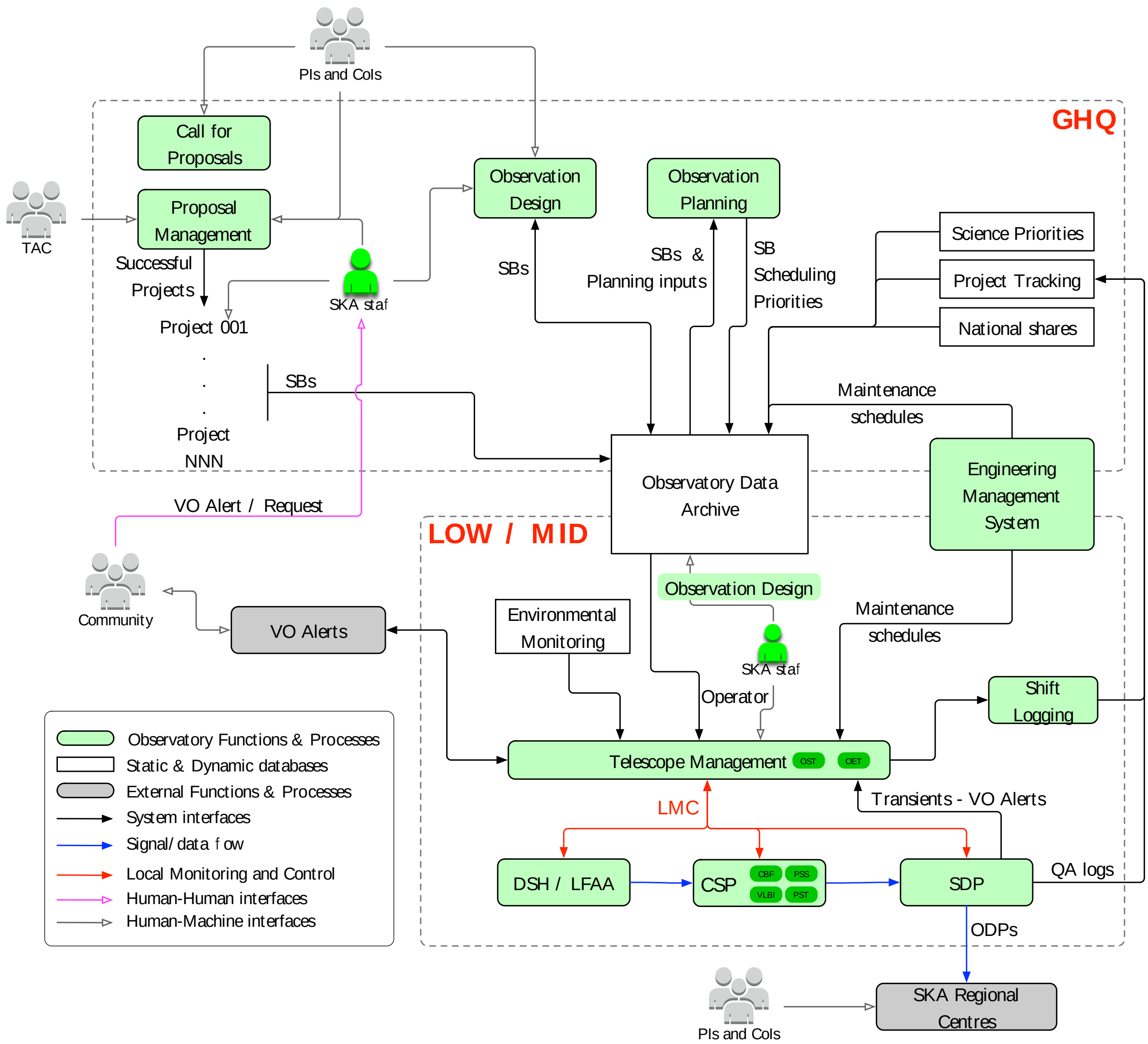

Figure 9: Science operations workflow for the SKA Observatory showing the flow of information (proposals and schedules), processes (project management, observation planning, telescope management, monitoring & control), and data**.**

As completion statistics are incremented (with each observed SB), this and other factors will influence the priority of remaining SBs when scheduling priorities are updated by the next iteration of observation planning (which can, in principle, be carried out at any time). The likely operating model is for scheduling priorities to be updated on a regular basis, e.g., every 2–3 days, informed with the most up-to-date information from across both SKA telescopes. The revised scheduling priorities for each SB are updated in the ODA and replicated to the telescope sites with minimum delay (the actual latency will depend on the database technology chosen), ensuring that observing continues seamlessly. In the event of a delay in receiving updated scheduling priorities, or some unforeseen

[11] Some external triggers, that are not associated with an existing project, may come in as a direct request to the Observatory (most likely at the GHQ). If approved by the Director-General (or their delegate), SKA staff can quickly create a project and SBs, and allocate a priority for immediate execution at the telescopes.

circumstance leading to loss of network communications, the SKA telescopes will be able to continue observing independently of GHQ, for the whole observing cycle if necessary, following their most up-to-date list of SB scheduling priorities.

Throughout, the systems are monitored for faults and alerts by the Local Monitoring & Control network of computers, and the quality of the data is automatically assessed by the data reduction pipelines. A fundamental role of the data processing systems, and of the SDP in particular, is to perform sufficient calibration of the raw data to allow output data products with much reduced average data rates – with a decrease in the average data rate from approximately 10 Tbit/s to around 100 Gbit/s. Note that for the SKA, data reduction is an integral part of the observing workflow. If the SDP ingest is not available for any length of time, data acquisition will also cease, and observations will need to be aborted and repeated.

The fault and QA statuses for each observation are recorded and logged by the Shift Log Tool. Any action taken in response to these, or any other alert or warning, should also be recorded in the Shift Log.

If the data quality falls below (or above) certain thresholds, then the Operator is informed (together with the relevant detail) with the Shift and project logs updated. The Operator may decide to continue or repeat the SB depending on the severity of any problem encountered. If the QA indicates failure at the start of execution of an SB then it may best to immediately abort/repeat/restart the observation (if it is safe to do so). If QA indicates a problem that is not discovered until well through the execution of an SB, then it is probably better to abort and repeat the SB at a later date after some investigation has been undertaken to understand and rectify the problem. If the observation fails and the reason and resolution to the issue are not immediately apparent, then the Operator will move on to the next SB and submit a ticket describing the fault for future investigation. The link to this ticket is automatically added to the Shift Log.

6.4.8 Science Operations Role Descriptions and Staffing Levels

Table 8 shows the roles and number of science operations staff required to deliver the model described above. Note that the science operations staff are supported by staff from other groups not represented in this table.

Table 8: Roles, location and number of staff to support the science operations of the SKA Observatory.

Role	Location	Description	Number
Director of Operations	GHQ	To lead and manage the Operations group and provide Operational policy direction for the SKA Observatory.	1
Admin Support	GHQ	To support the activities of the Operations group at the GHQ	1
Head of Science Operations	GHQ	To lead and manage the Science operations group and provide direction for science operations activities at the GHQ.	1
Operations Scientists	GHQ	To provide support to observing programmes and provide expert scientific domain knowledge in specific areas of science operations (e.g. imaging, VLBI, calibration). User support. Data analysis.	6
Proposal Management and Scheduling	GHQ	To generate and model observing plans, establishing observing priorities for projects.	2

Role	Location	Description	Number
		To support time allocation process with cycle planning.	
SRC Project Scientist	GHQ	To lead and manage the SRC activities within the science operations group. Liaise with the ensemble of SRCs to ensure data access to SKA users, and lead on ensuring the required level of compute support required is provided in the SRC network. Support the Head of Science Operations and Director of Operations in management activities related to SRCs.	1
SRC Scientists	GHQ	Model, maintain and develop techniques for the management of SKA science data products distributed to a distributed global network of SRCs. Maintain and continue development of SKA Science Gateway for SKA users. Maintain location database of science data products across the global network of SRCs.	3
Performance and Quality Manager	GHQ	Establish and manage the performance and data quality processes. Management of data analysts. Track Observatory performance against stated KPIs.	1
Data Analysts	GHQ	Monitoring QA logs and perform trend analysis of data quality. Maintain and develop dashboards for tracking efficiency of SKA Observatory against stated KPIs.	3
SAFe Product Managers	GHQ	Product managers for software development in support of present and future science operations in: Observation Management, Telescope control, Pulsar astronomy software, and Data Processing. Scientists responsible for defining the priorities for release development while maintaining the overall system integrity. Responsible for accepting work as done.	4
		GHQ TOTAL	*23*
Telescope Director	SKA1-LOW	To lead and manage all activities of the SKA1-LOW telescope. Represent the SKA Observatory to Host Country authorities.	1
Deputy Telescope Director	SKA1-LOW	Works closely with the Telescope Director in providing effective management of the operations of the SKA1-LOW telescope.	1
Admin Support	SKA1-LOW	Support the activities of the Operations group at the SKA1-LOW telescope	1
Head of Science Operations SKA1-LOW	SKA1-LOW	Lead and manage the Science operations group and provide direction for science operations activities at the SKA1-LOW telescope	1

Role	Location	Description	Number
Operations Scientists	SKA1-LOW	Provide support to observing programmes. Act as Astronomer-on-Duty during observing shifts. User support. Data analysis. Provide expert scientific domain knowledge.	10
Data Analysts	SKA1-LOW	Monitoring QA logs and perform trend analysis of data quality. Data reduction and analysis, including generating OLDPs from PLDPs (see §6.4.6.1).	6
Telescope Operators	SKA1-LOW	Operation of the SKA1-LOW telescope. Monitor progress of the observing schedule and the execution of science programme.	6
		SKA1-LOW TOTAL	*26*
Telescope Director	SKA1-MID	To lead and manage all activities of the SKA1-MID telescope. Represent the SKA Observatory to Host Country authorities.	1
Deputy Telescope Director	SKA1-MID	Works closely with the Telescope Director in providing effective management of the operations of the SKA1-MID telescope.	1
Admin Support	SKA1-MID	To support the activities of the Operations group at the SKA1-MID telescope	1
Head of Science Operations SKA1-MID	SKA1-MID	To lead and manage the Science operations group and provide direction for science operations activities at the SKA1-MID telescope.	1
Operations Scientists	SKA1-MID	To provide support to observing programmes. Act as Astronomer-on-Duty during observing shifts. User support. Data analysis. Provide expert scientific domain knowledge.	10
Data Analysts	SKA1-MID	Monitoring QA logs and trend analysis of data quality. Data reduction and analysis, including generating OLDPs from PLDPs (see §6.4.6.1).	6
Telescope Operators	SKA1-MID	Operation of the SKA1-MID telescope. Monitor progress of the execution of science programme.	6
		SKA1-MID TOTAL	*26*
TOTAL			**75**

6.4.9 Science Group Role Descriptions and Staffing Levels

Here we provide the staffing levels and role descriptions for the Science Group of the SKA Observatory. The key function of the Science Group is to champion and safeguard the scientific capabilities and accomplishments of the SKA Observatory. The responsibilities include engaging and communicating effectively with the scientific user community within current and prospective member countries.

The scientific interests and priorities of the community are channelled into the SKAO design and potential future upgrades. The Science Group have responsibility for the co-ordination and formulation of science input and priorities for the SKA Observatory Development Plan (as outlined in §3.1) and the Development Roadmap (through consultation/community workshops with the science community, the relevant advisory bodies and the member countries). The currently foreseen capabilities and upgrade opportunities are communicated back to the user community, so they remain optimally informed.

The scientific capabilities of the SKA telescopes are safeguarded through close involvement with the scientific commissioning of newly deployed equipment. The responsibilities include maximising the overall scientific return of the Observatory within the constraints of the agreed Access Policy. This is accomplished via a suitable peer review of submitted observing proposals prior to making recommendations for time allocation as well as the periodic progress review of any long-term allocations of observing time. Tracking scientific return of allocated observing time will include tracking of relevant publications and their citation impact. The Science Group is located at the GHQ.

Table 9: Role descriptions and number of staff required to support the science activities of the SKA Observatory.

Role	**Location**	**Description**	**Number**
Science Director	GHQ	To lead and manage the Science group and provide Science policy direction for the SKA Observatory. Lead the proposal review process.	1
(Project) Scientists	GHQ	To provide scientific domain expertise that is of relevance to the SKA Observatory in support of future instrumentation upgrades and undertake an independent research programme. Coordinate and manage the proposal review process.	6
Post-doctoral fellows	GHQ	To undertake independent research programmes that make effective use of the SKA Telescopes	6
Time Allocation Support	GHQ	To support the observing proposal call, peer review and time allocation activities at the GHQ	1
Admin Support	GHQ	To support the activities of the Science group at the GHQ	1
		TOTAL	**15**

6.5 SKA Regional Centres

There is a well-recognised need to have a network of regional or national compute and data infrastructures giving users access to SKA's data products and to the tools and capabilities needed to interact with and analyse these data products. These are referred to as SKA Regional Centres (SRCs). Here we describe the SRCs from the SKAO perspective. The SRC Steering Committee's White Paper provides a complimentary view.

The SRCs are logical and/or physical centres through which users will interact with the SKA ODPs. The existence of SRCs is required both by SKA and by the users, for slightly different reasons. From the Observatory's perspective SRCs perform two major, critical functions, referred to as "SKA-facing functions": Data Ingestion, and Project-Level Data Product generation, addressed in turn below:

1. **Data Ingestion**. SKA must be confident that science data products generated within the SDP can be interrogated by users without impacting the operation of the SDPs themselves – that is to say, *users will not have access to the SDPs*, since these are a fundamental and schedulable part of each SKA telescope. The Observatory must be confident when scheduling a particular

SB that the capability to ingest the data products is available somewhere across the SRC network and that there is sufficient data network bandwidth available to actually perform the transfers. This is because the space in the data staging area of the SDPs is also limited, and it would be very inefficient (and slow) to need to copy data out of the SDP's long term preservation systems rather than transferring data products whilst they still reside in the relatively fast data staging area of the SDP's data buffer. Ultimately, if an SRC cannot be identified as able to receive SKA data products as they are created in the SDP, there could be scheduling constraints imposed on the telescopes themselves.

2. **Project-level Data Product generation**. Many projects will require only one SB to complete or will have SBs that can be interpreted independently of other SBs. But other projects need, for example, deep images or stitched mosaics. For reasons related to the data ingest constraints, it is not anticipated that the SDPs will generally be able to combine data products from multiple SBs within the same project to produce the Project-Level Data Products. Workflows required to meet the observational goals set out in the proposal can be well-defined in advance, with estimates of the hardware resources needed to perform them. We anticipate that these workflows (e.g. combining overlapping images into a mosaic, or combining multiple data from the same field to get to the required depth) will be carried out in SRCs, by SKA Observatory staff (in liaison with science users), using software pipelines that the SKA Observatory develops and is responsible for. This is important to ensure data product integrity and traceability and for SKAO to be able to declare a project successfully complete. If SKAO gives time to a project requiring an image cube of sensitivity equivalent to 100hrs (say), then the SKAO has a responsibility to ensure that after committing telescope resources to collect the data, images of the appropriate depth and quality are indeed created and made available to authorised users in a timely manner.

In addition to the SKA-facing functions, SRCs will provide users with capabilities to perform their science analyses which are essential to deliver scientific return but are not operationally essential from SKAO's perspective. We refer to these as "User-facing" functions. Although SKAO is a very interested partner in the development of "User-facing" functionality for SRCs, it is the business of the user community and the SRCs themselves, rather than the SKA Observatory alone, to define these functions. Nevertheless, we can give a flavour of the types of activities that might be needed by users: provision of a collaborative space, uniformity of access to varied resources, data and software provenance tools, on-demand interactive compute sessions on large scale resources close to the data products, the ability to save workflow and share between collaborators, and remote visualisation and interrogation of large data objects.

There is also a suite of "SRC Community" functions required in order to enable the SRCs to share the burden of storing data products and providing archive resources and supporting users for which collaboration between the SRCs can greatly increase overall efficiency and reduce cost. SKAO anticipates performing a coordinating, operational role in the day-to-day work needed to manage the network of SRCs, in collaboration with colleagues employed at SRCs. Four areas requiring SKA operations input and coordination are envisaged:

- Global data management of the SKA archive (of Observatory Data Products and the higher-level "Advanced Data Products");
- SRC performance tracking - i.e. checking SRCs are available to perform compute requests and tracking delivered capabilities against those pledged;
- Undertaking network health monitoring and fault reporting; and
- SRC common software management to coordinate the development and deployment of shared software across the SRCs, and software to support SRC-collaboration activities.

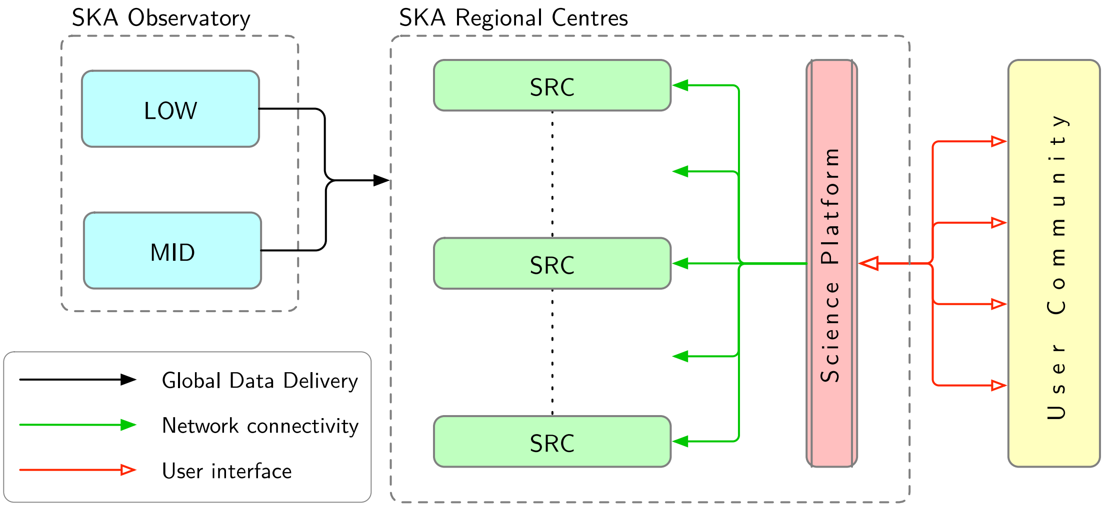

Figure 10: A collaborative network of SKA Regional Centres hosts Observatory Data Products produced by the SKA Observatory. Access to these ODPs, as well as the tools and processing power necessary to fully exploit the science potential of those products, is provided via a Science Platform**.**

SRCs will provide core functions to the Observatory and the SKA user community, but the SRCs are expected to differ from region to region in terms of the set of functions each individual SRC chooses to provide, based on their individual and specific business cases.

The Observatory will deliver ODPs to the SRCs from each SDP, buffered to remain within the capacity of the long-haul data links. Individual SRCs may be subscribed in advance, or allocated as part of the proposal review process, to receive data products from specific projects in order to plan for efficient use of each SRC. Copies of all the ODPs will reside in the Observatory's long-term storage. However, it will be exclusively through the SRC interface exclusively that SKA users will access SKA data products (Figure 10).

6.5.1 Roles and responsibilities

In Figure 11, a 'swimlane' diagram is used to show where the responsibilities of the Observatory, the SRC network and the SKA user (whether as a PI/CoI, or an Archive user) lie with respect to delivering the SKA science programme. It shows two phases: the Project Execution phase, and the Science Extraction phase. The Observatory is responsible for the project execution phase, which includes the generation, calibration and delivery of OLDPs and PLDPs into the SRC network. The SRCs are then responsible for supporting the SKA community of users in extracting the science from the ODPs delivered to them for publication and dissemination.

The science extraction phase will generally result in further, more advanced data products (ADPs, see §6.4.6.1) to be generated as a consequence of the advanced analysis and modelling techniques that will be employed by the science community. Those ADPs that will appear in publications by the PI, or that will be made public, will be added to the SKA science archive and made available to all users (while respecting the appropriate proprietary access periods). This will raise efficiency in the SRCs by avoiding repetition of the processing.

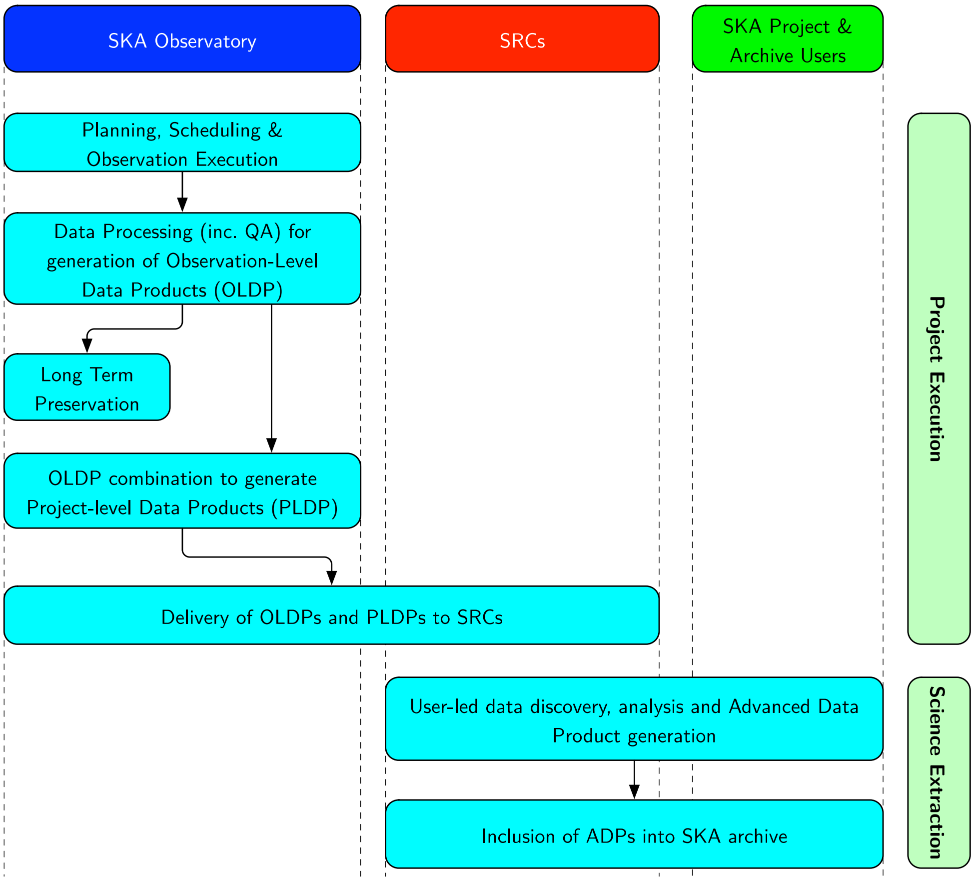

Figure 11: Swimlane diagram showing the responsibilities for the generation of science data products during the project execution and science extraction phases of a science project. The left lane depicts the Observatory's responsibilities, the middle lane those of the SRCs, and the right lane for the PIs and CoIs of SKA projects and general archive users. Observation-Level and Project-Level Data Products are generated by the Observatory, while Advanced Data Products are produced by users at the SRCs.

6.5.2 SKAO and user responsibilities for software and pipelines

The boundary between SKAO's responsibility for data products and the users' responsibility requires striking a balance between centralisation and the desire for SW quality and data traceability, and the ability to declare that the Observatory's responsibilities to a specific PI or KSP team have been achieved, against the somewhat competing need to encourage scientific freedom and innovation.

As the figure shows, the SKA has *responsibility* for data product generation up to the Project Level. However, though maintaining and running the software pipelines to generate the PLDPs from OLDPs will be the responsibility of the Observatory, the actual processing to generate these (for the projects that need it) will be undertaken within the SRCs. This is a core SKAO-facing function that the SRC network will provide. This extension of PLDP creation on top of SDP's OLDP generation is a relatively small change – it allows the Observatory to perform QA metrics on more complete data products, and of course, feed back difficulties and failures immediately to affect pipelines not just for combining OLDPs but also for their creation in the SDP. Since all PLDPs are in any case already delivered to the SRCs, users will also have access to those data products if they wish to combine OLDPs in other ways. This has the effect of reducing risk by bringing responsibility for PLDP generation within the SKAO's remit, without reducing opportunities for scientific innovation.

6.5.3 Data management model for SKAO and SRCs

SKAO will generate Project-Level Data Products in the SDPs. Once these are delivered to the SRCs the SDP sites will store copies of them in the Long Term Preservation (LTP) system, a high-latency data storage system existing only as a backup of the data products so that that can be re-delivered to SRCs if all copies in the SRC network are lost. In other words, the LTP system is a back-up of last resort and not an actively managed storage element in the network of SRCs. SKA has a responsibility to ensure that data products are preserved, forever, in the LTP which is independent of SRC activity – so for example, it will *not* be possible to delete items from the LTP on the grounds that there are copies in place in one or more SRCs.

Within the SRCs the management of data products can be more flexible. By agreeing to share the burden of data storage and access to users, SRCs can provide coverage of the whole SKA archive of Observatory and Advanced Data Products without requiring that each SRC must keep a full (and fully backed-up) copy of each data product. Instead there can be a global data management service that applies rules to data products or collections of data products and manages data transfer between SRCs in order to maintain adherence to the rules. The service can tag "spare" copies of data products for deletion (without necessarily performing the deletion) so that individual SRCs can clear space when resources become limited.

Using a global data management service to perform this function is essential to avoid confusion – SKAO's role in this will be to provide coordination (though Operations group personnel, see §6.4.8) and the necessary software to run the data management service as well as the hardware (e.g. servers) to maintain the catalogue of data product locations.

6.5.4 SKAO's Requirements on SRCs

The SKAO, working with regional representatives from across the SKA community (the SRC Coordination Group[12]), has developed a set of requirements to guide the development of SRC capability. These requirements relate to governance, the provision of a Science Archive, securing appropriate data storage capacity, accessibility and software tools, data processing capacity, and network connectivity.

Table 10 presents the key requirements on SRCs driven by the SKA's needs (see [RD19] for full details and description), though many are also necessary to enable users to interact with their data efficiently.

Table 10: SRC Requirements

ID	Name	Description
1	SRC designation	SRC designation will be awarded if individual prospective SRCs meet and maintain all the criteria set out in appropriate MoUs and Accreditation criteria. The ability of each SRC to meet its criteria, and the criteria themselves will be reviewed annually (TBC).
6	SRC Data policies	Each SRC will preserve and make available to users, the SKA Science Data Products, in adherence to SKAO data access policies and data security standards.
7	SRC Data Sharing	Each SRC will, when required, distribute the SKA Science Data Products to other SRCs.

[12] In 2019, the SRC Coordination Group was dissolved and a new body, the SRC Steering Committee, was convened.

12	Data product index	Collectively, the SRCs will maintain and provide access to an index of all Science Data Products (including Observatory Data Products and Advanced Data Products), capable of showing the location(s) of each one.
17	Common Environment	Each SRC shall support use of a common environment across all SRCs.
18	Common Software Tools	Each SRC shall maintain, at a minimum, a common set of software tools.
19	Science Gateway	The SRCs will host a single Science Gateway used by all SRC users, compliant with SKAO policies on User access interface.
20	External software	The SRCs will enable users to develop and run software in their sites.
23	Network monitoring	The SRCs will provide a system to regularly monitor the end-to-end performance of all network links.
24	Observatory data product ingest rate	Across the SRCs, the rate of ingest of SKA Observatory Data Products must match the rate at which they are dispatched. This is expected to be up to 100 Gbit/s per telescope site by 2025.
25	Data integrity	Each SRC will use data transfer protocols that ensure data integrity during data replication into the SRCs from the SKAO and between SRC sites.

6.5.5 Operational considerations

An operational SRC network must be able to continuously maintain both SKA- and User-facing functions – this means being ready to accept data pushed from the SKA Observatory, to allow SKAO to complete the data processing to provide Project-Level Data Products and the subsequent enabling of the users themselves to log into the systems and be given authenticated access to data and computing resources they need to pursue their science analyses.

Several areas of management are needed on various timescales. An SRC Coordination Committee (SCC), with representatives from each SRC and the SKAO will work together to:

Annually

- Oversee the pledging of SRC resources into the SKA-facing roles and for use-facing purposes. Interaction between the SCC and the SKA's resource allocation process will be required to ensure sufficient capacity to support the next cycle's science programme.
- Manage a roadmap for development of SRC-related technologies and pledging of (human) resources to enable this – for example, SRC collaboration tools, data management and transfer tools, improving best practice.

Ongoing

- Develop and maintain a long-term roadmap for altering data transfer, data storage and data processing capabilities of the SRC network in line with the prospective long-term science programmes of the SKA Observatory.

Quarterly:

- Agree priorities in development areas for subcommittees to work on.
- Track performance of SRCs against pledges, both for SKA-facing and user-facing activities and of the data transfer network links.
- Review data management policies to ensure appropriate quality of service (trading off performance and cost/capacity needs)

The SCC will be supported by an operations team of SKA and SRC staff, the SRC Operations Group (SOG), to implement the policies and priorities that have been agreed and provide the required monitoring and reporting capabilities to alert stakeholders to any difficulties. The SOG will ensure the continuous availability of the SRC network by:

- reporting to SCC the performance of SRCs against pledges, both for SKA-facing and user-facing activities and on the performance of the data transfer network links;
- updating data management policies to ensure appropriate quality of service (trading off performance and cost/capacity needs);
- maintaining a global data management service implementing the data management policies;
- monitoring the ability of each site storage element to accept data products from SKA sites;
- monitoring the ability of appropriate sites to accept batch processing jobs and to provide interactive sessions for users; and
- monitoring the network link availability and performance (e.g. through continuous monitoring of links in use and in liaison with network providers).

The SOG will report any problems to the SRCs concerned through a formal ticketing system. It will be the responsibility of each SRC to perform its own internal operational procedures to ensure its availability to the SRC network is in agreement with the terms in its MoU with the SKAO and the terms & conditions of its accreditation as an SRC.

The SKA Operations group will manage delivery of ODPs to specific SRC sites.

6.5.6 Pledging and accounting

At the time of writing, a model for how SRCs will be operated and governed is under active development with good agreement that resources, and not financial contributions, should be pledged by each SRC.

6.5.6.1 Hardware considerations

A mechanism wherein each SRC puts forward the data storage and processing capability it can offer for SKA-related use over the medium term (e.g. two years) and longer will be needed. These pledges would be fed into the proposal review process to ensure that the overall SRC resource is not overstretched by the projects planned for the coming observing cycles.

A longer term (greater than 2 years) view of the likely available resources will be used to understand how especially demanding, large scale, projects (e.g. KSPs with large output data rates) can be planned. SRC resource predictions and feedback from the science community will be required to ensure that long term SRC resource planning matches the community needs, and that, conversely, the SKA user community plans experiments that are appropriate within SRC resource and funding caps.

6.5.6.2 Software Development considerations

Each SRC will be different and this heterogeneity must be embraced. However, there will be aspects of user- (and SKAO-) facing software necessary to ensure interoperability between sites. The development work for this software should be centrally managed, enabling much greater efficiencies to be achieved so that each SRC's software team can benefit from the software developed by other teams. This model of in-kind contributions towards an evolving collective effort has been working very successfully in the SKA's main software development track during the project's pre-construction phase – making good use of globally distributed software teams with a broad range of differing expertise areas to contribute to the open-source SKA software code base[13]. The level of in-kind support will need to be pledged and road mapped in a similar way to the hardware in order to ensure that the work plan is sustainable, but possibly starting much sooner than hardware pledges. There are already active SRC software development projects happening in several locations – coordinating these efforts where appropriate would give better alignment.

6.5.6.3 Human Capital considerations

In addition to hardware and enabling software, SRCs or national SRC offices will need to provide users with access to experts with knowledge of how to use the systems effectively and possibly to give scientific expertise in the interpretation of SKA data products. Such expert staff will need to sit within the SRC organisations, but not necessarily co-located with the SRC infrastructure. Operational support to keep each SRC's infrastructure running smoothly is essential for the SRC to meet its accreditation requirements, however the extent of support for more user-facing functions will be determined by each country according to its needs and capacity.

Through use of a single identity management system across all SRCs, each user will have a single unique ID. The SRC network will be able to monitor use of its resources by users identified by SKA project ID, Member affiliation or any other relevant identified pertinent for accounting purposes. This will enable the SOG and SCC to monitor and check use against agreed limits, compare national fractions with overall pledges and adjust the future roadmap and resource prediction tools as necessary.

6.6 Engineering Operations

Engineering Operations comprises those activities necessary for the maintenance of the SKA telescopes and their infrastructure in the host countries. Engineering Operations will also be required to support development activities for the SKA telescopes.

The Engineering policy will be provided by GHQ and applied by separate engineering groups for each telescope site. These groups will include:

- Engineering management to ensure that the Engineering policy is applied and coordinated;
- Technical staff to carry out normal preventative maintenance;
- Engineering and technical staff to carry out specific repairs and modifications;
- Systems engineering to manage configuration and performance; and
- Software engineers to manage and maintain the software.

[13] see http://developer.skatelescope.org/

6.6.1 Availability

The scientific success of the SKA requires that the telescopes be available for science observations for as much of the time as possible within the constraint of available resources. The relevant availability definitions are:

Operationally Capable:	An SKA telescope is defined to be operationally capable when it can perform astronomical observations, including signal processing and data reduction, with at least 95% of its collecting area[14], irrespective of the location of the non-operational receptors.
Availability:	Availability is the probability that a system is operating to specification at any point in time under stated conditions. It is a measure of how often an item fails (reliability) and how quickly it can be restored to operation (maintainability).
Inherent Availability:	Inherent availability is the probability that a system is operationally capable at any point in time when used in an ideal support environment, i.e., one in which repair commences instantaneously upon failure. It is a measure of how easy it is for an item to be repaired or replaced.
Operational Availability:	Operational availability is the probability that a system is operationally capable at any point in time when used in a realistic support environment, i.e., one in which repair cannot commence until sometime after the failure has occurred. It is a measure of reliability and maintainability, and the response time of the support system.

Engineering analysis indicates that the SKA telescopes should offer an inherent availability of > 95%. From the perspective of observatory operations, however, operational availability is the relevant figure of merit. Both telescopes are required to have an operational availability of at least 95%.

Achieving this ambitious level of availability requires:

a) that all telescope systems (including both hardware and software) be designed for reliability and maintainability commensurate with this requirement. Allocation of inherent availability to the telescope elements is in [RD7]; and
b) that the support system be designed to provide a response time commensurate with this requirement. The Support Concept is described in [RD8].

In addition, the scale of the SKA demands an industrial level of logistics engineering: the Integrated Logistics Support Plan is at [RD9].

The definitions and requirements given above are based on probability and are appropriate for engineering design purposes. In practice, however, the actual availability will be monitored *post-facto*. The requirement in this case shall be interpreted to refer to the average operational availability achieved over any calendar year.

The availability definition given above is intended to be generally applicable. The SKA design, however, is extremely flexible and allows for multiple configurations. The availability definition must therefore be tailored for application in some specific situations.

[14] This value is strictly for the purpose of defining availability. It is clearly possible to carry out science observations with less than 95% of the full array.

6.6.2 Technical operations

Technical operations at the telescope sites are envisaged to take place in a similar way at the SKA1-LOW and SKA1-MID sites. The following activities are considered within the scope of technical operations.

System engineering and performance analysis	Each subsystem of the SKA provides real-time metrology that monitors performance and status of its LRU components during operations. This monitoring generates diagnostics to track the performance of the global system.
Troubleshooting and corrective maintenance	In spite of the efforts to provide a fully functioning and reliable system, we should anticipate the continuous need of intervention, in particular for the first years of operation. Trained and experienced engineers will keep the telescopes, arrays and instruments functional. It is necessary that an understanding of root causes of failures is established. This will require the presence of highly skilled Mechanical, Electronic and Software engineers with a deep know-how and understanding of the systems.
Instrument/software handling	New SKA instrumentation, equipment and software will be assembled, integrated and verified before shipment to the site according to their respective statement of works. The process of preparation on site will be organized in the following steps: • Re-integration (in case it cannot be shipped fully assembled) and (re-)testing at the EOC; • Integration on site or, for SKA1-MID, on the dishes; • On-site commissioning; and • Acceptance (see §6.9.2). Handling and transportation from the integration facility to its installed location shall occur with the minimum number of lifting processes (if appropriate). This is to limit one of the highest risks of such operation. The hand over process, as well as acceptance by the Telescope Director will follow a defined procedure. Any assembly will be carried out in the EOC (or by the OEM in their integration facility) to reduce the time necessary at the telescope sites, thus limiting interference with routine telescope operations, as well as minimising RFI. Once an instrument or component has been accepted by the Observatory it shall be under strict Configuration Control (to include hardware, software, documentation, manuals, drawings, etc.) and the Engineering Operations teams will be responsible for its performance, maintenance and configuration control.
Instrument support	There will be the continuous need of specialized crews of technicians and engineers to maintain SKA telescopes and their instrumentation. They will also support the installation of new instruments and

equipment and work together with instrument scientists to debug problems arising.

6.6.3 Maintenance strategy

A major challenge for any observatory is to achieve the optimal balance between science operations and engineering operations. This tension arises because maintenance activities will, in general, compromise availability and therefore scientific productivity, in the short term. Maintenance is nevertheless essential, not only to repair faults so that science observations can proceed, but also to ensure the long-term health of the telescope facilities. The SKA poses unique challenges in this respect due to its unprecedented scale. Obtaining the appropriate balance will be an evolutionary process.

Availability of the SKA telescopes will be enabled by design reliability and maintainability characteristics and a structured programme of preventive and corrective maintenance. Telescope maintenance will use engineering subarrays. In order to comply with the operational availability requirements science will generally proceed on one or more science subarrays in parallel with maintenance. The maintenance plan will describe both preventive maintenance and corrective maintenance, varying from system to system, depending on the known failure modes. The strategy is informed by a standard Failure Modes, Effects and Criticality Analysis (FMECA) of each telescope system.

Repair work in the field will be minimised. Maintenance of stations and dishes will be carried out at various locations in the array to minimise the impact on the telescope's science programme. All on-site telescope systems are designed to make maximal use of Line Replaceable Units (LRUs). The normal response, in the event of a fault, will be to replace the faulty unit with a working spare, and to return the faulty unit for repair or replacement off site. An inventory of working spares must therefore be maintained.

Work orders will be created for all repair and scheduled maintenance activities, including statutory and safety management activities. These work orders will be allocated to maintenance personnel. The maintenance management software (§6.6.10) will track resource usage, to ensure that adequate levels of support resources, personnel and spares are available. It will also assist to ensure that the observatory does not experience downtime from failures or unnecessary expenditure on inefficient maintenance procedures. All software versions will be identified and reported against the maintenance structure.

In order to minimise the number of staff needed at each telescope site, and to run operations and maintenance efficiently, a remote diagnostic capability is essential (§6.6.4). Each subsystem of the SKA provides real-time metrology that monitors performance and status during operations. The subsystem monitoring forms an integral part of operations and, in this way, every observation is also an engineering test of the system. Apart from the subsystem level monitoring, daily logging activities generate useful diagnostics for the performance of the global system. Monitoring of the overall metrics from the telescope forms a key task of the operations team.

Given the scale of the SKA telescopes, in terms of both size and geographical distribution, it is not envisaged that the entire array will be taken down for maintenance; rather, maintenance work on the front-end systems will, in general, take place whilst observations are in progress. Individual stations or dishes, for example, will be removed from service as required and assigned to an engineering subarray (§6.4.2.7) for work to be carried out. It will be the responsibility of the Telescope Operator to manage the switching of individual components in and out of service. Single-point failures and software updates, however, may require taking an entire telescope out of service for a period.

Software updates shall occur with little to no downtime. Downtime for updating software and/or preventive re-initialization shall comply with the operational availability requirement.

Given the scale of the two SKA telescopes and the level of redundancy, it is not anticipated that there will be designated maintenance windows during the week when each telescope will not be available for science.

The approaches to RFI management, safety management and security management will be structured to allow sufficient access for maintaining the SKA telescopes' operational availability.

Repair activities by the OEM and Service Level Agreements (SLAs) will be managed by Operations personnel. Any regular work orders/job cards will automatically be sent to the OEM or Service Provider to notify them of the work requirements.

6.6.4 Failure detection and identification

An objective for the SKA telescope design is to enable prompt restoration after a component failure. Identifying the failed replaceable unit is critical to minimising telescope downtime. A telescope health monitoring diagnostic system will be implemented and will enable:

- confirmation of telescope health for context of use;
- detection of failures;
- identification of operating fault cause to the level required for repair;
- identification of fault cause to the level required for repair of LRUs in off-site facilities;
- verification of repairs, prior to returning to service;
- control of health test/diagnosis risk to personnel, the telescope or environment;
- confirmation of health monitoring functionality, as a basis for confidence in the reported health status; and
- cost-effective telescope operation and support.

Diagnostic monitoring will be automated to enable short response times. The Telescope Manager will provide the operator with on-line Telescope status information to identify failures. This will be in the form of alarms and monitored sensor data aggregated from Local Monitoring & Controls (LMCs). The fault detection and diagnostic performance will enable compliance with the operational availability down-time requirement. In the event of a failure, the objective is for the diagnostic system to automatically identify the fault to the level of the LRU requiring repair.

Telescope health monitoring will provide remote access diagnostic capabilities. Engineering Operations personnel will have access to remote diagnosis features so that maintenance and repair activities can be planned and carried out efficiently. The Telescope Operator and engineering staff will regularly monitor the system's health indicators, logs and condition, with the ability of remote interrogation of sensor values as required. Once resources are placed in an engineering subarray, control of those resources may be ceded to local control by the operator to allow maintenance staff to carry out testing, maintenance or corrective procedures.

Testability requirements analysis will identify and prioritise failure modes to be detected and identified. Telescope health test performance requirements will be developed at system and equipment level and will be traceable to design Failure Modes Effects and Criticality Analysis (FMECA). Telescope health test approaches will allow margin for adjustment consistent with the failure characteristics of the telescopes. The SKA Operational Testability Standard (to be written) will describe the health test performance requirements and constraints.

Telescope condition and failure behaviour will be tracked to ensure alignment between the Telescope monitoring performance and the Telescope operational behaviour. Monitoring will be aligned mainly by way of configuring logging, status processing and aggregation in the LMCs and Telescope Manager (TM). This will be an ongoing process through construction and into Telescope operations.

The SKA Failure Recording Analysis and Corrective Action System (FRACAS)[15] will be operational from the start of construction to capture failure data and assess diagnostic performance. The Engineering Management System (EMS) interfaces with TM for equipment maintenance-related operating parameter and status information (see §6.6.10). Telescope FMECA data will be continuously updated in the EMS, as references for fault-finding, status aggregation and condition-based maintenance.

The telescope FMECA and health test configuration data will form part of the testability baseline deliverable for the Operational Baseline. Testability baselines shall be maintained during the life cycle to enable effective ongoing operation and engineering support.

6.6.5 Personnel and training

The SKA telescopes will be managed, operated and supported by personnel with suitable qualifications and experience. SKA personnel profiles and training requirements will take account of statutory certification requirements applicable to the telescope operating and maintenance roles.

The maintenance teams will be composed of technical persons that are skilled and qualified with appropriate technical training. They will be responsible for corrective and preventive maintenance and also involved during operations to regularly monitor the system health indicators and logs. When authorised by the Telescope Operator, the maintenance team will be able to take manual control of resources for the purposes of testing.

A guiding principle has been to design the system to minimise the number of operational staff required on the telescope sites to maintain them. This strategy is analysed as part of the Logistic Support Analysis (see §6.6.6) to ensure that only small teams will be required on the sites.

Personnel will be equipped with skills to competently perform SKA operating and maintenance task requirements. Trade-qualified maintenance personnel will receive SKA Subject Training to be competent for SKA maintenance tasks. Training shall include site policies and practices relevant to the scope of work, including training of industry support personnel accessing the site.

Training capabilities for the SKA will be formalised as an ongoing capability for the Observatory to maintain aptitudes and attitudes required. Personnel trained and suitably experienced during construction and commissioning will play a key role in ongoing training delivery. Training packs and instructional capabilities will be qualified as part of establishing the SKA operational baseline.

6.6.6 Maintenance management and implementation

A simulation model for SKA Engineering operations has been developed based on data in the Support Database. The model simulates 10 years of operation and uses Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) values that were supplied by design consortia for their element CDRs during the pre-construction phase of the SKA project. The model recognises the single-point failures with each element and their sub-systems. The simulation was used to validate the SKA Support Concept [RD8], the strategy and implementation of the maintenance plan for each of the SKA telescopes.

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[15] FRACAS is a capability of the SKAO Engineering Management System (EMS).

As with any model, there are a number of assumption and caveats. The principal assumptions are:

- A working day is 8-hours, spanning 0800-1600;
- A 5-day working week, Monday to Friday;
- A total of 220 workdays are available per year[16], to account for annual leave, holidays and other absences; and
- Travel times to and from the site are assumed and accounted for, including the time to travel to and along the spiral arms.

It should be noted that there is no accommodation for "disaster scenarios", e.g. an extended period when the telescope site is not reachable by staff as a result of a site after a severe storm. The model will therefore overestimate the telescope availability.

6.6.6.1 Definitions: Preventative and Corrective Maintenance

The following definitions apply where it comes to the maintenance of the telescope resources.

Preventative/Scheduled Maintenance	Maintenance that requires the resource or component/element (e.g. antenna, station, RPF, maser) to be unavailable for observing. Maintenance can be scheduled during science observing on the rest of the telescope, helping to maintain the availability of the telescope.
Corrective Maintenance	The resource is not available for science observations due to critical system failures and repairs. Depending on the nature and criticality of the element, the telescope may not be available for observing.

6.6.6.2 Working patterns

Given the different geographical locations of the two SKA telescopes, the working patterns for the two will differ. This is mostly driven by the fact that the location of the EOC for SKA1-LOW is in Geraldton, some 350 km from the site at the Murchison Radio-astronomy Observatory (MRO), while the EOC for SKA1-MID is in Klerefontein, a comparatively closer 70-km from the site and close to the town of Carnarvon. We anticipate that most of the technical staff, whether working on the site or at the EOC, will reside in Geraldton (for SKA1-LOW) or Carnarvon (for SKA1-MID).

For SKA1-LOW, we anticipate replicating the existing working pattern of CSIRO staff operating the MRO and the ASKAP telescope. SKA engineering operations staff will fly in to the MRO on Monday morning from Geraldton, stay at the Boolardy Accommodation Facility during the week before flying back to Geraldton on Friday afternoon. Driving to and from the site for transporting larger and heavier equipment, for instance, is possible but takes considerably longer. It is anticipated that a 15-18 week maintenance cycle will be employed wherein each of the 36 Remote Processing Facilities (RPFs), including the 6 stations attached to each RPF, will be visited for preventative maintenance work. Similar work in the core and Central Processing Facility (CPF) will be continuous during this period.

For SKA1-MID, site maintenance staff will report to the EOC on each day at 8am, review the work and job cards for the day before being bussed out to the site, returning to the EOC at around 4pm. A 12-month dish maintenance cycle is assumed.

Table 11 gives some high-level examples of preventative maintenance work that will be carried out for the SKA1-LOW and SKA1-MID telescopes. By estimating the time for these and other maintenance

[16] We have adopted these values based on the experience of both CSIRO and SARAO.

or repair tasks, it is possible to model the size of workforce that is needed to support the operations of the SKA telescopes, and to keep the telescopes within the 95% availability requirement.

Table 11: Examples of preventative maintenance work

Task	Telescope	Activity
RPF and core maintenance cycle	SKA1-LOW	Regular inspect and clean service following a regular preventative maintenance cycle
Dish maintenance	SKA1-MID	Regular inspect and clean service following a regular preventative maintenance cycle
Power and Electrical inspection and maintenance	BOTH	Power cable inspections, transformer services, breaker tests, UPS batteries, diesel generator and DRUPS service and test, load tests, gridline tests and maintenance, PV plant maintenance and cleaning
HVAC	BOTH	Monthly HVAC inspection and cleaning
UTC Calibration	BOTH	Annual calibration tests

The model also takes into account the travel time required to undertake a particular task. For the different roles that have been identified to support the operations and maintenance of each SKA telescope (see Table 12 and Table 14 below), the travel time makes up a significant fraction of the available work time given the size of each array and the distributed nature of the operational model (e.g. the distance between the EOC and the site, and between the core and the spiral arms).

6.6.7 Maintenance roles and staffing – SKA1-LOW

A total of 15 separate roles have been identified for the support of operations and maintenance of the SKA1-LOW telescope (not including the management roles). Of these, 12 are technical roles. Role descriptions and staffing numbers are provided in Table 12 and work patterns are illustrated in Figure 12. At any one time, most of the staff are located at the EOC, minimising the number of staff at the telescope site and their RFI impact. Each week, starting on a Monday, a team of approximately 8-15 people will fly into site to begin working on the scheduled maintenance and critical repairs for that week, residing at the Boolardy Accommodation Facility until their return to Geraldton on Friday afternoon. Of course, this number will vary depending on the nature and volume of work required at any point in time.

Work will be distributed between the core and the spiral arms. For the most part, the work will be based on an ‘Inspect and Replace’ basis, so that if anything cannot be quickly and easily fixed *in situ*, it is replaced with an LRU (or removed from service until which time it can be) and the faulty component returned to EOC for further fault diagnosis and repair. Prior identification of faulty components/LRUs is necessary so that the maintenance team can take the appropriate spare with them. The fault logging and EMS system will be able to provide this information.

The support model for the maintenance of the telescope is such that each of the 36 RPFs are visited over a 15-18 week cycle so that, on average, each RPF is visited and inspected approximately 3 times per year. Meanwhile, work in the core is performed on a station-to-station basis and is a continuous, on-going process.

The maintenance teams scheduled to fly-in and fly-out of the telescope site will have to be carefully managed, along with the work scheduled to be undertaken. This work needs to be selected and matched to the skills of the technical and engineering staff available and as described in Table 12 (see also Figure 13). The “multi-skilling” and cross-training of technical staff will be important to ensure this model is effective.

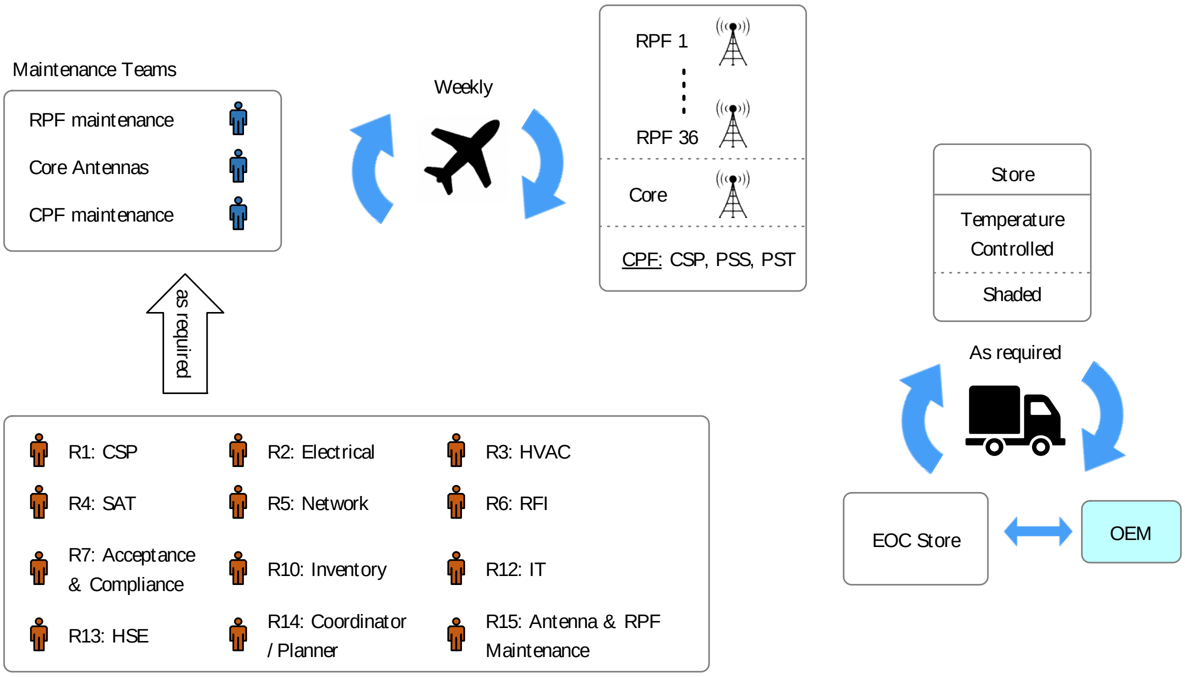

Figure 12: Framework model of the working pattern for engineering operations and maintenance of the SKA1-LOW telescope. Staff roles undertaking work at the telescope site (blue) and at the EOC in Geraldton (red) are shown. The maintenance teams working on site are selected from the individual teams. Role descriptions, and the number of staff in each role, are given in Table 12. Roles R8, R9 and R11 are non-technical roles and not shown here.

Emergency/out-of-hours work (i.e. late evenings, weekends) may be required on occasion for problems that cannot be dealt with remotely by the telescope operator. During the week, late-night emergencies may be dealt with by SKA staff resident at the Boolardy Accommodation Facility (with possible knock-on effects on their work schedule the next day due to lost sleep). Given the distance of the EOC/Geraldton from the site, weekend emergencies will be more challenging to accommodate. A rota of staff can be available on call to go to site to fix critical problems that arise at these times, but they will have to be the kind of problems that present a safety risk to personnel or the telescope if not dealt with relatively quickly. In some cases, it may be that if the problem persists but does not pose a safety risk, science time may be lost.

Table 12: Role descriptions for maintenance of SKA1-LOW, including number of staff in each role. Engineering level staff are identified by the asterisk

Role	Function	Description	Number
Maintenance Teams	RPF preventative & corrective maintenance	Inspect/Clean/Repair and replacement of station components. Replace LRUs, power, cooling, cabling, stations, networks, boards, cooling, antenna pyramid, antenna, modules, cabling, general maintenance	
	Antenna Core preventative & corrective maintenance		
	CPF preventative & corrective maintenance	Replace LRUs, network components, boards, power supplies, cooling, masers, cabling, general maintenance	

Role	Function	Description	Number
R1	CSP and CPF hardware maintenance	Replace: CBF/PSS/PST Network switches and cards, MCCS units, servers, Rack cooling components, Muxponders	2 + 1*
R2	Electrical	Electrical repairs and inspections	3 + 1*
R3	HVAC	HVAC repairs and inspections	2
R4	SAT	Replace: SAT LRUs	1*
R5	Networks	Replace: Network switches, switches, cable repair NMGR, network set up and monitoring	2 + 1*
R6	RFI	Testing for RFI compliance of incoming or repaired items. RFI test and monitoring campaigns on site.	4 + 1*
R7	Acceptance & Compliance	Acceptance testing of new and repaired equipment	2
R8	Purchasing	Purchasing spare parts and consumables	1
R9	Contract management	Management of SLAs and external contracts	1
R10	Inventory and logistics	Inventory and stores management	2
R11	Admin support	Administration support for management team and EOC staff, including HR	2
R12	IT Support	IT support services for EOC and CPF	2
R13	HSE Officer	Monitoring HSE on site and at EOC	1
R14	Coordinator/Planner	Logistics planning for personnel on site	1
R15	Antenna & RPF Maintenance Technicians	Maintenance of antenna stations and RPFs	14
		TOTAL	**44**

In addition to the site maintenance teams there are other roles that support the engineering operations and maintenance of the SKA1-LOW telescope. These are identified in Table 12. These positions are either technicians, engineers (identified by the asterisk), or serve as part of the administration support team. Senior management positions are also required in order to manage the site and EOC as well as to direct the work. The role descriptions for these are given in Table 13, with an assumed group and management structure shown in Figure 13. All except MR4 need to be engineers. The SKA-LOW Head of Engineering Operations will report to the SKA-LOW Deputy Telescope Director. The HSE Manager will report directly to the SKA-LOW Telescope Director.

Table 13: Role descriptions for management roles for SKA1-LOW Telescope operations and maintenance

Role	Function	Description	Number
MR1	SKA-LOW Head of Engineering Operations	Management of Site, Facilities and Engineering personnel on telescope site and at the EOC. Reports to the Deputy Telescope Director.	1
MR2	Stores Manager	Asset management and inventory. Planning of work carried out in EOC for quality assurance, acceptance and compliance of equipment for site.	1
MR3	Telescope Engineering Manager	Management and planning of maintenance work on site and at EOC, quality assurance, responding to and managing related faults	1

Role	Function	Description	Number
MR4	Financial and Administration Manager	Management of budgets and administration for the EOC	1
MR5	HSE Manager	Ensure that all HSE standards are met and followed. Training. Reports directly to the Telescope Director.	1
		TOTAL	**5**

Altogether, in order to maintain and run the engineering operations and maintenance of the SKA1-LOW telescope requires a total staff of 49. All will be based at the EOC and will only travel to the site as and when required or scheduled.

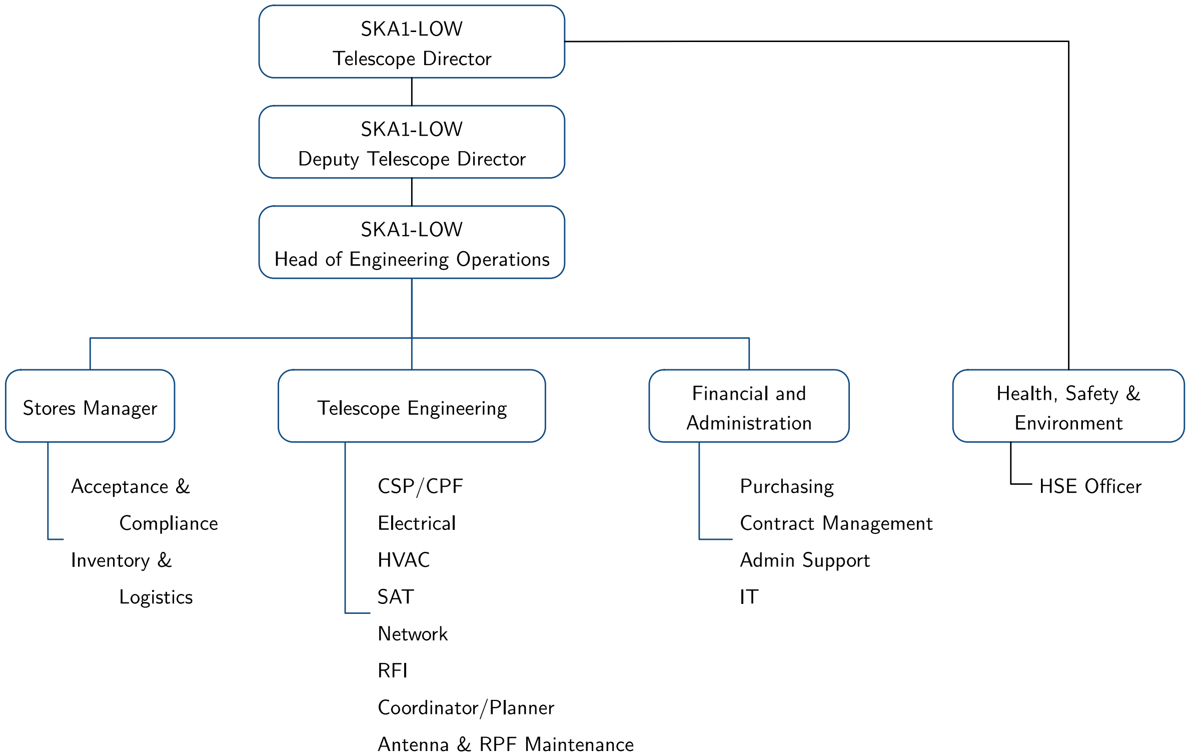

Figure 13: Management structure for running the operations and maintenance for the SKA1-LOW telescope from the EOC in Geraldton. The Telescope Director and Deputy Telescope Director will normally be located at the SOC in Perth.

6.6.7.1 SKA1-LOW station availability

The result of the 10-yr simulation is an indication of the probability of how many stations are available for science, and how many are unavailable and assigned to an engineering subarray for maintenance (whether preventative or corrective). Figure 14 shows the resulting probability density function from the SKA1-LOW model, for the staffing numbers in Table 12. The chart shows the probability that, at any given time, a given number of stations will not be available for science operations. Therefore, we might expect that on average 1-2 stations will be unavailable at any one time.

It is not just the number of unavailable stations that is important but also the location of those stations in the array and how the science might thus be impacted. For instance, an unavailable station located in the core will have lower negative impact on the science than if that station were located along a spiral arm. As such, in planning maintenance, priority will be given to those stations located along the spiral arms in order to bring them back into operation as soon as possible.

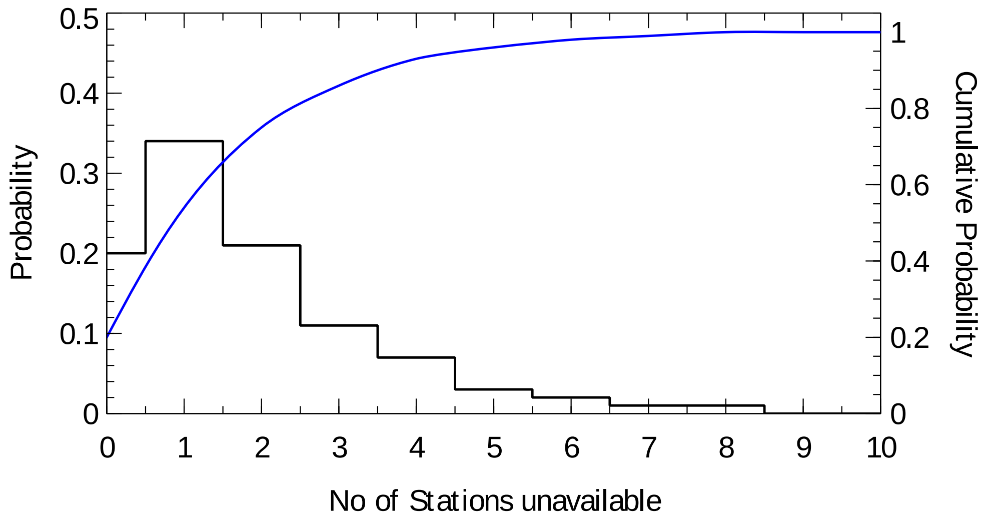

Figure 14: Probability (left axis, red shading) that a number of stations (x axis) in the SKA1-Low telescope are unavailable for science operations, on average, at any given time. The cumulative probability (right axis, blue curve) is also shown.

Note that this is a steady state model and gives an indication of the availability that results from the staffing levels assumed (predicated by the assumptions detailed in §6.6.6). Clearly, adjusting the working pattern or the staffing levels will change the availability results in Figure 14. If for any reason a backlog builds and an increasing number of stations become unavailable, then it will not be possible to reduce the backlog with the same maintenance team – they can only work on a set number of RPFs and stations per week. At such times, or when the backlog grows beyond a certain trigger point (e.g. approaching the 95% availability metric), more staff will be mobilised from the existing workforce (i.e. from the other technical roles described in Table 12, or from elsewhere in the Observatory) to repair and deliver stations back into service.

6.6.8 Maintenance roles and staffing – SKA1-MID

A total of 17 separate roles have been identified for the support of operations and maintenance of the SKA1-MID telescope (not including management roles). Of these, 14 are technical roles. Role descriptions and staffing numbers are provided in Table 14 and work patterns are illustrated in Figure 15.

At any one time, most of the staff will be at the EOC, minimising the number of staff at the telescope site and their RFI impact. Each day, a team of approximately 8-15 people will drive to the telescope site from the EOC at Klerefontein to begin working on scheduled maintenance and critical repairs. Of course, this number will vary depending on the nature and volume of work required at any point in time. Work will be distributed between the core and the spiral arms. For the most part, the work will be based on an 'Inspect and Replace' basis, so that if anything cannot be simply fixed *in situ*, it is replaced with an LRU (or removed from service until which time it can be) and the faulty component returned to EOC for further fault diagnosis and repair. Prior identification of faulty components/LRUs is necessary so that the appropriate spare can travel with the maintenance team. The fault logging and EMS system will provide this information.

Maintenance teams working on site undertake preventative and corrective maintenance of dishes in the core and along the spiral arms. The support model is built so that each dish is visited at least once every 12 months. There may be the occasional need for larger teams of technical and engineering staff to travel to site to work on specific problems on specific components/elements within the dishes or the CPF. Generally, there will be a sizable team based at the EOC working on other duties (such as testing or repairing faulty equipment).

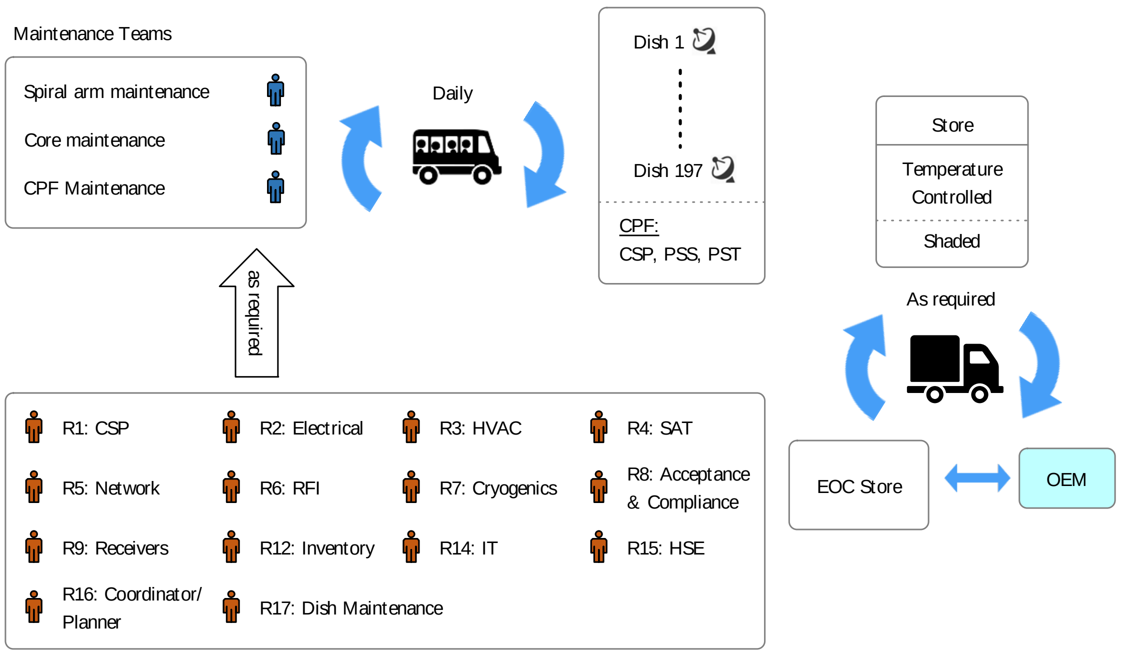

Figure 15: Framework model of the working pattern for engineering operations and maintenance at the SKA1-MID telescope. Staff roles undertaking work at the telescope site (blue) and at the EOC in Klerefontein (red) are shown, with the different roles needed to support the maintenance activities indicated. Role descriptions, and the number of staff in each role are given in Table 14. Roles R10, R11 and R13 are non-technical roles and not shown here.

Emergency/out-of-hours work (i.e. late evenings, weekends) may be required on occasion. A rota of staff will be available on call to go to site to fix critical problems that arise during these periods and that cannot be dealt with remotely by the telescope operator. The kind of problems envisaged are those that may present a safety risk to the telescope or personnel if not dealt with relatively quickly, or that are adversely impacting the science programme.

In addition to the site maintenance teams, there are other roles to support the engineering operations and maintenance of the SKA1-MID telescope. These are identified in Table 14, describing either technicians, engineers (identified by the asterisk), or as part of the administration support team. Senior management positions are given in Table 15. The assumed management structure is shown in Figure 16. All except MR4 need to be engineers. The SKA1-MID Head of Engineering Operations will report to the SKA-MID Deputy Telescope Director. The HSE Manager will report directly to the SKA-MID Telescope Director.

Table 14: Role descriptions for maintenance and support of SKA1-MID, including number of staff in each role

Role	Function	Description	Number
Maintenance Teams	Spiral arm preventative & corrective maintenance	Inspect/Clean/Repair and replacement of dish components. Replace LRUs, power, cooling, cabling, networks, boards, cooling, cryogenics, modules, cabling, general maintenance	
	Core preventative & corrective maintenance		

Role	Function	Description	Number
	CPF preventative & corrective maintenance	Replace LRUs, network components, boards, power supplies, cooling, masers, cabling, general maintenance.	
R1	CSP and CPF hardware maintenance	Replace: CBF/PSS/PST Network switches and cards, servers, Rack cooling components, Muxponders	2 + 1*
R2	Electrical	Electrical repairs and inspections	2 + 1*
R3	HVAC	HVAC repairs and inspections	2
R4	SAT	Replace: SAT LRUs	1*
R5	Networks	Replace: Network switches, switches, cable repair NMGR, network set up and monitoring	2 + 1*
R6	RFI	Testing for RFI compliance of incoming or repaired items. RFI test and monitoring campaigns on site.	2 + 1*
R7	Cryogenics	Repair and testing of Cryogenic cooling equipment, including Helium systems	4 + 1*
R8	Acceptance & Compliance	Acceptance testing of new and repaired equipment	2
R9	Receivers	Repair, maintenance and functional testing of receiver equipment	3 + 1*
R10	Purchasing	Purchasing spare parts and consumables	1
R11	Contract management	Management of SLAs and external contracts	1
R12	Inventory and logistics	Inventory and stores management	2
R13	Admin support	Administration support for management team and EOC staff, including HR	2
R14	IT Support	IT support for EOC and CPF	2
R15	HSE Officer	Monitoring HSE on site and at EOC	2
R16	Coordinator/Planner	Logistics planning for personnel on site	1
R17	Dish Maintenance	Maintenance of Dishes	16 + 1*
		TOTAL	**54**

Table 15: Role descriptions for management roles for SKA1-MID Telescope operations and maintenance

Role	Function	Description	Number
MR1	SKA-MID Head of Engineering Operations	Management of Site, Facilities and Engineering personnel on site and at the EOC. Reports to the Deputy Telescope Director.	1
MR2	Stores Manager	Asset management and inventory. Planning of work carried out in EOC for quality assurance, acceptance and compliance of equipment for site.	1
MR3	Telescope Engineering Manager	Management and planning of maintenance work on site and at EOC, quality assurance, responding to and managing faults.	1
MR4	Financial and Administration Manager	Management of budgets and administration of the EOC.	1

MR5	HSE Manager	Ensure that all HSE standards are met and followed. Training. Reports to the Telescope Director.	1
		TOTAL	**5**

Altogether, in order to maintain and run the engineering operations and maintenance of the SKA1-MID telescope requires a total staff of 59. All will be based at the EOC and will only travel to the site as and when required or scheduled.

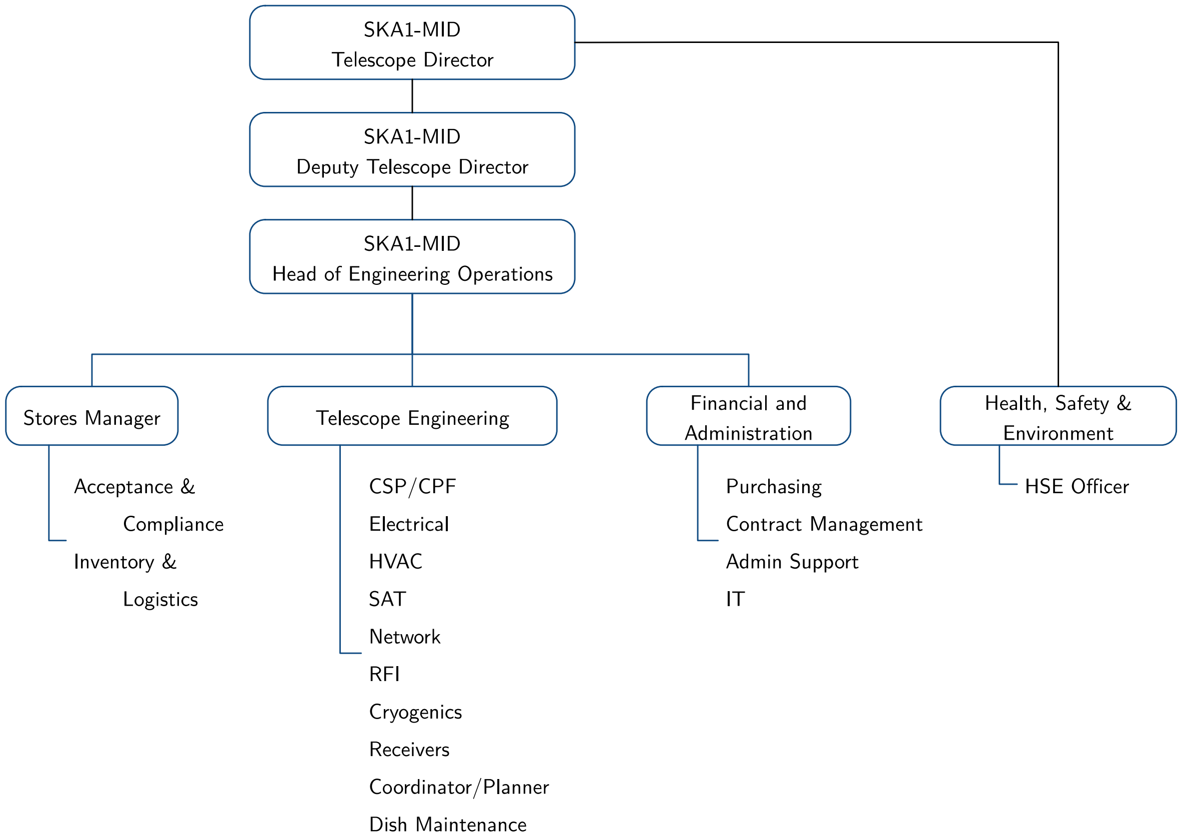

Figure 16: Management structure for running the operations and maintenance for the SKA1-MID telescope from the EOC in Klerefontein. The Telescope Director and Deputy Telescope Director will normally be located at the SOC in Cape Town.

6.6.8.1 SKA1-MID dish availability

The result of the 10-yr simulation is an indication of the probability of how many dishes are available for science, and how many are unavailable and assigned to an engineering subarray for maintenance (whether preventative or corrective). Figure 17 shows the resulting probability density function from the SKA1-MID model, for the staffing numbers in Table 14. The chart shows the probability that, at any given time, a given number of dishes will not be available for science operations. Therefore, we might expect that on average 2-3 stations will be unavailable at any one time.

Similar to SKA1-LOW, the location of the unavailable dishes is important to consider as this may impact the science programme. Priority will be given to those dishes located along the spiral arms in order to bring them back into operation as soon as possible.

Note that this is a steady state model giving a good indication of the staffing levels required (predicated by the assumptions detailed in §6.6.6). Clearly, adjusting the working pattern or the staffing levels will change the availability curve in Figure 17. If for any reason a backlog builds and an increasing number of dishes become unavailable, then it will not be possible to reduce the backlog with the same maintenance team – they can only work on a set number of dishes per week. At such times, or when the backlog grows beyond a certain trigger point (e.g. approaching the 95% availability metric), then more staff will be mobilised from the existing workforce (i.e. from the other technical roles described in Table 14 or elsewhere within the Observatory) to repair and deliver dishes back into service.

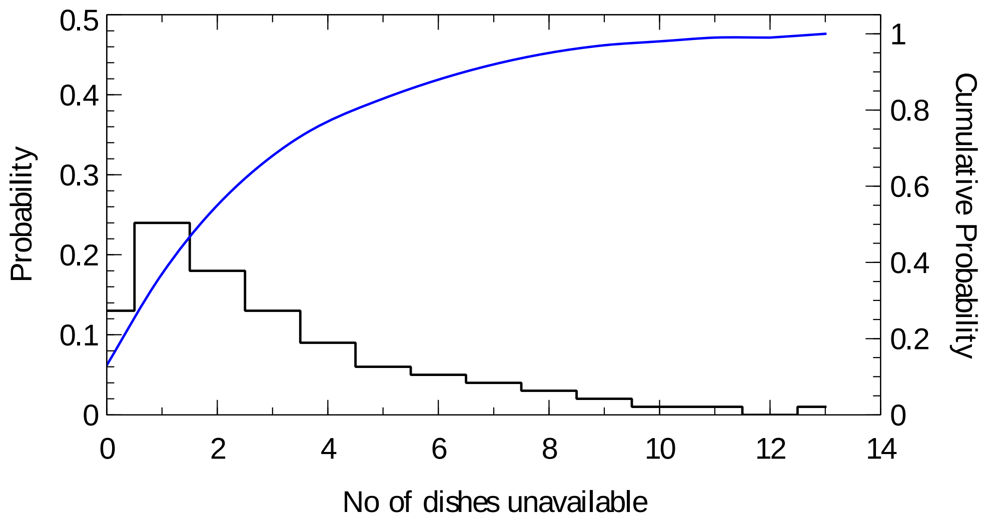

Figure 17: Probability (left axis, red shading) that a number of dishes (x axis) in the SKA1-MID telescope (for both MeerKAT and SKA1 dishes) are unavailable for science operations, on average, at any given time. The cumulative probability (right axis, blue curve) is also shown.

6.6.9 Maintenance contracting, warranty and service level agreements (SLAs)

All items delivered to the SKA Observatory shall be supported by a supplier warranty. Warranty conditions shall be agreed, accounting for storage at SKA facilities, handling, application and support context and environment. Parties contracted to the SKAO for installing supplied items shall take on the warranty obligations of the original supplier.

Warranty agreements shall clearly define the obligations, constraints and any associated non-warranty cost implications for problem investigation, item removal, storage, packaging, insurance, transportation, importation, repair, re-installation and verification. Items delivered to SKAO shall be managed for compliance to warranty conditions for notification, item preparation, preservation, packaging, handling, storage, transportation, storage, installation, maintenance and use. Each telescope element/component will have operational maintenance plans that will identify items under warranty and provide reference for maintainers to the warranty schedules, conditions and compliance process.

In general, the SKAO will establish support capabilities addressing requirements feasible and economical to sustain in-house. The balance of the Observatory support requirements will be outsourced. Special investment in internal capabilities will be considered where reliance on external supply is not feasible/dependable. This may be combined with strategic agreements for sustaining key capabilities at external suppliers. Strategic support agreement requirements will be monitored as part of obsolescence management.

The SKAO shall establish service level performance requirements for all externally-sourced support needs of the observatory, including warranty support. Service level assignments shall address requirements essential to telescope operational availability, whilst throughout minimising cost. Assignments shall consider economic trade-off.

Suppliers engaged through Service Level Agreements (SLAs) shall be tasked, based on their approved plans that shall demonstrate the supplier capabilities, planning and risk management for sustaining a specified level of service. Supplier SLA compliance reporting shall be on an exception basis. Duty of notifying, logging and instituting corrective action for any service level non-compliance shall in the first-place rest with the supplier’s quality management system.

SLAs intended to bridge establishment of SKA support capabilities shall include delivery of support data, training and other support products required to enable SKAO ongoing support. Contracted original equipment manufacturer (OEM) repair activities and SLAs will be managed by the support personnel. SKA monitoring of service-level compliance will reference to status and events logged by the Telescope Manager.

6.6.10 Engineering management system

Engineering Operations management software will be required to support the operations and maintenance of the SKA telescopes. The Engineering Management System (EMS) will serve as an integrated operational information system for the Observatory, providing the following functionalities:

- configuration management (§6.6.12);
- maintenance and support planning (maintenance base);
- technical publication development (documentation and training base) (§6.6.13);
- creation of an Operational Baseline;
- problem reporting and tracking (§6.8);
- maintenance activity management;
- warehouse/stores support;
- OEM repair and SLA support;
- serial number tracking;
- availability monitoring (§6.6.1);
- condition monitoring (§6.6.4); and
- training management.

The system will be managed by SKAO Engineering Operations and will consist of:

1. Problem Reporting and Tracking System (PRTS) - A ticketing system for logging and tracking of problems and failures (§6.8).
2. Logistic Support Analysis Database (LSA) - A database compatible with MIL-STD-1388-2B [RD12] to develop the Product Breakdown Structure (PBS), FMECA, task summaries and detailed support requirements. It will also include a Monte Carlo simulation model to predict and quantify the support requirements.
3. Configuration Management Database – eB will be used as a Configuration Control Database.
4. Data Module Content Management System - A data module manager compliant with S1000D [RD13] to manage the data modules.
5. Training Manager - A training management database to manage the training requirement and keep records of personnel and their competencies.
6. Computerised Maintenance Management System (CMMS) – a failure and planned maintenance database. It will also collect down time and repair data for all maintenance activities.

7. Interactive Electronic Technical Manual/Publications (IETM/P) Viewer - an online viewer, compliant with S1000D, to view electronic manuals, training and procedure information. It will also include a review capability to enable the review of documents during commissioning and initial training.
8. Application - Offline application that will allow the user to view and add content offline.
9. Documentation Editor – An XML editor used to prepare S1000D-compliant technical content for the IETM/P.
10. Illustration Software - A vector image editor which will be used to edit and draw Illustrations and to prepare S1000D-compliant technical Illustrations for the IETM.

The EMS will have interfaces to the Observatory wide systems, including observation management, and telescope monitoring and control. An interface to observation planning will allow for science observing to be scheduled together with the maintenance work (see §6.4.5.2 and §6.4.7). A detailed description of the architecture, requirements and interfaces is in [RD14] and [RD15].

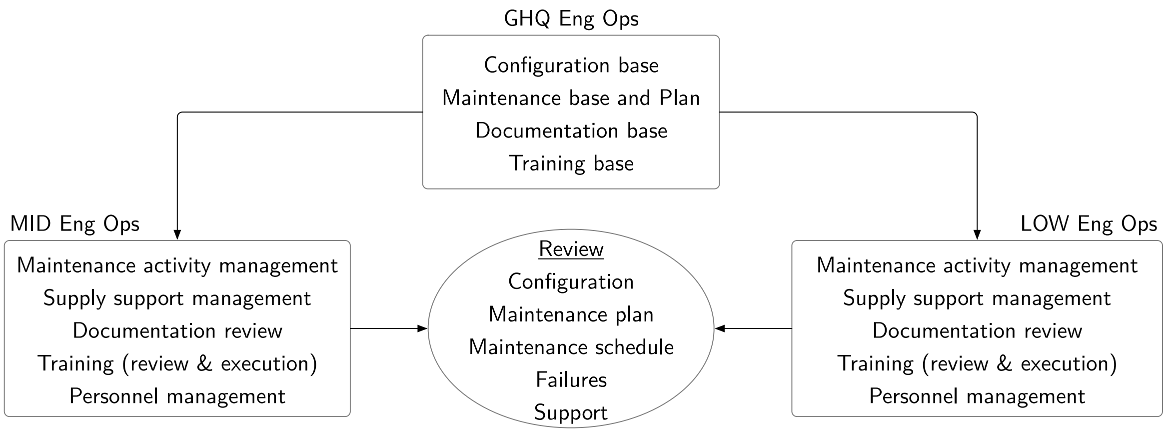

Figure 18: Usage of the Engineering Management System across the three SKA sites.

The SKA EMS will be supported and maintained as an engineering operations-critical capability for the Observatory. The high-level relationship between GHQ, SKA1-LOW and SKA1-MID operations for use of the EMS is shown in Figure 18.

6.6.11 Software Support

As for other observatories, the SKA software suite will continue to evolve during the lifetime of the telescope. This is necessary to support the science and engineering operations of the observatory and the type of work will include:

- new and improved diagnostics;
- minor new engineering and science functional and non-functional requirements (e.g. new observing modes, changes in telescope configuration, adapting to different scientific priorities, usability improvements)[17];
- addressing errors in the code base; and
- supporting expert users in understanding the algorithms in the code base.

The presence of software engineers at the telescope sites will be minimised with software and firmware maintenance performed remotely and tested off-line, where possible. This includes planned

[17] It is assumed that major software upgrades will be funded, managed and delivered through the Observatory Development Programme or from other sources outside the Observatory Operations budget.

updates and upgrades as well as unplanned maintenance (e.g. fixing bugs and errors). Software maintenance activities include, but are not limited to:

- periodic and non-periodic software maintenance activities;
- re-installing operating systems;
- loading and initialisation of software/firmware on components;
- roll-back and roll-forward of software versions;
- software configuration and version control; and
- testing of software functionalities.

There will be a limited need for technical support on site for swapping and configuring LRUs, but the systems will be constructed to avoid single points of failure, allowing this work to be normally scheduled in advance as a maintenance task.

Whenever possible, the use of engineering subarrays will be maximised so that software testing, patches and updates can be executed on an isolated operational system before rolling out and deploying on the full system. This allows the science programme to continue largely uninterrupted on the remaining resources of the telescopes while testing is being carried out.

6.6.11.1 Software and computing staffing and management structures

It is important that the observatory has suitably trained staff to support its functions at the end of construction, so the transition from construction to operations is managed and occurs as smoothly as possible and practicable. These operational staff numbers are based on pre-construction consortia estimates for steady state operations and cross-checked in discussions with SKA precursor facilities, and comparison against comparable telescopes (notably the ALMA Integrated Computing Team). However, the specific roles outlined by the pre-construction consortia have been adapted to develop a coherent computing and software team.

The staffing level is planned to ramp up during construction in advance of these duties. It is also anticipated that there may be significant transfer of construction staff to operational staff, particularly in the host countries, and this will have to be actively managed. The staffing complement in computing and software at the GHQ and at each of the two telescopes sites, who are based at the Science Operations Centres, is listed in Table 17.

Table 16: Role descriptions and number of staff supporting computing and software at the GHQ. Line management of these staff is shown in Figure 20.

Role	Description	Number
Head of Computing & Software	Responsible for all SKA Observatory Computing and Software activities. The role guides the use of computing and software resources to achieve the project mission and also leads the telescope IT responsibilities.	1
Lead Software Architect	Responsible for the overall SKA software high level design choices, technical standards, coding standards, tools, and platforms.	1
Head Software Architects	Responsible for software high level design choices and solution development. One each for: Data Processing, Observation Management, Controls, Pulsar Systems, Networks.	5
Software Quality Engineer	The Software Quality Engineer acts as the technical lead and is responsible for: maintaining and updating the SKA Software	1

	Engineering Process documentation, configuring and managing the software support tools.	
HP Data Analysis Specialist	Lead the platform team to define computing platforms that are suitable for the needs of the SKA, with a particular emphasis on the state-of-the-art systems that will be required for the Science Data Processor and the Pulsar Search systems.	1
DevOps Development Engineers	Develops and supports the Continuous Integration, testing and deployment systems.	2
Tango Core Support	Define changes needed to the Tango core to support the needs of the organisation. This role implements changes to Tango core software and feeds them upstream to the Tango collaboration.	1
Network Engineer	Responsible for supporting networks	1
Technical Writer	Prepares, maintains and updates the SKA Software Engineering Process documentation.	1
Controls Team	Engineers specialising in control systems	3
Data Processing Team	Supports the data processing services including algorithms, execution frameworks, workflows/pipelines.	8
Business Processes & Web Systems Team	Developers supporting business process tools based around databases with web front ends and appropriate business logic. Includes observation management tools, user interfaces, operational databases.	4
Solution Manager		1
	TOTAL	**30**

Table 17: Role descriptions and number of staff supporting computing and software in each of the SKA1-LOW and SKA1-MID telescopes in Australia and South Africa, respectively. Line management of these staff is shown in Figure 21.

Role	**Description**	**Number**
Head of Computing & Software	Responsible for all SKA Observatory Computing and Software activities in a particular SKA Host Country. The role guides the use of computing and software resources to achieve the project mission and also leads the telescope IT responsibilities.	1
Controls	Software engineers specialising in and responsible for control systems of the SKA telescopes.	6
Data Processing	Specialists responsible for data processing matters (covering PST,PSS and SDP) for the SKA telescopes	10
Platform & Networks	Supports platform development and networks for the SKA telescopes.	10
	TOTAL	**27**

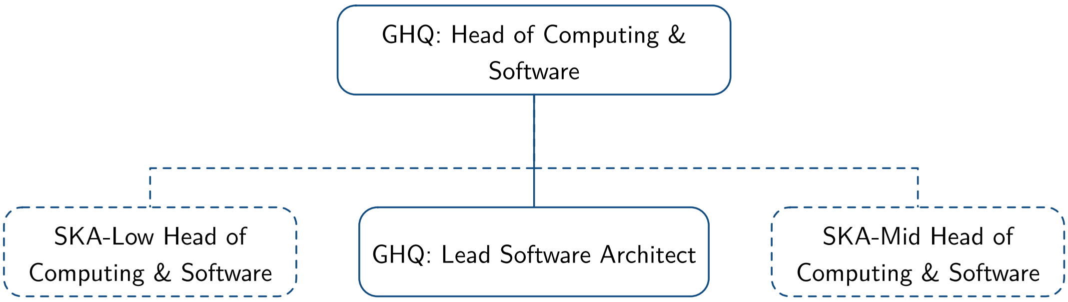

Figure 19: Computing and Software leadership roles at the SKA Observatory. High level leadership and planning to support the computing and software of the SKA Observatory will be delivered by this team. Dashed lines indicate the relationship is not a line management one.

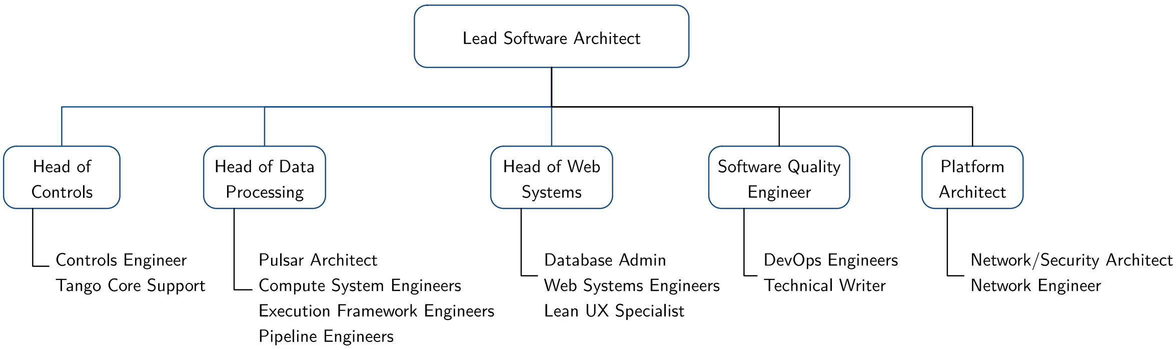

Figure 20: Computing and Software management lines of staff located at the GHQ

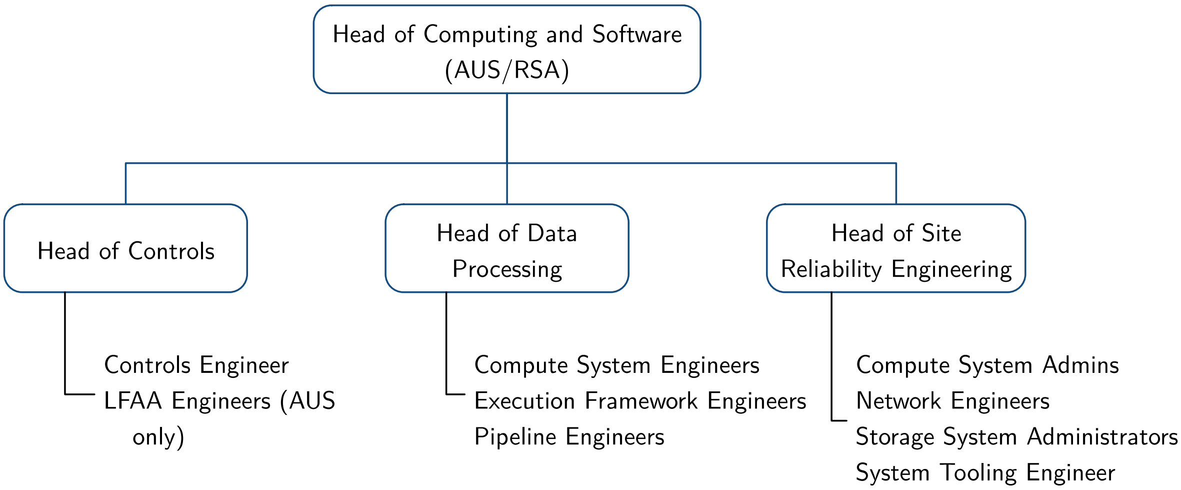

Figure 21: Computing and Software management lines of staff for SKA-LOW and SKA-MID, located in Perth and Cape Town, respectively.

It is anticipated that the computing and software teams at the three host country sites of the observatory will form a planning and leadership team as depicted in Figure 19. Long-term planning of the software and computing of the observatory will be led by this group, as will high-level engagement with the Operations group on the development roadmap.

Since the three largest bodies of software (the Telescope Manager, Science Data Processor and the Pulsar Search engines) plan a large shared codebase with different configurations for the two telescopes, for the purposes of planning it is assumed that support for common codebase items will be located at the GHQ. The line management of these staff and the group structure is depicted in Figure 20.

It is planned that the line management of the teams at the telescope host countries is independent and local, with the line management and reporting flowing through each Telescope Director to the Director of Operations at GHQ. The line management of these staff and the group structure is depicted in Figure 21.

Note that the Scaled Agile Framework (SAFe®) for software development is the chosen methodology within the SKA Observatory and will be prominent during the development and implementation phase of construction. It is anticipated that this methodology will persist into the Operations phase.

6.6.12 Configuration Management

Operational configuration management principles and practices will be developed during the construction phase, based on the design data pack and installation records, and then maintained throughout the operational phase. It will consist of data relating to the telescopes, infrastructure and support equipment. The as-built configuration will be recorded during construction.

All configuration changes will be managed and traced through the operational life cycle by means of an Engineering Change Proposal process. The change management relationships are shown in Figure 18. The SKAO configuration management requirements are described in the SKA Configuration Management Plan [AD3]. The Configuration Management System (eB) is part of the EMS.

6.6.13 Technical data and publications

Technical publications will be developed to provide the information needed for personnel to perform specific tasks for operation and maintenance. It will be based on international best practice and will complement training material development. Technical information will be managed and developed to provide Interactive Electronic Technical Manuals/Publications (IETM/P).

The Logistic Support Analysis will result in a “locations” structure based on the Product Breakdown Structure. This structure will define the locations and positions for all maintenance items (also referred to as slot positions in a maintenance structure). The locations structure will contain all hardware and software items down to the required maintenance level.

A common source database will contain all the maintenance and technical publication data. The data modules, in xml format, will be the prime source for the IETM/P. SKA support software systems will have access to the xml information. The xml format will provide the software products to make full use of the structured information and ensure an integrated system to operational personnel.

Operating and support task requirements will be developed to identify the technical information requirements and a Data Module Requirement List. (DMRL). This process will commence early in the construction phase. Developed operating and support procedures will be evaluated and matured as part of SKA1 AIV and Commissioning.

6.6.14 Supply support

Spare parts and consumables will be acquired to meet operational and support requirements at each stage of telescope deployment. Stocks used during commissioning will be replenished to ensure adequate stock levels for supporting the telescopes during full operation. It is assumed that initial spares and consumables (including any strategic spares requirements) will be delivered to meet the operating and support requirements at each stage of telescope deployment. Relevant spares or consumables stocks consumed during commissioning will be replenished / restored to operational stores before conclusion of construction activity. The number of spare parts & consumables required will initially be calculated as part of the LSA by simulation/modelling. Stock levels will be allocated based on criticality and the out-of-stock probability. Selective strategic stocks will be acquired to optimise operations costs over the Observatory’s life cycle and to mitigate supply chain risk. Strategic spares requirements will be determined by obsolescence management and by economy of scale considerations. Supply support stock levels will be determined based on an at least 85% probability of that spare being in stock when required.

Different levels of maintenance are identified from the simplest, organisation level (O-level) undertaken close to the location of the equipment, through intermediate level (I-level) undertaken back at the EOC, to depot level (D-level) undertaken at specialised centres.

Organizational-Level maintenance is performed on the telescope at the various locations. The following are examples of O-level maintenance locations for the SKA: the Karoo Array Processor Building (KAPB) at Losberg for the SKA1-MID Telescope; the Low Frequency Aperture Array (LFAA) Field Stations and Repeater Stations; the Science Processor Centres. O-Level maintenance can include corrective and preventive maintenance.

Corrective maintenance at I-Level is performed on LRUs removed at O-Level and brought to the EOC. It is performed by the removal and replacement of Shop Replaceable Units (SRUs). Complex I-Level preventive maintenance will also be performed on LRUs removed at O-Level.

Depot-Level maintenance will be performed at specialised maintenance centres (off-site). Corrective maintenance at D-Level is performed on LRU and SRUs from O- and I-Level maintenance facilities. Preventive maintenance at D-Level will be performed by executing specialist maintenance on equipment removed at O-Level and maintenance that cannot be performed at I-Level. D-level maintenance locations may include Perth for the SKA1-LOW telescope and Cape Town for SKA1-MID.

O-level stores will provide LRUs and consumables that will be used on-site. All items defined as spares at O-level shall be interchangeable with no item-level calibration, tuning or alignment required. I-level stores shall provide LRUs to the O-level and SRUs, as well as consumables required for I-level maintenance. All items defined as spares at I-level shall be interchangeable with installed items with a minimum of calibration and aligning required. If required, alignment and calibration procedures shall be developed as part of the technical publications. D-level stores shall provide long-lead LRUs, SRUs and components. D-Level supply support shall also provide LRUs and SRUs to the I-level and O-level maintenance facilities.

Operational stock levels of spares and consumables will be optimised and maintained by a programme of replenishment and by monitoring demand rates, turn-around times for repairable spares, and supply lead times. The accountability of all items and consumables will be controlled using Item Orders and Delivery Notes transaction logs. The electronic signatures on receive and dispatch notices will ensure item accountability.

The authorisation and routing of supplies is indicated in Figure 22. It applies to the supply of new items and repaired items.

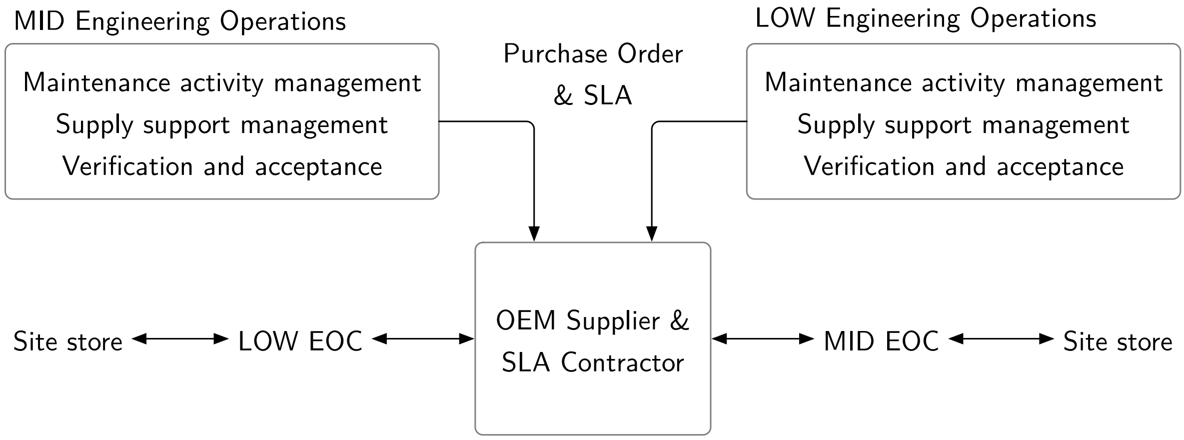

Figure 22: Supply routing and authorisation.

Selective strategic stocks will be acquired to optimise operations costs over the life cycle and to mitigate supply chain risk. Strategic spares requirements will be determined by obsolescence management and by economy of scale considerations.

6.6.14.1 Support, test equipment and tools

The Support and Test Equipment (S&TE) requirements for the various maintenance levels are to be determined during the LSA process – accounting for the support needs of the production baseline equipment. Test & Support Equipment must be suitable to operate in the telescope support environment, at the applicable levels of support. Test jigs and equipment used during development and integration will be utilised and standardised as far as possible. The use of commercially available equipment for meeting operational support and test requirements will be prioritised. Requirements for any specialised S&TE will be motivated by the LSA and by a cost/benefit trade-off.

Initial S&TE will be delivered to meet the operating and support requirements of each stage of Telescope construction. Suitable support equipment must be procured and support equipment operating procedures developed. The complete telescope S&TE requirements will be established for the commencement of operations.

6.6.14.2 Packaging, handling, storage and transportation

Spares and items removed from the Telescope for service or repair will be protected from damage during operational handling, storage and transportation. An SKA Packaging, Handling, Storage & Transportation standard and procedures will be developed.

6.6.15 Obsolescence Management

The telescope design and support concept will be continuously assessed for obsolescence-sensitive items and obsolescence risk. Obsolescence assessments and reporting will consider all critical items, including spares, skills and specialised support and test equipment. Assessments will focus on custom-design items, rapidly evolving technologies and products lacking backward compatibility with the installed base.

Strategies for management of obsolescence will be consolidated at system level and will include pre-emptive action to cost-effectively minimise obsolescence risk to Operational Availability and the cost of ownership. Mitigation strategies may include stockpiling, guaranteed long-term support and technology refresh.

6.7 RFI Management during Operations

RFI can be one of the most detrimental effects to radio astronomy. Effective RFI management during the operations phase will aim to avoid its growth and minimize its presence at the SKA sites, across the relevant frequency range as specified in the high-level policies [AD2]. When avoidance of RFI is not possible, the next best thing is to have as complete an understanding of the nature and characteristics of the RFI as possible. A plan for RFI management can be developed by answering three questions: (1) What do we need to do? (2) Who will do it? (3) How can we do it?

6.7.1 RFI Management functions

To answer the first of these questions we define what functions need to be implemented. These are:

Policy and procedure development and enforcement	Policies and procedures to control and mitigate RFI on the Observatory sites and their enforcement. Decision making on RFI issues at different levels within the observatory.
Measurement, characterisation and troubleshooting	Implement a site RFI monitoring strategy. Post maintenance RFI testing for compliance. RFI Characterisation.
Spectrum management	RQZ administration. International Spectrum Management. Interactions with Industry.

Policies and procedures to enforce, control and mitigate RFI on the Observatory sites need to be developed. Even though each site entity (i.e. CSIRO for Australia, and SARAO for South Africa) will be responsible for maintaining the radio-quiet zone (RQZ) on their sites, the SKA should have its own independent mechanisms in place to characterise the RFI environment of its telescopes, as that will directly impact the quality of the science data. The monitoring strategy will include:

- fixed RFI monitoring stations;
- routine mobile RFI monitoring campaigns;
- RFI investigations; and
- the use of Engineering subarrays for RFI monitoring campaigns.

The last point speaks to the fact that the most sensitive RFI monitor on site will be the telescopes themselves. Scheduling of specific, small, engineering subarrays will occur as a part of RFI monitoring campaigns. Techniques for software level flagging of RFI in signal and data processing will be pursued.

Equipment and telescope components may enter the telescope site either through delivery from a manufacturer, or after they have been repaired at the EOC. In the latter case, the physical characteristics may have changed and compromised its RFI shielding. All such equipment will be checked for RFI compliance at the EOC before being be delivered to site, and they will be issued with a permit and/or certificate of compliance before being allowed onto site.

6.7.1.1 Spectrum management

The regulatory aspect of RFI management is dealt with by Spectrum Management, a highly political discipline with interactions between national administrations, commercial and scientific groups. It deals with all RFI that is generated outside of the RQZ and detected by an SKA telescope (e.g. satellites, airplanes).

If the source is terrestrial in origin, the RQZ regulations would apply and the site entities and national stakeholders would need to manage and deal with the situation. As a major stakeholder, the SKA should have some oversight of the process, although the responsibility remains with the host country. The frequency range protected by the RQZ is between 100 MHz and 25.4 GHz for both Australia and South Africa.

Sources that are airborne or spaceborne are out of the control of the RQZ regulations and must be managed through international spectrum management, through the ITU-R Radio Regulations.

6.7.2 RFI Management Organisational Structure

The management structure for dealing with RFI issues is depicted in Figure 23. There are three levels, starting with RFI Groups at each telescope site, another group at the GHQ, and then a high level RFI Committee composed of the SKA Director of Operations, the Science Director, and the two Telescope Directors.

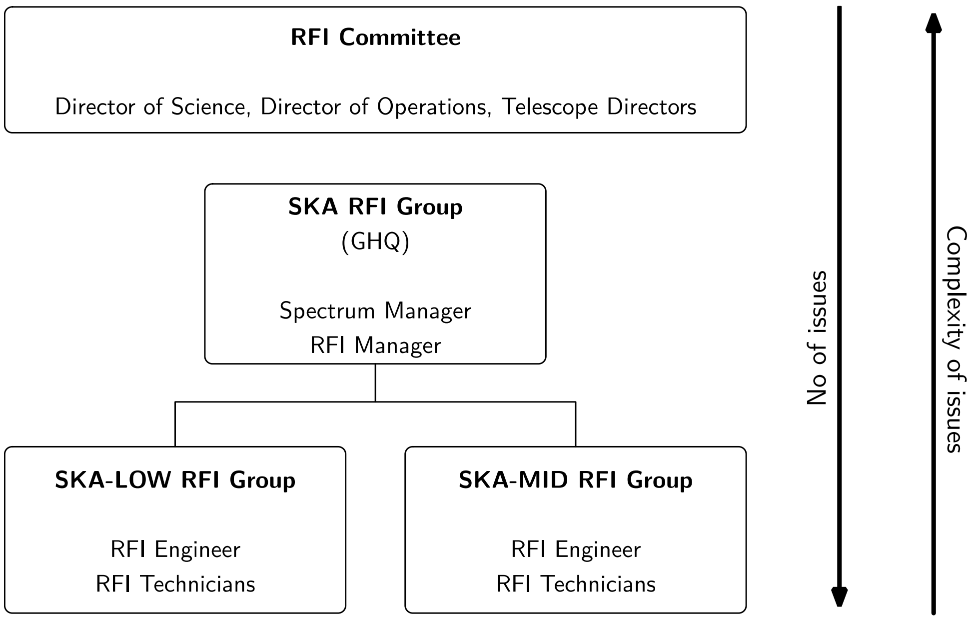

Figure 23: Organisational structure for dealing with RFI issues. RFI Groups at the telescope sites will deal with most of the issues that arise. More complex issues can be escalated all the way to the RFI Committee at the GHQ.

Day-to-day operations and the majority of RFI related issues will be managed by the RFI Groups at the two telescope sites. Issues include (but not limited to): maintenance, RFI acceptance and compliance testing, RFI monitoring, RFI investigations. The telescope RFI groups are responsible for monitoring and controlling the RFI environment of the telescopes.

The SKA RFI Group is responsible for defining and implementing RFI management strategies. Its primary role is in the area of development of policy and procedure. Furthermore, its remit will include engagement with the Site Entities responsible for the administration of each RQZ, as well as other external stakeholders.

The RFI Committee is a high-level group. It will be convened as required to address issues that cannot be resolved at any of the lower levels. The RFI Committee will also be responsible for reviewing and approving RFI policies and strategies.

6.8 Problem Reporting and Tracking

Operational problem notification to the Telescope Operator shall be automated in the form of telescope statuses and alarms presented by the telescope control, management and monitoring systems. The logging of faults detected shall occur automatically and the nature of faults will be automatically described in the logs (i.e. engineering logs, shift log tool) from the error condition and/or fault code.

There will be a Telescope Operator for each telescope at all times to ensure that observations are proceeding successfully, and to react to faults (or other events) if and when they occur. The system will automatically notify the Operator when a fault does occur. It will also be the responsibility of the Telescope Operator to monitor the data quality flags (as reported by the pipelines).

All problems identified during the construction and operational phases will be reported, logged and tracked by means of the operational Problem Reporting and Tracking System (PRTS) as a measure to effectively assign and track problem resolution.

Any deviations from telescope operational performance shall be investigated and appropriate action taken to resolve the cause and make corrections to achieve the required telescope performance. The Telescope Operator will open PRTS tickets for any telescope issues that arise, or after being notified by external parties, or reported by TM.

When a fault is detected, the Operator will decide whether to:

- allow observing and data processing to continue;
- abort the observation and repeat; or,
- stop all observing to chase down the fault.

The particular course of action chosen depends on the severity and impact of the fault. In the event of a fault, the Operator must:

1. Be informed that a fault has occurred.
2. Identify the nature and cause of the fault.
    - A database of currently open and closed faults, and their resolution (or otherwise), should be accessible for the Operator’s information.
3. Attempt limited troubleshooting, depending on the nature and severity of the fault.
4. Isolate the faulty system from the rest of the telescope if this is not done automatically.
    - For example, if a single dish or beam within a subarray fails then, depending on the severity and nature of the fault (and the type of observation), it could be automatically isolated from the rest of the subarray and observing should continue with the remainder of resources in the subarray.
    - QA alerts should inform the Operator whether there is any significant degradation to the data compared to expectations or previous performance.
5. Continue observing if possible.
    - If it is not possible to continue with the present observation, then the next feasible observation should be executed. In most cases, this should occur automatically, although following a fault it is prudent for the Operator to grant permission to execute the observation.

- The telescope status will be updated automatically once a serious fault occurs so that the next highest priority, available and feasible scheduling block can be identified and executed.

6. Annotate the fault report with information that should contain:
    - a concise narrative describing the fault, its characteristics and the impact to observations not already described by the automated report;
    - any corrective actions taken, and;
    - the amount of observing time lost, if any.
7. Update the Shift Log tool with the status of the observation affected by the fault, with a link to the fault report filed by the Telescope Operator.
    - Statuses reported for the observation may include: GOOD, BAD, QUESTIONABLE, or JUNK.
8. Notify appropriate personnel of the faults.
    - In the case of a severe (i.e. time-losing, or risk of component failure) fault, the telescope Operator should attempt to notify appropriate personnel.
    - Operations support staff should be regularly monitoring the logs and reports from the telescopes, identifying any issues that need to be elevated in priority.
    - It is the telescope Operator's responsibility to provide a clear and concise fault report that will allow local operations support staff to understand the problem encountered and respond in a timely manner.

The PRTS shall provide in-progress tracking information for open issues. It shall provide access to PRTS process records of all open and closed-out issues.

The CMMS will support the operational PRTS in accepting maintenance-related issues assigned to CMMS work orders. The maintenance management function will provide problem resolution maintenance in-progress and close-out status to the operational PRTS.

Problems related to telescope failures will be assessed for root cause and corrective action requirements, making use of the Failure Recording and Corrective Action System (FRACAS). The PRTS, CMMS and FRACAS form part of the Engineering Management System described in §6.6.10.

The PRTS shall enable tracking and coordination of the operational problem management activities and process flow, as illustrated in Figure 24.

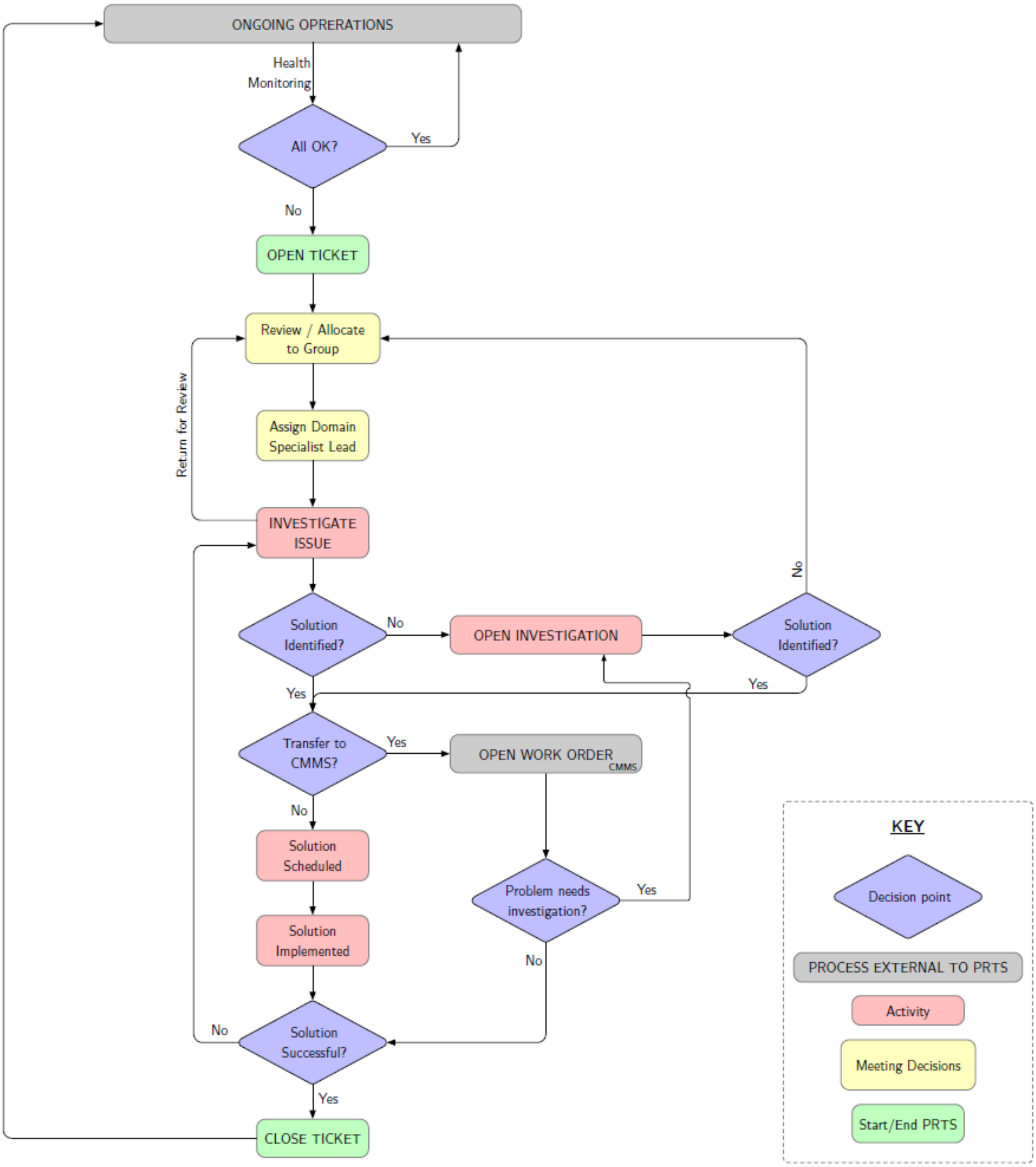

Figure 24: Problem reporting and tracking workflow.

6.9 Working on Site

6.9.1 Presence on telescope sites

A guiding principle for the SKA design has been to minimise the number of operational staff working on the sites. This is motivated by:

- the fact that human activity significantly increases the amount of RFI on the sites;
- the operational need to minimise the travel and accommodation costs; and
- the fact that both telescope sites present hazardous environmental conditions.

For these reasons, it is desirable to minimise the human footprint on the sites.

The maintenance strategy (§6.6.3) specifies that the normal procedure, in the event of a hardware fault in the field, will be to replace the faulty LRU with a spare, and then to repair the faulty unit at a facility elsewhere (either at the EOC or with the OEM). Repair of hardware faults *in situ* is not presently envisaged unless that repair can be achieved quickly, efficiently and safely.

6.9.2 Commissioning and delivery of new systems and instruments

The procedure that identifies the steps for the hand-over of systems to the Observatory will be augmented, if necessary, to cover special needs for the SKA. This includes a procedure of how commissioning teams hand over systems and how the Observatory accepts the system. Any new system that is delivered to the Observatory shall include:

- Operation and maintenance manuals;
- System transfer documents (including the commissioning report that will remain the reference document for the system performance maintenance on the Observatory);
- The full as built documentation, including optical, mechanical and electrical drawings;
- A procedure to verify the operational system performance on site;
- A procedure to verify the operational system configuration.

6.9.3 Infrastructure support

It is anticipated that maintenance support of the infrastructure will be contracted out, and it is further assumed that CSIRO and SARAO will manage those contracts for SKA1-LOW and SKA1-MID, respectively. The skill sets required are not observatory/telescope specific and therefore may be cheaper and more effectively procured externally. Moreover, obsolescence of skills is also avoided.

6.9.4 Site Communications

Voice communications will be required in a variety of circumstances. Some examples are:

Routine, on-site communications:	Workers in the field needing to communicate with personnel elsewhere on the site, for example regarding vehicle movements or requesting technical information to enable the work at hand to be carried out.
Routine, off-site communications:	Workers at the CPF needing to communicate with colleagues off-site, for example regarding the movement of spares between the EOC and the site; and personal communications.
Emergency, on-site communications:	Workers in the field needing to communicate with personnel elsewhere on the site, for example to report an accident.
Emergency, off-site communications:	Workers on the site needing to communicate with colleagues and external agencies off-site, for example calling the Royal Flying Doctor Service in Australia.

In order to provide for these situations, a variety of capabilities will be implemented, as follows:

1. an on-site telephone system, connected to the public telephone network;
2. an RFI-compliant, on-site communications system for routine operational use. Usage of this system should be minimised, but there will be many situations in which it is impossible or inadvisable for workers in the field to get to the nearest telephone;
3. an emergency communications system, capable of on-site and off-site communications, which need not be RFI-compliant. This system must be available on demand to ensure that emergencies can be swiftly reported whenever they occur; and

4. an accident detection system, to provide notification when a crew in the field ceases being active and is incapable of reporting.

6.10 Interaction with the user community

6.10.1 User Support

The support system for SKA users[18] will comprise both local and regional offices (including but not limited to SKA Regional Centres) and the Observatory itself. The Observatory will provide central user support functions to service requests received from users directly or received from a regional office on behalf of groups or individual users.

As explained in §6.5, the SRC network will be the primary access portal for users to access all information pertinent to their proposals and projects, including access to their data and processing platforms. This 'SKA Science Gateway' will be accessible from the web pages of the SRCs, or from the SKA home page.

The method of communication between SKA users and the Observatory will be via a Helpdesk facility. It is anticipated that SKA users will be able to use the Helpdesk to post requests for support on specific issues concerning their projects (i.e., either observing programmes or data quality), report software bugs, problems or faults, make general enquiries, and provide feedback to the Observatory. All Helpdesk tickets will be triaged by local staff at each SRC. Any issue may be escalated to the SKA Observatory if it cannot be resolved by local support staff. SKA operations support staff will then ensure that the tickets are assigned to appropriate owners, who may be situated in any of the three Observatory sites for instance, for an expert response. Of course, at times, the expert solution may reside within the community, and the Observatory will reach out to those individuals for assistance.

Science and operations support staff, from across the whole Observatory, will be assigned to each approved project as a "Friend of Project" (FoP). The FoP will serve as the point of contact for PIs and Co-Is to raise project-specific queries (e.g., observation design, data quality). FoP status persists after a project's data are collected and delivered to an SRC. Queries on specific projects that generate tickets via the Helpdesk system will alert the FoP automatically.

As part of user support, SKA Operations will be responsible for maintaining and providing electronic-based documentation for all aspects of SKA Observatory operations that are applicable for SKA users. This documentation can exist in various formats, e.g., PDFs, web-based guides, FAQs.

6.10.2 Advisory Committees

The SKA Observatory anticipates a number of committees by which its users can provide input.

- SKA Users Committee: The Observatory will create a Users Committee to solicit input from its users on different aspects of the Observatory's science and operations activity. This will include, but not be limited to, issues with respect to the SKA science programme, proposal and project management, data quality, and user support. The committee will hold regular annual meetings and provide their advice through a report to the SKA Director-General (or their delegate).
- SRC Users Committee: As described above (§6.5), SRCs will play a pivotal role in the management of the Observatory's data flow which includes the delivery of science data products to its community, and the provision of compute resources to convert those data into

[18] SKA users are those scientists with access rights to SKA science data products.

scientific knowledge. The SRC Users Committee will report to and advise the SKA Director-General (or their delegate) on the level of resources and user experience provided by the global network of SRCs.

In addition to these, a Science and Engineering Advisory Committee (SEAC), or something similar, will be established to advise on different aspects of the SKA Observatory's science programme, it's science and engineering operations, as well as the Observatory's Development Programme.

6.10.3 SKA Users Meetings

The Observatory will likely organise a major SKA meeting every two years that will be open to all stakeholders from across the SKA community. The scope of this meeting will be broad, covering all topics significant to the SKA Observatory, its users and stakeholders. The meeting will be used to:

- showcase SKA science highlights;
- present the activity and progress of the development programme;
- provide workshop and feedback opportunities for discussion of:
    - SKA operations;
    - SRC provision;
    - Key Science Projects;
    - SKA Observatory Development Programme; and
- provide updates on the future plans and growth of the SKA Observatory.

6.10.4 Publications and Dissemination

The SKA Observatory will disseminate news, information and events that are of relevance and interest to the SKA Observatory, its community and stakeholders. Additionally, the Observatory will provide support to the user community in communicating their research to a broad audience. This will include, but not be limited to:

- the SKA websites for:
    - press releases and announcements of recent results & other relevant news;
    - animations, simulations and any other assets illustrating science results;
    - up-to-date information regarding all activities of the SKA Observatory, including but not limited to science, engineering, strategy, outreach, etc.;
    - tailored content for the science and engineering communities, including persistence and access point for documentation, newsletters and annual reports;

- social media for:
    - engaging broadly with the SKA Observatory's community and key stakeholders to disseminate results & other content;
    - building and consolidating support & enthusiasm for the SKA Observatory's activities during construction & operation;
    - disseminating the SKA Observatory's key messages and values;
    - seizing opportunities and popular trends to maximise visibility of the SKA Observatory and its mission;

- electronic newsletters providing detailed reports of:
    - progress in the development programme;
    - science highlights from the community including pathfinder & precursor research;
    - summary of activities from the SKA telescopes;

- relevant information about other activities of the SKA Observatory and its affiliated partners;
  - news of relevance from the SKA Observatory and beyond;
  - events of relevance throughout the world;
  - SKA jobs throughout the SKA partnership;

- annual reports providing details of:
  - reports from the SKA Observatory (Director-General plus other departments and groups);
  - local news from the offices of the SKA members & observers;
  - report from the SKA Council;
  - reports on the operational performance of the SKA telescopes;
  - reports on the performance and activities of the SKA Regional Centres;
  - time allocation results and process;
  - scientific research highlights;
  - list of SKA research papers and other publications;
  - calendar of events;
  - list and profiles of employees, new starters, fellows, etc.; and
  - report on global outreach impact & human capital development.

In addition, the SKA Observatory will:

- engage with members of the public through regular public talks to disseminate its research;
- conduct educational workshops wherever appropriate; and
- provide teacher resources and lesson plans based on its research to the teacher community.

7 Observatory Lifecycle

All preceding chapters of this document have considered only the routine operations phase, i.e., when SKA1 is fully deployed, commissioned and verified. The scope of this Plan, however, includes all phases from construction through to decommissioning. This chapter presents a high-level summary of the project lifecycle. A simple schematic is provided in Figure 25.

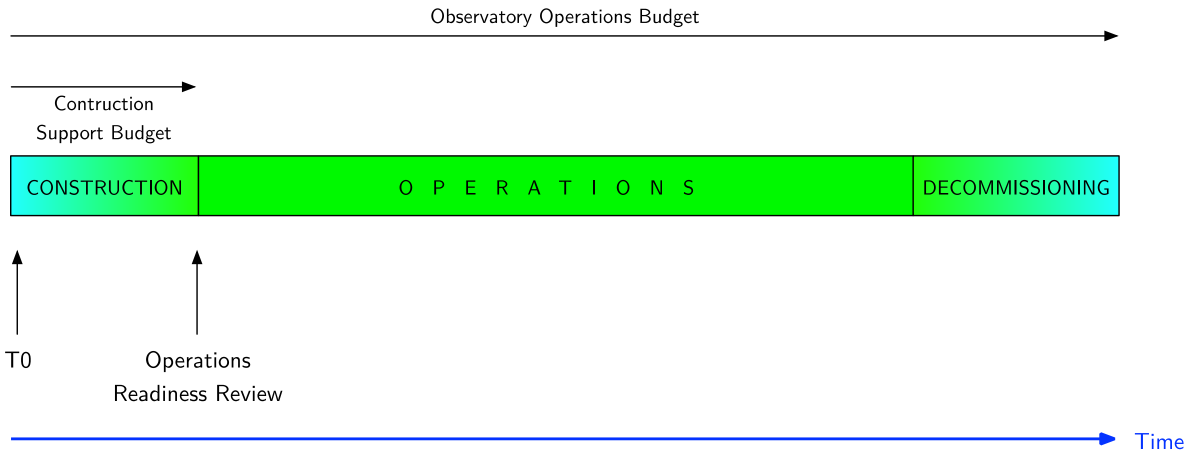

Figure 25: Schematic Lifecycle of the SKA Observatory.

7.1 Construction Phase

The construction phase of the project will commence at T0, defined as the point in time at which the SKA1 Construction Proposal and a companion SKA1 Establishment and Delivery Plan have both been approved by the SKA Observatory Council, and funds have been released.

The construction of the SKA Telescopes, including the SKAO resources required through the observatory budget, will be fully described in the SKA1 Construction Proposal. Because both SKA1-LOW and SKA1-MID will be deployed continuously there will be an overlap in time between construction and operations activities. As soon as the first component is accepted by the Observatory, it will need to be supported and maintained via the operations budget. From the perspective of telescope operations, the activities arising during this phase of the project will be:

- implementation of the EMS (§6.6.10);
- population of the EMS with supplier-provided and internally-generated documentation;
- training of maintenance and support personnel;
- preventive and corrective maintenance of accepted products;
- support for, and participation in, the commissioning and verification aspects of the construction project as specified in the SKA1 Science Commissioning and Verification Plan [RD18];
- working with the SRC Steering Committee to implement an ensemble of SRCs, and to support the regions in their implementation of individual SRCs;
- implementing the operational interfaces to the SRCs; and
- commissioning the operational facilities in the Host Countries: SOCs, SPCs and EOCs.

7.2 Transition to Operations

The transition from construction to operations activities will be a gradual one, with the two activities overlapping in time. Nevertheless, from a management perspective, it is necessary to define a clear end point for the construction programme.

The final activity of the construction project will be to demonstrate the ability of the Observatory to execute a selected set of day-one observing modes, from proposal preparation through to data delivery. The construction phase of the project will conclude with an Operations Readiness Review, marking the formal handover from construction to operations. This review will evaluate the verification evidence in order to determine whether the telescope system and all its support hardware, software, personnel, procedures, and user documentation accurately reflect the deployed state of the telescope. A successful Operations Readiness Review will be used to formally declare the telescope as operational.

7.3 Operations Phase

The conclusion of the construction project is an important management milestone, but it does not mark the end of construction-related activities. Additional observing modes will need to be commissioned, and software development will continue on an essentially continuous basis. Nevertheless, the Operations Readiness Review is a critical milestone because it marks the point at which the Observatory will be ready for some science programmes to commence. It is therefore anticipated that the first two years of the operations phase will be dominated by debugging and commissioning activities; following this, operations should become more routine.

8 Staffing and Budget Estimates

This section specifies the resources required to deliver this Operations Plan. The staffing profiles are shown for the 10-year period 2021-30, from the assumed start of construction in 2021 through to the end of construction in 2027, and the first three years of the Operations phase of the SKA Observatory. Costs across the four budget lines outlined in §1.2 are presented.

The estimated costs correspond to delivery of the Design Baseline of the SKA1 Telescopes. Any attempt to compare it against the estimated capital cost of SKA1 should use the corresponding capital estimate for the Design Baseline and associated infrastructure, including MeerKAT. The final version of this Operations Plan, to be submitted to the SKA Council, will correspond to the Deployment Baseline.

8.1 Staffing profile

The current estimate of the staffing profile (headcount) across the three host countries and for the three employers of SKA staff is in Table 18. An internal review of the staffing levels has taken place and, in the case for the Programmes Group, a comparison was made against the SKA Cost Book with a review at the work package level. The estimate of the Science, Science Operations, and Engineering Operations staff is described in §6.4.8, §6.4.9, §6.6.7 and §6.6.8. These estimates benefit from an increased confidence in the staffing profile due to the work in the Programmes area as well as the Logistics and Support Analysis modelling. This has resulted in improved understanding of the roles and numbers needed to support the operations of the two SKA telescopes.

Table 18: Staffing profile for the SKA Observatory across the three host countries.

	Construction							**Operations**		
	2021	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Country										
UK	145.1	152.1	156.1	164.6	173.6	177.1	180.1	147.6	144.1	143.1
AUS	19	36	65	85	103	118	129	125.5	124.5	116
RSA	29.5	51.5	77.5	99.5	123.5	133.5	144.5	130	130	123
TOTAL	**193.6**	**239.6**	**298.6**	**349.1**	**400.1**	**428.6**	**453.6**	**403.1**	**398.6**	**382.1**
Employer										
SKAO	157.1	172.1	182.1	204.6	219.6	223.1	232.1	180.6	177.1	173.1
CSIRO	18	33.5	58	71	86	101	106.5	109	108	101
SARAO	18.5	34	58.5	73.5	94.5	104.5	115	113.5	113.5	108
TOTAL	**193.6**	**239.6**	**298.6**	**349.1**	**400.1**	**428.6**	**453.6**	**403.1**	**398.6**	**382.1**

8.2 Basis of Estimates

The basis of the estimates used to arrive at the costs presented in this revision of the SKA Operations Plan is:

- salaries are calculated using 2020 GBP sterling and converted to Euros;
- non-staff costs have been estimated using 2017 Euros;
- operations and maintenance costs for the SKA telescope elements' hardware and software components were estimated by the design consortia using 2017 Euros and are as presented for their Critical Design Reviews; and
- no inflation or salary escalation has been accounted for.

8.3 Estimation of Staffing Costs

The currently estimated staff costs are presented in Table 19. Current renumeration rates have been assumed to continue into the IGO-era. On-costs are currently set at 20% and are broadly in agreement with the current practices at CSIRO and SARAO. However, indirect costs for CSIRO and SARAO employed staff are not included in these salary costs. Indirect costs for CSIRO and SARAO employed staff are estimated to be 15% of their salaries, and this accounted for separately under non-staff costs.

Table 19: Staff costs for the SKA Observatory by location and employer

€ (M)	Construction							Operations		
	2021	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Country										
UK	15.4	16.4	16.3	17.2	18.1	18.4	18.6	14.9	14.6	14.5
AUS	2.0	4.2	6.8	8.8	10.6	11.8	12.4	11.7	11.7	10.8
RSA	2.0	3.3	5.6	7.7	9.1	10.1	11.5	10.7	10.7	9.9
TOTAL	**19.5**	**23.8**	**28.7**	**33.8**	**37.9**	**40.2**	**42.5**	**37.2**	**37.0**	**35.2**
Employer										
SKAO	18.6	21.8	23.3	26.5	29.2	30.3	30.9	24.3	24.1	23.5
CSIRO	0.5	1.0	2.7	3.6	4.1	4.9	5.5	6.3	6.3	5.6
SARAO	0.4	1.0	2.7	3.7	4.6	5.0	6.1	6.6	6.6	6.0
TOTAL	**19.5**	**23.8**	**28.7**	**33.8**	**37.9**	**40.2**	**42.5**	**37.2**	**37.0**	**35.2**

8.4 Estimation of Non-Staff Costs

The currently-estimated non-staff cost profile is presented in Table 20. These costs are presented as:

- those costs which apply across the SKA Observatory as a whole (e.g. SAFe Programme Increments, IT); and
- those costs which are specific to one of the three locations.

Table 20: Estimated non-staff costs for the Observatory.

	Amount (€M)									
	Construction							Operations		
Location	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
SKA Observatory	9.1	10.6	16.3	17.3	18.3	19.0	19.6	22.1	20.7	20.2
UK	0.6	0.5	0.6	0.6	0.6	0.6	0.6	0.3	0.3	0.4
AUS	0.3	0.6	5.1	9.2	11.6	16.7	20.5	25.7	25.6	25.6
RSA	1.2	1.8	4.2	7.8	8.5	12.8	15.4	18.4	18.5	17.0
TOTAL	**11.1**	**13.4**	**26.3**	**34.9**	**38.9**	**49.2**	**56.1**	**66.6**	**65.1**	**63.2**

The non-staff costs within each of the four budget areas (§1.2) are presented in Table 21.

Table 21: Estimated non-staff costs against the four budgetary areas for the Observatory. (Note that, at the time of writing, the Observatory Development Programme budget has not received attention.)

	Amount (€M)									
	Construction							Operations		
Budget	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Construction Support	2.6	2.6	2.5	2.5	2.5	2.5	2.5	0	0	0
Observatory Operations	1.6	2.3	13.1	20.7	23.9	33.3	39.8	51.2	51.1	49.5
Business Enabling	7.0	8.5	10.7	11.6	12.5	13.3	13.8	15.4	14.0	13.7
Observatory Development	0	0	0	0	0	0	0	0	0	0
TOTAL	**11.1**	**13.4**	**26.3**	**34.9**	**38.9**	**49.2**	**56.1**	**66.6**	**65.1**	**63.2**

Table 22 ranks the budget lines that dominate the non-staff costs, for those groupings that contribute more than €2.0M/yr to the budget in the year 2030, i.e. as estimated for routine operations.

Table 22: Ranked order of the largest sources contributing to the non-staff costs.

Item	Total (€M)
Power	18.5
MID Ops & Maint.	7.5
Data transport	6.2
LOW Ops & Maint.	5.4
Travel	4.6
Compute Refresh	3.8
DG Contingency	2.5
SKA-LOW Running Costs	2.4
Decommissioning Fund	2.0

8.4.1 Power estimate

8.4.1.1 Grid/diesel power

Power for the telescope sites and the Science Processing Centres is by far the costliest non-staff item and the total power cost dominates the SKA non-staff budget (see Table 22).

Table 23: Basis of estimate for calculation of cost of power for running the SKA telescopes.

Telescope	Location	Rate (€/kWh)	Consumption (kW)	Annual cost (€M)
SKA1-LOW	Site	0.34	3300	9.8
	SPC	0.12	1900	2.0
			SKA1-LOW TOTAL	11.8
SKA1-MID	Site	0.12	4220	4.4
	DRUPS			0.2
	Remote PV			0.2
	SPC	0.12	1700	1.8
			SKA1-MID TOTAL	6.6
			TOTAL POWER	**18.4**

The basis for estimating these costs is given in Table 23. These rates are derived using current industry expectations for the next 10 years in Australia and South Africa. In South Africa, there is already grid power being delivered to the site and the tariff for its consumption is estimated to be €0.12 kW/hr, an average of the daytime (€0.18 kWh) and night-time (€0.06 kWh) rates. An estimate is also given for the use of Diesel Rotary UPS (DRUPS) for when grid power is not available. The baseline design for the observatory has the use of PV stations for the most remote dishes along the spiral arms of SKA1-MID. In Australia, there is no provision of grid power at the MRO, and so the baseline assumption, for the purposes of costing in this revision of the Operations plan, is the use of diesel generators. The two SPCs are located in Perth and Cape Town and will be drawing power from the relevant city grid.

The estimated cost profile of power for the SKA1-LOW and SKA1-MID sites over the 10-year period covered by this plan is shown in Table 24. The profile through the construction phase is scaled against the expected size of the arrays at that time.

Table 24: Cost profile for the delivery of power to the telescope sites and the Science Processor Centres.

Location	Amount (€M)									
	Construction							Operations		
	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
SKA1-LOW										
Site	0	0	1.7	3.2	4.9	6.6	7.9	9.8	9.8	9.8
SPC	0	0	0	0	0	1.0	1.6	2.0	2.0	2.0
Total LOW	0	0	1.7	3.2	4.9	7.5	9.5	11.8	11.8	11.8
SKA1-MID										
Site	0	0	0.8	1.5	2.2	3.0	3.5	4.4	4.4	4.4
DRUPS	0	0	0	0	0.2	0.2	0.2	0.2	0.2	0.2
Remote PV	0	0	0	0	0.2	0.2	0.2	0.2	0.2	0.2
SPC	0	0	0	0	0	0.9	1.4	1.8	1.8	1.8
Total MID	0	0	0.8	1.5	2.6	4.2	5.3	6.6	6.6	6.6
TOTAL	**0**	**0**	**2.4**	**4.7**	**7.5**	**11.8**	**14.8**	**18.4**	**18.4**	**18.4**

8.4.1.2 Hybrid power

The SKA Observatory is actively involved in pursuing alternate power solutions to that presented in §8.4.1.1 above. Not only is the current estimate costly, but it is not sustainable and does not make good use of the renewable sources of energy that are, and are expected to be, available.

The SKA Power Engineer has made a comparative study of possible cost savings if the SKA Observatory were to pursue a hybrid power solutions. In South Africa, this model uses renewable energy during the day, when grid power is generally more expensive, and reverts to grid/diesel power during the night when power from the grid is cheaper and the solar source is not available[19]. In Australia, the model assumes power from a PV station with a substantial battery bank together with diesel generators as backup during the night and periods of low solar irradiation.

Using the same power consumption for the SPCs and the telescope sites as in the costings presented in Table 23, and estimating power tariffs for renewable energy based on current industry expectations, the cost of powering the telescope sites and the SPCs in Australia and South Africa were calculated for the operational phase of the SKA Observatory. The result of this study is shown in Table 25, along with the potential saving over those presented in Table 23.

This initial study has shown that a hybrid solution for powering the telescope sites and the SPCs could potentially realise a 40% saving on the annual cost of power relative to the current estimate.

[19] At the time of writing, the cost of using batteries to store energy for night-time use in South Africa is expected to be more expensive than the cost of grid power.

Table 25: Cost estimates, during the Operations phase, for a hybrid power solution that includes renewable energy, and the associated savings relative to the current estimates.

Telescope	Location	Rate (€/kWh)	Consumption (kW)	Annual cost (€M)	Saving
SKA1-LOW	Site	0.18	3300	5.2	47%
	SPC	0.12	1900	2.0	-
			SKA1-LOW TOTAL	7.2	39%
SKA1-MID	Site	0.06	4220	2.2	50%
	DRUPS			0.2	-
	Remote PV			0.2	-
	SPC	0.06	1700	0.9	50%
			SKA1-MID TOTAL	3.5	47%
			TOTAL POWER	**10.7**	**42%**

The SKAO will actively pursue further industry engagement aimed at implementing power solutions in both Australia and South Africa that maximise the use of renewables and minimise cost over the life of the Observatory. SKAO will work closely with colleagues from CSIRO and SARAO to take advantage of their extensive experience in the relevant national contexts.

8.4.2 Computer hardware refresh and decommissioning funds

The SKA Observatory Convention states:

> *The SKAO may establish a fund for future liabilities associated with construction, operation, upgrade and decommissioning.*

As such, two funds are being built during the early years of operation. These funds are for the refresh of the computer hardware, and for the eventual decommissioning of the SKA telescopes, including the restoration of those sites.

8.4.2.1 Computer hardware refresh

It is anticipated that at least some of the telescope components will have lifetimes as short as a few years, and obsolescence management is therefore key to their operational support (§6.6.15). This plan builds a hardware refresh fund from 2023 at €3.75M/yr. The SDP CDR stated that a refresh of the HPC hardware would be required 5-years after the full deployment of SDP, at a cost of approximately €24M. A further €5M is required for the refresh of other computer hardware (i.e. PSS, PST, TM and networking hardware). Further study into the different refresh options will be undertaken as part of the hardware risk mitigation plan [RD17]. For now, a fund which provides a sum of €30M by 2030 for a refresh of all computer hardware is assumed.

8.4.2.2 Decommissioning

The expected lifetime of the SKA Observatory is 50 years (§6.1, Principle 6). This does not imply, however, that the SKA1-LOW and SKA1-MID telescopes being deployed in Phase 1 of the project will operate unchanged for the entire 50-year period: they may be upgraded or replaced or even terminated, depending in part on the evolution of scientific priorities. Accordingly, the Level-1 requirements to which the telescopes are being designed do not specify a 50-year lifetime. The Hosting Agreements state:

SKAO shall … be solely responsible for all aspects of the SKA Project … including … decommissioning and restoration of the Site.

Decommissioning and site restoration are the final phase of the SKA Project (Figure 25). The detailed requirements for this phase have not yet been established, and an implementation plan has therefore not yet been developed.

The fund to provide for decommissioning has been set to zero for the duration of the construction phase of the observatory, and then begins to build at €2M/yr during the operations phase.

8.5 Cost Risks

There are inherent risks associated with the budgets presented. In particular, there is no escalation of costs to take into account increasing costs due to:

- inflation;
- progression of staff along pay-scales; and
- exchange rate fluctuations.

Furthermore, in this Revision of the Operations Plan (Rev03) staffing and non-staff costs are evaluated on different cost-basis. That is, non-staff costs are currently presented in 2017 Euros, whereas staffing costs have been calculated using 2020 sterling (£) and converted to Euros (using the current standard exchange rate for the project of £1 = €1.1). For Revision 4 of the Operations Plan, all costs will be aligned and escalated to 2020 economic conditions.

To manage these, and potentially other risks, the Director-General will hold a contingency line in the budget, which is €2.5M/yr in this revision of the Plan.

8.6 Summary

Table 26 provides an overall summary of the non-capital cost for SKA1 for the period 2021-30. The 10-year non-capital cost for the SKA Observatory is estimated to be €761M.

Table 26: Estimated overall Observatory budget.

Location	**Type**	**Amount (€M)**									
		Construction							**Operations**		
		2021	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
SKA Observatory	Non-staff	9.1	10.6	12.6	13.5	14.5	15.3	15.8	16.4	14.9	14.5
	H/ware refresh	0	0	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
	Decommissioning	0	0	0	0	0	0	0	2.0	2.0	2.0
	SKA Obs. Dev.	0	0	0	0	0	0	0	0	0	0
UK	Staff	15.4	16.4	16.3	17.2	18.1	18.4	18.6	14.9	14.6	14.5
	Non-staff	0.6	0.5	0.6	0.6	0.6	0.6	0.6	0.3	0.3	0.4
AUS	Staff	2.1	4.2	6.8	8.8	10.6	11.8	12.4	11.7	11.7	10.8
	Non-staff	0.3	0.6	5.2	9.2	11.7	16.8	20.5	25.7	25.6	25.6
RSA	Staff	2.0	3.3	5.6	7.7	9.1	10.1	11.5	10.7	10.7	9.9
	Non-staff	1.2	1.8	4.2	7.8	8.5	12.9	15.5	18.5	18.6	17.1
TOTAL		**30.6**	**37.3**	**55.0**	**68.8**	**76.9**	**89.4**	**98.7**	**104.0**	**102.2**	**98.5**