SKA Hybrids Involving the US LNSD Concept

US SKA Consortium

Contents

Abstract

The likely Key Projects for the SKA demand both a large frequency range (potentially 0.06–24 GHz) and a large range of fields of view (potentially less than 1 $\deg^2$ at higher frequencies to as much as 200 $\deg^2$ below 1 GHz). The US SKA Consortium has proposed the Large-Number/Small-Diameter (LNSD) concept, which generally covers the frequency ranges and fields of view required by the Key Projects. Opportunities do exist, however, to enhance the design of this concept and provide access to larger ranges of frequency and field of view.

We describe a number of "hybrid" arrays, involving the LNSD concept, that are designed to increase the probability that most of the SKA Key Projects can be conducted. There are two broad classes of hybrids, those that combine concepts and those that combine technological aspects from the different international groups. We consider how the US LNSD concept could form the basis of both kinds of hybrids. We focus on two "strawman hybrids." The first is an SKA composed of high- and low-frequency sub-arrays, with the LNSD concept forming the high-frequency sub-array. In this **LNSD–low-frequency sub-array** hybrid:

- The frequency range 0.5–1.5 GHz is common to both the LNSD and the low-frequency sub-array;
- The frequency coverage of the low-frequency sub-array, either the **aperture array** or the **cylindrical reflector**, continues below 0.5 GHz;
- The LNSD frequency coverage continues above 1.5 GHz; but
- A key uncertainty is the extent to which infrastructure costs could be shared as separate high- and low-frequency "cores" are required.

The second is a **augmented LOFAR-LNSD** hybrid

- LOFAR would cover the frequency range below approximately 0.3 GHz;
- LNSD would cover the frequency range above approximately 0.5 GHz;
- The design of the LNSD dishes would be changed to a symmetric reflector, saving approximately $100M, roughly the amount estimated to increase the LOFAR sensitivity to required levels; but
- The Dark Energy Key Project probably could not be conducted and a reduced sensitivity, frequency "gap" between 0.3 and 0.5 GHz would exist.

Initial costing estimates are that either could be achieved for a cost similar to that for the currently proposed concepts (≈ $1.2–$1.4G). Finally, we describe how the US SKA Consortium could contribute an SKA design that did not make direct use of the LNSD concept.

1 Why Hybridize the SKA?

The International Science Advisory Committee has recommended a set of SKA Key Projects (Level 0 projects), projects that address fundamental questions in physics or astronomy and to which the SKA can make a unique or vital contribution.[1] The working groups of the ISAC also have developed a number of broader scientific projects, that while not rising to the level of Key Projects, are judged to be of importance (Level 1 projects). Finally, the ISAC also recommended a philosophy of keeping the telescope design as flexible as possible, to allow for the telescope to be used for general purposes.

From these Key Projects, engineering design specifications for the SKA are being developed and refined. Two notable requirements of the Key Projects are a large frequency range (currently potentially as much as 0.06–24 GHz) and a large field of view (currently 200 deg^2 at 700 MHz), as well as the desire to have the capability for obtaining multiple fields of view simultaneously with the full collecting area of the SKA ("multi-fielding").

It is not clear that any of the currently proposed SKA concepts are individually capable of accomplishing all of the Key Projects. There is also the desire for an inclusive project so that radio astronomers in all nations benefit from the SKA. These motivations have led to numerous discussions, in a variety of fora, of the possibilities for "hybrid" concepts for the SKA.

The US SKA Consortium has proposed the Large-Number/Small-Diameter (LNSD) concept. The operational frequency range of this concept is expected to be at least 0.5–35 GHz. An evaluation of the compliance of the LNSD concept with the requirements specified by the Key Projects has not yet been undertaken, however, the LNSD was evaluated favorably by the ISAC working groups with respect to the broader scientific goals (Level 1 projects). Thus, the LNSD concept can be a key component of any SKA hybrid.

2 What is a Hybrid?

There have been suggestions that a clear distinction should be made between "hybrids" and "combinations." The former would involve combining technologies from the different concepts, e.g., placing the European tiles at the focal plane of the Canadian large aperture reflector. The latter merely involves combining collectors from the different concepts, e.g., some fraction of the SKA composed of the Australian cylindrical reflectors and some fraction composed of the Indian pre-loaded parabolic receivers.

For the purposes of this document, we shall not make that distinction. We view the primary goal at this stage of the SKA project to be one of identifying a means of constructing a radio telescope to meet the requirements of the Key Projects while still maintaining a design flexible enough for other uses.

We shall consider three paths to an SKA hybrid: One in which the US LNSD concept is augmented at the lower frequencies (§3), one in which the US LNSD concept forms the

[1] At the time that this document was written, the ISAC recommendations for SKA Key Projects had not yet been adopted by the International SKA Steering Committee (ISSC).

basic concept but is augmented by technologies contributed by other groups (§4), and one in which the the US SKA Consortium members contribute to an SKA that does not involve the LNSD concept (§5).

3 Low Frequency Augmentation of the US LNSD Concept

The US LNSD concept offers a number of low-risk factors. First, it is recognized as being able to meet a large number of the broader scientific goals (Level 1), as evaluated by the ISAC working groups. Second, in relying on parabolic receivers, it makes use of either well-proven technologies or modest extrapolations of current technologies. Finally, the large number of elements composing an LNSD array implies robustness against failures.

Nonetheless, the LNSD concept would appear to have difficulty providing extremely large fields of view (i.e., much larger than the current specification of 1 deg^2 at 1 GHz) nor does it appear possible for the LNSD concept to provide "multi-fielding," multiple, widely-separated fields of view with the full collecting area. These difficulties would become particularly acute at frequencies near and below 1 GHz, for instance for the Dark Energy Key Project, which involves large-scale surveys for hydrogen emission at $z \approx 1$.

The LNSD could conduct some fraction of these observations, though with certain costs. For instance, larger fields of view could be obtained by decreasing the dish diameter, potentially at the cost of increasing the signal processing requirements. Multiple fields of view can be obtained by using sub-arrays, though these sub-arrays would necessarily have less than the full collecting area of the array.

One way of addressing these concerns of the LNSD is to augment it with collectors that have larger fields of view or can obtain multiple fields of view more easily. Examples of such concepts include the European aperture arrays, the Australian cylindrical reflectors, and Australian Luneberg lenses.

3.1 Example Hybrids

Some possible examples of such hybrid concepts that have been discussed within the US SKA Consortium, along with a preliminary assessment of their advantages and disadvantages, include (in no particular order):

- Separate "low" and "high" frequency sub-arrays forming the SKA, e.g., as in the EMT suggestion, with the high-frequency sub-array formed from the US LNSD concept.

  Pro Perhaps most obvious way to achieve all scientific goals

  Pro A symmetric reflector design could be adopted for the LNSD parabolic dishes, which should produce a modest cost savings

  Con Separate infrastructure likely to be required; some amount of central condensation ("cores") is required at both high and low frequency, the Dark Energy Key Project requires reasonable surface brightness sensitivity at low frequencies and the processing requirements for the pulsar search aspect of the Strong-Field

Tests of Gravity Key Project are a strong function of the array filling factor while the Cradle of Life Key Project also requires reasonable surface brightness sensitivity but at high frequencies

- Mount log-periodic feeds on the back of the secondary reflector (as well as possibly some on the main reflector).

  Pro Possibly shared hardware and infrastructure

  Con Mechanical stresses that may increase mount requirements and cost

  Con Poor $A_{\text{eff}}/T_{\text{sys}}$

- Illuminate the prime reflector with European aperture arrays.

  Pro Allows for shared infrastructure.

  Con Poor $A_{\text{eff}}/T_{\text{sys}}$.

  Con Requires separate beam former.

  Con Needs to be studied further for an hybrid concept.

- Only optimize the inner portion (e.g., 6-m diameter) of the antennas for high frequency observations, with the outer portion being a wire mesh

  Con Mechanical and/or labor costs may be increased.

  Con Does not provide "multi-fielding."

  Con Obtaining short baselines at high frequencies is difficult.

- Combine a large dish or dishes (e.g., Canadian Large Aperture Reflector) in the central region of the array with LNSD parabolic dishes forming the intermediate and outer portions of the array

  Pro Excellent surface brightness sensitivity

  Con Not clear that sufficient field of view can be obtained for the Dark Energy Key Project

  Con "Multi-fielding" appears difficult

- Use LNSD concept for inner portion of the SKA and make use of existing and future large telescopes for VLBI capabilities.

  Pro Makes use of existing and future infrastructure. For example, a collecting area of approximately 10^5 m^2 (10% SKA) exists or will exist in the northern hemisphere, including Arecibo, the future Chinese FAST, and Canadian LAR (or prototypes).

  Pro Reduces data transport costs.

  Con Shared use with other users of these telescopes.

  Con Many different telescopes to be integrated.

  Con Does not provide "multi-fielding."

  Con An "ad-hoc" array to some extent

3.2 LNSD–Low-frequency Sub-array SKA Hybrids: Initial Costing

As a first exercise in estimating the cost for a hybrid SKA involving the LNSD concept, we consider the first of the hybrids described above, in which the SKA is composed of high- and low-frequency sub-arrays with the LNSD concept forming the high-frequency sub-array. For a low-frequency sub-array, we consider both the European aperture arrays and the Australian cylindrical reflectors. We make these choice for two reasons. First, these models would enable most, if not all, of the Key Projects. Second, from the existing white papers, these models are the easiest for which to estimate a cost as no change to the basic receptor elements is envisioned.

The LNSD contribution to both hybrids is taken to be the same, 2500 12-meter parabolic dishes operating between 470 MHz and 24 GHz. In this model, the LNSD provides a high-frequency sub-array for the SKA with $A_{\mathrm{eff}}/T_{\mathrm{sys}} \approx 10^4\,\mathrm{m}^2\,\mathrm{K}^{-1}$ below 10 GHz. By removing the requirement that the parabolic dishes operate below 0.5 GHz, the dish design can be changed to be symmetric, rather than the offset design assumed in the current LNSD concept. In doing so, we obtain a modest cost savings, approximately \$20k per antenna. For both hybrids, the upper frequency limit of the low-frequency sub-array is taken to be 1.5 GHz. The frequency overlap, 0.5–1.5 GHz, is chosen to encompass H I emission at redshifts $z < 2$.

The estimated cost of the 2500 parabolic dishes outfitted with receivers and including the cost of making a foundation for the antennas is \$493M, which incorporates an approximate \$50M savings resulting from changing the LNSD concept from its current offset feed design to a symmetric antenna.

An important *additional cost* borne by both hybrids is the need for separate "core" arrays. Various Key Science Projects—the Dark Energy project, the Strong-Field Test of Gravity project, and the Cradle of Life project—all require a portion of the array to have a high filling factor. In order to avoid physical collisions between the different kinds of receptors or shadowing, the two cores would have to be separate, resulting in little savings for engineering, data transmission and processing, and civil costs for each core. As a rough indication of this separation, we take it to be comparable to the size of the most compact central portion of the SKA—specified currently to be approximately 2 km. Estimates for the cost of the infrastructure for the core differ in various white papers, ranging from \$30M in the US SKA Consortium's white paper to as much as \$90M in the European aperture array white paper.

The first strawman hybrid involves the LNSD and the aperture array. Table 1 summarizes the initial costing exercise for this hybrid. The aperture array concept is optimized to work below 1.5 GHz and offers the promise of multiple beams so as to obtain multi-fielding and large solid angle coverage, which is particularly useful for the Dark Energy Key Project. The estimated cost of 50 aperture array stations, including costs such as the station intra-network and mechanical costs, is \$495M. The different white papers estimate different costs for engineering, data transmission and processing, civil costs, and related costs. The total cost of this hybrid is estimated to be \$1.5G. One potential difficulty for this hybrid is that it provides, at 1.5 GHz, a collecting area of only 0.5 km^2; as in the original aperture array concept, though, larger collecting areas would be obtained at lower frequencies, though.

Table 1: SKA Strawman Hybrid: LNSD-aperture array

Component	Estimated Cost (millions of US dollars)
2500 12-m dishes	493
50 stations	495
infrastructure, etc.	518
Total	1505

The second strawman hybrid involves the LNSD and the cylindrical reflector concept, with the cylindrical reflectors optimized for performance below 1.5 GHz. Table 2 summarizes the initial costing exercise for this hybrid. Like the aperture arrays, the cylindrical reflector also offers the possibility of wide fields of view at frequencies near and below 1 GHz. The primary cost drivers for the cylindrical reflectors are the upper frequency limit and the processed bandwidth. By reducing the upper frequency limit to 1.5 GHz and the processed bandwidth to a maximum of 0.8 GHz, we estimate that nearly a full square kilometer of collecting area could be obtained with the cylindrical reflectors. Within the frequency overlap range, 0.5–1.5 GHz, more than a square kilometer of collecting area would be obtained. The estimated total cost for this hybrid is $1.1G.

Table 2: SKA Strawman Hybrid: LNSD-cylindrical reflector

Component	Estimated Cost (millions of US dollars)
2500 12-m dishes	493
500 reflectors	159
infrastructure, etc.	457
Total	1110

3.3 LOFAR-LNSD Hybrid

In considering hybrids for the SKA, a key aspect is the relation of the Low Frequency Array (LOFAR) to the SKA. LOFAR is being developed for the 10 to 240 MHz spectral range. The primary antenna elements are simple dipoles with a multi-steradian field of view; in order to cover the entire frequency range, three sets of dipoles are envisioned, covering the approximate ranges 10–40 MHz, 30–90 MHz, and 120–240 MHz. The maximum baselines for the array are anticipated to be 400 km.

The design goals for LOFAR are for it to have a collecting area of 10^6 m^2 at 15 MHz. The λ^2 dependence of its collecting area means that at higher frequencies LOFAR will have a smaller collecting area, though additional dipoles are being added for the 120–240 MHz band in order to compensate for this λ^2 dependence. While it will not be the Square Kilometer Array, it will have a square kilometer of collecting area at its lower frequencies.

There is general agreement within the ISAC that the low-frequency requirements for the SKA should be (re-)assessed after LOFAR has begun operation. The current requirement of a lower frequency limit of 0.2 GHz for the SKA concepts is set so that there is some overlap with the upper frequency range of LOFAR. If LOFAR observations indicate that additional sensitivity is needed at lower frequencies, one way of obtaining it would be to augment LOFAR.

The current LOFAR design goals imply $A_{\mathrm{eff}}/T_{\mathrm{sys}} \sim 500\,\mathrm{m}^2\,\mathrm{K}^{-1}$ at 200 MHz. This is a factor of 10–20 lower than the current SKA specification, which is driven by the Dark Ages and Epoch of Reionization Key Project goal to measure the fluctuations in H I at the EoR.

The current cost estimate for the "high-frequency" dipoles (120–240 MHz) is roughly \$50 m^{-2}. If the other infrastructure exists (fiber optics for data transmission, computational power for processing, etc.) the high-frequency capability of LOFAR could be augmented for roughly \$100M. Moreover, the high-frequency limit of these dipoles is not strict. Modest changes, e.g., making them slightly smaller or using a slightly closer spacing, would enable them to be used to higher frequencies, perhaps to 300 MHz.

The strawman LNSD concept employs offset paraboloid reflectors. Changing to a symmetric receiver should produce a cost savings of approximately \$100M, approximately the same amount needed to augment LOFAR to increase its sensitivity. Thus, an alternate low-frequency augmentation for the LNSD is a combination of an augmented LOFAR and the LNSD concept. In this hybrid, the frequency coverage would not be complete, containing a region between approximately 0.3 and 0.5 GHz, which could be accessed at best only at reduced sensitivity. The lower frequency of this "gap" would be set by the upper frequency limit for which the "high-frequency" LOFAR dipoles remain reasonably efficient. The upper frequency of the "gap" is set by low-frequency limit of the LNSD dishes and is taken to be near 0.5 GHz in order to allow H I observations out to $z = 2$.

While not technically demanding, this hybrid concept would imply that the Dark Energy Key Project probably could not be accomplished. Moreover, it may involve significant political risks. Is it possible to obtain money for construction of the SKA and for augmentation of LOFAR, without it appearing to be the funding of two separate projects? The significance of this issue may vary from country to country.

4 Technological Hybrids

An alternate approach would be to adopt a single concept that maximizes the scientific return at the expense of not being able to obtain full compliance with all scientific goals. If the LNSD concept were chosen as a result of such "descoping," international groups could contribute to a variety of aspects. *For illustration purposes only*, Table 3 summarizes these (non-exhaustive) potential contributions.

Table 3: International Contributions to the LNSD

Area	Group
Science	All
Receivers	China, Europe
Data Transport	China, Europe
Configuration	Australia
Simulations	Australia
RFI Mitigation	All
Correlator	Canada
Operations	All
Education/Public Outreach	All

Note—These categories and listings are intended to be illustrative only.

5 US Contributions to Potential Hybrids

Even if the LNSD concept is not selected as forming a portion of the eventual SKA, various aspects of the LNSD concept design and development would be important contributions to the SKA design and development and prototyping. Table 4 summarizes these potential contributions.

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Table 4: US Contributions to the SKA

Area	Institution
Science	All
Receivers	Caltech/JPL, Haystack/MIT, NRAO, UCBerkeley, U.Wisconsin
Data Transport	Haystack/MIT, NRAO
Configuration	Haystack/MIT, NRAO
Simulations	Haystack/MIT
RFI Mitigation	Cornell/NAIC, NRL, Virginia Tech.
System Analysis	Cornell/NAIC, Haystack/MIT, NRAO, SETI Institute, U.Wisconsin
Operations	Cornell/NAIC, NRAO, SETI Institute
Siting	Cornell/NAIC, NRAO, U.New Mexico
Education/Public Outreach	Cornell/NAIC, SETI Institute, U.Wisconsin