# SKA SADT TECHNICAL DEVELOPMENT PLAN

## PUBLIC VERSION

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ORGANISATION DETAILS

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2 Executive Summary

This proposal for the Signal and Data Transport Element of the Square Kilometre Array is being submitted by a consortium of academic institutes and Research and Education Networks. These include: The University of Manchester (UK, Lead Institute), ASTRON (The Netherlands), CSIRO Astronomy and Space Science (Australia), Instituto de Telecomunicações (Portugal), Joint Institute for VLBI in Europe (The Netherlands), National Centre for Radio Astronomy (India), National Physical Laboratory (UK), SKA Africa (South Africa), Tsinghua University and Peking University (China), University of Granada (Spain), and AARNet (Australia) and Dante (UK). The consortium is in discussion with a number of potential industry partners with a view to engaging their expertise during the pre-construction design phase.

This Technical Work Plan provides a concept description of the SADT element that addresses the Baseline Design, and the proposed Statements of Work for tasks at WBS Level 4 (developed to level 5) for the design work to be carried out. In the concept description, three networks are described: 1) Digital Data Backhaul (DDBH) that transports signals from the receptors to the Central Signal Processor (CSP), and data products from the CSP to the Science Data Processor (SDP), and from the SDP to the regional SKA Data Centres; 2) Synchronisation and Timing (SAT) that provides frequency and clock signals from a central clock ensemble to all elements of the system to maintain phase information to the required accuracy for all receptors, and timing signals for data identification and time critical activities at the receptors, and the CSP and SDP; and 3) Monitor and Control that transmits and receives monitoring and control information throughout the system and includes the Telescope Manager (TM), itself comprised of three logical networks: Production Network, Engineering Network and Safety Network, the Network Manager (NMGR), and local monitor and control for SAT.

There are three broad options for the DDBH element design. Option 1 is a turn-key solution, where we implement a standard communications network purchased through a major provider. This system would carry a low technical risk, since it would build on the considerable industry experience. However, such a network would have capabilities that are simply not required for the SKA, and would be expensive to purchase and operate. Options 2 and 3 are customised integrated COTS component solutions which could be tailored to provide only the capabilities required for SKA1. These options carry additional technical risk above that of the turn-key solution, but are likely to provide substantial savings in implementing and operating the network. Option 2 is a solution applicable to all three telescopes (SKA1-low, SKA1-mid and SKA1-survey) requiring the design and development of one or more PCB(s) which host FPGAs for processing the data (packetsiation, framing, etc) for transport, an optical transceiver module component, and a backplane to provide...
the physical interface to the appropriate system element. In Option 3 the optical transmitter/receiver are co-located on boards that implement functionality from other elements and offers possible further savings over Option 2. The interface boundary between elements is now located within a single board and potentially within a single FPGA chip, and it is likely that this option will require a different transmitter card design for each of the three telescopes.

We propose to investigate and develop these custom options in parallel with a turn-key solution with cut-down functionality.

After the data have been processed at the CSP element, they must be transported to SDP for further reduction. A benchmark solution for this transport problem is provided by the ASKAP precursor where ultra-low-loss fibre pairs are used to connect Geraldton and MRO with three amplification sites along the 390 km route. Carrier-class transmission equipment is used to light the fibre, with multiple channels sent down each. The South African CSP to SDP network could follow this model in principle but we understand that the option of locating the South African HPC centre at the Core site adjacent to the correlator is apparently under consideration. This would result in a considerable saving for this aspect of the data transmission network.

The SKA-RfP calls for the definition of an interface description between the output of the SDP and the Outside World. The SaDT and SDP consortia propose that this work be extended to include consideration of the full data delivery through to the desktop. The expanded workpackage includes: 1) consideration of the external access and distribution of the data by working closely with various global National Research and Education Networks (NRENs); 2) joint analysis and prototyping between SaDT and SDP, investigating aspects of tiered archive/processing systems using a number of HPC centres and software technologies already being developed; 3) ensuring that secure, remote and reliable access to other SKA Observatory networks (such as monitor and control, engineering etc) is available to allow technical, engineering and scientific staff to commission, debug and ultimately operate the facility from various locations.

It is important to fully engage with NRENs, since estimates of future requirements must be provided for their future planning processes; there will likely be a higher cost implication if these are not included in a timely fashion.

The physical location of the SDP HPC centre, whether at the core or a remote site, will also strongly influence the design of the required connectivity, and it may well be appropriate to have designs specific to each country.

Although the focus of the data transport work will be on SKA1, developing an understanding of future requirements necessary to meet SKA2 demands will provide valuable input into the planning process.
For Synchronisation and Timing for the SKA, there are multiple different, but related, requirements:
1) Ensuring that the whole synthesis array is phase coherent. 2) Providing high precision long-term
timing for pulsars and transients. In particular, pulsar monitoring experiments require timing
accuracies of 1-10 ns over time periods of 10 years. 3) Providing absolute time for system
management, antenna pointing, beam steering, time stamping of data and producing regular timing
ticks. 4) Providing frequency standards for Local Oscillators (LOs) etc, and 5) VLBI operations.

A central clock reference system will be required at both the South African and Australian sites. The
ASKAP and MeerKAT telescopes both have access to a hydrogen maser as their master reference
clock. Since these masers constitute a single point of failure for the telescope we propose to
augment these systems with additional clocks to be used together as an ensemble.

The benchmark frequency distribution system is an amplitude modulation, RF phase measurement,
with “off-line” compensation. This system meets the design requirements of the Baseline Design and
is a simplified and scalable development of the phase transfer system tested during PrepSKA and
implemented on e-MERLIN. Although the benchmark frequency distribution design meets the SKA1
requirements, there are a number of possible modifications that we propose to investigate that
could provide improved system performance or reduced cost or power consumption.

Significantly better stability may be achieved by active compensation of the phase or delay
variations on the fibre. This allows a frequency standard to be delivered directly to the remote site,
without relying on the quartz oscillator for short term stability. Once the delay has been
compensated it is then possible to transfer time and frequency to high accuracy using pulse
modulation of the laser transmitter. This would remove the requirement to monitor and transport
phase and/or delay terms to SDP/CSP (also removing an inter-element interface) and the necessity
to apply corrections as part of the correlation/beamforming process. We propose to investigate a
number of different such active compensation schemes including 1) amplitude modulation, RF phase
measurement, and real-time correction, and 2) the transfer of a large number of microwave
frequencies over fibre by propagating an optical frequency comb.

The Telescope Manager (TM) Network carries the monitoring and control signals for the SKA. It
comprises three logically separate pipes, although these are likely to be physically carried on the
same fibre. These are: 1) the Production Network (PNET). During normal operation of the telescope
the PNET carries all the monitoring and control signals from the central Telescope Manager to the
various telescope subsystems; 2) the Engineering Network (ENET). This network is used for system
diagnosis during periods of telescope engineering time or during commissioning; and 3) the Safety
Network (SNET). This network is used when the telescope has been commanded to enter a “safe”
mode; SNET will be used to command this shutdown and to report that the “safe” has been
achieved.
The second part of the Technical Work Plan describes the design effort required for each of the tasks in the Work Breakdown Structure in the Project Management Plan in terms of individual Statements of Work. The Statements of Work have been developed by the workpackage managers for each of the Level 4 sub-elements. The level 5 tasks are described briefly, prototyping and verification for each sub-element is considered...

Interface requirements will be drafted from the ICD meetings hosted by the SKAO who own these interfaces. SADT will lead the definition of a number of the interfaces. International standard OSI network layers will be referenced to help define standards-based ICDs with other level 3 WP Consortia, as well as improve communications between SADT and industry. The initial Prototyping and Verification Plan will need to evolve as the work progresses and the Baseline Design evolves. In Stage 1 of the pre-construction phase, the various options for the Synchronisation and Timing sub-system will be developed and following the down-select process it will become clear what level of prototyping is required. A system very much like the “benchmark” has already been implemented on a working telescope (e-MERLIN) while the other proposed options are currently laboratory bench systems and they will require additional prototyping to retile the increased technical risk.

The deliverables from SADT to the Office of the SKA Organisation will be 1) monthly progress reports, including budget and schedule status reports; 2) Inter-element ICDs; and 3) Review data packs for SRR, PDR and CDR including technical report, engineering drawings, engineering datasets. Engineering schematics, engineering models, design specifications, and construction and tendering documentation.

There are many challenges to be faced in SADT including cost; interfaces with every other element of the SKA; the requirement for a design for SKA1-low, SKA1-mid, and SKA1-survey and two site infrastructures; the need to optimise the joint implementation of three very different networks; the need to co-ordinate the design and implementation of the fibre reticulation with powered network reticulation in conjunction with the Infrastructure Team; and RFI considerations. The SADT element will be particularly strongly affected by changes in the Baseline Design in that the raw data volume could increase or decrease dramatically; bandwidth / time averaging smearing effects mean that array configuration changes can affect visibility data volumes; and the problem of designing a system in a rapidly changing technology and cost environment e.g. RFoF where costs have come down by orders of magnitude in recent years. As far as Synchronisation and Timing is concerned the main challenges are the long term timing requirements for the gravitational wave detection experiment using pulsars, and the likelihood that a single SAT solution will not be able to address all three telescopes over all distribution distances.

Given the above, we will have to carry forward several options for a longer period than would otherwise be desirable. Also we plan to develop good parametric models to allow accurate
assessment of impact of any proposed design changes and to allow rapid reassessment of the optimum technology to adopt if necessary.

The SADT consortium has the relevant experience and industry contacts, and sufficient committed resource, to address successfully the design of SADT for the SKA.
3 Dictionary of terms

AARNet ...................... Australia's Academic and Research Network
AIP ......................... Advanced Instrumentation Programme
ASKAP ..................... Australian Square Kilometre Array Pathfinder
ASTRON ..................... Astronomy institute Netherlands Institute for Radio Astronomy
BIPM ....................... Bureau International des Poids at Mesures
CDR ......................... Critical Design Review
CEV ......................... Controlled Environment Vault
CoDR ....................... Conceptual Design Review
Con-Ops .................... Concept of operations
COTS ....................... Commercial Off-The-Shelf
CSP ......................... Central Signal Processing
DANTE ...................... Delivery of Advanced Network Technology to Europe
DDBH ....................... Digital Data BackHaul
DWDM ...................... Dense Wavelength Division Multiplexing
e-MERLIN ................. UK's facility for high resolution radio astronomy observations
ENET ....................... Engineering Network, part of TM
FTE ......................... Full-Time Equivalent
GEANT ...................... The pan-European data network for the research and education community
GNSS ....................... Global Navigation Satellite System
HPC ......................... High-Performance Computing
ICD ......................... Interface Control Document
IT ........................... Instituto de Telecomunicações
JIVE ....................... Joint Institute for VLBI in Europe
LO .......................... Local Oscillator
MeerKAT ................. SKA pre-cursor telescope in South Africa
NPL ......................... National Physical Laboratory, UK
M&C ......................... Monitor and Control
MRO ......................... Murchison Radio-astronomy Observatory
NMMU ...................... Nelson Mandela’s Metropolitan University
NPL ......................... National Physical Laboratory, the UK’s National Measurement Institute
NREN ....................... National Research and Education Networks
NTP ......................... Network Time Protocol
NWA ......................... Network Architecture
OSI ......................... Open Systems Interconnection model (ISO/IEC 7498-1)
PAF ......................... Phased Array Feed
PCB ......................... Printed Circuit Board
PDR ......................... Preliminary Design Review
PLCs ………………… Programmable Logic Controller
PNET ………………… Production Network, part of TM
PoC …………………… Proof of Concept
PrepSKA ……………… Preparatory phase proposal for the Square Kilometre Array
PTP …………………… Precision Time Protocol
PV …………………… Photovoltaic
RFI …………………… Radio Frequency Interference
RFoF ………………… Radio Frequency over Fibre
SANReN ……………… South African National Research Network
SAT …………………… Synchronisation And Timing
SADT ………………… Signal and Data Transport
SDP …………………… Science Data Processor
SEMP ………………… System Engineering Management Plan
SKA …………………… Square Kilometre Array
SKA1 ………………… Phase 1 of the SKA
SKA1-Lo ……………… Low frequency aperture array of SKA1
SKA1-Mid …………… Mid frequency array of dishes of SKA1
SKA1-Survey ………… PAF equipped survey array of dishes of SKA1
SKAO ………………… SKA Office
SKA-RfP ……………… Request for Proposals for SKA1 issued by SKAO
SNET ………………… Safety Network, part of TM
SRR …………………… System Requirements Review
SfTaN ………………… Signal Transport and Networks
STFR ………………… System for the Time and Frequency Reference signals
TM …………………… Telescope Manager
TWSTFT ……………… Two-Way Satellite Time and Frequency Transfer
UGR …………………… Universidad de Granada
UMAN ………………… University of Manchester
UTC …………………… Coordinated Universal Time
WBS ………………… Work Breakdown Structure
4 Applicable Documents

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

5 Reference Documents

The following Reference Documents (RD) contain useful information

1. SKA Memo 130, SKA Phase 1: Preliminary System Description, P. Dewdney et al, SPDO
2. Requirements Document for Signal Transport and Networks     WP2-030.030.000-SRS-001vA
3. STAN High level Description                                 WP2-030.030.030-TD-001vB.pdf
4. Network Infrastructure Concept Description                  WP2-030.080.000-TD-001
5. COTS solutions for SKA DDBH Concept description            WP2-030.060.010-TD-001
6. SKA DDBH Concept design Document (Custom)                  WP2-030.060.040-SD-001B
7. Concept Description for Synchronisation & Timing for the SKA document WP2-030.070.010-TD-001
10. SKA-TEL.SADT-PROP_TECH-001                                Technical Development Plan
11. SKA-TEL.SADT-PROP_CA-001                                  Consortium Agreement and LoIs
12. SKA-TEL.SADT-PROP_PMP-001                                 Project Management Plan
13. SKA-TEL.SADT-PROP_SEMP-001                                System Engineering Management Plan
    and Integrated Logistics Plan
14. SKA-TEL.SADT-PROP_PV-001                                 Prototyping and Verification Plan
15. SKA-TEL.SADT-PROP_COST-001                               Construction and Delivery Cost Estimates
16. SKA-TEL.SADT-PROP_PAQA-001                                Product Assurance, Safety and Quality Assurance Plan
6 Introduction

6.1 Scope
This document describes the response of the Signal and Data Transport (SADT) consortium to the Request for Proposals issued by the SKA Office for the Signal and Data Transport network for the SKA Telescope Phase 1, through System Requirements Review (SRR)/Preliminary Design Review (PDR), otherwise known as stage 1, to Critical Design Review (CDR) or Stage 2.

7 Concept Description of SKA Signal and Data Transport (SADT)

7.1 Networks
The scope of this element is to provide 3 networks: 1) Digital Data Backhaul (DDBH) transports signals from the receptors to the Central Signal Processor (CSP), and data products from the CSP to the Science Data Processor (SDP), and from the SDP to the regional SKA Data Centres; 2) Synchronisation and Timing (SAT) provides frequency and clock signals from a central clock ensemble to all elements of the system to maintain phase information to the required accuracy for all receptors, and timing signals for data identification and time critical activities at the receptors, and the CSP and SDP; 3) Monitor and Control, transmits and receives monitoring and control information throughout the system and includes Telescope Manager (TM), itself comprised of three logical networks: Production Network (PNET), Engineering Network (ENET) and Safety Network (SNET), and the Network Manager (NMGR).

7.1.1 Network Architecture
The three separate networks each have very different requirements and specifications. The job of the NWA level 4 task is to develop an optimised global solution to realising all of these networks, managing trade-offs and compromises to achieve the best overall solution. NWA therefore maps the logical networks onto physical network elements and considers infrastructure and reticulation issues. There is also a strong link to the Network Manager task in assessing the management capabilities intrinsic to the architectural solutions being considered. Production of high quality models of the different network concepts and flexibility of approach will be essential for this task. For example, despite the point-to-point and end-node heavy nature of the SAT and DDBH networks, a ring solution for physically implementing these networks may be attractive.

7.2 Data Transport Networks

7.2.1 Digital Data Back haul (DDBH)
The scope of the DDBH (see Figure 7.1) for SKA1 is to transport data from the receiver elements to the CSP element. This must be implemented for all three telescopes, SKA1-low, SKA1-mid and SKA1-survey (although not for the precursor pathfinders ASKAP and MeerKAT – throughout we have assumed that the precursor networks are beyond the scope of this response). The total data rates based on the Baseline Design are large: for SKA1-low, the aggregated data rate from the stations to CSP is 9.2 Tb/s; for SKA1-survey, the data rate from dishes to CSP is 51.8 Tb/s (assuming digitisation at the pedestal); for SKA1-mid, the data rate from dishes to CSP is 17.1 Tb/s. The requirements for the data transport have important differences to those of a conventional communications network:

- The data flow is unidirectional – although there will be control and calibration signals to be distributed to the receiver elements, these are considered under the TM network.
- The physical data transport can be point-to-point and is deterministic – there is no necessity for routing decisions to be made.
- The data rate is known and not bursty – although particular experiments may have different bandwidth requirements, for example, there will not be any sudden peaks in demanded network capacity.
- The data are incompressible – the data out of the elements are essentially noise-like, with signal buried well below the noise and only becoming apparent after correlation.
- The required fidelity on data transport is much lower than that for a traditional network – since the data are noise-like, data loss only affects the overall sensitivity of the telescope, and a loss rate of 0.1% (orders of magnitude below acceptability for a traditional network) will have a close to negligible effect on the SKA’s performance.

An issue that must be borne in mind for possible DDBH options is that RFI considerations be made due to the close proximity to the receiving antenna.
Figure 7.1 SADT network product hierarchical description with DDBH transmission link example

### 7.2.1.1 DDBH Options

There are three broad options to be considered as possible solutions to the DDBH element design.

Option 1 is a turnkey solution, where we implement a standard communications network purchased through a major provider. This system would carry a low technical risk (with the majority of the risk residing in the interface), since it would build on the considerable experience of providing similar systems for a wide variety of other applications, though there would no doubt be issues to be resolved concerning the volume of data and the physical location of the network. However, such a network would have capabilities that are simply not required for the SKA, with the result that this solution will be expensive as a capital purchase and also likely to consume a large amount of power during operation.

An alternative possibility is to provide a customised integrated COTS component solution which could be tailored to only provide the capabilities required for SKA1; this we break down into the two further broad options to be considered. These options necessarily carry additional technical risk above that of the turnkey solution to be weighed against the possible savings in implementing and operating the network. However, we emphasise that these options are custom implementations built from commercial COTS building blocks. The first of these custom solutions (Option 2) requires
the design and development of a PCB(s), which host a FPGA for processing the data (packetisation, framing, etc) for transport and an optical transceiver module component. In addition, this solution requires the design and development of a backplane that will provide the physical interface to the appropriate system element. This option could therefore be a solution applicable to all three telescopes.

Option 3 is another custom solution, in which the optical transmitter/receiver are co-located on boards that implement functionality from other elements. For example, for SKA1-low the transmitter would be located on the station beam-former board. This would remove the requirement for producing a backplane with its associated inter-board data transport hardware, and allows for the possibility to use potential spare capacity on the beam-former FPGA to perform the processing of the data to make it ready for transmission. Therefore this option offers possible further savings over Option 2. However, it does introduce significant additional complications. The interface boundary between elements is now located within a single board and potentially within a single FPGA chip. In addition, the FPGA will require specific consideration during design to provide a clear route for validation of the DDBH functions. Finally, it is very likely that this option will require a different transmitter card design for each of the three telescopes.

Option 1, the turnkey solution, may well be simply beyond the available budget for this element. The custom solutions may be around an order of magnitude cheaper, so we propose to investigate and develop these custom options in parallel with the turnkey solution (where we will investigate the possibility of cutting down on the functionality provided). We present preliminary costings for Options 1 and 2 in the budgetary estimate document (SKA-TEL.SADT-PROP_COST-001).

7.2.1.2 Effect of changes to the SKA1 baseline design
The requirements for the DDBH are particular prone to (potentially dramatic) change if there are amendments to the baseline design. Even within the current baseline design, one unresolved question as to whether the SKA1-survey signals will be digitised in the telescope pedestal or be transferred as RF over fibre, changes the total receiver to CSP data rate from 26 Tb/s to 78 Tb/s. For this reason, a key part of our work will be to provide models of the network such that we can help assess the impact on DDBH from proposed changes to the baseline design.

7.2.1.3 DDBH product
The DDBH network (and indeed each of the telescope SADT networks) can be described as end-product entities (see Figure 7.1) with the following generic hierarchical product description:

- Telescope network type
  - SKA1 –Low, Mid, Survey
- Network operation mode & science experiment applications
Normal, commissioning, safety critical modes. Imaging and non-imaging science experiments

- Network element interfaces and mixed traffic integration
  - DDBH within receptor input and CSP output element interfaces considering mixed SAT, TM, NMGR traffic integration

- Physical and logical data path layers
  - OSI layer 1: Node termination (Network media type, modulation format), optical transmission (tributary and common equipment, multiplexing and amplification), and cable infrastructure
  - OSI layers 2-4: Logical layer hops and terminations - Framing (payload/overhead), node addressing, checksums, monitoring. Circuit and packet routing/switching protocols with reliability and flow control.

International standard OSI network layers will be referenced to improve communications between SADT and industry, SKAO, and help define standards based ICDs with other level 3 WP Consortia. One example of a low-level task required during the pre-construction could therefore be as follows:

During the pre-CDR manufacturable prototyping phase of the process, the performance requirement of an end-of-life discrete link component will have to be verified, so for example, referencing the product hierarchy above: SKA1-Mid telescope, in commissioning mode, with DDBH traffic, on spiral arm long haul link, a 1550nm channel will be required to saturate the mid-span optical amplifiers, and a NRZ-OOK modulation format with unframed PRBS data sequence will be used to measure BER performance ageing margin versus link amplifier input power.

Figure 7.2 Delivery and installation of ASKAP fibre ribbons (courtesy S. Amy, CSIRO)

7.2.2 CSP to SDP

After the data have been processed at the CSP element, they must be transported to SDP for further reduction. Similar to DDBH, the data rates are high: for SKA-low, 6.5 Tb/s; for SKA-survey, 12 Tb/s; for SKA-mid, 8 Tb/s. These figures are calculated using an estimate of the relative numbers of short
and long baselines, necessary because longer baselines require a shorter correlator dump time to avoid unacceptable time averaging smearing; the figures quoted here are therefore considerably lower than those found in Tables 18 and 19 of the Baseline Design (and have been calculated from data provided by SKAO as a response to a request for clarification). Thus in Australia, a total data rate of 18.5 Tb/s must be transported the 820 km from MRO to Geraldton and then to Perth; while in South Africa, the 8 Tb/s must be transported 915 km from the correlator in the Karoo to Cape Town.

In a similar manner to that described in the DDBH overview, a variety of possible solutions for this network will be studied during this work. However, a benchmark solution to address this problem can be extrapolated from the experience gained by the ASKAP precursor. Here, ultra-low-loss fibre pairs are used to connect Geraldton and MRO with three amplification sites along the 390 km route (see Figure 7.2 for pictures of fibre installation). Carrier-class transmission equipment is used to light the fibre, with multiple channels sent down each. CSIRO has successfully modelled a system which sends 80 channels, each carrying a data rate of 40 Gb/s, over a distance corresponding to the distance from MRO to the Pawsey Centre. Recent work has increased the data rate per channel to 100 Gb/s. Therefore a single fibre pair could provide transport for 8 Tb/s of data. 24 pairs of fibre have been laid between MRO and Geraldton for SKA1, while a Federal Government National Broadband Network programme has recently completed the installation of fibre between Perth and Geraldton. There is therefore confidence that this benchmark solution could successfully address the CSP to SDP network challenge. The amplification sites (CEVs) between MRO and Geraldton are solar powered with batteries which can provide 400 W of power over a 48 hour period (see Figure 7.3). Diesel generators provide backup power. Currently a single fibre pair is lit, which requires 200 W.

Figure 7.3 Solar powered CEV picture (left) and communications rack (right) installed at Geraldton (WA) (courtesy of S. Amy, CSIRO)
In South Africa, the current 10 Gbit/s network is contracted to a long distance fibre network operator by SANReN (South African National Research Network). For most of the route the SKA bandwidth is carried on a commercial fibre backbone network, with only the final leg of 140 km from Hutchinson to Carnarvon being a spur to connect the SKA site to the backbone. The existing fibre cable from Carnarvon to the SKA Core site comprises 48 cores, and the cable from Carnarvon to the Broadband Infraco backbone network at Hutchinson is 24 fibres. The SKA-1 bandwidth requirement of 8 Tbit/s can be met utilising a single pair of fibres. The provision of an additional 115 km of fibre route from the Core Site to an alternate fibre backbone network, planned to be attached to a new power line to site, will provide a redundant network route. All repeater installations along these routes are connected to grid power.

However, the South African CSP to SDP network may be significantly different to what is described for Australia and in the Baseline Design. The option of locating the South African HPC centre at the Core site adjacent to the correlator (see Figure 7.4) is being considered and this would result in a considerable saving for this aspect of the data transmission network and might also result to the adoption of a different optimum solution to that for Australia. The decision based on the SKA-1 bandwidth requirements must be considered relative to the final SKA-2 solution to ensure that the incorrect solution is not taken based solely on the SKA-1 bandwidth requirements.

Figure 7.4 Karoo Array Processor Building (courtesy D. Fourie)
7.2.3 SDP to Outside World
The SKA-RfP calls for the definition of an interface description between the output of the SDP and the Outside World. The SaDT and SDP consortia propose that this work be extended to include consideration of the full data delivery through to the desktop. This expanded workpackage therefore includes:

- consideration of the external access and distribution of the data by working closely with various global National Research and Education Networks (NRENs);
- joint analysis and prototyping between SaDT and SDP, investigating aspects of tiered archive/processing systems using a number of HPC centres and software technologies already being developed;
- ensuring that secure, remote and reliable access to other SKA Observatory networks (such as monitor and control, engineering etc) is available to allow technical, engineering and scientific staff to commission, debug and ultimately operate the facility from various locations.

Figure 7.5 Tiered data delivery system proposed by the Science Data Processing Consortium (courtesy P. Alexander, Cambridge)
• Data are pushed from the main on-site data archive to regional data centres. The default model is that data are not duplicated between these centres. Centres provide both local data archives and HPC compute resource shown local to the data. Additional processing resource for end-user astronomers is shown to possibly occur in the cloud (see Figure 7.5).
• User interaction is via web services with low-bandwidth traffic to the end-user astronomer desktop.
• Not shown is the possibility of a unified user interface provided via the cloud services which completes the data-lifecycle interface for the end user.

It is important to fully engage with NRENs, since estimates of future requirements must be provided for their future planning processes; there will likely be a cost implication if these are not included in a timely fashion.

The physical location of the SDP HPC centre, whether at the core or a remote site, will also strongly influence the design of the required connectivity, and it may well be appropriate to have designs specific to each country.

Although the focus of this work will be on SKA1, developing an understanding of future requirements necessary to meet SKA2 demands will provide valuable input into the planning process.

7.3 Synchronisation and timing

7.3.1 SAT Overview and Requirements
There are multiple different, but related, requirements for Synchronisation and Timing for the SKA:

1. Ensuring that the whole synthesis array is phase coherent. For a maximum allowable degradation in sensitivity of 2%, the rms phase error is 11°. At a maximum observing frequency of 20 GHz, this corresponds to accuracies of ~1ps. This stability needs to be maintained at the very least for the fundamental integration period of the interferometer (~1s) and probably at least for the typical phase calibration interval, which will vary with frequency but is likely to be ~100s. The requirements for instrumental stability over longer periods will be addressed as part of this work. While maintaining phase coherence is only a requirement on the relative phases of the LOs (or sampler clocks) at each element to be correlated, it is also necessary to maintain the delay stability, over similar timescales. For a maximum correlated bandwidth of 2.5 GHz, the relative timing stability requirement is ~10 ps. In order to find fringes without extensive fringe searches, then the relative timing needs to be always within 40ns.

2. Providing high precision long-term timing, for astrophysical phenomena such as pulsars and transients. In particular, pulsar monitoring experiments require timing accuracies of 1-10 ns over time periods of 10 years.
3. Providing absolute time for system management, antenna pointing, beam steering, time stamping of data and producing regular timing ticks.

4. Providing frequency standards for Local Oscillators (LOs), digitiser clocks, low frequency square waves or Walsh functions for phase switches and noise diode.

5. For VLBI operations, in which some or all of the phased SKA core will be combined with other telescopes around the world, the requirements of (1) apply, possibly with some degree of relaxation, but relative to the other, independent telescopes, rather than with in the SKA telescopes.

The derived technical specifications and possible options for addressing these requirements are addressed in depth in the documentation for the SKA STaN CoDR. Many of these documents were written by members of this consortium and here we draw heavily on this previous work while updating the material in light of the SKA site decision, the new baseline design and technical developments in the field.

7.3.2 Timing reference
A central reference system will be required at both the South African and Australian sites. The ASKAP and MeerKAT telescopes both have access to a hydrogen maser as their master reference clocks. Since these masers constitute a single point of failure for the telescope we propose to augment these systems with additional clocks to be used together as an ensemble. These central reference clocks will be monitored with respect to international time standards using various techniques in order to provide absolute timing which achieves the pulsar monitoring requirement. There is currently no requirement that the clocks at the two sites be locked to each other, but this would be feasible to achieve if required for SKA Phase 2. For low resolution timing the network will be provided with an Ethernet time service using for example Network Time Protocol (NTP) or Precision Time Protocol (PTP), typically used for telescope pointing.

7.3.2.1 Clock Concept
Commercial atomic clock technology is relatively mature with many clocks having well documented histories of both performance and reliability. The performance of the clocks under consideration may be assessed through examination of actual data sets, particularly where the clock has been used at the UK’s National Physical Laboratory (NPL) or other laboratories where NPL has access to clock measurements. Where the performance of a clock is not well established, it may be possible to use NPL’s timescale facilities to directly evaluate the clock performance.

The key characteristic in determining the suitability of a clock contributing to a reference timescale is its predictability. Clock instabilities usually consist both of well-known stochastic noise processes
along with deterministic aging characteristics, for example linear frequency drift. The stochastic noise usually places a limit on the predictability of the clock at a given prediction length that is related to the stochastic noise at the same averaging time. In contrast the deterministic aging is usually highly predictable, and may be corrected in the clock processing.

The environmental requirements of atomic clocks vary considerably. At the highest levels of frequency stability the performance of active hydrogen masers are sensitive to temperature changes. In contrast the performance of commercial caesium clocks are less sensitive to both temperature changes and to vibration effects. Cost, power consumption, reliability, procurement times and expected lifetime will all be considered.

Active hydrogen masers are a likely choice as a clock for inclusion in the SKA clock ensemble. They have a long lifetime, highly predictable behaviour and have excellent stochastic noise properties at averaging times between an hour and several days. These clocks have been used in primary timing laboratories for many years. There are several manufacturers, performance, reliability and price vary between manufacturers. Passive hydrogen masers are smaller than active masers and their stability is typically a factor of three worse; however they are considerably cheaper. Passive masers may play a useful role in the SKA timescale.

Commercial caesium clocks have better stability than active hydrogen masers in the long term at averaging times greater than 20 days, although their medium and short-term performance is considerably worse. They are however free from linear frequency drift. Caesium clocks have been used in primary timing laboratories for many years, and are considerably less expensive than the active hydrogen masers. There may be advantages in including at least one commercial caesium clock in the SKA clock ensemble. This is because in addition to being free from linear frequency drift, commercial caesium clocks are relatively portable and less sensitive to vibration. This feature can be advantageous for time calibrations.

Rubidium oscillators, tend not to be used in primary timing laboratories, however recent Rubidium oscillators used in GPS satellite clock have very good short term stability for averaging times up to a day.

<table>
<thead>
<tr>
<th>CLOCK TYPE</th>
<th>ADEV ($\tau = 1$ hour)</th>
<th>ADEV ($\tau = 1$ day)</th>
<th>ADEV ($\tau = 10$ days)</th>
<th>Linear Frequency Drift</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>High performance</td>
<td>3.00E-14</td>
<td>1.00E-14</td>
<td>1.00E-14</td>
<td>No</td>
<td>Free from linear frequency drift</td>
</tr>
</tbody>
</table>
Table 7.1 Overview of the typical relative performance of commercial atomic clocks and other possible clocks used in primary timing laboratories. ADEV is the Allan deviation, the square root of the Allan Variance, a two-sample variance measuring the frequency stability in clocks and oscillators; \( \tau \) is the averaging time.

### 7.3.3 Frequency distribution system

There are several possible ways in which a synchronisation and timing system could be implemented for the SKA. The choice of which of these categories is best suited for the SKA depends primarily on the stability requirements as well as the physical environment at the sites. Table 7.2 summarises possible technologies as a function of distribution length.

<table>
<thead>
<tr>
<th>Fibre link length</th>
<th>Up to 1 km (assuming delay stabilization is required)</th>
<th>Up to 10 km</th>
<th>Up to 80 km</th>
<th>Up to 1000 km</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intensity modulated laser</strong></td>
<td>Cheap lasers could potentially be used, test required.</td>
<td>DFB lasers can be used.</td>
<td>DFB lasers can be used.</td>
<td>Optical amplifiers required every 70-80 km (( \leq 5-10 ) each). Clean-up repeaters might be required.</td>
</tr>
</tbody>
</table>
Intensity modulated laser with optical carrier stabilization

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
<th>Price Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test would be required to establish if cheap DFB lasers can be used, narrow linewidth lasers likely to be required.</td>
<td>Narrow linewidth lasers required (£5k price range)</td>
<td>£50k price range.</td>
</tr>
<tr>
<td></td>
<td>Highly stabilized laser required (ultra stable cavity or other means). £40-50k price range.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Optical amplifiers required every 70-80 km (£5-10k each). Clean-up repeaters might be required (£30k-40k each).</td>
<td></td>
</tr>
</tbody>
</table>

Frequency comb (pulse train) transfer

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
<th>Price Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cheap CW lasers might be used with an external phase modulator instead of more expensive mode-locked laser.</td>
<td>Test would be required to establish whether cheap CW lasers can be used in case of external modulator.</td>
<td>Narrow linewidth laser likely to be required. Reflections are less of a problem when compared to intensity modulated laser based-techniques as chromatic dispersion greatly reduces</td>
</tr>
<tr>
<td></td>
<td>Optical amplifiers required every 70-80 km (£5-10k each). Clean-up repeaters might be required (£30k-40k each).</td>
<td></td>
</tr>
</tbody>
</table>

Notes: Laser free-running stability not crucial in case of mode-locked laser as the repetition rate is locked to reference to be transferred; As pulses are propagated in the fibre the technique is also suitable for time transfer.

Table 7.2 Possible frequency transfer technologies over different distances

Note on required actuator range: even on distances as short as 1 km active delay compensation might be required if the fibre are buried at shallow burial depth. For example, assuming an attenuation by a factor of 10 for of the night/day cycle surface temperature (which can be as high as 50 degrees) for a shallow burial depth, the fibre temperature would change by 5 degrees. This causes a 7ppm/K * 5 K * 1 km = 35 mm change of the optical path length, corresponding to 175 ps
delay change. The range of a single fibre stretcher is usually in the region of 5-6 mm, so 7 fibre stretchers would be required (or 4 double passed). Alternatively, a combination of fibre stretchers and thermally controlled spools can be used. Burial depth of 1m or more can reduce the temperature fluctuations by a factor of 1000 to 10000. In this case, active delay stabilization might not be required as the delay fluctuations would be at the ps level required by the SKA specs.

7.3.3.1 Telescope specific requirements for SAT
SKA1 comprises three different telescopes located on two different sites. It also incorporates the MeerKAT and ASKAP precursors which have their own SAT systems in place, and although these fall outside the remit of this bid, as noted before we will wish to reuse and augment their hydrogen maser master clocks. SKA1-low now comprises 911 Aperture Array stations, almost 20 times more than was envisaged in SKA memo 130. Although it would be feasible to provide a separate frequency distribution system for each of these stations, we will investigate whether in the core it is feasible to provide a reference frequency to a central point within a group of stations and then implement a short range fan out to the individual beam-formers. Such a fan-out will not be necessary if, in the core, stations are already organised into “superstation” groups with a processing bunker performing the digitizing and beam-forming for all its constituents. Should fan-out prove to be a viable solution then it could also be applied within the core of SKA1-mid, and, depending on the final decision of configuration, to the sets of clumped antennas in the spiral arms. To scope the potential size of the problem, we assume: for SKA1-low, two different levels of aggregation within the core and no aggregation in the arms, requiring a total of 135 STFR systems; an individual system for each of the 190 dishes of SKA1-mid and the 60 dishes of SKA1-survey. Finally, we note that, depending upon the trenching solution adopted for SKA1-mid, the length the fibre required for the distribution system may be considerably longer than ~100km, which is radius of the configuration.

The frequency-distribution-accuracy requirement arises from the need to maintain coherence across the telescope and so depends linearly upon the observing frequency. This varies by almost two orders of magnitude between SKA1-low and SKA1-mid. There is also likely to be a technology break requiring different solutions for short, medium and long distribution lengths (especially when considering extension to SKA2). Additionally, there is currently no requirement to accommodate pulsar timing experiments on SKA1-low and SKA1-survey, and so the timing precision requirements are lower than for SKA1-mid. We therefore propose to evaluate the several different SAT options and populate a matrix with optimum solutions for each of the three telescopes at each of the distribution lengths. Obviously we wish to minimise the number of different systems that will need to be brought to CDR, and the possibility exists that a single solution may be sufficient to address all the SAT requirements for SKA1.

7.3.3.2 Benchmark design of a frequency distribution system
A system which addresses the frequency distribution requirements for SKA1 is described in Section 4.2 of the Concept Description for Synchronisation & Timing for the SKA document [WP2-30.70.1]
This system meets the design requirements of the Baseline Design (SKA-TEL-SKO-DD-001) and is a simplified and scalable development of the phase transfer system tested during PrepSKA and implemented on e-MERLIN (see Figure 7.6). The e-MERLIN phase transfer system uses RF (1.5 GHz) modulation of an optical carrier to lock a high quality quartz oscillator at the remote end of the link, using a phase locked loop, with a time constant of a few seconds. This filters out all of the high frequency phase noise introduced by vibration effects on the fibre, and takes advantage of the short-term stability of a temperature controlled quartz oscillator, which can be used as a reference input to synthesise the LO and clock frequencies required at the remote telescope. The slower variations due to temperature effects in the fibre are measured using phase comparison of a signal transmitted in the reverse direction. The system uses a single fibre and is in operation on long lengths of fibre installed above ground (alongside rail tracks) with large diurnal temperature variations. The longest link is approximately 400km, in 5 segments with complete regeneration every ~80km. There is no active compensation of the phase variations and all the corrections are made as part of the delay compensation in the correlator. This system has been demonstrated to achieve the required performance over 110km distances (McCool et al. SKADS Conference Limetelle 2009).

Figure 7.6 Frequency distribution system with phase variations applied as delay compensation during correlation.
7.3.3 Possible enhancements to the frequency distribution benchmark design

Although the benchmark frequency design described above meets the SKA1 requirements, there are a number of possible modifications that we propose to investigate that could provide improved system performance or reduced cost or power consumption.

- At low frequencies and for short distances it may not be necessary to carry out any phase compensation (active or passive).

- Producing LO or clock signals at the receiver element can be a source of self-induced RFI. One method for mitigating this problem is to distribute frequencies with different, small, known offsets to each receiver element. Since the signals are therefore different, the contamination they cause will not be coherent between different receiver elements, with the result that during correlation their effects will tend to average towards zero and so provide an additional rejection of these contaminating signals. We will study whether this extra rejection is required for the telescope and assess the overhead in complexity that implementing this scheme will introduce.

7.3.4 Active compensation frequency distribution systems

Significantly better stability may be achieved by active compensation of the phase or delay variations on the fibre. This allows a frequency standard to be delivered directly to the remote site, without relying on the quartz oscillator for short term stability. The phase noise introduced by the optical fibre strongly depends on the environmental conditions (mainly acoustic and thermal) in which the fibre is installed. Consequently, the noise does not necessarily scale with the link length. It is possible that longer links installed in a relatively quiet environment are still quieter than shorter links installed in, for example, metropolitan environment; for fibre installed in the desert, lower vibration-induced noise should be expected. However, temperature-induced instability can be orders of magnitude higher both because of the typical temperature excursions in a desert and the low burial depth that will be likely to be used in the SKA fibre network. The system may therefore need to compensate for optical path length changes as large as (worst case) 7 ppm/K * 50 K = 350 ppm. For a 10 km link this corresponds to 3.5 m.

Once the delay has been compensated it is then possible to transfer time and frequency to high accuracy using pulse modulation of the laser transmitter. This would therefore remove the requirement to monitor and transport phase and/or delay terms to SDP/CSP (also removing an inter-element interface) and the necessity to apply corrections as part of the correlation/beamforming process. We propose to investigate a number of different such active compensation schemes drawing on the expertise of the Manchester, NPL, Tsinghua University, Peking University, UGR and JIVE teams; these include:-

- Amplitude modulation, RF phase measurement, real-time correction - see Figure 7.7. The reference frequency from the Clock System that is to be disseminated is boosted to a higher frequency (which leads to a higher signal-to-noise ratio for compensation) using a phase-
locking method and is converted to squared-wave timing pulses using a synthesised clock generator. Light from two lasers with different wavelengths carrying the frequency (amplitude modulation) and timing signals are transferred from the local to remote site via the same fibre link (Figure 7.7 (a)). Through round-trip transmission, the phase fluctuation induced during propagation is detected and compensated at the local site. The compensating error signal is applied to a voltage controlled crystal oscillator (Figure 7.7 (b)). The transfer delay fluctuation of the timing signal is compensated by a time delay compensation system (Figure 7.7 (c)). See Gao, C. et al., 2012, Opt. Lett., Vol. 37, No. 22, “Fiber-based multiple-access ultrastable frequency dissemination” for further details.

Figure 7.7 Schematic diagram of the high-quality fiber-based time and frequency synchronisation system. (a) The principle of the time and frequency synchronisation system. At the “remote” site, a slaved oscillator is phase locked to the received frequency signal from the “local” site, reproducing the frequency and phase of the oscillator. (b) The phase noise compensation system for frequency dissemination. (c) The time-delay compensation system for time synchronisation.

- Microwave transfer by propagation of an optical frequency comb – see Figure 7.8. The transfer of a large number of microwave frequencies over fibre can be achieved by propagating an optical frequency comb. The optical path-length changes are corrected in the same way as for the intensity-modulated light technique. At the user end, a large number of harmonically-related microwave frequencies can be extracted with a photodiode. The same harmonic of the repetition rate of the laser is detected directly at the output of the laser and after a round trip in the fibre. The phase of the extracted signals is compared using a microwave phase detector and the error signal so constructed, which contains information
about the fibre noise, is then fed to two actuators that change the optical path length of the link. In order to compensate for the environmentally-induced optical-path length changes, a fibre stretcher and a thermally-controlled fibre spool are used. The fibre stretcher allow for the fast fluctuations to be compensated whilst the thermally-controlled spool ensures the fibre stretcher is kept within its small range. See Marra, G. et al., 2011, “High-resolution microwave frequency transfer over an 86-km-long optical fiber network using a mode-locked laser”, Opt. Lett., 36(4):511–513 for further details.

![Figure 7.8](image_url) Schematic diagram for the transfer of a large number of microwave frequencies over an optical fibre link. RR det: repetition rate detection stage; CIR: circulator; Int.: integrator; DCF: dispersion compensating fibre; PRM: partial reflecting mirror.

7.4 Monitor and Control

7.4.1 Telescope Manager Network

The Telescope Manager (TM) Network carries the monitoring and control signals for the SKA. It comprises three logically separate pipes, although these are likely to be physically carried on the same fibre. These are:

- The Production Network (PNET). During normal operation of the telescope the PNET carries all the monitoring and control signals from the central Telescope Manager to the various telescope subsystems; it therefore touches almost every level of the SKA. PNET also carries calibration metadata such as beam-former weights.
- The Engineering Network (ENET). This network is used for system diagnosis during periods of telescope engineering time or during commissioning. It is used for trouble shooting of faults, maintenance and system performance optimisation and can be used to carry raw telescope data during engineering tests.
• The Safety Network (SNET). This network is used when the telescope has been commanded to enter a “safe” mode; SNET will be used to command this shutdown and to report that the “safe” has been achieved. SNET is not designed to have 100% reliability and this means that each element is responsible for its own safe shutdown in the case where all communications fail. However, options such as satellite links are being investigated as backup to physical fibre layer to improve SNET reliability.

It is likely that there will be three telescope manager networks, one for SKA1-low, SKA1-mid and SKA1-survey. There are three aspects to the physical layer of each TM network: the long haul TM network to an aggregation point near the core, probably using the same conduit, but different fibre as DDBH; the regional distribution of TM networking to antennas and AA stations; and the local management and control, which is the responsibility of the relevant element. The TM will have expected data rates of 10s of Mb/s from each receiver element, summing to Gb/s overall along the long haul network. The data flow will be bidirectional and support prioritisation, so will need a high level protocol (such as Ethernet, TCP/IP). Latency requirements for most metadata will typically be 100s milliseconds, but some services (such as delay estimates calculated from SAT required for correlation corrections at CSP) may require much higher performance.

7.4.2 Network Manager
The core function of the Network Manager will be to coordinate and optimise the performance of the various subsystems that comprise the networks being designed within the SADT element. In particular the Network Manager will:

• set up and configure subsystems during power-up;
• allow detection of faults, implementing alarm handling and maintenance;
• determine subsystem control parameters to allow optimum performance of the system as a whole.

Individual devices such as routers, switches and links will in general have powerful tools supplied with the equipment, generating a great deal of diagnostic information. This will provide a framework around which the overall Manager can be constructed. A key issue will be to understand what parameters can be controlled in each element of the system. There will necessarily be a strong interaction between the Network Manager and the Telescope Manager.
8 Statements of Work

The design effort required for each of the tasks in the Work Breakdown Structure in the Project Management Plan is summarised in individual statements of work in the remainder of this section. Figure 8.1 provides a pictorial summary of the main elements of the WBS.

![Diagram of the main elements of the SADT Work Breakdown Structure.]

The following sections detail the statement of work as developed by the workpackage managers for each of the Level 4 sub-elements. The level 5 tasks are described briefly, prototyping and verification for each sub-element is considered, and inputs, outputs and deliverables for the preconstruction work to CDR are presented.

Various assumptions have been made which are common to all the sub-elements.

- 1 FTE year constitutes 44 working weeks, except in the case of ASTRON, which uses 40 weeks.
- Interface requirements will be drafted from the ICD meetings at the start of the project; these meetings will be hosted by the SKAO, who own these interfaces. SADT will lead the definition of a number of these interfaces.

8.1 Digital Data Backhaul SKA.TEL.SADT.DDBH

Workpackage: SKA.TEL.SADT.DDBH
Workpackage lead institution: University of Manchester, UK

Organisations involved: ASTRON (Netherlands), IT (Portugal)
Potential industry involved: Large telecommunications industries
Planned start date: T0
Planned end date: T0+156

8.1.1 Description
The digital data backhaul networks of the telescope are responsible for transporting digitized science data from the receptor sensors to the central science processing facility. There are 3 discrete telescope networks SKA1-Low, SKA1-Mid, and SKA1-Survey requiring their own DDBH node termination equipment and optical fibre infrastructure. The baseline design outlines a concept for the 3 telescopes and shall be used as a starting point for the DDBH pre-construction work process. Each of the telescope SADT networks can be described as end-product entities with the generic hierarchical product description as shown in Figure 2.1. The network products will be designed to meet the upper telescope application and service layer requirements.

Generic system engineering processes for a product development will be followed during the pre-construction phase of the project, for example requirement capture, concept down selection, and detailed design.

8.1.2 Inputs
The DDBH work package will take inputs from the baseline design, concept of operations, previous concept design review, advanced instrument programme, and interface integrated task team documentation.

8.1.3 Outputs
The outputs from the work package level 5 elements will feed into the next level 5 elements in the system engineering process chain. These will include SADT requirements, concept designs, and optimisation modelling tools, down selection tools, interface control documents, detailed design document, prototypes, and procurement plans.

8.1.4 Tasks

Stage 1
1. SKA.TEL.SADT.DDBH.REQ and SKA.TEL.SADT.DDBH.FUN
   a) Telescope requirements, assumptions, and functional analysis.
      The top level telescope requirements will be captured from the project office documentation and other level 3 consortia elements. There will be traceability of the requirements captured such that any changes made during the first phase of the project can be tracked. Assumptions
will have to be made in some circumstances to progress this task and to proceed with the functional analysis. Assumptions will be made when Con-ops, AIP technology, and SKA2 upgrade descriptions are not available. DDBH representatives will be present at ITT meetings e.g. ICD reviews, and will present work from this task.

b) SADT requirements, assumptions, and functional analysis. This task will take the top level requirements, assumptions, and functions of the telescope and produce a set of SADT level requirements that will be required within the consortium to commence trade studies and concept generation. The requirements will fall into the product description categories as described in the hierarchical structure figure above e.g. including requirements in commissioning and normal operation modes, and for all science experiment cases. The detailed analysis will also feed into the draft ICDs required by the other level 3 elements i.e. the SKA1 Low, Mid, Survey receptors and CSPs. Initially CoDR and precursor documentation will be used as a guide for SADT sub-category requirement templates, for example data overheads and technology breaks versus link distance.

2. SKA.TEL.SADT.DDBH.CDB - Components database & Trade Studies.

Based on telescope and SADT requirements a component database will be formed as part the trade study activity. This database will include vendor component roadmaps and expected market sector trends over the next few years, gathered from trade shows and meetings. The component engineering work will continue for the entire 3 year duration of the program to ensure components can be sourced from multiple vendors as the DDBH designs mature, etc.

There will be strong focus to use off-the-shelf components that comply with international standards. In some circumstances it may be beneficial to design in COTS components that can operate outside of their recommended specifications e.g. extending the reach of short-range pluggable optic modules. This may require some lab testing and/or computer simulation. Results from these DDBH only applications will be recorded in the components database.

3. SKA.TEL.SADT.DDBH.CON - Concepts Generation.

Concepts for the 3 telescope networks will be generated once requirements and assumptions have been captured and reviewed. These concepts shall consider all OSI layers of the hierarchical product description described in the figure earlier.

There already exists a number of concepts from the prepSKA and CoDR phases of the project. These concepts will be considered and updated due to changes in technology, SKA requirements, and new time scales. Initially (up to PDR) the SADT element will have many undefined external interfaces, therefore strong emphasis will be placed modelling tools, such that architectures can be quickly updated when requirements change.

Modelling tools chosen for this task will be where there is considerable expertise and experience within the consortium. Examples of such tools include Matlab, Labview, VPItransmissionmaker (components and link transmission), Trenchcoat (Infrastructure), and
Rssoft MetroWand (network design/planning). Transmission equipment in-house planning tools are also being evaluated.

From the CoDR, there appeared to be two DDBH concept paths. The two potential development paths were to use ‘cut-down’ off-the-shelf telecoms grade equipment or custom developed products with element interfaces at the chip, board, backplane, and/or chassis level.

At the output of this phase there will be concept descriptions and models. The level 4 network architecture group will consolidate the DDBH options with the M&C and SAT concepts, and suggest changes that could be made to optimise the combined SADT network as a whole.

4. SKA.TEL.SADT.DDBH.ODS - Concept optimisation and down selection.
   Key parameters from the concepts generated will be analysed and optimised based on a number of factors. For example start and end of life performance budgets will be generated to show how much margin is available against requirements. Component technologies can be traded off against individual impairments highlighted in the budget.
   There will be a detailed down selection process of all optimised concepts put forward. A scoring scheme will be used to factor in the following: total cost of ownership (TCO), performance, RFI, reliability, power consumption, and product delivery risks.
   The down selected concept or concepts will then form the basis of the detailed network architecture(s) and will be considered during the SKAO PDR stage.

5. SKA.TEL.SADT.DDBH.ICD - Generate ICDs and internal interfaces for PDR.
   ICDs and internal interfaces will have to be frozen at or ideally before PDR. The interfaces will relate to the product description figure shown earlier. Detailed network architectures will be generated and will form part of a deliverable pack to the SKAO.

6. SKA.TEL.SADT.DDBH.PDES – Preliminary Design to Requirements Baseline
   Prepare document and presentation packs; address queries arising from the review; implement corrections to the documentation; close all other outstanding review issues.

7. SKA.TEL.SADT.DDBH.SKA2 - Support SKA2 activities
   The main issue for extending DDBH to SKA Phase 2 is likely to be accommodating the 3000km baselines; the technology required for this extension will be considered in this task.

8. SKA.TEL.SADT.DDBH.PPREP – SRR/PDR Activity

Stage 2

9. SKA.TEL.SADT.DDBH.PRO – Completion of Prototyping
   Manufacturable prototyping and verification cycles will be planned at the start of the final ~2year period before CDR. Manufacturable These prototypes will be required for custom designs as part of the design implementation stage. This may be in the form of design simulations (real-life models) or actual physical units.
Physical prototyping will require additional skilled effort including hardware design engineers, assemble and test technicians, embedded firmware developers, software interface programmers, and mechanical design engineers. The mechanical, electrical/optical hardware, and software can be developed in parallel to an extent, until integration is required.

Lab testing facilities and assembly tools will be required, and could be bought in, leased, outsourced.

10. **SKA.TEL.SADT.DDBH.FDES** – Design to Manufacture of DDBH Network

   a) **Detailed design specification.** The detailed design specification will comply with telescope and SADT detailed requirements. The down selected concept architectures will input into the hardware and software design specifications. The component database will be used to select components suitable for the chosen concept(s). Hardware, mechanical, firmware algorithm, and user interface software specifications will be generated at this point.

   b) **Development to manufacture and procurement.** This task will oversee the design of manufacturable prototypes, and will consider integration of prototypes into higher level systems and performance tests.

11. **SKA.TEL.SADT.DDBH.IPER** – Integration and Performance Tests

    Prototypes may have to be integrated at a system level and, for example, tested on cabled fibre systems with realistic data loading e.g. from receptors, through SADT network, to CSP test bed. A fully built prototype will be tested against functional, performance, and environmental pass/fail criteria such that the final iterated design is ready for volume manufacture.

12. **SKA.TEL.SADT.DDBH.PPS** – Prepare Procurement Specification Document

    This task involves documenting the DDBH procurement.

13. **SKA.TEL.SADT.DDBH.CPREP** – CDR Activity

    Prepare document and presentation packs; address queries arising from the review; implement corrections to the documentation; close all other outstanding review issues.

The complete documentation pack for CDR will be delivered that will include engineering documentation, final cost models, bill of materials, etc.

### 8.1.5 Models and Prototypes

Modelling and prototyping will be undertaken during concept generation/down selection (year 1) and during the detailed development phase (years 2 and 3), as explained in the task descriptions. The modelling and prototyping activities will require:

- Physical layer modelling
  - Component and transmission links (VPI transmissionmaker)
  - Network planning and topology design (RSoft MetroWand, Trenchcoat, vendor in-house tools)
- Parametric modelling (Matlab, LabView, Excel)
8.1.6 Verification

The models and prototypes will be used to verify that requirements and detailed design specs can be met. Planning and some testing will be done pre-PDR. The majority of verification will be done in the final 2 years of the pre-construction phase (pre-CDR). The verification activities will include:-

- Trade-off study/concept generation phase
  - Customised testing of component samples against SADT requirements, supplier datasheets, and factory accepted test data shipped with products
- Prototyping for manufacture design (pre-CDR) phase
  - Testing board assemblies against design specification pass/fail criteria
  - Integrated prototype performance margin testing again performance budget
  - Environmental testing – Thermal, power consumption, humidity, RFI, lightning, etc
  - System level testing – e.g. from SKA1-LOW station equipment to CSP equipment interface, across long-haul links with mixed M&C and SAT traffic.

8.1.7 Deliverables

The DDBH deliverables to the SKAO will include, and will not be limited to:-

Stage 1
- Co-consortia authored ICDs
- SRR pack – SADT.DDBH level requested requirements, status update, project risks report
- PDR pack – Trade study reports, components database, parametric optimisation and concept down selection tools, chosen concept architecture(s), project status update and risks report

Stage 2
- CDR pack – Detailed design specification, procurement guidelines, manufacturable prototype test reports, bill of materials, engineering drawings, physical prototypes and design simulations (if required)
8.2 CSP to SDP Data Transmission  SKA.TEL.SADT.CSP

**Work package:** SKA.TEL.SADT.CSP

**Work package lead institution:** CSIRO, Australia

**Organisations involved:** SKA South Africa, NRENs

**Potential industry involved:** Large telecommunications industries

**Planned start date:** T0

**Planned end date:** T0+156

8.2.1 Description

This work package defines the connectivity and transmission of science data from the Central Signal Processor (CSP) to the Science Data Processor (SDP). This includes the client-side physical interfaces at the CSP and SDP as well as the long-haul data transmission network and related infrastructure. This work package requires input from the CSP element in order to define the physical network interfaces at the output of the CSP and the logical flow of data. Likewise, the SDP element needs to provide input to define the interface into the SDP processor (e.g. location, number of ingest nodes, connectivity, data flow) to determine the interface requirements. Future extension to meet proposed SKA2 requirements must be considered.

Existing infrastructure, particularly the long-haul transmission network, should be utilised where possible. This may require upgrades to this existing infrastructure (e.g. space, power and cooling in “repeater” huts) to support the required bandwidth. Note that this long-haul transmission network will potentially carry all traffic (including M&C, engineering and production networks, voice and video traffic) between the observatory sites and the world with logical separation of different classes of traffic. Provision of adequate redundancy for these systems will be considered. Any design needs to be mindful of supporting real-time requirements (e.g. voice and video) alongside the CSP to SDP data transmission.

8.2.2 Inputs

Detailed analysis of existing precursor infrastructure, including currently installed equipment and capability and options for expansion, taking into account power and cooling requirements. Evaluation of current operational performance of precursor transmission networks.

8.2.3 Outputs

CSP and SDP interface and data flow requirements. Space, power and cooling requirements. Technology overview and potential future industry developments. Interfaces and network protocol definition (ICDs). Concept description, structural and behavioural models,
parametric and cost models, SRR and PDR documentation packs/presentations. Detailed final design including extensibility to SKA2 as appropriate. CDR documentation packs/presentations

8.2.4 Tasks
Stage 1

1. SKA.TEL.SADT.CSP.REQ – CSP/SDP: interfaces and power requirements
   a) Determine interface requirements and indicative data flows from CSP. Investigate economical aggregation techniques (e.g. say the output is many 1Gbit/s interfaces), being mindful of oversubscription, into 10, 40 or 100Gbit/s flows for transmission.
   b) Determine interface requirements and data ingest architecture for SDP. This needs to include, as a minimum, number of nodes, data rate to each node, methods to de-aggregate the transmission flows to ingest flows, ensuring no loss of data.
   c) Examine existing precursor infrastructure for relevant requirements including location and current configuration (i.e. installed equipment, support model, current bandwidth capability, options for expansion and impact of this on space, power consumption and cooling at both the intermediate and end-points).

2. SKA.TEL.SADT.CSP.FUN: Functional analysis
   Analysis of existing data transmission protocols and potential for development of modifications to existing protocols as deemed necessary for Proof-of-Concept testing. For example, examining the required packet re-transmission rates and those currently experienced on the pre-cursors, or investigating modification to suppress congestion avoidance techniques.

3. SKA.TEL.SADT.CSP.TRS Trade studies – identify appropriate technologies, modelling tools and companies:
   Conduct trade studies to identify appropriate technologies, taking into account future developments and vendor roadmaps. Need to balance “bleeding edge” technology against reliability, operational overhead and costs and support.

4. SKA.TEL.SADT.CSP.ICON – Manage concept generation by Industry
   Industry to develop conceptual transmission system design including the interfaces at the CSP and SDP, based on a brief developed as part of this work package. This work needs to ensure that industry is aware of the current precursor systems and to be able to re-use and integrate there where it is practical to do so.

5. SKA.TEL.SADT.CSP.DSL – Down Select
   Down-select concepts and options to best solution taking account of cost, and precursor integration.

6. SKA.TEL.SADT.CSP.ICD – Interface standards and protocols ICDs
   Define interface standards and protocols (in conjunction with CSP and SDP).
7. SKA.TEL.SADT.CSP.SKA2 – Support SKA2 Activities
   Where relevant the down-select should include extensibility to SKA2 but recognise that the
   technology chosen for SKA1 may need to be replaced to support SKA2. Because of the
   quadratic relation between number of visibilities and receiver elements, coupled with the
   much shorter correlator dump times required for SKA2 baselines, the data volume for the
   CSP to SDP task may be several orders of magnitude higher. In this task we will consider this
   issue.

8. SKA.TEL.SADT.CSP.PPREP – SRR/PDR Activities
   A final version of the documents being produced as work package deliverables will be
   prepared for the PDR data package. Any queries arising from the review will be addressed,
   and amendments to the documentation will be made.

Stage 2
9. SKA.TEL.SADT.CSP.FDES – Detailed Design to manufacture
   Detailed design, including vendor confirmation of final design, integration and installation
   issues. This needs to include Proof-of-Concept testing at vendor premises in the early stages
   before proceeding to final design to ensure that requirements can be met through scaling up
   the system.
   Refine and definitive design of interfaces and protocols based on CSP and SDP design and
   experience from prototyping and testing. Revise ICDs based on this task.

10. SKA.TEL.SADT.CSP.PROT – Prototyping
    Further develop prototyping and Proof-of-Concept testing based on PDR feedback, including
    that from CSP and SDP PDRs. This will involve both a combination of laboratory and in-the-field
    testing, taking advantage, where possible, of existing infrastructure (e.g. precursor
    transmission networks and HPC centres). Interface choice and protocol analysis based on
    extensive testing will be the central goal of this task; the choice of transmission protocol will
    require a balance between widely available protocols, development of new protocols and
    carriage of this across existing infrastructure (including switches, transmission equipment).
    Consider operational aspects of interface and protocol choice.

11. SKA.TEL.SADT.CSP.IPER – Integration and performance tests
    This aspect will be a part of and follow on from the prototyping and Proof-of-Concept testing
    above.

12. SKA.TEL.SADT.CSP.PPS – Prepare Procurement Specification Documents
    This task involves documenting the CSP-SDP procurement.

13. SKA.TEL.SADT.CSP.CPREP – Engineering documents, including costs, for CDR
    Generate CDR documentation including refined costing, Bill-of-Materials in a form suitable
    for issue of tender documentation.

8.2.5 Models and Prototypes
The network design modelling will, in the main, be undertaken by industry, often using vendor-specific proprietary tools providing commercial-in-confidence information. Proof-of-Concept (PoC) testing, most likely at vendor premises, and using networks provided by NRENs, will be required to validate designs. Once validated, further testing, using precursor infrastructure where available, may be required.

8.2.6 Verification

Once the design is finalised, extensive pre-installation testing and then in-situ acceptance testing will be required. This will involve initially running traffic test pattern generators and then moving to real or emulated end-to-end data transmission from the CSP to the SDP demonstrating the expected traffic flows.

8.2.7 Deliverables

Stage 1

- Co-consortia authored ICDs
- SRR pack – SADT.CSP requirements, status update, project risks report
- PDR pack – Trade study reports, components database, parametric optimisation and concept down selection tools, chosen concept architecture(s), project status update and risks report

Stage 2

- CDR pack and presentation – Detailed design specification, procurement guidelines, manufacturable prototype test reports, bill of materials, engineering drawings, physical prototypes and design simulations (if required)

8.3 SDP Interfaces and Data Transmission - SKA.TEL.SADT.SDP

Work package: SKA.TEL.SADT.SDP
Work package lead institution: CSIRO, Australia
Organisations involved: SKA South Africa, NRENs
Potential industry involved: Large telecommunications industries
Planned start date: T0
Planned end date: T0+156

8.3.1 Description

This work package defines the interface at the Science Data Processor (SDP) for the external distribution of science data products, and requires input from the SDP consortium. The SaDT consortium is of the strong opinion that this work package needs to also consider (in collaboration with the SDP consortium) the external access and distribution of the data by working closely with various global National Research and Education Networks (NRENs).
The interface to “the world” also needs to consider more than just the distribution of science data products from the SDP. Secure, remote and reliable access to other SKA Observatory networks (such as monitor and control, engineering etc) is required to allow technical, engineering and scientific staff to commission, debug and ultimately operate the facility from various locations.

Preliminary discussions with the SDP consortium indicate that SDP intends to conduct significant prototyping during the three-year design phase with a number of high-performance super-computer centres (HPC) located in the UK, Europe, Canada, Australia and South Africa. This will require collaboration with the appropriate NRENs to ensure the necessary network infrastructure can support this work. It is proposed that SaDT manages the interface with the NRENs, working closely with SDP.

The distribution of time and frequency reference signals over fibre may use the same physical network infrastructure and should be considered as part of the overall design of SKA Observatory networks e.g. there may be a clock based say in the National Standards Institute of that country that then distributes a reference on fibre to the observatory.

Although the focus of this work will be on SKA1, developing an understanding of future requirements necessary to meet SKA2 demands will provide valuable input into the planning process, particularly with the NRENs.

8.3.2 Inputs
SDP external interface and data flow requirements. Current and planned Research and Education connectivity and capacity as provided by the appropriate NREN.

8.3.3 Outputs
Agreements with the NREN community on supporting SDP prototype work. Study of applicability of current precursor infrastructure, including possibility for re-use. Technology overview and potential future NREN, industry developments and roadmaps. Operations concepts and management of commodity network equipment, compatibility and ease-of-integration with other SKA network components. Interfaces and network protocol definition (ICDs). Preliminary design leading to PDR report and presentation. Prototyping and Proof-of-concept studies in collaboration with SDP Consortium. Cooperative management plan between the SKA and NRENs to ensure current and future bandwidth requirements can be achieved. Detailed final design, including extensibility to SKA2 as appropriate. CDR documentation pack and presentation.

8.3.4 Tasks
Stage 1

1. SKA.TEL.SADT.SDP.REQ, SKA.TEL.SADT.SDP.FUN – Requirements and functional analysis
a) Determine external interface requirements and indicative data flows in discussion with the SDP element. This involves the number of SDP output nodes, what connectivity is required from each node, potential aggregation of the output data into a smaller number of higher bandwidth connections. Consideration needs to be given to parameters such as the expected data volumes, the traffic flows as a function of time, and time critical data rates.
b) Determine destinations for the replication of data (if any), including which super-computing centres are likely to be hosting SKA data. Investigate and evaluate the data transfer protocols to be used.
c) Define the extent of precursor reuse.

2. SKA.TEL.SADT.SDP.NREN - Approach NRENs
Manage the engagement with the NREN community to ensure that the proposed SDP prototyping work and can be undertaken between HPC centres located in the UK, Europe, Canada, Australia and South Africa. The will involve information on interface requirements, data volume, latency requirements, flow source and destinations, access methods, dedicated versus shared capacity, data transfer protocols and related development (if any). Manage the interface between SKA and the NRENs to support the SDP prototype work with the various global HPC centres. This will ensure that adequate bandwidth is provisioned and latency requirements met to support the prototyping that will be undertaken as part of the SDP design phase.

3. SKA.TEL.SADT.SDP.ITER – iterate on design of data products
With other elements and ConOps determine secure, remote and reliable access requirements to other SKA Observatory networks. This applies to both the on-site and Wide Area networks and includes consideration of technology such as network firewall requirements (functionality, throughput, management), use of Virtual Private Networks and the routing and switching of the different classes of network (including real-time voice and video services). The capability to support the distributing of time and frequency reference over fibre must be considered. Document current precursor access methodology with the aim to re-use where possible, as it is likely that the core of this infrastructure is already in place.

4. SKA.TEL.SADT.SDP.TRS – Trade Studies
Conduct trade studies to identify appropriate technologies, taking into account future developments and vendor roadmaps. Consider operational and support overheads in running a mixed-vendor environment. Consider potential issues with running “bleeding-edge” solutions.

5. SKA.TEL.SADT.SDP.COP – Concept Options Generation
Develop a conceptual design, involving industry, NRENs, supercomputing centre operations and management staff and applicable SKA elements. The design of the external network will be handled by the NRENs. Oversight and management of the external network activity will be undertaken as part of the SaDT work. Incorporate into the conceptual design the
ability and methodology for historic monitoring and on-demand performance testing of the external paths from the SKA instruments to relevant computing facilities around the world. This work would complement and have a link to NWGR activities and take input from the existing multi-domain network monitoring frameworks such as PerfSONAR.

6. **SKA.TEL.SADT.SDP.DSL – Down select architectures**
   Down-select concepts and options to best solution taking account of cost, operational overhead, re-use of precursor infrastructure and extensibility to SKA2.

7. **SKA.TEL.SADT.SDP.ICD - Interface standards and protocols ICDs**
   Define interface standards and protocols (in conjunction with SDP and NRENs) and generate ICDs.

8. **SKA.TEL.SADT.SDP.SKA2 - Support SKA2 activities**
   Future requirements necessary to meet SKA2 demands will considered and used to provide input into the planning process, particularly with the NRENs.

9. **SKA.TEL.SADT.SDP.PPREP – SRR/PRR Activity**
   A final version of the documents being produced as work package deliverables will be prepared for the PDR data package. Any queries arising from the review will be addressed, and amendments to the documentation will be made.

Stage 2

10. **SKA.TEL.SADT.SDP.PRO – Completion of prototyping**
    a) Extensive prototyping and Proof-of-Concept testing conducted in close co-operation with SDP, HPC centres and NRENs. It is envisaged that end-to-end data flows will be implemented using software similar to that to be used in production with processing of simulated or precursor data being undertaken as part of this task. This will allow the extensibility of the SDP model to be fully evaluated as a single complete system. Need to ensure the clear definition of interfaces, operational aspects such as network management; monitoring and control have been reviewed and appropriate solutions determined or risks mitigated.
    b) Manage the interface between SKA and the NRENs to support the SDP prototype work with the various global HPC centres. This will ensure that adequate bandwidth is provisioned and latency requirements met to support the prototyping that will be undertaken as part of the SDP design phase.

11. **SKA.TEL.SADT.SDP.FDES - Design to Manufacture**
    Detailed design, including vendor confirmation of final design, integration and installation issues. Finalise detailed user specification in conjunction with NREns and international submarine cable equipment manufacturers and operators, inclusive of link performance, reliability, latency, interfaces, and data protocols. Proposed routes from SDP to Regional Data Centres to be evaluated w.r.t. available bandwidths, latency, available compression
techniques and economics. Detail integration and installation issues in preparation for Integration & Performance testing phase.

12. **SKA.TEL.SADT.SDP.IPER – Integration and performance tests**

   Integration and performance testing will be carried out in collaboration with the SDP consortium and NRENs and, where possible, would aim to use “real-world” networks to undertake this work. Evaluate the existing multi-domain network monitoring frameworks such as PerfSONAR for making on-demand performance tests and recording the historic network behaviour of the connections between the SKA instruments and the external world sites.

13. **SKA.TEL.SADT.SDP.PPS – Prepare Procurement Specification Documents**

   Finalise documentation, produce Bill-of-Materials in a form suitable for issue of tender documentation.

14. **SKA.TEL.SADT.SDP.CPREP – Engineering documents, including costs, for CDR**

   Generate CDR documentation and presentation; address queries arising from the review; implement corrections to the documentation; close all other outstanding review issues.

   The complete documentation pack for CDR will be delivered that will include engineering documentation, final cost models, bill of materials, etc.

### 8.3.5 Models and Prototypes

The network design modelling may be undertaken by industry and NRENs, and will potentially use vendor-specific proprietary tools and commercial-in-confidence information. Some testing, particularly involving protocol choice and development (Proof-of-Concept) will be required.

### 8.3.6 Verification

Once the design is finalised, pre-installation testing and then in-situ acceptance testing will be required. This will involve initially running traffic test pattern generators and then moving to real or simulated end-to-end science data transmission. This will involve close cooperation with supercomputing centre staff and the NRENs.

### 8.3.7 Deliverables

**Stage 1**

- Co-consortia authored ICDs
- SRR pack – SADT.SDP requirements, status update, project risks report
- PDR pack – Trade study reports, components database, parametric optimisation and concept down selection tools, chosen concept architecture(s), project status update and risks report

**Stage 2**

- CDR pack and presentation – Detailed design specification, procurement guidelines, manufacturable prototype test reports, bill of materials, engineering drawings, physical prototypes and design simulations (if required)
8.4 Synchronisation and Timing: Clock Design – SKA.TEL.SADT.SAT.CLDES

**Workpackage:** SKA.TEL.SADT.SAT.CLDES  
**Workpackage lead institution:** National Physical Laboratory  
**Organisations involved:** University of Manchester

**Planned start date:** T0  
**Planned end date:** T0+68

**8.4.1 Description**

The aim of this work-package is to review all possible atomic clocks and any other suitable frequency standards that may possibly be used in the SKA clock system. These will include both those currently available commercially and those that are likely to come to market during the next three years. Commercial atomic clock technology is relatively mature with many clocks having well documented histories of both performance and reliability. The performance of short-listed clocks may be assessed through examination of actual data sets, particularly where the clock has been used at NPL or other laboratories where NPL has access to clock measurements. Where the performance of a clock is not well established, it may be possible to use NPL’s timescale facilities to directly evaluate the clock performance. The review should include, but not be limited to, active and passive hydrogen masers, caesium clocks, rubidium oscillators, and any suitable quartz oscillators. Once the review is complete, a down selection will take place, to choose the clocks that will be used in the SKA clock system.

**8.4.2 Inputs**

These include: requirements derived from the baseline design, stakeholder and functional analysis along with design assumptions produced by University of Manchester, inputs from both the clock system and monitoring and control work packages and relevant interface control documents.

**8.4.3 Outputs**

These include: inputs to clock system and monitoring and control work packages. Inputs to the SAT infrastructure requirements will be provided.

**8.4.4 Tasks**

**Stage 1**  
1. **SKA.TEL.SADT.SAT.CLDES-DEV - Clock Requirements and Market Survey:** A survey of commercial atomic clocks will be undertaken in this task. This should include but not be limited to information on the clock stability and frequency drift characteristics, physical outputs, supply
times, environmental sensitivity, reliability, power requirements, maintenance requirements, lifetime estimates, disposal requirements and cost.

2. **SKA.TEL.SADT.SAT.CLDES-DSL - Clock down selection:** The clocks to be included in SKA clock system will be identified in this task. An analysis based on the survey undertaken in task 1, input from the clock system work package, and inputs from the SKA requirements, will be used to decide upon the number and type of clocks to be used in the clock system. The performance of short-listed clocks may be assessed through examination of actual data sets, particularly where the clock has been used at NPL or other laboratory where NPL has access to clock measurements. Where the performance of a clock is not well established, it may be possible to use NPL’s timescale facilities to directly evaluate the clock performance. Other factors that will be considered when down selecting the clocks include cost, reliability, lifetime, power consumption, procurement time, portability of the clock and sensitivity of the clock performance to the local environment. Deterministic properties of the clocks, for example the presence of linear frequency drift will also be considered. Where there are several manufacturers of the same clock type, the performance, reliability and price may vary considerably between individual manufacturers.

3. **SKA.TEL.SADT.SAT.CLDES-ICD - Clock ICDs and internal interfaces:** The ICDs will be developed in consultation with colleagues developing other work packages. These will include elements that are being designed both by this and by other consortia. Particular attention needs to be given to the clock system work package, as this will make direct use of the outputs from the clock design. The laboratory requirements of individual clocks will require careful specification. This will include the power consumption and temperature control. The interface to monitoring and control will also require careful design as this may impact on the routine operation of the reference clocks.

4. **SKA.TEL.SADT.SAT.CLDES-SKA2 - Support SKA2 activities:** The design of the clock system should allow for expansion of the number and type of reference clocks. If more stringent SKA clock performance requirements become apparent during the design of the SKA, then the possibility of procuring additional clocks, possibly of a different type, may be considered.

### 8.4.5 Models and Prototypes

Prototyping will not be required in this work package.

### 8.4.6 Verification

The survey results obtained from task 1 will where possible be verified by examining characteristics of clocks currently operated at NPL, and where NPL has access to data sets obtained from clocks outside NPL. The performance of any clock new to market may possibly be evaluated at NPL.

### 8.4.7 Deliverables

The following documents are outputs from this work package:
Stage 1

1) Clock review report, to contribute to the clock system PDR documents.
2) Clock down selection to include recommendations of choice of clocks to be used in the SKA clock system, and contribute to the clock system PDR documents.
3) Clock interface document, to contribute to the PDR clock system ICD.

8.5 Synchronisation and Timing: Clock System – SKA.TEL.SADT.SAT.CLSYS

Workpackage: SKA.TEL.SADT.SAT.CLSYS

Workpackage lead institution: National Physical Laboratory

Organisations involved: University of Manchester

Planned start date: T0

Planned end date: T0+156

8.5.1 Description

The aim of this work-package is to design the infrastructure that will operate the SKA clock system, and produce the SKA reference timescale. It will be assumed, unless advised otherwise, that there will be two similar realisation of the SKA reference timescale, one in each continent.

Most of the hardware components e.g. phase micro-steppers, distribution amplifiers etc. required for a primary timing laboratory are off the shelf items that are available from several manufacturers. A detailed evaluation of the products currently available along with those becoming available during the next three years will be undertaken.

A physical realisation of the SKA reference timescale will be produced at each location. This will be vital for hardware calibrations and visiting clocks. Each location will almost certainly require the operation of a back-up timescale, to run in parallel with the generation of the master SKA reference timescale.

For long-term time keeping over periods of years, the SKA timescale must be related to other international timescales. The relationship between SKA timescale and Coordinated Universal Time (UTC), generated by the Bureau International des Poids et Mesures (BIPM) will be examined.

Time transfer links will be required, both to external timescales and between the two realisations of the SKA timescale. Global Navigation Satellite Systems (GNSS) time transfer links will almost certainly be used. Other well established time transfer methods e.g. Two-Way Satellite Time and Frequency Transfer (TWSTFT) will be considered along with methods that may only become practical during the later life of the SKA.
Depending upon requirements, a steering mechanism may be required for aligning the back-up timescale to the master, along with the possible steering of the SKA Timescale to UTC or other external timescale, and the synchronisation of the two physical realisations of the SKA timescale. Note that in this terminology, “timescale steering” means adding a phase or frequency offset to the signal from which the timescale is generated.

A detailed design will be produced, detailed enough to enable the manufacturing of the final clock system. This design process may involve the prototyping of any steering or other algorithms and analysis software at NPL, and if appropriate the testing on key components of the system at NPL.

8.5.2 Inputs
These include: requirements derived from the baseline design, stakeholder and functional analysis produced by University of Manchester, outputs from both clock concept and monitoring and control work packages and relevant interface control documents.

8.5.3 Outputs
These include: inputs to clock design, monitoring and control, direct distribution of frequency standards, remote locking of frequency standards, network architecture and remote time server work packages. Inputs to the SAT infrastructure requirements will be provided.

8.5.4 Tasks
Stage 1

1. **SKA.TEL.SADT.SAT.CLSYS-CD - Clock System Requirement Capture and Concept Development**: The key components of the clock system will be identified. For each component a survey all commercial hardware systems and software packages will be undertaken. This will include both currently available systems and systems likely to become available during the next three years. The hardware and software making up a primary timing laboratory is relatively mature. For much of the clock system, the likely preferred options may already be relatively clear at the start of the design process. The design for the SKA timescale, should initially meet all of the requirements for the SKA1 and SKA2 phases. However, the design should also permit upgrading during the SKA lifetime. This may be particularly important to ensure that the SKA timescale achieves future long-term time stability requirements.

2. **SKA.TEL.SADT.SAT.CLSYS-DSL - Clock System Down Selection**: For each of the components identified above a preferred design will be chosen. Key selection issues will include the choice of time transfer systems and choice of a strategy for the construction of a back-up timescale. A steering strategy may need to be chosen. This steering is likely to include the alignment of SKA timescale to UTC, TAI or other external timescale, synchronisation of the master and back-up SKA timescales, along with the synchronisation of two physical realisations of the SKA timescale. A method will be selected for switching from master to
back-up timescale. Other design options include: the implementation of a time transfer calibration programme, choice of measurement systems and anomaly detection techniques, hardware for the generation of all required time signals, clock messages and standard frequency outputs. A key design option will be the choice of clocks and associate hardware and software that will permit the SKA timescale to realise its required frequency stability over a wide range of averaging times.

3. **SKA.TEL.SADT.SAT.CLSYS-ICD - Clock System ICDs and internal interfaces:** The ICDs will be developed in consultation with colleagues developing other work packages. These will include elements that are being designed both by this and by other consortia. Particular attention needs to be given to the station time and frequency reference work package, as this will make direct use of the physical outputs from the clock system. Output from the clock design work package will be required in this work package, as the choice of reference clocks will be central to the clock system. Physical outputs and from the clock system work package are likely to include, standard frequency outputs, pulsed timing signals, time transfer measurements and clock and timescale measurements. Where practical, standard formats will be used with output data sets, details of these will be provided in the interface documentation. The sensitivity of clock system hardware to environmental changes, e.g. temperature control will require careful specification of the requirements on the building housing the clock system. The interface to monitoring and control will also require careful design as this may impact on the routine operation of the clock system.

4. **SKA.TEL.SADT.SAT.CLSYS-PDES - Preliminary Clock System design:** In this task the preferred design options identified in the clock design and clock system down selections will be expanded and a top level design for the clock system finalised.

5. **SKA.TEL.SADT.SAT.CLSYS-SKA2 - Support SKA2 activities:** The SKA timescale will be designed as far as is possible to meet all of the requirements of SKA 1 and SKA2. However the design will also be constructed so as to allow for the expansion of the clock system to permit the upgrading in order to meet any later more stringent requirements during the lifetime of the SKA. This would include designing to permit inclusion of additional clocks, and clocks with different performance characteristics into the clock ensemble, the possibility of expanding the time transfer methods e.g. to include optical fibre links.

6. **SKA.TEL.SADT.SAT.CLSYS-PPREP – SRR/PDR Activity:** A final version of the documents being produced as work package deliverables will be prepared for the PDR data package. PDR queries will be answered, corrections will be made to PDR documents, and all outstanding PDR issues closed.

**Stage 2**

7. **SKA.TEL.SADT.SAT.CLSYS-FDES - Clock system design to manufacture:** The top level design prepared for PDR will be expanded to provide a detailed design of all components of the
clock system. Much of this design will be developed based on the use of commercial products developed for use by primary timing laboratories. However some of the concepts that may be developed, for example steering strategies and anomaly detection, will require detailed prototyping.

8. **SKA.TEL.SADT.SAT.CLSYS-PRO - Construct and evaluate prototypes**: Depending upon the clock systems chosen and the manufacturer chosen, the testing and evaluation of individual hardware at NPL may be usefully employed to demonstrate that a manufacturer’s hardware meets its specified performance. Where practical, commercially available software will be used. Prototyping and evaluating some of the components of the clock system, particularly those designed to be implemented using in house software, will be required. This may include prototyping the strategy for aligning the SKA timescale to UTC or other reference timescales, and any schemes for ensuring that the SKA timescale meets any frequency stability requirements. The strategy for monitoring both the performance of the individual clocks and the resulting timescale, and other hardware elements may be prototypes, as may the schemes for detecting anomalous behaviour. Much of this work will involve the use of existing hardware and software currently available at NPL.

9. **SKA.TEL.SADT.SAT.CLSYS-ENV - Evaluate and specify physical and environmental clock system requirements**: The performance of hardware developed for use in primary timing laboratories depends strongly on environmental conditions. In this task physical and environmental conditions will be specified that will permit the clock system hardware components to perform with a performance that will meet the clock system requirements.

10. **SKA.TEL.SADT.SAT.CLSYS-IPER - Integration and performance tests**: Methods will be described for integrating individual components of the clock system, and for providing tests that the overall clock system meets its performance requirements.

11. **SKA.TEL.SADT.SAT.CLSYS-PPS - Prepare procurement specification documents and commissioning documents for clock system on site commissioning**: This task involves documenting the clock system procurement and commissioning processes. The methods for calibrating and characterising the clock system will be developed so as to verify that each component meets its performance requirement, as will the approach for delivering and installing the clock system hardware.

12. **SKA.TEL.SADT.SAT.CLSYS-CPREP - CDR activity**: A final version of the documents being produced as work package deliverables will be prepared for the CDR data package, including revised cost estimates for construction. CDR queries will be answered, corrections will be made to PDR documents, and all outstanding CDR issues closed.

### 8.5.5 Models and Prototypes

Software for clock and time transfer measurement, anomaly detection, clock monitoring, possible ensemble and steering algorithms, and other components of the clock system may be prototyped at NPL.
8.5.6 Verification
Where possible components of the system may be tested through operation of suitable hardware and software at NPL, and from NPL’s experience in running the UTC(NPL) timescale. A plan for verification of the performance of the clock system following installation will be provided.

8.5.7 Deliverables
The following documents are outputs from this work package:

Stage 1
1) PDR Performance Specification,
2) PDR Design Specification,
3) PDR Clock System ICD,

Stage 2
4) CDR Performance Specification,
5) CDR Design Specification,
6) CDR Clock System ICD,
7) CDR User Operations Manual

8.6 Synchronisation and Timing: Distribution of Time, Frequency and Phase - SKA.TEL.SADT.SAT.STFR

Workpackage : SKA.TEL.SADT.SAT.STFR
Workpackage lead institution: UMAN, United Kingdom
Organisations involved: NPL, Tsinghua University, Peking University, UGR, JIVE
Planned start date: T0
Planned end date: T0+156

8.6.1 Description
This work element is tasked with the design of a distribution system for the time and frequency/phase reference signals to each of the stations that constitute the SKA. The STFR system will use optical fibre to transport signals locked to the reference atomic clock system (SKA.TEL.SADT.SAT.UTCR). Several interferometer arrays, including e-MERLIN and EVLA already use various techniques of RF modulation of lasers for phase transfer over distances up to several hundred km, and with sufficient stability for observation frequencies up to tens of GHz. In addition, several groups around the world have been developing a range of techniques to distribute highly
accurate and stable time and frequency standards directly, by compensating the phase and/or delay variations on the fibre.

Links using a reflected signal with a round-trip distance more than 100 km (or a one-way distance > 150 km if an independent laser is used at the remote end) require the use of optical amplifiers to counteract the attenuation of optical fibre. For effective link stabilisation it is critical that the transmitted signal is perturbed by the same fluctuations on the outgoing and return trips along the optical fibre link. This implies that optical bi-directional amplifiers are used, or that phase-coherent regeneration is used (optically or electrically).

These signals will be used to derive all the required LO signals and sampler clocks for each station. The requirements on relative phase and time stability have been discussed in section 2.1. The requirements on absolute timing at each remote station are less demanding and it may be sufficient to use a combination of local GPS clocks and the distributed standard frequency. Alternatively, some of the distribution techniques considered below provide a more accurate means of delivering a time standard at [at the ps level] directly (SKA.TEL.SADT.TM).

This work element will fully characterise all the requirements for phase and timing stability in each of the 3 SKA telescopes, considering the expected astronomical and instrumental calibration techniques which will be employed over various timescales. It is unlikely that a single technical concept will be able to cover all of the SKA in a cost effective manner. Several concepts will have to be investigated simultaneously, and then ranked according to cost, accuracy and distance.

The STFR design will also establish specific requirements for the fibre network. Temperature variations of the fibre itself cause changes in propagation delay, which need to be measured or compensated for to maintain phase stability. These effects can be partly mitigated by choosing the right type of fibre, and burying it at the appropriate depth for temperature stabilisation. The optimal network topology for the STFR network might also be different than that for the other networking elements (DDBH and TM).

8.6.2 Inputs
This work package takes inputs from: the science requirements (Baseline Design); calibration and operational methodologies (ConOps; Dish, AA, Survey); station aggregation options; potential optical fibre network architectures.

8.6.3 Outputs
The outputs from this workpackage are: STFR requirements & functional analysis (performance, but also reliability, management, monitoring etc.); STFR Concept descriptions, prototypes, costing and performance analysis; parametric, structural and behavioural models to estimate performance and cost as a function of distances, network topology, highest frequency, and selected phase/frequency
distribution concept(s); reports on prototypes of each selected concept; down selection and synthesis of techniques for required frequencies and link lengths; detailed design for STFR element; verification of prototypes under SKA site conditions.

8.6.4 Tasks

Stage 1

1. SKA.TEL.SADT.SAT.STFR.REQ - Identify STFR requirements:
   Create a model for each of SKA-LOW, SKA-MID and SKA-Survey consisting of distances and phase stability requirements based on the Baseline Design and calibration methodologies. Preliminary investigations have already shown that in the quietest parts of the radio sky SKA-MID at 1.4 GHz will have sufficient signal to noise ratio for sources within the primary beam to use self-calibration on a timescale of 25s. (to reach a 1° phase error in a 100 MHz sub-band). At higher frequencies the signal to noise ratio (per antenna) is approximately

\[
\text{SNR} = 50 f (\frac{\lambda}{21\text{cm}})^{-2.7} \left(\frac{\text{Tsys}}{30\text{K}} \frac{\eta}{0.7}\right) \left(\frac{B}{100\text{MHz}} \frac{t}{s} \frac{N}{250}\right)^{0.5}
\]

For a bandwidth B, integration time t, and N dishes, assuming an integral source count of ~1 and an average spectral index of 0.7. At the top of SKA-MID band 4 (5.2 GHz), the signal to noise ratio is 30x lower, so self-calibration would be possible but would require integration over sub-bands. This technique is already routine for e-MERLIN, even in the quietest radio fields at 1.4 GHz. More detailed studies of these calibration methodologies using the baseline design, updated where necessary, will be carried out and will inform the coherence and dynamic range requirements for the phase stability.

2. SKA.TEL.SADT.STFR-FUN Functional analysis
   The requirements analysis will show the required phase stability over timescales determined by the science requirements and calibration methodologies. Potential network topologies will show the various link lengths and possible aggregation points. Environmental information will provide potential temperature fluctuations as function of fibre burial depth. Functional analysis will be used to determine the link length compensation performance required for each link, for each SKA telescope/frequency. This will provide the basic functional architecture for the SAT.STRF element.
   This model will later on be refined with information such as network topology and fibre reticulation as these become clear. Obtain all other requirements from the SKA RFP package in discussions with the consortia and other stakeholders. Other requirements include the level of reliability, detecting fault conditions, and other elements apart from antennas which may need to receive which signals (time, frequency, phase).

3. SKA.TEL.SADT.SAT.STFR-CD Frequency Time and Phase Concept development
Different techniques of phase transfer will be investigated as discussed in section 2.2, including:

- Passive transfer using RF modulation of laser transmitters. The link phase variations are compensated as part of the correlation or beamforming process. This technique can be adapted to different link lengths and frequencies, using cheaper transmitter lasers where appropriate.
- Active compensation of RF links by adjusting the RF modulation phase.
- Direct distribution of microwave frequency (and time) standards on actively compensated links.
  Each will include all the required optical and electronic equipment for transmission, reception, phase/time measurement and compensation.

4. **SKA.TEL.SADT.SAT.STFR.DSL - Down selection**
   Combine the requirements model with the performance and cost of the concepts under consideration, to create a ranking of the concepts. It is highly likely that no single concept will be able to provide a cost effective solution for all distances and stability requirements for the various telescope elements. The concepts can also have clearly different requirements in terms of network topology (e.g. ring, star or tree) and fibre characteristics both of which can have a major impact on the cost of deploying a particular concept (see Table 7.2). Consultation with the teams working on the other networks in SADT (through SADT.NWA) will be required to minimize overall costs for the element. Requirements for the higher frequency coverage and larger distances in SKA2 also need to be taken into account in the down selection. A final optimization is to minimize the number of different technical solutions on each of the sites.

5. **SKA.TEL.SADT.SAT.STFR.ICD - ICDs and internal interfaces**
   Establish ICDs in consultation with the other elements that are being designed by other consortia. These ICDs will describe a.o. the frequency, stability and amplitude of the reference signals, and how they will be delivered (connector etc.). For the passive compensation technique an ICD needs to be established that describes how these measurements are presented to the CSP (resolution, data format, measurement update rate) and which network will transport these measurements (DDBH or TM). Depending on the selected concepts, establish ICDs with TM for e.g. monitoring of fibres, active optical components and overall performance.

6. **SKA.TEL.SADT.SAT.STFR-PDES - Preliminary FTP design**
   Refine the model to fully describe the topology, selected concepts and equipment, so that an accurate prediction of performance and cost can be generated. Preliminary design to prototype level each of the selected concepts.

7. **SKA.TEL.SADT.SAT.STFR-SKA2 – Support SKA2 activity**
   Some of the technologies being considered can address STFR over the 3000km lengths required by SKA2.
8. SKA.TEL.SADT.SAT.STFR-PREP – SRR/PDR Activity
Generate PDR documentation and prepare for the review; address queries arising from the review; implement corrections to the documentation; close all other outstanding review issues.

Stage 2

9. SKA.TEL.SADT.SAT.STFR-PRO – Completion of prototyping
For the (benchmark) passive RF modulation scheme, the main task here is the completion of a prototype PCB for the RF modulation, phase locking and phase measurement signal processing using an FPGA-based design (or other designs) which is robust, reliable and performs to the required specifications over the appropriate distance and frequency ranges when paired with the appropriate laser transmitters.

10. SKA.TEL.SADT.SAT.STFR-FDES - FTP Distribution Design to manufacture
Evaluate PDR outcomes for changes in requirements, ICDs, available technology and pricing. Complete the design(s) to the component level, optimized for the environment at the sites and volume production. Verify design against ICDs for power delivery, management network, and interfaces to the stations. Create the full documentation needed for procurement, deployment, installation, calibration, operational use and EOL. For an FPGA-based solution (see above) specific tasks include the VHDL behavioural model, the RTL design and verification, embedded firmware development and physical packaging.

11. SKA.TEL.SADT.SAT.STFR-IPER – Integration and performance testing
A fully built prototype(s) of the down selected solution(s) will be tested against functional, performance, and environmental pass/fail criteria such that the final iterated design is ready for volume manufacture.

12. SKA.TEL.SADT.SAT.STFR-PPS – Prepare Procurement Specific Documents
Finalise documentation, produce Bill-of-Materials in a form suitable for issue of tender documentation.

13. SKA.TEL.SADT.SAT.STFR-CPREP – CDR Activity
Generate CDR documentation and prepare for the review; address queries arising from the review; implement corrections to the documentation; close all other outstanding review issues. The complete documentation pack for CDR will be delivered that will include engineering documentation, final cost models, bill of materials, etc.

8.6.5 Models and Prototypes
Complete design to prototype level each of the selected concepts and verify performance in real-world environmental conditions either in simulation or on-site.
For the (benchmark) passive RF modulation scheme, a series of prototype systems will be developed, to demonstrate increasingly robust, reliable and cost-effective techniques. These will be tested in the field on installed e-MERLIN fibre. The development of a prototype PCB for an FPGA-based phase-measurement unit can proceed in parallel.

For the other enhanced schemes, there is more work to be done in turning what are currently lab-based implementations towards products for the SKA.

8.6.6 Verification
- Prototypes for each of the selected concepts, tested under realistic environmental conditions. All of the prototypes can be tested on real-world installed fibre which is part of the e-MERLIN network over a range of distances and under various conditions. It will also be possible to carry out operational and astronomical tests using these systems for interferometric observations over the range of baselines and frequencies appropriate to SKA-1.
- Parametric model of performance and cost as a function of distances, topology, highest frequency and selected concepts.

8.6.7 Deliverables

Stage 1
- Co-consortia authored ICDs and internal interfaces
- SRR pack – SADT.STFR level requested requirements, status update, project risks report
- PDR pack – Trade study reports, components database, parametric optimisation and concept down selection tools, chosen concept architecture(s), project status update and risks report

Stage 2
- CDR pack – Detailed design specification, including full documentation, schematics, power and environmental requirements for the STFR systems, procurement and deployment planning and documentation, manufacturable prototype test reports, bill of materials, and engineering drawings with specifications of all COTS and custom components.

8.7 SAT Local Monitoring and Control SKA.TEL.SADT.SAT.LMC
Work Element: SKA.TEL.SADT.SAT.LMC
Work Element lead institution: NCRA, India
Academic Organisations involved: TRDDC, India; UGR Spain
Potential Industry involved: Tata Consultancy Services, large telecommunications industries

Comment [AW1]: Do we need to remove this?
Planned start date: T0
Planned end date: T0+156

8.7.1 Description
This work element is responsible for the monitoring and management of all the SAT systems. This includes the configuration and setup of all the equipment (including hardware and software elements), monitoring health and performance parameters, and detecting and responding to adverse situations. Monitoring data and reports should be provided to the Telescope Manager. Engineers should be provided with interfaces to facilitate troubleshooting and upgrades. The scope of the work element includes the design of instrumentation to facilitate monitoring of behaviour and remote control of the equipment. The LMC is expected to enable SAT to function as a semi-autonomous system that is responsible for managing its own performance and lifecycle, with only high-level control inputs from operators via the Telescope Manager.

8.7.2 Inputs
The requirements for SAT local monitoring and control come primarily from the Concept of Operations and the peer level 5 work elements in SAT, complemented by the baseline design and CoDR documentation. Design inputs will come both from the peer level 5 work elements as well as the standard LMC interface and instrumentation guidelines defined by the Telescope Manager in cooperation with the System. The inputs for detailed design of the situation detection and response logic will come from the experts responsible for the peer level 5 work elements.

8.7.3 Outputs
The outputs from this work element include: the requirements for local monitoring and control for each of the SAT components and subcomponents; engineering support interfaces and capabilities needed; preliminary designs and designs to manufacture for meeting these requirements, including the required instrumentation of SAT subcomponents; detailed behavioural models and mathematical analysis to verify the capability to maintain desired performance levels and PoCs as needed to validate the designs; definition of the interface to the Telescope Manager; a troubleshooting and system management interface for engineers; supporting documentation as needed for the SRR / PDR and the CDR. A.

8.7.4 Tasks
Stage 1

1. SKA.TEL.SADT.SAT.LMC-REQ - Identify SAT LMC requirements: Derive the requirements for SAT monitoring & control from the overall SAT performance parameter requirements, system requirements relating to the reliability and availability of components, and domain knowledge. The requirements should include the set of performance parameters to be monitored and maintained, system management responsibilities such as startup, shutdown and configuration, behavioural requirements including reliability, availability and safety
requirements (if any), and interfaces to be supported, including troubleshooting interfaces and the interface to the Telescope Manager to provide monitoring data and accept control inputs.

2. **SKA.TEL.SADT.SAT.LMC-FUN - Functional Analysis**: Derive the specific collection of parameters to be monitored and maintained for each SAT component. Identify the collection of lifecycle concerns to be addressed for each component. Identify the set of adverse situations to be addressed for each SAT component and the SAT system as a whole, including performance deviations, failure modes, and any possible security and safety threats. Identify the desired response outcomes for each adverse situation. Specify the requirements for the engineer and Telescope Manager interfaces. Define the Telescope Manager interface in accordance with the interface design guidelines from the Telescope Manager for monitored systems, and estimate the volume and timing patterns of monitoring data produced.

3. **SKA.TEL.SADT.SAT.LMC-DOPT - Design Options Analysis**: Identify options for the instrumentation (sensors) needed to acquire the desired monitoring data for each element. Participate in program-wide efforts to standardize instrumentation choices across the SKA program, including sensors, actuators, buses and control nodes (PLCs, computers, associated software technology choices) to ensure that the choices are consistent with SAT needs.

4. **SKA.TEL.SADT.SAT.LMC-CG – Concept Generation**: Develop tables of components to be monitored, situations to be detected for each component, and handling actions for each situation. Identify the functional responsibilities towards each component, including configuration and setup, parameters to be monitored, troubleshooting and upgrades support, and monitoring and control interfaces to be provided to TM for operators. Analysis of a combined timing & engineering network (for instance based on White-Rabbit) for supporting timing, monitoring and control activities. Evaluation of the effect of such a system on adverse situation and definition of their interfaces.

5. **SKA.TEL.SADT.SAT.LMC-ICD – ICDs and Internal Interfaces**: SAT LMC will conform to the standard LMC interface definition provided by TM, and supply to TM details of the specific interface between them, including set of commands accepted, events and alarms raised, and monitoring data provided. Internal interfaces will be defined with each of the peer level 5 work elements in terms of the instrumentation needed for monitoring and control of component behaviour.

6. **SKA.TEL.SADT.SAT.LMC-PDES – Preliminary Design**: Design algorithms to process the data, detect adverse events (including predictive analysis for potential future failures) and to respond to the adverse situations. Organize these into a multi-level control design scheme including any alarm handling capabilities to be supported by Telescope Manager, and any coordination and information flow requirements with other system elements e.g. handling of feedback from CSP indicating problems in synchronization. Identify the set of system management capabilities to be provided, including configuration, self-test, diagnostic and update capabilities. Design the history to be maintained for the engineering data and how it
will be used to support diagnosis and troubleshooting. Work with each SAT component to
design the integration of LMC capabilities into the component. Collate all these decisions into
a preliminary overall design for addressing the SAT LMC requirements. Identification of
instruments for back-up timing systems during failures as well as timing information
monitoring elements to prevent time deviations. Defining timing network topologies capable
to deal with node failures based on redundancy.

7. **SKA.TEL.SADT.SAT.LMC-SKA2 – Support SKA activities**
   Issues involving extension to SKA2 will be considered

8. **SKA.TEL.SADT.SAT.LMC-PPREP – SRR/PDR Activity**
   Generate PDR documentation and prepare for the review; address queries arising from the
   review; implement corrections to the documentation; close all other outstanding review
   issues.

Stage 2

9. **SKA.TEL.SADT.SAT.LMC-MA - Modelling and Analysis**: Create behavioural models to enable
   analysis of each aspect of SAT system behaviour. These will generally be paper models in the
   form of state diagrams and activity & sequence diagrams that show how each scenario will be
   addressed to produce the desired outcomes. It is possible but unlikely that simulation models
   will be needed to ensure that there are no adverse overall system behavioural dynamics
   resulting from the individual situation response actions. However, mathematical feedback
   control analysis is likely to be needed to evaluate the behaviour of the proposed control
   algorithms and refine them. Identify and evaluate technologies for implementation of the
   control capabilities, in accordance with applicable program-wide standards.

10. **SKA.TEL.SADT.SAT.LMC-PROT – Prototyping Support**: Support will be provided to prototypes
    being developed for other SAT components, to incorporate monitoring and feedback control
    as needed to enable their successful operation and fault handling. Create basic prototypes for
    evaluating backup timing instrumentation and instrumentation to prevent timing deviation as
    well as control algorithm for taking advantage of these functionalities. Measure performance
    parameters of design and verify integration with component.

11. **SKA.TEL.SADT.SAT.LMC-FDES Plan for Design to Manufacture**: Downselect the options for
    LMC instrumentation. Develop specifications for each control procedure and system
    management function, including the specific troubleshooting and upgrade capabilities to be
    supported. Develop deployment and costing models for LMC, including verification
    procedures during commissioning. Develop an implementation and procurement plan.

12. **SKA.TEL.SADT.SAT.LMC-IPER – Integration and performance tests**: Prototyping to verify
    instrumentation design concepts and integration, measure performance.

13. **SKA.TEL.SADT.SAT.LMC-PPS – Prepare procurement specification documents**
Finalise documentation, produce Bill-of-Materials in a form suitable for issue of tender documentation.

14. **SKA.TEL.SADT.SAT.LMC-CPREP – Documentation and cost models**: Create the documentation needed for CDR, including the entire design scheme for each component and all the interfaces supported. Develop cost models for the SAT LMC, including all the LMC instrumentation associated with each SAT component.

8.7.5 **Models and prototypes**
Models and prototypes will be developed as described in tasks 9 and 10 above.

8.7.6 **Verification**
- Behavioural models are validated to ensure that the desired outcomes are achieved for each scenario.
- Mathematical analysis of proposed control algorithms to ensure capability to deliver desired performance levels.

8.7.7 **Deliverables**
**Stage 1**
- SRR pack - SAT LMC requirements.
- Telescope Manager interface specifications.
- PDR pack - preliminary design concept for achieving SAT LMC requirements.

**Stage 2**
- CDR pack - control procedures for situation detection and response, design to manufacture documentation, including instrumentation choices and cost models.

8.8 **Telescope Management Networks – SKA.TEL.SADT.TM**
**Work Element**: SKA.TEL.SADT.TM
**Work Element lead institution**: NCRA, India
**Academic Organisations involved**: TRDDC, India.
**Potential Industry involved**: Tata Consultancy Services, Large telecommunications industries
**Planned start date**: T0
**Planned end date**: T0+156

[Comment [AW2]]: Likewise, should this be removed?
8.8.1 Description
This work element identifies the requirements and develops design concepts (in conjunction with Network Architecture, SKA.TEL.SADT.NWA) for the various logical networks used for Telescope Management: PNET (production Network), ENET (engineering network) and SNET (safety network). PNET carries all monitoring and control data related to normal telescope operations, including monitoring data from devices, alarms and events, and commands to devices from the central Telescope Manager. ENET carries both science data and monitoring and control data for any devices in non-operational modes, including commissioning and troubleshooting modes. The purpose of ENET is to provide isolation for PNET, so that traffic from defective devices does not interfere with the normal functioning of the telescope. Science data is also carried on the ENET, so that the DDBH (digital data backhaul) network is not impacted by commissioning traffic. SNET is backup connectivity for safety purposes. During threat situations (e.g. severe weather, floods, network failure) devices and stations are responsible for shutting themselves down safely, but there may be a need for the central system controllers to verify that safe shutdown has occurred e.g. power equipment has been shut down. Since adverse conditions may affect the functioning of the normal network, there is a need for a backup link that can be used to verify and ensure safe shutdown.

The traffic requirements for monitoring and control are identified by the Telescope Manager work package (SKA.TEL.TM). This SADT work element obtains the requirements from TM, works with NWA to identify candidate design options, and evaluates them to select and detail out the design solutions for the various TM logical networks.

A working assumption is made that the design of the local networks for monitoring and control data (within stations and within the core) is within the scope of this work package and falls within the purview of PNET.

8.8.2 Inputs
The initial requirements for this work element will be derived from the baseline design, Concept of Operations and the TM CoDR documentation. This will be refined based on interactions with the TM and INFRA work elements, and inputs from the Integrated Task Teams. The design decisions and analysis will use inputs from the SADT CoDR documentation as a starting point, and will be coordinated with the NWA and DDBH level 4 work elements.

8.8.3 Outputs
The deliverables to be produced include: requirements to be satisfied by the Telescope Management logical networks; preliminary design concepts for the networks; models of topology and traffic for each network; parametric models of network behaviour; simulation prototypes, as needed to complement behaviour models; cost models; reports summarizing the approach and results from modelling, analysis and prototype performance studies; packaged versions of the models for further use during the system lifecycle; and design to manufacture for the logical networks for all three.
8.8.4 Tasks

Stage 1

1. **SKA.TEL.SADT.TM.REQ - Identify PNET, ENET, SNET Requirements**
   Obtain requirements from the WBS Level 3 Telescope Manager work package, which in turn obtains these requirements from each of the other Level 3 work packages. Augment these requirements based on system level information: Baseline Design, Concept of Operations and the overall System Requirements. Requirements of interest include data rates, source locations, flow patterns (including peer-to-peer flows), desired latencies (particularly for metadata and parameters consumed by other parts of the system), commissioning and troubleshooting patterns, reliability, availability, safety, security, needs for maintenance access, and special features such as prioritization.

2. **SKA.TEL.SADT.TM.FUN - Functional Analysis**
   Process obtained requirements to develop a topological view of traffic patterns for the PNET and ENET, along with associated characteristics, including both long-haul traffic and local PNET traffic (some of which may potentially piggyback on DDBH connectivity with isolation). Develop safety and security threat models, along with desired handling, and analyze the implications for the design of security features and the requirements for SNET. Create requirements specifications for PNET (local and long-haul), ENET and SNET.

3. **SKA.TEL.SADT.TM.TRS – Trade studies**
   Interact with vendors and study alternative implementations to determine the set of available technologies and typical best practices for implementing each of the logical networks. Gather information about how similar requirements are addressed in other large scientific and industrial projects. Aspects of particular interest include low-cost backup options for safety, and creating logical isolation between science, production and engineering data over optical fibre links. Study the typical technologies and topologies used to provide LAN connectivity and the tradeoffs between them.

4. **SKA.TEL.SADT.TM.PCON/SCON/ECON - Design Concepts Generation**
   Work with NWA (and DDBH) to develop design concepts for the implementation of PNET, ENET and SNET i.e. the mapping of the logical networks onto physical network elements. Possible dimensions of choice include virtual vs. physical isolation of traffic on fibres, topological vs. on-demand backup links, and piggybacking with DDBH links vs. independent links for local networking. Develop parametric topological and behavioural models for each choice, and analyze the resulting parameters, including throughput, latencies, reliability, availability, potential for mutual interference and cost. Develop and analyze options also for the design of LANs within the core for each telescope, and at each station.

5. **SKA.TEL.SADT.TM.DSPN/DSSN/DSEN - Downselect each network**

Supporting documentation for these deliverables will be produced as needed for the SRR / PDR and the CDR.
Work with NWA to make choices for each of the networks (including PNET local). Dimensions to be defined include the network topologies, logical to physical mappings, protocols at each layer, isolation models, network interfaces and security features. Create initial documentation of the choice together with rationale. Also create associated PDR documentation such as Verification Plans.

6. **SKA.TEL.SADT.TM.ICD - ICDs and Internal interfaces:**
   Determine the APIs that will be used by TM to access each of the logical networks, based on the range of capabilities needed by TM, including prioritized messaging, passthrough access to devices for troubleshooting, and possibly QoS support for segregating streams of TMK traffic. Develop ICDs for these APIs in collaboration with TM. Develop internal interfaces to enable remapping logical networks to physical carriers in case of failures, and query of system operational status to trigger setup of on-demand backup links, if applicable.

7. **SKA.TEL.SADT.TM.PDESP/PDESS/PDESE - Preliminary Designs:** Work out capacities, associated devices and other system design aspects. Refine the parametric models created earlier and analyze the resulting behavioural parameters against requirements. As necessary, develop simulation prototypes of the networks. Develop approaches as needed to manage the network (including fault detection and handling and performance optimization) to achieve requirements such as reliability, availability and performance, and identify any needed supporting infrastructure. Define network access interfaces. Produce a preliminary design schema for each network with analysis to show how desired parameters are met.

8. **SKA.TEL.SADT.TM.SKA2 – Support SKA2 Activities**
   Analyze the scalability of the design options selected for PNET, ENET and SNET to the data volumes and number of nodes expected for SKA2. Determine the implications of the increased data volumes on the fibre capacity needed for the TM networks.

9. **SKA.TEL.SADT.TM.PPREP – SRR/PDR Activities**
   Generate PDR documentation and prepare for the review; address queries arising from the review; implement corrections to the documentation; close all other outstanding review issues.

**Stage 2**

10. **SKA.TEL.SADT.TM.PROP/PROS/PROE - Prototyping:** Work with NWA to include the TM logical networks in their prototyping of the selected technology option. Study the behaviour of the TM logical networks in terms of response times, mutual isolation between the logical networks and switchover between logical networks in case of faults.

11. **SKA.TEL.SADT.TM.FDESP/FDESS/FDESE - Design to Procurement:** Include technological characteristics (detailed sizing and features) and setup aspects. Refine the behavioural models, redo the costing and re-validate the choices made (to account for technological and market evolution).
12. **SKA.TEL.SADT.TM.IPERE** – Integration and performance tests, see section 8.8.5.

13. **SKA.TEL.SADT.TM.PPSP/PPSS/PPSE** – Prepare procurement specification documents
   - Finalise documentation, produce Bill-of-Materials in a form suitable for issue of tender documentation.

14. **SKA.TEL.SADT.TM.CPREPP/CPREPS/CPREPE** – Develop cost models and CDR
   - **Documentation:** Develop cost models for the TM networks, including the safety backup network and LAN costs. Create the complete set of documentation needed to meet all pre-construction requirements. Work with other SaDT work elements to create an integrated documentation set. Ensure that the behavioural and parametric models developed are packaged for further use during the system lifecycle.

#### 8.8.5 Models and Prototypes
Prototyping work is described in task 10 above.

#### 8.8.6 Verification
- Behavioural models and simulation prototypes are analyzed against Stage 1 Task 1 requirements using traffic patterns, including throughput, latency and isolation requirements.
- Fault trees and scenario analysis to ensure that the management approaches are sufficient to meet reliability, availability, security and safety goals.

#### 8.8.7 Deliverables
**Stage 1**
- Co-consortia authored ICDs including network access interfaces and protocols
- SRR pack – SADT.TM level requested requirements, status update, project risks report
- PDR pack – topology and traffic models for each network, parametric models of network behaviour, cost models, report on approaches for management of networks to achieve goals such as reliability, availability, security and safety, including events detection and response mechanisms and associated supporting infrastructure.

**Stage 2**
- CDR pack – Construction documentation, including procurement plans and deployment support documentation.

#### 8.9 Network Architecture (NWA) – SKA.TEL.SADT.NWA
**Workpackage:** SKA.TEL.SADT.NWA
Workpackage lead institution: ASTRON  
Organisations involved: University of Manchester  
Planned start date: T0  
Planned end date: T0+156

8.9.1 Description

The signal and data transport network architecture will define and design a physical layer fibre network capable of carrying all the network services required by the telescope. This will include the network services as required by the synchronization and timing, telescope manager, digital data backhaul, central signal processing and science data processing transmission systems.

For creating the design of the SKA data transport network, the system models and designs of the mentioned transmission systems that are generated by their SaDT Level 4 elements will be merged in a combined SaDT model. Using this model a SaDT design assessment will be conducted and a SaDT design will be generated that complies with the requirements at a minimum cost level. In determining the cost level of the various options, both OPEX and CAPEX will be taken into account. Important items for the OPEX level calculations are power consumption, repair costs and the ease of maintenance, while the CAPEX level calculations mostly concerns determining the cost of the network components and their deployment and the integratability of SaDT system with all other SKA systems.

In generating the most optimal SaDT design the focus is on an optimisation of the combined synchronization and timing (SaT), telescope manager (TM) and digital data backhaul (DDBH) system architectures. Since the central signal processing (CSP) and science data processing (SDP) transmission systems have no overlap with these three systems, the CSP and SDP transmission systems will not be taken into account in the assessment and optimisation task. The architectures of these two systems will be determined in the corresponding SaDT Level 4 elements.

After completion of the assessment and optimisation task, the transmission system architectures of the SaT, TM, DDBH, CSP and SCP systems will be combined into a single SKA network architecture. Since the SKA system will be build at two locations, also two separate SKA network architectures will be generated, each taking into account the requirements of the local systems and additional local characteristics.

The work in the NWA task uses a time frame with two stages. The first runs from the project start to the SRR/PDR, the second from the SRR/PDR to the CDR. In the first stage various network architectures will be investigated using the DDBH, SaT and TM network models after which several preferred architectures will be selected, according to the method that is described above. In the second stage the selected DDBH, SaT and TM architectures will be further developed in the corresponding SaDT Level 4 elements. In parallel to this work a NWA task will run that concerns a further refining of the selected network architectures. In addition support will be provided for the
SKA 2 work. At the end of stage 2, one or more final architectures will be defined and described in
the SKA Network Architecture Document. This latter document, which holds network architecture
description, design schematics and design drawings, can be used as an input document for the
technical part of the SKA-SaDT-Phase1 procurement documentation.

8.9.2 Inputs
The inputs for the NWA work package come from the SAT, DDBH, TM, LINFRA task team documents
and from Baseline Design, Con-ops, CoDR, AIP documentation.

8.9.3 Outputs
The output of the NWA workpackage consists of (1) requirements for the models to be provided to
the NWA workpackage and (2) requirements for and designs of the interfaces between the SKA-
SADT network and the other SKA domains and between the subsystems in the SADT system. (3) The
SADT architecture description, containing detailed a design document, a SADT model, SADT
prototype descriptions and SADT procurement plans.

8.9.4 Tasks
Stage 1

1. SKA.TEL.SADT.NWA.REQ - Requirements capture
Before defining the architecture of the SKA network, the requirements for the SKA network
need to be clear. As such, the first step in NWA level 4 work package concerns the capturing of
the requirements. Most of them are related to the SaT, TM, DDBH, CSP and SDP systems and
are determined by the corresponding level 4 tasks. These requirements will be inventoried
and combined into a single NWA requirement set. In addition, the general NWA requirements
will be retrieved from the SKAO documentation and added to the NWA requirement set.

2. SKA.TEL.SADT.NWA.FUN - Functional analysis
With the use of the NWA requirement set the overall functional requirements of the NWA
system are determined. This information is combined with the functional analysis results from
the SaT, TM, DDBH, CSP and SDP work packages.

3. SKA.TEL.SADT.NWA.OFM - Specification of output format for concepts
Within the SaT, TM, DDBH, CSP and SDP work packages system models and designs will be
generated. Within the NWA work package these concepts will be combined and used for the
investigation and design of one or more SKA network architectures. To be capable of
combining the models and designs a common approach needs to be used in the various
system modelling and design tasks.
Within this NWA task a common format for the concepts that will be provided to NWA work
package will be defined. This format will be determined in collaboration with the other SaDT
work packages.

4. SKA.TEL.SADT.NWA.ICD – ICDs and internal interfacing
The SaDT domain has many interfaces both to other SKA domain and, internally, between the various level 4 elements (both logical and physical layer interfaces). The inter-domain interfaces will be discussed and defined in one or more ICD meetings that will be organised by the SKA office. The SaDT consortium will be present at those meetings and the results from the meetings will be communicated with the SaDT consortium. The internal interfaces will be discussed and defined by the SaT, TM, DDBH, CSP and SDP work packages. In this NWA task the results of these activities will be inventoried and assessed for missing or incomplete items. After finishing this task, the interfacing information will be used in the NWA – Network optimisation task.

5. **SKA.TEL.SADT.NWA.NOPT - Network optimisation**
   Once the stage 1 system models and designs are generated in the SaT, TM and DDBH work packages, they are combined in this NWA task into a single system model tool. With the use of this tool and the information from SKA.TEL.SADT.NWA.REQ, SKA.TEL.SADT.NWA.FUN, SKA.TEL.SADT.NWA.OFM, SKA.TEL.SADT.NWA.ICD and info from the LINFRA work package and SKAO about existing infrastructure and environmental and terrain conditions at both SKA locations, a network architecture is investigated and defined that supports the SaT, TM and DDBH systems at a minimum cost level, both from OPEX and CAPEX point of view. The results of this work will be used for down selection and adjustment of the various SaT, TM and DDBH concepts.

6. **SKA.TEL.SADT.NWA.PDES - Preliminary Design of Physical Layer Fibre Network for all Network Services**
   Based on the results of the work in the SKA.TEL.SADT.NWA.NOPT task and the network design info from the CSP and SDP work packages, a report will be generated in which the results from the SKA.TEL.SADT.NWA.NOPT task are described. This report is to be used as deliverable for the SRR/PDR.

7. **SKA.TEL.SADT.NWA.SKA2 - Support SKA 2 activities**
   Support and information about network architecture options will be provided to the groups that work on the SKA-2 systems.

8. **SKA.TEL.SADT.NWA.PPREP –SRR/PDR Activity**
   Generate PDR documentation and prepare for the review; address queries arising from the review; implement corrections to the documentation; close all other outstanding review issues.

**Stage 2**

9. **SKA.TEL.SADT.NWA.PRO – Completion of prototyping**
   In the work SaT, TM, DDBH, CSP and SDP work packages prototypes will be constructed and tested. In the NWA work package, information about the functioning of the prototypes will be reviewed. If needed, the SaT, TM, DDBH, CSP and SDP prototypes will be used in one or more SaDT integration and performance tests.
10. **SKA.TEL.SADT.NWA.FDES** - Design to manufacture of a physical layer fibre network for all network services

After the SRR/PDR, a limited amount of network concepts remain. In parallel SaDT work packages these concepts are further developed, experimental investigation will take place and final descriptions of the most optimal concepts will be generated. In this phase of the project the NWA activity plays supporting role for this concept development work. In addition, the architectures of the remaining concepts will be further refined, using information from the SaT, TM, DDBH, CSP and SDP work packages.

11. **SKA.TEL.SADT.NWA.IPER** – Integration and performance tests

All the component and system tests in Stage 1 and Stage 2 will take place in the SaT, TM, DDBH, CSP and SDP work packages. In case of a strong interdependence between the SaT, TM, DDBH, CSP and SDP systems in the SaDT architecture, it might be necessary to do SaDT system integration tests. In Stage 2 the need for such SaDT system integration tests will be investigated, in collaboration with the SaT, TM, DDBH, CSP and SDP work packages.

12. **SKA.TEL.SADT.NWA.PPS** – Prepare Procurement Specification Documents

At the end of stage 2, before the CDR, one or more final architectures will be defined and described in the SKA Network Architecture Document. This information is to be used in the technical part of the SKA-SaDT-Phase1 procurement documentation. The selection of a single network architecture will take place in the procurement phase and will be based on the offers from possible suppliers. By having a few network architecture options available in the procurement phase, instead of just one, a larger amount of possible suppliers can submit an offer, which will result in low procurement costs.

13. **SKA.TEL.SADT.NWA.CPREP** – Engineering documents, including costs, for CDR

Based on the outcome of the results from the above mentioned items a number of documents will be generated as work package output. Details about this output are given in the Deliverables section below.

### 8.9.5 Models and Prototypes

The design, construction and experimental evaluation of prototypes takes place in the SaT, TM, DDBH, CSP and SDP work packages. The initial modelling will also take place in these workpackages. The approach in this modelling and the choice of the applied (NWA) modelling tools will be determined by mutual agreement in the consortium.

### 8.9.6 Verification

The verification of the SaDT components and subsystems takes place in the SaT, TM, DDBH, CSP and SDP work packages. If necessary, one or more integration tests will take place in the NWA work package. In these tests the functioning of the system under test is assessed with respect to its compliance with the SKA system requirements for the SaDT system, its integrability in the SKA system and its operational functionality.
8.9.7 Deliverables
The NWA deliverables to the SKAO will include, and will not be limited to:-

Stage 1
- SRR/PDR pack
  - SADT.NWA requirement set
  - Description of all relevant interfaces.
  - Network architecture optimisation study report, including a description of the most optimal SaDT network concept architectures and their cost

Stage 2
- CDR pack
  - Detailed description of the SKA-SaDT system architecture, including: technical report, costing, engineering drawings and engineering model.

8.10 Network Management – SKA.TEL.SADT.NMGR

Work Element: SKA.TEL.SADT.NMGR
Work Element lead institution: NCRA, India
Academic Organisations involved: TRDDC, India
Potential Industry involved: Tata Consultancy Services, Large telecommunications industries
Planned start date: T0
Planned end date: T0+156

8.10.1 Description
This work element deals with the management of the SaDT long-haul links and the associated networking equipment. The role of network management includes the configuration and setup of all the equipment (including hardware and software elements), monitoring health and performance parameters, optimizing the behaviour of the network and detecting and responding to adverse situations. Network monitoring and control interfaces are provided to operators and engineers, as well as to the Telescope Manager element. Engineers are provided with additional interfaces to facilitate troubleshooting, reconfiguration and upgrades.

It is expected that much of the functionality would be realized using standard network management tools, configured to meet the specific SaDT system objectives. The scope of activity during this phase includes establishing these system behavioural requirements, identifying the parameters to be monitored, designing the control strategy to achieve the requirements, exploring the available tools
and identifying any gaps in capability, designing the interfaces for operators, engineers and the Telescope Manager interfaces, and costing the work element.

8.10.2 Inputs
The requirements for the Network Manager are derived primarily from its peer level 4 work elements including NWA, DDBH, TM and SAT, complemented by system topology and sizing information derived from the baseline design. The Concept of Operations, SADT CoDR documentation provide additional sources of requirements and design inputs and constraints. This work element will also have strong relationships for design and analysis with the other peer level 4 work elements named above.

8.10.3 Outputs
The primary output from the work element will be a design to manufacture that lays out a design for network management, including the tools to be used, configuration and setup responsibilities, information to be gathered from network elements, adverse situations and optimization opportunities to be detected and handled, and monitoring and control capabilities to be provided to operators and engineers. Detailed behavioural models and simulations that verify meeting the network behavioural requirements will be produced. It will be completed by reports from trade studies, modelling, prototyping and costing activities. Required documentation sets will be produced for the SRR/PDR and CDR.

8.10.4 Tasks
Stage 1

1. SKA.TEL.SADT.NMGR.REQ - Identify network management requirements:
   Work with the overall SaDT requirements activity to determine SaDT network behavioural requirements, and derive specific network management requirements from that. Augment these requirements based on system level information. Requirements of interest include the set of behavioural parameters to be monitored, such as workloads, throughput, latencies, jitter, transient failure rates, link and device failures, security problems etc. Requirements should also identify the target values for parameters, including performance, availability and reliability, and desired overall situation/event detection and response behaviours.

2. SKA.TEL.SADT.NMGR.FUN – Functional Analysis:
   Perform functional analysis of identified requirements, identifying system management responsibilities such as startup, configuration and shutdown, detailing the particular parameters and situations to be managed for different types of network elements, identifying the set of fault modes and desired responses, and working out the data acquisition and control capabilities needed to achieve these goals.

3. SKA.TEL.SADT.NMGR.DOPT - Design Options Analysis:
Survey the network management capabilities available in the market, working with NWA to understand these capabilities in the context of the architectural solutions being considered. Determine the instrumentation available in typical network elements and analyze its adequacy for monitoring and managing the target behaviours. Identify applicable state-of-the-art capabilities and architectures e.g. perfSONAR for integrated performance monitoring and diagnostics of heterogenous WANs.

4. **SKA.TEL.SADT.NMGR.CGEN – Concepts generation**
   Develop a preliminary approach to achieving the network management objectives in terms of overall schemes for data acquisition, data processing and event detection, situation response, and generation of monitoring views. Develop and analyze a preliminary set of scenarios to understand the tradeoffs between options.

5. **SKA.TEL.SADT.NMGR.ODS – Optimisation and downselection**
   Coordinate with the downselection in NWA to determine the network management solution of choice, compatible with the technologies selected for the network implementation.

6. **SKA.TEL.SADT.NMGR.ICD - Specify interface requirements**
   Specify requirements for the operator and engineer interfaces, in terms of information delivery, control, troubleshooting and system management capabilities to be provided. Define the interface to the WBS Level 3 Telescope Manager.

7. **SKA.TEL.SADT.NMGR.PDES - Preliminary Designs and Analysis**:
   Design the methods for computing each parameter of interest from acquired data, and for detecting each situation of interest. Develop response procedures for each situation, including both fault response procedures and performance optimization algorithms, working with NWA and vendors as needed. Build behavioural models of the system incorporating probabilistic behaviours, the occurrence of adverse situations (fault injection) and the various responses to these situations. Study the resulting behaviour using simulation tools and analyze whether it meets the system objectives. Optionally, interact with precursors to pilot some of the management approaches.

8. **SKA.TEL.SADT.NMGR.SKA2 – Support SKA2 Activities**:
   Analyze whether the scale of SKA2 will require a hierarchical approach to network management. If needed, develop a preliminary architecture for hierarchical network management and analyze the ease of evolution to the hierarchical model.

9. **SKA.TEL.SADT.NMGR.PPREP – SRR/PDR Activity**
   Generate PDR documentation and prepare for the review; address queries arising from the review; implement corrections to the documentation; close all other outstanding review issues.

**Stage 2**

10. **SKA.TEL.SADT.NMGR.PRO – Prototyping Support**
Support the prototype being built as part of NWA to add network management aspects. This will be needed to determine the behaviour of the system in the presence of faults.

11. **SKA.TEL.SADT.NMGR.FDES - Plan for Design to Procurement:**
   For each type of network element, identify the specific instrumentation available, local parameter computation and control capabilities, and system management procedures. Design the overall network management capabilities for each site, including its data acquisition, processing, response procedures and monitoring & control interfaces. Design system troubleshooting capabilities leveraging the available diagnostic and control interfaces available for each network element.

12. **SKA.TEL.SADT.NMGR.IPER – Integration and performance tests**, see section 8.10.5.

13. **SKA.TEL.SADT.NMGR.PPS – Prepare procurement specification documents**
   Finalise documentation, produce Bill-of-Materials in a form suitable for issue of tender documentation.

14. **SKA.TEL.SADT.NMGR.CPREP – Develop cost models and CDR documentation:**
   Develop cost models, including the effort needed to configure the network management capabilities and implement the designed procedures. Create the complete documentation set needed for CDR, including the design-to-manufacture documentation, and reports from the modelling, analysis and prototype studies.

8.10.5 **Models and Prototyping**
   Prototyping is described in task 10 above.

8.10.6 **Verification**
   - Behavioural models and simulation prototypes are analyzed against Stage 1 Task 1 requirements using probabilistic behaviours and injected faults.

8.10.7 **Deliverables**
   Stage 1
   - SRR pack - Network Management requirements; operator and engineer interface requirements.
   - Telescope Manager interface specifications.
   - PDR pack - preliminary design for achieving network management requirements.

   Stage 2
   - CDR pack - procedures to compute parameters, detect and respond to situations, and optimize system behaviour; network management tool selection; and cost models.

8.11 **Signal and Data Transport Local Infrastructure – SKA.TEL.SADT.LINFRA**
Work Element : SKA.TEL.SADT.LINFRA
Work Element lead institution: SKASA, South Africa
Organisations involved: CSIRO
Planned start date: T0
Planned end date: T0+156

8.11.1 Description
This work element will consider individual site conditions and develop designs to provide a secure, stable and highly reliable fibre optic network to meet the specific requirements of the individual services operating across the fibre optic network. Fibre type, implementation methods, jointing and splicing techniques, accommodation and fibre termination requirements, and shielded room access methods will be considered to ensure the stability of services carried across the network, especially with regard to the telescope Synchronisation and timing sources.

Development of these designs will be carried out in conjunction the Site Infrastructure Design Workgroup (SKA.TEL.INFRA) to minimise duplication of effort and to develop the most economical and co-ordinated approach for the implementation of the SKA sites road, power and fibre optic reticulation networks.

8.11.2 Inputs
- Baseline Design
- SKA-2 Plan
- Con Ops
- AIP Requirements
- Network Architecture

8.11.3 Outputs
- Fibre reticulation diagram with distances / calculated losses agreed with Network Architecture
- Modelling of fibre network stability to SaT group, DDBH and other affected parties
- Input to SaDT ICDs
- Identification of required test equipments and skill set requirements
- Prototype Report - investigations detailing the options considered, the options selected with clear reasons regarding economics, network stability implications, practical implementations and/or safety requirements.

8.11.4 Tasks
Stage 1
1. **SKA.TEL.SADT.LINFRA.REQ - Requirements Analysis**: Obtain requirements from the SaDT Network Architecture work package, which in turn obtains these requirements from each of the other work packages.

2. **SKA.TEL.SADT.LINFRA.FUN - Functional Analysis**: Generate a topological overlay of all SaDT service layers inclusive of bandwidth and fibre core requirements ensuring connectivity to all required locations and user terminals.

3. **SKA.TEL.SADT.LINFRA.NCON - Define Network Configuration**: Develop network design in collaboration with Site Infrastructure Design Workgroup, establishing connectivity to array positions confirmed by the Project Science workgroup. This includes technology roadmap and Trade studies.

4. **SKA.TEL.SADT.LINFRA.MOD - Network Modelling Studies**: Ensure optimum route implementation wherever possible, with special attention to fibre and connector loss, fibre stability and RFI characterisation of the deployed network to meet service level requirements.

5. **SKA.TEL.SADT.LINFRA.CGEN - Design Concepts Generation**: Work with NWA and the Site Infrastructure Design Workgroup to develop designs for the implementation of the fibre optic reticulation network. Assess fibre selection, implementation and termination methods, and accommodation requirements, with emphasis on economics, rackspace, power and cooling requirements, and alignment with site infrastructure development and implementation methodologies.

6. **SKA.TEL.SADT.LINFRA.DSL - Downselection Process**: Evaluate the various designs developed, analysing each proposal with respect to cost, stability, ability to sustain service level specifications, lifetime cost models, inclusive of future operational and maintenance requirements.


8. **SKA.TEL.SADT.LINFRA.PRO - Prototyping**: Perform all necessary prototyping and analyse results e.g. Manhole designs, fibre joint enclosures, fibre termination frames, methods of access to the shielded equipment rooms via specified waveguide structure and/or alternative entry method.

9. **SKA.TEL.SADT.LINFRA.PDES - Preliminary Designs**: Document fibre cable lengths / core capacity requirements, fibre type, associated splicing, jointing, termination and accommodation requirements and other system design aspects, inclusive of all required engineering drawings. Define prototyping requirements. Analyse the network’s capability to meet and sustain service level specifications. State the alignment and/or impact of the fibre network implementation on the total site infrastructure construction programme, identify associated risks. Develop approaches to manage the network as regards ongoing maintenance and operational requirements to meet stated performance specifications. Prepare preliminary cost estimates.
10. **SKA.TEL.SADT.LINFRA.SKA2 – Support SKA2 activities**: Extension to SKA2 will be considered.

11. **SKA.TEL.SADT.LINFRA.PREP – SRR/PDR activity**: Generate PDR documentation and prepare for review.

**Stage 2**

12. **SKA.TEL.SADT.LINFRA.CPRO - Completion of Prototyping**: Develop prototyping requirements from preliminary designs, should commercially-available equipments not deemed satisfactory and/or too costly. Anticipate requirements such as cable manholes, fibre splicing arrangements within the manholes, fibre terminations (ODF) at the Data Correlator and methods of extending these fibres into the shielded equipment room via specified ‘wave-guide’ devices. Confirm fibre stability implications of these various network infrastructures.

13. **SKA.TEL.SADT.LINFRA.IPER - Planning, execution & reporting of integration and performance tests**: Liaise with all network Consortiums confirming agreed interface specifications and locations. Confirm that performance tests and/or specifications meet network stakeholder requirements.

14. **SKA.TEL.SADT.LINFRA.FDES - Design to Procurement**: Include technical specifications (detailed network design, fibre type, implementation methods, loss and stability characteristics) and interface requirements to user networks at all locations. Refine the cost models and re-validate the choices made (to account for technological and market evolution). Work with other SaDT work elements to create an integrated documentation set.

15. **SKA.TEL.SADT.LINFRA.PPS – Prepare procurement specification documents**: Create the complete set of documentation inclusive of Bills of Material, fibre and termination specifications, implementation methods etc. required to satisfy all pre-construction and tender enquiry requirements.

16. **SKA.TEL.SADT.LINFRA.CPREP – CDR activity**: Compile a CDR data pack for review and sign-off by all network stakeholders.

### 8.11.5 Deliverables

**Stage 1**

- Network ICDs
- SRR pack – SADT.LINFRA level requested requirements, project status update, risks report.
- PDR pack – engineering designs and cost models, preliminary design choices for each network with rationale, project status update and risks report.

**Stage 2**
- CDR pack – Detailed design specification - engineering specification and construction documentation in alignment with site infrastructure build programme, including procurement plans and deployment support documentation; maintenance report - approaches to manage the fibre network to meet network service level specifications with respect to reliability, availability, stability and safety.

### 8.11.6 Verification
- Behavioural models and simulation prototypes are analyzed against service level specifications relative to capacity, availability, stability and safety.
- Fault trees and scenario analysis to ensure that the management approaches are sufficient to meet reliability, availability, security and safety goals.