

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

Prepared by the USSKA Consortium

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This **draft** document contains only a skeleton for Part 1, a draft received from Ken Kellerman of Part 2 (with contributions by many), and a draft of Part 3 modified according to some of the discussion during our April 14 telecon. The Appendices are in a separate pdf file (for now) and were prepared by Sandy Weinreb.

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

To include:

1. Itemize changes that are essentially parametric and in response to particular scientific issues. I.e. size of core array, frequency coverage, etc.
2. Discuss alternative dish designs (on and off axis).
3. The ability to bring signals from all antennas directly to the correlator.
4. Itemize new emphasis on how the LNSD design can target blind surveys for pulsars, transients and ETI.
5. Summarize how we may address the low-frequency end (e.g.  $\leq 300$  MHz) with respect to WMAP results pertaining to the EoR; this might entail a preliminary discussion of how the LNSD design might be combined in a hybrid configuration with a low-frequency array.

## 2. 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 xxx, approximately 20 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 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 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  $26^\circ$ . 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 of the station beam. Figure xx shows a possible station configuration with 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.

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 strategies 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  $T_{\text{sys}}$  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  $\$45\text{K} \times 4400 = \$198\text{M}$  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 paraboloids 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 antenna (6 m) optimized for secondary focus operation above 2 GHz.

### 3. 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\\_matrix.html](http://www-astro.physics.ox.ac.uk/~sr/ska/ska_matrix.html) (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.

#### 3.1. 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. Table 1 summarizes the science Compliance 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. 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 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.

- 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

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

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

† Grades: As assessed by the International Science Advisory Committee:

1 = NO 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.

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) 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 §3.3.

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 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** (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 §3.4.
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<sub>2</sub>O 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 specifications (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, primarily because of its high-frequency coverage and long baselines.
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.

### 3.2. Configuration Issues

Level-1 science areas 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 ( $\sim 1$  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.

For polarization work, high polarization purity is essential. We 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  $b_c$  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  $(b_c/D)^2$  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.

### 3.3. 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  $V_{\max} = \frac{1}{3}\Omega D_{\max}^3$ , where  $\Omega$  is the solid angle and  $D_{\max} = D(S/S_{\min})^{1/2}$  is the maximum detectable distance for a source with flux density  $S$  at distance  $D$  and for a minimum-detectable flux density  $S_{\min}$ . 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  $S_{\min}$  and hence decrease  $D_{\max}$  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  $\sim 2$  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  $1 \text{ deg}^2$  at  $\lambda = 20 \text{ cm}$  while it is  $\sim 2.6 \text{ deg}^2$  for the 12-m antennas of the LNSD concept described in WP2002. The SKA requirements for both long baselines ( $> 10^3 \text{ km}$ ) and a large field of view do not allow pixelization of the entire FOV using all antennas with foreseeable 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  $f_c$  of the total collecting area.

In the proposed LNSD configuration in WP2002, about 25% of the collecting area is inside a baseline of  $b_c = 1 \text{ km}$ , corresponding to an areal filling factor  $F = N(D/b_c)^2 = 0.16$ , 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  $\Delta t = 64 \mu\text{s}$  time resolution for each of  $N_\nu = 10^3$  frequency channels across a total RF bandwidth of  $B = 400 \text{ MHz}$ . 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  $\Delta t$ . The computational requirements are quite high (**put here**) but are less than those required by an explicit beamformer. Channelization sufficient for dedispersion is also sufficient for full FOV sampling.

**Elaborate here**

### 3.4. Epoch of Reionization and Other Low-Frequency Science

A number of the Level 1 science goals require access to low frequencies. Perhaps 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 produced. (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 becoming quite large and the sidelobes of the main beam are becoming fairly high (e.g., the typical far sidelobe is at only  $-20 \text{ dB}$ ). 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.

Nonetheless, attempting to extend the frequency coverage of the LNSD concept (or many of the other concepts) to lower frequencies will result in increasing inefficiencies. Among other difficulties, the collecting area of the antennas remains constant, while the sky temperature (and therefore the system temperature) begins to increase as  $T^{2.6}$ .

An important aspect of the SKA specifications is that they are *astronomically* driven. The objective is 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 (or unfortunate?) coincidence, but it should not be construed as a *technical* requirement. That is, one need not use the same hardware to achieve the astronomical goals. Of course, once the incident radiation has been sampled, then similar

hardware is justified. However, the method of collecting the incident radiation can differ as a function of frequency.

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. We believe that the difficulties encountered with attempting to meet the specifications for *all* of the Level 1 science goals are not unique to the LNSD concept. 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.