The Large-N-Small-D Concept for the Square Kilometer Array: Addendum to the 2002 Whitepaper

Prepared by the USSKA Consortium

Version 0.5

22 March 2003

Contents: (When completed)

This is a **draft** document.

1. Introduction

This document complements the Whitepaper for the Large-N-Small-D Concept for the Square Kilometer Array, submitted by the USSKA Consortium to the International SKA Steering Committee in June 2002. In section §2 we summarize changes to the concept that we have identified over the last year. These largely consist of enhancements in the capabilities of the LNSD concept in order that it better enable particular science goals. In §3 we respond to specific questions posed by the EMT on various aspects of the LNSD concept. §4 addresses how the LNSD concept complies with the 18 science areas that have been posed as top-level goals by the ISAC. We discuss each science area individually and we discuss at length particular technical issues in the context of science goals. Our main conclusions in this section are summarized in our own rescoring of the LNSD concept taking into account details about observational modes and the advancement of the concept summarized in §2. The overall conclusions are contained in §5.

Remainder of this section is TBD:

Particular highlights of the LNSD concept that we explicitly discuss throughout the document include:

- The LNSD concept is particularly flexible and can be optimized for those science goals that emerge as key over the remainder of this decade. This includes the particular configuration adopted and also the possibility for extending the frequency coverage outside the formal range of 0.15 to 22 GHz.
- The 12m antennas can be extended to frequencies well above 22 GHz. Science goals emphasize the need to go to at least 25 MHz.
- The 12m antennas can be used to frequencies as low as 100 MHz.
- If alternative low-frequency receptors are desired, they can be sited so as to exploit much of the infrastructure in place for the dishes of the LNSD concept.
- Signals from individual antennas (rather than signals from stations of phased antennas) can be brought to the central processing site. Enormous scientific capabilities ensue for wide-field polarization work and blind surveys.

2. SUMMARY OF CHANGES TO THE LARGE-N-SMALL-D (LNSD) CONCEPT

To include:

- Itemize changes that are essentially parametric and in response to particular scientific issues. I.e. size of core array, frequency coverage, etc.
- Discuss alternative dish designs (on and off axis).
- The ability to bring signals from all antennas directly to the correlator.
- Itemize new emphasis on how the LNSD design can target blind surveys for pulsars, transients and ETI.
- Summarize how we may address the low-frequency end (e.g. ≤ 300 MHz) with respect to WMAP results pertaining to the EoR. This would include discussion re extending use of 12m antennas to 100 MHz. Also we would again highlight the great flexibility of the concept for a hybrid approach where different antennas could be used to cover (e.g.) low frequencies but would make use of much of the 'downstream' data transmission and signal processing.

3. RESPONSES TO EMT QUESTIONS ABOUT THE LNSD CONCEPT

(1) *Compared with filled aperture, large-D, proposals, the instrument outlined has somewhat reduced surface brightness sensitivity for low spatial frequencies. Can the authors quantify the brightness sensitivity at various array scales and mention how the reduced sensitivity might affect the science done with the instrument?*

The wide variety of SKA science drivers mandates a wide range of spatial frequencies. Short spacings are needed for good surface brightness sensitivity while large spacings are needed, especially at the longer wavelengths to avoid confusion, and to obtain adequate sub-arcsecond resolution. These requirements are common to all designs. For our strawman design. we have chosen to use a centrally condensed approximately scale free configuration as being the least arbitrary. As shown in Figure 1 , approximately 25 percent of the collecting area is contained within an area 1 km across where the antennas are packed about as tight as one can get within the inner few hundred meters; 50 percent is within an area 35 km across and 75 percent within an area 350 km in extent. For any given observational program, approximately half of the collecting area is effectively used, so the maximum loss of surface brightness sensitivity is about a factor of two over a configuration optimally configured for any specific problem. Small adjustments to this scale-free configuration are possible, but would have a correspondingly small impact on the surface brightness sensitivity.

The spacing of antennas in the inner part of our configuration ranges from the minimum to avoid shadowing at the center to about 30 meters at a radius of 500 m. Outside of this region, the antennas are located along a tightly wound single arm log-spiral. The spiral has a small pitch angle so has many turns within 35 km. The antennas are spaced along the arm with equi-angular spacing.

This configuration is given only as an example of what can be achieved with approximately 4400 elements within the constrained to minimize shadowing and to provide both high angular resolution and good surface brightness sensitivity. As with other radio telescope arrays, considerable study is needed to optimize the configuration and preliminary activity toward this end is underway at several locations.

(2) *With 15 m minimum spacing, the 12 m antennas will be closely packed. Would the authors clarify the low-elevation shadowing situation? What is the minimum unshadowed elevation?*

With any antenna configuration, there are tradeoffs between the need for close spacings to optimize the surface brightness sensitivity and image quality for

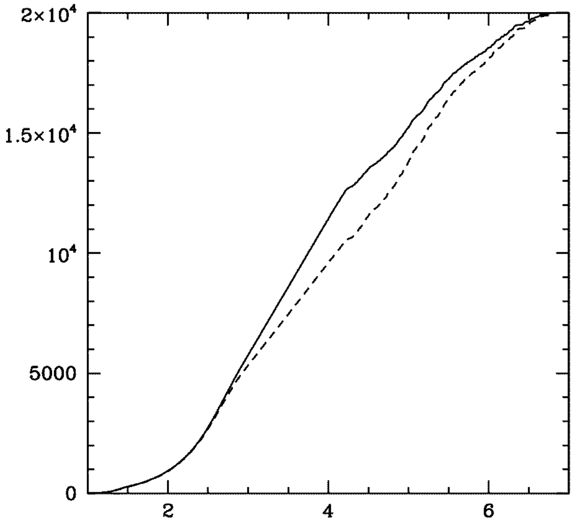

Fig. 1.— Cumulative sensitivity as a function of maximum baseline length for the LNSD concept. The dashed curve is for the configuration shown in Figure 3.4 of the 2002 Whitepaper on the LNSD concept. The solid curve shows the sensitivity for a configuration where 480 antennas are moved from the 160 outer stations to the spiral configuration in the 1 to 34 km diameter region. The new spiral configuration has a smaller pitch angle and makes 11 complete turns. These two examples underscore the flexibility inherent in the LNSD concept, which allows optimization to the highest-ranked science goals.

wide field imaging and the need to minimize shadowing. In fact the minimum spacing of 15 meters discussed in our white paper is probably too close to avoid mechanical interaction if an off-axis subreflector support system is used. Most likely a minimum spacing of 18 to 20 meters will be required. In any event, only a small number of antennas near the central part of the array are are so closely spaced that they are effected by shadowing.

Shadowing is of concern principally in two respects. First, it leads to a reduction in the total collecting area, and hence sensitivity, of the instrument. Second, if data from partially shadowed antennas are to be used, the altered antenna response must be taken into account. The latter concern can be avoided by discarding all data incorporating a partially shadowed antenna, at the cost of reducing the sensitivity further. The issues surrounding shadowing are somewhat different for the antennas within the inner 35 km and for those clustered in remote stations.

We consider the case of shadowing within the inner portion of the array first. Those antennas in the spiral from 1 to 35 km in diameter will suffer little shadowing. At the inner termination of the spiral the antenna separation is 25 m, corresponding to a minimum unshadowed elevation of 26°. However, these antennas are not closely packed: this shadowing will occur for only a very small fraction of the antennas at any given azimuth. Shadowing is more significant within the inner 1 km. Nearly or partially shadowed antennas are desirable in our design: the baseline foreshortening inherent in these allows sensitivity to the most extended structures while maintaining a safe antenna separation. But a tradeoff is available: shadowing can be reduced, along with the sensitivity to the most extended structure. In this case observations of the most extended sources could be made at low elevations to increase the brightness sensitivity.

The shadowing tradeoffs are different for the antennas at a remote station. For the station configuration, we want the antennas to be as closely spaced as possible to maximize the field-of-view (FOV) of the station beam. Figure 2 shows the level of shadowing vs. declination for a minimum spacing of 21 m which gives a FOV of 408 arcsec at 21 cm. Increasing the minimum spacing to 30 m reduces the FOV to 284 arcsec. In our initial strawman design, the closest spacing in each of the 160 stations was only 15 meters to maximize the size of the station beam at the expense of some shadowing, but as discussed above this will be increased to 18 to 20 meters. These outer station antennas are important only for high resolution studies, so a small degree of shadowing does not significantly degrade the performance. The selection of the optimum station configuration is not obvious. For most research programs minimizing the station sidelobes may not be fundamental. Further study will be needed to optimize the station configuration.

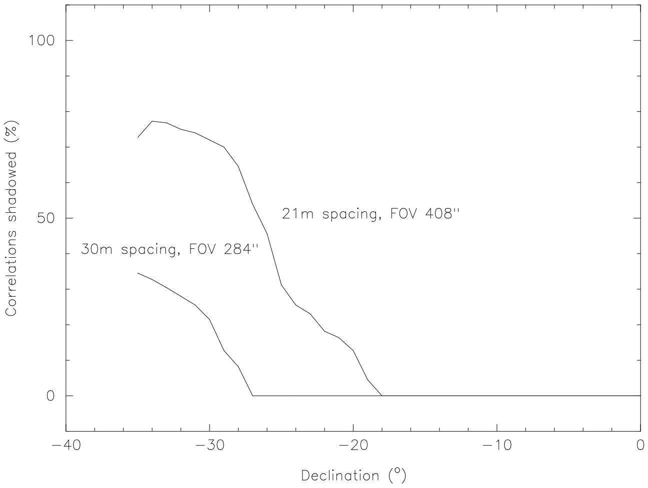

Fig. 2.— Shadowing as a function of declination for two minimum antenna spacings (21m and 30m), calculated for a latitude of (?) 33°. The percentage of correlations shadowed was calculated for a two-hour track around transit for some station configurations of the specified minimum antenna spacing. Any partially shadowed data are assumed discarded. The FOV is the mean FWHM at 1.4 GHz.

For many purposes, it will be sufficient to discard all correlations resulting from antenna pairs in which one or other is shadowed. This criterion was used for the plot in figure xx. Sometimes, it will be desirable to obtain the highest sensitivity by using data derived from partially shadowed antennas. To make this possible, the distortion of the primary beam shape, and the increase in its sidelobes due to a sharp edge in the strongly feed-illuminated portion of the shadowed dish, must be modeled. Present algorithms do not handle this well, but time-dependent variations in antenna and station gain as a function of station and pointing direction are fundamental characteristics of most SKA designs, and for LOFAR. For example, in our design, stations may have a variety of configurations to minimize regular sidelobes in the array beam. In any case, we will need to adopt strategies to deal with random failures of individual antennas within each station. Such stategies are already under development.

Another concern when partially shadowed data are used is the increase in system temperature as some ground radiation is coupled to the feed. For most cases of shadowing the lower part of each dish will be looking at the upper part of the back of another dish. Since our dish design features very little in the way of backup structure, most of what we will be looking at is smooth hydroformed metal reflecting cold sky, so the contribution to Tsys from reflections of the warm ground is likely to be small. The effect could be further reduced if included as a design constraint for the dish, or with a ground screen.

We note that the same principles and tradeoffs would apply for a design using smaller offset Gregorian dishes, should the economics and science at the time of the final decision dictate this. On the other hand, if an on-axis design is used, the minimum spacings may be substantially reduced at the cost of increased shadowing.

An additional concern about short spacings is possible cross-talk between the elements. Good engineering will minimize the effect of cross-talk. Experience with the ATA will contribute to our understanding of any potential problems.

(3) *The 12 m dishes are shaped for efficiency. Have the authors considered the effects on the off-axis performance and the implications this might have for any future retro-fit with focal plane arrays?*

The 12m antenna meets the SKA field of view requirement without focal plane arrays, which would greatly increase the receiver cost. In addition wideband feeds are large and would create large beam spacing at the high end of the feed frequency range. There are other considerations for the shaped vs unshaped decision which may be more important such as: a) effect upon A/T, b) sidelobe level, c) effect on polarization mapping, d) effect of surface degradation near the outer perimeter of the antenna, and e) increased spillover due to edge diffraction of the subreflector at the longest wavelengths used at secondary focus. Further study of these considerations is required.

(4) *Can the authors give any more details of the dish mount and its likely mechanical performance (including reliability)?*

> Three ATA 6m antennas have now been assembled with mounts and drive systems. The assembly process went smoothly with minimal labor and the performance is excellent with 10 arcsec rms pointing accuracy. More details are given in Appendix B. There will be much experience with the reliability of the 350 6m ATA drives during the next 5 years. A more accurate drive system is required for the 12m higher frequency antenna proposed for the SKA. For the DSN array, a mount for a symmetric 6m 32 GHz antenna will be assembled in 2004 and a mount for 12m 32 GHz will be designed also in 2004. Further details are in Appendix C.

(5) *Have the authors had any further thoughts on the form of the "swing away" arrangement for the prime focus receiver?*

> The proposed prime focus receiver is uncooled, light weight (under 20 kg) and need not be positioned very accurately (within 0.5 cm). For these reasons the "swing away" feed should be inexpensive and not a complex mechanical structure. A frequency range of 0.15 GHz to 1.5 GHz is anticipated with a receiver noise temperature of 15K from 1.0 to 1.5 GHz. A feed for 0.15 GHz would typically have a ground plane of 1.2m diameter and thus would fit behind the Gregorian subreflector. (It may be possible to use the subreflector for the ground plane in the lowest frequency band.) Operation at frequencies below 0.15 GHz may be possible with wire feeds which fold behind the subreflector. A scaled layout of the reflector showing the subreflector and feeds is shown in Appendix A.

(6+7) *Could the authors outline further the operation of the new-generation cryo-coolers and the commercial drivers for the assumed cost reductions?*

> In the ATA, cooling to $\sim$ 80 K is considered to be adequate and it appears that the path to cheap, reliable, pulse tube coolers is clear.

Could the authors comment on the technologies and tradeoffs involved in cooling to 15 K in their proposed design?

The new generation cryo-coolers are of the pulse tube or Stirling cycle technology with flexure bearing compressors which result in no rubbing parts. Long life, $> 40,000$ hours is predicted and has been achieved for expensive space-based systems. The ATA has been developing a single-stage pulse tube cooler with flexure-bearing compressor and now has a unit cooling to 80K; reliability data can be expected in the next few years. A commercial Stirling single-stage cooler for 2W at 40K, 50,000 hour life, and a cost of $2000 in 10,000 piece quantity is described at http://www.sunpower.com/products/index.html. This unit is on order and will be evaluated by JPL in 2003. The manufacturer, Sunpower, is also developing a two stage pulse tube cooler with expectation of 6W at 80K and 0.6W at 20K during 2003. These figures are with 200W of input power that is approximately 6 times more efficient than present Gifford-McMann coolers. The commercial driver for these coolers are for cooling superconducting filters in cell phone base stations. Cooling to 15K appears to be justified on a cost basis for currently available transistors. In the 4 to 8 GHz range LNA's have a 2K noise temperature at 15K and 9K at 80K. The projected system temperature with cooled feeds and spillover shields are then 18K and 25K for cooling to 15K and 80K. Thus for the same Aeff/Tsys the 80K system would require 1.4 times larger array which will cost of the order of $400M. On the other hand, If cooling to 15K tripled the $2K production cost of a 80K cooler the array cost is increased by only $18M. Total life-cycle cost and reliability need to be evaluated but at present it appears that 15K cooling is justified.

(8) *Could the authors clarify the feed proposals for the highest frequencies? Are ATA-style feeds a possibility? Given the possible applicability of the TRW feed to many SKA concepts, are the authors able to supply any further details at this stage?*

Three designs of wideband feeds are being considered at present for both prime-focus low-frequency and secondary-focus high-frequency operation; this number may grow as more feed designers become interested in the problem. The three designs are:

1) The ATA 0.5 to 11 GHz log-periodic feed developed by Welch and Encargiola at UC Berkeley and described in a publication at the 2002 IEEE AP-S/URSI meeting in San Antonio, TX. Test data for this feed installed on an ATA 6m antenna will be available in 2003. This design has also been analyzed by Ericsson and Kildal in a report to the USSKA NSF funded program at Caltech; some initial predictions of the feed performance installed in a large cryogenic dewar are included in Appendix A. A 1.2 to 22 GHz version installed in a dewar would have a base width of 12.5 cm and length of approximately 50 cm - dimensions which are feasible for installation in a large dewar but much more analysis is needed to assess the effects

of the dewar walls. This feed has a phase center location which varies with frequency and can be corrected by a motorized focus adjustment.

2) The TRW 0.5 to 11 GHz wideband feed developed by Paul Ingerson. Complete test data on this feed have been submitted in a report to JPL and some of the key results are presented in Appendix A. In summary the feed has acceptable patterns but unacceptable impedance variation with frequency; this is being further investigated by Ingerson. The feed has the same base width as the ATA feed (determined by half-wavelength at the lowest operating frequency) but is much shorter, has better access to the terminals, and has a constant phase center location with frequency.

3) A new design of wideband feed has developed by Per-Simon Kildal of Chalmers University in Sweden. Computer model results of the pattern are good and the feed is compact with constant phase center. Much more study and construction and test of a prototype unit are needed.

More conventional horn feeds each covering an octave bandwidth are a possible alternative to the wideband feeds for the cooled secondary focus receiver. Four such feeds would be required to cover 1.2 to 24 GHz. These could either be located in one large dewar with a mechanical turret rotation as ALMA (or rotation of an asymmetric subreflector as on the VLA) or in separate smaller dewars. These feeds have better control of spillover noise pickup compared to the wideband feeds, would not require a spillover shield, but do not simultaneously cover the entire band - an advantage which may not realized because of signal processing bandwidth limitations in the near term but could be important for upgraded signal processors. However, even with signal processing bandwidth limitations, observations can be made with narrow bands which fall anywhere in the feed bandwidth; for example, the ATA has four 100 MHz bands which can be tuned anywhere in the 0.5 to 11 GHz frequency range. Finally, a major disadvantage of multiple octave-band feeds is cost. Our present cost estimate for a cooled wideband receiver is approximately \$15K and the horn receiver cost would be similar. Thus 3 additional receivers per antenna would add \$45K x 4400 = \$198M to the cost of the array.

(9) *What is the confidence in being able to scale up from SETI 6m design to a 12m using current hydroforming techniques? Comment on transportation of 12m diameter antennas to remote sites. This is not a trivial problem.*

Fifteen ATA offset 6m antennas have now been hydroformed and the last 3 have rms errors of 0.5 mm which is a factor of 2.4 better than specified and satisfactory for 24 GHz operation. JPL has contracted with the manufacturer, Andersen, for three symmetric 6m antennas with 0.2mm rms to be delivered in mid 2003. Andersen is confident that 12m symmetric reflectors with similar accuracy can be manufactured and will give a cost estimate to JPL in 2003 for construction of a 12m mold and installation of the hydroforming equipment at an on-site factory. An extensive computer-aided finite-element non-linear analysis of the hydroforming process has been performed at Caltech with US SKA funding and will be important for predicting spring back and investigating forming and material variables to further improve the accuracy of the process. A 12m symmetric hydroformed 32 GHz antenna and test data should be available by 2006.

Regarding transportation, it is anticipated that 12m reflectors will be manufactured in an on-site factory and will be moved on a 3-wheel trailer to installation locations where a crane will lift the reflector on to the pedestal. This is feasible for distances where adequate road clearance is available. For longer moves, say in the 30 to 300km range, helicopter transport is feasible. The Sikorsky S-64 Skyhook can carry 9000 kg (12m reflector weighs 2400 kg) at a speed of 80 km/h with a range (before refueling) of 330 km. The cost of a 100 km move is of the order of $5K per reflector.

(10) *The US and India should be encouraged to collaborate to see if the Indian low-cost design concepts can be extended to the USA reflector design.*

There have been some initial discussions of drive systems components which may be less expensive in India. However the reflector concepts are incompatible because the Indian mesh surface does not allow frequencies above 5 GHz. We note, however, that there are practical problems in outfitting parabaloids to work over the entire range of 150 MHz to 86 Ghz with good efficiency. It may turn out to be cost effective to consider two sets of antenna elements. One with a larger diameter (15-25 m) using the technology being developed in India working below 1.47 GHz, plus another smaller antnna (6 m) optimized for secondary focus operation above 2 GHz.

(11) *Future comparisons of SKA concepts would benefit from elaboration of the pros and cons of the designs with regard to their RFI vulnerability or their systemic advantages in RFI mitigation.* (Question raised in the EMT report for all SKA concepts.)

It is well-known that RFI poses a present and apparently increasing threat to radio astronomy in many of the frequency bands of interest. Therefore, it is prudent to understand the likely impact of RFI on the SKA, and to identify the strengths and weaknesses of the LNSD design concept in this context.

RFI Is Not a Show Stopper: First, we note that the increased sensitivity of SKA by itself will not make it more vulnerable to RFI than less-sensitive instruments with comparable baseline lengths and bandwidths. Because the absolute gain of the far sidelobes of a radio telescope is essentially independent of main beam gain, the interference to system noise ratio (INR) will be the about the same for any SKA design concept as it is for other, existing telescopes. For imaging applications, the SKA, including the LNSD concept, will benefit from decorrelation of RFI on long baselines due to fringe rotation and bandwidth decorrelation, as do existing synthesis arrays. For non-imaging applications, all SKA design concepts offer some degree of redundancy and antenna separation, enabling anti-coincidence techniques capable of descriminating between astronomical signals of interest and RFI which happens to be local to some part of the array. Furthermore, the myriad existing proven techniques now used for RFI mitigation will continue to be available and applicable (and perhaps refined) for SKA, and to a LNSD instrument in particular.

Site Selection (Affects all SKA design concepts more or less similarly): Nevertheless, it is clear that certain key science drivers for SKA are threatened by external RFI. In particular, observations of H I at high redshift are threatened by interference from the legitimate emmissions from radars and other aviation-related applications in the 1000-1400 MHz band, and EOR studies are threatened by similarly-ligitimate narrowband transmissions in the VHF and lower UHF bands. In other bands, external RFI is a nuisance that can reduce or render impractical observations in certain frequency bands and at certain times. The most obvious defense against these forms of RFI is site selection. In particular, the chosen sites should have both low RFI spectral occupancy as well as a manageable rate of occurence of linearity-threatening RFI. These considerations apply to all SKA design concepts.

Self-RFI (Applicable to all SKA concepts, but some possible LNSD pros/cons): Similarly, all SKA design concepts must be concerned with the potential for RFI from signal processing electronics and other support equipment associated with operation of the array. However, certain features of the LNSD concept may be advantageous in this respect. First, the conversion of the feed-mounted LNA output to optical form for downconversion, digitization, and processing at a relatively distant, well-shielded location should be quite helpful in reducing self-RFI. Although certain other SKA concepts may employ this strategy, certain others – in particular, those employing dense focal plane or primary aperture arrays – may require downconversion and digitization close to the antenna. A potential disadvantage of LNSD, shared with other large-N concepts, is that the increased number of processed feeds, coupled with the need to keep the per-feed cost low, may make it difficult to acheive the same level of self-RFI immunity possible with a low-N approach. Furthermore, the most vulnerable part of a large-N SKA will be the compact center of the array, where RFI decorrelation will be the least effective, but ironically also where most of the control and initial signal processing electronics are likely to be concentrated. Clearly, special care will be required to manage self-RFI in the core. Fortunately, this challenge is being met directly through efforts in the development of the ATA and LOFAR, which are subject to precisely the same problems. Thus, considerable experience in this area will be available before the bona fide SKA design effort begins. Protection from self-RFI will be a top priority in the LNSD concept (as it would also need to be for any other design concept) from its initial development stages. Appropriate countermeasures include use of principled, modern EMC management techniques in designing electronics for minimum radiation, a systematic measurement and emission suppression program for all installed equipment, and continuous environmental control during all phases of construction and operation.

Wideband feeds required for Large N may be more vulnerable to RFI: Another potential weakness shared by all large-N concepts is the increased vulnerability of low-cost, wideband feeds to strong, linearity-threatening RFI. Such RFI is generated primarily by commercial broadcasts in the VHF and low UHF bands; ground-based radars in the L-, X-, and K-bands; and a small number of satellite-based radars and broadcasts. Once again, ATA and LOFAR are today pioneering wideband front-end technology, from which SKA and LNSD in particular will be able to benefit. Work so far indicates that wideband front-ends are practical for sites which are not too close to the indicated ground-based transmitters, and for pointings which are not too close to the indicated space-based transmitters. To further mitigate this risk, we anticipate a concurrent program of site RFI evaluation/characterization to be coupled with the receiver design effort, to ensure that the final result acheives a comfortable margin of linearity nearly all the time.

Need & ability to support new, active forms of RFI mitigation: Given the best possible sites, satisfactory control of self-RFI, and acceptable linearity, there remain external RFI problems which may limit the potential for certain key observing programs. For example, L-band OH spectral observations are threatened by satellite downlinks, for which site selection is not a mitigating factor. Also, terrestrial signals in the VHF and lower UHF bands can propagate long distances, making site selection less of a factor for certain observations in these bands. For this class of “stubborn” RFI problems, a number of promising new techniques for suppressing RFI are currently being studied, tested, and documented. These techniques include nullforming and blanking/canceling in the time and/or frequency domains, each of which can be applied at the pre and/or postcorrelation stages of processing. A few early versions of these techniques will probably be sufficiently tested in time to incorporate them into the basic design of the SKA. While these techniques are applicable to some extent to all SKA design concepts, the ability of the LNSD concept to exploit the full benefit of these techniques is exceptional. In particular, LNSD offers excellent flexibility in terms of beam shaping and nullforming. The reason for this is simply that many (perhaps as much as 1-10%) of the available "N" degrees of freedom can be allocated to the task of beam shaping and nullforming with little or no impact on beam quality or array gain. It has recently been demonstrated in both theory and simulation that the available degrees of freedom can be used to dramatically increase the angular extent and bandwidth of spatial nulls in an easily-controlled manner. This is a capability which has been designed into the ATA, will thus will soon be demonstrated. Although all large-N approaches can exploit this capability, the LNSD concept offers an excellent balance between the size of N and the instantaneous field of view; in other words, N is large enough to fully realize the advantages of spatial nulling, but – through the use of 12-m dishes – not so large as to require a complex, many-layered hierarchy of analog and/or digital signal processing to generate useful constituent element patterns.

4. Response to the ISAC Compliance Matrix for the LNSD Concept

The International Science Advisory Committee (ISAC) has assessed all concepts for the SKA in terms of their compliance with the Level 1 science goals for the project that have been identified by the ISAC and its working groups. Assessments are in the form of a compliance matrix, the current version of which may be found at http://www-astro.physics.ox.ac.uk/∼sr/ska/ska_matri (24 March 2003). We summarize the compliance matrix for the LNSD concept in Table 1 along with the compliance of the concept-independent specifications for the SKA itself.

In the following, we first comment on the assessment of the LNSD concept with respect to each Level-1 science goal. We find that where the LNSD concept falls short — or appears to fall short — of complete compliance, the relevant technical issues are common to two or more science goals. Consequently, we discuss several of these issues in greater detail in later subsections. For specificity, we refer to the 2002 Whitepaper describing the LNSD concept as WP2002.

4.1. Brief Discussion of each Level 1 Science Goal

In this section we consider the explicit assessment in the compliance matrix of the LNSD concept for each of the 18 Level-1 science goals identified by the ISAC and its working groups. Table 1 summarizes the matrix. The first column is an item sequence number, while the second column is the science working group number, the third is a short description of the science area, column 4 is the score on a scale of 1 to 5 of the *strawman SKA specifications* (i.e. independent of concept), while column 5 is the score for the LNSD concept, and column 6 is the textual assessment corresponding to the score. Column 7 is our own grade for the LNSD concept that takes into account our current views on its capabilities and also on the specific requirements needed for accomplishing the science goals. The last column indicates the issue(s) relevant to the particular science area that impinge most on feasibility with the LNSD concept. Our discussion is tagged according to the same working-group numbers used in the Compliance Matrix. *Our overall stance is that the LNSD concept can achieve most of the science goals and specifications and that it surpasses current specifications in some areas.*

We note note that the preliminary strawman specifications themselves do not satisfy all Level-1 science goals and, in many areas, the LNSD concept scores higher than the strawman specifications.

A detailed comparison and discussion of each Level 1 science goal is given below. However, we can identify a number of common themes that have resulted in the LNSD concept not being rated as in full compliance with all of the Level 1 science goals. The primary difficulty appears to be the particular array configuration discussed in WP2002 and whether it has sufficient surface brightness sensitivity. We chose a scale-free (or nearly so) configuration specifically so that the array would be optimized for the broadest range of astronomical topics. In particular, for an array spread over several thousand kilometers, we believe that there will be few observing projects that will be able to make efficient use of all of the collecting area. However, if the ISAC and/or ISSC decides that more centrally-condensed configurations are justified, no fundamental changes in the LNSD concept would result. A related, desireable goal is to process the signals from as many individual antennas as possible within the constraints of technology and cost. By doing so, several science areas are enabled.

Table 1: Level 1 Science Compliance Matrix & Comments (as of 2003 March 24)

Item	WG	Description	Strawman	ISAC Assessment		Our	Issues
			Grade†,*	Grade†	Wording	Grade	
1	1	Galactic H I	4	4	Yes	5	Low-surface brightness sens. Size of core array; u-v coverage
2	1	Galactic NT+B	4	3	MAYBE	5	Off-axis polarization capability Size of core array
3	2	Transients	3	2	Maybe	4	Blind surveys & response times
4	2	Pulsars	3	2	Maybe	4	″
5	2	SETI	3	2	Maybe	4	″
6	3	EoR	2	2	Maybe	3	Low-frequency coverage Low-surface brightness sens.
7	4	H I surveys / LSS	4	3	MAYBE	5	Imaging dynamic range
8	4	Continuum surveys	3	4	Yes	5	″
9	4	CO surveys	4	4	Yes	5	High frequency coverage
10	5	High-z AGN	3	3	Maybe	4	Low-frequency coverage
11	5	Inner AGN	3	5	YES		
12	6	Protoplanetary Systems	3	5	YES		
13	7	CMEs	3	3	MAYBE	3	Low-frequency coverage
14	7	SS bodies	4	3	MAYBE	4	Correlator bandwidth High frequency coverage
15	8	IGM (non thermal)	4	3	MAYBE	5	Low-surface brightness sens.
16	8	IGM (thermal)	3	5	YES	5	
17	9	Spacecraft tracking	3	5	YES	5	High-frequency coverage
18	9	Geodesy	3	5	YES	5	(IF separation)

† Grades: As assessed by the International Science Advisory Committee:
1 = N0 2=Maybe 3=MAYBE 4=Yes 5=YES

* Strawman Grade is the ISAC Grade to the current preliminary specifications for the SKA, independent of SKA concept.

1. **Galactic H I** (WG 1): The LNSD concept is assessed to be almost capable of meeting this Level 1 science goal. The only apparent difficulty is with the radius from the array center within which 50% of the collecting area is contained. This is not a

fundamental difficulty with our concept because our 2002 Whitepaper focused on a particular scale-free configuration that optimized the array with respect to the full slate of science objectives. More compact scale-free configurations are also possible that would optimize this particular science area. Further guidance from the ISAC on the balance between surface brightness and resolution and detailed simulations are required.

2. **Galactic Nonthermal and Magnetic Fields** (WG 1): The LNSD concept almost meets this Level 1 science goal, according to the assessment. The difficulties stem from the radius from the array center within which 50% of the collecting area is contained and the high-frequency field of view resulting from the size of the individual stations. The configuration of the array is not a fundamental difficulty with our concept because our 2002 Whitepaper focused on a particular scale-free configuration that optimized the array with respect to the full slate of science objectives. More compact scale-free configurations are also possible that would optimize this particular science area. The working group has noted that the high-frequency field of view becomes small at high frequencies as well. The station field of view depends upon the weighting used in combining the antennas. A larger field of view can be obtained by reducing the weights assigned the outer antennas in a station, at the cost of sensitivity. While we have not considered this explicitly, again preferring to optimize the design for a broad range of science topics, variable weighting within a station is an option within this concept. We also emphasize that this concern illustrates a strength of this concept, namely that it can operate at frequencies near 8 GHz. Further guidance from the ISAC on the balance between surface brightness and resolution is required.

3-5. **Transients, Pulsars and SETI** (WG 2): The LNSD concept is assessed to have difficulty meeting some of the Level 1 science goals. To be sure, the LNSD concept as described in the 2002 Whitepaper allows a wide range of *targeted* observations in these science areas. Blind searches for relatively slowly varying sources (e.g., $\gtrsim$days)[1] are straight forward because they involve only repeated mapping of the relevant regions on the sky. It is *blind searching* for *fast* signals having a high degree of time-frequency complexity that is challenging. We discuss the issues (and possible solutions) for blind searching in much more detail in the §4.3.

    We also believe that some of the stated requirements are not appropriate (e.g., the working group's understanding of the response time has evolved and 10 seconds is

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[1] We specify days as an approximate cutoff between slow and fast transients for the following reasons. With conventional mapping, one can of course detect transients with time scales equal to the correlator dump time. However, a blind survey requires repeated mapping on the region of sky of interest. If this is a large region, then it may be practical to make repeated images only for characteristic transient time scales of order 1 day. This time scale lessens if one is interested in only a small region of sky, as in a targeted search.

no longer considered to be justified). Many of the other requirements are met or nearly so. Thus, we believe that our concept performs better than the ISAC has evaluated it. Nonetheless, blind surveys for sources in these classes challenge the design requirements (and all current concepts) for the SKA, particularly with regard to real-time and postprocessing throughput. We discuss these requirements in detail below and present several approaches to conducting blind surveys.

6. **Epoch of Reionization (EoR)** (WG 3): The LNSD concept — along with all other design concepts — is assessed to have difficulty meeting this Level 1 science goal. The primary difficulty is with the low-frequency coverage (< 300 MHz). Recent WMAP results suggest that the relevant frequency range is from about 70 to 200 MHz, most of which is below the SKA specification for the low-frequency cutoff of 150 MHz. It is our assessment that EoR science with the SKA needs to be reconsidered completely in terms of the primary science objectives, while also taking into account capabilities and anticipated results from LOFAR, and the likely need for a hybrid design for the SKA that uses different antenna elements for two or more broad frequency bands. We discuss these issues below in §4.4.

7. **H I Surveys/Large Scale Surveys** (WG 4): The LNSD concept is considered to be almost capable of meeting this Level 1 science goal. The primary difficulty identified by the working group is the distribution of baselines (similar to the concerns identified in WG 1 above). We stress that the baseline distribution is not a fundamental aspect of our concept, but that we chose a configuration designed to optimize the array for a broad range of science topics. Thus, we believe that our concept essentially meets or exceeds all of the stated science requirements for this Level 1 science goal. Further guidance from the ISAC on the balance between surface brightness and resolution is required.

8. **Continuum Surveys** (WG 4): The LNSD concept almost meets this Level 1 science goal, according to the assessment. The only difficulties are with the spatial dynamic range obtained and the baseline distribution. While our stated dynamic range is 10^6, versus the requirement of 10^7, we believe that more simulations are required to assess both the actual dynamic range required as well as the dynamic range obtainable by our concept. We believe that the large number of antennas in our concept offers, in principle, the best method for obtaining the dynamic range requirement. Moreover, the baseline distribution is not a fundamental aspect of our concept, but that we chose a configuration designed to optimize the array for a broad range of science topics. Further guidance from the ISAC on the balance between surface brightness and resolution is required.

9. **CO Surveys** (WG 4): The LNSD concept is considered to be almost capable of meeting this Level 1 science goal. The only difficulty cited is with the baseline distribution.

The baseline distribution we have chosen is not a fundamental aspect of our concept; rather we chose a configuration designed to optimize the array for a broad range of science topics. Further guidance from the ISAC on the balance between surface brightness and resolution is required.

10. **High-redshift AGN (**WG 5): The LNSD concept is considered to be almost capable of meeting this Level 1 science goal. We believe that our concept meets or exceeds all of the stated science requirements of this working group. Indeed, many of the capabilities discussed in WP2002 are requested explicitly by this working group. The working group (in its report from the Bologna meeting [Jan 2002]) requires a scale-free configuration, in part to trace spectral index changes. The working group also favors strongly the ability to observe at the H_2O line near 22 GHz, which is possible in the LNSD concept. Perhaps the one difficulty that can be identified with the LNSD concept with regard to this Level 1 science goal is the low frequency coverage. However, it is not clear that the stated SKA specificiations (minimum frequency of 150 MHz) is even sufficient. Further clarification from the ISAC is needed.

11. **Inner AGN (**WG 5): The LNSD concept is considered to be fully capable of meeting this Level 1 science goal, primarily because of its high-frequency coverage, long baselines, or both.

12. **Protoplanetary Systems (**WG 6): The LNSD concept is considered to be fully capable of meeting this Level 1 science goal. Having 50% of the collecting area within 35 km is important for detecting H IḢigh-frequency coverage and wide-field imaging allows exciting studies of long-chain molecules.

13. **Coronal Mass Ejections (CMEs) (**WG 7): The LNSD concept is considered to have difficulty meeting this Level 1 science goal. The primary difficulty is with the low-frequency coverage ($<$ 300 MHz), however, it is also not clear that the SKA specifications (minimum frequency of 150 MHz) is sufficient. Bi-static radar imaging of CMEs requires frequencies below 100 MHz, and most passive imaging of CMEs has been done at frequencies near or below 150 MHz.

14. **Solar System Bodies (**WG 7): The LNSD concept is considered to be almost capable of meeting this Level 1 science goal. The only difficulty is with the bandwidth that can be handled by the correlator. This difficulty may face all current concept designs.

15. **IGM Nonthermal (**WG 8): The LNSD concept is considered to be almost capable of meeting this Level 1 science goal. The only apparent difficulty is with the radius from the array center within which 50% of the collecting area is contained. This is not a fundamental difficulty with our concept because our 2002 Whitepaper focused on a particular scale-free configuration that optimized the array with respect to the full slate of science objectives. More compact scale-free configurations are also possible

that would optimize this particular science area. Further guidance from the ISAC is required on the balance between surface brightness and resolution.

16. **IGM Thermal** (WG 8): The LNSD concept is considered to be fully capable of meeting this Level 1 science goal, primarily because of its high-frequency coverage.

17. **Spacecraft Tracking** (WG 9): The LNSD concept is considered to be fully capable of meeting this Level 1 science goals because of its high-frequency coverage.

18. **Geodesy** (WG 9): The LNSD concept is considered to be almost capable of meeting this Level 1 science goal. The only difficulty is with the maximum separation of the IFs for allowing removal of ionospheric effects. This difficulty may face all current concept designs.

4.2. Configuration Issues

Level-1 science items 1-6 and 15 all require sensitivity on large angular scales and hence short baselines.

For areas 1 and 2, short spacings are essential to recover extended emission. There is no hard minimum spacing required, as ultimately many experiments will require all spatial scales down to zero, and so will always need the addition of single-dish data. However, single-dish data require extra observations, more complications, and in the case of continuum observations and polarimetry, tackling of some extremely difficult calibration issues. Thus it is highly desirable to make the minimum spacing as small as possible, so as to minimize the number of projects which will need the single-dish component. This is best addressed by including a small number of very short spacings in the array, accepting that significant shadowing and possible collisions might be experienced when these spacings are used. These antenna pairs should be redundant and well-separated so as to overcome RFI at these short spacings.

Some projects (e.g. Galactic HI) nonetheless will always require a single-dish component. The SKA design should either include the capability to record single-dish data (with significant u-v overlap with the shortest spacings), or be sited such that some other appropriate single-dish facility can make the necessary measurements.

For both topics, continuous uv coverage is needed over a wide range of spatial scales (~ 1 arcsec to 30 arcmin). The scale free nature of the US design is a strength in this regard, in contrast to other concepts with lower N and larger D which will most likely produce gaps in the radial u-v coverage.

The Galactic Center is an important target for science item 2. The LNSD concept is amenable to adjustment of the array configuration to optimize Galactic Center science. Such would be the case if the SKA were sited in the Northern hemisphere.

For polarization work, high polarization purity is essential. The ISAC specified −40 dB over the entire field of view (−30 dB in hardware, with a further 10 dB after calibration). For polarization, many projects will need to image the full FOV at $\lesssim 1$ arcsec resolution. This requires visibilities from every antenna out to 50-100 km, so that individual correlations are required for antennas out to these distances.

Level-1 science items 3-5 (Transients, Pulsars and SETI)) include the need for blind-searching capability of as large a solid angle as possible. A suitable goal is to sample the full FOV at (e.g.) 1.4 GHz through formation of the appropriate multiple beams. We envisage that blind searching can be accomplished with a core array of diameter $b_{\rm c}$ involving a subset of the entire array. The size of the core array will be dictated by connectivity of the array (to how far out can the signals from individual antennas be brought to the correlator) and the processing requirements, which scale as $(b_{\rm c}/D)^2$ for dish-diameter D. Blind searching thus requires a minimal collecting area that can be used as a core array and that is superior by some factor to existing instruments (e.g. Arecibo). We discuss these issues in more detail in the next section.

Level-1 science area 15 (Non-thermal IGM) requires low-surface brightness sensitivity in order to map large-scale features in the IGM. The LNSD concept is very flexible and can be built around a more compact scale-free configuration than discussed in WP2002, should this be deemed a priority area and if a different configuration does not compromise other priority science areas.

4.3. Blind Surveys for Transients, Pulsars, and ETI

Working Group 2 has considered the scientific requirements for transients, pulsars (and other compact objects, and SETI. Much work in these areas can be accomplished through standard imaging analysis, such as detecting slow transients or astrometry.

Blind sky surveys for pulsars and for fast transients ($\lesssim 1$ day), however, represent one of the main Level 1 science goals and they are especially challenging. The Level 1 science goal for SETI involves targetted observations, but ETI transmitters may be a class of currently unknown transients.

The salient requirements for such blind surveys include:

1. Maximization of the search volume $V_{\rm max} = \frac{1}{3}\Omega D_{\rm max}^3$, where Ω is the solid angle and $D_{\rm max} = D(S/S_{\rm min})^{1/2}$ is the maximum detectable distance for a source with flux density S at distance D and for a minimum-detectable flux density $S_{\rm min}$. The luminosity function and spatial distribution of source populations need to be considered in this maximization.

2. Maximizing search volume with respect to radio propagation effects, which increase $S_{\rm min}$ and hence decrease $D_{\rm max}$ through smearing of time structure (dispersion and scattering) or modify the apparent flux density of the source (scintillation) as a function of time and frequency.

3. Sensitivity to a wide range of characteristic time scales (e.g., pulse widths and periods) and frequency scales. Pulsars display time scale ranging from ~ 2 ns to 8 s and provide the most stringent requirements. Known and hypothesized classes of transient sources span the pulsar range of scales and extend to longer time scales; currently unknown classes of transients may have a similar range of time and frequency scales. Frequency resolution is needed for dedispersion and for optimizing searches in the presence of scintillation-induced frequency structure. For SETI, frequency resolution to sub-Hz levels is required according to conjectures about signal properties; the corresponding minimum time resolution follows according to limits on the time-bandwidth product.

For efficient blind searching, one must simultaneously sample and analyze the entire field of view (FOV). The nominal FOV is specified to be 1 deg^2 at $\lambda = 20$ cm while it is ~ 2.6 deg^2 for the 12-m antennas of the LNSD concept described in WP2002. The SKA requirements for both long baselines ($> 10^3$ km) and a large field of view do not allow pixelization of the entire FOV using all antennas with forseeable computational technology, if both high time and frequency resolutions are required. This difficulty is essentially independent of concept. Therefore it is reasonable to consider blind surveys using only an inner *core array* comprising a fraction $f_{\rm c}$ of the total collecting area.

In the proposed LNSD configuration in WP2002, about 25% of the collecting area is inside a baseline of $b_{\rm c} = 1$ km, corresponding to an areal filling factor $F = N(D/b_{\rm c})^2 = 0.16$, and providing a core-array beam of $1'$ at 1 GHz. For full-FOV searching, one must pixelize the FOV with the appropriate number of core-array beams ($\sim 10^4$ pixels) and with time and frequency resolution dictated by the science requirements. As a benchmark for a blind survey, we use a pulsar search for which we require intensity data streams with $\Delta t = 64\,\mu$s time resolution for each of $N_\nu = 10^3$ frequency channels across a total RF bandwidth of $B = 400$ MHz. Given our uncertainty about the radio transient population(s), such a pulsar survey would also be a good initial survey for radio transients.

For these parameters, we find that real-time processing can be achieved with an FX correlator that (1) channelizes the RF bandwidth and (2) calculates auto- and cross-correlations between all antennas in the core array with an integration time Δt. The computational requirements are quite high. but are less than those required by an explicit beamformer that produces enough beams to cover the FOV. For example, if the inner 1 km is used as a core array, then approximately $10^{3.8}$ beams must be formed. Fast dump correlations for 25% of the SKA's collecting area contained within 1 km require $\sim 10^15$ op s^{-1} for 400 MHz bandwidth (e.g. at L band). This rate is independent of the number of chanels, though it is implicit that channelization sufficient for dedispersion is also sufficient for full FOV sampling. By comparison, direct beam forming for the same parameters requires ×6 higher operations rate.

4.4. Epoch of Reionization and Other Low-Frequency Science

A number of the Level 1 science goals require access to low frequencies. Most notable is the Epoch of Reionization, but other Level 1 science goals with similar frequency requirements include coronal mass ejections and high-redshift AGN.

At 150 MHz, the proposed 12-m antennas of the LNSD span only 6 wavelengths. As such, the antenna size in wavelengths is comparable to that for the 74 MHz system on the VLA (25-m antennas). Experience with that system has demonstrated that relatively high dynamic range images can be achieved. (With the VLA's 74 MHz system, a key limitation is the collecting area, an aspect that will not be a problem with the SKA!) However, the main beam of the antennas is quite large and the sidelobes of the main beam are fairly high (e.g., the typical far sidelobe is at only -20 dB). The LNSD concept will avoid some of these difficulties by phasing the individual antennas together so that the station beam should be smaller, with better sidelobe rejection, than the primary beams of the individual antennas.

Ongoing WMAP results on the cosmic microwave background (CMB) provide the impetus for further extending the frequency range downward to 100 MHz, at least, in order to explore as much of the redshift range implied for the EoR. Recent work on the optics of ATA antennas suggests that appropriate feeds can be installed for work down to 100 MHz. The efficiency may be degraded by $\sim 30\%$ at 100 MHz but it is expected that high-frequency observations will not be compromised because the swing-away arrangement would allow the low-frequency feed to hide behind the secondary.

Nonetheless, attempting to extend the frequency coverage of the *dishes* of the LNSD concept to lower frequencies may be problematic in providing sufficient sensitivity and fidelity for analyzing the EoR signal and mapping protogalactic clumps. However, we point out a great advantage of the LNSD concept: Ancillary antennas could make use of much of the infrastructure required for the small dishes, namely the data transmission, analog and digital signal processing, and correlator and signal-path hardware. The large number of dishes provides ample sites for situating ancillary antennas, either co-located with dishes or stations, or along the fiber paths to the central processor with sufficient separations to avoid electromagtic cross talk. The merits and costs of such an approach can be evaluated only after preliminary results have been obtained with LOFAR and further analysis of WMAP data and future results with PLANCK. For now, we simply stress that the LNSD concept lends itself to augmentation in a manner that can provide great flexibility in addressing future science goals as the science landscape reveals itself.

In more general terms, an important aspect of the SKA specifications is that they are *astronomically* driven by goals to detect and/or study various celestial sources or phenomena. That a variety of astronomical targets require a similar sensitivity across a broad frequency range is perhaps a fortunate coincidence, but it should not be construed as a *technical* requirement. That is, one need not use the same front-end hardware to achieve all the astronomical goals. Of course, once the incident radiation has been sampled, then similar hardware is justified.

It is not a new suggestion that the SKA might ultimately be a collection of different collectors or "front ends" feeding a common signal transmission system and correlator. The difficulties with meeting the specifications for *all* of the Level 1 science goals are not unique to the LNSD concept; in fact, as we have pointed out, they are inherent to the current, concept-independent specifications of the SKA. Thus, we consider a *hybrid* design, in which the low frequencies would be received with one type of collector and the high frequencies with another, to be an important option.

As an example we illustrate one such hybrid design. The Low Frequency Array (LOFAR) is being designed to operate in the frequency range 10–240 MHz, with the fundamental collectors being dipoles. Although it is not clear that LOFAR has a sensitivity commensurate with certain SKA goals, it could form the basis of a low-frequency SKA. Allowing for a modest overlap in frequency coverage, a dipole-based low-frequency SKA (modelled on LOFAR) could cover the frequency range below 200 MHz while the LNSD concept would cover the frequency range 0.2–35 GHz.

5. Summary and Conclusions

— TBD —

Note: the figure quality in the appendices is poor because of the way they have been extracted from original documents. We are in the process of getting better quality figures.

A. 2003 Update to USSKA Concepts for Antenna Elements and Receivers

Our proposed baseline antenna is a 12-m, hydroformed offset parabolic reflector with both Gregorian and prime focus feeds. An alternative, a 12-m symmetric antenna, also with Gregorian and prime focus feeds is also being considered. The key antenna requirements are shown in Table A.1, representative sample of the two types of antennas are shown in Figure A.1, and a comparison table is given in Table A.2.

Table A.1 Proposed Antenna Requirements

Item	Requirement
Reflector Type	Gregorian with projected area of 12-m diameter
Surface Accuracy	0.3 mm rms deviation from best fit caused by gravity, wind up to 15 mph, and a temperature of −10 to +55C
Beamwidth	12° at 0.15 GHz, 72′ at 1.4 GHz, and 3′ at 32 GHz
Pointing Accuracy	0.3° after correction table in 15mph wind
Phase Center Stability	Shall move less than 0.5mm due to 15mph wind or sun/shade condition
Survival	Drive to stow in 50 mph wind and survive at stow in 100 mph wind
Receiver Mounting	90 kg at Gregorian focus and 90 kg at prime focus including subreflector

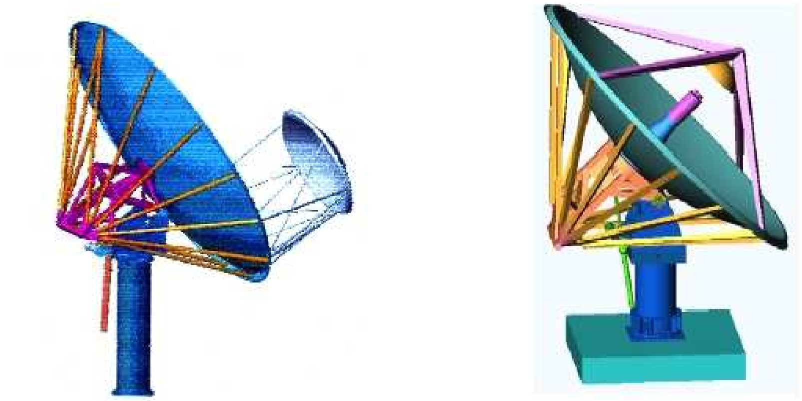

Figure A.1 — Examples of offset and symmetric 12m antennas.

The rationales for the major decisions of antenna size, technology, and optics are discussed below.

Antenna Size: The 12-m size needs further study but is the current strawman size for the following reasons: 1) Current total system cost estimates are broadly minimized at this

Table A.2 Comparison of Offset and Symmetric Antennas

Geometry	Offset 12m x 14m, F/D = 0.42	Symmetric 12m, F/D = 0.50
Subreflector	2.4m Gregorian	1.6m Gregorian
Efficiency (Parabolic & (Shaped)	65% and (75%)	60% and (72%)
Cost Factor and Total $	1.3, 4400 × $150K = $660M	1.0, 4400 × $120K= $505M
Technical Challanges	Surface accuracy, cost	Wideband feed shields to reduce spillover noise
Technical Advantages	Large subreflector without blockage More space for receivers	Lower mass, less wind torque Lower cross polarization
Prototype	ATA 6m	DSN 6m and 12m

diameter. Smaller antennas increase the number of receivers required which leads to higher construction and operating cost for a given total area (maintenance costs per antenna do not go down in proportion to antenna area). 2) A study of rms distortion due to gravity and wind (Figure A.2) of hydroformed shells shows a strong dependence upon diameter. For operation above 20 GHz the gravitational deformation of the shell is excessive for shells greater than approximately 12 m, and a stiff and accurate backup structure is required to support the reflector surface. This leads to a more expensive structure with costs proportional to D2.7 as are experienced for large antennas. 3) Twelve meters is close to the diameter that meets the one-degree field-of-view SKA requirement at 21 cm without a focal-plane array feed. Possible further reduction in electronics costs could lead to a cost minimum corresponding to a smaller antenna which would enlarge the FOV, although it is not clear if a smaller antenna element can reach our low frequency limit.

Hydroforming Technology: This is the process of forming aluminum to a rigid and precise mold by using a fluid or gas under pressure. It has been optimally developed for use in the production of low-cost reflectors for satellite communications and thousands of antennas in the 1 to 4 meter range have been manufactured (see www.anderseninc.com). The advantages are: 1) high rigidity due to the one piece aluminum shell, as illustrated by the stiffness of thin metal bowls or woks compared to the stiffness of flat sheets. 2) accuracy largely determined by the mold rather than human error (the repeatability of the process will be determined soon by the ATA production), and 3) low costs for both raw material and labor, estimated to be $8K and $7.5K (100 person-hours) respectively for a 12-m diameter reflector. A non recurring $6M cost for mold and manufacturing plant add only $1.5K per antenna when amortized over 4400 reflectors.

Optics: Offset and symmetrical antennas are compared in Table A.2. Further study of feeds and optimum parameters are needed and much experience will be gained through the ATA and DSN array projects. A prime focus feed and receiver would be used for 0.15 to 1.5 GHz range and two Gregorian receivers in the same dewar covering 1.2 to 11 and 11 to 34 GHz are anticipated. A subreflector as small as 1.6m is 6.4l at 2.7 GHz, which needs

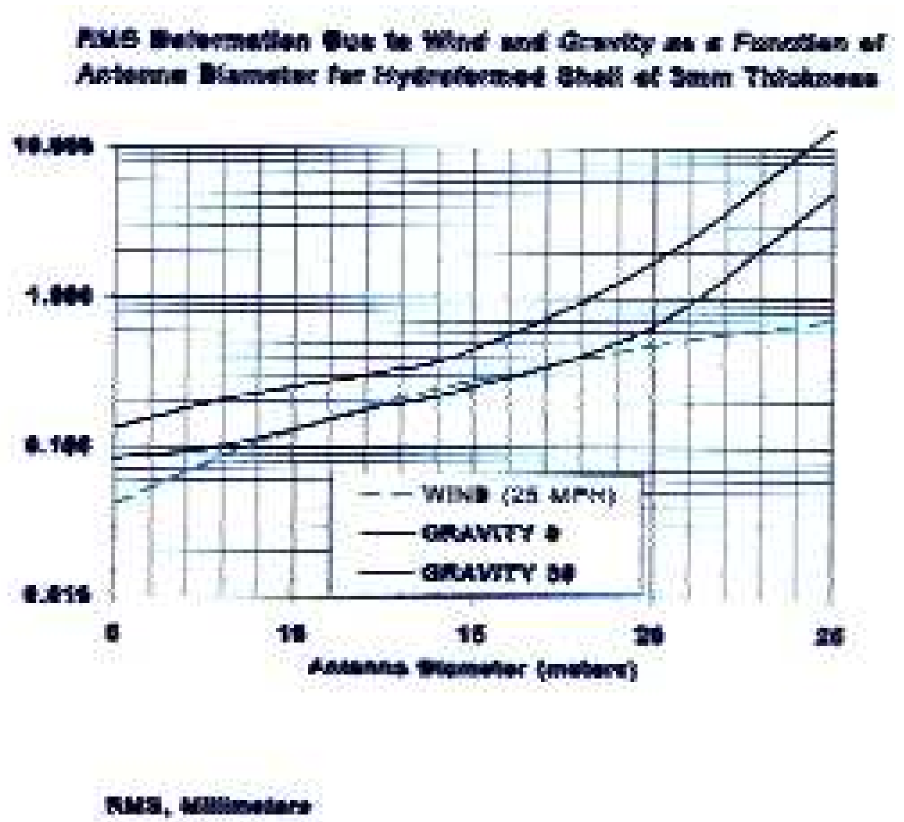

Figure A.2 — Computer-aided finite-element study of the rms deviation of 3 mm thick hydroformed shells gives the above results. An rms requirement of 0.3 mm multiplies the efficiency by 0.85 at 32 GHz. It is expected that a simple back-up structure support can compensate for a portion of the gravitational deflections analysis to determine the diffraction loss. The wide beamwidth (of the order of 100o) of wideband feeds can be accommodated by adjusting the distance to the subreflector Offset Gregorian optics can be designed for low cross polarization but offset prime focus operation will result in some degree of cross polarization at low frequencies.

Shaping: The question of shaping is mostly independent of the question of offset or symmetric optics. Shaping of the reflector and sub-reflector increases efficiency by 10 to 15% (multiplicative) which inversely scales the cost of the complete array for a given A/T. However it increases sidelobe levels (only for the secondary focus receivers above 1.2 GHz) and complicates multi-beaming with focal plane arrays if desired in the future. The spillover due to diffraction around the subreflector is also increased at the longest wavelengths used at secondary focus.

Feeds: The ATA project has led the development of very wide bandwidth (>decade) feeds. Welch and Engargiola at UC Berkeley have designed the pyramidal log-period feeds shown in Figure A.3 for the 0.5 - 11 GHz range and have good measured pattern results. The forward gain is approximately 12 dBi, and the addition of a perpendicular ”fin-line” yields a cross-polarization of about -26 dB. Computations show a VSWR < 1.3 across the band, and ohmic losses less than 3%. The total spillover is about 15%. Each opposing pair of elements of the feed receives one linear polarization. The feed point is a small feeder circuit mounted at the small end of the pyramid, which brings two balanced signals into an inner housing that contains the cryogenic amplifiers in a dewar very near the tip. The entire feed structure will be approximately 1.2-meters in length to cover the 0.5-11 GHz band. The coupling and feed pattern are constant with frequency; however the phase center shifts along the length with frequency. With the focus set for mid-band (6.25 GHz) the gain remains within 1 dB of the peak over the whole band. An actuator can be used to bring the feed to optimal focus at any frequency within the entire band.

Figure A.3 — At left are wideband feeds developed for the ATA and at right is a wideband feed developed by TRW. Both have potential for 20:1 frequency range and have a maximum lateral dimension of approximately l/2 at the wavelength of the lowest frequency of operation

Compact decade bandwidth feeds have been developed by Ingerson at TRW, Redondo

Beach, CA. These feeds have advantages of providing a large volume for the low noise receiver within 1cm of the feed terminals and also have the important advantage that the phase center location does not change wit frequency. A study involving extensive tests of a 0.5 to 11 GHz version of this feed was commissioned by JPL late 2002; this feed is shown in Figure A.3. The full amplitude and phase pattern of the feed was measured in 20 MHz steps from 0.5 to 11 GHz and extensive impedance data was measured. A typical pattern and the spillover and total aperture efficiency of the feed are shown in Figure A.4. A summary is as follows: 1) The aperture efficiency not including any degradation due to reflector deviation, feed loss, or feed impedance mismatch is approximately 68% with a stationary phase-center from 0.5 to 11 GHz. 2) The feed impedance varies from 50 to 500 ohms over the frequency range. This is too large for efficient coupling to the low noise amplifier and TRW is making a revised design. 3) Approximately 17% of the feed pattern energy is in spillover. The figure is about the same as the ATA feed and both feeds need a ground radiation shield to realize low system temperature. During 2002 a study for the USSKA was performed by Ericsson and Kildal of Chalmers University, Sweden to analyze the ATA feed and investigate the effect of surrounding the feed in a cryogenic vacuum chamber. A key result, shown in Figure A.5, is the reduction of sidelobes and spillover noise for the case of the ATA feed placed in a metallic cylinder of diameter 4 times the feed pyramidal base. The result needs much further investigation and optimization but is important for two reasons: 1) It demonstrates the feasibility of cryogenic cooling of small, high frequency wideband feeds; such cooled feeds could be used in the SKA at frequencies above a few GHz. 2) It shows the feasibility of a feed shield which can be used with symmetric reflectors as an alternative to the large ground shield planned for the offset ATA antennas.

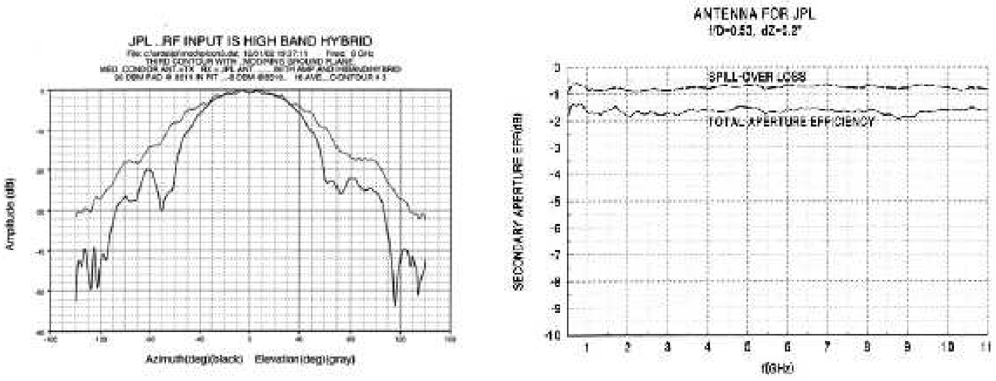

Figure A.4 — Measured 8 GHz E and H plane patterns of a compact wideband feed designed by TRW. The pattern has little variation with frequency and the computed spillover and total aperture efficiency is almost constant from 0.5 to 11 GHz as shown at right.

In summary regarding feeds for the SKA, the feasibility of efficient, low noise feeds with as much as 20:1 frequency coverage has been demonstrated. Further work to understand and optimize the feeds is in progress at a number of institutions.

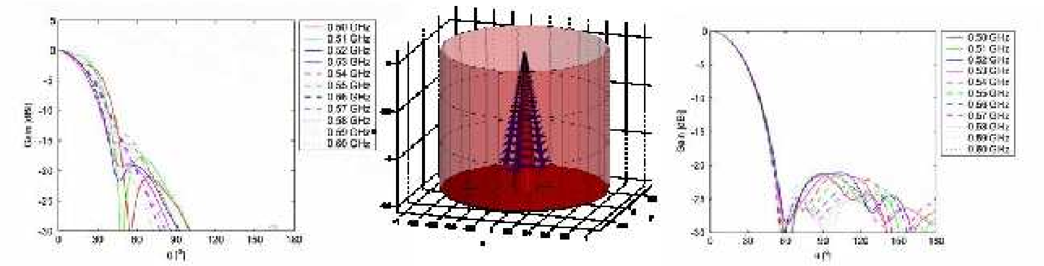

Figure A.5 — Computed patterns of an ATA type log periodic feed in the 0.5 to 0.6 GHz range with (left) and without (right) a cylindrical shield. Further study in other frequency ranges and with baffles and cooled absorbers in the dewar is needed.

Low-Noise Amplifiers: LNA's with decade bandwidth have been under development by Weinreb at Caltech using microwave monolithic integrated circuits (MMIC's) with high-electron mobility InP field-effect transistors (HEMT's). Figure A.6 presents the current state-of-the-art noise temperatures as a function of frequency for a single MMIC LNA at three temperatures. It is evident from this measured data that an LNA with less than 8 K noise temperature in the 1 to 12 GHz range operating at 15 K is feasible. Noise temperatures less than 18 K have been measured for both MMIC and discrete transistor LNA's operating at 15 K at 32 GHz. At frequencies below 1.5 GHz, transistors have improved sufficiently that uncooled 300 K or thermoelectrically-cooled 200 K receivers are attractive, with receiver noise temperatures under 15 K being feasible. This is supported by recent 300 K measurements at Caltech showing 31 K noise temperature over the entire 4 to 8 GHz range measured at an amplifier input connector and 20 K minimum noise for a Raytheon MHEMT device at 3 GHz. The frequency range below 1.4 GHz is especially important for red-shifted hydrogen-line measurements and attention must be paid to achieving receiver low receiver noise down to frequencies as low as 500 MHz where the synchrotron background noise is approximately 20K and rising as frequency to the -2.7 power.

Balun: All wideband feeds have output terminals which are balanced with respect to ground and have an impedance of the order of 200 ohms. A balanced-to-unbalanced converter, or balun, is required between the feed and the usual unbalanced LNA. The balun can be realized as a cooled, passive transmission line circuit but there is loss and added noise. A wideband passive balun has been designed by Engargiola and Welch for the ATA and a cryogenic version of this device will be tested in 2003. An attractive alternative is an active balun which is essentially an LNA with differential input. This device has been under development by Weinreb and others and in 2002 a MMIC implementation was measured with excellent results shown in Figure 6.5. There is solid theoretical and CAD models which show that the noise of the active balun should be identical to that of an LNA made with the same transistors such at that shown in Figure 6.4. Experimental confirmation is expected in 2003.

Antenna/Feed/LNA/Cryogenics Integration: These experimental feed and LNA re-

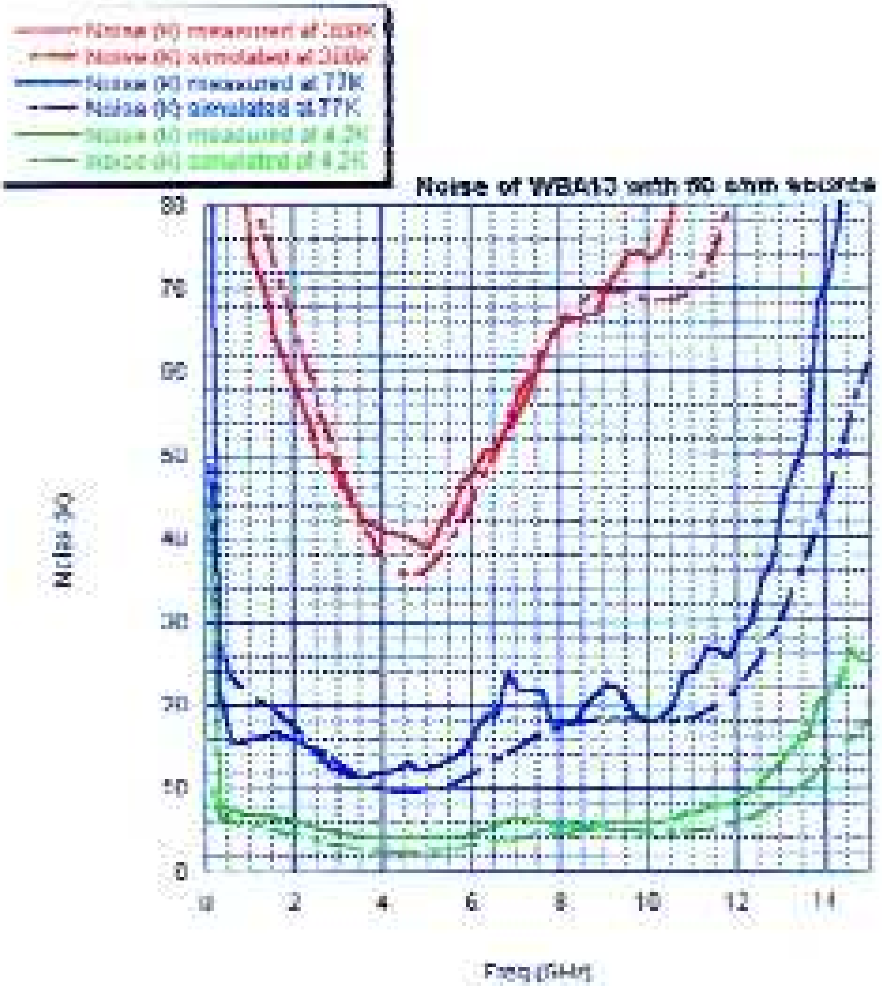

Figure A.6 — Measured and modeled noise temperature vs frequency for an InP HEMT MMIC LNA at temperatures of 300 K, 77 K, and 4 K. SKA operation of such an LNA at a temperature of 15 K with noise temperature < 8 K is proposed. Further transistor development during the next few years is likely to reduce this noise or allow operation at 77 K

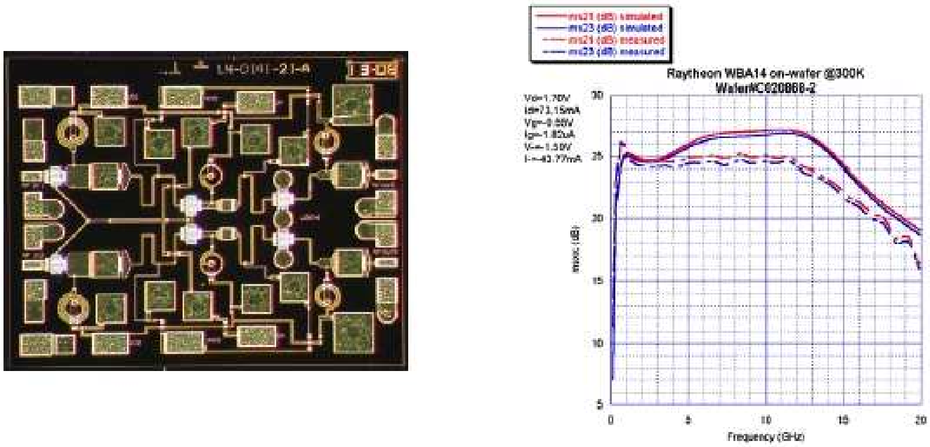

Figure A.7 — Photograph of MMIC low-noise, coolable, active balun of dimensions 1.5 x 2 x 0.1 mm. The test data compares measured and modeled gains from each input terminal to the output terminal. The gains are identical to within 0.5 dB (can be further improved with bias adjustment) and the phase differs by 180 degrees with 2 degrees, both over the frequency range of 0.5 to 15 GHz.

sults lead to proposed goals and configuration of three receivers covering the 0.15 to 34 GHz range are shown in Figure A.8. The two high-frequency receivers will be in one dewar, cooled with a single cryocooler with a moving mechanism to bring one feed or the other into focus. A light-weight, low-frequency, 0.15 to 1.5 GHz feed with a thermoelectrically cooled LNA will swing out of the ray path when either high frequency receiver is in use. We expect that our combination of antenna, feed, and receiver design will meet the SKA specification of A/T = 20,000 m2/K over the frequency range 1 to 8 GHz. Outside this range, the sensitivity will be degraded.

Local Oscillator and Downconverters: Local oscillator distribution within the array central core of < 100 km will be by microwave carrier signals on a round-trip corrected optical fiber. Similar systems are being developed at the EVLA, DSN array, and other radio astronomy arrays. A tracking filter or phase locked oscillator, is required at each antenna to remove noise on the LO reference signal. A 4-8 GHz reference signal with a YIG tuned phase locked cleanup oscillator and multipliers to higher frequencies may be appropriate. For array elements at distances > 100 km from a master LO, fiber LO distribution becomes difficult and costly. The loss in the fiber becomes appreciable and the phase stability of one-way amplifiers may degrade the phase stability of a round-trip correction system. Hydrogen maser or other new frequency standards could be used for distant clusters but this gets very expensive ($300K per standard) if there are many distant antenna in small clusters. Distribution of LO reference by round-trip corrected paths utilizing a commercial satellite are being investigated at JPL with a test of a system utilizing Telstar V planned in 2003. The electronics required for local oscillator distribution, down conversion, IF amplification, and optical transfer must be carefully designed for reliability and performance but no special

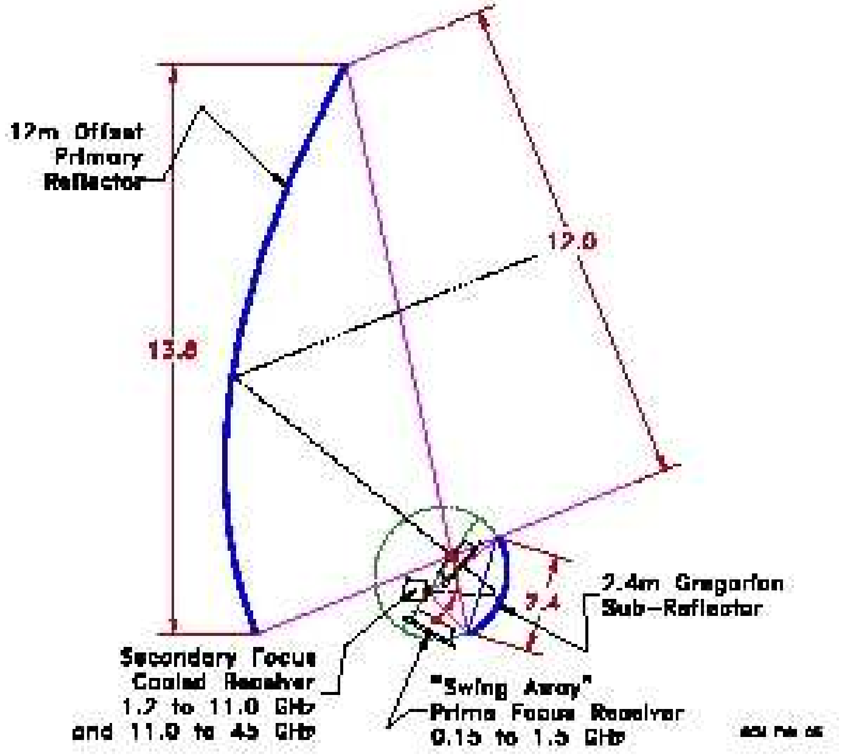

Figure A.8 — Possible configuration of feeds and receivers for an offset Gregorian antenna. It may be possible to combine the two higher frequency receivers into one. These configurations may also work with symmetric antennas if an efficient and compact spillover shield can be devised. The 0.15 GHz lower frequency limit significantly increases the size of the prime focus wideband feed and a separate dipole feed covering low RFI bands under 0.3 GHz may be preferable. If shaping is used it puts an upper limit on the crossover frequency between prime and secondary focus; a crossover frequency of 1.5 GHz range appears feasible and needs further study.

Table A.3 Receiver Parameters

Receiver	1	2	3
Frequency, GHz	0.15 – 1.5	1.2 – 11	11 – 34
Location	Prime	Gregorian	Gregorian
Maximum Feed Dimension	1.5 m	10 cm	3 cm
Physical Temp	200K	15K	15K
LNA Noise *	15K	5K	5K
Receiver Noise **	22K	11K	25K
System Noise***	32K	18K	45K

* Noise temperature at LNA connector

** Includes feed and window loss

*** Includes sky background at best frequency

technology requiring early proof of feasibility is required. Prototype design should start 3 years before array construction start.

B. Allen Telescope Array, 2003 Progress Report

The Allen Telescope Array baseline design is composed of 350 6.1-meter offset Gregorian antennas (6.1 7.0 m primary paraboloid) with a 2.4-meter secondary operating over 0.5-11.2 GHz utilizing a single wide-bandwidth log-periodic feed and a single wide-bandwidth analog optical transmitter. The use of the optical transmitter allows the entire bandwidth to be brought back to a central control room for processing, allowing a great deal of flexibility in the use of this instrument. The baseline design calls for four simultaneous, independent dual-polarization 100 MHz tunings anywhere within the RF band, each of which will have four independently-steerable beams, allowing a total of 32 independent beams. In addition, two of the tunings will be fed into a correlator for concurrent imaging. Currently, three antennas have been erected at the Hat Creek site (Figure B.1) and are undergoing RF and mechanical tests. Initial tests of pointing using an optical telescope mounted on the structure show $10''$ rms pointing error which is much better than the $2'$ specification. One additional antenna will be erected at a test facility in the San Francisco area and four additional antennas at the Hat Creek site by the summer of 2003. Scaled versions of the feed with a room temperature front-end have been manufactured and are installed on the antenna, along with production versions of the optical fiber links. The full-size feed with a cryogenic front-end is expected by the end of 2003. A test correlator is currently in place to allow interferometric measurements and a prototype correlator for six baselines is expected by the fall of 2003. Prototype boards for the digital processing have been manufactured and are currently undergoing tests. Full scale construction is expected to commence in 2004 and to last approximately 2 years. Given the modular nature of the telescope however, observations may begin as soon as the electronics are in place and well in advance of the completion of the last antenna.

Figure B.1 — First three 6.1m offset-paraboloid antennas of the Allen Telescope Array in Hat Creek, CA.

C. Deep Space Network (DSN) Communication Array Prototype

JPL, with NASA support, has interest in applying array concepts to deep space communications. JPL is closely monitoring the ATA antenna manufacture and is designing cost-conscious, 6- and 12-m steerable paraboloids for operation up to 38 GHz. An SKA-sized array equipped for downlink reception at the primary space communication frequencies of 8.4 and 32 GHz would allow of the order of 100 times greater data rate to the outer planets, smaller and less expensive spacecraft, longer missions in the case of Mars (where the distance varies from 0.33 to 2.5 AU), and very accurate real-time navigational data. The current concept is for an array of 3600 x 12-m antennas at each of three longitudes arranged in several large stations at each longitude for weather diversity. Much of the technology development for the DSN Arrays and the SKA can be shared. The DSN array will utilize radio astronomy sources for phase calibration and will have wide bandwidth correlation processing for this purpose.

An $80M development program has been proposed to NASA to develop the technology and prove the performance and cost of a very large DSN array; $4.2M has been allocated in FY03 to start this work at JPL. The program includes a breadboard 6-m interferometer by late 2004, a 25 x 12m cluster of antennas by 2006, and four 25 x 12-m clusters by 2009. During FY02 approximately \$1M was spent at JPL and Caltech to initiate development; some of the highlights of this work are: (a) contract to the ATA antenna reflector contractor, Andersen, to improve the accuracy of the 6 m mold for 32 GHz operation, (b) design of an antenna pedestal for 32 GHz operation, (c) contract to TRW for a compact feed with 22:1 frequency ratio, (d) assembly and testing of 8.4 and 32 GHz cryogenic MMIC LNA modules, and (e) system design for the prototype array. In FY03 the above work has been expanded to include first design of all electronics for the array and purchase of three 6m hydroformed symmetric reflectors with < 0.2mm rms accuracy.