THE SKA SCIENCE AND TECHNICAL OPERATIONS PLAN

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<tr>
<td>ALMA</td>
<td>Atacama Large Millimetre Array</td>
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<td>ASKAP</td>
<td>Australian Square Kilometre Array Pathfinder</td>
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<tr>
<td>ASTRON</td>
<td>Netherlands Foundation for Research in Astronomy</td>
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<td>CSIRO</td>
<td>(Australian) Commonwealth Scientific and Research Organisation</td>
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<td>DSN</td>
<td>Deep Space Network</td>
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<td>EF</td>
<td>ExaFLOP</td>
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<td>EPO</td>
<td>Education and Public Outreach</td>
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<td>ESA</td>
<td>European Space Agency</td>
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<td>ESO</td>
<td>European Southern Observatory</td>
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<td>EVLA</td>
<td>Expanded VLA</td>
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<td>FTE</td>
<td>Full Time Equivalent</td>
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<td>GB</td>
<td>Gigabyte</td>
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<td>HR</td>
<td>Human Resources</td>
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<td>HVAC</td>
<td>High Voltage Alternating Current</td>
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<td>ICRAR</td>
<td>International Centre for Radio Astronomy Research</td>
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<td>IF</td>
<td>Intermediate Frequency</td>
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<td>IVOA</td>
<td>International Virtual Observatory Alliance</td>
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<td>LSST</td>
<td>Large Synoptic Survey Telescope</td>
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<td>LO</td>
<td>Local Oscillator</td>
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<td>LOFAR</td>
<td>Low Frequency Array</td>
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<tr>
<td>MeerKAT</td>
<td>The precursor array being build on site in the Karoo</td>
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<td>MERLIN</td>
<td>Multi-Element Radio Linked Interferometer Network</td>
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<td>MW</td>
<td>Mega Watt</td>
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<td>MWA</td>
<td>Murchison Widefield Array</td>
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<td>NL</td>
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<td>NVO</td>
<td>National Virtual Observatory</td>
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<td>Pb</td>
<td>Petabits</td>
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<td>PrepSKA</td>
<td>Preparatory phase for the SKA</td>
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<td>RF</td>
<td>Radio Frequency</td>
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<td>RFI</td>
<td>Radio Frequency Interference</td>
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<td>RSC</td>
<td>Regional Science Centres</td>
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<td>SKA</td>
<td>Square Kilometre Array</td>
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<td>STScI</td>
<td>Space Telescope Science Institute</td>
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<td>STSF</td>
<td>SKA Technical Support Facility</td>
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TAC ............................ Time Allocation Committee
TB ......................... Terabyte
Tb .......................... Terabits
TDP ........................... Technology Development Programme
TF ............................ TeraFLOP
UK ............................ United Kingdom
US ............................ United States
VLA .......................... Very Large Array
VLT ............................ Very Large Telescope
VO ............................. Virtual Observatory
WA ............................ Western Australia
1 Introduction

Consideration of both the science and technical operations at an early stage in the Square Kilometre Array (SKA) design is important for three reasons: First, there may be elements of the science or technical operations plans that impact the design of the SKA. Second, the SKA will have a long lifetime, and the full life cycle costs will be dominated by operating, not construction costs, and it may be prudent to adopt design options to minimize operating costs, even if it results in a somewhat higher construction cost. Finally, it may be necessary to restrict the range of science operations if the cost of obtaining this science is disproportionately excessive.

The SKA will be the largest, most complex, and most expensive ground based astronomy facility in existence with an effective operational life extending well beyond the middle of the 21st century. As such it is difficult now to predict the nature of astronomical studies with the SKA the mix of targeted and survey type observations, or the distribution of program lengths. As a global project, the SKA will present additional challenges, as each country or region will expect returns and control commensurate with its investment. While some system of juste retour in proportion to contribution, will be likely, it must be done in a way which avoids potentially inflated contracts from partners who expect their entitlement with corresponding increases in costs. The process of contract and use allocation should, if possible, also avoid compromising the “open skies” policy which has become the de-facto standard for radio astronomy throughout the world and will result in the best science from the SKA.

The operation of the SKA on a remote site with a harsh environment and far from normal centers of support will present special challenges to the efficient operation of the SKA as a productive scientific instrument. It is difficult to fully predict at this early stage the nature of SKA operations and the associated cost, so the SKA Operations Plan will of necessity be an evolving document, especially during the early years as experienced is gained with the partially completed SKA. From the start, the SKA has been a global program with multinational involvement in all aspects of the development, and we anticipate in the construction and operation as well. While, it is important that the interests of multinational partners be recognized at all stages of design, construction and operation, the success of the SKA as a productive scientific instrument will depend on a governance model with strong central management and control. We will use the term “SKA Observatory” to describe the facility (antennas, receiver and other instrumentation), infrastructure (buildings, roads, local power generation and distribution, and owned fiber networks, and staff (at all locations in the host country) to describe the SKA operations.

Due to the size and complexity of the SKA, it is clear that operating costs will be substantial. It will therefore be important to streamline operating procedures to minimize the number of required staff and to keep operating costs to a minimum. This implies careful and complete tracking of personnel activities and expenditures along with well understood lines of authority and responsibility. But, it is also important that accountability does not become an end in itself, thus increasing rather than limiting costs, and that originality and innovation, as well as ownership of ideas and programs not be discouraged.
Since the SKA will be so much more complex and powerful compared to existing facilities, it is difficult to foresee an operating plan simply which is based on extrapolation from current procedures. Nevertheless, we attempt to outline the broad operating policies and plans which we feel appropriate, recognizing that these could and should evolve with time. In Section II we present a science operations plan; in Section III an outline of the facility operations requirements; in Section IV we discuss an appropriate governance model for the SKA, and in Section V we estimate the anticipated cost of operating the SKA Observatory as an international facility for research.

We anticipate that the operation of the SKA will comprise the following major components:

- **The SKA Headquarters** comprising the key scientific, administrative, and technical staff needed to support the SKA Operations including scheduling the telescope, executing the observing program, telescope monitor and control, the initial data reduction, software maintenance, coordinate hardware, software and algorithm development, provide the data and information links to the global scientific community, and which will be located in Geraldton/Perth or Capetown. SKA operations will be divided into six Divisions: Director's Office, Administrative Services, Array Operations, Facility Support, Research and Scientific Support, Computing Support.

  The Research and Scientific Support Division will be led by the Deputy Director. The Director, Deputy Director, and heads of the administrative, operations, scientific, and technical staffs will be located at the SKA headquarters with deputies as appropriate located at the Technical Support Facility.

- **The antenna array** itself and associated instrumentation including the correlator, emergency or supplementary power station, which will be primarily located on a remote site in Western Australia or the Northern Cape Province in South Africa but with extension throughout Australia and New Zealand or southern Africa respectively. Support for the antenna array will be coordinated through the Observatory Array Operations Division.

- **The SKA Technical Support Facility (STSF)** housing the technical staff needed to operate the array, provide the first level technical maintenance for the local service area (that which can be accessed within a day) to keep the SKA in optimum operating condition including antenna, electronics, and cryogenics maintenance, maintaining the buildings and grounds, install new instrumentation, provide feedback on the health of the array, and ensure site security. The Technical Support Facility will be located near Carnarvon or Boolardy. Staff at the STSF will be part of the instrumentation and Computing Divisions as appropriate and will report through local Associate Division Heads.

- **Distributed Maintenance Centers** to provide routine maintenance for those antenna stations located beyond the local service area. Staff at the DMCs will be part of the Instrumentation and Computing Divisions as appropriate and will report through local Associate Division Heads.

- **Regional Support Centers** located in Europe, North America, Asia, Australia, and Africa to provide first level support to the local scientific community and to coordinate participation in the key-science programs.
We note that the SKA, being so much more complex than any existing telescope, that with experience, the nature of the operation may well evolve into something very different from what is described here or even what may be described closer to the time of construction. Thus any SKA operations plan should be considered as only a guide to optimizing the scientific returns from this expensive investment, and not an agreement on who is responsible for doing what.
2 Science Operations

2.1 Headquarters Operations

The focal point of the SKA operations will be the SKA Headquarters which will be located in the host country, probably within a few hundred kilometers from the array, and will house all of the senior administrative, scientific, and technical staff including the Director, Deputy Director, and all Division Heads. The headquarters will also include staff to provide documentation of all facilities and science opportunities, prepare the daily observing schedule in collaboration with the technical operations staff, library facilities, publication support, Education and Public Outreach staff, as well as data analysts to provide the first level appraisal of data quality to feed back to the operations staff, and to prepare data for delivery to the users through the regional support centers. The division of data analysis between the Headquarters and regional support centers will be determined at a later time.

2.2 Scientific Staff

The residential scientific staff will play a critical role in the SKA leadership and in establishing the “culture” of the Observatory. So it is very important that the highest caliber scientific staff be recruited and offered working attractive working conditions which will include adequate time to pursue their own independent research activities. In addition to their “functional roles,” on average, half of the time of the scientific staff will be devoted to independent research, although this will vary considerably among individuals and with time for each individual. The scientific staff will be of a quality that they will also be asked to participate in reviews and programs at other facilities and will thus bring new ideas to the SKA as well as sharing SKA concepts with others. Tenure level appointments will be available to qualified senior scientific staff following appropriate review. Proximity of SKA Headquarters to a major university will offer the possibility of joint or adjunct appointments which will be attractive to the most qualified people. The cutting edge technical facilities and opportunities for significant research at the SKA will attract the best students and postdoctoral level scientists from around the world, thus bringing new skills to the SKA operations as well as playing a major role in training the next generation of skilled scientists.

2.3 Allocation of SKA Usage

The SKA observational program will consist of a mixture of large or “key-science” programs and smaller PI driven programs. We anticipate that the large programs will be coordinated through one of the regional science centers, and that the program teams themselves will contribute to new algorithmic development, software, and possibly new instrumentation needed to implement their program but which will be later available to the global community and supported by the SKA Observatory staff. Execution of the large programs or major surveys will require close coordination between the investigator team and the observatory staff to develop any specialized hardware or software that may be needed for the effective execution of the program, and for making the data products available to the global community.

Initially while construction is still underway, early science programs will likely be largely PI driven as experienced is gained in understanding the SKA, and will gradually morph into an equilibrium state consisting of roughly equal amounts of time devoted to large and PI driven programs. However, it is
hard to predict the scientific priorities a decade or more from now, and there is no prescribed formula for the split between small and large programs or among different scientific areas such as continuum, spectroscopic, or pulsar observing. We note, however, that because the SKA will represent such a large increase in capability over any facility at these wavelengths, there will be opportunities for unexpected new discoveries which may come primarily from “all-sky” surveys of various kinds, and we anticipate that once the SKA becomes fully and routinely operation, that that a significant amount of observing time will be devoted to such surveys, so that adequate resources will be needed to support these programs. SKA staff scientists will have adequate time and support to pursue their own independent research programs, but they will compete for time through peer reviewed proposals on the same basis as unaffiliated scientists.

The allocation of observing time will be the responsibility of the SKA Observatory Director as advised by a Time Allocation Committee (TAC) composed of scientists covering a broad range of astronomical and technical expertise with appropriate international distribution. The SKA Observatory will be operated under an “open skies” policy scientific program typical of most current large radio telescope facilities. Recognizing that open access to all qualified scientists will give the best scientific returns, the international community expects that the allocation of SKA observing time and access to data will be based solely on scientific merit, without regard to institutional, national, or regional affiliation, or to financial or in-kind contributions to the construction or operation of the SKA. We recognize, however, that some countries may not recognize the broader financial and intellectual returns from participating in the SKA and may prefer guaranteed access to observing time and data products as condition for their financial participation. This issue will need to be resolved by discussion among the signatories to the SKA implementation agreement.

2.4 Execution of Observations

The SKA will be operated in a predetermined mode to minimize the impact of inclement weather, RFI, scheduled maintenance, or component failures. Observers will not come to the remote antenna site, but may monitor the progress of their observations from one of the regional centers or even from their office or home. However, only SKA operations staff will control the motion of antennas and adjust any of the instrumentation. Criteria will be established to optimize the observing frequency and type of observation, e.g., spectroscopy, continuum, timing, in response to current and anticipated weather conditions and facility status supported by automated instrumentation for monitoring instrumentation status, weather and tropospheric/ionospheric stability and opacity. Emphasis will be on the timely completion of programs to optimize the science returns, especially those required for student dissertations, rather than maximizing the number of programs. Observatory staff will obtain and make available all calibration data needed to properly execute observing programs, implement data quality assurance, produce and deliver science quality data to the science community and to the Virtual Observatory.

It is hard to predict the number of potential SKA users more than a decade hence. We only note that the VLA currently has more than 600 individual users each year, and that an initial call for proposals for ASKAP, which will not be available for scientific observations for several years, had more than 400 individual scientists respond with proposals. No telescope can be effective without a community of scientists to use it, and without adequate resources to support their research and training of the next generation of users. Funding mechanisms for investigators will vary by country,
but it is important that each country support and nourish their scientific users of the SKA including adequate support for post doctoral researchers and doctoral students.

Users of the SKA will range from scientists with little practical experience in synthesis imaging such as theoreticians and experts in other wavelength bands to experienced radio astronomers. Operation of the SKA must allow for the delivery of science quality products to the less experienced users while also allowing the more experienced users to interact with the observing program and data at all levels. The former is needed to maximize the user base permitting the widest range of intellectual input to the scientific program; while the latter user will push the SKA to its limiting performance as well as train the next generation of experts.

2.5 Commensal Observing

Because of the large range of spatial frequencies sampled by the SKA, many science programs will require only a limited range of baselines; thus two or more observational programs may be implemented simultaneously. Control and data reduction software will need to allow for up to five independent sub arrays to be operated simultaneously.

2.6 Data Products

Much experience in data acquisition, reduction, display, dissemination, and archiving has been gained through the operation of other arrays such as the VLA, Westerbork, and MERLIN. Experience with the EVLA, ALMA, eMERLIN and LOFAR which are just beginning operations as well as with the SKA precursors, ASKAP and MeerKAT on the two candidate sites will give additional guidance in planning for the SKA era. However, in terms of the number of antennas, data rates, sensitivity, and required dynamic range, the SKA will be orders of magnitude more demanding than any previous instrument. We anticipate that with time both pipelined images as well as calibrated visibility data will be delivered to users. But, it will take time to acquire the experience needed to deliver science quality pipelined data. For the most demanding observations, access to the raw (uncalibrated) data will be delivered along with engineering and environmental data. At least initially, data storage capability will limit the data product to only the pipelined images and visibility data averaged over some combination of frequency and time as appropriate for the observation will be archived.

Raw data products from the output of the correlator will consist of approximately $5 \times 10^6$ fringe visibilities at up to 105 spectral channels every 200 ms. Normally data will be averaged in one or more dimensions as appropriate for the investigation at hand and as limited by the available data storage and processing capabilities. Without such data reduction, the data volume could be as high as one exabyte per day.

While the SKA Observatory will have a significant high performance computing capacity needed to support the large data volume and complex analysis required to produce science products, the load will be shared by a series of three to five SKA Regional Support Centers as well as through computing facilities located at other institutions. The distribution of data products will likely involve considerable data rates, the cost of which may significantly to the annual operating cost, unless suitable non commercial rates can be negotiated.
2.7 Data Rights and Archiving

In addition to SKA science products, the SKA will archive all raw data calibration data, engineering and monitoring data, observing logs, quality assurance, and maintenance records. At the start of full operation, a temporary storage capacity of up to 850 Petabytes will required to handle one month of SKA data and should grow at a rate of about 25 Petabytes per year. Long term archival data is expected to generate about 18 Petabytes of data per year. Transient observations could double the data storage requirements. Experience at the VLA where up to 30 percent of published papers make use of archived data rather than requiring new observations, suggests that data obtained with the SKA will be used in ways unanticipated when the observations were planned. In order to maximize the value of these data products for later unanticipated analysis, it will be desirable to retain data with a minimum of reduction, rather than a level of averaging in time or frequency data that might be acceptable for the purposes of the original program. This may not be realistic, especially in the early years of SKA operation, where data storage and processing speeds may not be adequate to retain all possible data products. Managing these large data volumes will be challenging and expensive.

The all sky transient array will be operated essentially independently of the dish array, except that unpredicted transient events will likely trigger observations with the dish array, as well as other telescopes operating throughout the electromagnetic and perhaps even other parts of the spectrum. Procedures for coordinating these activities will need to be negotiated, but should be no different than the many such arrangements currently in place.

Maximum scientific impact suggests that all processed data might be made immediately public. However, in order to motivate scientific users as well as to protect thesis dissertation programs, in general, there will be a proprietary period, probably of the order of one year after all data has been acquired when the observing team will have exclusive rights to the data, but this may vary in individual cases, such as surveys or monitoring programs where the data is acquired over a long period of time. Calibration data will be made public as soon as it is processed and analyzed by the staff.

In order to provide maximum impact of the SKA data products, all archived data will be compliant with the International Virtual Observatory Alliance. The conceptual design work for the SKA data flow, processing, and archival systems is contained within work package 2.9 of the PrepSKA program at the SPDO. The parties involved are Cambridge University, Oxford University, ASTRON (NL), CSIRO, UK VO-team, the US TDP (Illinois) and the International Centre for Radio Astronomy Research (ICRAR). Industrial involvement and collaboration has already been sought with IBM, Microsoft, Oracle, Google, the Large Synoptic Survey Telescope (LSST) Project and the Sloan Digital Sky Survey. The aim of the Software and Computing task within WP2 is to deliver a costed systems design of the SKA data flow, processing and archival system with a delivery milestone in 2012. The Perth based International Centre for Radio Astronomy Research has proposed to take a leading role in the conceptual design of the archival system. The SKA archive facility will contain long-term storage, high availability storage (associated with high performance database and query engines) and associated archival processing systems for on-demand processing, archival science team investigation and valued-added product generation. The user-interface will utilize VO technologies for inquiries and services, developed as part of the existing IVOA effort and deployed in other archive programs (NVO,
ESO and ESA archives, ALMA and LSST). The diagram below outlines a data flow concept for the SKA. The size of final data product storage elements, the size (and feasibility) of a visibility data temporary storage capability and the scope of user services will depend on the details of the observational program and the scale of investment in quality control of data. The numbers given reflect indicative operational modes from ASKAP, MWA and other contemporary facilities.

Until operational planning is further advanced, industrial involvement assessed and collaborative opportunities explored, it is not possible to accurately define the manpower necessary for systems design, software development and facility operations. For comparison, the ESO data flow system (dealing with a data flow of ~100 TB/year) required ~250 person-years for development and ~20 FTE in operations for quality control and user-support level of VLT operations.

![Figure 1: Schematic outline of data flow, data rates, and data storage requirement derived from and compared with ASKAP and the MWA.](image)

### 2.8 Transition, Commissioning, and Early Science

Due to its nature as a multi-element array, commissioning and early science observations will begin with a limited, but continually growing number of antenna elements well before the array is completed, or even before Phase 1 construction is finished. Pre-operations funding will be needed to hire and train staff, to establish procedures for time allocation, to develop operating procedures, and to prepare the scientific community to use the SKA. Pre-operations funding will ramp up to full operations funding well before by the end of the construction period. We anticipate that there will a continuous period of construction with a corresponding continual increase in operational capability.
and a seamless transition between Phase 1 and Phase 2. However, due to funding uncertainties, there may be an uncomfortable gap in construction, at the end of Phase 1 construction which will seriously compromise the ability to retain staff and so would incur additional costs and inefficiencies.

It will be important to begin astronomical observations as soon as there are a sufficient number of antennas that can be operated as part of an array. Such early-science programs may not result in significant science output, but they will provide important feedback on the performance of the array and prepare a core of experts to provide advice and support to future operations. Staff and long term visitors alike should participate in commissioning and early science activities, and they should be allowed sufficient time to pursue their own independent research programs, not only to provide motivation to get the most skilled and experienced people involved, but experience has shown that the more subtle bugs in new facilities are found not only when testing and calibrating, but when trying to extract scientific data.

In practice there will be a grey area between commissioning and early science observations.

Considering the advanced capabilities of the SKA, some important scientific discoveries may come out of the commissioning period, and commissioning exercises will continue into the early science era and beyond. The possibility of obtaining scientific results during commissioning should be encouraged as this will increase staff moral and motivate staff and visiting scientists to contribute to the commissioning program, as well as provide the public visibility appropriate to the large financial commitment made to the SKA. However, it is important to understand that the process of systems assembly, integration, and verification is part of the construction process, and should not be left to the operations phase.

A detailed commissioning program will be established by the Observatory staff and will include antenna position, pointing and gain calibration, interferometer delay settings, bandpass calibration and stability, phase and amplitude closure and their stability, polarization purity and stability, mosaicing, interference excision, and verification of pipeline imaging. The commissioning activities will include a mixture of line and continuum full field synthesis imaging made at various stages of construction to push the SKA to its limits, repeated observations of selected fields and sources, repeated observations of selected strong sources, and an appropriate high time resolution program, all made over the full range of SKA frequencies, baselines, and correlator modes. These tests will begin when there are as few as four antennas to determine closure. As the SKA nears completion, an all sky HI/continuum survey, probably lasting several months, should be made to exploit SKA capabilities and to provide unprecedented data products for further study. The antenna based tests and calibrations, will need to be repeated periodically, especially following major maintenance or upgrades. Due to the large number of elements involved, monitoring for deviant performance and measuring system parameters will need to be highly automated. If in the relatively simple arrays currently operating, it is not unknown to discover that a major pointing error or gain reduction has existed for an unknown period of time.

We recognize that the continued construction activities which will last for many years may compromise the testing and commissioning of the SKA which will begin during the Phase 1 construction process. This is an issue with all modern arrays, such as ALMA and the EVLA and will be with MeerKAT and ASKAP as well, but there are obvious steps which can be taken to mitigate the
impact of construction on operations such as limiting the most demanding observations and tests to weekends and nights when construction activities are minimal.

2.9 Regional Science Centers

As described elsewhere, it is anticipated that to ensure the most effective operation of the SKA Observatory there will be a strong concentration of resources at or near the array itself. While this may optimize the SKA operation, there is a clear danger associated with concentrating too much of the world’s radio astronomy resources at one facility at the expense of the more modest specialized facilities round the world which are crucial for pre and follow-up observations to SKA discoveries, where new instruments and techniques are being developed, and where the next generation of astronomers and instrument builders is being trained. We expect therefore that national and regional governments will establish a series of SKA Regional Scientific Support Centers in order to provide support for “local” scientists, through access to observing with the SKA and to the SKA archive, the development of new algorithms and software, provision of financial support for scientist research and travel, as well as the design and development of new instrumentation. These RSCs may organize scientific symposia and may also house a critical mass of experienced expert scientists in support of one of the key-projects or other large scientific programs. When setting up these Centers it will be necessary to consider the impact of the SKA on the then current national and institutional facilities which will remain.

Integration of the RSCs into the SKA operation will not be straightforward. They are likely to be locally or regionally funded, so their budgets and thus their operation will not be under the control of the SKA Director, and there is the danger that the Regional Centers might take on a life of their own.

A summary of baseline science operations requirements is listed below:

- The SKA will need operations funding for three to five decades.
- The SKA observatory will need to accommodate a wide range of users from theoreticians and observers skilled in other wavelength bands to expert radio astronomers who will challenge the capabilities of the SKA.
- Approximately 70% of the time will be spent on scientific observing with a split between PI driven and large key project times to be decided later and which will likely evolve with time
- Complete SKA downtime due to instrumental failure and/or inclement weather and RFI should be less than 5%
- From time to time, planned maintenance and upgrades will require the removal some array elements for installation and testing. This work will be scheduled in such a way as to minimize the impact to science operations. For example, work at the remote sites can take place during pulsar observations which do not require high resolution imaging.
- Dynamic scheduling will be used to minimize the impact of weather and instrumental failure
• Science quality data (e.g., images) will be provided by the Observatory for all but the most demanding PI driven programs.

• Large program science teams (e.g., surveys lasting hundreds of hours and more) will be expected to contribute to the analysis of their data through algorithmic development as well as hands-on interaction with the data and with the observatory staff.

• Data products will be VO compliant and archived and made available to the public in a timely way to an extent consistent with existing technical and financial realities. Proprietary data rights will need to be developed.

• Interaction between the SKA and the global scientific community will be primarily through a series of Regional SKA Support Centers each of which may have staff expert in different scientific areas and which will support many of the activities in these areas..

• The SKA headquarters will maintain a high performance computing capacity to support a significant amount of data reduction, but full exploitation of the SKA will require additional capacity not only at the Regional support Centers, but at other institutions as well.

2.10 Education and Public Outreach

EPO operations will promote media contacts, provide support for the preparation of press releases, organize tours and exhibits, prepare semi-popular articles about the SKA, and provide interfaces to industry wishing to use the SKA advertising or other commercial purposes. The EPO staff will prepare printed publications, web based resources, organize public events, prepare “local” school programs, and manage a visitor’s program. In addition to public outreach, the EPO Division will track all publications resulting from the SKA and assist in communication with the international science community.
3 Facility Operations

The remote location of the SKA core in WA or South Africa necessitated by the need to minimize RFI does not provide an optimum working or living environment for personnel. This creates a special challenge. A skilled engineering and scientific staff will be needed to support the complex SKA Operations, but experience at other remote astronomical facilities suggests that it will be hard to recruit and retain staff unless we can provide attractive living conditions including access to good shopping, medical facilities, schools, recreation, and transportation. Thus only the necessary minimum number of people required for daily operations, support, and maintenance at the site will live close to the site at Boolardy or Carnarvon and work at the site on a daily basis. Scientific, engineering, and most technical staff will reside in Capt Town or Geraldton/Perth and work at the site on a rotating basis following some variant of the “Turno” procedure in use at ESO and ALMA whereby staff, other than management staff either work alternate periods of the order of a week and then are off for about a week, or in the case of professional staff alternate periods at the site, at the Headquarters, and days off work. The SKA Headquarters, will be in Cape Town or Geraldton/Perth where the high level technical and administrative support staff will located and where instrumentation will be maintained and repaired. This may be contrasted with ALMA, where higher level technical support is provided offsite in Europe, North America, and Japan. While at the site, employees will be provided meals and lodging and transportation to the site at no cost to them.

Because of the size and complexity of the SKA, automated monitoring and analysis of key SKA operating parameters will need to be routine. Due to the remote nature of the site, to the extent feasible, corrective maintenance will largely consist of module replacement by STSF staff followed by module repair which will take place primarily at the headquarters site. Preventative maintenance will take place as appropriate for each SKA component.

Technical support for SKA operations will be divided between two sites as described below.

3.1 SKA Headquarters

The following groups will be located at the SKA headquarters:

- Senior Management including the Director, Deputy Director, Assistant Directors, and departments heads

- The engineering team which will provide high level activities needed to maintain and support, antenna, cryogenic, RF/LO/IF, and digital systems, RFI control, and together with the scientific staff plan for and develop upgrades and major enhancements to all SKA systems.

- Technician and other crafts personnel for drafting, machining, HVAC and unit assembly

- System administration and software maintenance staff

- The SKA administrative staff including purchasing, HR, fiscal, managerial, purchasing, shipping, transportation, and legal personnel will be largely concentrated at the Headquarters site.
3.2 SKA Technical Support Facility

The heart of SKA the technical support will be at the STSF which will maintain all instrumentation and software to ensure the greatest scientific output from the SKA. The STSF will enable both preventive maintenance procedures as well provide for timely corrective maintenance to minimize the impact to the scientific returns from the SKA. The STSF staff will include:

- An operations staff responsible for the day-to-day operation of the array comprising one or two array operators to control and monitor antenna/station and correlator performance, one RF/IF/LO technician, one digital hardware hardware technician, and one software support person on duty at all times, although in general, in the absence of unscheduled maintenance they will perform scheduled routine duties.

- Engineers and technicians to provide support to antenna, fiber optic, cryogenic, digital, RF, LO, and IF systems, to support computing hardware, and to support routine audio and video capabilities.

- Site security, building and grounds support, vehicle maintenance, health and safety staff.

While with time, it may be possible to migrate most of the functional duties to the Headquarters location, it least during the early science operation years, and likely well beyond, it is clear that there will need to be substantial personnel presence at the SKA site.

3.3 Power Consumption

Due to the large amount of digital processing involved primarily in the array correlator, and large computer needed for initial data reduction as well as operating the array, full (24/7) operation of the SKA could imply average power consumption as large as 50 to 100 Megawatts or more. At commercial rates this would cost €50M to €100M per annum or more and would dominate the operating budget. We are keeping abreast of the continuing industrial programs, such as at IBM, to reduce the power consumption of digital electronics, and are encouraged by the anticipated progress. We are also investigating the possibility of local renewable power generation such as solar, wind, and geothermal sources, through meetings with industrial experts. However, it is likely that the extent of digital electronics and amount of image processing requiring a large supercomputer capability will need to be limited at a level that might preclude the full utilization of all data products.

3.4 Preventive and Corrective Maintenance

Regular maintenance will be needed at all antenna elements, including RF/LO/IF, digital, and cryogenic systems, as well as for the central correlator and all computer systems. Routine maintenance will be split between major maintenance and overhaul which will occur only infrequently, and minor activities which will occur more frequently. Major maintenance activities will require that systems be routinely taken out of operation, say about every three years. In order to minimize the cost of operating the SKA, to the extent possible, systems such as antenna bearings and cryogenics will need to be designed for minimum service requirements and high reliability, even if this incurs increased construction costs. Sufficient spare parts will be procured at the same time as
those needed for construction, and in some cases to protect against obsolescence for consumer item components, sufficient spares for the life of the instrument will be needed.

Antenna based instrumentation such as front end and cryogenic systems will be designed for easy removal and replacement by local personnel, with failed modules returned to the STSF for repair. An adequate supply of spare modules based on a failure rate analysis will be kept at the site or at the STSF.

Because of the large number of elements involved, failures will frequently occur. These failures may be divided into two areas: single point failures that will terminate SKA operations and will need to be immediately addressed, and the failure of one or more elements that will reduce the performance capability in some way. Some of the latter category of failure is mitigated by the large number of elements, so that failure of individual cryogenic, electronic, or antenna systems can be tolerated and repaired only at the next scheduled maintenance. Other failures which may affect a single frequency band, or specialized instruments such as the pulsar backend, can be mitigated by adjusting the observing program.

Key components such as the correlator will have sufficient redundancy and self-diagnosis and repair capability to minimize the possibility of failure. By using identical computer systems for different tasks, sufficient spare capacity can be maintained to mitigate the failure of any one computer system.

3.5 Science Operation, Construction, and Maintenance

Experience has shown that at most radio observatories the primary source of radio frequency interference is locally generated. We anticipate that the SKA will be providing scientific data about 70 percent of the time. Perhaps 5 to 10 percent of the time will be lost due to serious environmental issues (wind or rain) or single path instrumental failures such as the correlator or power station, while 20 to 25 percent of the time will be spent in scheduled maintenance, upgrades, calibration and testing. To the extent practical, redundant systems and flexible observing schedule will minimize time lost due to equipment failure and/or weather.

3.6 Health and Safety

Due to the remoteness of the SKA core site as well as the outer stations, no less than two people will visit the sites for any purpose. Policies will be established to maintain safety standards consistent with those in place at similar facilities located in European and North American faculties. Health and safety standards will be established, implemented, and enforced by a Safety Officer who reports directly to the SKA Director.

3.7 Environmental Impact

All SKA operations will comply with the laws and policies of the host country as well as with normally accepted international standards. Appropriate expertise will be consulted during construction and operation and necessary mitigation will be used to minimize the impact of the SKA on the local environment. Owing to the desert location of the array, summer temperatures can be
uncomfortably high requiring substantial cooling for both personnel and equipment, with potential significant thermal impact to local environment.

As a result of the remoteness of the candidate sites, special attention will be needed to provide adequate 24/7 security. Protection from animal intervention on all scales ranging from Australian flies to African elephants as well as minimizing the impact to plant and animal and will be an important consideration for operation of the SKA Observatory.

The SKA Observatory will be located at one of the most RFI free sites on the Earth, so special attention will be needed to ensure that local instrumentation such as computers and other digital circuitry is designed to not generate RFI. Since the science operations will commence well before the end of construction, it is clear that there will be conflicts and tensions between the desire for optimum observing conditions and the requirement to complete the array within planned time and budget. It will be important that there be a full understanding between industrial contractors and Observatory management on minimizing RFI generated by construction activities, with minimum impact to either the construction or the testing/commissioning/observing program. Activities such as welding will require special attention.

3.8 Upgrading

No scientific facility can remain at the cutting edge of research without regular upgrades and enhancements to take advantage of technical advancements and to respond to increasing scientific demands. With so many individual elements it will be difficult and expensive to maintain the antenna based instrumentation at the state-of-the-art. Since all repairs and replacements will need to be done in the field, units will be modular and easily replaced by relatively low-skilled employees. We anticipate that there will be continued development of software throughout the lifetime of the SKA, although we stress that the initial software base needed to implement the full science requirements must be provided from the construction project, and not relegated to operations. Software, like hardware should be considered as a capital cost and not deferred to operations. Indeed, since the hardware platform is likely to change over the lifetime of the SKA, considering the huge labour costs in developing software, it is important that the software be portable to new hardware.

We have included €30M/yr (2% of construction budget) in the annual operating budget for the development and implementation of new instrumentation and software. We anticipate that such upgrades will be motivated by both evolving technological developments as well as evolving science goals.

3.9 Communications

The combination of the large number of individual antenna elements, the large instantaneous bandwidth, the need for high temporal and frequency resolution results in very large data rates which must be communicated from the antennas to the central correlator as well as output from the correlator to the main data reduction computer. Within the inner few hundred kilometers, we will install dedicated fiber as part of the construction project to handle the data transmission from the antennas. But, for the remote stations beyond a few hundred kilometers from the central cores, this
will not be practical, and the data transmission will rely on existing public networks. This will mean a recurring operating cost rather than a onetime capital cost.

### 3.10 Staffing SKA Operations

In estimating the number of individuals needed to implement the Observatory operations we assume, on average, that each staff member will be available for about 210 days, or 1680 hours per year. When in full operation, the breakdown of SKA staff will include approximately

- 200 engineers and technicians for direct support of array operations, maintenance, and upgrades of the antennas and instrumentation;
- 50 PhD scientists, postdoctoral appointment, and students to support users, to initiate and guide the development of new instrumentation, to continue algorithmic designs and software, to contribute to effective spectrum management, and who also carry out their own independent research programs;
- 20 individuals to support computing hardware;
- 40 individuals for support of systems and communications;
- 20 individuals to support Monitor and Control systems;
- 30 scientists and technical personnel to support data management and archiving;
- 80 individuals spread over the technical support centers to provide support for the antennas beyond the local service area (average of 2 per remote site);
- 30 individuals to maintain buildings and ground maintenance and to provide security;
- 50 administrative personnel including a fiscal/business division, procurement, shipping, HR, EPO, and secretarial support.
4 Governance

The establishment of formal policies for the governance of the SKA will be negotiated among the funding partners. Here we set out some guidelines which we believe will be important to the effective operation of the SKA as a resource for the global astronomical community to pursue what will surely be transformational research. It is anticipated that funding for the operation of the SKA will be provided in the same proportion as construction funding, probably equally from Europe, the United States, and the “Rest of the World.” While there will be pressures from the supporting countries to maintain influence and control of the operations, we anticipate that responsibility for the day-to-day operation will be vested to the SKA Observatory Director who will have the responsibility and authority normally associated with such a position.

The SKA Observatory Director will establish and implement broad policy, establishing priorities, for appointing senior scientific, engineering, and administrative staff, for developing the annual operating budget, and for resolving high level conflicts. The Director will be appointed by, and will report to a board whose membership reflects the SKA sponsoring partners, and who have the legal and financial responsibility for all SKA activities. Considering the expected long operating lifetime of the SKA, priorities and circumstances are likely to evolve, so that there will need to be adequate provision for the inclusion of new partners and the withdrawal of old ones.

All staff located at the SKA Headquarters, the Technical Support Facility, and Distributed Maintenance Centers will be employees of the SKA Observatory, and likely subject to the labour laws of the host country, while those located at the Regional Science Centers will be employed locally. It is anticipated that the scientific and technical staff as well as senior administrative staff will be recruited internationally, and compensated at international rates typical of Europe or North America. Craft, clerical, and some administrative staff will be recruited locally. Student and postdoctoral appointments will be globally competitive

4.1 Advisory apparatus

A robust advisory system will be important for two reasons. First, it will serve to bring a broad range of global experience to improve the operation of the SKA Observatory and to maximize the scientific returns from the SKA. Second, it will serve to help keep the SKA stakeholders involved and to bring back to their home institutions around the world, new ideas that they will have acquired. In addition to advisory committees that will be appointed by the Director to advice on Observatory priorities, we anticipate that the SKA Board will appoint a Visiting Committee to periodically review the operation and management of the Observatory and to report to the Board on the effectiveness of the Director and other senior management.
5 Operating Costs

The SKA operating budget was derived assuming international compensation rates for most scientists, engineers, and senior administrative personnel who will be recruited internationally and local rates for technical, craft, and other administrative staff. We anticipate that some software development will occur in countries where compensation is significantly less than in Europe or North America, although we note that the global salary gap for professionals is rapidly closing and there may not be significant cost savings in this area.

We suggest a system similar to that used for the European Space Agency (ESA) and Space Telescope Science Institute (STScI) personnel, where member countries would second their staff to serve under the SKA Director. The host country will also need to facilitate the movement of people and materials across international boundaries and this will involve many details including visas, tariffs, working rights for spouses, etc. which remain to be negotiated.

In addition to personnel costs, the operating budget will include power and fuel for vehicles, travel, hardware replacements due to component failure, publication costs, salary support for users, consulting and contracts, communications, data transmission, and expendable media. Other than personnel costs, uncertainties in the operating budget are dominated by two items: power requirements and long distance broadband data transmission from the remote stations to the central facility.

- The SKA power requirements and the cost of providing power are being studied by the SPDO Power Investigation Task Force (PITF). Current estimates of possible power need for full data analysis is in the range of 50 MW to 150MW, corresponding to an cost of about 50 to 150 M€ per year if provided at current commercial rates, but this will depend very much on the extent of digital signal processing required by Phased Array Feeds and Aperture Arrays. At least initially it may be necessary to limit the data analysis

- Within a radius to be defined, data transmission will be by a “self-built” network, but beyond a few hundred km, the installation cost become prohibitive. For these longer distances, data transmission could be via leased dark fiber or commercial networks and would thus be an operating expense rather than a capital expense. The cost of operating the long distance fiber networks is being studied, and is likely to impact the number and location of the distant stations.

Total annual operating costs are estimated as follows (€):

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personnel compensation (520 FTEs)</td>
<td>50M</td>
</tr>
<tr>
<td>Dark fiber lease (long baselines)</td>
<td>20M</td>
</tr>
<tr>
<td>Other M&amp;S (maintenance contracts, travel, etc)</td>
<td>10M</td>
</tr>
<tr>
<td>Replacements, upgrades and enhancements</td>
<td>30M</td>
</tr>
<tr>
<td>Regional Science Centers</td>
<td>20M</td>
</tr>
<tr>
<td>Power (antenna, correlator, signal transport, infrastructure)</td>
<td>35M</td>
</tr>
<tr>
<td>Power (high performance computer)</td>
<td>15M(^1)</td>
</tr>
<tr>
<td><strong>Total SKA operations</strong></td>
<td><strong>€180M</strong></td>
</tr>
</tbody>
</table>

\(^1\) The cost of providing high performance computing is very uncertain at this time as are the computing requirements themselves. A Power Investigation Task Force has been created by the SPDO to investigate green and other alternative power sources and to consider designs that minimize power consumption.
6 Acknowledgements

In preparing this operating plan for the SKA we have liberally borrowed ideas from the operation of existing facilities such as the VLA and the DSN as well as facilities currently under development and nearing operations such as ALMA and LOFAR, and the SKA precursors, ASKAP and MeerKAT. Paul Alexander, Peggy Perley, John Hibbard, Peter Quinn and many others have contributed to this report as well.

The following materials have been also been consulted:

- MeerKAT High-Level Operational Model, NRF-KAT-10.p-MP-064, T. Cheetham
- NASA JPL DSN Microwave Array Project, IND No. 900-001, Rev D, Caltech
- ALMA Operations Plan, Version D