



PROJECT EXECUTION PLAN

PRE-CONSTRUCTION PHASE FOR THE SQUARE KILOMETRE ARRAY (SKA)

Document number MGT-001.005.005-MP-001
Revision J
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Date 2011-01-12
Status..... Final

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DOCUMENT HISTORY

Revision	Date Of Issue	Engineering Change Number	Comments
A	2010-08-03	-	First draft release for internal discussion
B	2010-08-03	-	Updated after internal discussion. Distributed to Tiger Team
C	2010-08-26	-	Updated with inputs received from TT. Distributed for 2010-08-31 telecon.
D	2010-09-10	-	Updated with inputs received from TT since previous telecon. Distributed for 2010-09-13 telecon.
E	2010-09-24	-	Updated with inputs received from TT since previous telecon. Distributed for end of September face to face meeting.
F	2010-09-28	-	Updated with inputs from TT and edits of existing text
G	2010-10-07	-	Updated with input from the face to face meeting in Manchester, 29 Sept-1 Oct
H	2010-10-14	-	Refinements and formatting. Added new cost tables.
I	2010-10-15	-	Distributed to SSEC and ASG.
J	2010-12-02	-	Revised version for external review

DOCUMENT SOFTWARE

	Package	Version	Filename
Wordprocessor	MsWord	Word 2007	Project_Execution_Plan_Rev_J__2Dec10_Clean
Figures	Visio, Projects and Powerpoint	2007	PEP Rev H Drawings.vsd, Levels for Rev H.pptx, PEP Plan.mpp.

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LIST OF ABBREVIATIONS

2-PAD	Two Polarisation All Digital	EMBRACE	Electronic MultiBeam Radio Astronomy
A.....	Aperture	ConcEpt	
AA	Aperture Array	EMC.....	Electromagnetic Compatibility
AA-low	Low Frequency Aperture Array	e-MERLIN	electronic Multi-Element Radio Linked
AA-mid	Mid Frequency Aperture Array	Interferometer Network	
AAVP	Aperture Array Verification Program	EoI	Expression of Interest
AAVS	Aperture Array Verification System	EoR	Epoch of Reionization
ADC.....	Analogue to Digital Converter	EVLA	Expanded Very Large Array
AGN.....	Active Galactic Nucleus	FAST	Five hundred meter Aperture Spherical
AIP.....	Advanced Instrumentation Program	(Radio) Telescope	
ALMA	Atacama Large Millimetre Array	FCA	Functional Configuration Audit
APERTIF.....	APERture Tile In Focus	FLOP	FLOating point OPerations per Second
AR.....	Acceptance Review	FMEA.....	Failure Mode and Effect Analysis
arcmin	arcminute or minute of angle	FP	Framework Program
ASIC.....	Application-Specific Integrated Circuit	FPGA.....	Field Programmable Gate Array
ASG	Agencies SKA Group	FTA	Fault Tree Analysis
ASKAP	Australian SKA Pathfinder	FTE.....	Full Time Equivalent
ASTRON.....	Netherlands Institute for Radio Astronomy	Gbps	Giga Bits per Second
ATA	Allen Telescope Array	GCAM	Global Capability Assessment Model
BEST	Basic Element for SKA Training	GHz.....	Giga Hertz
CDR	Critical Design Review	GSMT.....	Giant Segmented Mirror Telescope
CMOS.....	Complementary metal-oxide- semiconductor	GW	Gravitational Wave
CoDR	Concept Design Review	HERA	Hydrogen Epoch of Reionisation Array
COTS	Commercial Off The Shelf	HI.....	Neutral Hydrogen
COST	European Cooperation in Science and Technology	HPC.....	High Performance Computing
CSIRO	Australia's Commonwealth Scientific and Industrial Research Organisation	IEEE	Institute of Electrical and Electronics Engineers
dB.....	Decibel	ICT	Information and Communication Technologies
DRM	Design Reference Mission	ICRAR.....	International Centre for Radio Astronomy Research
DSP.....	Digital Signal Processing	IF	Intermediate Frequency
DVA	Dish Verification Antenna	I/O	Input/Output
DVP	Dish verification Program	IP	Intellectual Property
EC.....	European Commission	IT	Information Technology
E-ELT	European Extremely Large Telescope	JRA.....	Joint Research Activity
e-EVN	electronic European VLBI Network	JWST.....	James Webb Space Telescope
		K	Kelvin

KSP	Key Science Project	R&D	Research and Development
Large-N small-D	Large Number Small Diameter	RF	Radio Frequency
LOFAR	Low Frequency Array	RFI	Radio Frequency Interference
LNA	Low Noise Amplifier	RFT	Request for Tender
LSST.....	Large Synoptic Survey Telescope	RFP	Request for Proposal
LWA	Long Wavelength Array	S&C.....	Software and Computing
M&C.....	Monitoring and Control	SE	System Engineer
M€.....	Millions Euro	SEMP	System Engineering Management Plan
MeerKAT	The precursor array being build on site in the Karoo	SKA	Square Kilometre Array
MHz.....	Mega Hertz	SKA1	Phase 1 of the SKA
Mpc.....	Mega Parsec	SKA2	Phase 2 of the SKA
MRO.....	Murchison Radio-astronomy Observatory	SKA3	Phase 3 of the SKA
Ms	Mega seconds	SKADS.....	SKA Design Study
MSP.....	Millisecond Pulsar	SKAMP.....	SKA Molonglo Prototype
MW	Mega Watt	SOMI	Statement of Mutual Interest
MWA.....	Murchison Widefield Array	SPF.....	Single Pixel Feed
NL.....	Netherlands	SPDO	SKA Program Development Office
NRC-HIA	Canada's National Research Council - Herzberg Institute of Astrophysics	SPO.....	SKA Project Office
NRE	Non Recurring Engineering	SRL.....	System Readiness Level
OBSPF.....	Octave-Band Single-Pixel Feed	SRR	(Sub)System Requirements Review
OMT	Ortho Mode Transducer	SSEC.....	SKA Science and Engineering Committee
PAF.....	Phase Array Feed	Tb/s	Tera bits per second
PAFSKA.....	Phased Array Feed for SKA	Tsys	System Temperature
PAPER.....	Precision Array to Probe the Epoch of Reionization	Tsky	Sky Temperature
Pb/s.....	Peta (10^{15}) bits per second	TDP.....	Technology Development Programme
PCA.....	Physical Configuration Audit	TMT	Thirty Meter Telescope
PDR	Preliminary Design Review	TRL	Technology Readiness Level
PHAD.....	Phased Array Demonstrator	TRR	Test Readiness Review
PM.....	Project Management/Manager	UK.....	United Kingdom
PO	Participating Organisation	USA.....	United States of America
PrepSKA	Preparatory Phase of the SKA	UV	Interferometer coordinate system
PRR.....	Production Readiness Review	VHDL	Very-High-Speed Integrated Circuits Hardware Description Language
PU	Public	VO	Virtual Observatory
Py	Person Year	WBSPF.....	Wide-Band Single-Pixel Feed
Q	Quarter	WIDAR.....	Wideband Interferometric Digital ARchitecture
R.....	Report	WP.....	Work Package
RAM	Reliability, Availability, Maintainability	WPC.....	Work Package Contractor
		z.....	Redshift

Summary

The Square Kilometre Array is a multi-purpose radio telescope covering the frequency range from 70 MHz to >25 GHz that will play a major role in answering key questions in modern astrophysics and cosmology. It will be one of a small number of cornerstone observatories across the electromagnetic spectrum that will provide astrophysicists and cosmologists with a transformational view of the Universe.

For the past 2.5 years, the global radio astronomy community has been engaged in the development of the system design for the SKA as a major part of the Preparatory Phase of the project. The end of the Preparatory Phase is now approaching, and a number of major decisions need to be made so that, at the end of 2011, the international SKA project can progress to the Pre-Construction Phase (2012-15). These decisions include approval of funding for the completion of the Preparatory Phase and for the Pre-Construction activities, the establishment of a legal entity for the SKA Organisation, and the selection of the SKA site. (A single site for the SKA is assumed in this document.)

The goals of the Pre-Construction Phase are to 1) progress the SKA design to the point that Production Readiness Reviews have been successfully completed and contracts for construction of major sub-systems have been let, 2) advance the infrastructure roll-out on the selected site to the point where sub-systems can be deployed (assuming the funds for infrastructure development are made available), and 3) mature the SKA legal entity into an organisation capable of carrying out the construction, verification, and operation of the telescope.

This Plan sets out the strategies for carrying out the Pre-Construction Phase, the work to be done and resources required to complete the Preparatory Phase and to carry out the Pre-Construction Phase, potential partnerships to carry out the work, and the governance principles for the legal entity forming the SKA Organisation in this phase. It will enable the start of construction of the first phase of the SKA and convergence on a viable technical pathway to the full SKA. The goal of this Plan is to provide the Funding Agencies and Governments in the Agencies SKA Group with the appropriate information to allow them to assess the scope and feasibility of the work proposed and, in some cases, facilitate the funding for the Pre-Construction Phase.

Phased implementation of the SKA

The construction of a radio telescope with a collecting area approaching one million square metres across a wide frequency range is a major undertaking and is planned to be implemented in phases in order to spread the cost impact. Phased implementation is an effective strategy for an aperture synthesis telescope which can start operating before construction is completed. The international project has adopted the following terminology to describe this phased approach: SKA1 is the initial deployment (10%) of the array at low and mid-band frequencies costing 350 M€ (in 2007 currency units) and is a sub-set of Phase 2 (SKA2), SKA2 is the full collecting area at low and mid-band frequencies (~70 MHz to 10 GHz), while Phase 3 (SKA3) sees the implementation at higher frequencies of up to 25 GHz or more. The SKA1 facility will represent a major step forward in terms of sensitivity, survey speed, image fidelity, temporal resolution and field-of-view. It will open up new areas of discovery space and demonstrate the science and technology underpinning SKA2. SKA2 will have 10 times the sensitivity and 100 -10000 times the survey speed of SKA1 and will transform astronomy.

Project Schedule

The project schedule for the low and mid-band frequencies is divided into six major phases: 1) Preparatory (2008-2012), 2) Pre-construction (2013-2015), 3) SKA1 construction (2016-2019), 4) SKA1 operations (2020→), 5) SKA2 construction (2018-2023), and 6) SKA2 operations (2024→). The schedule for SKA3 is not well-defined at this point in time.

Science Drivers

The five key science areas defined by the astronomy community as driving the specifications of the SKA, together with the Exploration of the Unknown, are described in detail in “Science with the Square Kilometre Array” (eds. C. Carilli and S. Rawlings) [1]. These drive the system design for the telescope. SKA1 will enable revolutionary science at decimetre wavelengths, with a particular focus on pulsars and gravitational wave astronomy, and H I in the distant and the nearby Universe. With its wider wavelength range, 10 times greater sensitivity than SKA1, and enormous increase in survey speed, SKA2 will transform our understanding of many key areas including: the formation of the first structures as the universe made its transition from a largely neutral state to its largely ionised state today; cosmology including dark energy via baryonic oscillations seen in neutral hydrogen; the properties of galaxy assembly and evolution; the origin, evolution and structure of magnetic fields across cosmic time; strong field tests of gravity using pulsars and black holes including measurements of black hole spin and theories of gravity, and the exploration of the dynamic radio sky with far greater sensitivity and instantaneous sky coverage. The ability of the SKA to detect a wide range of interstellar molecules will impact the detailed study of planet formation in proto-planetary disks.

SKA Design

The international SKA project has adopted a Baseline Design for the project which incorporates a low frequency aperture array operating at frequencies up to 450 MHz and an array of dishes with single pixel feeds initially operating at frequencies up to 2 GHz but capable of 10 GHz in terms of antenna accuracy. The Baseline Design will enable the key SKA1 science goals of understanding the role of neutral hydrogen in the early Universe, testing theories of gravity in extreme environments, and discovering gravitational waves.

The Project has also identified an Advanced Instrumentation Program (AIP), elements of which could be implemented in Phase 2 of the telescope construction. The AIP includes phased array feeds (PAFs) for the dishes and mid-frequency dense aperture arrays (AA-mid), both of which provide greatly expanded fields of view for fast surveying, as well as wide-band single-pixel feeds (WBSPFs) with much wider frequency coverage than currently available feeds. A review point is built into the schedule to assess whether any of the AIP technologies have reached sufficient maturity to be incorporated in SKA1 to enhance its performance.

Description of Work

Work in the post-2011 period (Preparatory Phase and Pre-Construction Phase) will be carried out on the Baseline Design and the Advanced Instrumentation Program (AIP) with the aim of preparing the international project for start of the construction of SKA1 in 2016. Key to this effort is the system

engineering approach and formal project management adopted during the system design in the Preparatory Phase. Eleven areas will be addressed: 1) management of the pre-construction phase and management support such as quality assurance, configuration management, and procurement, 2) science, 3) overall system, 4) maintenance and support, 5) dish sub-system, 6) aperture array sub-systems, 7) signal transport and networks, 8) signal processing, 9) software and computing, 10) power, and 11) site and infrastructure. This Plan provides a top-level Description of Work and a Work Breakdown Structure for these Work Packages, lists of milestones and deliverables, and the project structure, dependencies, and schedule including the planned formal reviews. The Risk Strategy and Risk Management principles are also outlined.

Project Model

The SKA project will have a strong central project office (SKA Project Office, SPO) with management and system design authority. The SKA Organisation, through the SPO, will contract the work on major subsystems to a small number of work package contractors. It is expected that work package contractors will be consortia of Participating Organisations (PO) and industrial partners, but could also be individual companies or POs. By forming consortia, the talent, capacity and ideas required to carry out large work packages can be assembled from several organisations so as to make maximum use of expertise.

The day-to-day project management and coordination will be undertaken by the SPO whose Director will report to a governing Board or Council. The SPO mandate in the pre-construction phase is to manage the successful design and development of SKA technology, and initiate procurement for SKA1 construction, as well as lay the foundations for the later phases of construction, verification, and operation. The main activities and responsibilities of the SPO will be: 1) provide the core management structure for the successful delivery of the SKA; 2) have specification and design authority; 3) provide overall project management, schedule and budgetary control; 4) prepare for and procure, detailed design and verification work from academic / industry consortia (Work Package Contractors (WPCs)); 5) provide project-level system engineering; 6) manage and provide support for contractual interactions between WPCs and the SPO; 7) monitoring of work-package progress and integration of work package deliverables; 8) initiating procurement contracts for SKA1 construction; and 9) own and manage the SKA brand and provide public outreach activities for the project.

Consortia of POs and industry will be required to deliver successfully the large work packages. The POs contain the largest reservoir of domain knowledge in the project, and they will have carried out most of the work to reach the end of the Preparatory Phase. They will be collaborators in setting up the pre-construction project and will carry out work packages on SKA sub-systems. The size and complexity of the SKA indicates that an industry culture in managing and costing the project is essential and that there is close engagement of industry throughout the pre-construction phase.

As the SKA Project moves through the design, development, construction and operational stages, industry will play a crucial role in the delivery and through-life support of the technologies and infrastructure. Industry participation at the pre-construction phase will be underpinned by strategic collaborations with commercial players, among them niche R&D companies, followed by increasing participation through pre-competitive prototyping work, commercial contracts with volume

manufacturers, technology systems vendors, site services and installation firms, and power and data transmission specialists.

A survey of the engineering competencies of the Participating Organisations involved in the SKA Precursors, Pathfinders, and Design Studies shows that, for each of the Work Packages in the Pre-Construction Phase, there are a number of potential partners to work together in Consortia as Work Package Contractors. In addition, as part of PrepSKA Work Package 5, a survey of the availability and competencies of potential industrial partners in the SKA around the world is being undertaken. It is premature at this stage to identify strawman sets of partners or particular commercial companies that would form the Consortia.

Resource Requirements

The resources required to carry out this work are a total of 90.9 M€ over the 4 year period, comprising 63.0 M€ for Work Package contracts and 27.9 M€ for SPO costs. The SPO costs include staff costs for project management, system engineering, science support for system engineering, and site work (19.7 M€), and office infrastructure and operational costs for the SPO (8.2 M€). 100 k€ has been adopted for the person-year cost for salary and benefits for both WPCs and SPO. No institute overhead or explicit contingency has been included. It should be noted that the cost of developing the Advanced Instrumentation Program to PDR level in the pre-construction phase is 10 M€.

Governance

The International SKA Organisation is the legal entity that will design, build and operate the SKA. It will be set up and governed to carry out this task on behalf of the SKA sponsors, those agencies who will pay for SKA construction and operation. This organisation will be responsible for setting up the SKA Project Office (SPO) and setting policy on all matters of procurement and operation.

This Plan provides a description of the process now underway to define the optimum legal structure, and the associated optimum location for the new legal entity. The outcome of this process will be known in early 2011. In terms of developing the Execution Plan, it is assumed that a legal structure, which could be in the form of a not-for-profit company, will be established. Behind that legal structure will be a set of statutes under an implementation agreement to which a set of funding partners will accede. It is expected that the SKA Organisation will be governed by a Board/Council that is composed of government and science representatives from each of the contributing countries. The SPO is the operational arm of the SKA Organisation and its Director reports to the Chair of the Board/Council.

The management of the international project in the Pre-Construction Phase will differ in two fundamental respects from that now in operation for the Preparatory Phase. 1) The Board/Council of the new legal entity will replace the current tri-partite governance provided by the SKA Science and Engineering Committee (SSEC), the Agencies SKA Group (ASG), and the PrepSKA Board. 2) SKA design work by POs will be carried out on the basis of formal contracts under the overall authority of the SPO, instead of on the current best-efforts basis. The Board/Council will approve the allocation of major work packages to POs and Industry after a bidding and review process managed by the SPO, or as direct allocations of work following the review process.

Socio-Economic benefits of the SKA

A description of the Socio-economic Benefits of the SKA is provided, based on the outcomes of a meeting on this subject organised by COST in March 2010. The SKA can be expected to stimulate innovation in ICT and sensor technology, serve as a global model for 100% renewable energy, serve as an enabler for improved global science-industry linkages, and stimulate human capital development and employment.

1 Introduction

The global radio astronomy community is currently engaged in the development of the system design for the SKA as a major part of the Preparatory Phase of the project. However, the end of the Preparatory Phase is now approaching, and a number of major decisions need to be made so that, at the end of 2011, the international SKA project can progress to the Pre-Construction Phase (2012-15). These decisions include approval of funding for the completion of the Preparatory Phase and for the Pre-Construction activities, the establishment of a legal entity for the SKA Organisation, and the selection of the SKA site.

The goals of the Pre-Construction Phase are to 1) progress the SKA design to the point that Production Readiness Reviews have been successfully completed and contracts for construction of major sub-systems have been let, 2) advance the infrastructure roll-out on the selected site to the point where sub-systems can be deployed, and 3) mature the SKA legal entity into an organisation capable of carrying out the construction, verification, and operation of the telescope.

This document sets out the work to be done and resources required to complete the Preparatory Phase and to carry out the Pre-Construction Phase, the potential partnerships involved, and the management of this phase of the project including a description of the governance principles for the SKA Organisation as a legal entity.

1.1 Purpose of the document

The purpose of this Plan is to provide the Funding Agencies and Governments in the Agencies SKA Group with the appropriate information to allow them to assess the scope and feasibility of the work proposed and, in some cases, facilitate the funding for the Pre-Construction Phase for the SKA.

1.2 Scope of the document

The flow of the document is as follows:

- A summary of the underlying management strategies and philosophies for the Pre-Construction including the roles of the SKA Project Office and Work Package Contractors (Participating Organisations and Industry), the overall system engineering approach, and cost estimation strategy
- A brief section on the science drivers for the SKA
- A description of the design process for the SKA including an overview of the current system description and a discussion of the evolution from SKA1 to SKA2
- A summary of the Work Packages in the Description of Work, the schedule (Gantt chart), and the overall resource requirement. A detailed description of each Work Package is given in an Appendix together with its milestones, deliverables and resources

- A brief section on possible partnerships to carry out the Work Package contracts based on the competencies displayed in the SKA Precursors, Pathfinders and Design Studies
- A summary of the principles underlying the future governance of the project and a possible organisation chart.
- A section on Project Management and key personnel. The detailed staffing plan for the SKA Project Office is given in an Appendix.
- A description of the Risk Strategy and Risk Management Plan
- An outline of the Technology and Industry Engagement Plan
- A section on Outreach objectives during the Pre-Construction Phase
- A summary of the Socio-Economic Return of the SKA based on the results from the COST Workshop held in March 2010
- A number of Appendices containing detailed information on aspects mentioned in the main body of the document, as well as background information on the Precursors, Pathfinders and Design Studies.

2 Management Strategies and Philosophies for the Pre-Construction Phase

The Pre-Construction Phase is a crucial period in the overall SKA planning, in ensuring the SKA is ready for construction not only in terms of design, but also with respect to procedures, infrastructure, governance and organisation. This section describes the most important aspects of how the Pre-Construction Phase will be carried out. Section 2.1 briefly describes the assumed status at the end of the Preparatory Phase. A key aspect of this are firmly understood requirements (functional and non-functional) for SKA1, a system design and a total system cost estimate. Section 2.2 outlines the roles of the International SKA Organisation, the SKA Project Office, and Work Package Contractors (Participating Organisations and Industry), respectively. Section 2.3 outlines the Systems Engineering approach adopted in this phase. Section 2.4 describes the basis for cost estimates assumed.

2.1 Project Status at the Beginning of the Pre-Construction Phase

2.1.1 Outputs from the Preparatory Phase

The Preparatory Phase will establish the science specifications and system requirements for SKA1 and the system design will be at Preliminary Design Review level. Costing for the system design will be broken down to the system hierarchy Assembly level. SKA1 receptor technology will have been prototyped and initial verification tests carried out. Functional supporting technology for SKA1 (signal transport, signal processing, and image processing) will have been verified and costed, and first order designs and costs for non-functional supporting sub-systems (infrastructure, power, buildings) will be available. The SKA site will have been selected, and the antenna array configuration for SKA1 determined.

2.1.2 Preparation for Phase 2 of the SKA

Two major milestones will have been met by the end of the Preparatory Phase concerning SKA2: 1) initial science and technical requirements for SKA2 will have been set, and 2) an outline of the system design for SKA2 will have been developed, sufficient to provide information on the extension of SKA1 to SKA2, and taking into account the potential introduction of technology of the Advanced Instrumentation Program (see Sections 4.2.1.2 and 4.2.4)

2.2 Organisation and Roles

2.2.1 The Role of the SKA Organisation

The SKA Organisation is the legal entity that will design, build and operate the SKA. It will be set up and governed to carry out this task on behalf of the SKA sponsors, those agencies who will pay for SKA construction and operation. This organisation will be responsible for setting up the SKA Project Office (SPO) and its Council or Board will be responsible for setting policy on all matters of procurement and operation.

The top level project structure is shown in Figure 1.

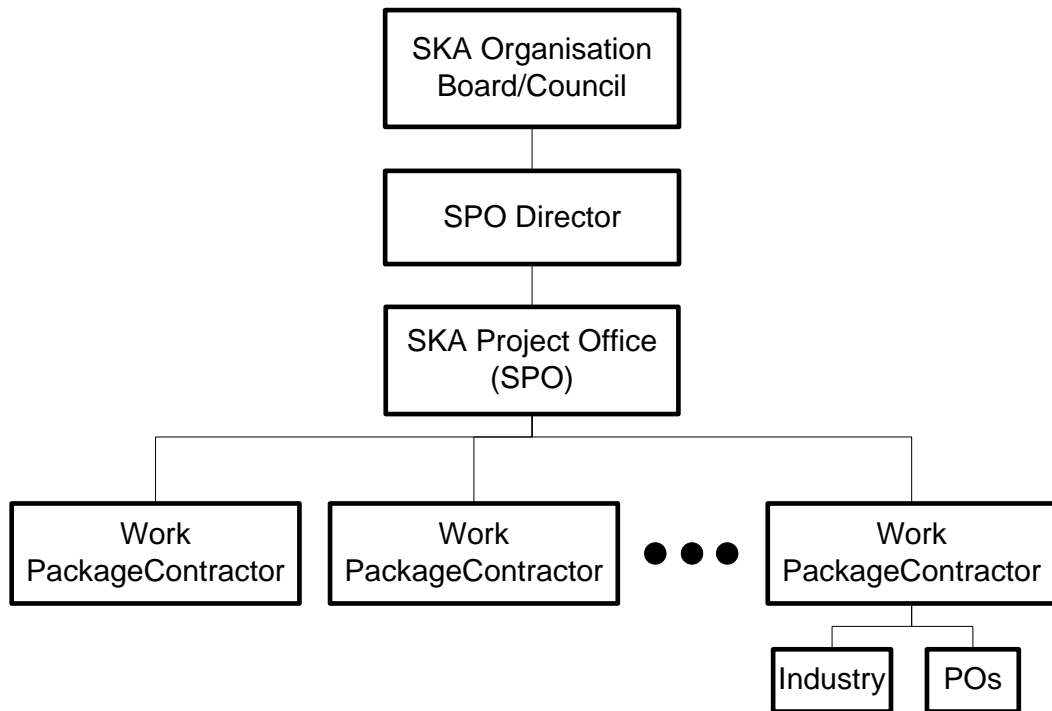


Figure 1: The global relationships of the SPO, participating organisations (POs) and industry partners. The figure illustrates how Work Package Contractors the consortia will normally consist of Participating Organisations (individually or in consortia) and industry. (For specific work packages, the SPO will let direct contracts with POs or industry).

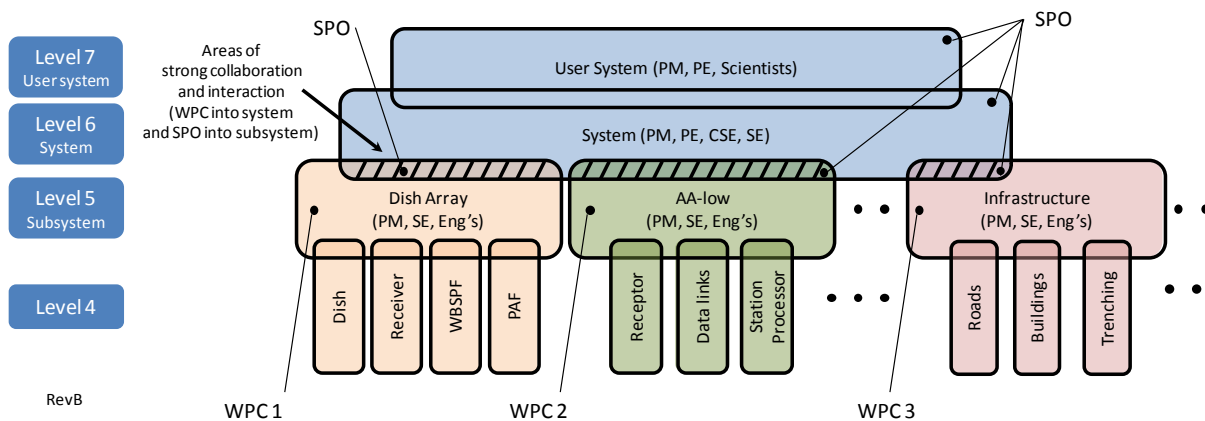


Figure 2: The relationships and interactions between system level activities carried out at SPO and the subsystem activities contracted to Work Package Contractors.

The SKA project will have a strong central project office with management and system design authority. The SKA Organisation, through the SPO, will contract the work on major subsystems to a small number of work package contractors. It is expected that work package contractors will be consortia of Participating Organisations (PO) and industrial partners, but could also be individual companies or POs. By forming consortia, the talent, capacity and ideas required to carry out large

work packages can be assembled from several organisations so as to make maximum use of expertise.

Figure 2 shows these relationships in more detail as well as the connections between the SPO and the work package contractors. In Figure 2 PM refers to Project Manager, PE to project Engineer, CSE to Chief System Engineer and SE to System Engineer. The overlap shown between levels 6 and 5 indicates the close collaboration and involvement between the SPO and WPCs, as well as inside the WPCs. This is required for both managerial and system design and engineering. The relationship between the SPO and the WPCs will be formal, but highly collaborative, managed via a formal contract structure with well-defined deliverables and milestones.

WPCs in the form of consortia will have a formal structure with a formal agreement in place between the consortium members, so that the consortia can take on legally enforceable contracts. Further there will be a proper management structure for the consortium which will provide a single point of contact for management issues to the SPO.

For some Participating Organisations, a formal contract may not be the appropriate mechanism for ensuring the delivery of the work and carrying the associated risk. This will be examined on a case-by-case basis.

2.2.2 The Role of the SKA Project Office

The day-to-day project management and coordination will be undertaken by the SPO executive officers who will report to a governing council representing the stake holders. The main activities and responsibilities of the SPO will be:

1. Provide the central management for the successful delivery of the SKA;
2. have specification and design authority;
3. provide overall project management, schedule and budgetary control;
4. prepare for and procure, detailed design and verification work from academic / industry consortia (Work Package Contractors (WPCs));
5. provide project-level system engineering;
6. manage and provide support for contractual interactions between WPCs and the SPO;
7. monitoring of work-package progress and integration of work package deliverables;
8. initiating procurement contracts for SKA1 construction;
9. own and manage the SKA brand and provide public outreach activities for the project.

The size and structure of the SPO directly reflects the work needed to carry out these activities. In more detail, the SPO:

- a) contains all the staff necessary to carry out the work listed above. In particular, the specification and design authority refer to in item 2 above will reside in the engineering

management staff who will have the appropriate domain knowledge. The staffing level is ramped up in phases, appropriate to the amount of work to be carried out;

- b) reports to the Council or Board of the SKA Organisation at regular intervals;
- c) takes routine decisions on the design and construction of the SKA, subject to policy provided by the Council or Board of the SKA Organisation;
- d) controls the SKA budget;
- e) develops and manages the work breakdown structure and the project schedule;
- f) is responsible, through the Council or Board, for assigning work packages to the contracting consortia;
- g) establishes contractual agreements with consortia, POs and Industry, including determining the value of in-kind contributions;
- h) hires and manages SPO staff;
- i) maintains oversight, authority and control of the system definition and design, integration, testing, qualification, roll out, verification and validation, configuration management and quality control;
- j) manages technical and non-technical risk at project and system level, subject to high-level policy;
- k) manages shipping, receiving and storage of equipment for the project.
- l) develops/manages operational and maintenance support plans.
- m) manages contract amendments and changes;
- n) organises independent project reviews for the entire project;
- o) manages all aspects of top-level system engineering including setting technical standards;
- p) manages interaction with the site owner(s).

2.2.3 Work Package Contractors

The expectation is that consortia of POs and industry will be required to deliver successfully the large work packages. The POs contain the largest reservoir of domain knowledge in the project, and they will have carried out most of the work to reach the end of the Preparatory Phase. They will be collaborators in setting up the pre-construction project and will carry out work packages on SKA sub-systems. The size and complexity of the SKA indicates that an industry culture in managing and costing the project is essential and that there is close engagement of industry throughout the pre-construction phase.

In more detail:

- a) Perform effective management of the work package;
- b) Work with the SPO on sub-system definition and establishing the detailed work programme.
- c) Fulfil the terms of the contractual reporting in a timely and efficient manner;

- d) In a collaborative spirit, respond positively and in a timely manner to all reasonable requests for information from the SPO regarding the progress of the work package independent of the contractual reporting requirements;
- e) During execution shall respond to requests for minor project modification from the SPO after due analysis of their impact;
- f) Manage all sub-contracts to be placed with industry within the context of the work package;
- g) The work package consortia will carry the risk associated with their deliverables. The SPO will manage risk at the system level.

The Technology and Industry Plan for the SKA is described in section 10.

2.2.3.1 Industry-SPO Relationships

Industry will play a direct role in supporting the SPO in two ways: 1) consulting on the set-up and structure of system engineering procedures, project management, and budgetary control; 2) providing technical support and experience with tools for the three activities in 1), throughout the project. Involving industry in this way can amplify the capacity of the SPO to manage a large project. For example, in complex projects specialised tools are used to isolate and track project requirements, and sophisticated approaches to expenditure management (e.g. tracking earned value), IP management and status reporting are used. Setting up a relationship between the SPO and industry in these tasks will require a core of SPO people with direct industry experience in managing large, complex projects, and will be managed so that the SPO, itself, retains full knowledge and responsibility for these activities.

2.2.3.2 Assignment of Work Packages

Two approaches to the assignment of work packages can be considered: a bottom up approach in which work packages are bid for and allocated competitively in a process managed by the SPO, or a top down approach in which the Board/Council of the SKA Organisation allocates work packages following a review process to determine compliance with the aims of the Work Package and suitability of the proposed Contractors.

In the bottom-up process, the Board/Council could call for expressions of interest from organisations, industry or consortia to undertake work packages. Bids would be made on the basis that the necessary resources come from national grant programs, industry in-kind, organisational resources, or in the case of direct contracts to industry from the SPO, funds would come from the SPO allocation. The bidding process managed by the SPO would ensure that potential Work Package Contractors have the capability and adequate plans to carry out the work. Mechanisms may be needed to ensure that each partner in the SKA Organisation has a commensurate stake in terms of Pre-Construction Phase project implementation and resource contribution. This might involve post-competitive re-balancing. The SPO would be responsible for making recommendations on the earned value of each Work Package to the Board/Council for approval.

In the top-down version of Work Package allocation, the Board/Council would invite countries/institutions/consortia to take on specific Work Packages on the basis of domain knowledge and potential availability of resources both in the POs and in industry, and after the SPO

has ensured that potential Work Package Contractors have the capability and adequate plans to carry out the work. Each designated Work Package Contractor would have overall responsibility for funding and delivery, including procurement and industry engagement where appropriate. The SPO would be responsible for making recommendations on the earned value of each Work Package to the Board/Council for approval.

Work Package Contractor management by the SPO after allocation of the contracts is discussed in section 8.2.2.

2.3 System Engineering Approach

For a project as large and complex as the SKA, the adoption and execution of a systems engineering approach is of fundamental importance, and has been adopted for the Preparatory Phase. The System Engineering Management Plan (SEMP) for the SKA [2] lays out how this approach has been implemented in the Preparatory Phase, and this will form the basis of the approach for the Pre-Construction Phase.

The SKA will use a balanced and iterative approach to system engineering to ensure the inclusion of the full spectrum of requirements and engineering disciplines and to provide a continuous view on the total life cycle of the system. The ability to influence the final life cycle costs of any system is particularly significant during the early stages of the project. As the project progresses, the decisions and the non-decisions, which were made or not made upstream, will impact the project downstream.

Since the SKA is a highly complex, large and very distributed project, the successful adoption and roll out of a systems engineering approach within the project is of critical importance. The process will guide and control the work to be done during all phases and at all the levels of the project through to the disposal phase of the project. The system engineering effort during the Pre-construction Phase will build upon, enhance and strengthen the foundation and principles established during Preparatory Phase. This will encompass all aspects of system engineering including requirements management, interface management, configuration management, and risk management. System engineering tools will be adopted and rolled out across the project. As the system design authority, the SPO will lead this effort. However, to ensure the success of this approach it will be important that the major subcontractors (POs, consortia or industry) adopt these principles.

2.3.1 Formal Reviews

Formal reviews will be conducted in adherence to the SEMF and at all levels of the project.

Reviews will include:

- Preliminary design reviews
- Critical design reviews
- Production readiness reviews
- Test readiness reviews

- Acceptance reviews

2.3.1.1 Preliminary Design Reviews (PDR)

The PDR will be conducted at the end of the preliminary design phase and is aimed to review and confirm the final design of the item as reflected in its relevant Architectural Design Description Document. The review will be performed at the conclusion of the functional analysis, verification, synthesis and design verification activities at the end of the preliminary design phase.

2.3.1.2 Critical Design Reviews (CDR)

The CDR will be performed at the end of the detailed design phase and will determine whether the item under review is ready to enter the preliminary production phase.

2.3.1.3 Production Readiness Reviews (PRR)

The production review will be performed at the end of the preliminary production phase. The main aim of this review will be to confirm that the items produced comply with requirements and are ready to go into full scale production. Test and verification results will be reviewed and manufacturing data packs will be audited. The output from this review will be utilised in the full scale production phase to produce the items against the approved set of baseline documents.

2.3.1.4 Test Readiness Reviews (TRR)

The TRR is performed in order to establish whether the specific item is ready for formal testing. Integration and integration testing must be complete, and evidence and proof of test results presented.

The aim of the review will be to verify the readiness of the equipment itself, associated test documentation, and test facilities and equipment in order to start with formal testing/verification.

2.3.1.5 Acceptance Reviews (AR)

The AR will be performed following the conclusion of the verification of the equipment. The aim of the review will be to confirm the completeness and the results of the verification phase. The review will take the form of a Functional Configuration Audit (FCA) and a Physical Configuration Audit (PCA).

The FCA is a formal audit intended to confirm that the equipment has achieved the performance and functional requirements; that it satisfies the characteristics specified in the relevant specifications, interface specifications, and other baseline documentation; and that test plans and procedures were complied with.

The PCA is intended to confirm the physical configuration of the equipment that was tested and to establish the “as-built” configuration.

2.3.2 Readiness Levels

Readiness Levels are a proven means to objectify the state of a system or technology. When applied systematically, they immediately point at areas of high-risk and/or non-compliance. The SKA project has adopted two measures: System Readiness and Technology Readiness.

System Readiness refers to the SKA project at large, starting from the initial phase and ending with the full completion. The System Readiness Levels as indicated in the “V” diagram in Figure 3 follow the project logic – that is: the top level sequence of activities and the major reviews and decision points. The “V” diagram is targeted at verification and validation (testing) at the various system levels. The System Readiness Level (SRL) of the SKA indicates to what extent the SKA system is ready for construction, for verification and validation and for final acceptance. Note that activities overlap at each level: the results of subsystem design typically influence the details of the system architecture, and might in some cases require revision of the user requirements (waivers). Testing of subsystems should take place as soon as possible, and not wait for construction to be completed.

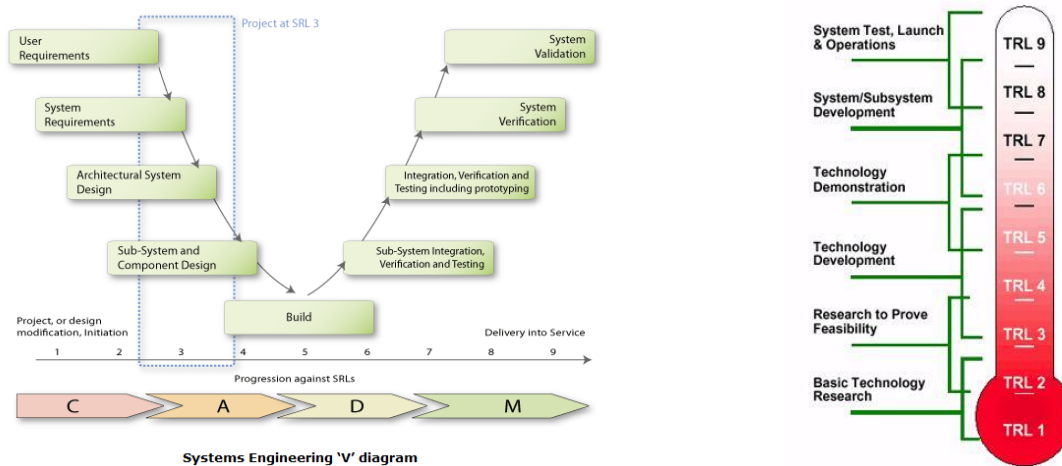


Figure 3: System and technology readiness levels.

(from http://www.aof.mod.uk/aofcontent/tactical/techman/content/srl_whatarethey.htm)

The expected system and technology readiness levels at the end of the Preparatory Phase and the Pre-Construction Phase are discussed briefly in section 7.2.3 and section 0.

2.4 Cost estimation

The cost estimation work undertaken in the preparatory phase will continue into the pre-construction phase. This will be done for the full SKA, so including both SKA1 and SKA2, for their respective planned construction time. This work will inform design decisions, trade-offs and proposals for construction funding.

The principles and process of cost estimation work for the SKA project is described in the “SKA Costing Strategy” [3]. The underlying philosophy of the costing strategy is that that cost estimation will be an ongoing and iterative process throughout the design, development and build stages of the SKA. The confidence levels attributed to cost estimates are predicated on both the maturity of the SKA design and the substantiating evidence in support of the cost estimate. In the pre-construction

phase confidence levels in cost estimations for SKA1 will be high as the design matures to the point that formal invitation to tender documentation has been prepared. Further work will be required to increase confidence levels in cost estimations for SKA2.

The work involved in estimation of project costs will include studies and comparison of costs against analogous systems as well as verification against precursors and pathfinders. It will furthermore include the extracting of cost estimation data from POs and industry and the analysis, assessment and administration of that data.

As the project moves forward, cost estimates will be gathered at opportunities such design and project reviews. The data will be integrated into the full SKA estimate and be reported. The aim will be to continuously refine and narrow down the uncertainty in the cost estimate.

3 Science drivers

3.1 Science Drivers for Phase 1

The science case for the SKA is broad, compelling and, in the case of the Key Science Projects (KSPs), clearly transformational (Carilli & Rawlings 2004). The concept design of SKA1 (Garrett et al. 2010) is driven by the subset of the KSPs that the SSEC have judged are guaranteed to deliver fundamental scientific breakthroughs in the first phase of the project. These are:

- The history of Hydrogen from the Dark Ages to the present day.
- The detection and timing of pulsars to test theories of gravity, discover and study gravitational waves, and probe the properties of supra-nuclear matter.

The design of SKA1 will not compromise on delivering breakthroughs in these core science areas but, within the available budget, should enable a much broader science case that paves the way for SKA2 capabilities and science. Both of the core science areas need the capabilities delivered by the baseline design including low-frequency (70-450 MHz) capable aperture arrays and high-frequency (0.45-3 GHz) capable dishes. Both core science areas have the potential to benefit from enhanced capabilities arising from the Advanced Instrumentation Programme (AIP).

3.1.1 The History of Hydrogen

Study of the Epoch of Reionization (EoR), through neutral Hydrogen (HI) at redshifts $z \sim 6-13$, and hence 100-200 MHz frequencies, has been highlighted by both the AstroNET and Decadal Survey processes as a key frontier in astrophysics. In EoR studies, SKA1 will be used alongside other facilities (e.g. ALMA, JWST, E-ELT/TMT/GSMT), but will undeniably be the most critical component because it provides the only direct measurements of the main baryonic content of the young Universe, and because it has the unique capability of mapping out the large-scale structure informing on how the first galaxies and supermassive black holes formed, how they re-ionized the Universe, and how this evolution reflects evolutions in the underlying dark matter. Mapping the EoR is an essential part of understanding our origins, and the aperture-array element of SKA1 allows this to happen.

To map features in the EoR in the same way that CMB experiments now map features in the epoch of recombination, requires a minimum temperature sensitivity that drives the requirements for the aperture array part of SKA1 in a very simple way. EoR fluctuations will have a (3σ) amplitude ~ 10 mK (similar to the amplitude of the EoR monopole that may prove more challenging to detect as it is an *absolute* measurement against bright foregrounds) providing a firm target for the *differential* measurements inherent in interferometry. For a 10-Ms exposure with a high-filling-factor SKA1 aperture, an $A/T_{\text{sys}} \sim 2000 \text{ m}^2 \text{ K}^{-1}$ gives a (3σ) temperature sensitivity ~ 1 mK in a map with the natural resolution (7 arcmin) of the SKA1 core. This means SKA1 will be the first facility to work in the $S/N > 1$ regime needed for EoR mapping, and by trading some temperature sensitivity for resolution, e.g. by placing some stations out to a radius $r=100$ km., will map EoR fluctuations in the range $\sim 1-7$ arcmin, whilst facilitating the subtraction of spatially-complex polarized foregrounds.

After the latest stages of re-ionization at $z \sim 7$, we expect most of the HI to reside in galaxies, and SKA1 needs the ability to measure this directly by comparing large-scale (~ 50 Mpc) HI measurements with the sum, using stacking techniques, of the HI in galaxies discovered by infrared or millimetre techniques. This provides further justification for SKA1 stations at $r = 100$ km as this delivers the ability to isolate, and hence sum, the emission in galaxies. Sparse aperture arrays provide increased sensitivity at lower frequency (higher redshift) that partially counteracts the combined effects of geometric and cosmic-down-sizing dimming between $z \sim 7$ and $z \sim 2$ where, at 0.45 GHz, with either the aperture array or the dish element, a 10Ms SKA1 exposure achieves $\sim 5\sigma$ HI detections of Milky Way analogues. Stacking techniques will be needed at the higher redshifts, and these will securely delineate the run of HI mass with redshift. Dish-based surveys can, however, directly track HI evolution down to $z=0$ which, in terms of covering large cosmic volumes may benefit from field-of-view expansion (via the AIP), delineating the whole history of atomic Hydrogen.

Bonus science includes arcsec-resolution radio continuum identifying counterparts to the massive photometric (e.g. LSST) and spectroscopic surveys planned, and enabling many of the experiments envisaged in the cosmic magnetism KSP that may prove crucial in the removal of polarized Galactic foreground from the most challenging Dark Ages/EoR experiments. Recent results have shown successful application of HI/optical cross-correlation techniques to measure the HI content of galaxies at $z \sim 0.75$ showing that SKA1 can utilize, and potentially extend (via HI autocorrelation), such techniques, certainly providing complementary information to optical/infrared surveys on the $z \sim 2$ dark-matter power spectrum, and potentially generating world-leading constraints on cosmological parameters. This would set the scene for truly transformational cosmology with SKA2.

Probing the dark ages of the Universe, say between $z=13$ and $z=20$, is another frontier science area that requires SKA1. Although the $T_{\text{sys}} \sim T_{\text{sky}} \sim \nu^{-2.7}$ scaling makes this a sensitivity challenge, the state-of-the-art simulations predict that the fluctuation signal is boosted from the ~ 10 mK EoR level to the ~ 100 mK level, meaning SKA1 has the potential to measure the HI power spectrum in the dark ages, and hence search for the signatures of the first (Population III) stars.

3.1.2 Pulsars and Gravity

Pulsars provide unique, powerful ways to probe gravity in the strong-field regime and to open the gravitational wave window for astrophysics. Accomplishing a program of transformational science requires finding rare, extreme objects, such as pulsars in very tight binaries with compact object

companions and millisecond pulsars (MSPs) with the best spin stability. SKA1 will lead to dramatic increases in the total number of known pulsars – and hence the chances of discovering ‘holy grail’ objects. The real science return derives from long-term, precision timing measurements that measure the evolution of relativistic binaries and to search for low-level perturbations from gravitational waves. For both components of the pulsar/gravity programme, timing needs to be sustained for many years with an SKA that is highly stable, including high polarization stability. For GW detection, sustained timing precision < 100 ns is required for an individual arrival time obtained in, say, a 10 to 30 min integration.

Relativistic binaries with white dwarf, neutron star, and black hole companions can have very small orbital periods (minutes) owing to inspiral caused by gravitational wave emission. Sub-hour binaries will be superb for testing general relativity but these have been selected against in pulsar surveys for a variety of reasons, but especially because of the lack of sky coverage with high A/T_{sys} in the southern sky and because the data processing for the most compact binaries pushes the envelope on computing resources.

Detection of nano-Hertz gravitational waves requires a set of some tens of MSPs with the best spin stability and distributed broadly over the sky in order to measure the correlated timing signal from GWs. The near-term goal is to make a detection using existing telescopes, but it is entirely possible that a detection will not occur without SKA1. More importantly, once a detection is made, a more ambitious, and challenging, programme of characterizing the GW spectrum will certainly require SKA1 with a significant amount of the dish-array devoted to MSP timing.

The location of SKA1 in the southern hemisphere is key to the pulsar programme, along with an A/T_{sys} comparable to the sensitivity of Arecibo and FAST in the north. An array approach allows the A/T_{sys} to be deployed in sub-arrays for timing of pulsars that are bright enough. Optimizing the timing is highly pulsar and direction dependent. Timing precision is limited by a number of factors that include the signal-to-noise ratios of pulse profiles, but can be dominated by an intrinsic pulse-counting effect and by chromatic effects from interstellar scattering. Reducing timing errors from these additional effects requires high timing throughput and measurements at frequencies up to 3 GHz with approximately an octave bandwidth. Pulsar surveys are also optimized with direction dependent frequency ranges. In the Galactic plane, frequencies ~ 1.4 GHz and higher are needed to combat the degradation of the search sensitivity from interstellar scattering. Out of the plane (e.g. latitudes higher than 5 degrees), the survey yield is optimized with lower frequency observations in the 0.4 to 0.8 GHz range, and may obtain significant benefit from the mapping speed of the SKA1 aperture arrays if they reach an upper frequency of ~ 450 MHz.

Pulsar surveys can be conducted in a variety of ways, ranging from blind surveys of the available sky to targeted surveys of point sources identified from continuum surveys culled through panchromatic cross-catalog comparisons that remove galaxies and AGNs in point source catalogs found in deep radio continuum surveys. Blind surveys require a compact array for the processing to be feasible. The targeted approach can use a larger array because it is based on small number of phased-array beams. The expected numbers of new pulsars are of order 2000 canonical and modestly recycled pulsars and 750 MSPs. Of the former group, approximately 1-2% will be extreme binaries, based on the currently known sample, which includes objects such as the double pulsar. The double pulsar has

been transformational in providing tests of GR and has had a wide range of other, astrophysical payoffs. There are undiscovered objects that will be even better.

3.2 Science drivers for Phase 2

The plan for SKA1 ensures breakthrough science early in the project, but the truly transformational science return across all the KSPs will need the full capabilities of SKA2.

SKA1 will make the first maps of the EoR and delineate the HI content in galaxies in the post-EoR Universe. The power of its statistical measurements of the power spectra of galaxies between $z=7$ and $z=0$ will rival, and potentially exceed that of other techniques, and it will have provided the only measurements of large-scale structure in the dark ages ($z=13$ to 20).

In EoR and Dark Ages studies, the chief SKA2 science driver will be to move from the limited resolutions and sky areas observable with SKA1 to higher resolution (e.g. that needed to map ionized structures directly associated with quasars and star-forming galaxies) over a large fraction of the sky, requiring the significant (~ 10 - 100) planned gains in mapping speed. This will provide a definitive, in parts cosmic-variance-limited, map of the EoR and Dark Ages, just as WMAP and Planck will soon have provided for the CMB, and allow a battery of new cosmological tests.

In the post-EoR Universe, the main science driver will be to use the results of the AIP to, in going from SKA1 to SKA2, enhance the mapping speed of the z^2 Universe by a factor ~ 100 - 10000 (depending on the adopted AIP technology) allowing the 'all-sky' and 'thresholded' (i.e. $>5\sigma$) 'billion galaxy' surveys needed to address key questions such as neutrino mass, that is measurable to the lowest limit allowed by particle physics experiments at SKA2 sensitivity, and sub-per-cent accuracy on the dark energy w parameter; both are provided by SKA2 galaxy power spectra (in several independent redshift bins) achieving high signal-to-noise-ratio on features due to Baryon Acoustic oscillations, and allowing marginalization over galaxy bias through accurate measurement of velocity-space distortions.

These same 'all-sky' surveys will generate a rotation measure grid sufficiently fine to study the cosmic history of magnetic fields in environments ranging from the large-scale structure of the intergalactic medium, through the ionized media surrounding galaxies and clusters of galaxies to star-forming regions in our own galaxy. With SKA2 this will probe the origin of magnetic field in the Universe by measuring its evolving strength in this variety of environments, and hence determining its role in the formation of structure from the cosmic web, through galaxies, to stars. The magnetic field KSP places demands on the polarization performance of the SKA that, in any case, bring huge additional benefits for the calibration of the most challenging EoR and pulsar studies.

For pulsars, the main science driver for going from SKA1 to SKA2 is to achieve the full planned increase in sensitivity. For pulsar surveys, SKA2 will then deliver the full census of $\sim 20,000$ normal and ~ 1000 millisecond pulsars in our galaxy, with the concomitant increase in chances of finding the rare 'holy grail' systems, and almost certainly the first known pulsar – black hole system. Such systems can be used to make definitive tests of the Cosmic Censorship Conjecture and the No-Hair Theorem. Pulsar timing experiments will also probe the equation of state of nuclear matter at extreme densities. The increase in timing precision of SKA2 over SKA1 is the main science driver here

because the sensitivity increase needs to allow timing (over $\sim 10 - 20$ days) of all the ~ 1000 millisecond pulsars to the ~ 100 ns time-of-arrival precision needed for their use in a Pulsar Timing Array (PTA). The science that can be done with the SKA2 PTA can go far beyond detection of a cosmic background of gravitational waves (that should be achievable with SKA1): e.g. experiments to measure the spin and mass of the graviton; and, crucially, the ability to pinpoint individual gravitational wave sources, with this capability requiring astrometry to provide distances, and hence long (few-1000 km) SKA2 baselines.

SKA2 will also be a critical instrument for understanding planet formation and astrobiology. The high frequency end of the SKA2 range will be sensitive to optically-thin thermal radiation from the 'pebbles' conjectured to be found where planets grow within protoplanetary disks. SKA2 sensitivity on the few-milliarcsec scale is required to probe the terrestrial planet zones in the nearest circumstellar disks, generating movies of planet growth, and hence informing on our origins that can be further probed by using SKA2 spectroscopy to map out the distribution of complex organic, and potentially biological, molecules. This SKA KSP is the main science driver for high resolution at high frequency (~ 10 GHz) and hence dishes separated from the core to a few thousand km.

4 System Description for the SKA

4.1 Overall System Block Diagram

A high level conceptual block diagram for the SKA is shown in Figure 4. The diagram shows the major subsystems and their interconnections, as well as the main flow of data from the antennas to science-ready data products. Control interconnections between the Operations and Maintenance Centre and the on-site components are not shown.

4.2 Initial System Description

4.2.1 Introduction

The SKA system specification and top-level design derives from the science case for the SKA as given in [1]. The SKA will be realised in two phases in order to take advantage of the advances in technology while realising transformational science at an early phase. The description of the Phase 1 system has been put forward in SKA Memo 125 "Concept Design for SKA Phase 1 (SKA1)" [4] and "Preliminary System Description for Phase 1 of the SKA" [5].

As described in section 3.1, the major science goals for SKA1 will be to study the history and role of neutral Hydrogen in the Universe from the dark ages to the present-day, and to employ pulsars as probes of fundamental physics. The baseline technical concept selected to realize these science goals consists of 1) an aperture array operating at low frequencies with optimum performance in the range from 100 to 250 MHz, and capability over the wider range of 70 to 450 MHz, and 2) an array of dishes initially operating at frequencies up to 3 GHz, but capable of 10 GHz in terms of antenna surface accuracy.

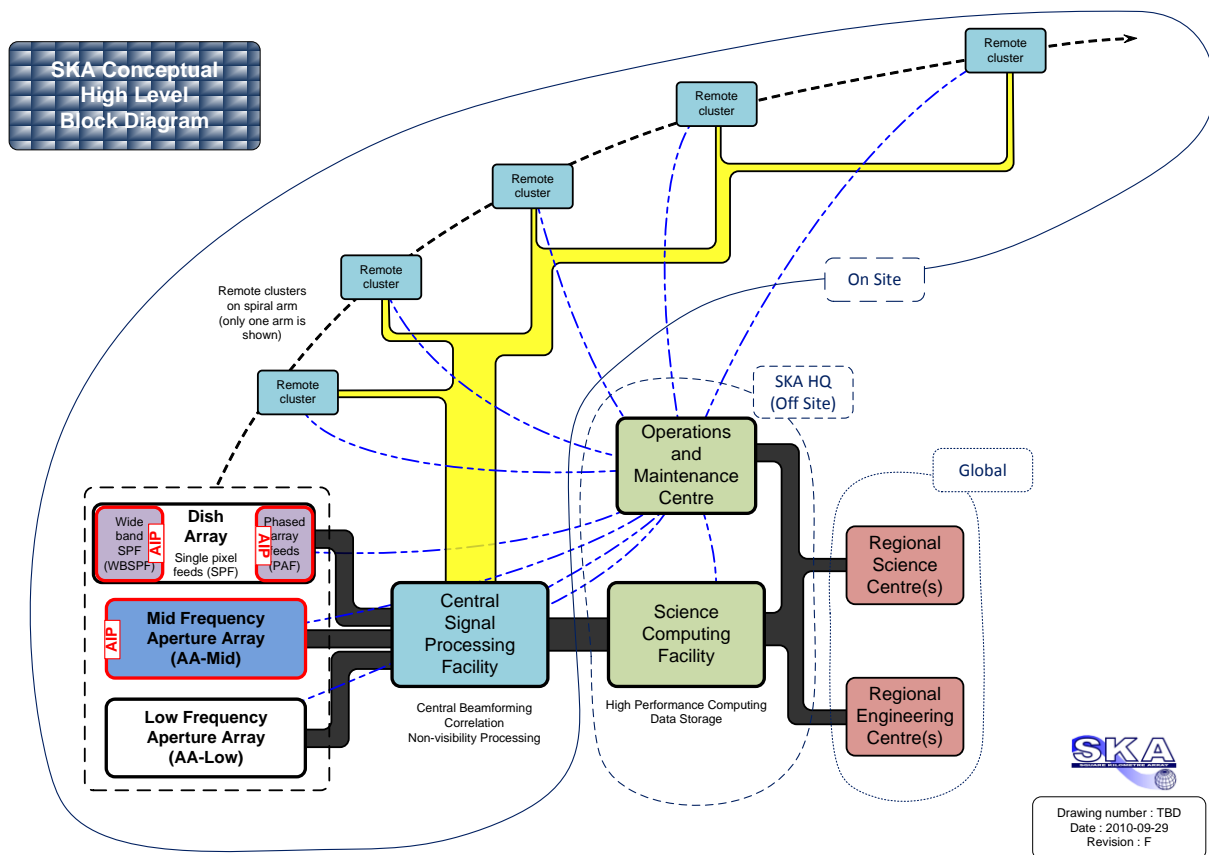


Figure 4: SKA High Level Conceptual Block Diagram

4.2.1.1 Baseline Technologies

The technologies selected for SKA1 are mature and demonstrated in Pathfinder and Precursor telescopes. They have been designated the Baseline Technologies and will play a central role in both SKA1 and SKA2. In the first place, they need to be tuned to the detailed SKA1 specifications taking into account optimisation for low-power operations and for the larger production scale required by SKA1. Cost estimates of several major elements of the system are currently being refined, in particular the infrastructure costs at the two sites. The detailed SKA1 definition is expected to be modified according to the outcome of these assessments.

4.2.1.2 Advanced Instrumentation Program

In conjunction with the detailed design and pre-construction work on the SKA1 system, an Advanced Instrumentation Program (AIP) will be executed to further develop the new technologies (wide field of view options: mid-frequency Aperture Arrays or Phased Array Feeds on dishes, as well as ultra-wideband feeds on dishes). These technologies will be assessed in terms of science impact, cost and technical readiness, and deployed in SKA2 if shown to be feasible and cost-effective. Since Pathfinder and Precursor science systems using Phased Array Feeds and ultra-wideband feeds are currently being developed, these technologies might be sufficiently well developed to be deployed on SKA1 to enhance its capabilities. This will be assessed at Critical Milestones (in particular SKA1 PDR) and, if adopted following an impact analysis, will require a formal change to the SKA1 baseline design.

The SKA1 facility will represent a major step forward over current instruments in terms of sensitivity, survey speed, image fidelity, temporal resolution and field-of-view. It will open up new areas of discovery space and provide the science and technology underpinning for SKA2.

4.2.2 Major Elements of the initial SKA1 Design

As noted above, the receptor technologies required to achieve the two major science goals lead to a baseline design for SKA1 that consists of a dish array with single pixel feeds and a low frequency aperture array. These arrays require correlators which may be shared. Computing and software systems will consist of a Central Processing system for further streaming processing, a distributed e-Science environment and common system level software. The two arrays may also use shared infrastructure including data transfer networks and power systems. These elements are described briefly in the following sections.

4.2.2.1 Low frequency Aperture array subsystem (AA-low)

The main technical goal of the low-frequency sparse aperture array will be to achieve an $A_{\text{eff}}/T_{\text{sys}}$ of up to 2000 m^2/K operating at frequencies between 100 MHz and 250 MHz (and possibly 70-450 MHz). Antenna and (uncooled) LNA designs will build on the experience of LOFAR and MWA (see Appendix 1), and PAPER. The array will be centrally condensed, but some of the collecting area will be in stations located out to a maximum baseline length of 100 km from the core.

RF signals from the individual antenna elements will be digitized at central locations, with relatively low resolution of 4-6 bits. Low-power digital signal processing will be deployed for initial signal conditioning, typically filtering and digital beamforming. Data will then be sent over the common data network to the central processing facilities.

Specific software/firmware will be used for beamforming and filtering, as well as for the detection of transient events. Specific algorithms will be used for the calibration of individual antenna elements, in particular exact position, complex gain, and polarization properties. The low-frequency array will be accessed and controlled through the common system software by Local Control Units.

Specific infrastructure required for the low-frequency array includes EMC shielded housing ("bunkers") for the digital signal processing equipment, connected to the common power infrastructure, data network and time reference subsystems. A local time-distribution system will be used.

4.2.2.2 Dish array subsystem

The main technical goal of the dish array will be to achieve an $A_{\text{eff}}/T_{\text{sys}}$ of up to 1000 m^2/K using approximately two hundred and fifty 15-metre antennas. To accomplish this, the dishes will employ an instrumentation package that will use single-pixel feeds to provide high sensitivity and excellent polarisation characteristics over a frequency range of 0.45-3 GHz.

The array will be centrally condensed but some of the elements will be co-located with the sparse aperture array stations out to a maximum baseline length of 100 km from the core.

Specific control software will be used for pointing and tracking of the dishes, including low level motor control, and the control of RF and IF equipment. The dish array will be accessed and controlled through the common system software by Local Control Units.

Specific infrastructure required for the dish array includes EMC shielded housing for digital equipment. The dishes will be powered from the common power infrastructure, data network and time reference subsystems. A local time-distribution system will be used.

4.2.2.3 Central Signal Processing Subsystem

The Correlator subsystem will combine the data from the aperture array stations or dishes [assuming no dish station-beamforming takes place]. For imaging observations, the signals will be correlated. Alternatively, signals can be centrally summed by a tied array beamformer. Options for non-visibility processing will be provided.

4.2.2.4 Software & Computing subsystem

The Software & Computing subsystem has three main components: Central Data Processing, Science Processing and System Software.

The Central processing (hardware & software) takes data from aperture array stations and dishes as its input and delivers science-ready calibrated data products. Given the data rates of the SKA, visibility calibration, gridding and imaging will use a streaming processing architecture. This will require high-performance computing infrastructure, which can also be used for non-imaging applications. The data from the central processing subsystem will be stored on an intermediate large storage system, this forms the interface to the science processing systems. Advanced and optimised software and algorithms will be developed for the streaming calibration of the data from the aperture array and dish array subsystems. Other shared components are the streaming processing framework and various real-time databases.

The Science Processing for SKA1 will follow a multi-tier distributed processing model. Tier-0 will be co-located with the central processing systems and have sufficient storage and processing resources to reduce the data rate for distribution to the Tier-1 sites. Data will be distributed using the world-wide academic networks. Tier-1 regional centres will provide storage and high performance processing resources for further processing and analysis, and make subsets of data available for further distribution to specialized Tier-2 sites and individual scientists. Software for handling and transporting data will largely be reused from existing facilities, in particular LOFAR, APERTIF and ASKAP. SKA Science Teams will develop advanced and optimised software and algorithms for the further calibration and analysis of the data from the aperture array and dish array subsystems.

A common set of System Software will be developed for Monitoring & Control, Proposal Preparation, Scheduling and Observation handling, System Health Management and real-time processing frameworks. Major parts of this can be subcontracted to industrial partners or be extended from existing facilities.

4.2.2.5 Common infrastructure

Several major components of the SKA will be designed and deployed for the above subsystems in common. These include in particular:

- Medium and long haul digital data transport subsystems,
- Central timing and synchronisation subsystem, including time and frequency reference distribution,
- Infrastructure (buildings, roads, facilities, labs etc.),
- Power delivery and distribution,
- Support and maintenance equipment and facilities

4.2.3 Major Elements of the SKA2 Baseline Design

To realise the full SKA science case as described in [1], SKA1 will be extended in terms of collecting area, baselines and performance, in particular for wide-field imaging, to SKA2. There will be up to ten times more total collecting area (depending on frequency), additional antenna stations at longer baselines, upgraded Central Signal Processing systems to accommodate the additional dataflow, and scaled up Software & Computing systems. A system description for SKA2 can be found in [6].

The phased construction of the SKA enables the project to make maximum use of advances in technology. Depending on the results of the Advanced Instrumentation Program, the SKA2 Baseline Design can be optimised for wide-field imaging by the inclusion of Phased Array Feeds on the dishes or a mid-frequency Aperture Array (AA-mid), and/or for ultra-wide band observations by the inclusion of Ultra-Wide Band Feeds on the dishes. These modifications will have a large system impact and will require a thorough impact analysis prior to deployment.

A limited number of SKA1 subsystems will be obsolete by the construction of SKA2, and will be decommissioned accordingly.

4.2.4 Advanced Instrumentation Program (AIP)

The Advanced Instrumentation Programme (AIP) will continue to develop innovative technology beyond the Preparatory Phase for:

- Phased Array Feeds on the dishes (PAFs),
- Mid-frequency Aperture Arrays (AA-mid), and
- Ultra-wideband single pixel feeds on the dishes.

The AIP is being designed to build up the level of maturity in these three technologies as well as anticipate their use in SKA2. PAFs or ultra-wideband feeds may also be deployed as modular subsystems on the SKA1 dishes to enhance the science impact of SKA1. AA-mid will require the construction of a substantial stand alone demonstrator in the pre-construction phase. The

opportunity for individual research groups to fund new instrumentation relevant to the SKA should not be excluded. The decision on selection of the PAF deployment in SKA1 will be made in 2014, and the technologies to be deployed in SKA2 will be made at the end of the SKA1 pre-construction phase.

4.3 The Design Process leading from SKA1 to SKA2

The conceptual route to the final SKA system can be summarised as follows:

1. From the SKA1 science requirements selected in [4], the details of SKA1 technical requirements will be derived (see [5]). Initial SKA2 system technical requirements will be developed, based on the science requirements contained in the Design Reference Mission (DRM) [7].
2. This will be followed by a full preliminary system design for SKA1, informed by early preliminary designs for the SKA2 options, so as to ensure extendability to SKA2.
3. The full detailed design for SKA1 is the third major step. In conjunction with this, the development of the AIP components will be continued and incorporated into the final SKA design when sufficiently mature and cost-effective.

Although this overall process is inherently complex, it is closely linked to standard system engineering design procedures, shown diagrammatically in Figure 5. This figure shows these standard design steps interlinked at key points and approximately how they relate to the overall SKA project schedule. After User and System Requirements are obtained for SKA1 and SKA2, SKA1 design/development is the pacing process. The AIP work must also be on track to meet the technology decision points in 2014 and 2016. SKA2 system design work will be carried out at a slower pace aimed at a Preliminary Design following the completion of the AIP.

Figure 6 shows the process in more detail. The coloured boxes and labels in both Figure 5 and Figure 6 show the relationship of the process to standard system design steps.

Feedback Loops in the Preliminary Design Process

System design ultimately requires trading performance against cost. This is an iterative process. In Figure 5 the iterations are confined to the Preliminary Design part of the design process. In the feedback loop, the system scope will be adjusted, which means that not all of the requirements can be met. This process will be tracked so that a clear record of the reasons for changes in scope is available.

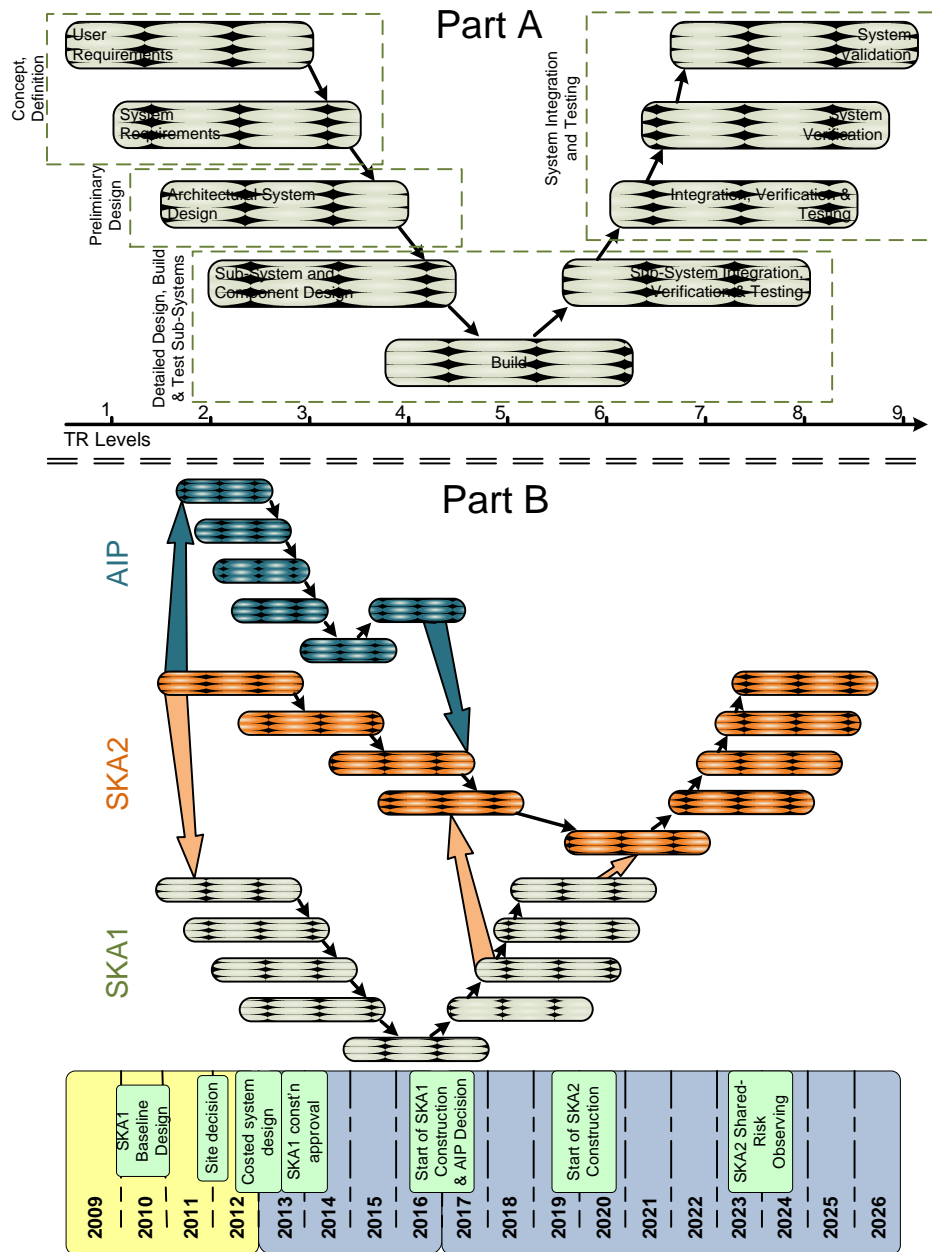


Figure 5: Part A. A standard 'V' diagram showing the phases of a large project.

The dashed boxes correspond approximately to those in **Figure 6**. **Part B.** A schematic representation of the juxtaposition of these phases for SKA1 and SKA2, and how the SKA2 process is informed by the AIP. All parts of the project will be managed according to the standard process. The arrows between the 'V's illustrate critical information flows that inform decision-making. Major milestones are shown at the bottom.

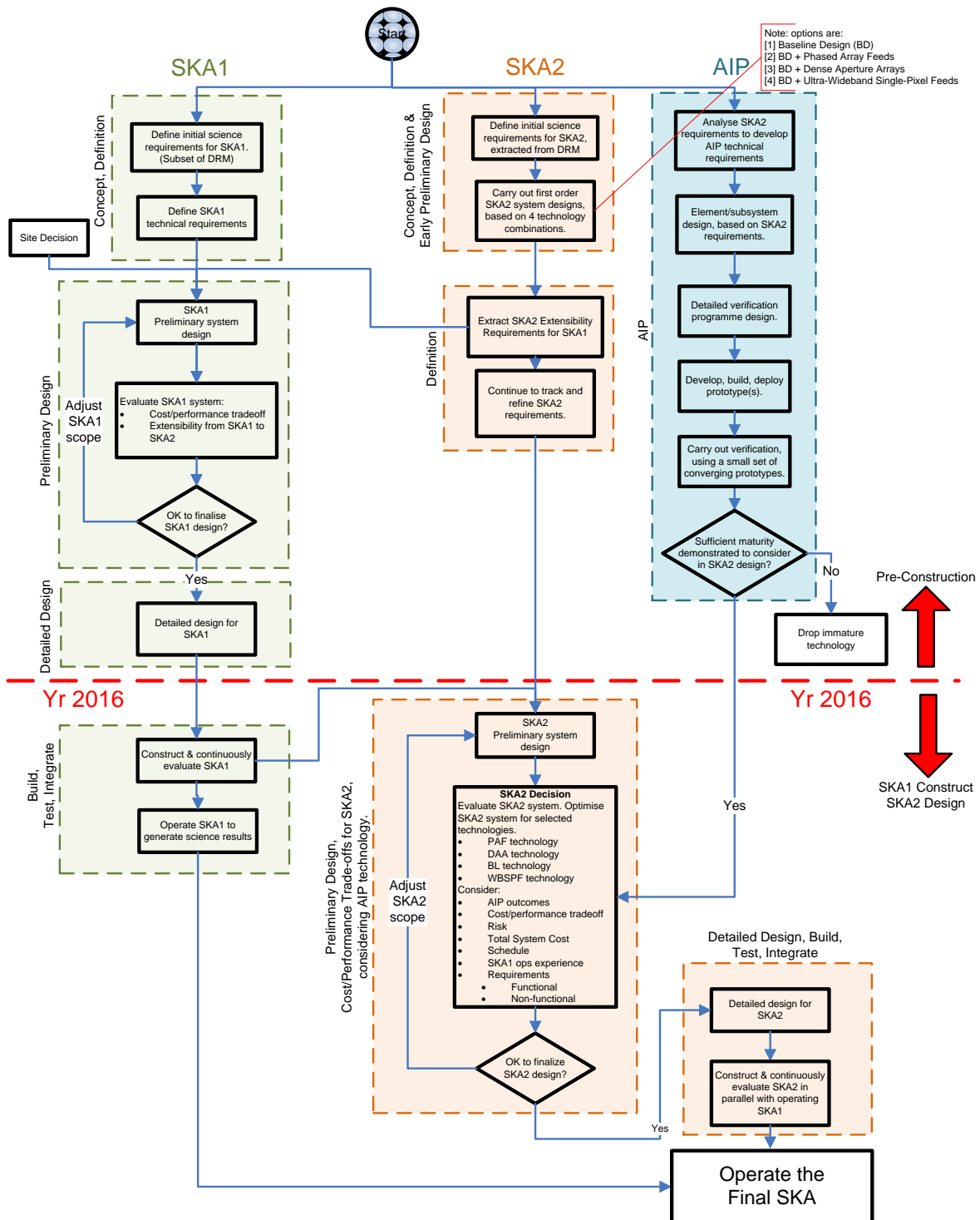


Figure 6: A flowchart representation of the SKA design and construction.

The dashed boxes correspond to activities in the schedule shown in **Figure 5**. The decision on SKA2 technology is made at the beginning of 2016, based on the results of the AIP. The important step of incorporating technology developed in the AIP programme and from the SKA1 telescope is part of the SKA2 Preliminary Design. Note that the iterations in the Preliminary Design (SKA1 and SKA2) boxes are the normal, managed trade-off process needed to optimise cost and performance targets.

4.3.1 Notes on the SKA1 Design Process

- Part of the SKA1 design process will include a categorisation of elements/sub-systems: 1) those too valuable to abandon must be designed/constructed for SKA2, 2) those with short lifetimes or that impede SKA2 installation must be removed or abandoned from the built SKA1 system, 3) software, algorithms and much of the underlying hardware that will be continuously developed and upgraded for at least a decade. Examples of category 1 are dishes; category 2, correlator and/or non-visibility processor; category 3, image processing software.
- Anticipating the build-out to SKA2 will consume resources (time and funds); the cost of extensibility to SKA2 will have to be balanced against the cost of SKA1 performance. As a result, it must be accepted that SKA1 will cost more than if it were the final product, and that some elements may be discarded afterwards or be re-done. Examples include planning for additional fibre routing from intermediate baseline stations for either PAFs or AA-mid; provision of additional power for dishes for PAFs; opening up an additional core for AA-mid; provision of additional power for the entire site.
- SKA1 will be cost-capped. Science/cost/performance trades will be carried out, using the methods outlined in [8] and [9]. The SKA1 scope will be adjusted to fit the cost and to satisfy as many of the initial requirements as possible, including aspects related to extension to SKA2.

4.3.2 Notes on the SKA2 Design Process

- To inform the SKA1 design process, it will be necessary to draft initial technical requirements for the four system options for SKA2 (Baseline Technology alone + the three AIP options in combination with the Baseline Technology), and carry out early preliminary system designs for each of the options.
- In parallel with the detailed design work being done on SKA1, Phase 2 requirements will continue to be tracked (see Figure 6 SKA2 Definition box). This will be necessary to prepare for a decision on technology selection in 2016.
- The SKA2 Preliminary Design will consider all the mature technology options in a system design in which the use of the technologies is fully optimised. In particular, the fractions of collecting area, the frequency ranges and the array configuration for each technology will be optimised to maximise science performance under cost constraints.
- Before an AIP technology can be considered in the SKA2 Preliminary Design, a separate assessment of the AIP technologies will take place to determine whether its level of maturity is sufficient to be included in the SKA2 system.
- More detail on actual SKA1 system performance and cost will be available from the initial rollout of SKA1, which will use Baseline Technology. This information flow is shown in Figure 6 as a connection from the SKA1 to the SKA2 column.

- Detailed design for SKA2 will be required after the selection of design option is made.

4.3.3 Notes on the Advanced Instrumentation Programme

- The AIP will be designed to build up the level of maturity of each of the three technologies, as well as anticipate their utilisation in SKA1 and SKA2.
- The three technologies will require different approaches in detail, but they will share the following general steps (see Figure 6):
 - Analyse the SKA requirements to maximise the potential of the new technology to enhance system performance, achieve more of the initial system requirements and/or reduce cost, as compared with the baseline.
 - Develop a preliminary design assuming the particular AIP technology will be used at the element or subsystem level of the system.
 - Carry out a verification program to test the level of achievement of requirements, to develop performance/cost models for the AIP technology, and to ascertain remaining risk.

The expected outcomes of the verification programmes are hard data on the following: in-system performance; good estimates of volume manufacturing, deployment and maintenance costs; verified operational models in the physical environment; verified calibration models; risk assessments.

5 Systems Approach to Science Operations

5.1 SKA as an operational international observatory

The science drivers for SKA1 and SKA2 are dominated by a set of large survey programs. These surveys will need to be designed by international teams, scheduled, executed, processed, quality controlled and delivered to the SKA community in a manner that makes optimal use of SKA Observatory. To do this, the operational system of the SKA Observatory has to be designed with the life cycle of these observational projects in mind. Given the amount of data involved, the cost of operations in human and consumables terms and the international scientific ambitions for the SKA, the operational system will have to be largely automatic, self-checking and tuned to deliver the maximal scientific return on the investment in the SKA. Over the past twenty years, a significant body of experience has been developed in optimal observatory operations starting from the Hubble Space Telescope and extending to ground based facilities like the ESO Very Large Telescope and the Atacama Large Millimetre Array. Based on their key science drivers, these observatories have designed end-to-end operational models that trace the observing program lifecycle and deliver science-ready data for the community. Such models are particularly important when executing survey programs which require specialized scheduling, processing and coupled quality control of data and data products at multiple stages of the operations loop.

Figure 7 shows a potential end-to-end operations model for the SKA Observatory. This loop follows an observational program through the key stages and interfaces of science operations. The stages

involve *products* (boxes between arrows) and *processes* (blue boxes on arrows). The whole life cycle can be divided into four domains, 'Proposal Domain', 'Observatory Domain', 'Processing Domain', and 'Science Domain'.

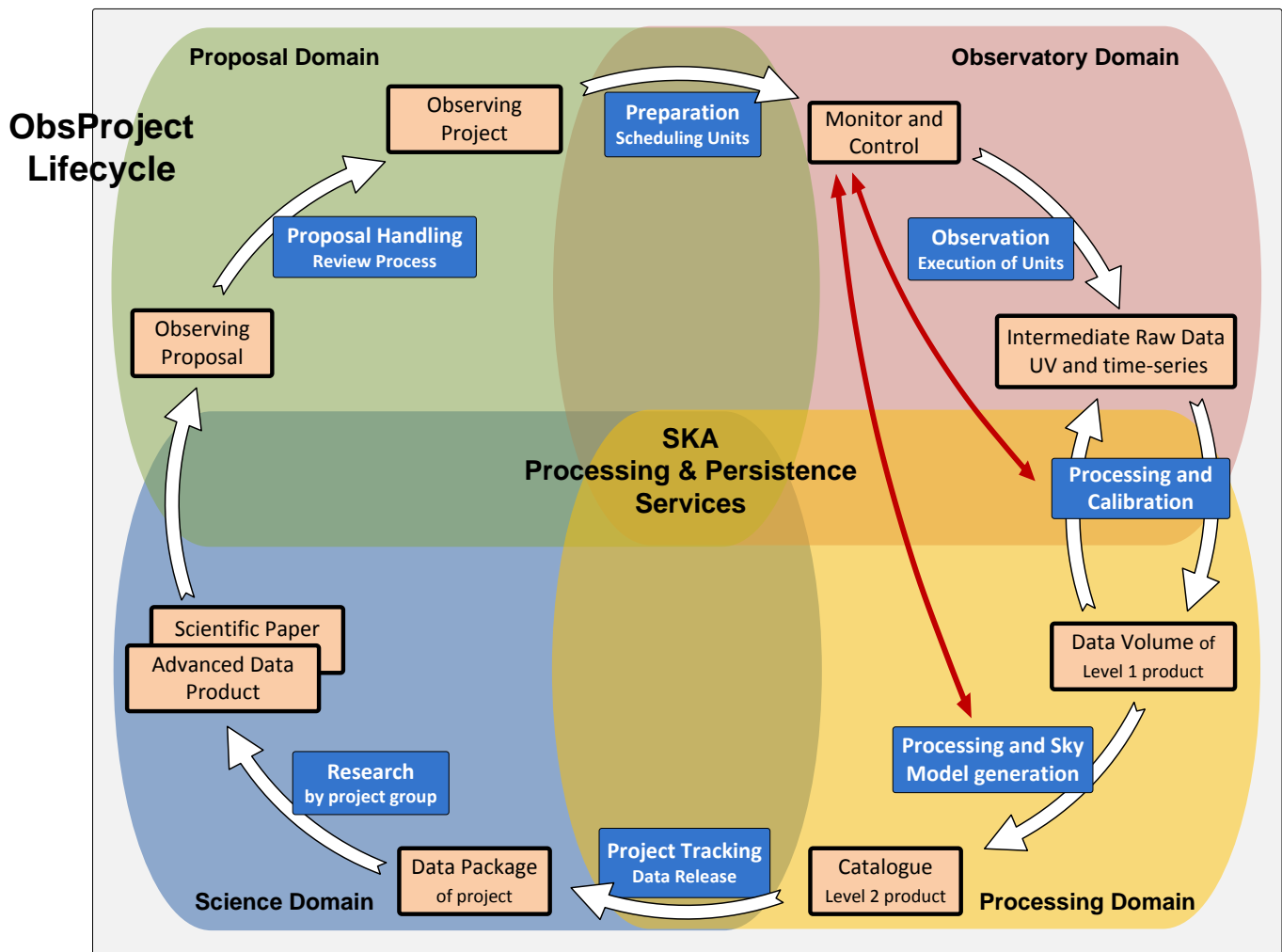


Figure 7: Life cycle operations model for the SKA Observatory.

Domain' and Science Domain'. In reality there is no sharp boundary between these domains and this is also indicated by the overlapping domain regions in the figure. SKA operational domains will most likely be realized as a set of *distributed or "tiered" and coupled operational processes*. The proposal domain will involve activities at regional centres and at SKA central operations. The processing domain and the science domain will also be implemented in two or more tiers, depending on a detailed analysis of the science and regional requirements and resources.

Underlying the whole life cycle there is a layer of *persistence and processing services*, which are available to all of the processes to store and retrieve their respective products and gain access to all relevant metadata and science data as required.

5.2 SKA Operational Products

Observing Proposals: The SKA community will write proposals for SKA time that need to be standardized, easy to create and deliver to the SKA Observatory. Support tools will be required to make the SKA observatory fully accessible to non specialist radio astronomers. The proposals will cover survey projects, PI projects, targets of opportunity and potentially coupled observations with other facilities.

Observing Projects: Successful proposals will need to be converted into observation descriptions (scheduling units) that define particular targets, exposures and operational measures to be taken and executed by the SKA. In addition to community provided science projects there will also be technical and calibration projects, which have to be executed by the system.

Schedule: The scheduling units need to be assembled into executable schedules of observations for the SKA that take into account the scientific priorities, resource availability and optimal observing conditions. There will be a long-term, a mid-term and a short-term schedule providing different granularity. The long-term and mid-term schedules should also be used to account for planned down-times and general availability of resources. The flexibility of wide-field enhanced technologies will allow for multiple observing programmes being observed concurrently – this mode of operation will be available via the low-frequency aperture array and sub-arraying of the dish array even in SKA₁. In principle, planned down-time could also be modelled as a project.

Intermediate raw data products: Once a scheduled observation is executed, the immediate output will be full-polarization correlated UV “raw” data, beam-formed time-series data, wide-field alert information for transients or a combination of these from multiple concurrent observational programmes. The observatory near real-time data reduction pipeline must process these data to produce science ready data products.

Data Volumes: Standard data products will be multi-dimensional data volumes. For imaging and spectroscopic experiments data volumes will be full polarization imaged data with either coarse or fine spectral resolution. Other data products will include position-dependent time-series data and RM synthesis cubes.

Catalogues: Data volumes are processed further to produce survey science data products such as catalogues of sources. In addition to providing an astronomical data product the observatory will require a global sky model for calibration purposes.

Data Packages: At various stages in the assembly of surveys, or at the completion of PI or other programs, data packages are created for distribution to science teams as the final output of their observational programme.

Advanced Data Products and Scientific Publications: Survey Science Teams and PIs utilize data packages to produce advanced data products (e.g. correlations, cross-matches) that are subsequently published in journals and the SKA archive system.

5.3 SKA Operational Processes

Proposal Handling: Proposals from the community, will need to be checked for completeness, distributed to referees and time assignment panels, tracked, assessed, ranked and the results communicated to the proposers and SKA science operations. The process from the support for the development of science proposals through submission and tracking of progress will be supported by a common eScience portal.

Observation Preparation: PIs and Survey Science Teams, with support from the SKA Observatory, will utilize SKA observation preparation tools to convert their successful proposals into executable scheduling units which are submitted to the SKA Observatory for checking and logging into the scheduling system. Again this will be provided via the common portal used for proposal development.

Observation: Schedules of observations are received by SKA Operations and executed. This process box hides all the complexity of the actual execution of a scheduling unit.

Monitor and Control: The monitor and control system (M&C) will accept the scheduling units and execute them on the telescope system. Monitoring of the system will be tightly integrated into monitoring of the quality and integrity of the intermediate data products. The expert M&C system will adjust the operational aspects of the telescope in response to determined instrumental, atmospheric or RFI issues, flagging or excising data as required. M&C information will be persistent and available to the pipeline data reduction system for purposes of calibration etc.

Quality Control: Via tools and automatic systems, SKA Operations checks the validity and quality of final data products and determines whether these data products have met the prioritised requirements of the programme.

Project tracking and data release: Via tools and automatic systems, SKA Operations assembles data and metadata required by Survey Science Teams and PIs at a given point in the observing program, and releases/delivers it to those teams

Project team research: PI and Survey Science Teams, based on the released data packages, prepare advanced science data products using community or private tools and systems. These products will potentially be published in journals and/or the SKA archive system.

5.4 Persistent Operational Services

The end-to-end operations loop of processes will need to exchange and store operational information, science and technical and other M&C data. Scheduling systems need to know about schedule requirements in proposals, data packing systems need to know about project requirements on data releases and program completion, quality control systems need to know about target lists and setups as well as monitoring information from instruments, dishes and arrays. This need to store and share data and to allow tracking of systems monitoring data and actions, requires the SKA Observatory end-to-end system to be underpinned with a persistent data storage and data management layer – the third dimension of the operations loop. This persistence layer covers technical and scientific data and includes database, archive and data warehousing technologies. The

efficiency and capabilities of this persistent data fabric will largely determine the overall efficiency and effectiveness of SKA operations.

5.5 SKA Processing Services

Given the ICT nature of the SKA observatory, the processing services are an integral part of the telescope. The processing hardware system will require a layer of processing services to provide a level of abstraction between the software and hardware architectures. Throughout the processing life cycle of the data the processing services will need efficient access to the persistent information regarding operations and M&C data. This ensures that resources are used in the most efficient way and also allows for the optimization of the global data flow. Given the amount and complexity of data generated in the course of the observation loop the optimization of the data flow requires careful attention and is one of the highest priority tasks.

6 Science and Technical Pathfinding that informs the SKA Design

In the Preparatory Phase, the SPDO and Participating Organisations are involved in Design Studies, Precursor and Pathfinder telescope projects to develop the science requirements and investigate many of the technical design issues leading to the primary deliverable for this Phase, the costed system design for Phase 1. These projects and studies are critical to the success of the SKA design and are described in Appendix 1.

7 Description of Work

7.1 Introduction

This section presents the high level description of work for the SKA Project from 1 January 2012 to 31 December 2015. Work packages are described in summary form in section 5.3 and in more detail, together with milestones, deliverables, and resource requirements, in Appendix 2. During this period the Preliminary Design (finalizing the SKA Preparatory Phase and its major deliverable: the costed system design) and the Detailed Design, Production, Engineering and Tooling (Pre-Construction Phase) will be executed. The work will be milestone and deliverable driven.

Figure 8 gives the overall planning of the project in bar chart form. A Gantt chart is provided in section 7.5. The diagram below illustrates the major phases. Critical milestones at system and subsystem level are given in Appendix 2.

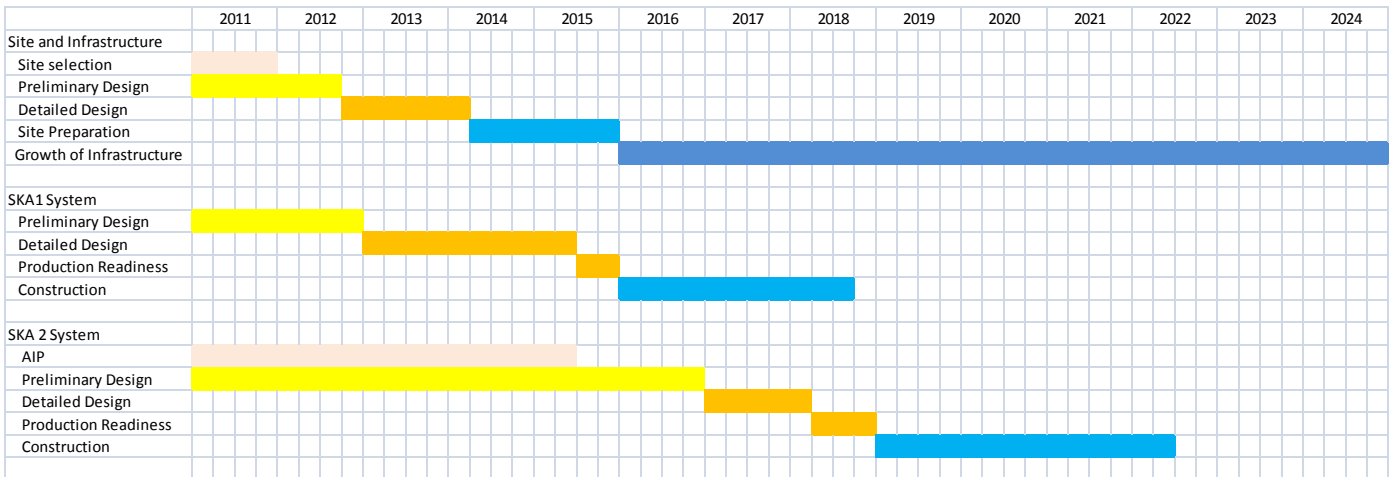


Figure 8: Overall schedule for the major phases of the SKA project

Note that this overall planning assumes that the site decision is taken in 2012Q1, and that construction funding for Site Preparation becomes available in 2014Q2.

The Preparatory Phase runs until the end of 2012 when the costed system design for SKA1 will be delivered. Funding sources for this work are PrepSKA, TDP, and the pre-cursor and pathfinder projects. PrepSKA is a 3 year project with a one year no-cost extension, and runs until 31 March 2012. It has provided the global vehicle for developing technical, site and policy aspects of the SKA project (see Appendix A1.1). It has also provided funding for the engineering component of the SPDO. In order to complete the Preparatory Phase and prepare the transition to the Pre-Construction Phase, specific funding for the SPO staff is required from 1 January 2012 to 31 December 2015 in addition to that for the Participating Organisations. This is taken up in the resource tables in section 7.6 and in Appendix 2.

7.2 Completing the SKA Preparatory Phase (2012)

7.2.1 Objectives

The principal engineering objective of the Preparatory Phase is to produce a detailed costed system design for Phase 1 of the SKA.

The Preparatory Phase will deliver a stable set of requirements that are baseline inputs to the Pre-Construction phase. This will have been achieved by iterating through the feedback loop between requirements and partitioning the architectural design across adjacent levels in the hierarchy. It is expected that further changes to the requirements will occur during the pre-construction phase as a result of the detailed design process but these will be under change management and configuration control.

7.2.2 Description of Work

The objectives and activities for each of the top-level work packages for the Preparatory Phase have been taken up in the Description of Work for the Pre-Construction Phase in section 7.3 and Appendix 2 in order to make clear the continuity from the one phase to the other.

7.2.3 Technology Readiness at the end of the Preparatory Phase

Technology Readiness Levels have been introduced in section 2.3.2. The definition of the levels and their required state for the major subsystems at the end of the Preparatory Phase are given in Appendix 4.

At the end of the Preparatory Phase, the System Readiness Level of the SKA will be SRL 3 (Preliminary Design). Technology for the major hardware subsystems for the Baseline Design will be at TRL 6 or higher (subsystem prototypes in representative environment). Software and computing subsystems will be at TRL 4 (basic technological components integrated), which means that they can be realised given industrial roadmaps.

7.3 Pre-Construction Phase (2013-2015)

7.3.1 Objectives

The principal engineering objective of this phase is to bring all SKA1 subsystems to Production Readiness level, and to complete the Preliminary Design for the SKA2 informed by the results from the Advanced Instrumentation Program. After the Pre-Construction Phase, construction of the SKA1 can proceed, and Detailed Design for SKA2 can be started.

The Pre-Construction Phase will deliver a stable and verified detailed design based on the requirements and preliminary designs established in the Preparatory Phase. This will have been achieved according to the Systems Engineering process described in Section 2.3. Strict change management and configuration control will be exercised on both requirements and design specifications (in particular interface definitions).

Specific activities are to:

- 1) bring all SKA1 subsystems to Critical Design level
- 2) close Production Reviews for all SKA1 subsystems, including contract preparation
- 3) manage trade-offs for SKA2 technology, taking into account the results from the AIP
- 4) bring all SKA2 subsystems to Preliminary Design level

7.3.2 Summary Description of Work

A summary of the work to be done per Work Package in the last year of the Preparatory Phase and the three years of the Pre-Construction Phase is given in this section. More detailed descriptions are given in Appendix 2 and in Table 1.

7.3.2.1 WP1: Management

The management and integration of the technical effort, especially during the early phases of the pre-construction phase, will be challenging due to the distributed nature of participating organisations and industry. The SPO will be staffed with several project managers, system engineers and other engineers at different levels of the organisation to ensure a coherent and effective effort with sufficient oversight and system-orientated leadership.

A strong system engineering team that will lead and perform the system design and system control will be assembled. In support of this effort a system engineer per domain, working closely with the participating organisation, consortium or industry counterpart will be appointed. These system engineers not only support the system team with their efforts, they will also ensure that the full system lifecycle view will always be present in the subsystem. It is foreseen that these system engineers will be heavily involved in the sub-system on-site installation, setting to work, testing, acceptance and handover to the system team.

More specialised SPO engineers for each domain are envisaged embedded within the work package contractors, and paid for by the Participating Organisations. Their role is to ensure SPO oversight of the low level subsystem. It is foreseen that these engineers will transfer to the SPO in the later stages of the pre-construction phase and form the core of personnel responsible for the maintenance and upgrades of the equipment.

7.3.2.2 WP2: System

Preparatory phase. At the system level, work during this phase will be aimed at completion of the SKA1 preliminary design. This work will build on the output of the concept and definition phases. The technical solution(s) will be refined and preliminary designs drafted. Functional analysis, validation and synthesis will be performed and functions will be mapped to configuration items. The system requirements for SKA1 should be fairly stable during this period and work will focus on the mapping of requirements to physical entities and the flow down of these requirements to lower levels. The design will take into account the required extensibility of the system to SKA2 as well as the level of integration to be achieved to facilitate the AIP.

Specifically, the work to be done is complete SKA1 preliminary design phase including science and engineering tradeoffs, costing and interfaces definition, and conduct a SKA Phase 1 preliminary design review.

Pre-construction phase. During this phase the main aim of will be to conclude the critical design of SKA1 and to control and manage the system engineering effort at all levels and across levels. The designs developed during the preliminary design will be refined for aspects such as manufacturability and full scale production. Ideally this will imply only minor updates and modifications to the already existing designs.

7.3.2.3 WP3: Science

Preparatory phase

The first objective for the science work package in this phase is to determine the science drivers of SKA1 and to work with the SPO design team in using these drivers to set minimum specifications for the SKA1 system. The second objective is to set out desirable science features of stretching these specifications above and below the limits set by the drivers. The third objective is to work alongside the SPO design team in finalizing the system requirements so as to deliver the capabilities demanded by the drivers alongside as many desirable science features as can be achieved without compromising the main science drivers or significantly stretching the overall cost envelope. Science goals will have to be made specific to Instrumentation requirements to inform detailed design choices: e.g. required frequency coverage, time domain requirements, required correlator modes, data-rate requirements from remote sites etc.

Pre-construction phase

Science activities in this phase will need to include an element of monitoring for any need for changes in the SKA1 science drivers and science design requirements, with the expectation that the need for substantial changes will be rare and subject to stringent change control procedures. The main objective in the early part of this period will be to support detailed science and engineering trade-offs for SKA1. Engineering choices at all levels in the system need to be informed by proper trade-off of their science consequences. The science work package will support these trade-offs through analysis and simulations (e.g. on required bit-depths, effects of instabilities, etc). The science work package will have to support the analysis of the science return of potential adoption of AIP technologies in both SKA1 and SKA2. The main objective in the later part of this period will be development of the science operations plan (see section 5) which will require detailed analysis of observing modes, data flows and failure modes. The science work package will provide the necessary input through projections for initial observing and processing schemes and analysis of use cases.

The science work package will also support the analysis, commissioning and operations of real science verification systems and simulated SKA realizations with specific activities including:

- Ingestion of early results from precursors and pathfinders into the SKA science narrative
- Detailed science simulations supporting CoDR for dish antenna elements
- Detailed science simulations and commissioning plans
- In preparation for commissioning and science operations, SKA1 observing schemes will be worked out in detail, e.g. planning of surveys (dwell-time, sequence, array usage), including estimates of follow-up observations.
- Data Management Plan. A science data management plan will be worked out, within the boundaries of the science operations plan. This covers the needs for local and regional processing and the requirements on archiving and data curation.

7.3.2.4 WP4: Maintenance and Support

This work package will deliver the design of the SKA maintenance and support system. In both the preparatory and preconstruction phases this work will be performed in conjunction with the system design activities. This will ensure that the design influences the maintenance and support but equally

that the requirements on the maintenance and support influences the design. Although requirements for SKA2 will be considered, the work during these phases will be focussed on SKA1.

7.3.2.5 WP5: Dishes

The work on the dish array for SKA1 will provide a costed, detailed engineering design for a cost-effective, antenna system with performance to meet the key science goals of both SKA1 and SKA2 and that can be readily mass-produced. This is a deliverable required in the latter part of the preconstruction phase in order to proceed to procurement for SKA1. The proposed work builds on the antenna developments being carried out currently for PrepSKA as part of the TDP and Canadian SKA programs, and by the precursor (ASKAP and MeerKAT) and pathfinder (ATA, EVLA) arrays. A uniform program of performance test and cost analysis of each of these dish systems is anticipated as input to the design process for the SKA1 dish system. Key aspects of the design are optimizations for cost reduction and improved performance, and cost-effective mass production.

Feed antennas and receivers options will be finalized for SKA1. This work includes assessment of wideband, single-pixel feeds (WBSPFs), octave-band single-pixel feeds (OBSPFs), and phased-array feeds (PAFs). An important consideration is the cost impact of subsystems designs, especially for mass-production. The current default is that the SKA1 feeds will be OBSPFs, with developments of PAFs and WBSPFs being advanced as part of the Advanced Instrumentation Program. Feed/receiver prototype testing is envisaged on the SKA1 prototype dish system.

The PAF design and development work will be guided significantly from the results of the PAFSKA program in PrepSKA, which encompasses the pathfinder systems APERTIF, ASKAP and PHAD. The aim is to design, fabricate and test a prototype feed system in preparation for procurement for the SKA1.

The dish elements and related antenna/receiver subsystems represent one of the major components of the overall SKA1 program, and hence the overall cost. With the constraints of excellent performance at low cost, risk mitigation through fabrication of prototypes is included in the plan.

Requirements for each major area below include design reviews (CoDR, PDR and CDR), prototyping as needed, fabrication, acceptance testing, detailed testing. Documentation will be a deliverable for all stages.

7.3.2.6 WP6: Aperture arrays

Preparatory phase. All components of the SKA1 AA-low array will be developed to the point where they have demonstrated functionality and performance compliant to SKA1 system requirements. Designs that are currently successfully deployed in LOFAR, the MWA and PAPER will serve as a reference and starting point. Critical development areas in this phase are:

1. System temperature: Noise temperature of uncooled LNAs and frontend matching, particularly for AA-mid
2. Extending the Bandwidth for array, antenna element and LNA, particularly for AA-low
3. Compliance with the environmental conditions at the site

4. Stability of element, complex gain and station beams and the ability to calibrate to the level required
5. Performance and power requirements of digital processing systems (remaining connected to DSP/HPC roadmaps)

In conjunction with this, the key technologies for an SKA2 AA-mid array will be developed to TRL6, to identify areas where major improvements are needed.

To demonstrate functionality and compliance with requirements, a verification system will be constructed. This AAVS₁ will consist of a small AA-low array and a small, single AA-mid array using the same digital infrastructure with specific software for each array. Given the reference point provided by LOFAR, AAVS₁ need not be a large scale system, but will target the critical areas where SKA1 differs from LOFAR, as well as the key technologies for the AA-mid array. This verification system will be constructed at the selected site. LOFAR software will be used to process the data from AAVS₁.

Pre-construction phase. This top-level work package will progress the SKA1 AA-low array through to the Production Readiness Review. It will also bring the AA-mid array to the Preliminary Design Review stage, for an informed decision on SKA2 technologies. Critical areas in this phase are:

1. Preparing for mass-production
2. Further improving compliance with environmental conditions
3. Optimisation for power, in particular using the current digital processing systems

The preliminary design for an AA-mid array in SKA2 will also be developed, demonstrating performance, functionality and compliance with science and system requirements.

To demonstrate production readiness of the SKA1 AA-low system and feasibility for AA-mid, a second verification system will be constructed at the selected site. This AAVS₂ will consist of a substantial production pilot for the AA-low subsystem (all subsystems). In addition multiple AA-mid stations will be included to demonstrate imaging performance LOFAR based software will be used to process the data from AAVS₂.

7.3.2.7 WP7: Signal Transport and Networks

The signal transport networks are the backbone of the SKA. The array configuration will dictate the network connectivity, but the choice of signal transport technologies will dictate the physical configuration and layout of cables between antennas and the correlator and the equipment required in between. The cable routes are part of the fixed infrastructure of the telescope and as such need to be designed to support the instrument throughout its lifetime. At the antenna, the signal transport subsystems are an integral part of the antenna back-end. In this phase this detailed design will be undertaken as connection requirements from other sub-systems mature. Significant parts of the Signal Transport and Networks area will be commercial products and therefore performance and cost information will be straightforward to obtain.

7.3.2.8 WP8: Signal Processing

The top level breakdown of the signal processing comprises of three subsystems: Correlator, Non-Imaging Processor, and Beam-forming. Each of these sub-systems is developed as part with a hierarchical frame work as detailed in the Systems Engineering approach.

An evolution of the Signal Processing is being considered even within the time frame of SKA1 of the project. This is aimed at providing maximum flexibility and minimum development time in the early stages of deployment but efficiency in terms of cost and thermal dissipation as the system grows. To achieve this, more than one parallel technology development is under consideration, namely: Software processing, FPGA processing, ASIC processing.

Each of these approaches has advantages and disadvantages that will be assessed against the requirements for SKA1 as part of this work package.

7.3.2.9 WP9: Computing and Software

Preparatory phase. In the Preparatory Phase, this work package will develop the software and computing (S&C) subsystems through to a top-level design, with a detailed requirements analysis for SKA1. The work is structured as three main sub-work packages: central processing, science processing and system software. The main objectives are to implement a focussed R&D phase coupled to a detailed requirements analysis so that road-mapping of available technologies and algorithm developments can inform the development of realistic requirements for the S&C system.

Pre-construction phase. This work package will develop the software and computing (S&C) sub systems through to the CDR phase for SKA1, and PDR level for SKA2. There are a number of significant challenges that this WP must address which inform the overall SKA system design. Both SKA1 and SKA2 will be extremely complex systems which require a sophisticated system for interaction with users and observatory staff closely integrated with an advanced monitor and control system. Furthermore the processing challenge of the SKA is immense and must be sufficiently flexible to enable those actions which are required to achieve high dynamic range. The deliverables of this work are therefore critical to the overall realisation of the SKA system. To achieve the required performance, a highly integrated system approach will be used for the development of the S&C sub-system. Both the information flow for the whole observing and science process and the data flow through the telescope will be analysed to develop combined software/firmware/hardware solutions. . Each sub-WP will go through the following phases: Detailed requirements analysis, Design & benchmarking, Prototyping and detailed design. Production of final software products will commence during the SKA Construction Phase.

The required system integration is achieved by:

- A system-level work package which will follow a information-flow and data-flow approach to develop an integrated system view of the S&C domain.
- Implementing a focussed R&D phase coupled to a detailed requirements analysis so that road-mapping of available technologies and algorithm developments can inform the development of realistic requirements for the S&C system.

- Linking of the review structure for the entire S&C system.
- Linking a design and prototyping phase on candidate hardware / software architectures.
- Verification of analysis and design, by a full S&C system prototyping phase following the PDR.

The work on the System software, Central Processing and Science Processing systems will be coordinated by an integrated S&C design team who are responsible for the delivery of the SKA S&C sub-system design to CDR level for SKA1 and PDR level for SKA2.

7.3.2.10 WP10: Power

Power is a critical consideration for the SKA, with current demand estimates being in the region 50-100 MW, assuming significant innovation in electronic system design and environmental conditioning arrangements. Apart from the direct operating cost implications and the implied opportunity costs to areas such as telescope upgrades, experience with large radio telescopes has shown that high quality design, construction and maintenance of power systems is crucial to minimizing overall lifetime costs and maximizing science returns. While many of the tasks associated with the provision of SKA power are most efficiently undertaken by experienced industry consultants, it is important that the project-specific requirements are built into the power solutions from inception. In practice, this means dedicating full-time SPO resources to working alongside industry partners, and drawing on experience with SKA precursors and other telescopes in framing the solutions.

Preparatory phase. The last stage of Preparatory Phase will focus on delivery an energy-efficient system design for SKA1, briefing a pool of power industry consultants and suppliers on the needs of the SKA, and on conducting (in association with power industry representatives) a Preliminary Design Review of the top-level power specifications for the telescope. The latter will focus on (i) ensuring that critical SKA technical and operational demands (including EMC) have been encapsulated in the specifications and (ii) that the specifications are in a form suitable as the basis of the pre-construction work package WP10.4, an activity designed to produce, in conjunction with selected industry engineering consultants, detailed specifications for the SKA power systems.

Pre-construction phase. The following assumptions are made in setting out a pre-construction plan for power systems.

- (a) The Preparatory Phase has delivered an SKA1 design, including an electronics system design framed in the context of power demand minimization requirements;
- (b) Exemplar physical layouts and representative electrical loads are available for SKA2;
- (c) Top-level EMC and RFI standards for the SKA system and subsystems have been put in place;
- (d) An operational model for SKA1, and at least a representative operational model for SKA2, are available; and

- (e) A pool of qualified and briefed consultant engineers and suppliers is available from which to select prime contractors, sub-contractors and suppliers.

It is important to stress that detailed power system design, construction and operation will be done by industry. The role of the SPO is to frame the SKA-specific requirements in terms understood by one or more prime contractors, to provide a specialized consultancy service during design and construction, and to be actively engaged in the commissioning and acceptance testing processes. With this in mind, all of the pre-construction power work packages listed in Appendix 2 have SPO and industry participation, and most draw on the experience of SKA precursor and other telescopes.

7.3.2.11 WP11: Site preparation

Significant effort will be required to prepare the site for installing the dishes and aperture array antennas, to connect them to power, to transport the data to the central processing facility and to build other required infrastructure. Work towards that end is already underway in the Preparatory Phase through the collection of site-related data, with the primary objective to provide input to the site selection process, which will complete with a site decision in Q1 2012. It is assumed that preparations for site infrastructure roll-out will take two years following which (2015) funding for the physical roll out will be required to complete the process.

The selection of the site will be a major milestone because it will define the actual site conditions and appropriate methods of work for building the SKA. Aspects of site properties and site infrastructure can then be turned into specifications. In the period prior to the start of the Construction Phase a full understanding must be obtained of the infrastructure already present at the site, fit for re-use, and any required clearing of the site. It is essential to evaluate the infrastructure and services that will be provided in-kind by the host country.

Work on the design of the configuration that started in the Preparatory Phase must be continued for SKA1, allowing this design to merge into the target SKA2 configuration. This involves the final stages in optimising the configuration of SKA1 for science merit and infrastructure cost. All locations for antennas and stations must be surveyed. For establishing the cost of infrastructure the soil properties at these sites must be investigated. This configuration work must be completed before the start of the Construction Phase.

Certain components of the site infrastructure must be completed or construction started during the Pre-Construction phase. In addition the required preparations for many of these components must be started directly after site selection. The central processing facility design must commence during the Pre-Construction phase, roads must be planned, including a minimum road plan completed to allow construction supplies to be delivered at the appropriate locations.

Establishing a construction camp must be partly completed during the Pre-Construction Phase in order to be able to ramp up the construction activities on SKA telescope structures and buildings during the Construction Phase.

The availability of electrical power at the site is of high importance, even at an early stage in the Pre-Construction Phase. Temporary solutions using the precursor power facilities must evolve into a

power infrastructure that is capable of powering SKA1 and which must be suited for further expansion towards SKA2.

Table 1: List of tasks in each Work Package

WP 1	Management		
WP 2	Science		
2.1	Review and Refinement of Science Case and Science Goals	2.2	Support science/engineering tradeoffs for SKA1
2.3	Science Operations		
WP 3	System		
3.1	Work Package Management	3.2	Preliminary Design of SKA1
3.3	Detailed Design of SKA1	3.4	Early Definition and Preliminary Design of SKA2
WP 4	Maintenance and Support		
4.1	Work Package Management	4.2	Preliminary Design of SKA1 Maintenance and Support System
4.3	Detailed Design of SKA1 Maintenance and Support System		
WP 5	Dishes and Dish Array		
5.1	Engineering and Management	5.2	Review Management
5.3	Dish Development and Testing Program		
5.3.1	DVA-1 Testing	5.3.2	Precursor Antenna Testing
5.3.3	Dish Array Verification	5.3.4	Risk Assessment
5.3.5	SKA1 Antenna Design	5.3.6	Costing and Preparation for Procurement
5.4	Single Pixel Feeds and Receivers		
5.4.1	Assessment of Feed Designs	5.4.2	Design and Development of SKA1 feeds and receiver systems
5.4.3	Preparation for Procurement		
5.5	Phase array feeds (PAF) Design and Development	5.5.1	Complete preliminary design phase of PAF for SKA (PAFSKA)
5.5.2	Design, fabricate and test SKA1-ready phased array feed	5.5.3	Costing and Preparation for Procurement
5.6	SKA1 dish array procurement		
WP 6	Aperture Arrays		
6.1	Engineering and Management	6.2	Consortium Management
6.3	Handling of Reviews	6.4	Subsystem Design of SKA1 AA-low array
6.5	Subsystem Design of SKA1 AA-mid array	6.6	Quality, RAMS
6.7	Specific technical developments		
6.7.1	AA-low Antenna & LNA	6.7.2	AA-mid Antenna & LNA
6.7.3	RF transport and analogue systems, AA-low	6.7.4	RF transport and analogue systems, AA-mid
6.7.5	A/D conversion	6.7.6	Digital Signal Processing: hardware
6.7.7	Network interface	6.7.8	Time Distribution

6.7.9	Power Distribution	6.7.10	Infrastructure
6.7.11	Local Control Software	6.7.12	Digital Signal Processing: firmware and software
6.7.13	Station calibration	6.7.14	Station configuration
6.8	Environmental Tests	6.9	Tooling and NRE
6.10	Preparing for Manufacture	6.11	Self-generated RFI and EMC
6.12	Verification Models	6.13	Technology studies: AA-mid
WP 7	Signal Transport and Networks		
7.1	Engineering and Management	7.2	Preliminary Design
7.3	Network Infrastructure	7.4	Digital Data Backhaul
7.5	Synchronisation	7.6	M&C Networks (Physical Layer)
7.7	Antenna Networks	7.8	Central Facility Interconnects
7.9	Imaging Distribution		
WP 8	Central Signal Processing		
8.1	Engineering and Management	8.2	Electronic Design and Implementation
8.3	Signal Processing Software Design and Implementation	8.4	Signal Processing Integration and Verification
8.5	Mechanical Design	8.6	Environmental Testing
8.7	Signal Processing Cable Management		
WP 9	Software and Computing		
9.1	Engineering and Management	9.2	Overall Design
9.3	Central Processing		
9.3.1	Analysis of data streams	9.3.2	Design and prototype data routing
9.3.3	UV-processor design, benchmarking and prototyping	9.3.4	Imaging processor design, benchmarking and prototyping
9.3.5	Data model design	9.3.6	Streaming framework design
9.3.7	Algorithm research	9.3.8	Application development
9.3.9	Local control software	9.3.10	Real-time databases
9.4	Science processing		
9.4.1	Data access software	9.4.2	Algorithm research and sky simulations
9.5	System Software		
9.5.1	Top-level architecture	9.5.2	Monitor and control
9.5.3	Scheduling and Observation handling	9.5.4	Observing proposal tool
9.5.5	System health management	9.5.6	Common Libraries
WP 10	Power		
10.1	Engineering and Management	10.2	Intra-System Power Design
10.3	Power System Design	10.4	Power Systems Operation
10.5	Strategic Power Planning		
WP 11	Site and Infrastructure		
11.1	Engineering and Management	11.2	Determine the properties of soil on site
11.3	Trenching	11.4	Preparation for dishes

11.5	Preparations for aperture array	11.6	Power System Construction and Commissioning
11.7	Buildings	11.8	Roads
11.9	Construction camp	11.10	Other site preparations

7.4 System and Technology Readiness at the end of the Pre-Construction Phase

Technology Readiness Levels have been introduced in section 2.3.2. The definition of the levels and their required state for the major subsystems at the end of the Pre-Construction Phase are given in Appendix 4.

At the end of the Pre-Construction Phase, the System Readiness Level of the SKA will be SRL 4 (Ready for Construction) for SKA1 and SRL 3 (Preliminary Design) for SKA2.

Technology for the major hardware subsystems for SKA1 will be at TRL 8. Software and computing subsystems will be at TRL 6 (subsystem prototypes available, ready for production coding). SKA2 subsystems will be at TRL 6 (subsystem prototypes available), allowing informed decisions on SKA2 technology.

7.5 Gantt Chart

The overall plan of work is given for the final year of the Preparatory Phase (2012) and the Pre-Construction Phase (2013-2015) in Figure 9. The lower level milestones associated with the system and sub-system design during this period, are provided in Appendix 2 and graphically in Appendix 3.

7.6 Resource Requirements

The Resource Plan for the 2012-2015 period is provided in rolled up form in Table 2 and in more detail in Appendix 2 for each of the Work Packages. Information from the Pre-cursor and Pathfinder projects as well as the specific Design Studies has been used as the basis of estimate for the resource costs is given here and in Appendix 2. In cases where this is not available, rough order of magnitude estimates have been made. The resource plan for the SPO is shown in Table 3, and the SPO staff requirements per year in rolled up form in Table 4. The detailed staffing plan for the SPO is provided in Appendix 5 and discussed in section 8.2.3 .

The resources required to carry out this work are a total of 90.9 M€ over the 4 year period, comprising 63.0 M€ for Work Package contracts and 27.9 M€ for SPO costs. The SPO costs include staff costs for project management, system engineering, science support for system engineering, and site work (19.7 M€), and office infrastructure and operational costs for the SPO (8.2 M€). 100 k€ has been adopted for the person-year cost for salary and benefits for both WPCs and SPO. No institute overhead or explicit contingency has been included.

It should be noted that the cost of developing the Advanced Instrumentation Program (sections 4.2.1.2 and 4.2.4, Phased Array Feeds, ultra wide-band feeds and mid-frequency Aperture Arrays) to PDR level in the pre-construction phase is 10 M€.

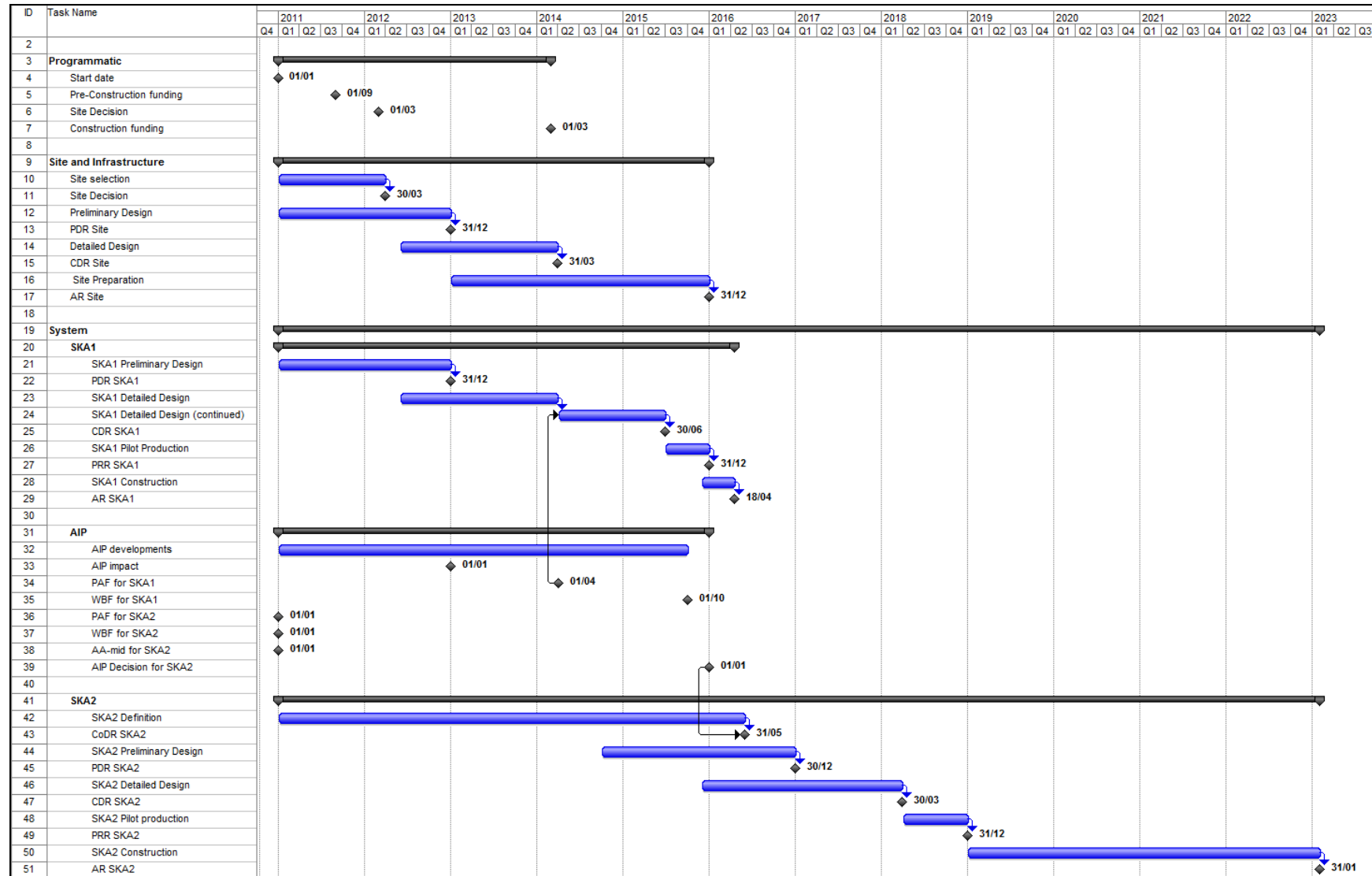


Figure 9: Gantt chart.

Table 2 : Rolled up resource plan for the 2012-2015

	2012		2013		2014		2015		Total			TOTAL Cost €
	py	Material €	py	Material €	py	Material €	py	Material €	py	Personnel €	Material €	
Rolled up Total	116	5,650,000	156	5,890,000	184	6,310,000	182	9,390,000	637	62,860,000	27,240,000	90,900,000
1 SPO Management, Admin, Outreach and Office Costs	11	2,050,000	22	2,710,000	26	1,770,000	27	1,670,000	86	8,600,000	8,200,000	16,800,000
2 Science	2	-	2	-	4	-	5	-	13	1,300,000	-	1,300,000
3 System	4	-	5	-	7	-	7	-	23	2,300,000	-	2,300,000
4 Maintenance & Support	0	-	1	-	1	-	1	-	3	300,000	-	300,000
5 Dish Array	18.5	2,275,000	22.7	1,475,000	20.7	2,375,000	17.2	1,225,000	79.1	8,010,000	7,350,000	15,260,000
6 Aperture Array	40.25	1,100,000	40.25	155,000	37.5	365,000	37.5	5,535,000	155.5	15,550,000	7,155,000	22,705,000
7 Signal Transport and Networks	6	-	8	-	10	-	10	310,000	34	3,400,000	310,000	3,710,000
8 Central Signal Processing	13	-	27	200,000	37	300,000	35	200,000	112	11,200,000	700,000	11,900,000
9 Software & Computing	16	225,000	18	1,350,000	22	1,500,000	22	450,000	78	7,800,000	3,525,000	11,325,000
10 Power	2	-	4	-	11	-	11	-	28	2,800,000	-	2,800,000
11 Site Engineering and Site Office	2	-	6	-	8	-	9	-	25	2,500,000	-	2,500,000

Table 3 : SPO resource plan for the 2012-2015

	2012		2013		2014		2015		Total			TOTAL
	py	Mat	py	Mat	py	Mat	py	Mat	py	Personnel	Material	Cost
Totals	25	2,050,000	47	2,710,000	59	1,770,000	62	1,670,000	193	19,300,000	8,200,000	27,500,000
1 SPO Management, Admin, Outreach and Office Costs												
Management	3	-	6	-	8	-	8	-	25	2,500,000	-	2,500,000
Support personnel	7	-	14	-	16	-	17	-	54	5,400,000	-	5,400,000
Outreach	1	-	2	-	2	-	2	-	7	700,000	-	700,000
Office cost	-	690,000	-	730,000	-	510,000	-	270,000	-	-	2,200,000	2,200,000
Office operational costs	-	1,360,000	-	1,980,000	-	1,260,000	-	1,400,000	-	-	6,000,000	6,000,000
2 Science												
Project Scientists	2		2		3		3		10	1,000,000	-	1,000,000
Commissioning Scientists	-		-		1		2		3	300,000	-	300,000
3 System												
SKA Project Manager	1		1		1		1		4	400,000	-	400,000
Detailed System Design & Engineering SKA1	3		3		4		4		14	1,400,000	-	1,400,000
Early Definition and Preliminary Design SKA2	-		1		2		2		5	500,000	-	500,000
4 Maintenance & Support												
Maintenance and Support Design	-		1		1		1		3	300,000	-	300,000
5 Dish Array												
Management and Engineers	1		2		2		2		7	700,000	-	700,000
6 Aperture Array												
Management and Engineers	1		2		2		2		7	700,000	-	700,000
7 Signal Transport and Networks												
Management and Engineering	1		2		2		2		7	700,000	-	700,000
8 Central Signal Processing												
Management and Engineering	1		2		2		2		7	700,000	-	700,000
Engineers	-		-		1		1		2	200,000	-	200,000
9 Software & Computing												
Management and Engineering	1	-	2		2		2		7	700,000	-	700,000
10 Power												
Management and Engineering	1		1		2		2		6	600,000	-	600,000
11 Site Engineering and Site Office												
Project manager and site managers	1		2		2		2		7	700,000	-	700,000
Site and civil engineers	1		3		5		6		15	1,500,000	-	1,500,000
Office support personnel	-		1		1		1		3	300,000	-	300,000

Table 4 : SPO staff requirements per year

	2011	2012	2013	2014	2015
Management	4	4	7	9	9
Engineering	6	9	16	20	20
Science Support	1	2	2	4	5
Site Development	2	2	6	8	9
Outreach	1	1	2	2	2
Administration Staff	3	7	14	16	17
TOTAL	17	25	47	59	62

7.7 Potential Partnerships to carry out Work Packages

In the Preparatory Phase, the SPDO and Participating Organisations are involved in Design Studies, Precursor and Pathfinder telescope projects to investigate many of the technical design issues underlying the SKA system design. These projects and studies are briefly described in Appendix 1. A summary of the competencies in these projects is provided here in tabular form. Although not explicit in the tables, there is substantial industrial participation in all of these projects.

Table 5 is applicable to the baseline design for SKA (see section 4.2.1.1) which will be implemented in SKA1. Table 6 is applicable to the Advanced Instrumentation Program (see sections 4.2.1.2 and 4.2.4). The baseline design implementation is able to satisfy the two key science drivers for SKA1, namely the history of neutral Hydrogen and the use of pulsars to test theories of gravity and nuclear matter.

Table 5 and Table 6 provide confidence that all the key technologies required for the baseline design and the AIP are being investigated by the Participating Organisations and associated Industry and that competent consortia can be formed as Work Package Contractors to tackle the work packages described in this document. It would be premature at this stage to predict which POs will be members of which consortia.

Table 5: Summary of competencies in precursor, pathfinder and design studies for the Baseline Technologies.

	Pre-cursors			Pathfinders									Design Studies		
	ASKAP (Aus)	MeerKAT (ZA)	MWA (Aus, USA)	LOFAR (NL)	ATA (USA)	APERTIF (NL)	e-MERLIN (UK)	e-EVN (EU)	EVLA (USA)	LWA (USA)	SKAMP (Aus)	Arecibo (USA)	Canadian SKA program	TDP (USA)	SKADS (EU)
Dish Array															
Sky-mount dishes															
Gregorian offset dishes															
Dish fabrication															
Cryogenic receivers															
Wideband digitization															
Low frequency Aperture Array															
Antennas															
Receivers															
beam-forming															
Signal Processing															
Signal transport															

	Pre-cursors			Pathfinders									Design Studies		
	ASKAP (Aus)	MeerKAT (ZA)	MWA (Aus, USA)	LOFAR (NL)	ATA (USA)	APERTIF (NL)	e-MERLIN (UK)	e-EVN (EU)	EVLA (USA)	LWA (USA)	SKAMP (Aus)	Arecibo (USA)	Canadian SKA program	TDP (USA)	SKADS (EU)
Timing & Synch.	█	█		█			█		█						
Central array processor	█	█	█	█	█			█	█		█		█		
RFI mitigation				█				█	█	█	█	█			█
Data Processing															
Calibration & Imaging	█	█	█	█	█	█	█	█	█	█			█	█	
Non-imaging	█	█	█	█	█				█		█			█	
Archiving & VO	█	█	█					█				█	█	█	
System Issues															
System Engineering	█	█	█	█					█						█
Control & Monitoring	█	█	█	█					█						
Infra-structure	█	█	█	█											
Power	█	█	█												█
Cooling	█		█		█										

	Pre-cursors			Pathfinders								Design Studies			
	ASKAP (Aus)	MeerKAT (ZA)	MWA (Aus, USA)	LOFAR (NL)	ATA (USA)	APERTIF (NL)	e-MERLIN (UK)	e-EVN (EU)	EVLA (USA)	LWA (USA)	SKAMP (Aus)	Arecibo (USA)	Canadian SKA program	TDP (USA)	SKADS (EU)
RFI shielding & EMC															
Operations & Logistics															

Table 6 is applicable to the Advanced Instrumentation Programme (AIP), as defined in [4]. AIP technologies have the potential to extend the scientific capability of SKA1 and SKA2 (primarily survey speed and instantaneous bandwidth), but are not required to achieve the scientific objectives of SKA1. They will be assessed for technical readiness at various project milestones, and included in the design concept should the impact on the entire system be positive in terms of cost and performance.

Table 6: Summary of the competencies of precursors, pathfinders and design studies for the Advanced Instrumentation Program

	Pre-cursors		Pathfinders					Design Studies		
	ASKAP (AUS)	MeerKAT (ZA)	LOFAR (NL)	ATA (USA)	APERTIF (NL)	Arecibo	Canadian SKA Program	TDP (USA)	SKADS (EU)	
Single Pixel Wideband Feeds										
Phased Array Feeds										
Dense Aperture Arrays										

8 Management

8.1 Management of the Organisation

8.1.1 Organisational Model

In June 2010, the members of the Agencies SKA Group (ASG) agreed that “in order to progress toward construction of the SKA, the next stage (phase), designated ‘Pre-Construction’, should be governed and led through an appropriate legal entity that is adequately resourced”. The overall Execution Plan describes the case for the resourcing, while this section describes the current assumptions being made on the development of an overarching legal entity and the resulting project organization. At the outset, it must be appreciated that the development of this governance structure will proceed in parallel with the assessment of the Execution Plan. The overall requirement remains, however, that a revised, alternative governance structure must be operational from 1 January 2012.

A process is now underway to define the optimum legal structure, and the associated optimum location for the new legal entity. The outcome of this process will be known in early 2011. In terms of developing the Execution Plan, it is assumed that a legal structure, which could be in the form of a not-for-profit company, will be established.

Behind that legal structure, we assume the ASG funding bodies with an intention to fund the pre-construction phase of SKA will prepare a Pre Construction Agreement that will establish the legal entity for the SKA Project Organisation and define the aims and operation of this new entity. Decisions to fund the pre-construction phase will be based on the Project Execution Plan and individual processes within each potential funding organisation. The path to an agreement is the subject of discussion within the ASG working group at present.

The detailed formation of this group of pre-construction funders will emerge in the coming period, involving a feedback discussion based on the resource requirements and availability of resources from funders. We assume that a partnership of several funders will be present in the establishment of the pre-construction entity and that the funding arrangements will address the uncertainty that the site selection will not have been completed until 2012, after the establishment of the legal entity.

8.1.2 A strawman concept for the pre-construction governance structure

PrepSKA WP4 (see Appendix 1.1) aims to develop viable options for the governance of the full SKA including SKA1 and SKA2. It is envisaged that the discussions towards initiating the pre-construction governance structure will benefit from development through the ASG of the Joint Implementation Agreement (JIA) for the SKA. In some scenarios, it could be that the governance arrangements in the pre-construction phase evolve with minimal re-framing to the governance arrangements for Phase 1 the construction phase, but this will be subject to much more detailed discussion.

As a strawman concept for discussion as part of this Project Execution Plan, the following assumptions are made:

- The new SKA legal entity should be open to potential interested partners, including funding agencies, governments and non-governmental bodies
- The SKA Project Office (SPO), under the newly-created legal entity, has the overall aim to deliver the SKA Project to the point of construction readiness of SKA1 (CDR level), to take the design of SKA2 to PDR level, and to prepare the establishment of the construction/operation phase of the SKA Organisation (draft Joint Implementation Agreement).
- The preferred location and nature of a legal entity to deliver the agreed aims of the project will be determined by early 2011 and will form the basis for detailed discussions on the governance structure, in parallel with this resourcing plan.
- Management oversight of the SPO will be provided by the governing Board or Council, with the potential for advisory bodies as required.
- Membership of the Board/Council may comprise a mix of representatives of funding contributors as core voting members, and include agency and scientific representatives from each core partner. Observers may attend meetings at the discretion of the Chairman of the Board/Council.
- The Board/Council provides oversight for the programme and is the primary decision-making body for strategic issues in the project. Consensus would be sought wherever possible, but voting, where required, may be weighted according to the agreed value of cash and in-kind contributions attributable to each partner.
- The relationship between Governing Board/Council, Advisory Committees and Project Director is key for the success of the SKA project in the pre-construction phase but also in the construction phase.
- The Board/Council appoints and oversees the performance of the Director.
- The Board has ultimate responsibility for all the legal and financial responsibility for all SKA project activities.

A possible structure for the SKA Organisation, based around a generic type of legal entity (but based on the various likely options that could be employed, is shown in Figure 10. The precise arrangements will be determined as the shape of the pre-construction consortium and nature of the partnership, is defined.

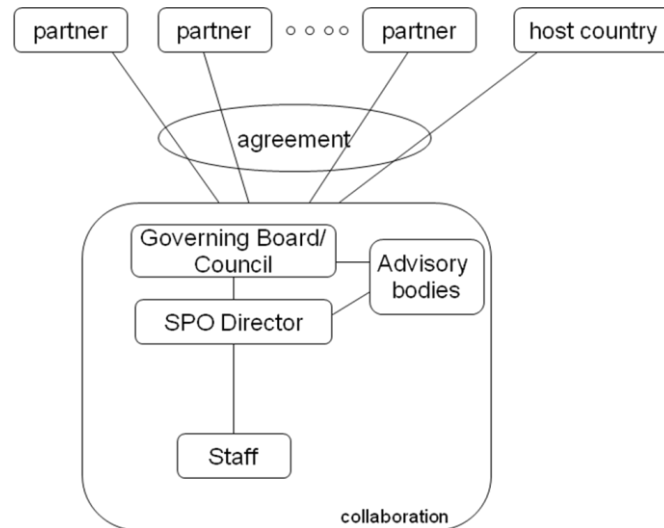


Figure 10: Basic organisation diagram for the SKA Organisation in the Pre-Construction Phase

8.1.3 Key Individuals and Responsibilities

The international SKA Organisation will need to expand substantially in both number of staff and budget over the next few years. Section 2.2.1 outlined the roles of the SPO and the work required to manage the global effort prior to start of construction in 2016. This and the following section detail the responsibilities of key SKA Management and Project Management personnel for the SPO and WPC's. The rationale for the SPO staffing plan is described in Section 8.2.3, and details of the staff distribution and functions in Appendix 5.

Project Director

The Project Director is responsible to the Board/Council for overseeing the execution of the Pre-Construction Phase in all its aspects (engineering, science, site development and stakeholder management). He/she has the authority to set priorities, appoint staff, develop the annual budget, engage Work Package Contractors, and initiate procurement contracts for SKA1 construction.

Project Manager

The Project Manager (operating at levels 7 and 6 in Figure 2) is responsible to the Project Director for the detailed management of the Pre-Construction Phase project. He/she will establish the core management structure for the successful delivery of the SKA, act as the specification and design authority, and exercise the overall project management, schedule, and budgetary control.

8.2 Project Management

8.2.1 Strategy and Philosophy

As outlined in section 2, the SKA project will have a strong central project office with management and system design authority. The SPO will contract the work on major subsystems to a small number of Work Package Contractors. The project management strategy and philosophy within the

project will be based on internationally accepted project management standards and practices. The structure of project management will support the system engineering philosophy of the project.

To ensure full coverage of management, technical, control and integration aspects of the project, there will be project management and system engineering functions at each level of the project in both the SPO and WPCs (see Figure 2). They will be supported by functional services including configuration management, quality assurance, contract management and procurement.

8.2.2 Work Package Contractor management

WPCs will include participating organisations (individually or in consortia) and/or industry. The WPCs will be contracted by the SKA Organisation to supply services/equipment at the appropriate level of the project. The management of the contract at the detailed level will be the responsibility of the responsible SPO project manager and his/her counterpart in the WPC. WPCs will need Technical Project Managers, System Engineers, and Quality Assurance Officers at sub-system level to interface with, and mirror, the sub-system equivalents in the SPO.

- Project Managers (at levels 5 and 4)
 - responsible for the successful development and eventual delivery of the contracted items in terms of schedule, cost, quality and performance.
- System Engineers (at levels 5 and 4)
 - The role of the level 5 and 4 System Engineers will be to provide technical leadership to the respective system engineering teams to ensure the successful implementation and execution of the systems engineering process at their respective levels.
- Quality Assurance
 - Quality Assurance will be an independent function and will mirror the responsibilities of the SPO quality assurance effort.

Deliverables and reporting

WPCs will be contracted to deliver qualified items to the SPO against approved specifications and in accordance with an agreed-to schedule. The contractual agreements will stipulate the reports required to the SPO and their timing as well as the review processes to be followed. Reports include regular progress reports, and specific reports on specification reviews, design reviews, and periodic progress meetings where technical, contractual, schedule and risk related issues are discussed. It should be noted that the Board/Council of the SKA Organisation contains representatives of the Governments and funding agencies underwriting the PO effort and these representatives will be able to monitor compliance with the contract terms by the POs they are funding to do the work.

Communication

Regular contact (by visits, telephone and e-mail) with the WPCs will be maintained to ensure that the lines of communication are kept open at all times. An important element in this is the

appointment by POs of “embedded” SPO engineers to work as SPO staff in the WPC team with responsibility for communication at the engineering level with the system engineers in the SPO.

8.2.3 SPO Staffing Plan

The SPO mandate in the pre-construction phase is to manage the successful design and development of SKA technology, and initiate procurement for SKA1 construction, as well as lay the foundations for the later phases of construction, verification, and operation. In support of this mandate, the technical personnel of the SPO will carry out a number of roles in different locations, including the SKA headquarters, the selected site, and embedded for certain periods within participating organisations. The long term aim of these technical personnel and activities is to prepare for the successful operation of a mega science facility.

In support of these aims the SPO will need to be staffed with general management and support personnel in addition to the technical project personnel.

The management and integration of the technical effort, especially during the early phases of the project, will be challenging due to the distributed nature of participating organisations, consortia and industry. To ensure a coherent and effective effort with sufficient oversight and system orientated leadership, the SPO will be staffed with several project managers and system engineers and embedded engineers in the WPCs (Figure 2).

A strong system engineering team to carry out the system design and system control will be assembled. In support of this, a system engineer per domain, working closely with the participating organisation, consortium or industry counterpart will be appointed. These system engineers not only support the system team with their efforts, they will also ensure that the full system lifecycle view will always be present in the subsystem. It can be expected that, on the longer term, these system engineers will be heavily involved in sub-system on-site installation, setting to work, testing, acceptance and handover to the system team.

The more specialised engineers within each domain that are embedded in the WPCs will ensure that the SPO understands the low level designs of the subsystems and their impact on the overall system. It is foreseen that these engineers will eventually form the core of personnel being responsible for the maintenance and upgrades to the equipment.

Each of the teams at system and subsystem level will be led by a project manager. It will be his/her responsibility to manage the system or subsystem to ensure on time and within budget delivery of high quality equipment.

The staffing plan for all functions in the SPO is provided in tabular form in Appendix 5A. Key engineering personnel are listed below (refer to Figure 2) and their roles and responsibilities described in more detail in Appendix 5B.

- SPO Scientists (at level 7 and 6)
- SPO Project Managers (at levels 7, 6 and 5)
- SPO System Engineers (at levels 6 and 5)

- SPO Project Engineer (operating at levels 7 and 6)
- SPO Quality Assurance Manager
- SPO Engineers (Dishes, AA, DSP, STaN, SW&C, Logistics, Power, Infrastructure) (at levels 5 and 4), embedded in WPCs
- SPO Logistic Engineers
- SPO site personnel
- SPO Configuration Manager

8.2.4 Integration of the Global Effort

To ensure cohesion of the global effort various mechanisms will be utilised during the execution of the project. These mechanisms will include progress meetings, work sessions, integrated teams, design groups, progress reports, teleconferences, video conferences, face-to-face meetings, and email

Standardisation of the effort will be by means of review plans and procedures, progress report templates and interface document templates.

8.2.5 Project management system

To effectively control and manage the project, project management tools will be utilised by all parties within the project, including the SPO and WPCs, to ensure a coherent and consistent view of the status of the project. The SPO will be responsible for integrating all the data and information to provide a complete view of the project. The SPO will be supported in this effort by the WPCs in terms of the delivery of data and information concerning planning, budgeting, progress and expenditure.

The toolset will be utilised to facilitate reporting on the project finances, project planning, the measurement of progress against the plan and the identification of critical paths, thereby creating a transparent process. Apart from the project management aspects, the tools will also support configuration management, change control and collaboration. The utilisation of existing tools in the community will be investigated, and taken into account in the choice of the toolset.

8.2.6 Project Control

Various mechanisms will be employed to control the technical effort of the project. More detailed descriptions of some of the mechanisms are provided in the next paragraphs.

8.2.6.1 Change control

As part of the control of the system engineering process, change control mechanisms and procedures will be developed and rolled out across the SPO and its contracted partners. It will include the definition and authority of change control boards at various levels, change control procedures, change classification mechanisms, change request handling procedures and templates.

8.2.6.2 Information management

Information flow in the form of documents, data and other deliverables will be pivotal to the success of the project. However, it will also be important to structure and manage this information. Two important mechanisms to accomplish this goal are described below.

- Configuration management
 - Because of the distributed nature of the project it will be important to keep control of the configuration of all items, data and information generated during the project. Apart from the obvious management of documents, the configuration management program will also include the management, control and release processes for hardware, firmware, and software.
 - Configuration management includes:
 - Document numbering and version control including one page information documents such as block diagrams, timelines and other drawings.
 - Management of part numbering and hierarchical structures from the highest to the lowest level.
 - Management of software, firmware and gateware version number and releases.
 - Management of PC board designs and documentation with related numbering and control of the boards themselves.
 - Establishment and management of history and route cards for hardware in particular, reflecting the steps within the build process of the equipment and the status of each of the steps. This will primarily be part of Phase 1 activities.
- Interface management
 - Interface definition and management will be one of the key aspects underpinning the project. During the initial phases of the project, interfaces will be identified and high level requirements will be captured in the requirements specifications. This will be followed by the development of separate documents for the interfaces and as the design of each particular piece of equipment progresses, the interfaces will be refined. These documents will exist on all levels of the project with varying degrees of detail and will include mechanical, functional, data and electrical aspects.
 - A high level interface register will be compiled and maintained within the SPO. Within this register the owners, the parties involved, and the type of interface will be identified.

9 Risk Strategy and Risk Management

As an advanced technology project, the SKA faces many risks and uncertainties but also opportunities. Although the identification and management of uncertainties and opportunities will have to be a focus within the project, the discussion in this paragraph is limited to the strategy for the management of risk.

It is fundamentally important that a sound and effective risk management philosophy and process is followed. In combination with other aspects such as the management and engineering processes, risk management enhances visibility into the project activities, strengthens decision making and facilitates the project goals. Risk management is already an integral part of the management of the project in the Preparatory Phase and will continue to occupy a central position throughout the project lifecycle. As the project progresses, the nature of the risks and the context and environment in which they will have to be managed, will change and therefore this risk management process will be reviewed and adapted on a regular basis. The existing Risk Management Plan (document MGT-040.040.000-MP-001-1) [13] forms the basis of this program and will be reviewed and expanded as appropriate.

The risk management program will be established at all levels and within all domains of the project. It will be maintained and managed by the project managers and system engineers.

The integration of the risk management effort across the project will be the responsibility of the project managers and project/system engineers of directly related projects/programs in both the SPO and WPCs. An overall and integrated risk register/database will be established and maintained and will be the central source of information on the status of risks and will be utilised for management of the risks as well as internal and external communication purposes.

Communication will form the backbone of a successful risk management structure and participants will be encouraged to communicate freely, openly and regularly on these aspects.

Regular reporting and communication to external stakeholders will also be conducted. The level and detail of these communications will vary and it will be the responsibility of the SPO management to ensure that the correct level of communication is achieved towards relevant stakeholders. For this purpose appropriately condensed and rolled up information from the centralised risk register/database will be utilised.

Regular risk focus events will be conducted. These events will include:

- Brainstorming sessions,
- Risk assessment workshops,
- Work sessions during Technical Design Reviews,
- External review(s) of risk register/database,
- Structured or semi-structured interviews with experts,
- Using knowledge, expertise and experience of team,
- Failure Mode and Effect Analysis (FMEA), and
- Fault Tree Analysis (FTA)

To accomplish this goal the utilisation of risk management and tracking tools will be defined, rolled out and maintained across the project.

10 Technology and Industry Plan

10.1 Introduction

As the SKA Project moves through the design, development, construction and operational stages, industry will play a crucial role in the delivery and through-life support of the technologies and infrastructure.

Industry participation at the pre-construction phase will be underpinned by strategic collaborations with commercial players, among them niche R&D companies, followed by increasing participation through prototyping work, commercial contracts with volume manufacturers, technology systems vendors, site services and installation firms, and power and data transmission specialists.

A full description of the proposed approach to SKA industry engagement is described in the document *“SKA Industry Engagement Strategy”* [10]; its premise is to establish a framework supporting full, fair and reasonable opportunity for businesses within SKA Consortia regions to supply goods and services to the Project.

In preparing for the SKA1 program, industry will have expectations of the SKA Project reflecting a professional level of engagement, and an efficient, mutually beneficial, and above all fair, approach to participation in the project.

First, it will be expected that the SKA Project takes a world-view of procurement, that applied procurement policies will be well researched, and that a level of harmonisation is in place across the SKA Consortia regions and countries.

Second, the global capability assessment (or scouting) process (planned to occur prior to the pre-construction phase) will be impartial, diligent, and recognise actual and potential capability, and not result in early elimination of potential suppliers. Industry will expect that weightings applied as a result of any juste-retour, and capacity building policies will be applied evenly, and that due notice is taken of offerings that support strategic (win-win) collaborations, and generation of potential intellectual property.

Third, pathways will enable commercial exploitation (spin-offs) and legacy capability that is recognised and supported both by national Governments, and the global SKA program. This may be manifested through new infrastructure, new jobs, exploitation of Intellectual Property, compliance with local indigenous content rules, and creation of new supply chains.

Lastly, industry is offered opportunities at pre-construction to engage strategically with the SKA program, as it has at the pre-cursor and pathfinder stages.

Large global organisations have a special capability to engage with the SKA Project at the design, cost, and pre-construction stages under the aegis of a Statement of Mutual Interest (SoMI) that permits strategic interaction and high level technical planning and communication to occur for the benefit of the Project.

Industrial liaison, beyond the procurement interaction, is planned to continue into the construction phase of the Project. The Industry Liaison Officer will focus on sustainable industrial engagement, and communications support between the Project and industrial agencies and groups.

10.2 SKA Technical Domains with Potential for Industry Engagement

The SKA will be built by industry and there will be many areas in which industry will contribute; Table 7 sets out some of these.

Table 7 : Areas in which industry will contribute

Site studies and infrastructure engineering
SKA scheduling, operations and maintenance models
Low-cost, mass manufacturing of small to medium diameter dishes
Decade bandwidth feed antennas for dishes
Broadband, active, phased arrays for aperture and focal plane applications
Low-noise, highly integrated, receivers for both cryogenic and uncooled applications
High-speed (Tb/s) digital fibre optic links for distance regimes extending from 100 m to >3000 km
Low-cost, high-speed (Gs/s) analogue to digital converters
High-speed digital signal processing engines (Pb/s) and ultra-fast supercomputing (at exaflop rates)
Software engineering for robust, intelligent, array control and data processing
Radio-frequency interference mitigation using coherent and incoherent techniques
High dynamic range (>70 dB) image formation using sparsely-sampled Fourier plane data
Outreach and public education

10.3 Communication of Opportunities at the Pre-construction Phase

Potential suppliers will become aware of SKA supply opportunities through channels shown in Table 8.

Table 8 : SKA supply opportunity channels

Prior involvement with one or more SKA stakeholders
Involvement in site studies and infrastructure engineering
Attendance at SKA related road-shows, briefings and conferences
SKA newsletters and website material
Active development of markets through commercial opportunity scanning
Notification from a public database of SKA (and pre-cursor) vendors
Via the SKA Global Capability Assessment process
Public advertising of business opportunities (EoI, RFT, etc)
Direct approach by an SKA Participating Organisation (PO)
Membership of a national industry consortium or cluster

10.4 SKA Pre-Construction Phase Strategy and Process

The PrepSKA WP5 group is developing guidelines to support the SKA preparatory phase, including the document *“Towards a Procurement Model for the SKA”* [11]. This (draft) document discusses models, structures, methods, and global frameworks for procurement. One section deals with alternatives for procurement planning which are considered to be relevant to the SKA pre-construction phase, including matrices covering arrangements for global/local sourcing, and global/local funding.

For the pre-construction phase, procurement (studies, prototyping, testing etc.) will largely be conducted and funded by SKA Participating Organisations, exploiting local supplier networks. There may also be instances (e.g. the initial purchasing of high volume requirements) where procurements may draw on international (possibly distributed) supply sources.

In the pre-construction phase, the Board/Council will establish a formal Procurement Office, or at least have an operating procurement function, to provide centralised management of global procurement and be the supervision and approval body for dispersed procurement i.e. through the POs. Any regional procurement will be conducted in strict conformance to global procedures from the central procurement office in order to effectively track Project acquisition execution, supplier performance, *juste-retour* allocations, and conduct proper accounting of value contributed to the SKA Project.

10.5 Intellectual Property

As a large global, cutting-edge science enterprise, the SKA Project promotes innovation in order to fulfil its mission of developing, constructing, and operating a next-generation radio telescope through cooperation among the SKA Consortia and institutes. The SKA Project will also encourage worldwide competitiveness in terms of regional industries, and the development, production, and deployment of their technologies and applications.

The SPDO has developed a document titled the “SKA Intellectual Property Policy” [12] which encapsulates the early commitments of SKA Consortia members to make IP available to the Project on the favourable terms.

The policy recognises the right and obligation of the SKA partners to:

- create, retain, use, assign, share and promptly protect IP relating to the SKA Project, including its sub-systems, and production technologies, according to the applicable local and international laws;
- maintain confidential all confidential information, whether made/developed alone or in collaboration with other Parties, or acquired through discussions (whether formal or informal) with members of the SKA community, or Third Parties where the Party is aware or should reasonably be aware that the information was obtained subject to an obligation of confidentiality;
- disclose promptly (by registering with the SPDO or its legal successor) IP developed/owned pursuant to this Policy or created pursuant to funded research or other contractual arrangements with Third Parties;
- permit (unless otherwise agreed) ‘freedom of use’ of such IP to the SKA Project to enable the SKA Project to proceed unhindered, or to satisfy the terms of any applicable Third Party Contracts or patent application or other regulatory requirements; and
- not unreasonably restrict any party interested in the commercial exploitation of the IP.

The SKA Project will:

- provide all reasonable co-operation and assistance, to the Parties to secure, protect and commercialise the IP, including;
- provide information and executing documents which may be required to obtain patent, copyright, or other suitable protection for the IP developed by the Party;
- provide assistance in legal actions taken in response to infringement prosecutions and defences;
- generally encourage and assist, when IP protection is secured, in the marketing and promotion of IP to industry as and when required; and
- take steps to protect the SKA brand against usage not approved by the SSEC.

In the case of copyright, if research by a Party leading to any IP has been funded by or through the SKA Project, all rights, title and interest in the IP will jointly belong to that Party and the SKA Project. Further, the Parties agree and accept that copyright ownership of all other Copyrighted Works, including:

- (i) software;

- (ii) technical designs including blueprints (with detailed methodologies), configuration diagrams, Integrated Circuit Designs;
- (iii) algorithms, formulas and codes describing any compounds or material;
- (v) integrated Circuit designs, masks, etc;
- (vi) data arising from SKA research and experimentation;

shall be owned by, or granted free access to, the SKA Project.

10.6 Industry Engagement Risk Management at Pre-Construction

Apart from the strategic risk of lack of interest or capability within industry (already largely retired through active engagement at the design and cost stage); the principal risk lies in the procurement process and fulfilment of the contract. Procurement outcomes may be endangered by several kinds of risk as listed below, some of which are outside the direct control of the SKA Project:

- Poorly drafted contracts;
- Inadequate resources assigned to contract management;
- Procurement team not matched to the supplier team in terms of either skills or experience (or both);
- Context, complexities and dependencies of contracts not well understood;
- Failure to check supplier assumptions;
- Unclear authorities or responsibilities relating to commercial decisions;
- Lack of performance measurement or benchmarking by the buyer;
- Failure to monitor and manage retained risks (statutory, political and commercial);
- Lack of supplier capacity, or scope creep beyond ability;
- Loss of supplier's key staff;
- Financial insecurity, and *force majeure*; and
- Risk of lock-out through an inadequately managed prior-relationship between a Project entity and a supplier.

11 Outreach

11.1 Objectives of SKA Outreach

As the project moves into the Pre-Construction Phase effective communication of the project goals is essential for gaining and maintaining support from key stake holders. Central to the current outreach strategy is the clear presentation to governments and funding bodies of both the

astronomy objectives of the SKA and the non-astronomy benefits. As the project progresses, greater emphasis will be made on outreach specific to the general public, teachers and the media to gain ongoing public support for the project and to inspire the next generation of scientists and engineers. Outreach required during the Pre-Construction Phase falls into three main categories of implementation: marketing, public relations and education.

11.2 Marketing

A strong, business-like corporate identity will be developed to ensure that the SKA compares favourably with other large ground-based astronomy projects with which it competes for funds and to assure stakeholders that the project is being run professionally. The corporate identity will encompass all stakeholder-facing elements including the appearance and functionality of the website, the design of business cards, the conference stand, the style of presentations and all other materials produced by the SKA organisation. The use of online marketing, including e-newsletters, podcasts, blogs, social networking sites and interactive functions on the SKA website, is another important area that will be developed.

11.3 Public relations

Media relations will be developed and press releases will be issued to maximise the amount of SKA coverage in print, online and broadcast media. Potential press release topics include funding wins, senior appointments, major events and important engineering developments. Technical articles pitched to niche publications will also be used as another important method of engaging with specific stake holder groups.

11.4 Education

As the Construction Phase approaches, the level of education-based outreach is set to increase and with this comes the opportunity to make the SKA website a leading resource for high quality astronomy education material. Creating an online astronomy education and information centre, with regularly updated content, will increase traffic to the website and will raise the profile of the organisation. Importantly, it will also encourage other organisations to link to the SKA site thus improving its profile in online search engines. A balance between formal education (school-based or group learning) and informal education (outside the classroom, including exhibitions and events) will be achieved by producing resources and activities for schools, and exhibits and resources for visitor centres.

11.5 Target stakeholder groups for engagement

- Funding Agencies
- Governments / Politicians
- Astronomers
- Physicists
- Engineers
- Computer Scientists
- SKA Committees / Task Forces / Working Groups
- Industry

- Journalists
- General public
- Teachers
- School students

11.6 Methods of engagement

- Printed promotional materials, including brochures, flyers, posters and factsheets.
- Website, including development of an astronomy education section.
- Computer animations.
- E-newsletter.
- Conference displays.
- Promotional gifts.
- Press releases.
- Articles.
- Broadcast media.
- Media days/press conferences.
- New media (social networking sites, podcasts, blogs, vodcasts).
- Conference presentations.
- Talks for special interest groups (astronomy societies, professional institutes, industry groups).
- Public engagement through 'meet the expert' sessions at science museums and planetariums.
- Development of teaching resources and educational activities for schools.
- Development of a travelling suite of tabletop, hands-on exhibits for use in schools, suitable to be shipped internationally.
- Development of study aids for students.
- School visits targeting students and parents.
- Travelling exhibition for the temporary exhibition space in museums and science centres.

11.7 Evaluation of the outreach strategy

As the project progresses and outreach activities increase, ongoing evaluation of the outreach strategy will be necessary to monitor its effectiveness, to provide opportunities for improvement and to identify the need for changes in the allocation of resources.

11.8 Resources and implementation

International SKA outreach activities will need to increase substantially during the Pre-Construction Phase to effectively communicate the goals and activities of the growing SKA organisation and enable expansion of the range of outreach activities and resources prior to start of construction in 2016. The outreach strategy will be coordinated by the Chief Outreach Officer, with support from the international Outreach Committee. Further support from a PR and Marketing Officer will be required from 2013 and as activities continue to increase, an Education Officer will be required for the development of both formal and informal educational resources from 2014. An overview of the main requirements and division of responsibilities is given in Appendix 5B.

12 Socio-Economic Return of the SKA

(Partly adapted from *Non-astronomy benefits of the Square Kilometre Array (SKA) radio telescope, Sept 2010*; compiled & edited by Phil Crosby & Jo Bowler, SKA Program Development Office)

Radio astronomy has produced some of the greatest and inspirational discoveries of the last century as well as significant innovations in technology. The SKA will continue this tradition of innovation by combining the skills of participating countries to develop, construct and operate this mega-science infrastructure project. The remote location, complexity and size of the SKA will drive technological innovation leading to capability development, as well as direct economic and indirect social benefits.

In March, 2010, a strategic workshop was organised entitled “Benefits of Research Infrastructures beyond Science - the example of square Kilometre Array (SKA)”. Supported by the COST organisation, its purpose was to bring together a group of European and global business representatives, governments and stakeholders to improve understanding of mega-science boundary conditions and to exchange ideas and experiences that best enable ‘non-science’ outcomes.

A pre-workshop study group determined that the most valuable payback areas for socio-economic benefit were - Information and Communication Technologies, Green Energy, Global Science-Industry-Government Linkages and Human Capital. At the workshop, expert groups then explored the impacts to technology, education, society, economic potential, and global cooperation. The conclusions are summarised below, followed by a few general comments.

12.1 Innovation in ICT and sensor technology

The SKA is a potential model for the future of global communication and information technology. If successfully exploited, the tangible benefits to industry and society will equal the astronomical discoveries.

Engineers for the SKA will challenge the ICT industry to innovate for efficiency and cost savings in high performance networks, power and capital investment. New software and hardware that will drive the SKA and make it smart will be developed, potentially setting global standards for ICT engineering and construction. The anticipated benefits involve not only signal processing, storage and computation, but also reliability and maintainability for remote SKA use, providing a backbone for development of remotely distributed ICT commercial services, as well as ‘public good’ in terms of education services, emergency networks, and the employment this brings.

ICT innovations necessary for the SKA will also be useful for all other systems that process large volumes of data retrieved from around the globe, including activities essential to financial, commercial, environmental monitoring and communications industries.

12.2 A global model for 100% renewable energy

The SKA infrastructure will have considerable energy needs in the order of 50-100 MW, with much of the demand concentrated in remote areas. The use of renewable energy for the SKA would pioneer remote power generation with low running costs that would be unaffected by fluctuations in global

fuel prices. Such a renewable strategy would accelerate technology development in the areas of scalable energy generation and storage, distribution, efficiency and demand reduction and provide a launch pad for commercialisation of innovative green energy technologies.

Spin-off benefits are also expected for human quality of life, especially in the developing nations. Cheaper (renewable) power will bring education, medical, and transport benefits for remote less wealthy communities, enabling improved practical application of science e.g. food production.

12.3 An enabler for improved global-science-industry linkages

The SKA has the opportunity to lead in the development of new techniques for mega-project management and effective global research collaboration. The nature of the project will inspire individuals, research groups, industrial partners and governments to be part of a global fellowship that will endure beyond their involvement. Furthermore, the profit and benefits to all those involved will be realised over a long timescale and in the broadest sense, build capacity and kudos for those who engage.

Effective collaborations have demonstrated pathways for talented individuals and Institutions to develop skills and capacity that can be applied domestically and globally. Linkages and co-locations (technology parks) between industry and science foster innovation and commercially exploitable patents, bring wealth and create jobs.

12.4 Positive impact on human capital development and employment

The SKA will provide employment opportunities in a wide range of associated fields. The SKA, by its scale and scope, has the potential to inspire generations of young people with science. It can do so not only because astronomy appeals to our natural curiosity but also because it is a stepping stone to many other fields of science and technology development including engineering, aerospace, mathematics and the natural sciences.

The SKA can provide long-standing benefits, proportional to the long-term investment it requires. The construction and operation of the SKA facilities will impact local and regional skills development in science, engineering, technology and in associated industries, see Figure 11.

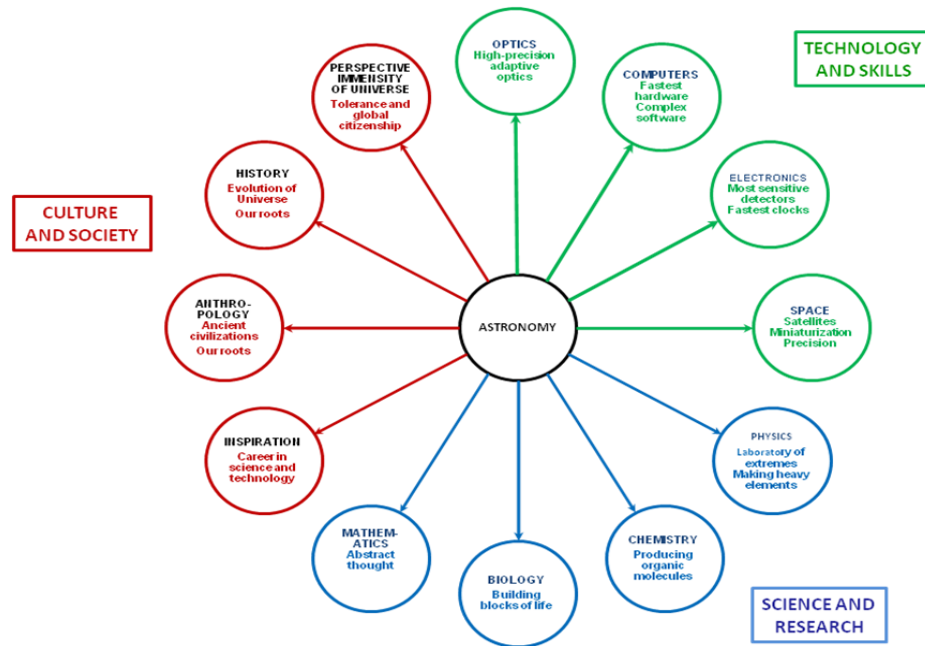


Figure 11: How astronomy impacts on Science & Research, Technology & Skills, and Culture and Society

12.5 Effects of SKA Procurement processes

Public expenditure for the SKA is likely to be ~€350 million for SKA₁, the main focus of the pre-construction phase. The SKA Procurement Strategy under development by PrepSKA WP5 contemplates a pre-cursor or interim procurement office established to manage and supervise the purchasing and contracts administration of SKA1. Sourcing of materials, products and services for the SKA will be significantly informed by a ‘scouting’ process defined in the Global Capability Assessment Model (GCAM) expected to be undertaken prior to the pre-construction stage.

The GCAM describes how the project will undertake an assessment of each SKA Consortia (country or region) in order to determine industrial (including niche) capacity, domain competency, and national programs to support industrial capability. Significantly, the GCAM process also seeks to encourage and reveal *potential* national/regional capability, where industrial start-ups, innovation centres, and production facilities are expected to be developed, and supported by Governments.

Finally, in adopting a strategic procurement approach, informed by global capabilities and SKA project spend policies, the SKA is empowered to balance member state returns, acknowledge just-retoire ambitions, and foster enduring industrial capabilities for long term socio-economical impact.

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(Reference documents available at:

http://www.skatelescope.org/~cloete/2010-10_PEP_RevH_Reference_Documents/)

APPENDIX 1. Science and Technical Pathfinding that informs the Pre-Construction Activities

In the Preparatory Phase, the SPDO and Participating Organisations are involved in Design Studies, Precursor and Pathfinder telescope projects to investigate many of the technical design issues underlying the SKA system design, and develop some of the science themes and techniques necessary for the SKA. These projects and studies are briefly described here.

A1.1 PrepSKA

PrepSKA is a consortium that consists of 24 partners from around the world and acts as a coordinating body for much of the technical and policy work currently underway for the SKA. It is a 4-year programme running from 1 April 2008 to 31 March 2012.

The principal objectives of PrepSKA are:

- 1) to produce a deployment plan for the full SKA, and a detailed costed system design for Phase 1 of the SKA. The technical development work is being carried out in Work Packages that are informed by the SKA Precursor and Pathfinder projects and the Design Studies.
- 2) to further characterise the two candidate SKA sites in Southern Africa and Australia and to analyse the various risks associated with locating the SKA at each of the sites;
- 3) to develop options for viable models of governance and the legal framework for the SKA during its construction and operational phases;
- 4) to develop options for how the SKA should approach procurement and how it should involve industry in such a global project;
- 5) to investigate all aspects of the financial model required to ensure the construction, operation and, ultimately, the decommissioning of the SKA;
- 6) to demonstrate the impact of the SKA on society, the economy and knowledge.
- 7) to integrate all of the activities, reports and outputs of the various working groups to form an SKA implementation plan.

A1.2 Pre-cursors

A1.2.1 ASKAP (Australia)

The Australian SKA Pathfinder (ASKAP) is a CSIRO project being built at the Murchison Radio-astronomy Observatory (MRO), Australia's SKA candidate core location. It is a facility to trial wide-field-of-view high-dynamic-range technologies for the SKA, deliver cutting edge science, and develop the MRO as a world-class observatory. ASKAP will be operational by mid-2013, and early hardware will be available to test technology and science in 2011. Many of the technical developmental aspects to be addressed in the SKA design are included in the ASKAP design

- The inexpensive sky-mount telescopes represent one possible configuration and allow one to directly measure the effects of parallactic rotation of the image. Aspects of cooling and other environmental effects are being investigated.
- The phased array feed (PAF) represents one possible implementation for the SKA. ASKAP provides a platform to trial PAFs on a large-N small-D array, and the group is working with other teams around the world to jointly develop the best PAF for science.
- Given the vast amounts of data to be transported, ASKAP signal transport and network developments are directly relevant to the SKA. ASKAP is looking at a variety of signals over optical fibre as well as networking protocols.
- The ASKAP digital system represents architectures and developments directly related to the SKA. Digital hardware studies to scale the beamformer for SKA cost and energy goals will be pursued, as well as correlator architectures for the SKA.
- ASKAP software, calibration, imaging and temporal solutions will have direct relevance to the SKA. Scaling studies to the SKA are also being pursued.
- Power and communication solutions appropriate for the SKA are being investigated and implemented.
- System engineering, life-cycle studies, operations planning, logistics engineering management plan and cost models are all being developed and evaluated.
- ASKAP will deliver cutting edge science to inform the SKA science case and development. Examples: large sky area, low-redshift HI surveys to measure the galaxy power spectra and hence cosmological biases of the galaxy populations; large sky area continuum surveys to trace the evolution of black holes to high redshift, and star-forming galaxies to moderate redshift. The Science Survey Team process instituted by CSIRO has been an effective way to involve the broader international community effectively at an earlier stage.

A1.2.2 MeerKAT (South Africa)

The MeerKAT will be an array of 60 13.5-metre offset-fed dishes with single pixel wideband feeds, and is therefore closely related to a major component of the SKA baseline design. Technologies being developed and used for the MeerKAT that have direct relevance to the SKA include:

- *One-piece moulded reflectors fabricated using composite materials.*
Costing and performance information resulting from the design, construction and operation of these composite dishes will be made available to the international project.
- *Electromagnetic modeling of feed and dish optics.*
Simulations of the MeerKAT feed and dish optics aimed at optimizing Ae/Tsys and sidelobe characteristics will be made available to the international project
- *High fidelity single pixel octave bandwidth digital receivers.*
The specific components and technologies relevant to the SKA include: novel feed horns, OMTs

and LNA coupling, low cost, low maintenance and high reliability cryogenic systems based on Stirling cycle refrigerators, integrated RF chain systems, wide bandwidth ADCs, temperature stabilization, and RFI shielding.

- *Packet-switched architectures for radio astronomy signal processing applications.*
The MeerKAT will test the scalability of the CASPER packet-switched architectures for digital signal processing applications for radio astronomy.
- *Calibration, imaging and time-domain processing.*

The design and operation of the MeerKAT data pipelines will provide valuable experience for the SKA. The relevant MeerKAT scientists and engineers will interact with the SPDO in this regard.

- *System Engineering.* life-cycle studies, operations planning, logistics engineering management plan and cost models.
- MeerKAT will deliver science on the pathway to the SKA. Example: deep HI surveys to establish the cosmological evolution in HI to redshift $z \sim 1.4$ and, potentially piggybacked, a deep continuum survey to reach (with stacking) the populations likely to dominate SKA surveys; pulsar timing for fundamental physics as precursor to SKA pulsar KSP. The call for large proposals issued by SKA South Africa has caused early involvement by a broad international community.

A1.2.3 MWA (USA, Australia)

The Murchison Widefield Array (MWA) is a low-frequency SKA precursor being built at the Murchison Radioastronomy Observatory (MRO). The telescope is designed to cover the frequency range 80-300 MHz in a single band, with a maximum processed bandwidth of about 31 MHz. In concept, it is an 8000 m² (at 200 MHz) sparse aperture array based on tiles of bow-tie dipole elements. At present there are 32 tiles installed at the MRO, with a build out to 512 tiles envisaged over the next two years.

MWA informs SKA in the following ways:

- In its compact form, correlation-rich signal processing and superb u-v coverage allow new regimes of sparse array imaging and calibration to be developed.
- The small amount of signal aggregation prior to processing and the relative proximity of the array to the Pawsey Centre for High Performance Computing will allow non-imaging science and systems to be explored in considerable detail.
- The instrument is situated at a candidate SKA site, yielding large amounts of information about the deployment, commissioning and operation of aperture arrays on very remote sites. Already, important lessons are being learned in areas as diverse as imperfect ground effects, coherent noise coupling, physical durability aspects of cabling, site logistical and infrastructure challenges, and EMC requirements needed to maintain the radio silence of the MRO.

- While much information is yet to emerge and be codified, first engineering lessons from the MWA are already being channelled to next-generation SKA array design via, for example, the links between ICRAR and the AAVP. Currently, the AAVP activity is formally incorporated into PrepSKA WP2, this being the primary path for informing Pre-construction activities
- MWA science will include statistical measurements of HI signal from the EoR and novel searches for transient radio phenomena.

A1.3 Pathfinders

A1.3.1 LOFAR (NL)

LOFAR is a low-frequency aperture array telescope developed by ASTRON and partners, with the 40 antenna stations and central processing facilities in the Netherlands, and a growing number stations in European countries (Ref: IEEE paper). LOFAR operates in two frequency bands: 15-80 MHz (96 antenna's per station) and 110-240 MHz (48 antenna tiles per station, European stations have 96 antenna tiles). Flexible station-based signal processing allows for trading bandwidth against instantaneous sky coverage. Central processing implements a software correlator, which can be reconfigured as a full tied array beamformer, and online calibration functions to handle the large data streams produced by the system. The key science programs for LOFAR challenge the technical specifications in several directions, which resulted in a highly reconfigurable architecture.

LOFAR is an important pathfinder for the Square Kilometre Array (SKA) in the following ways

- Proving the performance of aperture arrays, in developing solutions to major calibration issues that are directly applicable to the SKA
- Demonstrating industrial collaboration models and mass-production for such large distributed radio telescope systems. The system design and engineering processes developed for LOFAR have been migrated to the APERTIF project.
- Experience built up in LOFAR can be readily applied to the SKA in areas ranging from EMC specifications to logistics, from LNA design to control software development. Extensive documentation packages are available.
- The FP7 RadioNet JRA Uniboard continues the line of LOFAR digital processing boards at a European level. LOFAR is also a pathfinder in developing operational models for large distributed arrays in an advanced e-Science environment with multiple science centres, and distributed supercomputer and storage facilities.
- LOFAR science is arranged around a set of Key Science Projects: EoR; Extragalactic Surveys; transients; cosmic rays; solar science; cosmic magnetism. It is pathfinding international collaboration in radio astronomy via the International LOFAR Telescope (ILT).

A1.3.2 Allen Telescope Array (USA)

The Allen Telescope Array (ATA) is a 42-element array built at the Hat Creek Radio Telescope in California. The ATA offers an existing operational platform to test various aspects important to the

deep imaging required for the SKA, such as the coupling effects between shrouded offset Gregorian antennas as well as polarization effects. Many of the technologies developed for the ATA are part of the SKA baseline design. These include

- inexpensive rim-mounted hydroformed dishes
- a shrouded offset Gregorian dish design, similar to the current preferred configuration for the SKA
- ultra-wideband single pixel feeds
- inexpensive wide-band RF optical links
- the digital system which represents architectures and developments potentially directly related to the SKA, including large-N correlators and beamformers
- software, calibration, imaging and temporal solutions, and
- total intensity and polarimetric wide-field imaging for a dish array, real time calibration and imaging, and commensal observing.
- ATA science includes transient surveys and large-sky-area high frequency surveys.

A1.3.3 APERTIF (NL)

APERTIF (“APERTure Tile In Focus”) is a Phased Array Feed system (PAF) that is being developed for the Westerbork Synthesis Radio Telescope (WSRT) to increase its survey speed with a factor 20 (ref: IEEE paper). APERTIF will operate in the frequency range 1000 – 1750 MHz, with an instantaneous bandwidth of 300 MHz, a system temperature of 55 K and an aperture efficiency of 75%. The goal is to have 37 beams on the sky for an effective field of view of 8 square degrees. The current horn feeds have a 30 K system temperature, 55% aperture efficiency and 160 MHz bandwidth. The PAF will reduce the sensitivity of a single beam observation compared to the current horn feeds, but in terms of survey speed this is more than compensated by the 37x larger field of view. Each PAF consists of a dual polarized antenna arrays of 121 tapered slot elements with Low Noise Amplifiers and a Uniboard-based digital beamformer. The APERTIF correlator will also be based on Uniboard.

APERTIF is an important SKA PathFinder in the following ways:

- Demonstrating the capabilities for PAF technology on an existing, well-characterized telescope array.
- Measurements with the first APERTIF prototypes (called DIGESTIF) already demonstrate the unique capabilities of PAFs in practice: wide field of view (scan range), low system temperature, excellent illumination efficiency, synthesis imaging and a significant reduction of the reflector – feed interaction.
- APERTIF is providing a clear performance and cost benchmark for PAF technology.

- APERTIF science will include medium-deep HI surveys aimed at measuring evolution in the number density and cosmological bias of the HI population

A1.3.4 e-MERLIN (UK)

e-MERLIN is a cm-wavelength array, spanning 217 km, connected by a new dark fibre network. It is the first full-time array to be connected at 10's Gb/sec using a combination of specially installed fibre cable (90km in total) and trunk dark fibre (600km in total) leased from a number of providers. SKA pathfinding activity includes:

- Low-cost techniques of cable installation and the experience of procuring, managing and maintaining this dark fibre network are valuable for the SKA. The data transmission equipment follows the EVLA/ALMA design (in which Manchester/e-MERLIN staff participated), but e-MERLIN has extended this approach to more than ten times the maximum link used in these arrays, by using multiple amplification/regeneration sites. e-MERLIN will provide useful experience in operating this type of link over these distances.
- As part of the SKADS project e-MERLIN has been used to demonstrate optical phase transfer links over >100 km and with multiple hops, allowing this approach to be extended to hundreds of km, if required. The system is based on an optical implementation of the pulsed L-band link system designed for MERLIN, over the installed e-MERLIN optical fibre network.
- e-MERLIN science pathfinds for the SKA in the high-resolution study of the SKA populations using gravitational lensing and in the high-resolution follow-up of radio transients

A1.3.5 e-EVN (Europe)

The European VLBI Network (EVN) is a consortium of institutes operating an interferometry network of radio telescopes on a global scale from Europe to China to Puerto Rico and South Africa. The e-EVN is a development programme to transfer data in real-time from the remote EVN telescopes to the central processing facility via optical fibre cables – to replace the “traditional” implementations of VLBI in which the data are first recorded at the telescopes on magnetic media (tapes or discs) and then physically delivered to the processor. Over the last four years, fibre links have been established to most of the EVN telescopes. Data rates achieved currently are 1 Gbps per VLBI station, but the expectation is that this will increase to 16 Gbps/station.

- The e-EVN will serve as a test-bed for the SKA for long distance signal transmission across national boundaries.
- e-EVN science pathfinds for the SKA in separating AGN and starburst emission in distant sources and obtaining ultra-high-resolution follow-up of radio transients

A1.3.6 EVLA (USA)

The EVLA is a 27-element array of 25 m diameter dishes located in New Mexico. Technical areas of interest to the SKA are:

- High-rate data transmission (120 Gbit/s from each of 27 antennas) over an internally installed and maintained fibre network. SKA pathfinding activity includes:
- 2:1 bandwidth receivers with low system noise temperatures and high polarization purity
- RFI-tight designs and detailed RFI-testing protocols to prevent self-interference that can limit the dynamic range of a large array
- Data archiving and default image production in real-time or near-real-time
- Wide field-of-view imaging by means of new imaging algorithms that involves parallel processing
- Remote operations, including dynamic scheduling of the array in short scheduling blocks (an hour and shorter) to take optimal advantage of atmospheric conditions
- EVLA science pathfinding for SKA includes first surveys for galaxies in the EoR via low CO transitions and studies of cosmic magnetism

A1.3.7 LWA (USA)

LWA will consist of ~53 stations, each comprised of ~256 dipole pairs spread over a ~100 m diameter area. These stations will be distributed across New Mexico with baselines ranging up to ~400 km in length. The LWA frequency range will be 10-88 MHz.

- While the frequency overlap between SKA-low (as currently planned) and the LWA is fairly narrow, the technology of sparse aperture arrays being developed and implemented for the LWA project is highly applicable to SKA1.
- Improved understanding of the effects of mutual coupling, array design, analogue receiver design, beam forming and other digital processing issues for electronic arrays
- Development of the algorithms needed to make high fidelity, high dynamic-range images over wide-fields of view in the presence of a rapidly fluctuating ionosphere and both strong and weak RFI.
- LWA pathfinds SKA science in the studies of populations at very low frequencies.

A1.3.8 SKA Molonglo Prototype (Australia)

The SKAMP Project aims to provide a new low frequency spectroscopy and polarisation capability in the southern hemisphere, to make both science and technology contributions to the SKA Program as one of the Pathfinder Projects.

The technologies and techniques being demonstrated include

- low cost digital signal processing and transport over >1km, a flexible and highly scalable correlator design

- Proof of the efficiency and high performance with uncooled electronics for a large element system
- implementation of robust and reliable remote diagnostics in a harsh environment
- Development of software algorithms for RFI mitigation, real-time data compression and calibration, and transient detection.

A1.3.9 Arecibo (USA)

Arecibo technology programs of interest to the SKA involve

- Data management and cyber infrastructure related to the ALFA surveys, data analysis and archiving. These resources include high-speed networking, high-performance computing, large-volume storage, databases and web services. Systems are being developed with scalability in mind so the work being done on cyber infrastructure for Arecibo is relevant to the data management needed for the SKA.
- Instrumentation development of a phased-array feed for Arecibo that will lead to construction of a state-of-the-art system that, like ALFA, will make use of the high sensitivity while maximizing the available field of view. The system will involve design choices that are particular to Arecibo's optics but will provide input to any large-scale production program of PAFs for the SKA.
- Arecibo is being used for pioneering HI and pulsar surveys and for pulsar timing.

A1.4 Design Studies

A1.4.1 Technology Development Program (USA)

The Technology Development Project is a US National Science Foundation funded effort that is concentrating on two main areas for the mid-frequency range part of the SKA. These are (1) reflectors outfitted with broadband single-pixel feeds and (2) calibration and processing algorithms and assessments for high dynamic range imaging and for non-imaging applications. The nominal term of the project is from late 2007 through late 2011 but is expected to be extended through the end of 2012.

The TDP, working in collaboration with partners in Canada, Australia, and South Africa along with the SPDO, have identified a 15m offset Gregorian reflector as the design for construction of a prototype SKA antenna, known as Dish Verification Antenna 1 (DVA-1). The purpose of DVA-1 is to (1) verify the sensitivity performance of the optical design, which has been optimized for a particular suite of feed antennas; (2) demonstrate low sidelobe levels needed for high-dynamic range imaging with particular emphasis on stability of far-out sidelobes; (3) realize a low-cost mount and verify that it meets performance specifications under variable thermal and wind-loading conditions; and (4) provide a testbed for a variety of candidate wideband single-pixel feeds. The current timeline is to have a series of design reviews that will lead to delivery of the antenna to the EVLA site in approximately mid-2012 for testing and assessment by the end of the year.

The Calibration and Processing part of the TDP is investigating imaging algorithms that can meet imaging dynamic range requirements while also minimizing processing costs. Another goal is to provide constraints on pointing stability and far-out sidelobe levels that influence the antenna design.

A1.4.3 Canadian SKA program

Canadian SKA program

The Canadian SKA programme is focussed on carrying out R&D in areas of critical importance to the cost and performance of the SKA, involving university, government and industrial interests across Canada. The specific areas of interest are:

- The design and manufacture of composite dish antennas that can readily attain the performance specifications and can be readily mass-manufactured, reducing the overall cost. Two generations of prototype antenna have been constructed and tested successfully at the NRC-HIA site in Penticton that demonstrate the feasibility of this approach for the mass-manufacture of reflectors that have high efficiency up to 20 GHz. This effort is currently focussed on the engineering design and materials research for a 15-m offset reflector envisaged for SKA1.
- The design and testing of focal-plane phased-array feeds systems based on broad-band Vivaldi slot-line antennas, addressing the specific challenges of element cross-talk, polarization calibration, efficient beam forming, and noise reduction. On-the-sky tests have been carried out using a 212-element dual polarization system at the focus of the composite prototype reflectors at NRC-HIA. The current focus is R&D into the impact of different element designs and amplifier configurations on overall system performance.
- Room temperature CMOS Low-Noise Amplifiers (LNAs). Initial prototype devices designed by researchers at the University of Calgary have noise temperatures that suggest a potential enabling technology for cost effective, high sensitivity phased-array feeds.
- Low-power, high-speed analogue-to-digital converters at the University of Calgary. Such devices are critical for attaining cost-effective performance of broad-band phased arrays envisaged for the SKA.
- Space-time digital filtering algorithms, at the University of Calgary and University of Victoria, for efficient beam-forming and filtering of array element cross-talk and over-the-horizon or non-reflected RFI signals in both aperture and reflector-based antenna systems.
- Post-correlation algorithms and techniques for full-primary beam polarization calibration and imaging with both single beam and multi-beam systems, essential to attaining the high-dynamic range goals of the SKA.
- The Cyber-SKA program to develop cyber-infrastructure for the distributed data management, processing and mining required to execute the major survey projects required for the key SKA science. This multi-institute and industrial partnership program is being developed using observing programs underway on the world's most powerful radio

telescope systems, the Expanded Very Large Array and Arecibo. It is based on open-source social networking tools, and currently involving close to 80 researchers and developers across Canada and the US.

Digital system designs. This work builds on the experience of the engineers at NRC-HIA in designing, building and commissioning the WIDAR correlator for the Expanded Very Large Array, currently the largest digital correlator system in the world. The work is focussing on key technologies required for a telescope array the size of the SKA, with cost and power being leading constraints.

A1.4.3 SKA Design Study (Europe)

SKADS was an EC funded design study for the SKA running from July 2005 nominally for 4 years, which was completed in December 2009. Participation included most European countries, principally The Netherlands, UK, France and Italy, plus contributions from Australia, South Africa and Canada. SKADS received EC-FP6 €10.4M funding with national matching funding bringing the total to ~€38M.

SKADS covered multiple aspects of SKA research and design including science simulations, configuration, communications, costing plus technical development and technology road mapping to implement mid-frequency phased aperture arrays. The physical culmination of SKADS was the construction and testing of three demonstrators: EMBRACE – 144m² aperture array with RF beamforming; 2-PAD – 9m² entirely digital aperture array tile and BEST – a focal line installation on the Northern Cross radio telescope.

The results from SKADS have been highly influential for the SKA and are discussed in detail in final Conference proceedings [Torchinsky et al. 2009] and the SKADS White Paper [Faulkner et al. 2010]. In summary:

- Sky simulations have been produced which are the de-facto test data for the SKA project;
- SKA configuration packages that are being used to optimise the SKA physical layout;
- Development and use of a Cost modelling tool, now being used internationally;
- Road mapping of wide-area communications technology;
- Development of a pico-second level precise time transfer over fibre;
- Element and array design for phased arrays operating from 400MHz to 1400MHz;
- Scalable system design for very large (>75,000 element) aperture arrays;
- Development and research in ambient temperature low noise front ends;
- Road mapping of the critical digitisation and signal processing technologies into the SKA timeframe;
- Review, research and reporting on the effects of terrestrial radio frequency interference effect and their mitigation;

- Implementation and test of three demonstrator systems
- Production of a costed SKA implementation using aperture arrays which meets all the principal scientific requirements.

SKADS was very successful at taking advanced engineering concepts and reviewing potential implementations of the SKA to maximise the scientific output. SKADS also formed a major collaboration between many countries and institutions, which is continuing in the PrepSKA phase of the project.

The principal conclusion of SKADS is that an SKA implementation based on aperture arrays operating from 70MHz to 1.4GHz, with dish based receivers above 1GHz is achievable, affordable and a highly desirable solution in the SKA timeframe.

APPENDIX 2. Detailed Description of Work, Milestones, Deliverables, and Resource Requirements

A2.1 Work Package 1 (WP1) – SPO Management

During pre-construction, the SPO has to manage the successful design and development of SKA technology, initiate procurement for SKA1 construction, and provide the foundations for later phases of construction, verification and operation. This work package covers the structure of the SPO to fulfil these goals, and to ensure a coherent and effective effort with system oversight and system orientated leadership. The SPO will be staffed with several project managers, system engineers and other engineers at different levels of the organisation.

Each of the teams at system and subsystem level will be led by a project manager. It will be his/her responsibility to manage the system or subsystem to ensure on time and within budget delivery of high quality equipment.

Further detail on the roles and responsibilities of these SPO personnel is provided in Appendix 5.

The SPO technical resources per sub-system (project managers, system engineers and engineers) are included in the relevant sub-system WP. Only the staff and office costs of SPO's senior management are included in this work package.

A2.1.1 WP1 Deliverables

Milestone #	Deliverable #	Deliverable title	Nature of deliverable	Dissemination level	Due date
M1	D1	Midyear project status report	Report	PU	2012Q2
M2	D2	Year end project status report	Report	PU	2012Q4
M3	D3	Midyear project status report	Report	PU	2013Q2
M4	D4	Year end project status report	Report	PU	2013Q4
M5	D5	Midyear project status report	Report	PU	2014Q2
M5	D5	Year end project status report	Report	PU	2014Q4
M6	D6	Midyear project status report	Report	PU	2015Q2
M7	D7	Year end project status report	Report	PU	2015Q4

A2.1.2 WP1 Resources

Description	Organisation	2012		2013		2014		2015		Total		TOTAL Cost (€)	
		py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Personnel (€)		Material(€)
Totals		11	1,850,000	22	2,510,000	26	1,570,000	27	1,470,000	86	8,600,000	7,400,000	16,000,000
1) Management	SPO	3		6		8		8		25	2,500,000	0	2,500,000
2) Support personnel	SPO	7		14		16		17		54	5,400,000	0	5,400,000
3) Outreach	SPO	1		2		2		2		7	700,000	0	700,000
4) Office cost	SPO		490,000		530,000		310,000		70,000	0	0	1,400,000	1,400,000
5) Office operational cost	SPO		1,360,000		1,980,000		1,260,000		1,400,000	0	0	6,000,000	6,000,000

Note:

Office Costs include:

- Office rental
- Office infrastructure acquisition
- Computer acquisition
- Recruitment costs
- Vehicles

Office operational costs include:

- Education & Public Outreach Materials
- Travel expenses
- Review Panel Expenses
- Working Group meetings
- Other meetings
- Engineering Consultancies/sub-contracting
- Site-related Consultancies
- Legal Consultancies
- General Expenses
- Software Tools

A2.2 Work Package 2 (WP2) - Science

A2.2.1 Description of Work

- **WP2.1 – Review, Refinement and Monitoring of Science Drivers and Science Breadth**

This task provides for the SKA scientists to review and refine the SKA science narrative as the project moves forward. Once reports on SKA1 are delivered to support design reviews any substantial changes will be rare and will require following a change control procedure.

- **WP2.2 – Support science and engineering tradeoffs for SKA1 and SKA2**

This will be an ongoing task to support the engineering staff with science/engineering trade-offs. The main aim will always be to maximise the science that the instrument will deliver.

- **WP2.3 – Science operations**

This task provides for the SKA scientists to develop and refine the SKA science operations plan in close collaboration with the engineers. This will include full details of SKA surveys (including need for follow-up and supporting observations) and plans for data analysis and management.

- **WP2.4 – Science Simulations**

This task provides detailed science simulations to support the aperture array and dish verification programmes.

- **WP2.5 – Commissioning Science Support**

This task provides science support for commissioning observations with the aperture arrays.

A2.2.2 WP2 Milestones

This work package will have the following major milestones:

Milestone #	Description	Milestone date
M2.1	SKA1 Science Drivers	2011Q1
M2.2	Science Simulations for AAVS	2011Q3
M2.3	SKA1 Science Design Requirements	2011Q4
M2.4	SKA1 Trade-off Analysis+(delta)	2012Q3+2013Q3
M2.5	SKA1 Operations Analysis	2013Q3
M2.6	Science Simulations for Dishes	2013Q3
M2.7	SKA2 Trade-off Analysis	2015Q3
M2.8	SKA2 Operations Analysis	2015Q3

A2.2.3 WP2 Deliverables

The deliverables and resources for each of the major milestones are shown in the table below.

Milestone #	Deliverable #	Deliverable title	Nature of deliverable	Dissemination level	Due date
M2.1	D2.1	SKA1 Science Drivers	Report	PU	2011Q1
M2.2	D2.2	Science Simulations for AAVS	Report	PU	2011Q3
M2.3	D2.3	SKA1 Science Design Requirements	Report	PU	2011Q4
M2.4	D2.4	SKA1 Trade-off Analysis	Report	PU	2013Q3
M2.5	D2.5	SKA1 Operations Analysis	Report	PU	2013Q3
M2.6	D2.6	Science Simulation for Dishes	Report	PU	2013Q3
M2.4	D2.4	SKA2 Trade-off Analysis	Report	PU	2015Q3
M2.6	D2.6	SKA2 Operations Analysis	Report	PU	2015Q3

A2.2.4 WP2 Resources

Description	Org	2012		2013		2014		2015		Total		TOTAL Cost (€)	
		py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Personnel (€)		Material(€)
Totals		2	0	2	0	4	0	5	0	13	1,300,000	0	1,300,000
1) Project Scientists	SPO	2		2		3		3		10	1,000,000	0	1,000,000
2) Commissioning Scientists	SPO					1		2		3	300,000	0	300,000

A2.3 Work Package 3 (WP3) – System

At system level this work is aimed at completion of the SKA1 preliminary design, taking into account the required extensibility of the system to SKA2 as well as the level of integration necessary to facilitate the AIP. This work package leads to conclusion of the critical design of SKA1 and to control and manage the system engineering effort at all levels and across levels.

A2.3.1 Description of Work

- **WP3.1 – Work Package Management**

This task will be managed by the lead project manager in the SPO. Their responsibilities are described in more detail in section 8.

- **WP3.2 – Preliminary Design of SKA1**

Utilising the outputs from the SKA1 definition design phase, the system engineering team within the SPO will perform the preliminary design of the SKA1 system. Aspects that will be taken into account include the extensibility requirements of the AIP projects as well as scalability to SKA2. Activities will include the draft of specifications, initial architectural designs, initial interface design and a series of trade-offs against cost and science performance of the system. The output from this task will be a preliminary and detailed costed SKA1 system design.

- **WP3.3 – Detailed Design of SKA1**

Utilising the outputs from the SKA1 preliminary design phase, the system engineering team within the SPO will perform the detailed design of the SKA1 system. Activities will include the finalisation of specifications, completion of architectural designs, completion of interface design and final trade-offs against cost and science performance of the system. The output from this task will be a complete set of SKA1 system design documents against which eventual verification and validation will be performed. All aspects of the SKA1 system lifecycle will be covered during this phase.

Specific activities will include:

- a) Complete SKA1 detailed design phase including science/engineering tradeoffs, cost refining and interfaces design
- b) Conduct SKA1 critical design review
- c) Oversee and participate in system engineering activities at all levels
- d) Perform requirements management and change control
- e) Finalisation of SKA1 layout configuration

- **WP3.4 – Early Definition and Preliminary Design of SKA2**

To ensure coherency and continuity between SKA1 and SKA2 while considering and preparing for the technology result of the AIP technology decision, the SPO system engineering team will initiate early definition and preliminary design activities for SKA2. Although no major milestones are being foreseen within this task during this phase of the project, the integrative influence of this work will be very important. Specific activities will include the development of the full set of requirements from the Design Reference Mission, development of SKA2 requirement specification and early SKA2 architectural design. The

work will be based on the four potential SKA2 options (Baseline Design, Baseline Design + PAFs, Baseline Design + AA-mid, Baseline Design + Ultra-wideband feeds).

A2.3.2 WP3 Milestones

This work package will have the following major milestones¹:

Milestone #	SKA1	SKA2	Milestone date
	System CoDR		2011Q1
	SKA1 System SRR		2012Q1
M3.1	SKA1 System PDR		2012Q4
M3.2	Decision AIP for SKA1		2014Q1
M3.3	SKA1 System CDR		2015Q2
M3.4		Decision AIP for SKA2	2016Q1
	SKA1 System PRR		2016Q1
		SKA2 System CoDR	2016Q1
		SKA2 System PDR	2016Q4
		SKA2 System CDR	2018Q1
	SKA1 TRR		2018Q3
		SKA2 System PRR	2018Q4
	SKA1 AR		2019Q1
		SKA2 AR	2022Q4

¹ Shaded milestones do not fall within the pre-construction period.

A2.3.3 WP3 Deliverables

The deliverables and resources for each of the major milestones are shown in the table below.

Milestone #	Deliverable #	Deliverable title	Nature of deliverable	Dissemination level	Due date
		Report on the System CoDR			
		Report on the System SRR			
M3.1	D3.1	Report on the SKA1 System PDR	Report	PU	2012Q4
M3.2	D3.2	Report of decision for AIP inclusion into SKA1	Report	CO	2014Q1
M3.3	D3.3	Report on the SKA1 System CDR	Report	PU	2015Q3
M3.4	D3.4	Report of decision for AIP inclusion into SKA2	Report	CO	2015Q4
		Report on the SKA1 System PRR			
		Report on the SKA2 System CoDR			
		Report on the SKA2 System PDR			
		Report on the SKA2 System CDR			
		Report on the SKA1 TRR			
		Report on the SKA2 System PRR			
		Report on the SKA1 AR			
		Report on the SKA2 AR			

A2.3.4 WP3 Resources

Description	Org	2012		2013		2014		2015		Total			TOTAL Cost (€)
		py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Personnel (€)	Material (€)	
Totals		4	0	5	0	7	0	7	0	23	2,300,000	0	2,300,000
1) SKA Project Manager	SPO	1		1		1		1		4	400,000	0	400,000
2) Detailed System Design & Engineering SKA1	SPO	3		3		4		4		14	1,400,000	0	1,400,000
3) Early Definition and Preliminary Design SKA2	SPO			1		2		2		5	500,000	0	500,000

A2.4 Work Package 4 (WP4) – Maintenance and Support

A2.4.1 Description of Work

- **WP4.1 – Work Package Management**

The management of this package will be done as part of the overall system design management.

- **WP4.2 – Preliminary Design of SKA1 Maintenance and Support System**

During this task the maintenance and support model for SKA1 will be finalised. The model will be documented and be reviewed as part of the system preliminary design review.

Specific work to be done will include:

- a) Finalisation of maintenance and support model for SKA1
- b) Preliminary design of maintenance and support system
- c) Development of first draft maintenance and support documentation
- d) Conduct preliminary design review for SKA1 maintenance and support

• **WP4.3 – Detail Design of SKA1 Maintenance and Support System**

The design of the maintenance and support system for SKA1 will be finalised, documented and reviewed and part of the system critical design review. All aspects of maintenance and support including test equipment, spares, consumables, personnel, handbooks, training, supply lines, etc. will be addressed.

Specific work to be done will include:

- a) Detailed design of maintenance and support system
- b) Conduct review of the maintenance and support element as part of the SKA1 system critical design review for SKA1
- c) Complete the maintenance and support documentation
- d) Complete other activities as described in logistics engineering management plan

A2.4.2 WP4 Milestones

Milestone #	SKA1	Milestone date
M4.1	SKA1 System PDR	2012Q4
M4.2	SKA1 System CDR	2015Q2

A2.4.3 WP4 Deliverables

Milestone #	Deliverable #	Deliverable title	Nature of deliverable	Dissemination level	Due date
M4.1	D4.1	Report on the SKA1 Maintenance and Support PDR	Report	PU	2012Q4
M4.2	D4.2	Report on the SKA1 Maintenance and Support CDR	Report	PU	2015Q3

2.4.4 WP4 Resources

Description	Org	2012		2013		2014		2015		Total		TOTAL Cost (€)	
		py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Personnel (€)		Material (€)
Totals		0	0	1	0	1	0	1	0	3	300,000	0	300,000
1) Maintenance and Support Design	SPO			1		1		1		3	300,000	0	300,000

A2.5 Work Package 5 (WP5) – Dishes and Dish Array

A2.5.1 Description of Work

- **WP5.1 – Engineering and Management**

Within the SPO both management and engineering resources are allocated to this task. The SPO team consists of a Technical Project Manager, System Engineer and engineers. This team's responsibilities are described in more detail in section 8. The contract work will require organization and management. This will be resourced from a combination of SPO and PO personnel.

- **WP5.2 - Reviews Management**

Design reviews are required for all the major WBS elements and will be conducted by the relevant members of the SPO and POs.

- **WP5.3 – Dish Development and Testing Program**

This top level program concerns the design and fabrication of SKA antenna prototypes along with assessment of several antenna options presented by precursors and pathfinders. The goal is to design the reflector antenna for the SKA1 array that meets performance specifications and can be readily mass manufactured cost effectively. It builds heavily on previous antenna developments. Total dish system costs will be assessed throughout, reducing uncertainties as risks are identified and retired.

- **WP5.3.1 – DVA-1 Testing**

Complete the testing of DVA-1 and identify design modifications and optimizations for improved performance and reduced costs.

- **WP5.3.2 – Precursor Antenna Testing**

Conduct tests of the ASKAP and MeerKAT antennas to identify design modifications and optimizations for improved performance and reduced costs.

- **WP5.3.3 – Dish Array Verification**

Identify constraints derived from array performance in a dish array verification program that alter the antenna design, such as those that improve side-lobe and pointing stability.

- **WP5.3.4 – Risk Assessment**

A detailed characterization of the performance of the ATA, ASKAP, MeerKAT and DVA-1 is required to complete a risk assessment of each design to identify technical and cost risks. Risk assessment includes cost-performance analysis against SKA specifications. Complete any necessary prototyping, as required to retire risks. It will be necessary to decide to undertake a second prototype (DVA-2) or proceed directly to a final design for SKA1. This determines whether the next stage is a set of “Delta” designs and reviews or a complete antenna-system prototype (DVA-2). The default plan is for a Delta process to apply.

- **WP5.3.5 – SKA1 Antenna Design**

This is the final detailed dish design for SKA1, incorporating design elements from previous prototypes and ready for mass manufacture. Note: if necessary, a separate work package will have to be defined if DVA-2 is required.

- **WP5.3.6 – Costing and Preparing for Procurement**

Develop a procurement plan for dishes for SKA1.

- **WP5.4 – Single Pixel Feeds and Receivers**

This work package is to complete the design of the feed and receiver system for SKA1, from the feed element through amplifiers to the output of the receiver system. The working plan is for receivers to include digitisers. Alternative choices will depend on signal transport decisions.

- **WP5.4.1 – Assessment of Feed Designs**

Consolidate results on WBSPFs and OBSPFs based on developments prior to 2013.0. Review the various systems and select feeds for SKA1.

- **WP5.4.2 – Design and Development of SKA1 feeds and receiver systems.**

The current default plan is for these to be OBSPFs but WBSPFs will be either chosen from current prototypes or further developed in the AIP. The design must account for mass manufacture, most especially of receiver components e.g. cryogenics. Fabrication of SKA1 feed/receiver prototypes and testing on SKA prototype antenna(s).

- **WP5.4.3 –Preparing for Procurement**

Develop the procurement plan for feeds and receivers for SKA1.

- **WP5.5 – Phased array feeds (PAF) Design and Development**

During this period phased array feeds will be developed, tested and evaluated as part of the Advanced Instrumentation Program (AIP). Activities will include:

- **WP5.5.1 – Complete preliminary design phase of PAF for SKA (PAFSKA)**
- **WP5.5.2 – Design, fabricate and test SKA1-ready phased array feed.** Integrate, test and evaluate complete prototype phased-array feed on the SKA1 prototype antenna, as needed. The design includes mass manufacture requirements.
- **WP5.5.3 – Costing and Preparation for Procurement**
- **WP5.6 – SKA1 dish array procurement**

For the SKA1 dish array the following activities will be performed:

- a) Complete dish array detailed design phase (based on results and inputs from DVA-2)
- b) Conduct critical design review for SKA1
- c) Initiate procurement of SKA1 dish receptors (dish, receiver, feed with cryostat and LNA).
- d) Support contractor in re-work of documentation and build of first production model
- e) Test and evaluate production model (including dish, receiver, single pixel feed and LNA)
- f) Perform SKA1 dish receptor production readiness review

A2.5.2 WP5 Milestones

Milestone #	Dish	Single Pixel Feed	Phased Array Feed	Milestone date
M5.1	DVA-1 ready for testing (TRR)	Results from research		2012Q1
M5.2	Antenna results ASKAP and ATA			2012Q2
M5.3		Selection SKA1 feeds		2012Q2
M5.4	DVA-1 testing complete			2013Q1
M5.5	Antenna results from MeerKAT			2013Q3
M5.6	Assessment of three antenna options		PAF SKA1 decision	2014Q1
M5.7	CoDR SKA1 antenna			2014Q2
M5.8		PDR SKA1 feeds		2014Q2
M5.9		CDR SKA1 feeds		2014Q3
M5.10	PDR SKA1 antenna			2015Q1
M5.11	CDR SKA1 antenna			2015Q2
M5.12		Constr. Prototype		2015Q3
M5.13	Prep. Procurement			2016Q1
M5.14		TRR SKA feeds	PAF SKA2 decision	2016Q1
M5.15		Prep. Procurement		2016Q2

A2.5.3 WP5 Deliverables

Milestone #	Deliverable #	Deliverable title	Nature of deliverable	Dissemination level	Due date
M5.1	D5.1	DVA1 TRR report	Report	PU	2012Q2
M5.2	D5.2	Reports on ASKAP and ATA antenna evaluations			2012Q3
M5.3	D5.3	Selection of feeds report	Report	PU	2102Q3
M5.4	D5.4	DVA1 test results report	Report	PU	2013Q2
M5.5	D5.5	Report on MeerKAT antenna evaluation	Report	PU	2013Q4
M5.6	D5.6	Report on result of assessment of three antenna options	Report	PU	2014Q2
M5.7	D5.7	SKA1 antenna CoDR report	Report	PU	2014Q3
M5.8	D5.8	SKA1 single pixel feeds PDR report	Report	PU	2014Q3
M5.9	D5.9	SKA1 single pixel feeds CDR	Report	PU	2014Q4
M5.10	D5.10	SKA1 antenna PDR report	Report	PU	2015Q2
M5.11	D5.11	SKA1 antenna CDR report	Report	PU	2015Q3
M5.12	D5.12	Report on SKA1 single pixel feed prototype	Report	PU	2015Q4
M5.13	D5.13	SKA1 antenna preparation for procurement documents	Report	PU	2016Q2
M5.14	D5.14	SKA1 single pixel feeds TRR report	Report	PU	2016Q2
M5.15	D5.15	SKA1 single pixel feed preparation for procurement documents	Report	PU	2016Q2

A2.5.4 WP5 Resources

Description	Org	2012		2013		2014		2015		Total			TOTAL
		py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Personnel (€)	Material (€)	Cost (€)
Totals		20	2,275,000	23	1,475,000	21	2,375,000	17	1,225,000	80	8,010,000	7,350,000	15,260,000
1 Management and Engineers	SPO	1		2		2		2		7	700,000	0	700,000
2 Consortium Management	WPC	1	125,000	1	125,000	1	125,000	1	125,000	4	400,000	500,000	900,000
3 Handling of reviews	WPC									0	0	0	0
4 Dish Development & Testing		6	600,000	6	400,000	4	400,000	4	0	20	2,000,000	1,400,000	3,400,000
4.1 DVA1 Testing	WPC	3	500,000							3	300,000	500,000	800,000
4.2 Precursor Antenna Testing	WPC	3	100,000							3	300,000	100,000	400,000
4.3 Dish array verification	WPC			3	200,000					3	300,000	200,000	500,000
4.4 Risk Assessment	WPC			3	200,000					3	300,000	200,000	500,000
4.5 SKA1 Antenna Design	WPC					4	400,000			4	400,000	400,000	800,000
4.6 Dish Costing & Preparation for Procurement	WPC							4	0	4	400,000	0	400,000
4.7 DVA-2 prototype (if required)	WPC								0	0	0	0	0
5 Octave-Band Single Pixel Feeds and Receivers		1	25,000	4	75,000	4	75,000	2.5	100,000	11.5	1,150,000	275,000	1,425,000
5.1 Assessment of feed designs	WPC	1	25,000							1	100,000	25,000	125,000
5.2 Design & Development	WPC			4	75,000	4	75,000	1.3	75,000	4.8	480,000	225,000	705,000
5.3 Costing & Procurement	WPC							1.2	25,000	0.7	70,000	25,000	95,000
6 Wide-band Single Pixel Feeds and Receivers (AIP)		1	25,000	2	75,000	2	75,000	1.5	100,000	6.5	650,000	275,000	925,000
6.1 Assessment of feed designs	WPC	1	25,000							1	100,000	25,000	125,000
6.2 Design & Development	WPC			2	75,000	2	75,000	0.8	75,000	4.8	480,000	225,000	705,000
6.3 Costing & Procurement	WPC							0.7	25,000	0.7	70,000	25,000	95,000
7 Phased Array Feeds (AIP)	WPC	9	1,500,000	8	800,000	8	1,700,000	6	900,000	30	3,010,000	4,900,000	7,910,000

A2.6 Work Package 6 (WP6) – Aperture arrays

A2.6.1 Description of Work

- **WP6.1 – Engineering and Management**

Within the SPO both management and engineering resources are allocated to this task. The SPO team consists out of a Technical Project Manager, System Engineer and Engineers. This team's responsibilities are described in more detail in section 8.

- **WP6.2 – Consortium Management**

This will be a major international grouping of institutes and industrial partners, the programme will need considerable management to ensure timely, consistent results with the expected reporting from the partners and to the SPO. This is the task that covers this activity. It includes all non-developmental work.

- **WP6.3 – Handling of reviews**

Reviews of the AA system need to be handled in a professional and consistent manner with the SPO and external reviewers. This task ensures the review process will have the relevant time and resources assigned to it.

- **WP6.4 – Subsystem Design SKA1 AA-low array**

The electromagnetic design for the overall AA-low station array and element is covered in this task. It covers the overall layout, the simulated performance and measurement of the actual performance achieved.

- **WP6.5 – Subsystem Design SKA2 AA-mid array**

The electromagnetic design for AA-mid array and element is performed in this task. It covers the overall layout, the simulated performance and measurement of the actual performance achieved.

- **WP6.6 – Quality, RAMS**

This is an oversight task for all of the developments within the AA Work package. It will ensure consistent quality standards and set the required reliability, availability, maintainability and safety requirements consistent with SPO requirements at system level. It will further conduct the testing required to ensure that the standards are met for SKA implementation.

- **WP6.7 – Specific technical developments**

There is a substantial amount of sub-system technical development required; all these developments are grouped into this task:

- **WP6.7.1 – AA-low Antenna & LNA**

This task covers the detailed physical design of the AA-low element and associated local hardware, comprising all components that are part of the front end and including the signal transport interface to the copper or fibre link which connects to the first stage of processing. It covers: elements, LNA and matching, control and monitoring, if required, and physical implementation.

- **WP6.7.2 – AA-mid Antenna & LNA**

This task covers the detailed physical design of the AA-mid element and associated local hardware, including all of the components that are part of the front end

including the signal transport interface to the analogue gain and filter elements. It covers: elements, LNA and matching, and physical implementation.

- **WP6.7.3 – RF transport and analogue systems, AA-low**

This covers the design of the RF transport, which may be using copper systems from the AA-low elements to the first stages of processing. The analogue systems will need to amplify, equalise, normalise and provide Nyquist filtering prior to digitisation. It will also consider the option of analogue signal processing prior to digitisation within the element electronics for signal transport using fibre.

- **WP6.7.4 – RF transport and analogue systems, AA-mid**

This work covers the analogue signal conditioning between the output of the LNA and the input to the digitiser. In the AAVS demonstrators this may include a level of RF beamforming prior to digitisation. Unlike the AA-low systems, the signal transport is not expected to be more than a few metres, so is likely to be implemented in copper.

- **WP6.7.5 – A/D conversion**

The digitisers are planned to be identical for the AA-low and AA-mid systems. This task covers the procurement of the digitisers for the AAVS and subsequent SKA AA implementations, with increasing levels of integration.

- **WP6.7.6 – Digital Signal Processing: hardware**

Core to the implementation of AA systems –low and –mid is the signal processing. This hardware will evolve with improving performance and reduced power consumption through the development period. Initial AAVS systems will rely on the current FPGA performance; this may evolve into ASICs or many-core processors, or both, for SKA implementation. Due to the extensive nature of the processing, this task also includes the implementation of the short range (50-100m) station level optical interconnect.

- **WP6.7.7 – Network interface**

This is the connection hardware required for the output of the DSP hardware to the wide-area network back to the correlator.

- **WP6.7.8 – Time Distribution**

Stable timing and phase is essential to the operation of the AAs. This task covers the reception of timing from the central systems or local maser and its distribution across the station processors and principally to the digitisers. While phase differences can be accommodated by calibration, variations in frequency and jitter cannot. This task designs the implementation and ensures that the distribution network meets the required specifications.

- **WP6.7.9 – Power Distribution**

AA systems will draw considerable power, with distribution required to central and tile processing plus wider distribution to elements. This task will specify the distribution topology to the various systems and ensure that self generated RFI is minimised.

- **WP6.7.10 – Local Infrastructure**

This is the wide scale mechanical construction which will be fundamental in meeting the RAMS specification discussed above. It is also closely coupled with the power distribution to provide the required cooling. It is also closely linked to the RFI mitigation task to provide the required screening of the active systems.

- **WP6.7.11 – Local Control Software**

Each AA station is a major IT installation. It will need complex control and monitoring, with reporting back to the central SKA control systems. The hardware for control and monitoring will be intrinsic to many of the subsystems, extending to the element level. This level of information will be essential for properly calibrating the arrays. The control systems will also be responsible for setting up the required observation modes and tracking the beams.

- **WP6.7.12 – Digital Signal Processing: firmware and software**

The large DSP systems will need some sophisticated and well tested software and firmware as appropriate. This design will be done in this task.

- **WP6.7.13 – Station calibration**

The calibration of all aspects of the SKA system is essential to providing the performance and dynamic range required. The AA station level calibration provides the coefficients required for the optimisation of the beams. This is a multi-stage process with initial, pre-observation and observation phases. This will require some specification of hardware particularly for the AA-mid and software techniques to be performed and to be determined intervals to maintain performance. This task provides the means of delivering this performance.

- **WP6.7.14 – Station configuration**

The overall station configuration determines the data rates and processing required at the various stages of the system. It designs the power budgets for the different sub-systems to meet the total requirements.

- **WP6.8 – Environmental tests**

There will be a rigorous test programme to ensure that all aspects of the system meet the RAMS requirements. The system will be in a challenging environmental location with high

temperatures, diurnal cycles, potential precipitation, and dust will need to be tested for, as well as transportation and installation stresses.

- **WP6.9 – Tooling & NRE**

To meet the challenging cost and power requirements will require substantial investment in tooling and chip development. This is the package that brings all these costs into a single place for assessment and budgeting.

- **WP6.10 – Preparing for Manufacture**

This is the production engineering task to ensure that the high volume systems are manufacturable in the costs and quantities required. Much of this work will be disseminated across many of the tasks and is closely allied to the tooling and NRE requirements. It is expected that industry partners will provide much of the input for this task.

- **WP6.11 – Self-generated RFI and EMC**

Minimising self-generated RFI and ensuring electromagnetic compatibility is a critically important aspect of the AA development, since these sub-systems contain a significant amount of high-speed digital electronics. This task will ensure that the entire system meets the stringent requirements for the SKA.

- **WP6.12 – Verification Models**

The major physical deliverables of this work package are the AAVS1 (Preparatory Phase) and AAVS2 (Pre-Construction Phase) systems. These tasks cover the construction followed by test and verification of the systems for both AA-low and AA-mid. The verification results will be fed directly into the Design Reviews to inform the rest of the development process. The results for AA-mid on AAVS2 will be used to determine whether AA-mid can be implemented in SKA2.

- **WP6.13 – Technology studies: AA-mid**

The AA-mid is technologically very challenging and is scheduled to start construction on SKA scales in 2019. The ability to meet the performance, power and cost required for deployment is dependent on the continuing advance of semiconductor technology. This task will roadmap and continually update the expectations of the technologies and evaluate the opportunities that are presented from industry and commercial use of the period of the Pre-construction. The reports will be used in the decision for implementation of AA-mid.

A2.6.2 WP6 Milestones

Milestone #	AA-low	AA-mid	Milestone date
	AAVP Start		2010Q1
	CoDR		2011Q1
	AA element review		2011Q2
	Element performance Review	Front-end design	2011Q3
	AAVS1 CDR		2011Q4
M6.1	AAVS1 PRR		2012Q2
M6.2	Start AAVS1 Construction		2012Q3
M6.3	Start AAVS1 Commissioning		2012Q4
M6.4	SKA1 Subsystem PDR		2013Q1
M6.5	AAVS2 PDR		2013Q2
M6.6	AAVS2 CDR		2013Q3
M6.7	AAVS2 PRR		2013Q4
M6.8	Start AAVS2 Construction		2014Q1
M6.9	TRR AAVS2		2014Q3
M6.9	Start AAVS2 Commissioning		2014Q4
M6.10		PDR	2015Q2
M6.11	SKA1 Subsystem PRR		2015Q4
	Construction for SKA1		2016Q3

A2.6.3 WP6 Deliverables

Milestone #	Deliverable #	Deliverable title	Nature of deliverable	Dissemination level	Due date
M6.1	D6.1	AAVS1 PRR report	Report	PU	2012Q3
M6.2	D6.2	None			
M6.3	D6.3	None			
M6.4	D6.4	SKA1 AA-low PDR report	Report	PU	2013Q2
M6.5	D6.5	AAVS2 for AA-low PDR report	Report	PU	2013Q3
M6.6	D6.6	AAVS2 for AA-low CDR report	Report	PU	2013Q4
M6.7	D6.7	None			
M6.8	D6.8	AAVS2 for AA-low TRR report	Report	PU	2015Q1
M6.9	D6.9	None			
M6.10	D6.10	None			
M6.11	D6.11	AA-mid PDR report	Report	PU	2015Q3
M6.12	D6.12	SKA1 AA-low PRR report	Report	PU	2016Q1

A2.6.4 WP6 Resources

Description	Org	2012		2013		2014		2015		Total			TOTAL
		py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Personnel (€)	Material (€)	Cost (€)
Totals		40.3	1,100,000	40.25	155,000	37.5	365,000	37.5	5,535,000	156	15,550,000	7,155,000	22,705,000
1) Man. and Eng.	SPO	1		2		2		2		7	700,000	0	700,000
2) Consortium Man.	WPC	2.5	50,000	2.5	50,000	2.5	50,000	2.5	75,000	10	1,000,000	225,000	1,225,000
3) Handling of reviews	WPC			0.5	50,000	0.5	50,000	0.5	50,000	1.5	150,000	150,000	300,000
4) Subsystem Design SKA1 AA-low array	WPC	3		3		3		3		12	1,200,000	0	1,200,000
5) Subsystem Design SKA2 AA-mid array (AIP)	WPC	1		1		1		1		4	400,000	0	400,000
6) Quality, RAMS	WPC	0.5		0.5		0.5		0.5		2	200,000	0	200,000
7) Specific developments		24.25	50,000	24.25	55,000	19	65,000	17	10,000	84.5	8,450,000	180,000	8,630,000
7.1) AA-low Antenna & LNA	WPC	3	10,000	3	10,000	1	10,000	1		8	800,000	30,000	830,000
7.2) AA-mid Antenna & LNA (AIP)	WPC	2	10,000	2	10,000	1	10,000	1	10,000	6	600,000	40,000	640,000
7.3) RF transport and analog systems	WPC	2		2		1		1		6	600,000	0	600,000
7.4) RF transport and analog systems (AIP)	WPC	1		1		0		0		2	200,000	0	200,000
7.5) A/D conversion	WPC	2	10,000	2	10,000	2	10,000	2		8	800,000	30,000	830,000
7.6) Digital Signal Processing (hw)	WPC	4	20,000	4	20,000	4	20,000	2		14	1,400,000	60,000	1,460,000
7.7) Network interface	WPC	0.75		0.75		0.75	10,000	0.75		3	300,000	10,000	310,000
7.8) Time Distribution	WPC	1		1	5,000	0.75	5,000	0.75		3.5	350,000	10,000	360,000
7.9) Power Distribution	WPC	0		0		0		1		1	100,000	0	100,000
7.10) Local Infrastructure	WPC	1.5		1.5		1.5		1.5		6	600,000	0	600,000
7.11) Local Control Software	WPC	2		2		2		2		8	800,000	0	800,000
7.12) DSP (fw)	WPC	2		2		2		1		7	700,000	0	700,000
7.13) Station calibration	WPC	3		3		3		3		12	1,200,000	0	1,200,000
7.14) Station configuration	WPC									0	0	0	0
8) Environmental tests	WPC	1		1		1		1		4	400,000	0	400,000
9) Tooling & NRE	WPC					200,000		400,000		0	0	600,000	600,000
10) Prep. for Manufacture	WPC			1		1		1		3	300,000	0	300,000
11) Self-gen. RFI and EMC	WPC									0	0	0	0
12) Verification Models		7	1,000,000	4.5	0	7	0	9	5,000,000	27.5	2,750,000	6,000,000	8,750,000
12.1) Construction of Perf. Model (AAVS1)	WPC	5	1,000,000							5	500,000	1,000,000	1,500,000
12.2) T&V of Perf. Model	WPC	2		3						5	500,000	0	500,000
12.3) Construction of Manf. Model (AAVS2)	WPC			1.5		3		5	5,000,000	9.5	950,000	5,000,000	5,950,000
12.4) T&V of Manf. Model	WPC					4		4		8	800,000	0	800,000
13) Tech. studies (AIP)	WPC	p.m.											

A2.7 Work Package 7 (WP7) – Signal Transport and Networks

A2.7.1 Description of Work

- **WP7.1 – Engineering and Management**

Within the SPO both management and engineering resources are allocated to this task. The SPO team comprises a Technical Project Manager, System Engineer and Engineers. This team's responsibilities are described in more detail in section 8.2.3.

- **WP7.2 – Preliminary Design**

a) For all the subsystems:

- i. Complete SKA1 preliminary design phase
- ii. Conduct SKA1 preliminary design review
- iii. Completion and auditing of documentation

b) Subsystems for review in this phase include:

- i. Dish cabling
- ii. Digital data back haul
- iii. LO and timing
- iv. M+C network

c) Fibre Network Infrastructure connection schematic delivered

- **WP7.3 – Network Infrastructure**

This work will include leadership and coordination of the network infrastructure task, including review of plans and designs. The integration of site information and network infrastructure designs are included in this task as well as the preparation of the procurement datapacks. There will be some preparatory work on plans to manage the 'as built' network and test results.

- **WP7.4 – Digital Data Backhaul**

This work will include the detailed definition and monitoring of interfaces, review of designs and the completion of procurement ready datapacks. Prototype systems will be constructed and test software/firmware developed, if applicable.

- **WP7.5 – Synchronisation**

This work will include the detailed definition and monitoring of interfaces, review of designs and the completion of procurement ready datapacks. Prototype systems will be constructed and test software/firmware developed, if applicable.

- **WP7.6 – M&C Networks (Physical Layer)**

This work will include the detailed definition and monitoring of interfaces, review of designs and the completion of procurement ready datapacks. Prototype systems will be constructed and test software/firmware developed, if applicable.

- **WP7.7 – Antenna Networks**

This work will include the detailed definition and monitoring of interfaces, review of designs and the completion of procurement ready datapacks. Prototype systems will be constructed and test software/firmware developed, if applicable.

- **WP7.8 – Central Facility Interconnects**

In this task a central facilities fibre network cabling and routing plan will be developed. Work will include the detailed definition and monitoring of interfaces, review of designs and the completion of procurement ready datapacks.

- **WP7.9 – Imaging Distribution**

This work will include the detailed definition and monitoring of interfaces, review of designs and the completion of procurement ready datapacks. Prototype systems will be constructed and test software/firmware developed, if applicable.

A2.7.2 WP7 Milestones

Milestone #	STaN	Milestone date
	CoDR for SKA1	2011Q3
	Gap analysis and plan for industry involvement and covering gaps	2012Q1
M7.1	SRR for SKA1	2012Q4
M7.2	PDR for SKA1	2014Q1
M7.3	CDR for SKA1	2015Q4

A2.7.3 WP7 Deliverables

Milestone #	Deliverable #	Deliverable title	Nature of deliverable	Dissemination level	Due date
M7.1	D7.1	Signal transport and networks SRR report	Report	PU	2013Q1
M7.2	D7.2	Signal transport and networks PDR report	Report	PU	2015Q1
M7.3	D7.3	Signal transport and networks CDR report	Report	PU	2016Q1

A2.7.4 WP7 Resources

Description	Org	2012		2013		2014		2015		Total			TOTAL Cost (€)
		py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Personnel (€)	Material (€)	
Totals		6	0	8	0	10	0	10	310,000	34	3,400,000	310,000	3,710,000
1) Management and Engineering	SPO	1		2		2		2		7	700,000	0	700,000
2) Network Infrastructure	WPC							150,000		0	0	150,000	150,000
3) Digital Data Backhaul	WPC	1		1		2		2		6	600,000	0	600,000
4) LO & Timing	WPC	1		1		2		2	150,000	6	600,000	150,000	750,000
5) M&C Network	WPC	2		2		2		2		8	800,000	0	800,000
6) Antenna networks	WPC	1		2		2		2	10,000	7	700,000	10,000	710,000
7) Central Facility Interconnects	WPC	0		0		0		0		0	0	0	0
8) Imaging distribution	WPC	0		0		0		0		0	0	0	0

A2.8 Work Package 8 (WP8) – Central Signal Processing

An evolutionary development of the Signal Processing is being considered, aimed at providing maximum flexibility and minimum development time in the early stages of deployment but efficiency in terms of cost and thermal dissipation as the system grows. To achieve this, more than one parallel technology development is under consideration.

Software processing offers maximum flexibility but ultimately will have limitations with respect to thermal dissipation and cost as the system grows. The same processing hardware can be used for Central Beam-forming, Correlation and Non-Imaging processing in the early stages of the system.

FPGA processing offers a more power efficient solution while still maintaining a reasonable level of flexibility. Its efficient programming requires specific skill sets which are likely to include the use of hardware description languages such as VHDL or Verilog.

An ASIC solution is the most efficient solution with respect to thermal dissipation and cost. This, however, is at the expense of flexibility and development cost. The design of an ASIC device needs specific skill sets and a good working relationship with the ASIC foundry house.

The software processing needs to be fully integrated and verified up to the Assembly level in the systems hierarchy as part of the Pre-Construction Phase. In addition, partial verification of sub-systems is required for scaled down prototypes (primarily in factories).

FPGA and ASIC based solutions are to be developed in parallel with the software processing during the preconstruction phase and include development and integration of:

- PCB development

- Firmware
- Test harnesses
- Mechanical assemblies
- Environmental testing
- Cabling

A2.8.1 Description of Work

- **WP8.1 – Engineering and Management**

Within the SPO both management and engineering resources are allocated to this task. The SPO team consists out of a Technical Project Manager, System Engineer and Engineers. This team's responsibilities are described in more detail in section 8.

- **WP8.2 – Electronic Design and Implementation**

The electronic design work package is to cover all activities associated with providing electronic hardware for the Signal Processing domain. This activity is to include (but is not limited to):

- 1) Inputting the technical infeed to COTS equipment procurement specifications
- 2) Detailed design and interface specifications
- 3) FPGA and ASIC design and implementation
- 4) Schematic capture of bespoke board designs
- 5) Detailed test specification and execution
- 6) Requirement sign-off

- **WP8.3 – Signal Processing Software Design and Implementation**

The electronic design work package is to cover all activities associated with providing electronic hardware for the Signal Processing domain. This activity is to include (but is not limited to):

- 1) Inputting the technical infeed to COTS equipment procurement specifications data exchange specifications
- 2) Detailed software design
- 3) Configuration Management
- 4) Test Harness design and documentation
- 5) Detailed test specification and execution

6) Requirement sign-off

- **WP8.4 – Signal Processing Integration and Verification**

The Integration and verification work package is to cover the integration at each level of the systems hierarchy. This activity is to include (but is not limited to):

- 1) Stress testing of components, sub-assemblies, assemblies and sub-systems.
- 2) Detailed integration test execution and documentation
- 3) Requirement sign-off

- **WP8.5 – Mechanical Design**

Although the equipment practice for the signal processing is expected to be based on COTS Cabinet design, the scale of the SKA in terms of the amount of processing and signal connectivity are likely to require mechanical design support:

- 1) Thermal Modelling and testing
- 2) Heat-sink design
- 3) Cable Management
- 4) Connector panels
- 5) Shock mounts (if required)
- 6) Technical input to COTS procurement specifications
- 7) Verification and Requirement sign-off

- **WP8.6 – Environmental Testing**

Specify, co-ordinate and document testing at Environmental test house. This activity is to include (but is not limited to):

- 1) Conducted and radiated emission testing and documentation.
- 2) Shock and Vibration testing
- 3) Verification and Requirement sign-off

- **WP8.7 – Signal Processing Cable Management**

Generation of wiring diagrams

A2.8.2 WP8 Milestones

Milestone #	Software Correlator	Embedded Correlator	Non Imaging Processing	Milestone date
	Signal Processing CoDR			2011Q1
	Signal Processing SRR			2012Q3
M8.1	PDR for SKA1			2014Q1
M8.2		PDR for SKA1		2014Q4
M8.3			PDR for SKA1	2014Q4
M8.4	CDR for SKA1			2015Q1
M8.5	PRR for SKA1			2015Q4
M8.6		CDR for SKA1		2015Q4
M8.7			CDR for SKA1	2015Q4
	FAT of SKA1 software correlator			2016Q1
		PRR for SKA1		2016Q3
		AR for SKA1		2016Q3
			PRR for SKA1	2016Q3
			AR for SKA1	2016Q3
		On Site AR for SKA1		2017Q1
			On Site AR	2017Q1
		SKA2 Design		2018Q1

A2.8.3 WP8 Deliverables

Milestone #	Deliverable #	Deliverable title	Nature of deliverable	Dissemination level	Due date
M8.1	D8.1	Software Correlator PDR Report	Report	PU	2014Q2
M8.2	D8.2	Embedded Correlator PDR Report	Report	PU	2015Q1
M8.3	D8.3	Non Imaging Processing PDR Report	Report	PU	2015Q1
M8.4	D8.4	Software Correlator CDR Report	Report	PU	2015Q2
M8.5	D8.5	Software Correlator PRR Report	Report	PU	2016Q1
M8.6	D8.6	Embedded Correlator CDR Report	Report	PU	2016Q1
M8.7	D8.7	Non-Imaging Computing CDR Report	Report	PU	2016Q1

A2.8.4 WP8 Resources

Description	Org	2012		2013		2014		2015		Total		TOTAL	
		py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Personnel (€)	Material (€)	Cost (€)
Totals		13	0	27	200,000	37	300,000	35	200,000	11	11,200,000	700,000	11,900,000
1) Management and Engineering	SPO	1		2		2		2		7	700,000	0	700,000
2) Engineers	SPO/WPC					1		1		2	200,000	0	200,000
3) Inetral WP management	WPC	1		1		1		1		4	400,000	0	400,000
4) Electronic Design and Implementation	WPC	4		8	200,000	8	200,000	8	200,000	28	2,800,000	600,000	3,400,000
5) Software Design and Implementation	WPC	7		8		12		8		35	3,500,000	0	3,500,000
6) Integration and Verification	WPC			4		6		10		20	2,000,000	0	2,000,000
7) Mechanical Design	WPC			4		4	100,000			8	800,000	100,000	900,000
8) Envionmental Design	WPC							2		2	200,000	0	200,000
9) Cable Management	WPC					3		3		6	600,000	0	600,000

A2.9 Work Package 9 (WP9) – Software and Computing

The principle elements of this system are system analysis and design, system software, central processing and science processing.

Sub-System analysis and design

There will be a systematic approach to the design of the S&C sub-system based on an analysis of both the information flow through the observing process and data flow through the SKA system. These two aspects are clearly strongly interrelated and this interrelationship and the requirements which flow from it will be crucial elements of the design. The other work packages address detailed aspects of the overall sub-system.

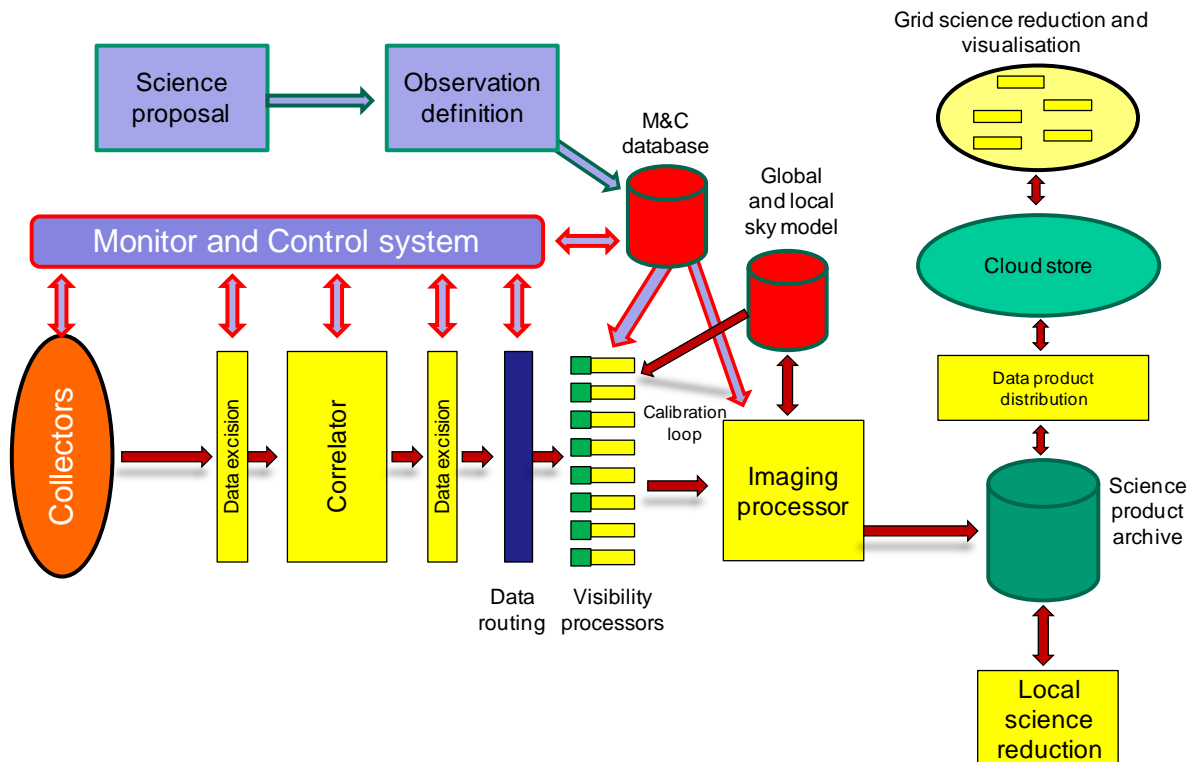
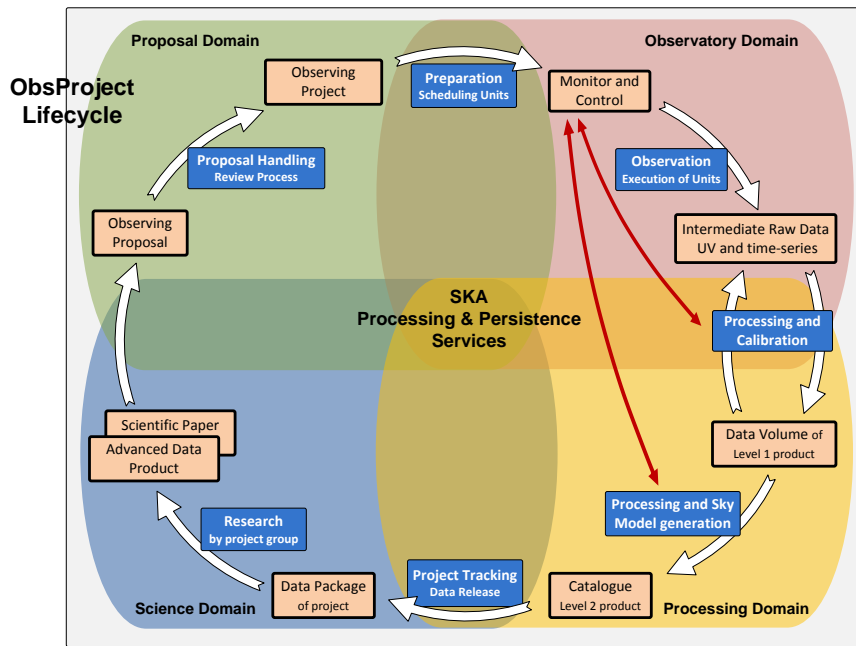


Figure A.1: Figure showing the information flow (top) and data flow (bottom)

System software – proposal and observatory domains

- Observing proposal tool provides the external astronomer access to the facility and is critical software for presenting the observatory to its user base

- Scheduling and observation handling layer accessible to observatory staff and linked closely to the M&C system
- Monitor and control system (M&C) communicates with all other sub-systems, synchronising sub-systems routing control information and logging monitor data to the central system database. The M&C system will be built from industry standard components and interfaces as far as possible.
- The health-management system is an expert system employing monitor data to maintain an optimised system communicating with sub-systems via the M&C sub-system.

Central processing – processing domain

Data rates from the correlator are extremely large and necessitate careful consideration of the data flow through the system. To facilitate the management of these data careful data routing is required to ensure that, for a given observing mode, data are organised so that they can be efficiently processed by a highly parallel system, the UV-processor. The re-ordering of the data ensures the algorithms on the UV-processor can be “embarrassingly parallel”.

The UV-processor is a highly parallel sub-system dealing with streaming data ordered by the routing system. Buffering of the data is required for multi-pass analysis algorithms. Very careful analysis and design of the software/hardware is required in this sub-system.

Data rates drop after the UV-processor and data are routed to an imaging processor. For multi-pass calibration approaches, results from the imaging-processor must be communicated back to the UV-processor (e.g. updated sky model).

The central-system database serves information on monitor data and the evolving sky model to both the UV-processor and imaging processor as required.

Calibrated data products are output from the imaging processor and passed to the Tier-0 science processing system where standard analysis (e.g. source detection etc.) is performed and the science ready data are archived.

Science Processing – science domain

The baseline design is based on the LOFAR/ASKAP model, where:

- Science processing is a Tiered and distributed process. Tier-1 processing and archiving is associated with the key-science areas and will be the responsibility of the science teams. Data are accessed from the Tier-0 archive using standard interfaces.
- Further Tiers of processing/archiving may be required and regional/national science requirements demand.

The WBS for the pre-construction phase is discussed in more detail in the following sections – all tasks follow the project structure discussed above.

The three sub-tasks are coordinated by an integrated S&C design team who are responsible for the delivery of the SKA S&C sub-system design to CDR level for SKA1 and PDR level for SKA2.

A2.9.1 Description of Work

- **WP9.1 – Engineering and Management**

Within the SPO both management and engineering resources are allocated to this task. The SPO team consists out of a Technical Project Manager, System Engineer and Engineers. This team's responsibilities are described in more detail in section 8.

- **WP9.2 – Overall design**

This work package will analyse the top-level S&C sub-system requirements by considering the flow of information, flow of data and interactions with the overall system design. The workpackage will deliver an overall software architecture, define interfaces and provide configuration control within which the other workpackages will operate. The relationship between the work packages is shown in the figure below.

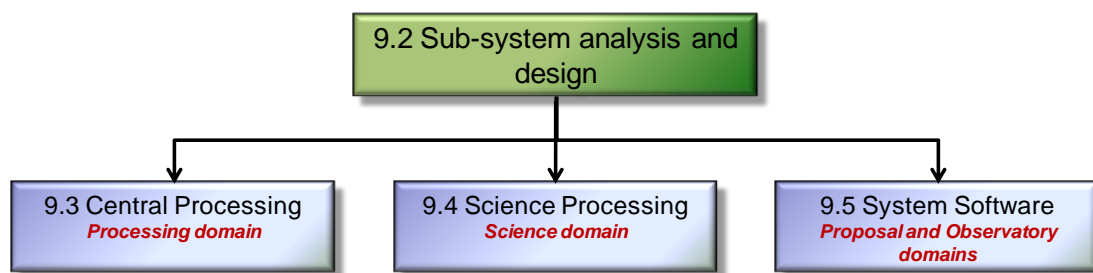


Figure A.2: Relationship between work packages

- **WP9.3 – Central processing**

This sub-WP consists of 10 tasks. The sub-WP runs through all phases of the project and provides critical input to all review stages.

- **WP9.3.1 – Analysis of data streams**

The deliverable of this task is an analysis of detailed requirements for the data flow based on the Design Reference Mission (DRM) [6]. The task completes in time for the requirements review in Q3 2012.

- **WP9.3.2 – Design and prototype data routing**

Data routing is critical to maintain the throughput of the system by ordering the data to enable very efficient parallel processing of the streaming data. This task starts following the requirements review and will be undertaken by an industrial partner or sub-contractor. The task will deliver a design for the data routine sub-system and a prototype demonstration system.

- **WP9.3.3 – UV-processor design, benchmarking and prototyping**

The UV processor accepts streaming data which has been ordered so that the processing can be implemented in a highly parallel fashion – the processing and I/O requirements of this sub-system place very significant demand on the required architecture and performance. This task continues work started in PrepSKA and runs throughout the programme. An initial R&D phase develops the conceptual model determining the level of parallelisation achievable, analysis of candidate software/hardware architectures through to the requirements review. Design, benchmarking and prototyping of the sub-system follow.

- **WP9.3.4 – Imaging-processor design, benchmarking and prototyping**

The imaging processor accepts gridded data from the UV-processor. The architecture is almost certainly a massively parallel system. The system performs all processing operations on the gridded data through to the delivery of science ready calibrated data products to the Tier-0 science processor. The algorithms to be implemented on this processor are the most complex in the analysis pipeline. This task continues work started in PrepSKA and runs throughout the programme. An initial R&D phase develops the conceptual model and requirements of this processor based on the evolving understanding of algorithms algorithm development from the pathfinders & precursors and task 7. Design, benchmarking and prototyping of the sub-system follow.

- **WP9.3.5 – Data model design**

This task analyses the requirements for the data models at all stages of the analysis pipeline and the technologies to implement them on distributed file systems. The data model must support streaming data and complex data structures through the pipeline. A major challenge is to ensure efficient data access, while providing an interface layer which encapsulates the complexity of the implementation on a highly distributed system. The task will begin with an R&D phase to determine the requirements of the system as well as possible available architectures and solutions. A team with input from both radio astronomers and industrial partners/sub-contractors will be required to define the data model and implementations in the design, benchmarking and prototyping stages.

- **WP9.3.6 – Streaming framework design**

This task continues and builds on work being undertaken in PrepSKA to design and implement a software architecture to manage the distribution of streaming data and manage load balancing in a distributed environment. The R&D phase in PrepSKA will inform a detailed requirements analysis. Detailed design and prototyping will follow. The sub-system delivered by this task must interact with the routing, data model, UV-processor and image-processor sub-systems and close interaction with the relevant tasks is required.

- **WP9.3.7 – Algorithm research**

Developments in the algorithms used in the pipeline calibration and imaging system is a very active field. Significant work is being undertaken in the precursor and pathfinder projects as well as the wider astronomical community. Much of the work is in the design of algorithms which (a) eliminate user intervention, (b) implement calibration techniques and instrument model to achieve higher dynamic range and (c) reduce the computational load. The role of this task is to evaluate and coordinate this work in the context of the SKA, and ensure the adoption of appropriate developments into the project. This task will continue through to the CDR. The task will deliver requirements and an algorithmic-level design for the processing pipeline at PDR and CDR stages.

- **WP9.3.8 – Application development**

This task will implement a prototype design and implementation to be used during the prototyping phase.

- **WP9.3.9 – Local control software**

This task will develop the specification design, and prototype of control software for the pipeline and interface to the M&C system.

- **WP9.3.10 – Real-time databases**

This task will develop the specification for data bases required for the all the real-time requirements including the M&C sub-system, sky-model and calibration. A prototype system will be deployed (implemented by an industrial partner/sub-contractor) to validate the design, interfaces and performance in the prototyping phase.

- **WP9.4 – Science processing**

This sub-WP consists of 2 tasks. The sub-WP runs through all phases of the project. As described above the baseline design assumes the science processing will be performed in a distributed, Tiered structure. Science teams for the key science areas will be responsible for the development of specialised algorithms and software for the specific tasks and to undertake those sky simulations that are required for the development of this software. The SPO will provide coordination and a point of contact for this work and the design and prototyping of the data access interfaces.

- **WP9.4.1 – Data access software**

Design and implementation of data access model and interface for science data – this will re-use work developed for the pathfinders and precursors.

- **WP9.4.2 – Algorithm research and sky simulations**

Within this task the science teams (independently funded) will develop the necessary sky simulations, reduction algorithms and software to support the key science projects. The starting assumption for this work will be the availability of science-ready calibrated data products. The task will inform the requirements analysis for the data products and data models.

- **WP9.5 – System Software**

This sub-WP consists of 6 tasks. The sub-WP runs through all phases of the project and provides a critical interface between the S&C WP and the system design activity. Monitor and control is a key element of the telescope, however in this area in particular there is very significant opportunity for the re-use of design and system analysis developed for the pathfinders and precursors as well as industrial experience and expertise. The adoption of industry standards and interfaces will also be central. In this way the resource requirements of the design and prototyping work of this sub-WP will be minimised.

- **WP9.5.1 – Top-level architecture**

This task will build on the work in PrepSKA to specify and design the top-level architecture of the system software. The task will emphasize the re-use of design, specification and implementations from pathfinders and precursors and other application areas. Interface specifications, messaging protocols etc. Will adopt industry standards as far as possible. The task will deliver final interface specifications to the other sub-systems.

- **WP9.5.2 – Monitor and control**

The development of the M&C specific design within the overall system software architecture will be undertaken by industrial partners/sub-contractors to ensure the adoption of industry standards. The industrial partners will be required to take input from the pathfinder and precursor projects. A design and prototype system will be provided to CDR level.

- **WP9.5.3 – Scheduling and Observation handling**

This task will develop the design of the scheduling and observation handling tool for SKA1 and analyse the requirements for SKA2. The task will take input from the pathfinder and precursor projects.

- **WP9.5.4 – Observing proposal tool**

This task will develop the design of the observing proposal tool for SKA1 and analyse the requirements for SKA2. The task will take input from the pathfinder and precursor projects.

- **WP9.5.5 – System health management**

This task will develop the design of a system health management system which interfaces to the M&C sub-system. The task will be undertaken by industrial partners/sub-contractors to ensure the adoption of industry standards. The industrial partners will be required to take input from the pathfinder and precursor projects. A design and prototype system will be provided to CDR level.

- **WP9.5.6 – Common libraries**

This task will design and implement in a prototype system the common libraries required for system-software. Very significant re-use of code and infrastructure will be made as well as the adoption of industry standard libraries wherever possible.

A2.9.2 WP9 Milestones

Milestone #	Central Processing	Science Processing	System Software	Milestone date
	Software & Computing CoDR			2011Q4
	Start detailed requirements analysis			2012Q1
M9.1	S&C Requirements Review			2012Q3
M9.2	Complete Benchmarking and design			2014Q1
M9.3	Subsystem PDR			2015Q1
M9.4	Subsystem CDR			2016Q1
	Start writing of production code			2016Q2

A2.9.3 WP9 Deliverables

Milestone #	Deliverable #	Deliverable title	Nature of deliverable	Dissemination level	Due date
M9.1	D9.1	Software & Computing SRR Report	Report	PU	2012Q4
M9.2	D9.2	Central processing and science processing benchmarking and design reports	Report	PU	2014Q2
M9.3	D9.3.1	Central processing PDR Report	Report	PU	2015Q2
M9.3	D9.3.2	Science processing PDR report	Report	PU	2015Q2
M9.3	D9.3.3	System software PDR report	Report	PU	2015Q2
M9.4	D9.4.1	Central processing CDR Report	Report	PU	2016Q2
M9.5	D9.4.2	Science processing CDR report	Report	PU	2016Q2
M9.6	D9.4.3	System software CDR report	Report	PU	2016Q2

A2.9.4 WP9 Resources

Description	Org	2012		2013		2014		2015		Total			TOTAL Cost (€)
		py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Personnel (€)	Material (€)	
Totals		16	225,000	18	1,350,000	22	1,500,000	22	450,000	78	7,800,000	3,525,000	11,325,000
1) Management and Engineering	SPO	1		2		2		2		7	700,000		700,000
2) Subsystem design SKA1	WPC	2		3		3		3		11	1,100,000	0	1,100,000
3) Subsystem design SKA2	WPC									0	0	0	0
4) Central Processing		10	0	10	950,000	10	1,050,000	10	0	40	4,000,000	2,000,000	6,000,000
4.1) Analysis of datastreams	WPC	2								2	200,000	0	200,000
4.2) Design and prototype data routing	WPC				100,000		100,000			0	0	200,000	200,000
4.3) UV-processor design and benchmarking	WPC	2		2	300,000	2	300,000	2		8	800,000	600,000	1,400,000
4.4) Imaging processor design and benchmarking	WPC	2		2	300,000	2	300,000	2		8	800,000	600,000	1,400,000
4.5) Datamodel design	WPC	1		2	250,000	2	250,000	2		7	700,000	500,000	1,200,000
4.6) Streaming framework design and prototyping	WPC	2		2		2		2		8	800,000	0	800,000
4.7) Algorithm research	WPC	1		1		1		1		4	400,000	0	400,000
4.8) Application development (gridding, imaging etc.)	WPC			1		1		1		3	300,000	0	300,000
4.9) Local Control Software design	WPC									0	0	0	0
4.10) Real-time databases (monitoring, sky model etc)	WPC						100,000			0	0	100,000	100,000
5) Science Processing		1	0	1	0	2	0	2	0	6	600,000	0	600,000
5.1) Top level architecture	WPC	1		1		1		1		4	400,000	0	400,000
5.2) Data access software	WPC					1		1		2	200,000	0	200,000
6) System Software subsystem		2	225,000	2	400,000	5	450,000	5	450,000	14	1,400,000	1,525,000	1,900,000
6.1) Top level architecture	WPC	2		2		2		2		8	800,000	0	800,000
6.2) Monitoring & Control	WPC		150,000		250,000		300,000		300,000	0	0	1,000,000	1,000,000
6.3) Scheduling & Observation handling	WPC					1		1		1	100,000	0	100,000
6.4) Observing Proposal Tool	WPC					1		1		1	100,000	0	100,000
6.5) System Health Management	WPC		75,000		150,000		150,000		150,000	0	0	525,000	525,000
6.6) Interfaces for Users and Operators	WPC	0		0		1		1		2	200,000	0	200,000
6.7) Common libraries	WPC					1		1		2	200,000	0	200,000

A2.10 Work Package 10 (WP10) – Power

A2.10.1 Description of Work

- **WP10.1 – Engineering and Management**

Within the SPO both management and engineering resources are allocated to this task. The SPO team consists out of a Technical Project Manager, System Engineer and Engineers. This team's responsibilities are described in more detail in section 8. The task handles the overall management of the work package as well as interfaces with other WPs.

- **WP10.2 – Intra-System Power Design**

This activity will review the PrepSKA system design for SKA1 (and the top-level design for SKA2) from the perspective of power minimization and optimization of intra-system power distribution. It will be led by the SPO, will involve participants from the space and other relevant sectors, and will feature active participation from the prime contractor(s) selected to design the SKA power solution. It will produce a detailed design report, with particular attention to the light-current ("electronics") to heavy-current ("power") interfaces.

- **WP10.3 – Power System Design**

This is the major power design activity for the SKA; it will produce a complete, costed power solution for SKA1, and a detailed plan for the extension of the solution to SKA2. It will be led by one or more prime contractors from the power industry and will set out power generation and transmission designs, taking account of SKA-specific requirements. The SPO and in-kind collaborators will supply specialist engineers to work alongside the contractor(s), providing continuous design and review functions in critical areas such as EMC/RFI, monitoring and control, and protection and test. The SPO will also supply critical information related to the evolving power requirements of the SKA. Prior to the finalization of the design, the contractor(s) and SPO will conduct a Detailed design Review and a Critical Design Review, the review panels to include independent power engineering specialists, industry sector representatives, and engineers familiar with SKA precursor and other large facilities in remote sites.

- **WP10.4 – Power Systems Operation**

This activity will develop and prosecute a plan for operating and maintaining the SKA power system, having regard to power quality, demand evolution, and related issues. It will be led by power engineering consultants, in association with power providers and the SPO.

- **WP10.5 – Strategic Power Planning**

This activity will assess the applicability of emerging power solutions to the SKA. It will be led by a specialist power engineering consultancy, working closely with proponents of various generation and environmental conditioning technologies. The SPO and POs will provide specialist telescope operational and other engineering expertise.

A2.10.2 Milestones

Milestone #	Description	Milestone date
M10.1	PDR for SKA1 (SKA Intra-system power design)	2012Q4
M10.2	CDR for SKA1 (Power system design)	2013Q4
	On Site AR for SKA1	2015Q4

A2.10.3 WP10 Deliverables

Milestone #	Deliverable #	Deliverable title	Nature of deliverable	Dissemination level	Due date
M10.1	D10.1	SKA1 Intra-system power design PDR report	Report	PU	2013Q1
M10.2	D10.2	SKA1 power system design CDR report	Report	PU	2014Q1

A2.10.4 WP10 Resources

Description	Org	2012		2013		2014		2015		Total			TOTAL Cost (€)
		py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Personnel (€)	Material (€)	
Totals		2	0	4	0	11	0	11	0	28	2,800,000	0	2,800,000
1) Management and Engineering	SPO	1		1		2		2		6	600,000	0	600,000
2) Intra-System Power Design	WPC			1		1		1		3	300,000	0	300,000
3) Power System Design Liaison	WPC	1		2		2		2		7	700,000	0	700,000
4) Power System Design	WPC	0		0		0		0					
5) Power System Construction and Commissioning	WPC									0	0	0	0
6) Power Systems Operation	WPC					4		4		8	800,000	0	800,000
7) Strategic Power Planning	WPC					2		2		4	400,000	0	400,000

A2.11 Work Package 11 (WP11) – Site and infrastructure

Before SKA1 receptor and other systems can begin to be deployed on site in 2016, the site infrastructure must be rolled out. In view of the lead-time involved, significant infrastructure work will need to commence in 2014, and continue into the Construction Phase. This has implications for the environment in which the precursor telescope is operating, an issue that must be understood by and coordinated with the precursor operator.

Preparatory phase. Tasks to be carried out in 2012 after site selection include

- a) Assessment and audit of existing infrastructure
- b) Assessment and audit of infrastructure to be delivered by host country
- c) Preliminary design of infrastructure for SKA1 taking into account the results from the audits (including buildings, roads and power)

- d) Conduct SKA1 infrastructure preliminary design review
- e) Continue RFI and tropospheric measurement campaigns
- f) SKA1 configuration
 - a. Finalise design
 - b. Review design

Pre-construction phase. Site infrastructure tasks to be completed in the Pre-Construction Phase are:

- a) Conduct SKA1 infrastructure detailed design review
- b) Conduct SKA1 infrastructure critical design review
- c) Initiate procurement of SKA1 infrastructure (sub)systems (via procurement process)
- d) Support selected contractor(s) in re-work of documentation
- e) Start with construction and roll out of infrastructure on core and remote sites
- f) Test and accept relevant infrastructure on core and remote sites

A2.11.1 Description of Work

- **WP11.1 – Engineering and Management**

Within the SPO both management and engineering resources are allocated to this task. The SPO team consists out of a Technical Project Manager, System Engineer and Engineers. This team's responsibilities are described in more detail in section 8. The task handles the overall management of the work package as well as interfaces with other WPs.

- **WP11.2 – Determine the properties of the soil on site**

Investigate the geophysical properties of the soil for the cable routes and at antenna locations before trenching and antenna pad construction takes place in order to estimate the required effort for trenching, rock crushing or soil compacting.

- **WP11.3 – Trenching**

Carry out the required surveys and ground work prior to laying optical fibre cables from the on-site processing building to the antenna locations. Thorough preparation will be required to plan for the trenching routes required for SKA1, while taking required routes for SKA2 and possible existing infrastructure in the ground into account.

- **WP11.4 – Foundations for dishes**

Carry out the required surveys and ground work prior to the pouring of the concrete pads and make the fibre and power connections.

- **WP11.5 – Preparations for aperture array**

Plan the clearing and levelling of the ground, and station hut construction.

- **WP11.6 – Power System Construction and Commissioning**

This activity will deliver the SKA1 power supply system on the SKA site, the system being extensible to meet the needs of SKA2. It will be led by prime contractor(s) from the power engineering industry, with the SPO and POs supplying engineers to monitor the roll-out, develop SKA-specific test and acceptance protocols, and take a leading role in the commissioning of central and remote facilities. The prime contractor(s) will manage procurement and related activities, with the SPO providing technical oversight of major specification documentation. The SPO will work closely with the contractor(s) to ensure that all required design and "as built" documentation is supplied. A Post-Commissioning Review, of a scope to be agreed between the SPO and contractor(s) will be conducted.

- **WP11.7 – Buildings**

Plan the construction of the on-site processing facility.

- **WP11.8 – Roads**

Plan road access to the core site and to locations of more remote antennas and stations since this interacts with the design of trenches, foundations and other site planning aspects. Before SKA1 construction starts, roads required for getting building materials and pre-built components to the site in general and to the locations of antennas in the field in particular, will need to be in place.

- **WP11.8 – Construction camp**

Prepare for the establishment of the construction camp, to be done before the Pre-Construction Phase ends:

- Planning of construction hall(s) for dish production; commence building this facility before the start of the Construction Phase.
- Planning of concrete supply: location of concrete plant, supply of raw materials. Commence building the concrete plant before the start of the Construction Phase.
- Planning of water supply, including construction water, waste treatment; the facility for construction water to be completed before the start of the Construction Phase.
- Planning of construction crew accommodation. The design and planning to be done with a view towards reuse of the facility after construction of SKA1 and SKA2 is complete. Build a first phase of the facility before the start of the Construction Phase.
- Planning of other temporary services.

- **WP11.10 – Other site preparations**

Miscellaneous preparations are required at the site to allow a speedy ramp up of construction activities, including:

- - planning of parking, fencing and other facilities
- - planning of earthing and lightning protection

A2.11.2 WP11 Milestones

Milestone #	Description	Milestone date
M11.1	PDR for SKA1	2012Q4
M11.2	CDR for SKA1 (fibre and power)	2013Q4
M11.3	CDR for SKA1 (buildings)	2014Q1
M11.4	PRR for SKA1 (buildings)	2014Q3
	AR for SKA1	2015Q4

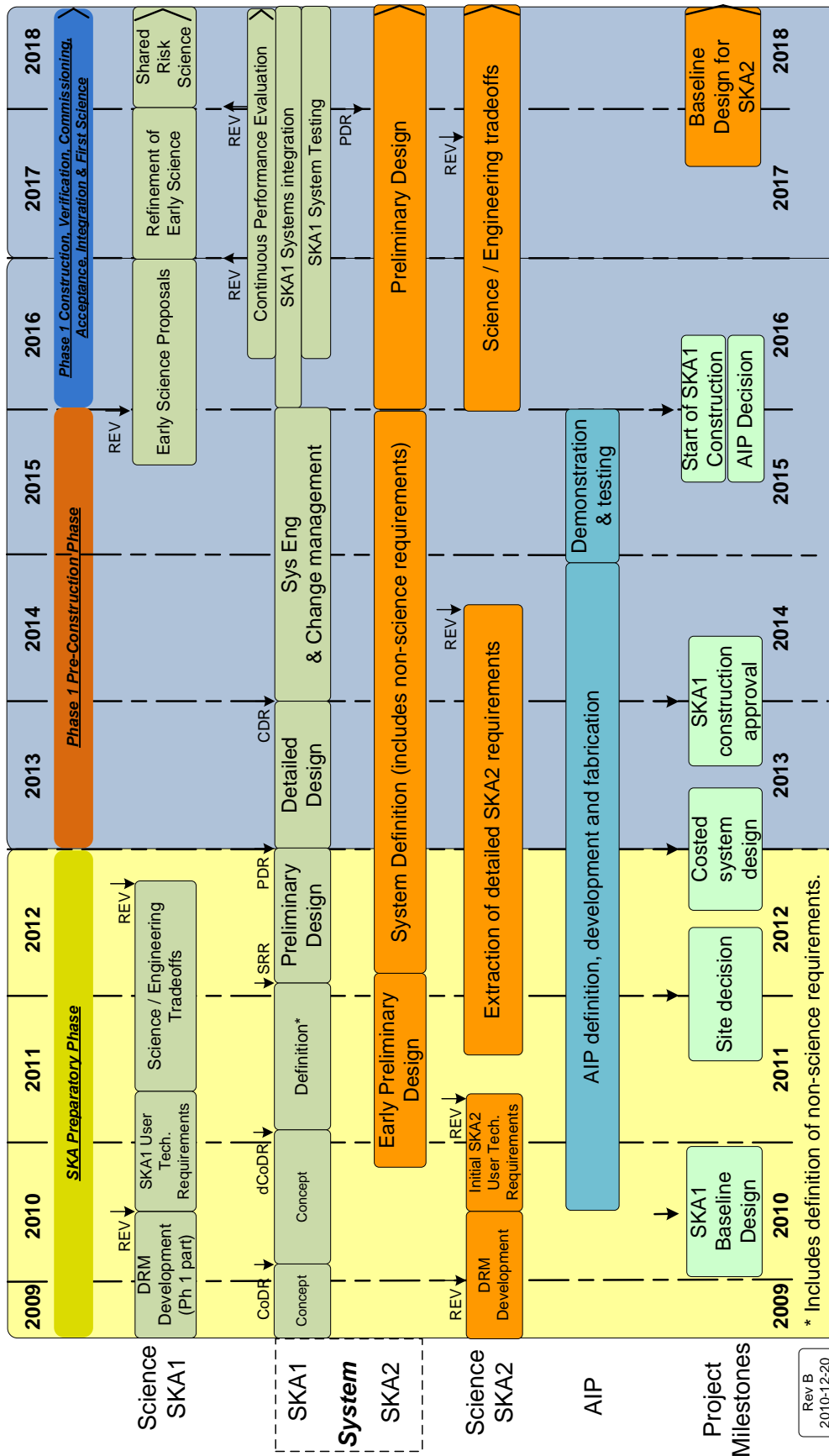
A2.11.3 WP11 Deliverables

Milestone #	Deliverable #	Deliverable title	Nature of deliverable	Dissemination level	Due date
M11.1	D11.1	SKA1 infrastructure PDR report	Report	PU	2013Q1
M11.2	D11.2	SKA1 fibre and power CDR report	Report	PU	2014Q1
M11.3	D11.3	SKA1 buildings and facilities CDR report	Report	PU	2014Q2
M11.4	D11.4	SKA1 buildings and facilities PRR report	Report	PU	2014Q4

A2.11.4 WP11 Resources

Description	Org	2012		2013		2014		2015		Total		TOTAL Cost (€)	
		py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Mat (€)	py	Personnel (€)		Material (€)
Totals		2	0	6	0	8	0	9	0	25	2,500,000	0	2,500,000
1) Project manager and site managers	SPO	1		2		2		2		7	700,000	0	700,000
2) Site and civil engineers	SPO	1		3		5		6		15	1,500,000	0	1,500,000
3) Office support personnel	SPO			1		1		1		3	300,000	0	300,000

APPENDIX 3: SKA High Level Schedule (2009 to 2018)



APPENDIX 4. Definition of Readiness Levels and subsystem rankings

TRL Level	Description
9	Actual application of the technology in its final form and under operational conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last aspects of true system development. Examples include using the system under operational conditions.
8	Technology has been proven to work in its final form, under expected conditions and using production tooling (in case of systems that need to be mass produced). In almost all cases, this level represents the end of true system development. Examples include developmental test and evaluation of the system on its selected site to determine if it meets design specifications.
7	Prototype near or at planned operational system. Represents a major step up from the previous level (TRL 6), requiring the demonstration of an actual system prototype in an operational environment, such as on a representative site, in a computer centre, or integrated within an existing facility.
6	Representative model or prototype system, which is well beyond the breadboard tested for the previous level (TRL 5), is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment.
5	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include 'high fidelity' laboratory integration of components.
4	Basic technological components are integrated to establish that the pieces will work together. This is "low fidelity" compared to the eventual system. Examples include integration of 'ad hoc' hardware in a laboratory.
3	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
2	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.
1	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Example might include paper studies of a technology's basic properties.

SysBrk	Description of System/subsystem	Target phase	Current	End of Prep. Phase	End of Pre-Construction	Remarks
2	System (SKA1)	SKA1	SRL2	SRL3	SRL4	
	System (SKA2)	SKA2	SRL1	SRL2	SRL3	
3	Maintenance & support systems	SKA1		TRL2	TRL8	Basic concepts known, no major risks
4	Dish Array	SKA1		TRL6	TRL8	
4.1	Dish structures	SKA1	tbc	TRL6	TRL8	TRL6 demonstrated with DVA1, TRL8 with DVA2
4.2	Single Pixel Feeds	SKA1	tbc	TRL6	TRL8	
4.3	Phased Array Feeds	SKA2	tbc	TRL4	TRL6	TRL4 demonstrated with APERTIF/ASKAP (not compliant with SKA dishes)
5	Aperture Array	SKA1		TRL6	TRL8	
5.1	AA-Low Antenna's	SKA1	tbc	TRL6	TRL8	TRL6 demonstrated with AAVS1 and LOFAR, TRL8 with AAVS2 (production pilot)
5.2	Digital processing systems	SKA1	tbc	TRL6	TRL8	Demonstrated through continued connection to roadmaps (AAVS, APERTIF)
5.3	AA-Mid Array	SKA2	tbc	TRL4	TRL6	TRL4 demonstrated with AAVS1 (concept), TRL6 with AAVS2 (feasibility)
6	Signal Transport and Networks	SKA1		TRL6	TRL8	
6.1	Digital data Backhaul	SKA1	tbc	TRL6	TRL8	Technology exists as standalone items
6.2	LO & Timing	SKA1	tbc	TRL6	TRL8	Technology exists as standalone items, TRL8 demonstrated on AAVS2/DVA2
7	Central signal processor	SKA1		TRL4	TRL6	
7.1	Correlator hardware	SKA2	tbc	TRL4	TRL6	
7.2	Correlator software	SKA1	tbc	TRL4	TRL8	Software Correlator for SKA1, to be deployed on standard platform
7.3	Non-visibility processor	SKA1	tbc	TRL4	TRL6	
8	Software & Computing systems	SKA1		TRL4	TRL6	TRL6: design ready for production coding
8.1	Central Processing	SKA1	tbc	TRL4	TRL6	TRL4 demonstrated: Potential architectures identified (exist as standalone items)
8.2	Science Processing	SKA1	tbc	TRL4	TRL6	TRL4 demonstrated by completed dataflow analysis
8.3	System Software	SKA1	tbc	TRL4	TRL6	TRL4 demonstrated by defined system architecture
9	Power	SKA1	tbc	TRL2	TRL9	Power installation to start before end of Pre-Construction Phase
10	Infrastructure (buildings etc.)	SKA1	tbc	TRL2	TRL9	Site preparation to start before end of Pre-Construction Phase

APPENDIX 5A: Staffing Plan for the SKA Project Office

	2012	2013	2014	2015
Management				
Director	1	1	1	1
Project Manager	1	1	1	1
Project Officer	1	2	2	2
Industry Liaison Officer	1	2	2	2
Quality Assurance Officer			1	1
Configuration Management Officer		1	2	2
Number of staff	4	7	9	9
Engineering				
<i>Overall system</i>				
Project Engineer	1	1	1	1
Chief System Engineer	1	1	1	1
System Engineer	1	1	1	1
Procurement Engineer			1	1
Monitor & Control Engineer		1	1	1
EMC/RFI Engineer			1	1
Logistics Engineer			1	1
<i>Hardware & Software Sub-Systems (5)</i>				
Technical Project Manager	5	5	5	5
System Engineer		5	5	5
<i>Power Sub-System</i>				
Power Engineer	1	1	2	2
<i>Maintenance and Support</i>				
Design Engineer		1	1	1
Number of staff	9	16	20	20
Science				
Project Scientist	1	1	1	1
Scientist	1	1	2	2
Commissioning Scientist			1	2
Number of staff	2	2	4	5
Education & Public Outreach				
Chief Outreach Officer	1	1	1	1
Outreach Officer		1	1	1
Number of staff	1	2	2	2
Site Development				
Site Project Manager	1	1	1	1
Chief Site Engineer	1	1	1	1

	2012	2013	2014	2015
Site Engineer Core Site		1	1	1
Site Engineer Remote Stations			1	2
Civil Engineer		1	2	2
Site Manager		1	1	1
Office Worker		1	1	1
Number of staff	2	6	8	9
Administrative staff				
Head of Administration	1	1	1	1
Financial Officers	1	2	2	2
Procurement Officers		1	2	2
Human Resources Officers	1	2	2	2
Legal Officer	1	1	1	1
Safety Manager				1
Personal Assistant	1	2	2	2
Office Assistant			1	1
Receptionist	1	1	1	1
IT	1	2	2	2
Expeditors/ SKA Headquarters/Site		2	2	2
Number of staff	7	14	16	17
TOTAL NUMBER OF STAFF	25	47	59	62

APPENDIX 5B: Roles and responsibilities of SPO staff

Engineering and Science staff (refer to Figure 2)

Overall Project Manager

The role of the overall Project Manager (operating at the user (7) and system (6) levels in Figure 2) has been described in section 7.1.3, as follows: The Project Manager is responsible to the Project Director for the detailed management of the Pre-Construction Phase project. He/she will establish the core management structure for the successful delivery of the SKA, act as the specification and design authority, and exercise the overall project management, schedule, and budgetary control.

Project Engineer

The Project Engineer will operate at the user (7) and system (6) levels in Figure 2 and form the bridge between the engineering effort and the science to be delivered. He/she will assist the system engineering team in translating the science to technical requirements, interact with scientists to develop science operation plans and models, assist the system engineering team with science/engineering trade-offs, provide guidance to system engineers and engineers with regards to technology selections and implementation. In summary, he/she will be responsible to ensure that SKA1 delivers maximum science potential.

Scientists

The SPO scientists (operating at the user (7) and system (6) levels in Figure 2) will engage with the global science community as well as the SPO technical teams. They will provide a focus within the astronomical community for the development and maturing of new science areas for the SKA, and will translate the science requirements into technical requirements together with the engineering staff. They will form part of the teams to perform the science/engineering trade-offs.

Technical Project Managers at sub-system level

The Technical Project Managers (operating at the sub-system level (5) in Figure 2) will have the responsibility for the successful development and eventual delivery of all aspects of the project related to their level in terms of schedule, cost, quality and performance. Their role will be to provide leadership to the teams for the development, design, construction, integration, testing, qualification, verification and eventual acceptance of the entire scope of supply delegated to them. These Project Managers will have domain expertise for the particular sub-system they are managing.

System Engineers

The role of the level 6 System Engineer will be to provide technical leadership to the level 6 system engineering team as well as to all the level 5 teams to ensure the successful implementation and execution of the systems engineering process at all levels.

The role of the level 5 system engineers will be to provide technical leadership to their element, to support the level 6 system engineering team by overseeing all aspects of system engineering within his/her element (including the subcontracted parts of the element). Each individual system engineer will be a domain expert in the relevant sub-system.

Quality Assurance Manager

Quality Assurance shall be an independent function and as such the Quality Assurance Manager will report directly to the Director. He/she will be responsible to:

- Establish, maintain and monitor quality assurance processes throughout the project and at all levels. Note that the execution of these processes shall be the responsibility of the managers at all levels.
- Establish, maintain and monitor configuration management processes throughout the project and at all levels. Note that the execution of these processes shall be the responsibility of the managers at all levels.
- Report all non compliances to the agreed processes to the Director.
- Be involved in the development processes, especially technical reviews, configuration control board reviews etc. with the aim of monitoring and ensuring compliance to quality assurance processes.

Configuration Management Officer

A dedicated configuration control administrative officer will report directly to the Quality Assurance Manager. He/she will be responsible for:

- Issue document/parts/unit numbers from the configuration management system
- Ensure that all configuration items (including documents, software, firmware, gateway, pcb datapacks etc) developed on the project are submitted to configuration management. This will be applicable to both internal SPO and external contracted development efforts.

Site staff

The SPO site personnel will be responsible to oversee and to interact with all the contractors and activities on site to ensure the on-time delivery and quality of the items delivered and constructed on site. The team will comprise specialists in various fields such as construction and power.

Site Project Manager

The Site Project Manager will be responsible for all aspects of the preparation of the rollout of site infrastructure and will carry out his/her duties in close collaboration with the host country site staff.

Site Engineers

The Chief Site Engineer and the Site Engineers for the Core and Remote Sites will be responsible for leading the design and roll-out of infrastructure (buildings, roads, power reticulation, fibre connectivity, etc)

Civil Engineer

The civil engineer will support the activities of the site engineers.

Site Manager

The site manager will be resident at the site and responsible for the coordination of all activities at the site.

Outreach staff

Chief Outreach Officer

The role of the Chief Outreach Officer will be to develop a progressive outreach strategy and align this with the organisational strategy, in particular the industry participation activities. The Chief Outreach Officer will also direct the development of the SKA corporate identity and manage all outreach activities including the ongoing development of the website, media relations and coverage, the design, content and production of all promotional materials and the production of teaching resources, and study aids. One of the goals of SKA Outreach will be to develop the SKA website as a leading resource for astronomy education.

PR and Marketing Officer

The role of the PR and Marketing Officer will be to carry out the design, development, production and dissemination of all marketing materials and campaigns including conference displays and online social media. The PR and marketing officer will also develop media relations, maintain a communications schedule, distribute press releases and monitor media coverage, and arrange SKA events in schools and science centres, and assist with the development of a suite of touring interactive activities for schools and a travelling SKA exhibition.

Administrative support staff

Head of Administration

The Head of Administration will lead the administration team and will be responsible for:

- strategic and operational financial planning, monitoring and reporting;
- maintaining organisational performance benchmarks;
- overseeing the development of human resources processes to support the effective running of the organisation;
- contractual agreements, intellectual property and other legal affairs;
- adherence to the organisation's procurement policy; and
- establishing and maintaining an information technology infrastructure to support the operational activities of the organisation.

The Head of Administration will be responsible for providing the secretariat to the SKA Council.

Finance Officers

The Finance Officers will be responsible for:

- providing finance administration, such as finding suppliers, raising requisitions, receipting orders;

- maintaining accounts payable and accounts receivable ledgers;
- handling all purchasing and payroll activity;
- supporting the development of the organisation's annual budget;
- ensuring adequate cash flow to meet the organisation's needs;
- producing financial management reports, such as financial statements, cash flow projections, balance sheet reports; and

Procurement Officers

The Procurement Officers will be responsible for:

- developing, implementing and reviewing procurement strategy, and associated policies and procedures, to take account of current and emerging best practice;
- establishing and maintaining a central register of main contracts, developing appropriate databases for key suppliers and main contractors;
- executing all procurement for the organisation;
- compiling and maintaining all data and information regarding procurement;
- negotiating with suppliers;
- working with suppliers to ensure delivery to schedule;
- expertise to colleagues undertaking strategic procurement exercises; and
- monitoring procurement activities to ensure compliance with host country legislation.

Human Resources Officers

The Human Resources (HR) Officers will devise and implement policies which select, develop and retain the right staff needed to meet the operational requirements of the SKA organisation. The responsibilities of the HR Officers will include:

- developing HR planning strategies and policies on issues such as working conditions, performance management, equal opportunities, disciplinary procedures and absence management;
- managing the recruitment of staff, including the development of job descriptions, preparation of advertisements, checking of application forms, shortlisting, interviewing and selecting candidates;
- advising on pay and other remuneration issues, including promotion and benefits and undertaking regular salary reviews;
- interpreting and advising on employment legislation;

Legal Officer

The Legal Officer will advise senior SPO management on all legal matters related to the running of the SKA organisation. The Legal Officer will be responsible for:

- supporting the organisation in becoming a legal entity in its host country;
- maintaining an overview on the content and applicability of the of the organisation's governance agreement, and advising on changes, as required;
- implementing legislative regulations to ensure compliance with all local and contractual guidelines, ensuring that all regulations and requirements are communicated to appropriate personnel, and monitoring compliance;
- advising on changes to legislation relevant to the organisation's operation;
- representing or arranging for appropriate representation in all instances where legal action affects the organisation; and
- ensuring appropriate business insurance policies are in place.

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