

# Project Execution Plan

## The U.S. Square Kilometer Array Technology Development Project

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### Table of Contents (Some sections redacted)

|  |    |
|--|----|
| 1. Introduction .....                                    | 1  |
| SKA Science .....  | 1  |
| International Activities for the SKA .....               | 1  |
| Focus of the TDP .....                                   | 2  |
| Preparatory SKA EC-funded Project (PrepSKA) .....        | 3  |
| 2. Baseline Project .....                                | 4  |
| Primary Goals .....                                      | 4  |
| Overview of the Work Breakdown Structure .....           | 5  |
| Rescoping from the 2007 January Request .....            | 6  |
| Schedule .....   | 12 |
| Risk Assessment and Management .....                     | 13 |
| Contingencies .....                                      | 15 |
| Integration with PrepSKA .....                           | 16 |
| 3. Organization of U.S. SKA Activities and the TDP ..... | 16 |
| The U.S. SKA Consortium .....                            | 16 |
| The SKA-TDP Advisory Committee .....                     | 18 |
| SKA-TDP Antennas Working Group (AWG) .....               | 18 |
| SKA-TDP Calibration and Processing Group (CPG) .....     | 19 |
| 4. TDP Management .....                                  | 19 |
| Managing Organization .....                              | 19 |
| TDP Project Office .....                                 | 19 |
| Interaction with Other Projects .....                    | 20 |
| Reports and Reviews .....                                | 22 |
| 5. Funding Agency Oversight .....                        | 22 |
| Attachments:   |    |
| A: Cost Tables vs. WBS and Year .....                    | 24 |
| B: WBS and Subproject Descriptions .....                 | 25 |
| C: Schedule .....  | 49 |
| D: Subawards .....                                       | 51 |
| E: Acronyms Used .....                                   | 52 |
| F: Letters of Commitment .....                           | 53 |
| G: NSF-Cornell Cooperative Agreement .....               | 53 |

## 1.0 Introduction

The Technology Development Project (TDP) is a four-year effort to develop technology for meter and centimeter wavelength astronomy that will provide design choices for the Square Kilometer Array (SKA) program. These options will include hard cost determinations for key elements for the SKA. The work plan for the TDP is integrated with those of other international efforts for developing the SKA, including those organized under the European-Commission funded Preparatory SKA Project (PREPSKA).

The SKA is the next-generation radio observatory for meter and centimeter wavelengths. It will be used to answer key questions at the frontiers of fundamental physics, cosmology and cosmic evolution, and astrobiology. Areas of fundamental physics include characterization of dark energy and dark matter and the nature of gravity. The SKA will detect and quantify the epoch of reionization and the formation of the first stars. It will map out the structure and evolution of galaxies using spectral lines from atomic hydrogen and carbon monoxide. The origins of cosmic magnetism and its role in structure formation will be studied through a massive survey of Faraday rotation. Astrobiology includes the birth of solar systems, organic molecules, and searching for signals from other civilizations (SETI).

With U.S. participation, it has converged to a reference design and identified two acceptable sites — Australia and Southern Africa. The reference design is based on a large number of small-diameter dish antennas, the LNSD concept originally suggested by the US SKA Consortium, along with phased arrays. Proceeding from concept to design is the goal of the next four years, the term of our work plan, and also the time frame identified by the SKA Project Development Office (SPDO) that will lead to a state of project readiness for Phase 1 of the SKA.

**SKA Science:** SKA science is described in detail in the book, “Science with the Square Kilometer Array,”<sup>1</sup> which presents key science areas along with a large body of compelling science also enabled by the SKA. Also available at [www.skatelescope.org](http://www.skatelescope.org) is a brochure with a good overview of SKA science and numerous technical as well as scientifically-oriented memoranda.

**International Activities for the SKA:** Technology development is taking place in multiple countries around the world. The next four years are critical, when the SPDO — working with regional groups (like ours) — tackles technology issues, makes trades between science goals and design, and produces a detailed design for a Phase 1 array. Current planning in the international project includes the possibility that construction may begin in the first half of the next decade.

Phase 1 of the SKA is in the process of being defined within a larger plan for the full SKA. The science case, if fully implemented, would require coverage of 0.1 to 25 GHz with a wide range of antenna baselines. For reasons of both technology readiness and programmatics, buildout of the SKA will require at least two (and perhaps three) different antenna receptors, implemented within a long term program:

1. **Low-frequency Array:** < 0.1 – 0.3 GHz to cover Epoch of Reionization studies of

<sup>1</sup> *Science with the Square Kilometre Array*, eds. C. Carilli and S. Rawlings, *New Astronomy Reviews*, 48, 2004; available online at [www.sciencedirect.com](http://www.sciencedirect.com) and individual articles at [http://www.skatelescope.org/pages/page\\_sciencegen.htm](http://www.skatelescope.org/pages/page_sciencegen.htm)

redshifted hydrogen and other science areas (see below). This array will comprise dipole antennas organized in tiles and will be a follow-on to pathfinder arrays (LOFAR, LWA and MWA).

2. **Mid/High-frequency Array:** 0.3– X GHz with X in the range of about 3 to 25 GHz (see below). This too will include hydrogen science in the form of a billion-galaxy redshift survey, along with serving as a survey and follow-up instrument for gravity studies using pulsars, cosmic magnetism, the transient universe, and the search for extraterrestrial intelligence (SETI). If X extends to 25 GHz, this array will address “Cradle of Life” science — including synoptic imaging of protoplanetary disks on sub-AU length scales, complex molecules, and SETI — and high-redshift detection of the first metals (CO) on targets that will complement those studied with ALMA and the EVLA at radio wavelengths and JWST in the IR.

A central goal of the TDP is to develop hardware and algorithms and aggregate sufficient information from our own and others’ work on the SKA, including industry, to understand costs as a function of  $X$ , as defined above. This will inform decisions about how the SKA can be deployed over time under realistic budget expectations.

As described in the recent document “Preliminary Specifications for the Square Kilometer Array,” (dated 10 December 2007)<sup>2</sup> developed with U.S. participation (J. Cordes and K. Kellermann), the SKA will be built in three phases:

**Phase 1:** will implement approximately the first 10% of the array that covers frequencies from about 0.3 GHz to 10 GHz. Depending on results from pathfinder projects attempting to detect the Epoch of Reionization signal at low frequencies, Phase 1 may also include a component at  $< 0.3$  GHz.

**Phase 2:** will complete the construction of the low and mid-band arrays with a target year of completion of 2020.

**Phase 3:** comprises construction of the high-frequency component of the SKA, extending to 25 GHz or higher (depending on science results from the EVLA and ALMA), with construction beginning after 2020.

**Focus of the TDP:** The TDP focuses on several areas of risk that pertain to performance and cost of antenna elements and that will contribute to key decisions about deploying the SKA. Our activities are to contribute significantly to the engineering design for the first phase of construction of the SKA that will commence in the next decade. The primary areas of risk, as discussed in our original 2004 proposal and highlighted in the review panel’s comments, are: (1) identifying cost effective ways for producing antenna elements that operate with adequate  $A/T_{\text{sys}}$  and (2) assessing signal processing methods that drive costs via their influence on the choice of antenna diameter. The first of these corresponds to the primary development area in our work breakdown structure (WBS), Antennas, Feeds and Receivers, in which we will develop the technology needed for optimizing the sensitivity of a single antenna while also identifying, through collaboration with manufacturers, how to

<sup>2</sup> available at the SKA website <http://www.skatelescope.org>

build antennas at the lowest possible cost. The second area — Systems Analysis and Design — considers the array aspects of the SKA, including signal transport and processing needed to achieve scientific goals. SKA science comprises a great deal of survey work, whose specifications impact the systems design and cost. Part of our work necessarily considers the role of the SKA as a radio synoptic survey telescope, optimized for discovery and follow-up, and identifying ways in which we can trade field of view against sensitivity. Most of the work in WBS 2 is unfunded under the current budget for the TDP; however, work is supported under the TDP that influences the choice of antenna diameter and the number of antennas.

**Preparatory SKA EC-funded Project (PrepSKA):** PrepSKA is an umbrella project for the international SKA project that whose direct funding is from the EC combined with national matching funds from European countries. There are also in-kind contributions from workers in non-European countries. PrepSKA is a comprehensive program whose goal is to develop a design for the SKA, including a technical design and governance and funding structures.

PrepSKA is intended to address key issues that are needed before construction of the SKA can begin:

1. What is the design for the SKA?
2. Where will the SKA be located?
3. What is the legal framework and governance structure under which SKA will operate?
4. What is the most cost-effective mechanism for the procurement of the various components of the SKA?
5. How will the SKA be funded?

The purpose of PrepSKA is to address all of these points. PrepSKA will integrate the R&D work from around the globe in order to develop the fully-costed design for Phase 1 of the SKA, and a deployment plan for the full instrument. With active collaboration between funding agencies and scientists, all of the options for the policy-related questions will be investigated. The principal deliverable will be an implementation plan that will form the basis of a funding proposal to governments to start the construction of the SKA.

PrepSKA is organized into seven work packages:

**WP1** Management of the SKA Preparatory Phase Project

**WP2** SKA Design

**WP3** SKA Sites

**WP4** SKA Governance and Legal Framework

**WP5** SKA Procurement and Industrial Involvement

**WP6** Developing the Funding Model for the SKA

## WP7 SKA Implementation Plan

The total EC funding is 5.5M€. WP2 (SKA Design) is the technical portion of PrepSKA and has the most funding 3.3M€. In addition to the EC funds, there are an additional 16.5M€ from matches from national European sources and in-kind contributions. The TDP work plan is well integrated with that of PrepSKA.

Activities within the TDP are chosen to tap areas of expertise in the U.S. and which complement work done outside the U.S. Some of our results will comprise unique contributions to the SKA project, while others will be achieved via collaborations within the context of international working groups. For example, while technology development outside the U.S. focuses exclusively on a mid-range frequency band (e.g. 0.3 to 3 GHz), within the U.S. we are also interested in developing technology solutions for the higher frequencies, extended up to perhaps 11 GHz for the mid-range SKA and up to 25 GHz for the full SKA. The deployment plan for the SKA is likely to include in its earliest phases the mid-range band and a low-frequency “Epoch of Reionization” (EoR) band (0.1 to 0.3 GHz); for the latter, considerable pathfinder work is being done worldwide (e.g. LOFAR, LWA, MWA). However, the SKA project is not yet informed as to the most cost effective way to define the upper frequency of the mid-range band (given above as 3 GHz only as an example). We need to invest in development of antennas, feeds and receivers and their use in a large-N array as a basis for formulating a sensible, long-term deployment plan for the SKA. This plan must optimize resource development, such as infrastructure and predictable technology trends (e.g. Moore’s law), for the *entire* frequency range demanded by SKA science. Consequently, some of our activity concerns technology solutions for the high-frequency band that will influence early decisions to be made about the overall SKA program.

The prime driver for the SKA is, of course, science. But at this stage, much of the work to be done concerns *costing*. We are well aware that next generation telescopes like the SKA, because of their expense, must be costed accurately and with cost/performance tradeoffs identified. The SKA is likely to be built to fixed cost, so we must assess the intricate set of tradeoffs that exist between deploying, operating and maintaining a large number of antennas and processing the signals to achieve science goals. The multidimensional tradeoff space is the subject of our third work area, costing; it will be coordinated explicitly with the activities of the SPDO to enable decisions needed internationally that will lead to technical and project readiness on the necessary time scales. Life-cycle and divestment costs will also be assessed. The fourth main WBS area is the system design of the SKA. The U.S. will contribute directly to the design via the efforts done under WBS areas 1-3, which will be integrated with working groups that are being organized by the SPDO. Major funding for the SPDO’s design effort will come from the EC-funded SKA design project, PrepSKA.

The TDP is managed at Cornell University through the National Astronomy and Ionosphere Center (NAIC) with the U.S. SKA Consortium serving an advisory role.

### 2.0 Baseline Project

**2.1 Primary Goals:** The scope of the TDP has been identified through (a) consideration of local (U.S.) priorities for the direction of the SKA that have been identified through the community meetings mentioned earlier; (b) identification of a target timeline for the SKA

project and for milestone events such as the next U.S. Decadal Survey and various design reviews; and (c) identification of unique areas of R&D that are not being done elsewhere and which are critical to moving the project forward. The four-year TDP will span the current Reference Design to an engineering design (for Phase 1) that is targeted for late 2011/early 2012.

**2.2 Overview of the Work Breakdown Structure:** TDP work is organized into four primary areas in a work-breakdown structure (WBS) that are listed in the order of specific technology R&D followed by activities that aggregate knowledge gained to develop an SKA design:

**WBS 1. Antennas/Mounts/Feeds/Receivers:** Identification of inexpensive manufacturing methods and an optimal antenna design developed in parallel with broad-band feeds, wide-FoV feed arrays, low-noise receivers and assessment of costs.

**WBS 2. Calibration and Processing:** There are real issues in the processing that will influence the cost equation, both directly and indirectly, via the affect on antenna diameter and on the antenna optics.

**WBS 3. Cost Function Analysis:** Determine the cost of individual antennas as a function of upper frequency capability ( $X$ ), diameter  $D$ , and field of view (FoV),  $C(X, D, \text{FoV})$ . This quantity is crucial for making SKA project decisions. Implicit in  $C$  is the method of manufacture and economies of scale. We do not include the number of antennas explicitly because it is best included as a multiplicative factor owing to science considerations on sensitivity and FoV. We have rescoped this area from our 2007 January workplan submitted to the NSF but will cover it through activities of the TDP Project Office. It is included as a necessary activity that consolidates results from WBS 1 and WBS 2.

**WBS 4. SKA Design Project:** Evolve the Reference Design into a phased implementation plan and develop an engineering design for Phase 1. This too is descoped from our 2007 January plan but is a necessary part of our interaction with the international project.

In addition to specific work areas under these four WBS research and development items, the TDP will fund the management of the TDP, and it will fund work and activities that are crucial to U.S. involvement in the international SKA project and that ensure broad national participation in the project. These programmatic areas include:

**WBS 5. SKA Research Associateship:**

The SKA Research Associateship is intended to attract a young engineer to work on technology development or to fund a senior person taking a sabbatic leave. A person working on the Antennas part of the TDP will be favored and s/he will be encouraged to spend a significant amount of time at the CDIT.

**WBS 6. TDP Management:** The TDP is centrally managed with a part-time Project Director, a full time Project Manager, a Business Manager at 10% FTE, and an

administrative aide at 15% FTE. The roles of the Project Director and Project Manager are described below. Direct costs to the TDP grant include a portion of the Project Director's salary, a full FTE for a Project Manager, and the administrative support, including budget management, report preparation, and communications. Associated travel and contingency are also budgeted. Work done under subawards and subcontracts issued by Cornell to TDP partners and to industry will be managed by the TDP Project Office.

**WBS 7. U.S. SKA Consortium Participant Costs:** The TDP will support meetings of TDP working groups (those working on one of the WBS-subareas, such as antenna manufacturing), travel between participating institutions, travel by U.S. members (currently seven) of the SSEC, and travel to other international working-group meetings.

Also included are contributions to the International SKA Project Office (SPDO):

1. Subscription fee to the SPDO as agreed upon by the SSEC and funding agencies.
2. In-kind contributions via work on SPDO directed work packages and personnel seconded to the SPDO and its working groups. The summary WBS Timeline page does not show explicit entries under this item because the FTEs and costs are included under the primary WBS 1-4 entries. The international project is developing a mechanism — with our participation — for counting in-kind contributions based on the level of control the SPDO has over the personnel and/or funds. We expect our in-kind contributions to be at the level of several FTEs by the time the Framework 7 Design Project commences in 2008.

Table 1 gives a more detailed listing of the WBS while Attachment A gives detailed descriptions and goals of the WBS.

### **2.3 Rescoping of the Current TDP from the 2007 January Request:**

The current plan is costed at \$12M over four years as compared to the workplan of 2007 January that was costed at \$19M over five years. The specific items contained in the current WBS are largely the same as in the 2007 January WBS. However, there has been substantial rescoping of the actual work activity for some of the work areas in order to accommodate the lower funding level and the shortened time line.

In the baseline plan of 2007 January, TDP work was organized into seven high level areas that include technical work, collaborative work with the international project and project management. The rescoped plan here keeps the same structure, but with significant reweighting of the funded work to address the most pressing issues for technology development while fitting within the funding profile. Here we describe reweighting of the WBS that takes into account the reduced funding and the four-year duration of the project instead of five years.

In brief, WBS areas 1, 6 and 7 are largely unchanged, WBS 2 has been descoped significantly, and areas 3,4 and 5 have been modified as described below.

**WBS 1. Antennas/Mounts/Feeds/Receivers:** This is the primary part of the entire TDP in both the baseline plan and in the current plan. The effort is largely

unchanged but we have modified the details of proposed funding levels in some of the subareas.

To ensure direction of this work, the PI has organized a working group, the “TDP Antennas Group,” that will identify and organize specific work to be done in accord with the Project Execution Plan and with the advice from the SKA-TDP Advisory Group (see below). The working group will report to the TDP Project Office through the Project Manager. Participants include those involved in explicit TDP work along with representatives from related foreign projects involved in antenna prototyping and acquisition.

Changes in the workplan are as follows:

#### WBS 1.1 Antenna Manufacturing Methods

There is a small change in total funding of this important work area, reducing somewhat the funding level for an industry assessment of manufacturing methods and a small change in funding level for consolidation of cost information into scaling laws.

#### WBS 1.2 Feeds and Receivers

Cost reduction is commensurate with the four instead of five year plan. Also, no funds will be sent to Chalmers (Sweden) as that work is now being self supported in Sweden. There will be less emphasis on delivering feeds and receivers for the highest frequency band. Effort will be concentrated on the lower frequency bands that are most likely to be implemented in the prototype array to be proposed for next decade. However, as decisions are made for the international project in the out years, the work plan on high-frequency systems may be modified.

#### WBS 1.3 Optical Design and Performance

Cost reduction is commensurate with the four instead of five year plan.

#### WBS 1.4 Antenna Deployment

There is a slight cost increase for deploying two antennas, the first one for testing feeds and antennas, the second a fully optimized antenna whose design is the outcome of the TDP.

#### WBS 1.5 Antenna Performance Testing

Reduction by about 50% of personnel costs for on-the-sky testing the optimized antenna. The antenna’s availability is a deliverable to both the TDP and to the PREPSKA project, so testing costs should be shared with PREPSKA. We will negotiate this with the PREPSKA managers.

**WBS 2. System Analysis and Design:** Given the TDP budget level of \$3M/year, TDP funding will support only a restricted subarea, now called “Large-N Calibration and Processing.” The justification is that there are real issues in processing that influence the cost equation, both directly and indirectly, via the affect on antenna diameter and on the antenna optics. For example, two groups involved with the international SKA program went through an initial costing exercise for a strawman SKA. Processing

costs were not only significant, they varied by a factor of two, indicating that work is needed to refine the processing cost estimates.

The rescoped plan here zeroes out funding of WBS 2.1 (Signal Processing), 2.3 (RFI Mitigation), 2.4 (Radar Capability Study), 2.5 (Survey Design) and 2.6 (Data Management). We intend to fund work in WBS 2.2, now renamed to *Large-N Calibration and Processing*, because its results will bear on the optimization of antenna diameter and costs. This work will be done at three institutions (U. Illinois, MIT/Haystack and UC Berkeley) in a collaboration led by U. Illinois that will interface to the international project.

To ensure direction of this work, the PI has organized a working group, the "TDP Calibration and Processing Group," that will identify and organize specific work to be done in accord with the Project Execution Plan and with the advice from the SKA-TDP Advisory Group (see below). This group will report to the TDP Project Office through the Project Manager.

**WBS 3. Cost Function Analysis:** The goal is to consolidate costing information that emerges from WBS 1 and 2 along with information from our international partners and develop the cost function,  $C(X, D, \text{FoV})$ , which is the basis for making SKA project decisions.

We have zeroed out the modest funding included in the baseline plan. The work will be covered by the TDP Project Office with consulting assistance as needed.

**WBS 4. SKA Design Project:** The goal is to evolve the Reference Design of 2006 into a phased implementation plan and develop an engineering design for Phase 1. This too is not directly funded but is a necessary part of our interaction with the international project. U.S. involvement will proceed through participation in working groups and via the TDP Project Office's direct participation in PREPSKA.

**WBS 5. SKA Research Associateship:**

After considering zeroing out this item, we decided that it was valuable to use the SKA Research Associateship mechanism as a means for attracting talented people into the TDP. We wish to fund one of these instead of the original two. Also, we will define the role of the position more narrowly than before. The intention is for the Associate to work in either WBS 1 and WBS 2. It is not an open-ended post doc type position, but rather a position related to the Antennas work or possibly the Large-N Calibration and Processing area.

**WBS 6. TDP Management:** The management plan remains the same (centrally managed with a part-time Project Director, a full time Project Manager, a Business Manager at 10% FTE, and an administrative aide at 15% FTE). The roles of the Project Director and Project Manager are described in the baseline plan.

Management costs have been reduced commensurately with the reduced cost of the total TDP budget and implied changes in work plan. Reductions come from the shorter duration of the TDP but also from reductions in travel and modest changes in other areas.

**WBS 7. U.S. SKA Consortium Participant Costs:** The TDP will support meetings of the SKA-TDP Advisory Committee that will be formed to advise the Project Director, working group meetings for the TDP, travel for some U.S. members of the ISSC, and travel for those interacting with the PREPSKA project.

Travel costs have been reduced somewhat on a per-year basis.

This area also includes U.S. contributions to the International SKA Project Office (to become SPDO under the new governance plan). Compared to the baseline plan, we have increased the budget for ISPO/SPDO contributions in accord with anticipated levels now being discussed by the NSF with other funding agencies. The proposed levels are conservative in the sense that they provisionally can accommodate maximum possible dues.

Table 1: TDP WBS

| WBS Item  |
|---|
| <b>1. Antennas, Feeds and Receivers</b>                         |
| 1.1 Antenna manufacturing                                       |
| 1.1.1 Assess Reflector Manufacture                              |
| 1.1.1.1 Composite Antennas                                      |
| 1.1.1.2 Segmented Antennas                                      |
| 1.1.1.3 Hydroformed Antennas                                    |
| 1.1.1.4 Industry Assessment                                     |
| 1.1.1.5 Cost Assessment   |
| 1.2 Feeds and Receivers   |
| 1.2.1 Single Pixel Broadband Feeds                              |
| 1.2.1.1 ATA Type Feeds  |
| 1.2.1.2 Chalmers/Kildal Feeds (informational only)              |
| 1.2.1.3 CIT Quad-ridge Feeds                                    |
| 1.2.1.4 Cornell QSC Feeds                                       |
| 1.2.1.5 NRAO Feed Concepts                                      |
| 1.2.1.6 Final Feed Development                                  |
| 1.2.2 Focal Plane Phased Arrays                                 |
| 1.2.3 Feed Clusters   |
| 1.2.4 Receivers   |
| 1.2.4.1 0.3-1.7 GHz (nominal)                                   |
| 1.2.4.2 1-11 GHz (nominal)                                      |
| 1.2.4.3 11-25 GHz (nominal)                                     |
| 1.2.4.4 MMIC Wafer Processing                                   |
| 1.2.5 IF/LO Development   |
| 1.2.6 Cryogenics Assessment and Development                     |
| 1.2.7 Integration of Feeds and Receivers                        |
| 1.3 Optical Design  |
| 1.4 Antenna Deployment  |
| 1.4.1 6m Test Antenna   |
| 1.4.2 Prototype Optimized SKA Antenna                           |
| 1.4.2.1 Acquire/Fabricate Antenna & Mount                       |
| 1.4.2.2 Outfit Antenna with Feeds, Receivers, etc.              |
| 1.4.2.3 Composite Antenna Deployment                            |
| 1.5 Antenna Testing   |
| <b>2. Systems Analysis and Design</b> (* denotes primary areas) |
| 2.1 Signal Transport  |
| 2.2 Calibration Algorithms (*)                                  |
| 2.3 Imaging, Spectroscopy and Time-domain Processing (*)        |
| 2.4 Scalability and High-Performance Computing (*)              |
| 2.5 RFI Mitigation  |
| 2.6 Surveys   |
| 2.7 Data Management   |
| <b>3. Cost Function Analysis</b>                                |
| <b>4. SKA Design Project</b>                                    |
| <b>5. SKA Research Associateships</b>                           |
| <b>6. TDP Management</b>  |
| <b>7. USSKAC Participant Costs</b>                              |

The ‘\*’ in WBS 2 areas designates the primary areas of emphasis.

Table 2 lists the WBS areas, the managers, and institutions that are providing team members for each WBS area. We show the WBS areas of the baseline plan and indicate which sub-areas are directly funded or not.

Table 2: TDP Baseline WBS (TDPPO = TDP Project Office)

| WBS Item   | Adviser/Manager     | TDP Funded?     | Team Institutions in Baseline Program  |
|--|---------------------|-----------------|--|
| <b>1. Antennas, Feeds and Receivers</b>              | TDPPPO              |                 |  |
| 1.1 Antenna manufacturing                            | W. J. Welch (UCB)   | Yes             | UCB, SETI Institute/Minex, CIT, JPL, DRAO, ATNF, MeerKAT <sup>1</sup> , Industry |
|  | M. Fleming (Minex)  |                 | CIT, UCB, Cornell, Chalmers  |
| 1.2 Feeds and Receivers                              | S. Weinreb (CIT)    | Yes             | UWisc., UCalgary/DRAO <sup>2</sup>   |
|  | G. Cortes (Cornell) | Yes             | Cornell, UCB, CIT  |
| 1.3 Optical Design and Optimization                  | TDPPPO              | Yes             | CIT, Cornell, UCB, DRAO  |
| 1.4 Antenna Deployment                               | TDPPPO              | Yes             | TDPPPO et al.  |
| 1.5 Antenna Performance Testing                      | A. Kemball (UIUC)   | No <sup>3</sup> | NRAO, JPL, MIT/Haystack, UCB, DRAO   |
| <b>2. Calibration and Processing</b>                 |                     |                 |  |
| 2.1 Signal Transport<br>(including correlators)      |                     |                 |  |
| 2.2 Calibration Algorithms                           |                     | Yes             | UIUC, UCB, MIT/Haystack, NRL, UNM  |
| 2.3 Imaging, Spectroscopy and Time-domain processing |                     | Yes             | Ditto  |
| 2.4 Scalability and High-performance Computing       |                     | No              |  |
| 2.5 RFI Mitigation                                   | T.J.W. Lazio (NRL)  | No              | NRL, MIT/Haystack, UCB, UNM, VT  |
| 2.6 Surveys  |                     | No              | Cornell, MIT/Haystack, UCB, UIUC, UNM, UCalgary, UWisc                           |
| 2.7 Data Management                                  |                     | No              | Cornell, UIUC, Cfa/SAO, UWisc.   |
| <b>3. Cost Function Analysis</b>                     | TDPPPO              | No              | Cornell, NRAO, UCB, UI   |
| <b>4. SKA Design Project</b>                         | TDPPPO et al.       | No              | Participants in WBS 1-3 and additional as needed                                 |
| <b>5. SKA Research Associateship</b>                 | TDPPPO              | Partial         | USSKAC member institutions   |
| <b>6. TDP Management</b>                             | TDPPPO              | Yes             | Cornell  |
| <b>7. USSKAC Participant Costs</b>                   | TDPPPO              | Yes             | USSKAC member institutions   |

1. South Africa (MeerKAT) will contribute fabrication information on composite antennas.

2. Canada (DRAO, U. Calgary) will contribute information on composite antennas, low-noise amplifiers, and participate in the Calibration and Processing Group.

3. A “No” entry signifies that no direct subaward for the item is made. However, the item is kept in the WBS because the TDPPO will facilitate communication to PrepSKA of other U.S. activities in these areas.

Table 3 itemizes the deliverables from the WBS areas, some of which are hardware, some are algorithms/software, with all producing reports that will provide input for the design of the SKA.

Table 3: Deliverables from WBS Areas 1-4

| WBS Item                                       | Deliverables  | Comments                                      |
|--|---|---|
| <b>1. Antennas, Feeds and Receivers</b>        |   |   |
| 1.1 Antenna manufacturing                      | Identification of optimal manufacturing methods with cost breakpoints vs. $D$ and maximum frequency | Reports, data                                 |
| 1.2 Feeds and Receivers                        | Working broadband feeds and receivers   | Hardware                                      |
| 1.3 Optical Design                             | Antenna design that optimizes G/T vs. frequency.  | Reports                                       |
| 1.4-1.5 Deployment/Testing                     | Optimized SKA antenna fully outfitted with feeds and receivers                                      | Hardware                                      |
| <b>2. System Analysis and Design</b>           |   |   |
| 2.1 Transport                                  | Data transport cost estimates   | Reports                                       |
| 2.2 Calibration Algorithms                     | Algorithms for widefield imaging  | Algorithms, Software                          |
| 2.3 Imaging, Spectroscopy                      | Processing assessment   | Report  |
| Time Domain Processing                         |   |   |
| 2.4 Scalability and High-performance Computing | Processing assessment   | Report  |
| 2.5 RFI Mitigation                             | Algorithms for RFI excision   | Algorithms, Software                          |
| 2.6 Surveys                                    | Commensal survey plan and requirements  | Reports<br>Simulation codes                   |
| 2.6 Data Management                            | Plan for short-term and long-term DM  | Reports                                       |
| <b>3. Cost Function Analysis</b>               | Multidimensional costing study and input to critical project decisions                              | Data, codes, reports                          |
| <b>4. SKA Design Project</b>                   | Design for Phase 1 of the SKA with roadmap for deployment of full SKA                               | SKA design<br>Subsystem designs<br>Prototypes |

## 2.4 Schedule

Table 4 shows salient milestones for the international SKA project as set out by the SPDO for the primary work package of PrepSKA. The SKA Specifications Review Committee has reviewed the document “Preliminary Specifications for the Square Kilometer Array” as the first step of a series of development milestones and reviews that will take place over the next five years, spanning the time frames for both the TDP and PrepSKA. The series of reviews through 2012 aim at achieving a state of construction readiness for Phase 1 in the first half of the next decade.

The emphasis in Table 4 on the review of wide fields of view reflects the importance on phased arrays as a means for achieving very high throughput in SKA surveys. However, significant technical hurdles must be dealt with in order that they become part of the SKA design. The “initial verification system” (IVS) is a set of subsystems developed under PrepSKA that will provide real-world characterization of performance needed to go forward with an engineering design for Phase 1. The TDP’s deliverables in antennas, feeds and receivers are a contribution to the IVS. Finally, the site decision in 2011 requires no direct work from the TDP, though some of the site characterization will be done by the SPDO, which is funded in part by a contribution from the TDP.

Table 4: International SKA Timeline for Reviews and Decisions

| Date     | Event  |
|----------|--|
| 2008 Jan | SKA Specifications Review Committee <sup>‡</sup>   |
| 2008 Apr | Top-level SKA Phase-1 and Phase-2 Specifications set   |
| 2009 Feb | International Engineering Advisory Committee review of SKA concept design                                  |
| 2009 Mar | Final specifications for SKA design options set  |
| 2010 Jan | SKA Phase 1 First Design Review  |
| 2011 Jan | Wide Field of View First Design Review   |
| 2011 Sep | SKA Phase 1 Second Design Review   |
| 2011 Dec | Costing of SKA Phase 1 and SKA Phase 2 completed<br>Initial Verification System completed<br>Site decision |
| 2012 Dec | Wide Field of View Second Design Review  |

<sup>‡</sup> Review of the document “Preliminary Specifications of the SKA”

Table 5: Timeline for Salient TDP Events

| Date          | Event   |
|---------------|---|
| Year1         | Begin TDP<br>Initiate Antennas Working Group (AWG)<br>Initiate Calibration and Processing Group (CPG)<br>Begin work on antennas, mounts, feeds and receivers<br>Begin work on processing algorithms and requirements<br>Begin collaboration with PrepSKA partners (2008 April)<br>Begin cost modeling effort<br>Begin SKA design contributions                      |
| End of Year 1 | Report on TDP antenna and mount options<br>Report on feed and receiver development<br>Report on antenna optics designs<br>Report on major calibration and processing issues that drive antenna design   |
| Year2         | Continue work in all areas<br>Consultation with industry on large-scale antenna manufacturing methods<br>Contributions to SKA concept design for IEAC review<br>Contributions to SKA design options for review<br>Design of SKA/TDP mount and reflector for prototype development options   |
| End of Year 2 | Reports as for Year 1   |
| Year 3        | Testing of calibration and processing algorithms<br>Generate bid package for antenna and mount; select bidder and release funds<br>(contingent on design requirements multiple feeds, including phased arrays)<br>Delivery of first generation wideband, single-pixel feeds and receivers<br>Contributions to Phase 1 Design review # 1 from all WBS 1-4 activities |
| End of Year 3 | Reports as for Years 1-2<br>Report on Antenna manufacturing methods   |
| Year 4        | Delivery of antenna and mount at U.S. site for testing<br>Delivery of second generation wideband, single-pixel feeds and receivers<br>(Contributions to PrepSKA IVS)<br>Integration and testing of TDP antenna<br>Contributions to Phase 1 Design Review # 2<br>Contributions to final costing effort   |
| End of Year 4 | Final reports in all areas  |

Figure 2 shows the timeline for the WBS with milestones and reviews marked at the bottom.

## 2.5 Risk Assessment and Management

The current risks to the SKA and thus to the TDP derive from the expectation that the SKA will be built to a fixed cost  $\sim 1 - 1.5\text{B}\text{€}$ . The rich science case places great demands on sensitivity, frequency range, field of view, configuration, and signal and data processing. Most of those involved in the project expect that it will need to target the most important

SKA TDP Timeline for Top WBS Levels  
1 Feb 2008

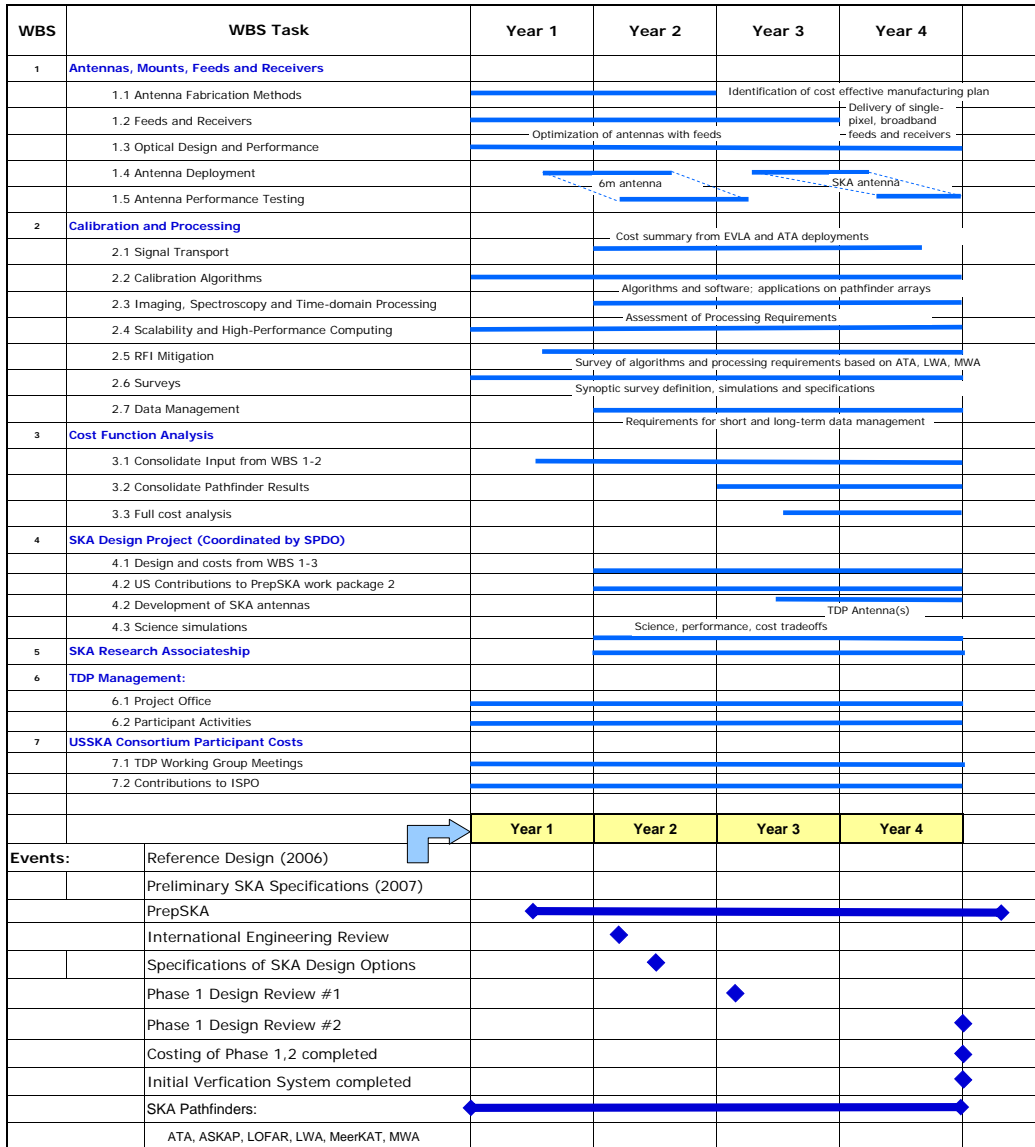


FIG. 1.— TDP timeline for the WBS areas with international milestones and reviews shown at the bottom.

subset of the science goals in order to be affordable. The TDP will provide crucial input for focusing the SKA. Broken down into components, the technological risks that must be addressed imply the following challenges:

1. Identifying antenna types and their manufacture that allow sensitivity goals to be met with an affordable array. Balancing cost against performance requires that we look at a number of options:

- (a) Prime-focus (PF) or secondary-focus (SF) only solutions vs. combined PF+SF solutions. The decision couples into the need for and success in developing phased-array feeds and whether they must co-exist with single-pixel feeds.
  - (b) The maximum frequency (X) of anticipated use and whether X will evolve with time.
  - (c) Phased deployment of different antenna types for an evolved roll-out of frequency coverage vs. use of one antenna type designed early on.
2. Achieving low system temperatures across wide bands using single broadband LNAs and feeds. It pays to put substantial effort into low  $T_{\text{sys}}$  systems because they trade against collecting area. Other options include:
    - (a) Use of dual 3:1 feed/receiver combinations if 10:1 systems cannot achieve adequate  $T_{\text{sys}}$ . Go to 2:1 systems if necessary.
    - (b) Covering more than 10:1 frequency range (e.g. 0.3 to 25+ GHz) will require two 10:1 systems, or four 3:1 systems.
    - (c) Phased deployment or rescoping science goals to a minimum is another approach to mitigating costs.
  3. Developing and testing image processing algorithms that allow science goals to be met, particularly for an all-sky HI galaxy survey to redshifts of at least 1.5 but also for continuum surveys. Image processing costs scale very strongly with an inverse power of antenna diameter and thus drive costs.
  4. Managing and mitigating radio frequency interference (RFI) so that sensitivity goals can be met for imaging, spectroscopy and time-domain science. We currently do not think that RFI is any kind of show-stopper for either of the two sites that have been identified for the SKA (the Karoo in South Africa and the Boolardy site in Western Australia). Measurements by the SPDO (in its previous incarnation as the ISPO) indicate that the two sites are substantially better than sites with current radio telescopes, as quantified by spectral-temporal occupancy and power levels) Moreover, the two sites are now protected under radio-quiet zone agreements. Nonetheless, RFI from satellites needs to be tracked and understood in terms of its affect on SKA measurements. The TDP is not funding this area explicitly, but TDP participants are involved in other projects or facilities that will provide information that the TDP can consolidate and deliver to the international project.
  5. Developing a processing plan for widefield surveys of steady and time-variable sources in a synoptic survey mode.

Along with technology risks, programmatic issues affect the SKA project. The TDP cannot address funding constraints in the U.S. or elsewhere, but it can promote development of a fully multi-wavelength approach (as well as non-photonic techniques, such as gravitational wave detection and constraints on the neutrino mass) to surveys and follow up observations that address overarching science goals.

**2.6 Contingencies:** Direct cost uncertainties are largest in the area of antenna manufacturing and deployment. The project office has specified appropriate consulting funds to allow flexible use in working with industry. The budget has explicit contingency funds to cover

unanticipated costs. Flexibility has been built into the TDP for providing personnel to the CDIT via the SKA Research Associateship (WBS 5) in order to meet goals of the TDP and PrepSKA.

Project decisions will be made during the four years in accord with milestone achievement and evolving science priorities. Some of these, such as the choice of frequency range to cover in initial construction will influence the scope of the TDP as we proceed.

**2.7 Integration with PrepSKA:** The TDP work plan explicitly provides results to PrepSKA. Elements of the WBS for the TDP are mentioned explicitly in the work packages for PrepSKA, particularly from our WBS 1 and 2 areas. Consolidation of results into SKA designs comprises joint efforts under TDP areas WBS 2 and 3. The TDP Project Director sits on the PrepSKA board, which will have its first meeting in 2008 April. The timeline for the TDP overlaps that of PrepSKA and the primary end goal is the same: to provide a baseline design for the first construction phase of the SKA.

### **3.0 Organization of U.S. SKA Activities and the TDP**

The TDP was conceived of and developed by the US SKA Consortium, which has organized U.S. SKA efforts since 2000. Cornell University via NAIC offered in 2001 to manage NSF-funded SKA efforts for the Consortium and that has led to the current TDP. The TDP is centrally managed at Cornell as shown in the organizational chart, Figure 1. The TDP is associated with NAIC because administrative staff that handle grants, subawards and TDP logistics are shared. No funds go to NAIC for Arecibo-related activities.

### **3.1 The U.S. SKA Consortium**

The USSKAC has been the forum for U.S. participation in the SKA since 2000. The TDP itself has been planned through consensus reached in semiannual meetings and telecons of the USSKAC. During the course of the TDP, the Consortium will remain both a stakeholder in U.S.' contributions to the SKA project and a source of advice for the TDP. Consequently, as shown in Figure 2, the Consortium will form a USSKAC TDP Executive Committee, comprised of those members of the Consortium that can provide advice on both technical matters and programmatic issues. It is envisioned that project decisions — including any changes in work plan that ensue from intermediate results of the TDP or through interaction with the international SKA project — will be reached by consensus between the TDP Project Office and the USSKAC TDP Executive Committee.

The Consortium comprises the following full-member institutions:

- California Institute of Technology with the Jet Propulsion Laboratory
- Cornell University (with the National Astronomy and Ionosphere Center)
- Harvard-Smithsonian Center for Astrophysics
- Massachusetts Institute of Technology with Haystack Observatory
- National Radio Astronomy Observatory (NRAO)
- Naval Research Laboratory (NRL)

## U.S. SKA TDP Organization

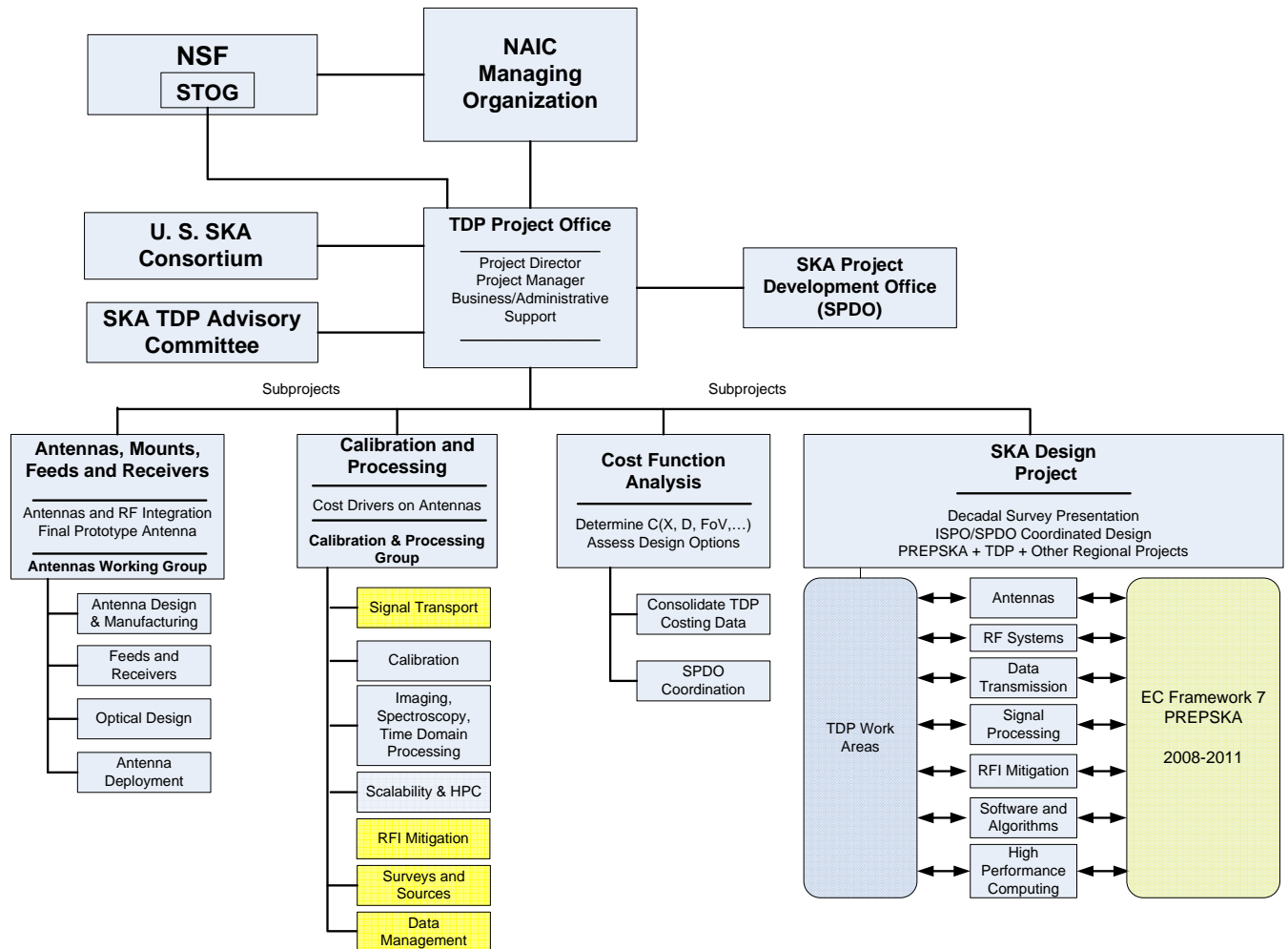


FIG. 2.— Organization of the TDP. The two primary work areas are “Antennas, Mounts, Feeds and Receivers” and “Calibration and Processing.” Subprojects of these work areas are drawn as blue boxes if they are directly funded by the TDP while those in yellow are areas that are important to the TDP but not supported by TDP funds. Additional work by the project office is for a “Cost Function Analysis” that consolidates work done in the first two areas. Coordination with the (international) SKA project takes place at two levels: (1) via TDP Project Office interactions with the SPDO (upper right) and (2) via working groups associated with the PREPSKA design project, as shown on lower right.

SETI Institute

University of California at Berkeley

University of Kentucky (under consideration)

University of Illinois

University of New Mexico

University of Wisconsin

There are two representatives from each institution and several at-large members: S. Weinreb (Caltech), D. Jones (JPL) and C. Lonsdale (MIT/Haystack). There also are associate

member institutions.

The U.S. SKA Consortium is a major stakeholder in the TDP in addition to approving Cornell's leadership of the TDP. The TDP Project Director will make reports to the Consortium at its biyearly meetings and more frequently, as needed.

### 3.2 SKA-TDP Advisory Committee

In agreement with the NSF, an SKA-TDP Advisory Committee (SAC) has been set up to make a top-level review of the TDP — its goals and achievements — and to make mid-term recommendations about how to proceed.

#### 3.2.1 Membership

Membership of the SAC is

1. Sarah Church (Stanford)
2. Phil Diamond (Jodrell Bank Observatory, University of Manchester)
3. Paul Goldsmith (JPL)
4. Peter Hall (Australia National Telescope Facility)
5. John Webber (NRAO)

#### 3.2.2 Responsibilities

The SKA TDP Advisory Committee (SAC) is to advise the TDP Director and his staff on issues of project management and radio-astronomy technology and also to make high-level reviews of the TDP work plan. The SAC is to meet face-to-face once per year and by teleconference, as necessary.

**3.3 SKA-TDP Antennas Working Group (AWG):** An important part of the TDP is assessment of antenna manufacturing methods so that we can assess costs vs. diameter and upper frequency rolloff. This subproject will build upon experience from the ATA, from prototype antennas for the DSN Array, and from our international partners working on pathfinder projects (ASKAP: Australia and Canada; MeerKAT: South Africa). It will also use industry expertise. We will look at antenna optics that accommodate feeds developed under the TDP and as well as phased-array feeds (PAFs) developed as part of the Australian and Canadian effort for ASKAP. Specifically, though the TDP includes explicit development work only on wide-band, single-pixel feeds (SPFs) and receivers, the options we develop for antennas and mounts must take into account the possibility that they will be outfitted with PAFs along with SPFs. The go/no-go decision on PAFs is several years in the future and is dependent on technical work and decisions about science priorities.

To ensure that we have a coherent plan that evolves through the duration of the TDP, the Antennas Working Group will develop the work plan and decision tree for identifying an optimal SKA antenna design and viable antenna manufacturing methods for large volumes of such antennas.

The TDP plan includes close consultation and collaboration with our international partners in the SKA project, on a no-cost basis. This is to occur in two ways. First, the TDP work is a U.S. contribution to the International SKA Project Office's SKA design study under the

PREPSKA project, now approved for funding by the EC. Second, we have agreed informally to bilateral interactions with Australia, Canada and South Africa on antennas and feeds. We may make these agreements somewhat more formal through an MoU.

Tasks that need to be done:

1. Define work aimed toward determining the cost function  $C(X,D,FoV)$  ( $X$  = upper frequency,  $D$  = diameter,  $FoV$  = field of view) so that informed trades may be made by the SKA Project Office working on PrepSKA.
2. What R&D is needed from antenna manufacturer(s) and industry consultants.
3. Assess work and results taking place outside the U.S.
4. Ensure that the work plan is consistent with PrepSKA and vice versa.
5. Develop a plan that is consistent with the general plan adopted by the International SKA Steering Committee of a phased-deployment plan for the SKA that involves three frequency bands (low, mid and high, with boundaries to be defined).

**Membership:** German Cortes (Cornell), Matt Fleming (Minex), Bill Imbriale (JPL), Roger Norrod (NRAO), Roger Schultz (Schultz Associates), Sandy Weinreb (CIT), Jack Welch (UCB), Peter Napier (NRAO)

External partners: Dave de Boer (ATNF) or designate from Australia, Peter Dewdney (DRAO) or designate from Canada, Justin Jonas (MeerKAT) or designate from South Africa, Phil Diamond, Richard Schilizzi (PrepSKA/SPDO) or designate from the SPDO.

**3.4 SKA-TDP Calibration and Processing Group (CPG):** Costs of antennas cannot be isolated from array-processing costs. Work must be done to identify algorithms for calibration, continuum imaging, spectroscopy and time-domain science and RFI mitigation. Signal and data processing costs are strong functions of the number of antennas and the field of view, so optimization of overall costs necessarily requires consideration of these issues.

**Membership:** Athol Kemball (U Illinois) (Chair), Geoff Bower (UCB), Jim Cordes (Cornell), Joe Lazio (NRL), Colin Lonsdale (Haystack/MIT), Steve Myers (NRAO), Jeroen Stil (U Calgary), Greg Taylor (UNM)

External partners: organized under PREPSKA, including Australian, Canadian, and South African participants

#### 4.0 TDP Management

Funding for the TDP is through a cooperative agreement between the NSF and Cornell University (see attached). An SKA-TDP Advisory Committee (SAC) will advise the Project Director on the progress and direction of the project. The members and charge of the SAC have been determined by the PD and the NSF. In addition, an SKA-TDP Oversight Group (STOG) has been established inside the NSF.

**4.1 Managing Organization** The managing organization is Cornell University, working under a Cooperative Agreement with the NSF (see attached document).

**4.2 TDP Project Office** The TDP Project Office includes a Project Director (J. Cordes), a full-time Project Manager (L. Baker), and part-time administrative assistance that includes a business manager (10% of D. Howe's time) and an administrative aide (15%).

**4.2.1 TDP Project Director:** The Project Director (PD) is responsible for the success of the TDP. This entails oversight of milestones and deliverables and actively using them to further the U.S.’ involvement in the international SKA project. To do so, he will play a liaison role to the international project, as he does currently (as one of the U.S. members of the SSEC, by contributing to the PrepSKA proposal to the EC, and through participation in the international Science Working Group). Over the course of the TDP, the PD will facilitate updating or other refinement of the project’s goals as needed during the project. The purpose of the TDP is to identify design options for the SKA with the implication that design choices will be made over the course of the TDP; this requires an active approach to the project. Because the TDP’s results and findings are of interest to the broad U.S. astronomy community, any changes in goals and methods for achieving them will be determined by consensus between the US SKA Consortium, which provides broad representation of the U.S. community, the TDP Project Office, and the WBS managers, who are on the front lines of the technical work and thus can provide critical input about feasibility, etc. The PD will supervise the Project Manager.

**4.2.2 TDP Project Manager:** The Project Manager (PM) is responsible for ensuring compliance of WBS outcomes with the timeline and deliverables of the TDP. He will communicate with WBS managers via telecommunications, video communications and face-to-face meetings. The PM will review the progress of subcontracted work and manage invoices related to that work. The PM will manage TDP documents, including technical reports, journal articles, and web-based information that represent outcomes of the work. The PM will consolidate TDP results into technical reports and communicate them to NAIC, the International SKA Project Office, and to the National Science Foundation. The PM will monitor performance of WBS managers and will recommend to the PD any personnel changes that are needed.

**4.2.3 TDP Project Administrator:** This position includes handling of sub-awards, working in conjunction with Cornell’s Sponsored Program Services office; contract management; financial accounting for reports to the NSF; and other activities.

**4.3 Interaction with Other Projects:** The fourth WBS area, the SKA Design Project, includes contributions from the TDP, as shown, to work packages defined under the Framework 7, EC-funded PrepSKA design project that will be lead by the International SKA Project Director (R. Schilizzi) and the SPDO. While the work packages are itemized somewhat differently than those under the TDP, there is a clear mapping of TDP work to that of PrepSKA. Our international colleagues are planning for and expect that work done under the TDP will explicitly accomplish work-package goals defined for PrepSKA. Work done in other countries is similarly being distilled into a focused plan for addressing project risks and designing the SKA. The mapping of regional efforts to PrepSKA work packages was an integral part of the activity leading to the PrepSKA proposal to the EC. The U.S. participated in PrepSKA planning meetings (Jodrell Bank Observatory, 2006 Oct; Bonn, 2007 Feb) and subsequent telecons that led to the proposal. The organizational chart in Figure 3 emphasizes the relationship between “regional” efforts, like the TDP, and the SPDO. The

SKA Design Project will balance regional efforts with those by a group that is physically centralized at the SPDO.

**Relationship of the TDP to Other U.S. Array Projects:** The ATA, EVLA, LWA and MWA are significant in terms of their scope and funding but also in their potential for contributing to the TDP and the SKA design effort. To various degrees, each of these projects will yield development and application knowledge that is useful to the TDP — from antennas and receivers to calibration and imaging and transient detection. It is therefore important that the TDP efficiently tap the expertise of those involved with these projects. At the same time, the TDP is not intended to help construct or operate any of these projects nor should the TDP place demands on the personnel from these projects that would distract them from their responsibilities to their projects. The approach we are taking is to fund a post-doc (or equivalent) from several of these projects, who will work on the TDP and will serve as liaison between the TDP and the particular array project. These personnel will be active in one or more of the WBS areas in which the project they represent is relevant, such as calibration and imaging, RFI excision, survey design, transient detection, etc. In the case of the NRAO and the EVLA, this function will be provided at no cost to the TDP. The DSN array project will make contributions to the TDP in the area of antenna manufacturing and optical design. This too will be at no cost to the TDP.

**Strategic Collaborations With Australia, Canada and South Africa:** TDP work is aimed at costing and defining the SKA. As such, it will be conducted in collaboration with the SPDO and its working groups. Under this umbrella, we have identified partnerships that are of particular strategic importance in achieving our goals. Groups in Canada at the DRAO and the University of Calgary are working on antenna manufacturing, phased-array feeds, and correlators in areas that highly complement TDP-funded work in the U.S. Australia's development of ASKAP and its associated components (including low-frequency antennas and phased-array feeds), will provide input for determining cost and also will provide a platform for testing feeds and algorithms in a low-RFI environment (the Boolardy site in Western Australia). South Africa's MeerKAT project will be a science capable array in its own right but also serves as an LNSD pathfinder for the SKA. We have agreed with the South Africans to pursue common interests under the context of the MeerKAT project and the TDP. A prime area is antenna-optics optimization and the development of broadband feeds.

The overall TDP plan is to consolidate the results of technology development conducted by the U.S., Australia, Canada and South Africa into a cost-function analysis that will form the basis for making tradeoff decisions on the Phase 1 array and for laying out an implementation plan for the SKA as a whole.

Like the ATA, ASKAP and MeerKAT will provide platforms for testing feeds and receivers and also for implementation of wide-FoV algorithms for calibration and imaging, transient detection, etc.

Table 6: The SKA, R&amp;D Projects and Related Pathfinder Arrays

| Project  | Entity                         | URL                  |   |
|--|--------------------------------|----------------------|---|
| <b>The International SKA Project:</b>                |                                |                      |   |
| SKA  | Square Kilometer Array         | International        | <a href="http://www.skatelescope.org/">http://www.skatelescope.org/</a>                               |
| <b>SKA Design Projects:</b>                          |                                |                      |   |
| PrepSKA  | Framework 7 Preparatory Phase  | Europe/international | TBD   |
| TDP  | Technology Development Project | U.S./international   | TBD   |
| SKADS  | SKA Design Studies (FP6)       | Europe               | <a href="http://www.skads.org">http://www.skads.org</a>   |
| <b>Pathfinder Projects (LNSD and Phased Arrays):</b> |                                |                      |   |
| ATA  | Allen Telescope Array          | U.S.                 | <a href="http://astro.berkeley.edu/ral/ata/">http://astro.berkeley.edu/ral/ata/</a>                   |
| MeerKAT  | Karoo Array Telescope          | South Africa         | <a href="http://www.kat.ac.za/">http://www.kat.ac.za/</a>   |
| LWA  | Long Wavelength Array          | U.S.                 | <a href="http://lwa.unm.edu/">http://lwa.unm.edu/</a>   |
| MWA  | Murchison Widefield Array      | Australia/U.S.       | <a href="http://www.haystack.mit.edu/ast/arrays/mwa/">http://www.haystack.mit.edu/ast/arrays/mwa/</a> |
| ASKAP  | Australia SKA Pathfinder       | Australia            | <a href="http://ntd-wiki.atnf.csiro.au">http://ntd-wiki.atnf.csiro.au</a>                             |
| <b>SKA Relevant Array Projects:</b>                  |                                |                      |   |
| DSNA   | Deep Space Network Array       | U.S.                 | <a href="http://dsnarray.jpl.nasa.gov">http://dsnarray.jpl.nasa.gov</a>                               |
| EVLA   | Expanded Very Large Array      | U.S.                 | <a href="http://www.nrao.edu/evla/">http://www.nrao.edu/evla/</a>                                     |
| eVLBI  | Real-time VLBI                 | Europe and U.S.      | <a href="http://www.express-eu.org">http://www.express-eu.org</a> , NRAO web site                     |

**4.4 Reports and Reviews** The TDP Project Office will report to the NSF and to the U.S. SKA Consortium every six months. The SAC will review the project in a face-to-face meeting once per year and in teleconference meetings as needed, most likely quarterly. Internal working groups (the AWG and the CPG) will hold meetings as frequently as needed and will report to the TDP Project Office on a quarterly basis.

Development of the SKA-optimized antenna will be subjected to a preliminary design review and critical time review in year 2 of the TDP in order to get delivery in late year 3 or early year 4.

## 5.0 Funding Agency Oversight Responsibilities

The NSF will provide general project oversight, monitoring, coordination, and evaluation of the ACT project to help assure effective Awardee performance and project administration. These agency activities will be coordinated through the SKA-TDP Oversight Group (STOG).

The primary responsibility of the STOG is to see that the SKA-TDP Project is effectively managed and executed. The STOG will coordinate agency policies and procedures regarding project oversight and management. The STOG will serve as the point-of-contact for the SKA-TDP Project Office with the NSF. The STOG will oversee implementation of the SKA-TDP Project Execution Plan (PEP). Additional responsibilities of the STOG include, but are not limited to:

1. Coordinating, as necessary, the level of effort from any individual-investigator grants, as they apply to the SKA-TDP Project; and monitoring performance of these efforts;
2. Conducting technical, cost, schedule, and management reviews in a timely and effective manner in accordance with the milestones the Project and STOG have set;
3. Reviewing SKA-TDP Project budgets and status reports;
4. Reviewing the NSF funding plans to assess their impact on the optimal execution of the objectives of the SKA-TDP Project;
5. Monitoring developments in the SKA-TDP Project and its related activities;

6. Reporting to senior NSF officials on major developments in, and external events affecting, the SKA-TDP Project; and
7. Identifying and forwarding issues to other NSF officials as appropriate. The STOG shall also perform such other activities as it deems appropriate and within its programmatic responsibilities, but within authorities as specified in the relevant award instruments issued by NSF. The membership of the STOG shall consist of appointees who are Program staff of the NSF Division of Astronomical Sciences.

## Attachments

### A. Table of Costs vs. WBS and Subawards

#### APPENDIX A

##### Cost Tables vs. WBS and Year

###### Summary WBS Project Budget

| WBS Task Name   | Yr 1             | Yr2              | Yr3              | Yr4              | Total             |
|---|------------------|------------------|------------------|------------------|-------------------|
| 1. Antennas, Mounts, Feeds, Rx                                | 1,378,368        | 1,375,844        | 1,494,462        | 1,453,224        | 5,701,899         |
| 2. Systems Analysis and Design                                | 514,000          | 534,560          | 424,377          | 441,352          | 1,914,288         |
| 3. Cost Function Analysis <sup>¶</sup>                        | 0                | 0                | 0                | 0                | 0                 |
| 4. SKA Design Project <sup>¶</sup>                            | 0                | 0                | 0                | 0                | 0                 |
| 5. SKA Research Associateship                                 | 100,548          | 104,570          | 108,753          | 113,103          | 426,973           |
| 6. TDP Management   | 446,951          | 447,101          | 461,126          | 473,598          | 1,828,777         |
| 7. USSKA Consortium Participant Costs<br>(Includes ISPO dues) | 456,882          | 449,425          | 481,782          | 489,223          | 1,877,312         |
| IDC on subs   | 103,250          | 88,500           | 29,500           | 29,500           | 250,750           |
| <b>Total</b>  | <b>3,000,000</b> | <b>3,000,000</b> | <b>3,000,000</b> | <b>3,000,000</b> | <b>12,000,000</b> |

¶ WBS 4 and 5 show no extra cost but are implicitly covered by the TDP Project Office (WBS 6)

###### Subawards as currently defined:

Funds are budgeted for subcontracts necessary to provide project support to consortium member institutions and vendors. The list of subcontractor tasks/funds by WBS is as follows:

| WBS Task Name   | Year 1           | Year 2           | Year 3           | Year 4           | Total            |
|---|------------------|------------------|------------------|------------------|------------------|
| 1. Antennas, Mounts, Feeds, Rx                                | 1,065,000        | 1,050,100        | 1,145,353        | 1,260,764        | <b>4,521,217</b> |
| 2. Systems Analysis and Design                                | 514,000          | 534,560          | 424,377          | 441,352          | <b>1,914,288</b> |
| 3. Cost Function Analysis                                     | -                | -                | -                | -                | -                |
| 4. SKA Design Project   | -                | -                | -                | -                | -                |
| 5. SKA Research Associateships                                | 100,548          | 104,570          | 108,753          | 113,103          | <b>426,973</b>   |
| 6. TDP Management   | -                | -                | -                | -                | -                |
| 7. USSKA Consortium Participant Costs (ISPO/SPDO Common Fund) | 383,000          | 373,000          | 400,000          | 409,000          | <b>1,565,000</b> |
| <b>Total</b>  | <b>2,062,548</b> | <b>2,062,230</b> | <b>2,078,482</b> | <b>2,224,218</b> | <b>8,427,478</b> |

###### Cornell Indirect Costs:

F&A costs have been proposed at the following rates: 59% (all 5 years) of Modified Total Direct Costs (MTDC). MTDC exclusions include capital equipment, GRA tuition/fees/health insurance, participant support costs, contingency, and subcontract costs in excess of \$25,000 per subcontract. The indirect costs on each subcontract are 59% of the first \$25,000.

**Inflation Factor:** Non-salary and wage costs have been inflated by 3% in years 2-5.

## B. WBS and Subproject Descriptions

WBS areas are outlined here with summaries of the work to be done, the issues to be addressed, how the work will be coordinated with the international project, and what the deliverables are.

### WBS 1: Antennas, Feeds and Receivers:

This work area will develop the fundamental building block for the array receptor, a parabolic reflector outfitted with feeds and receivers. The end product will be an optimized receptor design and a prototype that will be tested as a single system and also with an existing array (e.g. the ATA and the EVLA). Work will cover the mid-range band defined previously and will also consider the highest frequency range (up to 25 GHz and possibly higher, if feasible) in order that the SKA project can make deployment decisions about the rollout of the full frequency range.

**An Antenna Evaluation Matrix:** Optimization of antennas with respect to cost and performance necessarily involves consideration of manufacturing issues and industry expertise. A major contribution to the SKA's cost function is from antennas (including mounts), feeds and receivers. The wide variety of options can be mapped into a matrix that includes antenna type (fabrication), geometry, optics and the type of feed antenna or feed array. All of these cases need to be considered, some in depth, others only cursorily. If we recognize three antenna fabrication methods (segmented, composite and hydroforming), two geometries (symmetric and off-axis paraboloids), two kinds of feed optics (prime focus and secondary focus), and three broad classes of feed antennas (single-pixel feeds, focal-plane feed clusters, and phased-array feeds), there are  $3 \times 2 \times 2 \times 3 = 36$  possible cases.

The TDP will deliver a top-down assessment of all of these possibilities. Some cases can be dismissed right away, while others will need only a modest paper study based on prior experience, while still others can be considered by scaling from existing antennas, such as the ATA and DSNA prototypes. Only a small residual number will need explicit modeling and presumably only one will need prototyping.

The frequency range we will consider (e.g.  $1.4 \text{ GHz} \leq X \leq 25 \text{ GHz}$ , or higher) is larger than the likely range for the SKA, but to aid the decision process and for broad consideration as a general resource, we will study the extended range. For the high frequency part of the study, we expect to get assistance on a no-cost basis from the DSN array project.

Because cost will be influenced strongly by antenna type and manufacturing, we need to work closely with industry partner(s). An industry partnership would have as goals:

1. Determine the antenna/mount portion of  $C(X, D, \text{FoV})$ . It is the job of the TDP and SKA project to assess the FoV dependence of  $C(X, D, \text{FoV})$ , so an industry partner will focus on cost dependences on  $X, D$ , antenna type, and manufacturing method.
2. Identify break points in  $C(X, D, \text{FoV})$  related to antenna type, mount, manufacturing method, transport to site, etc.
3. Provide sufficient information to the TDP Project Office that we can interact with the International SKA Project Office and associated science and engineering working groups

to assess tradeoffs, i.e. to iterate with the international group on defining science scope and the implied design.

Under TDP funding, the U.S. alone cannot do all the work needed to assess these cases. We require a coordinated effort with PrepSKA and in particular with our SKA colleagues in Australia, Canada and South Africa who are also working on subsets of the antenna evaluation we have framed here. The matrix of potential combinations of antenna fabrication technology (segmented, composite or hydroformed), antenna geometry (symmetric or off-axis), optics (prime focus and secondary), and feed types (single-pixel, feed clusters, or phased-array feeds) is quite large. We expect that viable cases will be identified early within the TDP and detailed study will be needed on only a small subset.

Our foreign partners have development plans in place, especially for antenna fabrication, phased-array feeds, and associated electronics. Their work and TDP-funded work can be coordinated with no implied transfer of funds between the three countries.

### **WBS 1.1 Antenna Design and Manufacturing:**

Statement of Work: The goal is to assess costs of antennas of different sizes and types to aid cost estimates and to identify likely choices that meet science goals. The work will identify break points in the cost function vs. diameter and antenna type, including the cost of the mount. The work will include collaboration with at least one antenna manufacturer to assess costs associated with different manufacturing methods and also to identify innovations that reduce manufacturing costs.

By jointly working with antenna vendors and with independent antenna experts, provide a written assessment of all of the following:

- Manufacturing methods and suitability for mass production.
- Expected manufacturing precision and replication errors.
- Lifetime analysis, failure modes, maintenance requirements, and maintenance intervals.
- Susceptibility to environmental conditions. For hydroformed (and perhaps composite) antennas, susceptibility to “oil can” figure distortions resulting from solar heating.
- Expected gravitational deformations as a function of antenna diameter and zenith angle.
- Pointing accuracy for tracking and synoptic survey scanning.
- Design costs for project-specified specifications.

Industry assessment: Competitive contract among antenna vendors for the selected vendor to do a value engineering study of antenna reflector+mount design, manufacturability and technology. One key deliverable is a cost minimization assessment of reflector technology break points as a function of reflector diameter and highest operational frequency.

Cost assessment, with scaling laws: TDP project analysis based on input from the reflector fabrication assessments and the industry assessment.

Issues to be Addressed, Including Areas of Risk and Risk Reduction:

Antenna costs are a large fraction of the total cost of the SKA and are too high using current manufacturing methods for the anticipated total collecting area needed. Our goal is to identify a cost-effective solution that is affordable. Economies of scale will play a role in affordability but manufacturing innovations may also be needed. Factors that will be considered include the longevity and failure rate of mounts and reflectors, which impact maintenance costs. Costs may be dominated by mounts if high-frequency operation is chosen. Transport of antennas from factory to SKA site will be cost assessed. Work in this area will identify the most cost-effective solution for antennas.

Coordination with the International SKA Project: Collaboration with Canada will provide information on composite antennas while explicit TDP-funded work will focus on hydroformed and segmented antennas. Collaboration with Australia will provide information on antennas optimized for low frequencies. The SPDO will serve as a clearing house for antenna work done in South Africa and India on low-frequency optimized antennas as well. We will consolidate information from TDP-explicit work and from our international partners.

Deliverables:

A report on antenna cost  $C_A(X, D)$  vs. upper frequency  $X$  and diameter  $D$  for different manufacturing methods and for mounts optimized to the antenna.

A report on failure rate and longevity of antennas and mounts.

A report that assesses manufacturing plans for different antenna options.

A report that identifies the option for a prototype SKA antenna to be delivered in year 4.

Timeline:

Year 1: Antennas group defines task list for industry consultant(s) concerning definition of the antenna/mount component of the cost function,  $C_A(X, D)$ .

Let consulting contract(s) to industry consultant(s) with report expected by year end.

Initiate internal (to TDP) assessment of  $C_A(X, D)$  for other antenna types and plan for consolidation with report from antenna manufacturer. This includes ATA antennas and those considered for the DSN array and arrays being planned in Australia and South Africa.

Contribute to international roadmap plan.

Year 2: Continue work started in year 1; let additional consulting contracts as needed.

Integrate manufacturing assessment tasks with those of the international SKA project under the SPDO and PrepSKA. Contribute to preliminary design review in 2008.

Consolidate information from industry and partners for costing.

Identify preliminary options for antenna deployment for Phase 1 of the SKA and follow-on phases. This may include reflectors that can be retrofitted for higher-frequency work or it may include alternate reflector designs that would be deployed later on for high frequencies.

Year 3: Provide input to TDP decision on type of prototype antenna to be acquired under WBS 1.4.

Consolidate information from industry and partners for costing.

Year 4: Contribute to international decision on antenna choice for Phase 1 of the SKA and later phases.

Identify work needed to plan for deployment of high-frequency capable antennas.

## **WBS 1.2 Feeds and Receivers:**

Statement of Work: The goal is to determine the best feed and receiver technology for the SKA and validate the performance and cost of manufacture in the first half of next decade.

### **1.2.1 Single Pixel Broadband Feed Design**

Development and study of four broadband feed types will be done because it is not yet clear which architecture will yield the best performance. These include the axial ATA feed, currently designed for 0.5 - 11 GHz, a log-periodic, compact feed under development by P-S. Kildal (Chalmers University, Sweden), a quad-ridge feed at Caltech, and a quasi-self complementary feed at Cornell. The Chalmers work was originally funded through an NSF/ATI grant for SKA technology development.

The issues that drive the need for four parallel studies include: beam solid angle of the feed (or, equivalently, the gain), which has implications for the  $f/D$  of the antenna, impedance matching of the feed to a low-noise amplifier, and noise temperature vs. frequency.

Design and fabricate prototype feeds for the nominal frequency range under consideration for the SKA (1-25 GHz), with identification of break points for division into two or more bands (three identified here for specificity):

- Establish design requirements for SKA feeds (based on antenna optics,  $f/D$  specified by the TDP project) for each of the three frequency ranges: 0.3 – 1.7 GHz, 1.0 – 11.0 GHz, 11.0 – 25.0 GHz or 1.0 – 25 GHz.
- Optimize the design of each feed type for the three frequency ranges and produce a written report of the expected feed performance. Note in the report any problems anticipated in matching the feed to the LNA.
- Fabricate prototypes of the four types of feeds for the three SKA frequency ranges to matching requirements specified by the TDP project.
- Task includes separation of the polarizations as applicable to the specific feed design and assessment of feed cross talk.
- Deliver the prototype feeds to the TDP project for testing on 6m ATA and identified TDP/SKA reflector.

### 1.2.2 Phased Array Feeds (PAFs)

Development of focal plane phased arrays is actively progressing at several institutions worldwide for use on existing or planned telescopes at these institutions. The TDP project will coordinate with the institutions involved with these developments, including DRAO (Canada), the ATNF (Australia), U. Manchester (UK) and Astron (Netherlands). Wide instantaneous field of view is a requirement of the international SKA project and focal plane phased arrays are one approach to meeting that requirement. The TDP project will not allocate development resources to this task but will rely on the work done by our international partners. Focal plane phased arrays are high risk but have potential for very high return on survey capabilities. The TDP will seek single-pixel solutions but will incorporate the possibility that phased-array feeds will become viable by allowing for them in the design of the overall antenna optics (WBS 1.3).

### 1.2.3 Feed Clusters (0.7 – 1.4 GHz)

Feed clusters are a more conventional way to achieve wide FoV, such as those used on the Parkes and Arecibo telescopes (ALFA). Development of feed clusters for observations of redshifted hydrogen is actively progressing at several institutions worldwide for use on existing or planned telescopes at these institutions. The TDP project will coordinate with the institutions involved with these developments. Feed clusters are a fall-back position from focal-plane phased arrays to meet the FoV requirement. The TDP project will not explicitly develop feed clusters, but as with WBS 1.2.2, we will allow for their inclusion in one or more of the optical designs of WBS 1.3. Receivers for feed clusters will be considered only at the conceptual design level initially. Later in the TDP, if other contingencies suggest so, we may elect to develop a feed

cluster receiver.

#### 1.2.4 Receivers

To cover 0.3 – 25 GHz in three bands (0.3 – 1.7 GHz nominal, 1-11 GHz nominal, 11-25 GHz nominal) or two bands (0.3 – 1.7 GHz nominal, 1-25 GHz nominal). Most of the work will be done at CIT and U. Wisconsin with TDP funding. The U. Calgary group is also working on chip-level LNA development, initially with uncooled systems, that will also contribute to our effort at no cost to the NSF.

This task includes:

- Design and prototype of LNA for the specified frequency range and its packaging.
- The TDP project will specify the LO frequency and IF range requirements for the LNA in addition to the type of signal connectors.
- Task includes demonstration that the LNA can be cooled.
- Delivery of a written report of the LNA measurement of the gain and the receiver noise temperature across the entire frequency band of the LNA, cooled and uncooled.
- Delivery of prototype LNAs to the TDP project.

Specific tasks are:

1.2.4.1 Mid Frequency Receiver - A receiver package for the 0.3 to 1.7 GHz will be designed, fabricated, and tested with Tsys goals at 1.4 GHz of 30K by 2009 and 20K by 2012. The design will consider a variety of feeds, HEMT and SiGe low noise amplifiers, and operation without cryogenics.

1.2.4.2 and 1.2.4.3 High Frequency Receivers - These tasks are for design, fabrication, and test of a receiver package for 1.2 to 11 GHz with Tsys goal of 25K by 2009 and 18K by 2012. This design will require cryogenic cooling of the feed and LNA. New technology (Stirling or pulse tube) coolers which appear to be available for long life (> 50,000 hour MTBF) and low cost (<\$6,000) will be evaluated. A receiver for 11 to 25 GHz will also be prototyped.

1.2.4.4 MMIC Wafer Processing: Monolithic Microwave ICs that comprise the receivers will be cut in several foundry runs and packaged at Caltech.

**1.2.5 IF/LO Development IF/LO System** - A substantial portion of the cost of a large-N array is the portion of the receiver between the LNA and A/D converter. Integrated-circuit processes such as SiGe/BiCMOS or CMOS allow this to be accomplished mostly within a single chip with off-chip components such as microwave filters or photonic transmitters (if required) within a small hybrid. The goal for this hybrid is to accept a 1.2 to 11 GHz LNA output, and down-

convert a selected bandwidth selectable from 50 MHz to 1000 MHz to baseband in-phase and quadrature (I/Q) outputs.

[IF/LO designs] Design and prototype of the receiver LO and IF based on specifications of the SKA system LO and IF provided by the TDP project.

[LNA-A/D Integration (SiGe)] Design and prototype of a fully integrated LNA with its IF A/D circuitry based on specifications provided by the TDP project.

Study self-generated RFI for analog vs. digital approaches.

**1.2.6 Cryogenics Assessment and Development** By means of discussions with cryogenic system vendors and with independent cryogenic experts, provide the following:

- Assessment of cryocooler technology options suitable for the SKA based on specifications established by the TDP project.
- Assessment of COTS cryocoolers suitable for the SKA based on expected lifetime, failure modes, mean time between failures, maintenance requirements, power dissipation loads and efficiency.
- Recommend to the TDP project manager whether a COTS cryocooler should be purchased as a TDP prototype or whether a vendor should be engaged to design and/build one to project specifications.
- Procure the prototype cryocooler.

**1.2.7 Prototype Feed and Receiver Integration**

- Assemble and test the integrated prototype receivers, feeds and cryocooler in the laboratory.
- Deliver a report of the test results to the TDP project.
- Deliver the tested prototype subassemblies to the TDP project.

Issues to be Addressed, Including Areas of Risk and Risk Reduction:

The sensitivity of the SKA,  $A_{\text{eff}}/T_{\text{sys}}$ , is critically dependent upon the feed and LNA design and particularly upon how they integrated. Thus work will concentrate on complete packages tested on one or more SKA candidate antennas. The integration includes: a) match of the feed to the antenna optics, b) weather protection of the feed, c) feed to LNA impedance match, d) transmission lines between feed and LNA, and e) packaging commensurate with whatever cooling or temperature control that is required.

Coordination with the International SKA Project: The feed and receiver tasks recognize the international developments that are occurring in LNSD demonstration arrays such as ASKAP and MeerKAT which provide prototype antennas and much system integration and test information. Areas

where the US has more experience and a strong industrial base such as MMIC's, LNA design, and cryocooler development will be exploited in the TDP. The wideband feed development will be coordinated between groups in the US and Sweden. The feed cluster task, 1.2.3, is a back-up to the phased-array feed development in Australia and is a natural outgrowth of task 1.2.1 and 1.2.2.

Deliverables: Deliverables include single-pixel feeds (one or more, depending on the success of the four candidate designs) integrated with receivers. Performance reports for each candidate feed will be provided. A verifiable manufacturing cost estimate will be provided for viable feed and receiver designs.

Timeline: Work on the high frequency receiver has already started due to other funding. During the first two years concentration will be on development of single-pixel feeds and receivers with tests on prototype SKA telescopes in years 2 and 3. In Years 4 is for further improvements and consideration of manufacturing technology including cryocoolers leading to cost reduction for these receivers.

### **WBS 1.3 Optical Design and Performance:**

Statement of Work: The work consists of two parts: first we will obtain an appropriate optical design that matches the electromagnetic properties of each of the single-pixel prototype feeds under consideration in the TDP.

Second, to assess the expected antenna  $A_{eff}/T_{sys}$  as a function of frequency and elevation angle for each of the prototype feeds under consideration, including now both single-pixel and multiple-pixel feeds, with the assumption of a noise temperature background (that considers sky, atmospheric, and ground emission) which is also frequency and antenna elevation dependent. Information on multiple-pixel feeds will be obtained from non-TDP-funded efforts that are on-going.

We will calculate the antenna overall far-field radiation pattern, both co-polar and cross-polar at specified frequency bands for the SKA mission, when applicable, from 0.3 GHz up to a frequency  $X$  (as defined earlier) yet to be specified, (as large as 25 GHz, or perhaps even higher).

For the analysis we will rely on calculated or measured full radiation pattern of each of the feeds, both single-pixel and multiple-pixel, provided to us from other WBS or external collaboration within the frame of the TDP.

For single-pixel feeds, the work will identify the reflector optics geometries (symmetric, off-axis, prime focus, secondary focus) appropriate for each of these prototype feeds under consideration for the TDP.

We will analyze the performance of the different reflector types, optics

configurations, and feeds over a number of frequency bands determined by the type of wideband feed, starting at 0.3 GHz and ending at a high frequency yet to be specified, (initially 25 GHz). A number of the order 20 frequency points spanning the full band and specified at a later time will be analyzed for each wide band single-pixel feed.

For multiple-pixel feeds, which includes both prime focus feed cluster systems and prime focus focal phased array systems, in addition to the feeds radiation patterns, we will use the optics design provided to us from the appropriate WBS or external collaboration within the framework of the TDP. The number of frequency points to be considered for analysis for these types feed will be determined at a later time in coordination with the TDP project office.

For these types of feed systems we will also analyze the antenna performance when they are used in combination with a selected single-pixel reflector optics mentioned earlier.

We propose to identify a short list of optimal optical designs and specifications for a selected set of single-pixel feeds and compared these with the multiple-pixel design options.

#### 1.3.1 G/T Performance for Single-Pixel Feeds and Reflectors

Computational analysis of G/T as a function of frequency and zenith angle for reflector geometries provided by the TDP project and using the feed patterns of the single pixel prototype feeds measured in task 1.2.1. Note that the role of G/T performance in scientific observations is one of the subjects of WBS 2.5.

#### 1.3.2 G/T Performance for Multiple Pixel Feeds and Reflectors

[Feed Cluster System] Computational analysis of G/T as a function of frequency and zenith angle for reflector geometries provided to the TDP project (ATA antenna and TDP/SKA antenna) and using the feed patterns of the feed cluster systems measured or calculated by the institutions involved with these efforts (task 1.2.3).

[Focal Plane Phased Array Systems] Computational analysis of G/T as a function of frequency and zenith angle for reflector geometries provided by the TDP project and using the feed patterns of the focal plane array feed systems measured or calculated by the institutions involved with these efforts (task 1.2.2).

#### 1.3.3 Identification of a Short List of Optimal Designs and Specifications

TDP Project assessment of the results from tasks 1.3.1 and 1.3.2. Recommendation of options to retain for further analysis and prototype.

Issues to be addressed, including areas of Risk and Risk Reduction: One

of the issues to be considered from the beginning project is the reduction of the design space by a more precise delimitation of the antenna reflector diameter that will allow us to complete a preliminary optical design by the beginning of the second year into the project for the astronomy decadal survey, based on all relevant information gathered up to that point.

Factors that will be considered include: specifying a baseline edge taper illumination, polarization characteristics, both co-polar and cross-polar, blockage, antenna noise temperature as a function of elevation angle, antenna gain, beamwidth and sidelobe levels.

For single-pixel feeds, we will compare prime focus with secondary focus feeds when feasible, and also we propose to compare the performance of symmetric optics with respect to offset optics for selected feeds.

We will compare the antenna sensitivity ( $A_{\text{eff}}/T_{\text{sys}}$ ) of the single-pixel feeds configurations with the calculated performance of multiple-pixel feed configurations.

We will explore the possibilities of combining prime focus multiple-pixels systems with single-pixel feeds into the same optics.

Coordination with the International SKA Project: For the single-pixel feed cases, the work will include collaboration with the different feed prototype options WBS under consideration within the TDP framework to obtain detailed calculated or measured radiation pattern information, volume dimensions and matching characteristics.

For the multiple-pixel feed systems, the work will include collaboration with the Australian SKA Pathfinder (ASKAP) project office as well with the Canadian SKA project office to obtain detailed information about focal phased array feeds system radiation pattern and associated reflector optics. For the feed cluster systems, in addition to this avenue of collaboration we will collaborate with the South African SKA project office to obtain detailed information about feed cluster system radiation pattern and associated reflector optics.

Finally we will consolidate information from TDP-explicit work and from our international partners including also the European SKADS project.

Deliverables:

1. Identification of a preliminary optical design specification by the first half of year 2.
2. Identification of a short list of Optimal Design and Specifications.
3. For this list we will provide, far field radiation patterns cuts, Antenna noise temperature ( $T_a$ ), and  $A_{\text{eff}}/T_{\text{sys}}$  as a function of frequency and elevation, polarization characteristics, beam width and sidelobe levels.
4. A performance comparison between Symmetrical vs. Off-set design for selected cases.

5. A performance comparison between selected single-pixel vs. multiple-pixels feed systems for selected cases.

Timeline (Times relative to start of TDP): Feed radiation patterns will be quantified in year 1. Detailed optical design work will be concentrated in years 1 through 3, leading to a choice of design for the SKA antenna (in collaboration with our international colleagues) late in year 3 or early in year 4. This will provide input into specifications given to an antenna manufacturer in year 4 for providing a prototype antenna (task 1.4). Work will continue in years 4 and 5 on optical designs, as agreed upon for the international SKA project under the aegis of the FP7 design project.

### **WBS 1.4 Antenna Deployment:**

Statement of Work: The plan is to deploy up to two working reflectors during the TDP. The first will be a 6m antenna, either an off-axis ATA antenna or asymmetric antenna that can be used for testing new feed antennas and receivers as they become available in the TDP from WBS 1.2. The second antenna will be a fully optimized antenna — the result of TDP work in years 1 to 3 that is consolidated in WBS 1.3 and assessed according to overall performance of reflector, feeds and receivers. This second antenna has diameter, geometry, and manufacturing type that is to be determined in the first three years of the TDP. During the third year, a contract will be let for providing the antenna and delivery will occur in year 4.

A primary goal of this work is to operate and assess two kinds of feeds on the reflector — single-pixel, broadband feeds and phased-array feeds. This will be contingent, of course, on how well phased-array feed work progresses outside the US. If phased-array feeds appear promising, we will of course have to build an antenna that optimizes for use of both kinds of feeds.

#### **1.4.1 ATA/SKA Test Antenna**

Assemble, erect and commission a 6-m ATA/SKA test antenna at the ATA site to be used as a test platform for completed TDP prototype subsystems.

#### **1.4.2 Prototype Optimized SKA Antenna**

[Acquire/Fabricate Antenna and Mount] This task consists of the following:

- Establish complete antenna specifications for prototype antenna
- Determine whether the SKA prototype antenna should be procured from a vendor or whether only the reflector should be procured from a vendor with the TDP project responsible for erecting the prototype antenna using an optimized mount and a vendor-supplied reflector. We expect that both the antenna and mount will emerge

from close collaboration with industry.

- Assemble or procure the prototype antenna. Site TBD.

[Outfit the Prototype Antenna with Motors, SKA Prototype Receiver/Feed Subsystem and Integrate with Existing Array(s)] Fully outfit prototype antenna; deliver to TDP project for commission testing.

[Prototype Composite Antenna (10-m nominal)] Coordinate with the Canadian SKA team in assembling, outfitting and testing their prototype 10-m composite antenna. No exchange of funds in developing the antenna and mount. Depending on outcomes early in the TDP, we may outfit the Canadian reflector with single-pixel feeds in order to assess its on-sky performance.

#### Issues to be Addressed, Including Areas of Risk and Risk Reduction:

Paper and computer studies will play a key role in the TDP, but real-world, on-sky tests of feeds and receivers need to be done. The resulting information will provide critical input into the choice of antenna type and size, feed type, etc. The same holds true for deployment of a fully optimized antenna (which we term "SKA Antenna"), in which actual performance will contribute to the engineering design of the SKA that will take place in year 5.

Coordination with the International SKA Project: Australia and South Africa will be building arrays during the time period of the TDP that will use antennas optimized for low frequencies and have a size (12 to 16 m, TBD) based on only a subset of all the relevant considerations needed to design the Phase 1 SKA. Canada is expected to deploy a carbon-composite antenna of approximately 10m size. Our TDP-funded work and the work elsewhere nicely complement each other in exploring antenna space and our intention is to use the real-world tests on each antenna type as input to the cost-performance analysis that we will do under the TDP and that will be a primary US contribution to the international SKA design effort.

Deliverables: a 6m antenna and a TBD-diameter antenna with mount and receivers, most likely a hydroformed or segmented type reflector. In addition, access to a composite antenna and/or Canadian results on testing the composite antenna.

#### Timeline:

Years 1-3: assess antenna performance through paper studies and consolidated experience from JPL, NRAO, UCB, and industry.

Year 2: Delivery of 6m antenna for use in feed and receiver tests.

Year 3: Let contract for SKA antenna.

Year 4: Receive SKA antenna and outfit with feeds, receivers, and necessary signal transport hardware.

### **WBS 1.5 Antenna Performance Testing:**

Statement of Work: Antennas deployed in WBS 1.4 will be used as testbeds for new feeds and receivers and will serve as the basis for full systems tests, particularly of the SKA antenna. Work here includes all activities needed to assess performance: determination of pointing accuracy and stability, gain, system temperature, and beam shape vs. frequency.

Issues to be Addressed, Including Areas of Risk and Risk Reduction:

Real-world performance provides crucial input to design of the SKA and will impact overall cost, because science goals require particular G/T per antenna in order to determine the number of antennas needed.

Coordination with the International SKA Project:

Antennas, feeds and receivers tested will complement those being considered elsewhere around the world. Our results will be contributed directly to the international SKA design effort, particularly for Phase 1, which is likely to be based on paraboloids with single-pixel feeds. Broadband feeds like those developed in the US are critical to meeting science goals for Phase 1 and their performance needs to be assessed and understood in order to move the international project forward.

Deliverables: Test results and reports.

Timeline:

Years 2-3: tests of receivers and feeds on the 6m antenna.

Year 4: tests on the SKA antenna.

### **WBS 2: Calibration and Processing:** Manager: A. Kemball (U. Illinois)

**Goals:** Calibration and processing is recognized by the SKA program as a substantial area of design risk and project cost. Many calibration and processing issues required for the SKA represent substantial advances over current state-of-practice at existing radio interferometers. WBS 2 strengthens the TDP by developing a comprehensive case for achieving SKA science goals with a reference LNSD design. No plausible SKA construction proposal for either Phase 1 or the full SKA is possible without answering feasibility and cost equation questions concerning calibration and processing. These issues play a particularly important role in the SKA project as a result of the science need for large field-of-view and high sensitivity, and various considerations that drive digitization much closer to the receptors in contemporary radio interferometer designs, making calibration and processing costs an increasingly dominant design and cost driver. It is also important for the US to maintain engagement in this important area of the CDIT/PrepSKA and international SKA program. It is expected that calibration and processing costs will be large enough to influence the overall cost optimization and thus will influence both the diameter,  $D$ , and number of antennas,  $N$ , in Large- $N$  Small- $D$  (LNSD) designs, and, hence, the range of solutions pursued in WBS 1.

With a special focus on problems related to the LNSD parabolic antenna SKA design, single-pixel feeds, and the mid- to high-range SKA frequencies, the overall goals of this work package are to:

1. Determine the *feasibility* of calibration and processing required to meet the SKA science goals (e.g. dynamic range, calibration and imaging feasibility).
2. Determine the quantitative *cost equation contributions* and *design drivers* arising from calibration and processing, as a function of key design parameters (e.g. antenna diameter, mount type, frequency, instantaneous and multiple field-of-view, array geometry, bandwidth and spectral resolution, amongst other factors).
3. To *measure* algorithm cost and feasibility using *prototype implementations* of new or existing calibration and processing algorithms.
4. To *demonstrate* calibration and processing solutions using pathfinder data.

This work package will be organized as a TDP Calibration and Processing Working Group (CPG), with current members: Geoff Bower (UCB), Jim Cordes (Cornell), Athol Kemball (UIUC, Leader), Joe Lazio (NRL), Colin Lonsdale (Haystack/MIT), Steve Myers (NRAO), and Greg Taylor (UNM). The teaming agreement is described in Section 3 below.

**WBS 2.0: General:** Cross-cutting issues that are needed across WBS 2. The first concerns a science requirements matrix that maps each science goal to implied quantitative calibration and imaging requirements, including dynamic range and sensitivity, field-of-view, survey speed, and related issues. The second is a limited (given the existence of the SKA Simulations Working Group), though important investment in simulated skies and instrumental effects targeted in specific areas that are particularly important for research tasks in this work package. Other tasks include coordination of the CPG and liaison with PrepSKA/CDIT, and compilation and maintenance of CPG results and documentation.

**WBS 2.0.1:** Translation of SKA science goals into quantitative imaging and calibration requirements (For each of the SKA key science projects, what are the associated quantitative requirements they pose on resolution, sensitivity, imaging dynamic range and fidelity, field-of-view, and survey speed? What are the breakpoints in these relationships as a function of science sub-goals (e.g. Phase 1 versus full SKA) in each key science area?).

**WBS 2.0.2:** Sufficiently realistic model skies and simulated instrumental effects for WBS 2 research tasks (What is a sufficiently-realistic model sky and set of instrumental effects for the research tasks in WBS 2? What is the most cost-effective means of adapting an existing simulator to generate them?).

**WBS 2.0.3:** Coordination of CPG activities and project reporting within the TDP (Project management and coordination of the CPG within the teaming agreement outlined below).

**WBS 2.0.4:** Compilation and editing of CPG Project Book (Maintenance of a CPG project book, containing CPG results on feasibility, cost modeling, and demonstration of calibration and processing design elements and technologies addressed in the WBS, and including community meta-study results in areas in which the CPG is not directly active).

**WBS 2.0.5:** Liaison with PrepSKA/CDIT and national and international pathfinder projects (Coordination of research and development activities between the CPG and PrepSKA, attendance at SKA workshops and conferences, publication, and community engagement activities).

**WBS 2.1: Signal transport:** The large-N aspect of LNSD designs poses important calibration and processing issues that depend on the design of the immediate (pre-calibration) telescope data flow. LNSD arrays have data rates that make storing all visibilities prohibitive; this in turn poses important calibration and imaging constraints (e.g. full self-calibration is not possible). Similarly, station formation from individual elements is an important aspect of LNSD designs, but it will strongly affect calibration and processing, depending on beam-forming methods used (e.g. stability and ability to calibrate station beam sidelobe patterns).

WBS 2.1.1: Real-time calibration and imaging, without storing all visibilities (Does this operational mode allow all required calibration and imaging needed to meet SKA science goals? To what degree will this calibration and processing mode require (and permit) downstream reversibility or science product refinement?).

WBS 2.1.2: Beam-forming and station aggregation:

- Sidelobe stability and calibration of station beams (Do station beam sidelobe levels and beam pattern stability permit SKA imaging at the required dynamic range? ).

WBS 2.1.3 Central processor signal transport, processing, and architecture (What is the cost model for the reference SKA LNSD central processor data transport architecture and what implications does the architecture have for downstream calibration and processing?).

**WBS 2.2: Calibration algorithms:** Key instrumental or propagation effects for which robust, stable solvers and optimized parametrized models need to be fully developed to meet the high dynamic-range imaging requirements of the SKA. These calibration effects are primarily, but not exclusively, image-plane generalizations of corrections typically determined and applied in the visibility plane by current interferometers.

WBS 2.2.1: Calibration parametrization and interferometric solvers for image-plane effects:

- WBS 2.2.1.1 Non-isoplanatism
  - Full-field gain self-calibration (Will full-field gain self-calibration be feasible at mid to high frequencies with weaker sources and smaller fields-of-view?)

- Peeling or source partitioning strategies (Does peeling or source partitioning meet the calibration and imaging requirements needed for SKA science goals?)
- General, position-dependent parametrized models (Are more general, parametrized models needed to address non-isoplanatism at the level of SKA calibration and imaging goals? Are these methods stable and robust?).
- WBS 2.2.1.2 Antenna pointing (Is interferometric antenna pointing self-calibration sufficiently robust and stable to meet SKA calibration and processing requirements? Do systematic errors in source or beam models prevent pointing calibration accuracy at the level required by the SKA? What are the implications for antenna pointing performance specifications?)
- WBS 2.2.1.3 Beam response (time- and frequency-dependence) (Is there a sufficiently accurate parametrization of LNSD SKA beams (either TDP antenna-specific or generic parametrization) and is there a stable and robust associated interferometric solver? What constraints do the limits imposed by feasible interferometric beam response calibration place on antenna and feed designs?).
- WBS 2.2.1.4 Polarization beam response (time- and frequency-dependence) (Analogous to questions in beam response calibration, as above, but addressing polarization-specific aspects of this problem).

WBS 2.2.2 Calibration parametrization and solvers for visibility plane:

- WBS 2.2.2.1 Bandpass (Given expected SKA sensitivity per spectral channel, and proposed multi-pixel focal plane configurations, are there feasible bandpass response function parametrizations and solvers that meet SKA calibration fidelity requirements? What hardware design and observing operations constraints does this pose on TDP antenna and back-end designs?).
- WBS 2.2.2.2 Non-closing errors (At what point do non-closing errors provide a ceiling to achievable SKA imaging dynamic range, and is this beneath the target SKA requirements? What is the origin of the non-closing errors (e.g. polarization) at the ultra-high dynamic ranges required by the SKA and how can they be corrected?).

WBS 2.2.3 Stability and robustness of large-parameter image and visibility plane calibration solvers (SKA calibration parametrizations typically have a large number of free parameters, driven primarily by SKA imaging fidelity requirements; are these parametrizations and their associated solvers convergent and numerically stable for real data? Do these high-order parametrizations impose implicit constraints on instrumental effects (e.g. smoothness or time-variability) that are unphysical for realistic LNSD antenna, feed, and back-end designs or do they pose unaffordable constraints on these designs?).

**WBS 2.3 Imaging, spectroscopy, and time-domain imaging:** Imaging

modes known to be required to meet the dynamic range and sensitivity requirements of the SKA. For non-coplanar baselines, faceted wide-field imaging has been in specialized use for a decade or more, while w-projection is a contemporary algorithm. Other wide-field imaging strategies have been proposed (e.g. delay field-of-view shaping). Interferometric imaging incorporating time- and frequency-dependent image-plane instrumental effects primarily remains an area of current research, but will be essential for SKA imaging goals. All these image formation algorithms have substantial feasibility and cost implications for the SKA.

WBS 2.3.1 Wide-field imaging with non-coplanar baselines (What is the subset of non-coplanar imaging algorithms, and which is most optimal amongst them, for meeting SKA imaging requirements? What are their true theoretical cost scaling laws as a function of SKA design parameters, particularly antenna diameter?). WBS 2.3.2 Full beam imaging with rotating, offset, polarized, non-symmetric beams (Is full-beam imaging with realistic LNSD beams, i.e. beams with pointing offsets, non-rotationally-symmetric structure and polarization response, (solved for as discussed above), feasible for SKA imaging goals? How do their computational costs (a sensitive function of required binning in time or parallactic angle) drive antenna design decisions (e.g. antenna mount type)?). WBS 2.3.3 Full-beam imaging in the presence of confusing sources; related edge effects (What are the true sources of full-beam imaging errors away from the pointing center, at the level of dynamic range required by the SKA? Is it feasible to correct these (e.g. through improvements in the knowledge of beam response frequency dependence, source spectral indices, and deconvolution of confusing sources, amongst others)? WBS 2.3.4 Continuum subtraction in spectral-line imaging modes (What are the optimal continuum subtraction methods for SKA LNSD spectral-line observations? What are the dynamic range limits of these algorithms?).

**WBS 2.4 Scalability and high-performance computing:** This area concerns the efficient parallelization of SKA calibration and imaging algorithms to achieve adequate cost, performance, and scalability (sufficient parallel efficiency as the number of processors is increased to the required level) to meet SKA science goals. The costs and scalability of calibration and processing algorithms are a large component of the SKA design optimization, as noted above. There remains much to be done in this area for the SKA program. Matching advances in computational science and engineering will be essential to deploy parallel, scalable calibration and imaging algorithms needed by the SKA. This includes mapping SKA calibration and processing algorithms to projected high-performance computing architectures that will be available to the SKA Phase 1 and full telescope designs. This is a critical matching activity in order to achieve feasible cost, performance, and scalability of SKA calibration and processing algorithms. Experience across the physical sciences shows that a substantial investment is needed to achieve sustained high-end computational performance, as will be needed for the SKA.

WBS 2.4.1 Parallelization of calibration and imaging algorithms (What

are the optimal parallelization strategies for the calibration and imaging algorithms required by SKA (as determined from the tasks described in the preceding sections)? Do those algorithms that are not fully separable into uncoupled processing tasks (so-called “non-embarrassingly-parallel” problems) parallelize sufficiently to achieve SKA calibration and imaging requirements?) WBS 2.4.2 Scalability of calibration and imaging algorithms to petaflop architectures (What is the net parallel efficiency of SKA calibration and imaging algorithms (relative to SKA science goals) when scaled to teraflop systems (hundreds to thousands of processors; as needed by current pathfinders) or petaflop systems (hundreds of thousands of processors; as needed by Phase 1 or the full SKA)? What are the break-points in the scaling relations, their underlying causes and SKA design cost implications?) WBS 2.4.3 Algorithm-specific acceleration (Will acceleration hardware (e.g. general purpose graphical processing units (GPGPU), field-programmable gate arrays (FPGA)) be needed to achieve SKA calibration and imaging cost and performance goals? If needed, what will be the implications of their adoption on SKA hardware, software, and engineering costs?). WBS 2.4.4 Benchmarking and measuring computational costs (What will be the actual measured performance, at petaflop scale, of SKA calibration and imaging algorithm benchmarks? What cost implications will measured bottlenecks in I/O, computation, or memory bandwidth have on SKA computing cost models, both hardware and software, and optimal parallelization strategies?) WBS 2.4.5 Cost of calibration and processing computing hardware required (What is the projected architecture of HPC systems on the time-scale of SKA and how closely will commodity systems match SKA needs (e.g. CPU clocking limits are driving processors to highly multi-core architectures; will SKA algorithms map to these architectures)? What are the cost curves for computing hardware required to meet SKA science goals?).

**WBS 2.5 RFI:** This area concerns the mitigation of radio-frequency interference for LNSD SKA designs. This research activity is not directly-funded in the TDP, so this task includes only tracking PrepSKA or community developments in this area.

WBS 2.5.1 Tracking PrepSKA or community developments in RFI mitigation relevant to LNSD SKA designs.

**WBS 2.6 Surveys:** This area concerns the development and optimization of commensal survey strategies for LNSD SKA designs. This research activity is not directly-funded in the TDP, so this task includes only tracking PrepSKA or community developments in this area.

WBS 2.6.1 Tracking PrepSKA or community developments in survey design and optimization relevant to LNSD SKA designs.

**WBS 2.7 Data Management:** This area concerns data management for LNSD SKA designs. This research activity is not directly-funded in the TDP, so this task

includes only tracking PrepSKA or community developments in this area.

WBS 2.7.1 Tracking PrepSKA or community developments in data management relevant to LNSD SKA designs.

**Teaming agreement:** The organizing principles under which the CPG will operate are:

1. The group will be a design and development research working group, tasked with producing agreed upon deliverables meeting the goals outlined in Section 1. The group will not be a production software engineering effort for the SKA program.
2. The working group leader will foster collaboration and coordination, collate results, assist the TDP Project Office as needed with reporting and planning for the group, and monitor and engage international SKA program activities in this area at the CDIT/PrepSKA and pathfinder projects. Coordination with PrepSKA will ensure that the goals of the TDP and the goals of PrepSKA are overall the same and that the work will be complementary.
3. Research tasks will be divided cleanly across sites, so they can proceed efficiently without fine-scale central coordination, in so far as possible, with every effort made also to map tasks to local expertise and experience.
4. Prototype development as part of the research tasks will be software package-neutral, i.e. delivering answers to the TDP goals is the highest priority; any software package that allows this can be used for a given research task.
5. Some members of the CPG will be funded directly by the TDP grant, others will contribute in-kind. Small-fraction FTE contributions funded by the TDP will be avoided where possible, due to well-established difficulties this introduces in terms of time-scheduling and overhead.
6. Face-to-face meetings will be held approximately every 6 months by the CPG. The working group will encourage US community engagement and be open to community input and interaction.

This work package aims to address the sub-system goals listed in Section 1, so that it can feed directly into the high-level TDP objective of producing a costed LNSD reference design for the SKA. As in the broader TDP, this sub-system requires cooperative engagement with PrepSKA/CDIT and national and international SKA pathfinder projects. Figure 1 shows the schematic execution plan for WBS 2. The base of this workflow shows prioritized calibration and processing issues, as expressed in the WBS, that need to be resolved in order to produce a costed, feasible SKA design. These issues need to be explored as a function of relevant reference design parameters (e.g. antenna diameter, mount type, mid-range upper cutoff frequency, and other factors noted above). As discussed above, these calibration and processing issues will be addressed by focused prioritized research within the TDP project or, wherever possible, by leveraging results obtained by PrepSKA/CDIT or national or international SKA pathfinder projects. The deliverables that flow upwards are feasibility assessments, quantitative cost equation contributions, and prototype implementations and pathfinder demonstration results (where possible).

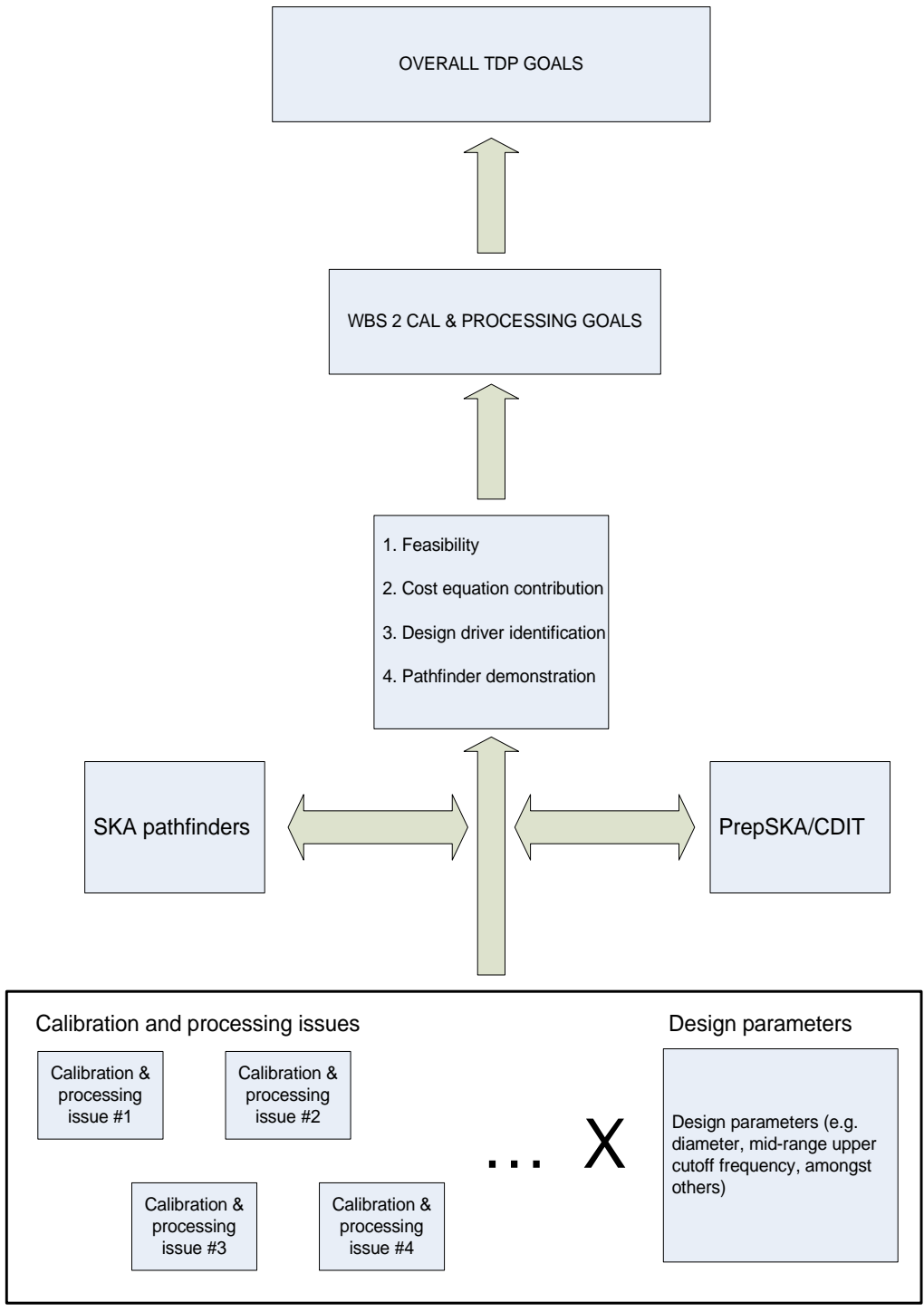


FIG. 3.— WBS 2 schematic execution plan and workflow.

**Calibration and processing issues not covered by TDP WBS 2** This section lists those calibration and processing issues not currently included in WBS 2. They are important for the SKA science goals but are assigned a lower weighted priority given limited TDP resources, and work known to be underway elsewhere in PrepSKA or the international SKA program.

1. **General (not sub-prioritized)** Cross-cutting, general issues not covered in the TDP.
  - (a) Multi-resolution and multi-frequency synthesis and deconvolution
  - (b) Pixon or shapelet deconvolution
  - (c) Optimal deconvolution of extended emission
  - (d) Automatic source extraction and deblending
  - (e) Compilation and updating global sky catalogs including source spectral indices for multi-frequency synthesis.
  - (f) Non-imaging science (e.g. transient detection, pulsar signal processing).
  - (g) Optimal detection strategies
  - (h) Software engineering cost estimation
  - (i) Advanced calibration and imaging pipeline processing heuristics for non-survey modes.
  
2. **Issues related to LNSD designs with multiple-pixel feeds (not sub-prioritized)** These issues are important for SKA LNSD designs that include multiple single-pixel or phased-array feeds in the focal plane. In this area, we will get input from international collaborators in PrepSKA, including Australia, Canada, and South Africa, that have or will have significant investments in developing these technologies for their pathfinder telescopes. The TDP calibration and processing group will remain highly cognizant of multiple-pixel contexts for LNSD designs however, especially when examining scaling laws for processing costs.
  - (a) Multiple single-pixel feed LNSD arrays:
    - i. Optimal calibration and survey strategies
    - ii. Optimal survey mosaicing with multi-feed arrays
    - iii. Efficient bandpass calibration
  - (b) LNSD arrays with focal plane phased array feeds:
    - i. Gain stability and gain calibration
    - ii. Polarization calibration and element coupling
    - iii. Efficient bandpass calibration
    - iv. Optimal beam weighting, shaping and forming
    - v. Eigenbeam decomposition calibration methods
    - vi. Implications of non-rotating and rotating focal-plane array (FPA) mounts

vii. Optimal survey mosaicing with FPA systems

### 3. Issues more important for low frequencies or non-LNSD designs (not sub-prioritized)

These issues are particularly important for lower SKA frequencies or non-LNSD designs, such as tiled aperture or dipole arrays.

- (a) Optimal calibration effect parametrization and solvers:
- (b) Ionosphere:
  - i. Non-isoplanatism
  - ii. Phase-screen models (including Zernike expansions)
  - iii. Calibration over a scale range of baseline lengths
  - iv. De-focusing on longer baselines
- (c) Receivers and IF signal path
- (d) Digital signal processing effects
- (e) Calibration redundancy solvers and/or baseline-length bootstrapping of calibration solutions
- (f) Calibration using external auxiliary data
- (g) Imaging with dynamic, adaptive, time- and position-variable beam

### **WBS 3: Cost Function Analysis:** Manager: The TDP Project Office et al.

Statement of Work: The primary goal is to determine the cost function  $C(X, D, \text{FoV})$  as defined previously to inform decisions about design and phasing of construction for the SKA. The cost function will include information from TDP-funded work in WBS 1 and WBS 2 and also from exchange of information with international groups working on complementary technology and/or on collaborative work (such as calibration and imaging, which will be highly collaborative). Work on costing is also taking place under the SPDO and the SKA Project Engineer (Peter Dewdney), who are working with the SKADS team in a complementary effort. Our work on costing will be collaborative with the international effort too, but we also see the benefit of maintaining independence in order to cross-check costing estimates.

#### 3.1 Consolidate Input from TDP Subprojects 1.0 and 2.0

##### 3.1.1 **Antennas, Mounts, Feeds, Receivers Costs and Scaling Laws**

Assemble all the test, technical and costing information from the project technical tasks and establish a methodology to extract costs in a systematic, parameterized manner. Deliverables are reports and software tools.

##### 3.1.2 **Systems Costs and Scaling Laws**

Assemble all the technical and costing information from the systems costs and establish a methodology to extract costs in a systematic, parameterized manner. Deliverables are reports and software tools.

### 3.1.3 Contribute to International Cost Equation

Coordinate the costing methodology and results from the TDP project with the international SKA project team working on costing the SKA project.

## 3.2 International Pathfinder Results

### 3.2.1 Consolidate Antenna Results from Regional Efforts Around the World

Work done in coordination with the SPDO and based on experience with SKA prototype antennas from regional SKA national efforts.

### 3.2.2 Consolidate Systems Results from Regional Efforts

Work done in coordination with the SPDO and based on experience with SKA system analysis from regional SKA national efforts.

### 3.2.3 Participate in SPDO Consolidation of Other Relevant Cost Information

Coordination task to assure full US representation in international SKA project

## 3.3 Develop Full Cost Analysis for Use in SKA Construction Proposals

Task to fund U.S. participation in the SPDO costing of the international SKA.

Issues to be Addressed, Including Areas of Risk and Risk Reduction: Costing, costing, costing.

Coordination with the International SKA Project: See statement of work.

Deliverables: Costing data from WBS 1 and 2 and from our international partners. Cost equations for subsystems of the SKA and for the entire project. Software that evaluates costs. Reports and conclusions about costs.

Timeline: Costing efforts will be ongoing throughout the TDP, and continuing thereafter in the lead-up to Phase 1 construction and in planning for post-Phase 1 construction. Interim reports will be made as needed to inform the broad community (e.g. via the U.S. decadal survey), funding agencies, and partners in the SKA project.

## **WBS 4: SKA Design Project:** Manager: The TDP Project Office

Statement of Work: This work area targets the 2008-2010 time frame (inclusive) for developing a project design for Phases 1,2 and 3 of the SKA, where Phase 1 is approximately the first 10% of sensitivity with (perhaps) reduced frequency and baseline coverage and reduced field of view. We are planning close collaboration with the European Framework 7 Design Project for this effort. Under this plan, the engineering design would be done in 2011 with Phase 1 construction commencing in 2012. It is not clear that this aggressive schedule for Phase 1 construction can be met, but the International SKA Project Director (R. Schilizzi) has laid this out as the goal. Regardless of any slippage for Phase 1, the TDP will provide input crucial for project decisions as well as providing technology that may find uses in pathfinders and prototypes leading up to the SKA.

- 4.1 Consolidate Design and Cost information from WBS 1-3
- 4.2 Develop prototype antennas (fully outfitted) as needed for SKA assessment
- 4.3 Conduct science simulations needed for project decisions about construction phasing.
- 4.4 Design hardware backend design(s) and prototype(s) for Phase 1

Issues to be Addressed, Including Areas of Risk and Risk Reduction: The design project necessarily addresses all factors relevant to constructing and operating a major radio array. The PrepSKA design project comprises work packages that address all these factors and the TDP contributes to many of them. WBS 4 of the TDP explicitly accounts for TDP participation in PrepSKAa. Many of the contributions are included in WBS 1, 2 and 3 and thus are not itemized here. Consequently, costs associated with WBS 4 appear modest in the budget but are much larger than they appear because they are included in WBS 1-3. Explicit costs for WBS 4 target support of U.S. scientists and engineers for particular work areas that either bridge TDP work to PrepSKA or for areas not explicitly included in the TDP under WBS 1-3 but for which U.S. expertise is needed. The explicit WBS 4 costs are a vehicle for this U.S. contribution via summer salary, sabbatical leaves, or fully funded engineer, as needed.

Coordination with the International SKA Project: Coordination, as described above, is through PrepSKA, directed by the SPDO and with explicit U.S. contributions to specific work packages.

Deliverables: Subsystems designs and full SKA design, with costing.

Timeline: WBS 4 will proceed through the entire TDP. Initial work in year 1 will provide a baseline design, with costing, for consideration by the U.S. astrophysical community. Work in will be highly coordinated with the PrepSKA, leading to preparations for the construction phase as soon as possible thereafter.

### C. Schedule

**WBS Timeline:** Table 7 shows the timeline for the TDP along with milestones for the SKA Project. Our four-year plan meshes well with that for PrepSKA. The outcomes of the TDP, PrepSKA and pathfinders will be a plan for the SKA program and a detailed design for Phase 1. Additional engineering will be needed prior to construction of Phase 1 (which, optimistically, may within a year or two after the FP7 project is done).

**TDP Timeline:** The timeline for the TDP is closely tied to the external timeline milestones given in Table 4 for the SPDO and PrepSKA. In broad brush, we need to have preliminary concept designs for the SKA (starting with the current Reference Design and its follow-ons) several times over the duration of the TDP: in early 2008 when the project will have an external review; later in 2008 when a presentation to the U.S. decadal survey is expected; and some time after 2010 when the design for Phase 1 will be identified, along with a roadmap plan for later buildout phases. Table 7 lists in more detail the resulting activities for the TDP.

Table 7: TDP Timeline

| Date/frequency   | Event   |
|------------------|---|
| <b>Meetings:</b> |   |
| Biyearly         | Calibration and Processing Group (CPG) meeting  |
| Monthly          | CPG telecon   |
| Biyearly         | Antenna Working Group (AWG) meeting   |
| Monthly          | AWG telecon   |
| <b>Reports</b>   |   |
| biyearly         | TDP Project Office (TDPPPO) Report to the NSF   |
| biyearly         | TDPPPO Report to U.S. SKA Consortium  |
| biyearly         | TDPPPO Report to the SPDO/SSEC  |
| <b>Schedule:</b> |   |
| Year 1           | Assemble AWG and define antenna development plan (WBS 1)<br>Begin work on antennas, feeds and receivers<br>Assemble CPG and define work plan (WBS 2)<br>Begin CPG work on key issues that drive costs<br>Begin collaboration under PrepSKA (2008 April)<br>Work-package Contents:<br>WBS 1:<br>Antenna fabrication (including composite antennas, Canada, South Africa)<br>Feeds (including phased arrays from Australia, Canada, Netherlands, UK)<br>Receivers (including phased arrays from Australia, Canada, Netherlands, UK)<br>Optical design<br>WBS 2:<br>Signal transport<br>Calibration Algorithms<br>Imaging, Spectroscopy and Time-domain Processing<br>Scalability and High-performance Computing<br>RFI Mitigation<br>Surveys<br>Data Management<br>WBS 3:<br>Preliminary version of cost function $C(X, D, \text{FoV})$<br>WBS 4:<br>Organization of joint TDP/PrepSKA design project |
| Year2.0          | Continue work in all areas  |
| Year2.Q2         | Report from industry partner(s) on roadmap on antenna development and manufacture   |
| Year2.Q3         | Preparation of SKA design for Phase 1   |
| Year2.Q4         | Identification of optimal SKA antenna (D, optics)<br>for perceived choices of feeds and receivers   |
| Year3.0          | Continue work in all areas  |
| Year3.Q1         | Let contract on delivery of optimized antenna   |
| Year3.Q2         | Deployment plan for feeds and receivers (X, FoV):<br>e.g. single-pixel first then multiple-pixel systems?<br>Report = deployment roadmap: SPDO directed with strong TDP participation   |
| Year3.Q2         | Phase-1 Design Review   |
| Year3.Q3         | Delivery/tests of version 1 feeds and receivers for SKA bands   |
| Year4.0          | Continue work in all areas  |
| Year4.Q1         | Refine Phase 1 SKA as defined by<br>First Phase-1 Design Review<br>continuing TDP/PrepSKA Project:<br>Identify subsystems for TDP work (feeds, receivers)   |
| Year4.Q2         | Delivery of SKA antenna to test site (TBD)  |
| Year4.Q2         | Begin integration of SKA antenna with feeds/receivers   |
| Year4.Q4         | Finish integration of SKA antenna, start assessment, deliver as PrepSKA IVS   |
| Year4.Q4         | Final reports for TDP/PrepSKA design project  |

## D. Subawards

Subawards are/will-be issued by Cornell University for much of the TDP technical work. These will be in accord with standard Cornell policies that include acceptance of a proposal to Cornell from each subawardee institution. Table 4 lists the subawards and how they map into the WBS structure.

### TDP Subawards in Current Plan (Redacted)

| Institution or Target           | WBS Areas                 | Award Level (\$k) |        |        |        |       |
|---------------------------------|---------------------------|-------------------|--------|--------|--------|-------|
|                                 |                           | Year 1            | Year 2 | Year 3 | Year 4 | Total |
| Caltech                         | WBS 1.2.1.3, 1.2.4, 1.2.5 |                   |        |        |        |       |
| MIT/Haystack                    | WBS 2.2, 2.3              |                   |        |        |        |       |
| SETI Institute/Minex            | 1.1, 1.2.1.1              |                   |        |        |        |       |
| UC Berkeley                     | WBS 2.2, 2.3, 2.5         |                   |        |        |        |       |
| U. Illinois                     | WBS 2 (lead)              |                   |        |        |        |       |
| U. Wisconsin *                  | WBS 1.2.6, 1.2.7          |                   |        |        |        |       |
| Industry Antennas Partner (TBD) | WBS 1.1.1.4               |                   |        |        |        |       |
| TBD (Academic)                  | WBS 1.1.1.5               |                   |        |        |        |       |
| TBD * (Academic/Industry)       | WBS 1.2.1.6               |                   |        |        |        |       |
| TBD (Commercial)                | WBS 1.2.4.4               |                   |        |        |        |       |
| TBD * (Academic/Commercial)     | WBS 1.2.6                 |                   |        |        |        |       |
| TBD (Commercial)                | WBS 1.4.1                 |                   |        |        |        |       |
| TBD * (Commercial/Academic)     | WBS 1.4.2                 |                   |        |        |        |       |
| TBD * (Academic)                | WBS 1.5                   |                   |        |        |        |       |
| TBD (Academic)                  | WBS 5                     |                   |        |        |        |       |

\* implies subawards in the TDP's outyears

## E. Acronyms Used

|         |   |
|---------|---|
| ALFA    | Arecibo L-band Feed Array   |
| ALMA    | Atacama Large Millimeter Array  |
| AA      | Aperture Array (a phased array that looks up)   |
| ASKAP   | Australia SKA Pathfinder (subsumes xNTD, MIRA)  |
| ATA     | Allen Telescope Array   |
| ATNF    | Australia Telescope National Facility   |
| AWG     | Antennas Working Group (TDP)  |
| CDIT    | Central Design and Integration Team (PrepSKA)   |
| CPG     | Calibration and Processing Group (CPG)  |
| CSIRO   | Commonwealth Scientific and Industrial Research Organization (Australia)  |
| DSNA    | Deep Space Network Array (under development)  |
| EoR     | Epoch of Reionization   |
| EVLA    | Expanded Very Large Array   |
| eVLBI   | electronic VLBI (real time correlation)   |
| FoV     | Field of view   |
| FP6     | European Commission Framework Program 6   |
| FP7     | European Commission Framework Program 7, in particular the “preparatory phase” design project now being planned |
| GBT     | Green Bank Telescope  |
| GLAST   | Gamma-ray Large Area Space Telescope  |
| HSA     | High Sensitivity Array  |
| IEAC    | International Engineering Advisory Committee  |
| ISPO    | International SKA Project Office (now the SPDO)   |
| ISSC    | International SKA Steering Committee (1/3 U.S. membership, now the SSEC)  |
| IVS     | Initial Verification System   |
| JWST    | James Webb Space Telescope  |
| KAT     | Karoo Array Telescope (now expanded to MeerKAT)   |
| LFD     | Low Frequency Demonstrator (former name for component of MWA)   |
| LNSD    | Large-Number/Small-Diameter array concept   |
| LWA     | Long Wavelength Array (New Mexico)  |
| MeerKAT | Larger version of KAT (subsumes KAT)  |
| MIRA    | Mileura International Radio Array (an extension and rename of xNTD)   |
| MIT     | Massachusetts Institute of Technology   |
| MMIC    | Monolithic Microwave Integrated Circuit   |
| MWA     | Mileura Widefield Array   |
| NAIC    | National Astronomy and Ionosphere Center  |
| NAPRA   | North American Program in Radio Astronomy   |
| NRAO    | National Radio Astronomy Observatory  |
| PAF     | Phased-array feed (to provide multiple pixels on a dish antenna)  |
| PrepSKA | Preparatory SKA Design Project (EC funded under Framework 7)  |
| RD      | Reference Design (for the SKA; c. 2006)   |
| RFI     | Radio Frequency Interference  |
| SKA     | Square Kilometer Array  |
| SKADS   | SKA Design Study (European FP6 funded)  |
| SPDO    | SKA Project Development Office (formerly ISPO)  |
| SPF     | Single pixel feed   |
| SSEC    | SKA Science and Engineering Committee (1/3 U.S. membership; formerly ISSC)                                      |
| TDP     | Technology Development Project (U.S.)   |
| USSKAC  | U.S. SKA Consortium   |
| VLBA    | Very Long Baseline Array  |
| VLBI    | Very Long Baseline Interferometry   |
| WMAP    | Wilkinson Microwave Anisotropy Probe  |
| xNTD    | Extended New Technology Demonstrator (component of MWA)   |

**F. Letters of Commitment**

See attached pages

**G. NSF-Cornell University Cooperative Agreement**

See attached pages