1. Background

Various analyses, including the recent IEMT report [1], have noted that meeting the SKA frequency range and sensitivity goals with a single antenna technology is very difficult, principally because sensible high frequency (> 2 GHz) optimizations result in too little effective area at low frequencies. When independent multi-fielding is added to the list of goals, the attractiveness of a technology split increases. Aperture phased arrays offer multi-fielding at low frequencies but are not feasible above ~1.5 GHz from either an economic or performance viewpoint. The other proposed SKA multi-fielding technology – Luneburg lenses – has been disadvantaged in that lenses which are big enough to perform well at 100 MHz are too lossy at high frequencies. In this short paper we outline a hybrid, or composite, SKA solution which exploits the optimum performance regime of both antenna components. It uses aperture arrays to 1.5 GHz and small Luneburg lenses to cover the range 1.0 – 22 GHz. As expected, there are some compromises if the total budget is to remain in the range USD 1 – 1.5 B. While optimizations are not explored in this brief submission, we have selected a representative design in which the original SKA sensitivity goal of 20 000 m²K⁻¹ is approached at 1.4 GHz. The SKA design space is still very wide and part of our motivation in presenting the suggested hybrid is to establish a practical design boundary for the multi-beaming domain.

2. Independent Multi-Fielding

A review of the scientific merits of multi-fielding is given in [2]. The ability to place widely-separated (“independent”) fields is a special feature, intrinsic to a telescope design. The summary in [2] shows that attempts to recover limited capability in this domain (e.g. by sub-arraying a single-field instrument) usually lead to inefficient use of the collecting area. If multi-fielding is important, our conclusion is that the SKA design must reflect this from the outset – it is truly a primary driver in the choice of antenna technology.

Whilst there are sound scientific reasons for choosing a multi-fielding approach (Section 4), we believe that the potential operational gains alone are so great that this capability should be thoroughly studied in the SKA design process. A complementary view is that area re-use maximizes the investment return on a mega-science project.

3. Our Proposal

We propose an SKA incorporating aperture arrays (AAs) and small Luneburg lenses (LLs), along the lines depicted in Fig. 1. The concept draws on material presented in both the 2002 AA and LL whitepapers [3, 4] and the 2003 updates [5, 2]. We retain, for the present, the four-FOV specification of the constituent AA and LL components and have based our design on shared infrastructure, including the remote station and signal transmission hardware. With the LL component dominating demands for bandwidth, most of the infrastructure is as described in [4]. The great flexibility of this design allows many possible observing options, including simultaneous use of AA and LL collecting area (providing parameters such as observing bandwidth are chosen appropriately).

Significant changes to the ideas presented in the updated whitepapers include:

- Halving the physical area of the three AAs to give effective areas of 1, 0.49 and 0.26 km² at spot frequencies of 0.2, 0.4 and 0.9 GHz, respectively;
- Reducing the diameter of the LL concentrators from 7 m to 3.5 m and increasing the number of lenses to 92 lenses per station, giving about one third of the LL area in [2]; and
- Using efficient, low-cost, solid-state, “consumer-grade” coolers for the LL receivers.
Table 1 summarizes some important parameters of our design, while Fig. 2 is a plot of the sensitivity of the hybrid SKA as a function of frequency. Fig. 3 shows the cost of the telescope apportioned across various major components, with the split between antenna technologies explicitly identified.

Luneburg Lenses

We use a total of 27,600 lenses of 3.5 m diameter, saving nearly 80% of the dielectric material needed for the array of volumetric concentrators in [2]. In light of recent measurements, a slightly lower dielectric loss has been adopted \( \tan^2 \delta = 0.75 \times 10^{-4} \). The weight of a single lens is reduced to 960 kg and the smaller antenna is easier to manufacture, transport and erect. For costing purposes we retain a four-arm feed positioner [2]. However, with steel and mechanical components now dominating antenna costs, a more advanced focal-plane feed positioner (similar in principle to those used for fibre positioning in new-generation optical spectrographs) may be attractive, especially as the requirement to move large feeds is now relaxed. We see opportunities for wider international mechatronics partnerships in this area (Section 5).

Aperture Arrays

In general, we adopt the hierarchy described in [5] for SKA signal aggregation in aperture arrays. The flow from elements to tiles to patches to station sits well with the now-familiar LL architecture and its associated signal processing architecture. For topology design purposes we establish the rough equivalence of “patches” (typically 40 mid-band tiles) with an individual 3.5 m LL; the compatibility with subsequent station DSP is then almost exact. We accept that, on a 2015 timescale, some level of RF beamforming will be necessary at the tile level. However, we wish to explore possibilities for the international development of achromatic beamformers (Section 5).

4. Science

Few of the SKA goals explicitly demand operation above 10 GHz [6]. The main high-frequency drivers include S-Z, high redshift CO and solar system observations. The AA-LL hybrid offers the moderate sensitivity needed for these applications whilst still providing sufficient sensitivity for all mainstream SKA applications identified by the science working groups. While the A/T compromise will result in longer integration times, this hybrid uniquely enables multi-fielding across the entire frequency range. Many of the advantages come in the hitherto poorly explored time-resolved regime and give substantial science returns in areas such as pulsar, transient and SETI studies. Our enthusiasm for multi-fielding is bolstered by the recognition that important extended programs may simply never be scheduled on a single FOV instrument. We see a multi-fielding instrument as offering much more opportunity to explore new parameter space whilst still permitting the currently envisaged base science studies. Appendix 1 shows some first thinking in this area.

5. Links With Other SKA Concepts

As with previous LL proposals, much of the system design and many major components of the AA-LL hybrid are applicable across a range of SKA concepts. With active programs in Australia, Europe and the USA in areas such as wideband feed design for concentrators, dense phased arrays, highly integrated receivers (cooled and uncooled) and scaleable DSP systems, we see many opportunities for work on the AA-LL hybrid (or its constituents) to contribute to whichever SKA technologies are eventually selected. We feel that it is important to pursue the possibility of low-cost achromatic phasing systems for phased arrays, and we would be interested in gauging international interest in this area. (While a full digital approach may be feasible for some focal plane applications, a level of accurate, low-loss, RF beamforming is necessary in most other applications). Finally, we are especially interested in exploring the mechanical, mechatronic and manufacturing engineering ingenuity of (for example) Chinese colleagues across a number of SKA concepts, including the AA-LL hybrid.
Fig. 1. Pictorial overview of hybrid SKA.

Fig. 2. Sensitivity curves for AA-LL hybrid.
Table 1 – Abbreviated Specifications of AA-LL Hybrid SKA

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna types</td>
<td>3-band aperture phased array + 3.5 m Luneburg lens</td>
</tr>
<tr>
<td>Frequency coverage (GHz)</td>
<td>0.1 – 22 GHz</td>
</tr>
<tr>
<td>Number of independent fields</td>
<td>4</td>
</tr>
<tr>
<td>Field-of-view (each field)</td>
<td></td>
</tr>
<tr>
<td>0.1 GHz</td>
<td>312 deg^2</td>
</tr>
<tr>
<td>1.4 GHz</td>
<td>14 deg^2 (LL); 10.5 deg^2 (AA)</td>
</tr>
<tr>
<td>22 GHz</td>
<td>0.056 deg^2</td>
</tr>
<tr>
<td>Number of stations (N)</td>
<td>300 (153 outside central 2.4 km dia array)</td>
</tr>
<tr>
<td>Station composition</td>
<td>~ 40 AA patches (0.35 GHz) + 92 lenses</td>
</tr>
<tr>
<td>Station diameter</td>
<td>100 m (LL component)</td>
</tr>
<tr>
<td>Total number of lenses</td>
<td>27 600</td>
</tr>
<tr>
<td>Longest baseline (Australian site)</td>
<td>3 000 km (5 000 km possible)</td>
</tr>
<tr>
<td>Physical area</td>
<td></td>
</tr>
<tr>
<td>0.1 GHz</td>
<td>1.25 km^2</td>
</tr>
<tr>
<td>1.4 GHz</td>
<td>0.60 km^2</td>
</tr>
<tr>
<td>22 GHz</td>
<td>0.27 km^2</td>
</tr>
<tr>
<td>Sensitivity (A_eff/T_sys per FOV)</td>
<td>See Fig. 2</td>
</tr>
<tr>
<td>Best array angular resolution</td>
<td></td>
</tr>
<tr>
<td>0.1 GHz</td>
<td>0.15 arcsec</td>
</tr>
<tr>
<td>1.4 GHz</td>
<td>0.011 arcsec</td>
</tr>
<tr>
<td>22.0 GHz</td>
<td>0.0005 arcsec</td>
</tr>
<tr>
<td>Number of polarizations</td>
<td>2 linear</td>
</tr>
<tr>
<td>Number of spectral channels</td>
<td>8192</td>
</tr>
<tr>
<td>Number of simultaneous frequency bands</td>
<td>Flexible within station data transport limits</td>
</tr>
</tbody>
</table>

Cost Breakdown of Hybrid SKA Concept

Total = $US1.1 Billion

- Lenses (inc. feed arms) 4%
- Lens feeds & LNAs 15%
- Aperture array tiles 2%
- Antenna DSP (inc. filterbanks) 2%
- Short-haul digital links 11%
- Long-haul digital links 12%
- Optical fibers 4%
- Trenching 4%
- Central array beamforming 16%
- Station beamforming 11%
- Main correlator 4%

Fig. 3. Component costs for AA – LL hybrid SKA. The full SKA cost estimate includes an additional infrastructure allowance of 200 M and a software estimate of USD 130 M, making a total of USD 1.43 B.
6. References


Appendix 1 – One Week’s Work for the AA-LL SKA

We looked at some of the possibilities for exploiting the parallelism of a multi-FOV telescope. Perhaps a week of SKA time in 2018 might look something like the example below.

<table>
<thead>
<tr>
<th>Freq. (GHz)</th>
<th>FOV no.</th>
<th>Aperture Array</th>
<th>Aperture Array</th>
<th>Aperture Array</th>
<th>Luneburg Lens</th>
<th>Luneburg Lens</th>
<th>Luneburg Lens</th>
<th>Luneburg Lens</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1-0.3</td>
<td>0.07-0.67</td>
<td>0.6-1.5</td>
<td></td>
<td>1-22</td>
<td>1-22</td>
<td>1-22</td>
<td>1-22</td>
</tr>
<tr>
<td>1a</td>
<td>1b</td>
<td>1c</td>
<td>1d</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2a</td>
<td>2b</td>
<td>2c</td>
<td>2d</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>3b</td>
<td>3c</td>
<td>3d</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Day 1
- Diagnostics and calibration (weekly)
- Calibrator monitoring (weekly)
- EOR imaging (ongoing)
- Hi survey (Z ~ 3 for LSS and dark energy)
- Weekly all-sky 10 µJy map transient hunt 3a 3b 3c
- Transient followup 3d
- Triggers obs from transient survey
- Calibrator monitoring (weekly)
- Earth orbit synthesis (monthly)

Day 2
- Interference mitigation development
- Deep continuum survey (ongoing)
- SETI survey
- ISM monitoring through large number of scintillating sources
- VSOP - 2

Day 3
- CME imaging
- GRB (external trigger)
- GRB (external trigger)
- Galactic polarisation survey
- TV feed (8 GHz)
- Full-array AGN imaging (15 GHz)

Day 4
- Ionospheric measurements
- SETI survey 3a 3b 3c
- SETI follow-up 3d
- Groveys
- Triggered obs

Day 5
- GRB (external trigger)
- Galactic polarisation survey
- TV feed (8 GHz)
- Full-array AGN imaging (15 GHz)

Day 6
- SETI survey 3a 3b 3c
- SETI follow-up 3d
- Groveys
- Triggered obs

Fig. A1. A week of observing with a multi-FOV SKA.
From: A. van Ardenne

Date: 13/02/04, v2

Subject: Hybrids; a combined concentrator for high frequency observing

Scope:
This is a brief description on an observing instrument that may serve the SKA for high frequency observing, say in the range >10 – 35 GHz. This has particularly become more relevant because the version 7 of the SKA observing requirements indicates the desirability to increase the upper frequency limit.

Outline:
The proposal is an outline only and serves to suggest a potentially cost-effective solution to compensate for the decreasing field of view going to higher frequencies. As the concept relies on small dishes of order 2-3mΦ, it alleviates severe pointing requirements that otherwise would occur with a 12m paraboloid (as is presently suggested) as required for its use at the highest frequency. It can potentially rely on “simpler” mass produced high frequency-dish manufacturing technologies. Also, the need for an extremely wideband high performance low noise receiver system can be relaxed with the addition of “only” <4:1 BW high(est) band receiving system.

Description:
Herewith some suggestions of a concept in which 4 small dishes are mounted on a single azimuthal frame in two different possible realizations. I presume, that costing considerations will point the way to a preferred solution. The picture show two different optical realizations; one with low and one with higher F/D in which the “low” F/D design uses on-axis parabaloids while the other with a higher focal length ratio (although not ultimately required for this purpose), uses slightly off-axis paraboloids in order to realize a more “concentrated” (single) focal-package

Discussion/Consequence:
Clearly, this suggestion, if implemented, would add another physically different system to the SKA. While it may result in a cost effective and optimal system, this may at first glance of course seems undesirable. Alternatively, a number of smaller dishes can be mounted on a single, larger paraboloidal system with similar benefits. The “concentrated” focal package as described above, may also be more cost effective and practical for the use of a focal plane array.
A Cylinder plus 12-m Dish Hybrid
John D. Bunton
18 November 2003

At low frequencies antenna technologies that do not use concentrators are used. The main reasons for this are:

- the large effective area that an elemental receptor already has, e.g. a simple dipole at 30 MHz has an area of about 10 m²
- the low cost of LNAs, downconverters and A/D converters at these frequencies.

As the frequency increases, the cost of electronics increases. For example at a frequency of 30 GHz all current radiotelescopes use cooled receivers making the cost of the electronics per receptor orders of magnitude dearer than at 30 MHz. This together with the fact that the effective area of an elemental receptor has gone down by a factor of one million dictates that a two dimensional concentrator such as a parabolic dish be used. This increases the effective area by a factor of one million or more and makes high frequency observing possible. However, the concentrator now becomes the major cost in the system.

A cylinder is a lower cost alternative for building a concentrator, but as it concentrates in only one direction the increase in effective area per receptor is less. This is illustrated in the table below for 10 m concentrators.

Table 1 Effective area per receptor (m²). Cylinder, lens and dish diameter 10 m.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Dipole</th>
<th>Cylinder</th>
<th>Lens or Dish</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>0.3</td>
<td>0.1</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>1</td>
<td>0.01</td>
<td>3</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>0.001</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>0.0001</td>
<td>0.3</td>
<td>100</td>
</tr>
</tbody>
</table>

For radiotelescopes operating at a frequency of ~0.4 GHz all current major instruments have been cylindrical reflectors because when compared to a phased array the 100 fold reduction in electronics costs has more than compensated for the cost of the reflector. When compared to a fully steerable concentrator it is the significantly lower cost of a cylindrical reflector that has been the economic advantage. This has resulted in the building of instruments such as Molonglo [1], the Northern Cross [2], Ooty [3], the Radio-Star interferometer [4], and the DKR-1000 [5]. Because of the HI line no instrument has been built to operate just at 1 GHz. Instead, most designs aim for an operating frequency of at least 3 GHz, for example the original Parkes and Lovell telescopes. At this frequency the 100 fold increase in electronics costs needed for a cylinder has traditionally driven the design towards a fully steerable dish. However, over time, the cost and noise figure of electronics is decreasing whereas the cost of mechanical structures, if anything, increases. By the time that the SKA will be built it is estimated [6, 7] that a cylindrical reflector will be cost competitive at frequencies above 10 GHz. At frequencies around 1 GHz the cylindrical reflector almost certainly becomes the most cost competitive solution. As frequency decreases further this remains true until somewhere below 300 MHz where phased arrays become the most economic solution, as exemplified by LOFAR [http://www.lofar.org/].
Because of its cost advantage it is interesting to consider hybrid solutions to the SKA where the frequencies below about 5 GHz would largely be handled by cylindrical reflectors. For the higher frequencies a hybrid solution would use one of the proposals that to go to 22 GHz such as the LNSD proposal [8] using 12-m hydroformed parabolic dishes, LAR [9] with a 200m adaptive reflector and in a non hybrid solution the cylinder itself. Of these the LNSD 12-m proposal is interesting because it is the one that is most easily adapted to operation beyond 22 GHz. Indeed, the original white paper concept proposal [8] included feed systems that extended the operation up to 45 GHz. That proposal required additional hardware to allow it to operate down to 150 MHz, consisting of a focal plane array and a mechanical arrangement to flip the focal plane array into the prime focus of the dish. In a hybrid design this added hardware might be dispensed with, saving some of the antenna cost. Instead it might be useful to extend the low frequency limit of the Gregorian feed to 0.5 GHz. Below this frequency, sensitivity is proportional to the effective area as galactic noise determines the system temperature. In the 12-m proposal the design is optimised to give minimum system noise, resulting in a design where the effective area for full SKA sensitivity is 360,000 m² compared to 700,000 m² for the cylinder. Thus the contribution to sensitivity from the 12-m component decreases more rapidly below 1 GHz. It may be best to recover sensitivity at these frequencies with a third component in the hybrid design, such as a 500 MHz cylindrical reflector.

**Antenna cost**

Both the cylinder and the 22 GHz 12-m proposals had similar antenna costs of US$860M. In designing the hybrid the total antenna cost will be constrained to this limit. This necessarily means that sensitivity will decrease at some frequencies. At other frequencies, particularly where the two contributors to the hybrid overlap, the sensitivity is enhanced.

Costs for the 12-m reflector are US$150k and US$39k for the cryogenically cooled receiver [8]. Depending on whether it is shaped or not the aperture efficiency is 65% or 75%. With a Tsyn of 18K and assuming 70% aperture efficiency, the number of antennas needed for AM Tsyn of 20,000 is 4551. Total cost for these antennas is US$860M and the effective area is 360,000 m².

For the cylindrical reflector the costs will be estimated at 5 GHz and 500 MHz. These are shown in the table below. The reflector costs come from the initial design concept white paper [6] and the others are mainly from the update [7]. The line feed hardware was costed at $115 per m at 1 GHz. Scaling these costs as the cube root of frequency gives the values shown for a 15 m reflector. The LNA and beamformer was also assumed to cost $115/m but this cost is assumed to scale directly with frequency. Downconversion and analogue to digital conversion cost is estimated to be $150/GHz per m of linefeed with a dual polarisation converter every 0.3 m. For a 5 GHz maximum frequency the SKA required bandwidth is 1.5 GHz. This is considerably less than the 4.9 GHz specified in the design concept white paper update [7]. The bandwidth reduction considerably reduces the survey capabilities of the instrument. but a full bandwidth solution would be too expensive for a low frequency cylinder. As a compromise a 2.4 GHz bandwidth is used here. This reduces the survey speed by one half for a cost of US$24 per square metre.
The digital signal on the line feed needs to be sent to the central beamformer optically, and this is estimated to cost $200/GHz per metre of linefeed. For a 2.4 GHz bandwidth this comes to $32 per square metre of reflector. For a 500 MHz maximum frequency there is one feed element every 0.3m. Fully digitising the signal requires a 400 MHz bandwidth.

With a system temperature of 35K and an aperture efficiency of 70% the total area required to meet the SKA specification is one million square metres and the total antenna cost is US$282M for a 3 GHz instrument but only US$123M if the maximum frequency is reduced to 500MHz.

**Hybrid Mix**

It is seen that the cost of a 5 GHz cylindrical reflector SKA is about one third of that for a 22GHz 12-m parabolic dish SKA, and a 500 MHz cylindrical reflector SKA is one sixth the cost of the dish proposal. A possible compromise is to build half of the 12-m antennas and both sets of cylinders. The total antenna cost is very similar to that of a full-sensitivity 12-m antenna SKA. The hybrid solution has traded high frequency sensitivity for low frequency sensitivity as well as extending the low frequency limit from about 150 MHz to 100 MHz. Above 10 GHz the sensitivity is halved but above 27 GHz this is still an order of magnitude more sensitive than ALMA, assuming the SKA antennas have one quarter the sensitivity.

A pure 12-m solution has an effective area of 360,000 m$^2$ and can work down to a frequency of about 150 MHz. The cylinders are wider and can work down to a frequency close to 100 MHz and the total effective area below 500 MHz is 1.4 million square metres. Thus the combined 0.5 and 5 GHz cylinders provide a low frequency sensitivity that is three to four times higher than a 12-m SKA. The low frequency cylinder can still work at frequencies above 500 MHz but with reduced sensitivity. Here it is assumed that the sensitivity decreases linearly over the next octave of frequencies. This gives an almost uniform sensitivity from 0.5 to 1 GHz at which point the 12-m antennas become available. The effectiveness of the 5 GHz cylinders reduces at 5 GHz and they become unusable by 10 GHz. Above this frequency range the total sensitivity decreases from 30,000m$^2$/K to 10,000m$^2$/K. The hybrid then relies on the 12-m antennas only which have good sensitivity up to 22 GHz. Above 22 GHz the aperture efficiency will drop but there may be some useful performance up to 40+ GHz. The resulting estimated sensitivity expressed as a function of frequency is shown below.

<table>
<thead>
<tr>
<th></th>
<th>Cost at 5 GHz (US$/m^2)</th>
<th>Cost at 0.5 GHz (US$/m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflector</td>
<td>228</td>
<td>105</td>
</tr>
<tr>
<td>Linefeed hardware</td>
<td>13</td>
<td>6</td>
</tr>
<tr>
<td>LNA and RF beamformer</td>
<td>38</td>
<td>4</td>
</tr>
<tr>
<td>Downconversion and A/D</td>
<td>24</td>
<td>3</td>
</tr>
<tr>
<td>Line feed to beamformer</td>
<td>32</td>
<td>5</td>
</tr>
<tr>
<td><strong>Total cost per m$^2$</strong></td>
<td><strong>335</strong></td>
<td><strong>123</strong></td>
</tr>
</tbody>
</table>
An area where the 12-m antennas and cylinders differ is field-of-view FOV. At 1.4 GHz the cylinder has a FOV of 24 square degrees at a bandwidth of 800 MHz compared to 1 square degree for the 12-m antenna. Thus the cylinder component of the hybrid is much faster for survey work. Adding 12-m data increases the survey speed by only 12%. Where the hybrid has the biggest improvement in performance is below 700 MHz. At 200 MHz it is more than ten times more sensitive than LOFAR and still four times as sensitive at 120 MHz. The high sensitivity increases survey speed by a factor of 10 compared to a pure 12-m design. The large FOV adds another factor of at least 10 making the cylinder/12-m hybrid more than 100 times faster at observing HI at high redshifts than a 12-m alone design.

The price paid for this high performance at low frequencies is decreased sensitivity above 7.5 GHz. Only three science cases [10] depend on these frequencies alone: Sunaev-Zeldovich effect, Molecules at high z, and Solar System Science. These three science cases need only moderate sensitivity and are adequately catered for by the hybrid design. Rough estimates [10] for the other 29 science cases show that half have critical observing bands at high and low frequencies. Of these, seven have requirements for high sensitivity. For the seven cases 60% of the critical frequency bands have higher sensitivity and 20% lower sensitivity than the standard SKA specification. This would indicate that the hybrid design proposed here provides a good solution to the requirement of many of the seven high-sensitivity high-frequency science cases as well as all other science cases.

**Conclusion**

A hybrid solution that uses low and mid frequency cylindrical antenna arrays each with full sensitivity together with 12-m hydroformed antennas with a sensitivity of 10,000 m²/K has been proposed. This increases the sensitivity below 5 GHz by a factor of 1.5 to 3.7. Full SKA sensitivity of 20,000 m²/K is maintained down to 370 MHz and the ability to probe HI in the early universe is considerably enhanced. At high frequencies all proposed science can still be done. In a hand full of cases the science is adversely affected over part of the observing range. This is balanced against an almost equal number of science cases which can take advantage of the increased low frequency sensitivity.
Bibliography


Hybrid Solutions

A European Perspective
Level 0 Science

- Strong field tests of gravity using pulsars and black holes
- Probing the dark ages
- Origin and Evolution of Cosmic Magnetism
- Cradle of Life
- Evolution of Galaxies and large scale structure

Low frequency contribution

- Survey needs large f-o-v; timing needs dedicated access + flexible beam configuration
- High-z HI / EOR needs large f-o-v/ long observation periods
- Mostly at higher frequencies
- Requires very large f-o-v and long observation periods
- Mostly at higher frequencies
Hybrid solutions are thus “required”

- **Level 0 science requires combination of:**
  - \( \nu \) from \(~100\,\text{MHz}\) to \(>22\,\text{GHz}\)
  - Large (\(>>1\,\text{deg}^2\)) f-o-v at “low” frequencies for surveys
  - Wide range of surface brightness sensitivity

- **Implies highly flexible design in all respects**
  - Hybrid collector concept is just one aspect of flexibility
  - “only one SKA” \(\rightarrow\) must offer many users a chance of time, as is the case with accelerators.

- **Low-frequency/large f-o-v achievable with**
  - Aperture arrays, but only at \(\nu<2\,\text{GHz}\)
  - Cylinder-based arrays (\(\nu\) limit more flexible)
  - Not so easily with other concepts
Generic advantages of hybrid solutions

• Low-frequency part can offer:
  • Large/multiple f-o-v allowing flexible use by (many) different groups
  • Completion of science-critical surveys in finite time ("a year in the life of SKA" needed)

• In conjunction with distinct high-frequency part:
  • More groups able to utilise the basic SKA infrastructure simultaneously
  • Flexibility of overall design: maximising ways of looking at the sky most likely to lead to new science.

• Facilitates definition of equitable international work packages for design/construction phase
Generic disadvantages of hybrid solutions

- **Cost**
  - Neither part may be a “full” SKA

- **Complexity**
  - Management of design/construction
  - Increased running costs?

**Other Issues**

- Upgrade paths – more or less difficult to plan?
SKA Convergence
ISSC Capetown Jan 2004
Ron Ekers
CSIRO, Australia
An interesting path to the SKA

- Note the incredible potential of a really wide FOV
  - HI surveys (evolution, LSS, dark energy)
  - Pulsar surveys (gravity waves, n-bh binary)
- Full SKA with a wide FOV is overkill for this level 0 science
  - About 1/5 of an SKA would make a major impact
- These two level 0 science cases
  - don’t need high spatial resolution
  - don’t need high frequency and
  - only need modest bandwidth
An opportunity emerges

- The ultimate instantaneous FOV comes from the aperture plane arrays [Dutch concept]
  - Note that the FOV is only limited by processing power and coms bandwidth
  - So we can expand the FOV with time as more processing power becomes affordable [US OSS concept]

- Astronomically interesting collecting area is still too expensive

- The cylinder was proposed [Oz-Cyl] as an intermediate solution using a 1D aperture array and a 1D concentrator
  - Still has as much FOV as we can process
  - Collecting area is cheap
The Solution

- Initially build a small (1/5 SKA) using cylinders and 1D focal plane arrays
  - 10km max, centrally concentrated
    » Compact for pulsar survey
    » Sufficient resolution for HI survey (8”)
  - 0.6 -1.4GHz
    » HI to z = 1.3
    » Optimum for pulsars
  - FOV 100 sq deg
  - Cost $US60M

- Start building it as soon as we have a site

- Turn the focal plane array upside down for pure aperture plane array experiments

- Abandon the cylinders when the aperture plane array cost is low enough
  - 3% cost impact in return for killer science demonstration by 2010
  - Use the old cylinders for the solar power generator for the full SKA?
  - The infrastructure and backend are SKA phase 1
Dark energy: $w = -\frac{P}{\rho}$
Current limit: $w < -0.7$ 95% confidence

- **HIFAR**
  - 600-800MHz
  - $0.8 < z < 1.4$
  - 100deg2

- **Experiment**
  - 1400deg2/yr
  - $3 \times 10^6$ gal/yr
    - $Dw=0.08$ (1yr)
    - $Dw=0.04$ (5yr)
    - Evolution of $w$ with $z$? 

![Graph of Radial and transverse](image)
What does it do for SKA?

- Early first science
- Technically low risk
- Keeps scientists fully engaged over the time period needed to build a full SKA
- Becomes a demonstrator for the International collaboration
Dear Peter et al.,

I thought that it might be useful to mention that a further reason for the hybrid approach concerns the effects of the ionosphere at meter wavelengths. In particular, synthesis imaging becomes very much more difficult when the beamwidth of the antennas (or groups of phased elements that are cross correlated) is wider than the angular size of the isoplanatic patch of the ionosphere. The isoplanatic patch size can be defined as the area over which the variation of the excess phase due to the ionosphere is small compared with a 2π radians. If the beam is wider than the isoplanatic patch, and if it is necessary to map the full beam area, then one has to allow for variation of the phase calibration over the field of view. Data on the angular size of the isoplanatic patch is not precise, but at 100 MHz a representative value is 5 deg. If we take the full width (between first zeros) of the beam of a circular aperture as 2.4 x (wavelength/diameter), the diameter for which this is equal to 5 deg at 100 MHz is 82 m.

If the individual receiving elements have beams wider than the isoplanatic patch, a possible approach is to form phased subarrays of elements and cross correlate the subarray signals rather than those from individual antennas. However, since one is using the beam response to limit the synthesized field, sources outside the field entering through sidelobes can degrade the dynamic range. To minimize sidelobes the individual elements should be closely spaced to provide a combined aperture that is as nearly continuous as possible. However, this requirement is likely to be at odds with the avoidance of shadowing or the optimization of (u,v) coverage at shorter wavelengths. Problems associated with the isoplanatic patch size at long wavelengths are a prime concern for LOFAR (see, e.g. J. E. Noordam, Report ASTRON-LOFAR-11227) and sophisticated methods of calibrating the angular variation of the phase are likely to be developed. Nevertheless, for the SKA, the use of small diameter paraboloids or Luneburg lenses at the frequencies of a few hundred MHz, at best complicates long wavelength observations, and may jeopardize the possibility of success in the important studies of the epoch of ionization for which high dynamic range is required. The large continuous apertures of the Aperture Array, or concepts with large reflectors, are better adapted for achievement of high dynamic range at such frequencies. The station diameter of the AA in the 120-300 MHz band is 160 m, so the hybrid scheme suggested in the IEMT report provides a good solution to the problem.

The variation of the size of the isoplanatic patch with frequency is
also of interest. The excess phase introduced by the ionosphere on any path is proportional to $\nu^{-1}$, where $\nu$ is the frequency. This results from the variation of the refractive index [proportional to $\nu^{(-2)}$], and the path length. Thus, as frequency is decreased, smaller structures in the ionosphere become important and one can take the patch size as approximately proportional to frequency. To be more precise, the structure of the ionospheric irregularities also affects the frequency dependence, and if this is taken into account the isoplanatic patch size is found to be proportional to $\nu^{(6/5)}$. This result was pointed out by Jim Moran, and is derived as follows. The atmospheric irregularities are characterized by the structure function which gives the variance of the phase difference for two paths separated by a distance $d$. This is discussed for the case of Kolmogorov turbulence in the neutral atmosphere in TMS2 (pp. 534-539) and results are shown in Table 13.2. For distances up to a few tens of km (i.e. small compared to the thickness of the ionosphere) it is appropriate to consider 3D turbulence, for which the structure function is proportional to $d^{(5/3)}$, so the rms phase difference is proportional to $d^{(5/6)}$. For the ionosphere, the frequency variation of the refractive index also introduces a further dependence on $\nu$. As noted above, for a fixed path in the ionosphere the phase is proportional to $\nu^{-1}$. The dimensions of a blob of the turbulent structure are assumed to be similar in directions parallel and perpendicular to the line of sight. Thus the rms phase difference for paths with separation $d$ is proportional to $d^{(5/6)} \times \nu^{-1}$. The isoplanatic patch size (in length or angle) is represented by a constant phase difference, so $d^{(5/6)} \times \nu^{-1}$ is a constant, in which case $d$ is proportional to $\nu^{(6/5)}$. Applying this result, the 82 m aperture required at 100 MHz becomes 18 m at 200 MHz and 7 m at 300 MHz. Thus the problem disappears rapidly as the frequency increases, but remains serious over the frequency range that is essential for the important epoch-of-ionization studies.

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Outline of potential combined solutions: an view from KARST project team in China

2003/11/15, Beijing

1. Combined with AAT

In order to enlarge the FoV and the sky coverage of the FAST, we have set-up a project to investigate our own focus array at the FAST focus, adopting the AAT technology. This combined solution for large dish will enlarge the FoV of the 300m illuminated area of the FAST from ~3 arcmin to half a degree and form at least 100 simultaneous beams within it. The phased array technology also enables us to form an asymmetric illumination pattern as the focus goes to the edge of the active reflector by dynamically weighting the Vivaldi-elements in the array. This kind of focus can get avoid the pick-up from ground without involving the complex and expensive metal fence around the main dish as Arecibo telescope. The application might be also possible to reduce the surface accuracy request by correcting the errors of large dimensional scales on the reflector at the focus.

There are three groups working on the layout design of the AAT type feed from Tsinghua University, Beijing Astronautics University and NAOC. The array will include 1300 vivaldi antennas on a plate of diameter 2.5 m by a very rough estimation. The electromagnetic field analysis near focus has been completed now, and the results appear close to the ones of FARADAY project.

2. Combined with LAR

LAR and FAST face to number of similar technical challenges. Both have flexible network to support the focus package – aerostat or suspended cables. The analysis on the dynamic characteristics of the soft system could be compared and checked by each other through cooperation. Some feasibility studies on practical engineering realization are possibly applicable to each other, and approved by some experiments, i.e., stabilizer of feed pointing/tracking.

Their active reflectors also share many key techniques as segmentation of the surface, mechanical control of the active elements, low-cost panels and their reliability, complicated fieldbus to drive large amount of actuators, and maintenance etc.

LAR and FAST require powerful ranging system to measure the spatial position of feed or feed platform (3-D solid body). The ranging system need to work at large distance of km with high refresh rate to track those moving and oscillating objects, and at high accuracy of about sub-mm scale. The equipment operates in open air and must be well calibrated.
There are no solid connections between the focus and reflector as those conventional antennas. Pointing and tracking, as well as the harmonization between feed and reflector, are difficult to FAST and LAR.

3. Combined with Preloaded

The previous design of the FAST reflector consists of ~2000 hexagon-shaped elements, whose back structure is made of large amount of steel rods and spherical joints. Recent years, element of tensegrity back structure of FAST has been modeled and evaluated by the expert board as a feasible solution to future FAST reflector, reducing its total weight by a factor 3. This design replaces solid network by preloaded steel wires without welding technics, which is applied by Indian concept. From the experiment, we learnt how to distribute and measure the tension forces in the prestressed structures, and how to control the energy-loss. The merit of this technology is its potential advantage in reducing the project cost of all kind of SKA concept. FAST elements have identical curvature and little dimension difference, Indian preloading process seem to be helpful for the mass production of FAST elements.

4. Site

Compared with those site surveying programs, Karst site shows two outstanding aspects – large number of candidate depressions of perfect anti-cone profiles and the extremely quiet RFI environment due to remoteness and the local terrestrial shielding. We believe that Karst site benefits AAT-type SKA concept which is not expected to operate at very high frequencies and is limited to large zenith angles.

5. Commons

Besides combines solutions mentioned above, there are certainly many R&D developments in different concepts are in common, e.g. science drivers, array optimization, day-1 receivers and back terminals of different purposes, data transmission and correlation, and post data analysis.
1 Key issues that should drive the SKA design

We believe the following are important points to consider when discussing SKA hybrid designs.

1. Any design, hybrid or otherwise, needs to have maintain the capability required for Level-0 science. Presumably, this will encompass science goals compatible with other future instruments addressing mainstream astronomy questions of the day e.g. studying high-redshift galaxies at $z \sim 5 - 9$ (complement to JWST), or high-redshift CO (complement to ALMA).

2. It is important to maintain the sensitivity of the SKA relative to contemporary telescopes, namely the VLA. The SKA sensitivity specification is derived from the original goal to build a telescope 100 times more sensitive than the VLA, yielding $A_{\text{eff}}/T_{\text{sys}} = 20 \times 10^3$ m$^2$/K. However, the VLA will be improved during the time that the SKA is planned and constructed.
Assuming a reduction of \( T_{\text{sys}} \) to 30 K (EVLA Phase I) and an increase of \( A_{\text{eff}} \) to 9300 m\(^2\) (8 new dishes in EVLA Phase II), \( A_{\text{eff}}/T_{\text{sys}} \) for the VLA at 1.4 GHz will be increased 55\% from 200 to 310 m\(^2\)/K. If this improvement in the VLA is not tracked, there is a danger that along with a few other compromises, that the SKA sensitivity will be significantly less than two orders of magnitude better than the VLA.

3. It is necessary to decide whether multiple fields of view are essential and also whether high frequency capability is essential.

4. Some science, such as searching for the signature of the Epoch of Reionization, may be best done by a dedicated instrument. There is a precedent for this: Cosmic Microwave Background science is done with special-purpose telescopes. What we are seeing at the moment is that EoR science is distorting the SKA specifications by pulling the low-frequency limit down so that the SKA will have a significant overlap with LOFAR. This will likely drive up the cost of the SKA and may make some technologies unsuitable. If instead a special-purpose EoR telescope is constructed, it would probably see first-light at an earlier date than an EoR-capable SKA, and would be better-matched to EoR science than a general-purpose SKA. However, if a dedicated EoR instrument is not possible, it may be worth considering a “LOFAR-hybrid” which has additional elements optimized for EoR science since the EoR signature is believed to fall within the LOFAR frequency range.

5. We also recognize that a variety of hybrids are possible:

   (a) **Frequency hybrids:** where one station concept cannot cover the full SKA frequency range, add a different station concept so as to extend the overall range. There should be significant frequency overlap (presumably at \( \nu \sim 0.5 - 1.5 \) GHz) to maximize \( A_{\text{eff}} \). The downside of this approach is that outside the overlap band, \( A_{\text{eff}} \) is significantly less than \( 10^6 \) m\(^2\) and we are really building two instruments that share some common infrastructure (roads, power, fibre-optic transmission system, correlator, data reduction centre). This is currently the definition of hybrid that has been used in discussions within the SKA community.

   (b) **Complementary hybrids:** this is a hybrid of elements that share similar frequency ranges, but somehow complement each other. For ex-
ample, the surface-brightness sensitivity of an array of small concentrators may be greatly enhanced with the addition of at least one large-diameter element near the centre of the array.

(c) **Technology hybrids**: a single implementation may be composed of several classes of technology. The cylindrical reflector is a very good example of this. Elevation pointing of the cylinder is accomplished mechanically, while pointing in the meridian distance direction is done electronically using phased-array techniques. Similarly, focusing in the vertical plane is a result of standard reflection optics, while focusing in the horizontal direction is achieved electronically in a beamformer. It could be argued that a hybrid like this will have a lower cost than either a system using entirely conventional components (ie. fully-steerable reflector antennas) or one using new, all-electronic technology (ie. an aperture array). By removing one dimension from each, the cost is reduced by eliminating a large number of mechanical components and by reducing the size of the electronic array.

(d) **Risk hybrids**: much like a prudent investment portfolio that has both lower- and higher-risk components, the SKA could be constructed with a combination of “safe” technology (such as small-diameter reflectors) and new, less-proven technology (such as LAR, Luneburg Lens, Aperture Array, or Cylindrical Reflector). Most of the collecting area would be constructed with the “safe” technology. Elements constructed with the more experimental technology would augment the capabilities of the overall SKA, and would provide operational experience and time to develop the new technology. Over time, if the new technology is both scientifically useful and is technologically practical, then more elements could be added to the SKA.

(e) **Political hybrids**: the SKA consortium is an international organization that must somehow deal with national politics. It may be necessary to construct a heterogeneous array to ensure participation of certain countries. For example, this may happen with the ALMA project. However, we must be careful that such a hybrid does not significantly compromise the performance compared with a homogeneous array.
2 Key considerations for hybrid solutions

1. No impact on Level-0 science goals. This implies no impact on the specifications ie. physical area, frequency range, FoV etc.

2. Frequency hybrids should be designed so that the frequency overlap of the two subarrays is significant, thereby maximizing the effective area in part of the overall observing band.

3. Any hybrid should not increase the projected cost of the SKA. Here are several ways that a hybrid could lead to cost increases:

   (a) Frequency hybrids will not have the full collecting area available over the full band. Therefore to achieve the sensitivity goals of the SKA may require additional collecting area to be constructed. (Will this be the two-square-kilometre array?)

   (b) Having several different element designs could increase maintenance costs because there will be two maintenance crews, two sets of spares, etc. An analogy could be made with the airline industry: the lowest-cost carriers typically have fleets with only one type of aircraft.

3 Potential hybrid solutions to the SKA

3.1 Strengths of the LAR concept

1. Wide frequency range

   (a) The high-frequency limit of the LAR is determined by the panel size. This is because the surface is made up of (nearly) flat panels which form a piece-wise continuous approximation to a paraboloid. At high frequencies the performance drops as the deviation from the ideal paraboloid becomes a significant fraction of a wavelength. However, if the panels are made smaller (at the expense of an increase in the number of vertical actuators), then the deviations become smaller and the reflector is capable of operating at higher frequencies. Currently
we have specified panels about 5 metres across that will allow the LAR to observe to around 22 GHz.

(b) The low-frequency limit is determined by the size of the reflector, the size of the focal-plane array, and the focal-length to diameter ratio of the telescope. The reflector is so large (200-metre diameter) that it will function very well into the metre-wavelength region of the spectrum because the aperture will still be many tens or hundreds of wavelength across. However, since the focal-ratio of the LAR is so large \( (f/D \sim 2.5) \) the feed must have significant gain. Fortunately, spillover can be largely ignored at the low-frequency end of the spectrum because the galaxy is so bright. Therefore we only need to worry about efficiency. Simulations have shown good performance down to \( \sim 100 \) MHz.

2. Fully-filled aperture for high surface-brightness sensitivity.

### 3.2 Hybrids with the LAR concept

The brightness sensitivity of an array of small elements will be improved by adding one or more LAR near the centre of the array. The LAR focal-plane array would match the field-of-view of small-aperture antennas.

This hybrid helps to mitigate some of the perceived weaknesses of the LAR.

- **Downtime due to weather, maintenance, etc.** Since the LAR-elements would be a fraction of the total collecting area, downtime would be less significant unless surface-brightness sensitivity is required.

- **Slow slew speed.** Again, the degradation to sensitivity if one or several LAR elements were slow to acquire a transient source would be small. In this case, since transients are point-like sources, the loss of surface-brightness sensitivity is much less important.

### 3.3 Hybrids without the LAR

In our humble opinion, there are none!!!
4 What can Canada contribute to the SKA aside from the LAR concept?

1. Phased-array technology development

   (a) Currently have two graduate students working on front-end aspects (Vivaldi-element design, integrated LNA design).

   (b) An engineer is working on high-level specification and architecture of digital beamformer.

   (c) Within one year the group currently developing the ACSIS autocorrelator for the JCMT will be available to work on a digital implementation of the beamformer.

2. Correlator development

   (a) The team currently developing and constructing the EVLA correlator will be available later this decade for development of SKA correlators.

3. Image formation techniques

   (a) We have considerable experience within our group in making images from instruments with non-ideal characteristics (such as differing primary beam sizes).

   (b) Also have considerable experience with wide-field imaging, both in terms of the primary field-of-view and mosaicked images.

4. Antenna measurement and array calibration system using multi-tether aerostat technology to provide a stable airborne platform

   (a) Much smaller than an LAR airborne system: transmitter + simple antenna, differential GPS.

   (b) Computer-controlled winches for active control of platform position.

   (c) Can achieve much higher elevation angles than possible with a tower.

   (d) System would be portable so that it could be transported between SKA stations.
SKA Hybrids Involving the US LNSD Concept

US SKA Consortium

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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 ($\approx$ $1.2\text{–}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. 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

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1At 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 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 $1 \, \text{deg}^2$ at $1 \, \text{GHz}$) 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 $1 \, \text{GHz}$, 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 \( \frac{A_{\text{eff}}}{T_{\text{sys}}} \approx 10^4 \frac{\text{m}^2}{\text{K}^{-1}} \) 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 HI 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 km²; 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

<table>
<thead>
<tr>
<th>Component</th>
<th>Estimated Cost (millions of US dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500 12-m dishes</td>
<td>493</td>
</tr>
<tr>
<td>50 stations</td>
<td>495</td>
</tr>
<tr>
<td>infrastructure, etc.</td>
<td>518</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1505</strong></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Component</th>
<th>Estimated Cost (millions of US dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500 12-m dishes</td>
<td>493</td>
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<tr>
<td>500 reflectors</td>
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<td>infrastructure, etc.</td>
<td>457</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>1110</strong></td>
</tr>
</tbody>
</table>

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 $10^6 \text{ m}^2$ at 15 MHz. The $\lambda^2$ 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 $\lambda^2$ 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 $A_{\text{eff}}/T_{\text{sys}} \sim 500 \text{ m}^2 \text{ K}^{-1}$ 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 $\text{H}^1$ at the EoR.

The current cost estimate for the “high-frequency” dipoles (120–240 MHz) is roughly $50 \text{ m}^{-2}$. 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 $100\text{M}$. 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 $100\text{M}$, 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 $\text{H}^1$ 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

<table>
<thead>
<tr>
<th>Area</th>
<th>Group</th>
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<tbody>
<tr>
<td>Science</td>
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<tr>
<td>Receivers</td>
<td>China, Europe</td>
</tr>
<tr>
<td>Data Transport</td>
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<tr>
<td>Configuration</td>
<td>Australia</td>
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<td>Simulations</td>
<td>Australia</td>
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<td>RFI Mitigation</td>
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<td>Correlator</td>
<td>Canada</td>
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<tr>
<td>Operations</td>
<td>All</td>
</tr>
<tr>
<td>Education/Public Outreach</td>
<td>All</td>
</tr>
</tbody>
</table>

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.

Acknowledgments

This document was edited by J. Lazio. Partial support for SKA activities in the US is provided by the National Science Foundation. Basic research in radio astronomy at the NRL is supported by the Office of Naval Research.
<table>
<thead>
<tr>
<th>Area</th>
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</thead>
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<td>Science</td>
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<td>Receivers</td>
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</tr>
<tr>
<td></td>
<td>UCBerkeley, U.Wisconsin</td>
</tr>
<tr>
<td>Data Transport</td>
<td>Haystack/MIT, NRAO</td>
</tr>
<tr>
<td>Configuration</td>
<td>Haystack/MIT, NRAO</td>
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<tr>
<td>Simulations</td>
<td>Haystack/MIT</td>
</tr>
<tr>
<td>RFI Mitigation</td>
<td>Cornell/NAIC, NRL, Virginia Tech.</td>
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<tr>
<td>System Analysis</td>
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<tr>
<td>Operations</td>
<td>Cornell/NAIC, NRAO, SETI Institute</td>
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<tr>
<td>Siting</td>
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</tr>
<tr>
<td>Education/Public Outreach</td>
<td>Cornell/NAIC, SETI Institute, U.Wisconsin</td>
</tr>
</tbody>
</table>
Summary of the First SKA Design Convergence Workshop, 13 January 2004

R. T. Schilizzi, on behalf of the Workshop participants
February 2004

This document summarises the main points of the workshop held in Cape Town on 13 January 2004 to discuss the desirability and options for combined or hybrid technical designs for the SKA. It is not a set of minutes and does not ascribe individual comments to individuals at the meeting, but attempts to draw together the various strands of discussion that took place at different times during the meeting. The Workshop programme is included as Annex 1.

The purpose of the workshop was to explore the parameter space of combined designs and narrow down the possibilities to a small number that can be focussed on in the future. In addition, the workshop held a discussion about how to continue to engage the community in the pre-SKA era. Input material to the Workshop included a number of papers outlining possible combined concepts and ideas on how individual engineering groups in the world could contribute to the alternative concepts. These papers can be found in the international SKA Memo series as memo 49.

Introduction

1) In its meeting in January 2003 the ISSC defined the options for selecting the SKA design concept as being
- mutual convergence to a single cooperative design concept
- down-selection amongst cooperative designs including combinations of two or more concepts
- down-selection amongst individual concept proposals

The top-level selection criteria for the design concept are:
- it captures a significant fraction of the science of the Key Science Projects
- it has demonstrated engineering feasibility and compatibility with the site choice
- it is maintainable at a reasonable cost
- it is upgradable
- it is within the nominal cost envelope of 1 B€/USD

The timescale to concept selection and beyond is currently foreseen to be:
- 2004-7 demonstrator development including a major external review in 2006, submit funding proposals for a 5% SKA demonstrator
- 2008 selection of technical design, start construction of the 5% demonstrator on chosen site (SKA phase 1)
- 2009 submit funding proposals for full array
- 2012 start construction

2) Why talk about convergence? The trigger for this workshop was the clear ISSC preference to encourage thinking towards a mutually agreed single concept that is inclusive and engages the global community. This preference is based on the following considerations:
- It is not clear that any of the individual design concepts can, by itself, cover the wide range of science goals proposed for the SKA.
- The SKA is only affordable through a global collaboration, so it makes sense to engage the global community as fully as possible in the final design.

3) Five different types of hybrids can be identified (see SKA memo 48, Veidt et al):
- **frequency hybrids**, such as aperture arrays + the LNSD parabolas
- **complementary hybrids** such as one or more LARs at the centre of the compact core + small parabolas in the outer regions
- **technology hybrids**, of which the cylinder concept is an example
- **risk hybrids** eg LNSD (relatively safe) + cylinders or AA/LL/LAR (more risk)
- **site hybrids**, one telescope - 2 sites; a high frequency site and a low frequency site
- **political hybrids**, in which political funding considerations (juste retour) play a role

The general goals for hybrid concepts for the SKA are that the cost should not exceed the 1 BE/$ goal and must not compromise the science goals. In practical terms, the study of hybrids must be part of the overall engineering demonstration process, not a separate effort; we need to match the scientifically interesting hybrids to this process.

The workshop only considered hybrids that covered all or most of the frequency range specified in the SKA Science Requirements document. Other options providing a restricted frequency coverage and reduced cost (eg pre-loaded parabolic dishes or aperture arrays on their own) were not considered.

### Hybrid proposals considered

<table>
<thead>
<tr>
<th>Hybrid proposals considered</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNSD+aperture arrays</td>
<td>Covers full frequency range; multi-fielding in low band for fast all-sky surveying and multiple users; symmetric LNSD design possible → cost savings</td>
<td>Duplication of central core infrastructure needed for high and low freq science</td>
</tr>
<tr>
<td>AA &lt;1.5 GHz; LNSD &gt;1.5 GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LNSD+cylinders</td>
<td>Covers full frequency range; large FOV &lt;1.5 GHz for fast all-sky surveying; symmetric LNSD design possible → cost savings; cylinder collecting area is relatively cheap</td>
<td>Duplication of central core infrastructure needed for high and low freq science</td>
</tr>
<tr>
<td>cyl &lt;1.5 GHz; LNSD &gt;1.5 GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LNSD+LAR</td>
<td>Excellent surface brightness temp sensitivity; matched FOV across the full frequency range</td>
<td>FOV too small for fast all-sky surveying for dark energy; multi-fielding impossible</td>
</tr>
<tr>
<td>LAR(s) in central core; small parabolas in intermediate and outer parts of array</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LNSD+Luneberg Lenses</td>
<td>Covers full frequency range; multi-fielding in low band for fast all-sky surveying and multiple users; symmetric LNSD design possible → cost savings</td>
<td>Large diameter lenses needed at the lowest frequencies (weight, cost?); duplication of central core infrastructure needed for high and low freq science</td>
</tr>
<tr>
<td>LL &lt;1.5 GHz; LNSD &gt;1.5 GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aperture arrays+Luneberg Lenses</td>
<td>Multi-fielding from 100 MHz to 22 GHz for fast all-sky surveying and multiple users</td>
<td>Poor sensitivity for freq &gt; 10 GHz; many components</td>
</tr>
<tr>
<td>AA&lt;1.5 GHz; LL 1-22 GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LAR+other large N concepts</td>
<td>Excellent surface brightness temp sensitivity</td>
<td>Unmatched FOV; FOV (LAR) too small for fast all-sky surveying for dark energy</td>
</tr>
<tr>
<td>LAR(s) in central core; AA/cyl/LL in intermediate and outer parts of array</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LNSD+focal plane array</td>
<td>Large FOV possible for fast all-sky surveying including dark energy project</td>
<td>Extra mechanical structure to swing FPA away for high freq ops; requires separate beam-former</td>
</tr>
</tbody>
</table>
LNSD+log-periodic antennas mounted on back of secondary reflector

Shared hardware and infrastructure

Mechanical stresses increase mount requirements and cost; poor $A_{\text{eff}}/T_{\text{sys}}$

LNSD (inner 6m) + mesh (outer 6m)

Mechanical costs increased; no multiple-FOV possible

LNSD+existing large single dishes

Uses existing and future large collecting area infrastructure (in northern hemisphere); reduces data transport costs using existing fibre networks

Shared use with other users of non-SKA telescopes; different telescope types to be integrated; no multiple FOV

Elements consisting of four 2-3 m diameter solid parabolas mounted on a single azimuthal frame

Reduces pointing requirements at high frequencies; simpler mass production

Not enumerated

LNSD+LOFAR+

Augmenting LOFAR collecting area (LOFAR+) a cheaper option to cover low end of the frequency range

Reduced sensitivity 200-800 MHz; insufficient sensitivity for dark energy project

LNSD+AA+LOFAR+

Covers the full frequency range

Not enumerated

LL+AA+LOFAR+

A multi-fielding instrument across a wide frequency range

Not enumerated

LAR+LOFAR+

Not enumerated

LNSD+Cyl+LOFAR+

Not enumerated

LL+Cyl+LOFAR+

Not enumerated

Rough estimates of costs for LNSD+Aperture Array Tiles was $B 1.5, and $B 1.1-1.3 for LNSD+Cyl. No cost estimates were available for other possible hybrid concepts.

It was also noted that LOFAR in northern Europe does not allow SKA +LOFAR+ combinations since Europe is not a candidate for the SKA site.

Pathfinders for the SKA

The following instruments were noted as being pathfinders or niche-science instruments for the SKA:

EVLA (phase 1 funded, phase 2 proposal submitted, phase 2 expected to be completed 2012); ATA (partially funded, to be completed 2008); LOFAR (funded, to be completed 2008); eMERLIN (funded, to be completed 2007); eEVN (partially funded, to be completed in 2005-7) SKAMP (funded, to be completed 2007); FAST; CLAR; HIFAR.

The FAST, CLAR and HIFAR concepts are all very large collecting areas targeted on low surface brightness temperature science and surveys (HI and pulsars). FAST (500 m diameter) would cost about USD 60M, CLAR (300 m diameter) about USD 30M, and HIFAR (200000 m$^2$) about USD 60M. FAST has been proposed to the Chinese Academy of Sciences and there is hope that construction could start in 2006. CLAR and HIFAR have not yet been proposed for funding; the earliest start is 2006.

Comments by the IEMT on the concept selection process

1) there is a need to make sensible optimisations, and modify our ambitions where necessary. Magic is unlikely to play a role in the SKA development.
2) The continuing focus on demonstrators is important to determine the viability of the various constituent concepts.

3) Concept costs need updating, in particular for the aperture array. The initial HIFAR costs may be optimistic. The engineering cost/performance simulator in preparation should help.

4) Need to assess the scale and cost of post-processing for imaging and non-imaging applications for all concepts, including hybrids. This may be significantly helped by the new simulation and software engineering efforts, and may be a major factor in concept selection.

5) Experimental verification of the engineering simulations by demonstrators is essential.

6) Need to share knowledge on non-antenna areas of the SKA – workshops at URSI are a possibility.

7) Dynamic range and fidelity issues, large N vs small N, affect data processing and software, and ultimately the concept choice.

8) Issues to be considered for hybrids:
   - Are there advantages in sharing infrastructure; do they justify keeping the SKA in one site and as one project? 20-25% of the cost of the array is in non-concept-specific infrastructure.
   - Can we use one backend to do all the signal processing for the different parts of the hybrid?
   - The role of LOFAR in meeting the low-frequency goals of the SKA (SKA-low or LOFAR+)

Comments on the hybrid concepts by the ISAC

1) the $A_{\text{eff}}/T_{\text{sys}}$ vs frequency must remain the most important parameter, do not want a factor of 2 lower as compromise for full frequency coverage

2) Multi-fielding across the full frequency range needs further investigation for its scientific benefits; the “week in the life of the SKA” (see Hall and Chippendale in SKA Memo 48) is a means of coming to grips with this question.

3) The polarisation purity of hybrids needs investigation

4) Can non-hybrids do the key science projects better than hybrids?

5) Operational modelling of the use of the SKA may show that it is desirable to give preference to particular key science projects and delay others. Are people prepared to wait? Need a “Year in the life of the SKA” expanding on the “week” included in the Hall and Chippendale document.

6) Some frequency overlap is necessary between the antenna concepts in hybrids, for calibration, but this does not need to be large.

7) Flexibility in design should include the use of distributed computing. Software should take account of Moore’s Law

Discussion

What is the best strategy for optimising the chances of funding the full SKA?

Three options were discussed, all of which found support amongst the Workshop participants:

1) form a global cooperation from 2008 onwards on a hybrid concept.
   
   But are we not trying to prove that 1+1=1? Can we build a hybrid which maintains the broad science case for 1 B$?

2) concentrate on a single concept after 2008 providing either low frequencies or high frequencies in order to keep costs within the nominal limit.

   A hybrid would not be needed in this case.
Restricting the frequency range to frequencies 100 MHz-1.5 GHz would mean that the AA, Cyl, KARST, LAR, PLPD concepts remain in contention; restricting the frequency range to 1-25 GHz would mean that the LNSD and LAR concepts remain in contention.

This requires the ISSC to assign weights to the key science projects.

3) **build a number of 5-10% SKA pathfinders from 2008 onwards that are major science and technology demonstrators in their own right and that at the same time build up the national and regional radio astronomy communities.**

It is clear that with as broad and frequency-dependent a science case as we have for the SKA, it is inevitable that proposals for niche-science or SKA pathfinder instruments will be made, to be realised on shorter timescales than the SKA. Examples are HIFAR and CLAR. Whether niche-science instruments can be regarded as SKA pathfinders depends on whether the technology is that chosen for the full SKA and whether the timescales for realisation are sufficiently short not to delay proposals for full SKA funding.

The concern was raised that manpower resources for the SKA will be absorbed by the pathfinders. One can argue that the SKA community needs to keep its eye on the goal of building a single instrument, and not get too caught up in advocating local designs. “Ask not what SKA can do for you, but what you can do for the SKA.”

**Hybrids selected for further analysis**

At the end of the discussion, a small number of hybrids were selected for further analysis (see table). These included LNSD+AA, LNSD+CYL, LL+AA, and LL+CYL, while the LAR was recognised as a frequency hybrid in itself since it will cover the full frequency range. Additional information will be requested from the proponents of the four non-LAR hybrid concepts.
Preliminary inventory of technological expertise around the world

The workshop considered the contributions that could be made to the various design concepts from the different groups around the world. A number of possibilities were highlighted, for example, the mechatronic expertise in China developed for the FAST focal platform control is applicable to the LAR concept and vice versa. The following table summarises current expertise in a number of areas of importance to the SKA project, and should be viewed as a first attempt to capture this information.

<table>
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<tr>
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Timescale for the convergence process

Jan 04: first workshop at Cape Town
June 04: assessment of the feasibility, cost and science benefit of the propose hybrid concepts by ISAC and IEMT. Draft report on options for international collaboration.
July 04: second convergence workshop at Penticton to refine and narrow the list of hybrid concepts
Oct 04: global teams report interest in supporting hybrid options
Nov 04: report on status of possible hybrid approaches
Jan 05: third convergence workshop in GuiYang. Define international hybrid concepts to be pursued/proposed.
Discussion on engaging the radio astronomy community in the pre-SKA era

Comments made:

- With EVLA, ALMA, eMERLIN, LOFAR, eVLBI, ATA all in the pipeline, there is no danger that the astronomical community will disengage from radio astronomy in the pre-SKA era.
- None of these instruments attack the SKA key science projects; one can argue for SKA niche-science instruments to be built to attract young people into the SKA project early on.
- The upgrades all miss the scale and scope of the SKA, eg EVLA will not do HI science in the way the CLAR and HIFAR will.
- We should be looking to engage the entire electromagnetic community in radio astronomy and the way to do that is build a niche-science instrument that attacks one or more of the current big issues in astronomy.
- ATA, EVLA and LOFAR are not fully funded yet, so one shouldn't muddy the waters with new proposals.
- A pathfinder/ niche-science instrument is a distraction unless it is Phase 1 of the SKA.
- Aperture arrays is a winning technology on the longer term; is there any way of accelerating its development

This debate will clearly continue!
Annex 1.  

**Convergence Workshop Programme**

**Capetown, 13 January 2004**

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
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<tbody>
<tr>
<td>09:00</td>
<td>1. Scope and purpose of the workshop (Richard Schilizzi)</td>
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<td>2. Short presentations on potential hybrid solutions (10\textsuperscript{th} talk, 10\textsuperscript{th} discussion)</td>
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<tr>
<td>09:15</td>
<td>2.1 SKA Hybrids using the US LNSD Concept (Joe Lazio)</td>
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<tr>
<td>09:35</td>
<td>2.2 Hybrid solutions – A European perspective (Peter Wilkinson/Arnold van Ardenne)</td>
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<tr>
<td>09:55</td>
<td>2.3 Hybrid solutions for the Square Kilometre Array: perspectives from the LAR (Bruce Veidt)</td>
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<tr>
<td>10:15</td>
<td>2.4 A cylinder plus 12-m dish hybrid (Ron Ekers/John Bunton)</td>
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<tr>
<td>10:35</td>
<td>Coffee/tea</td>
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<tr>
<td>11:00</td>
<td>2.5 A multi-fielding SKA covering the range 100 MHz to 22 GHz (Peter Hall/Aaron Chippendale)</td>
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<tr>
<td>11:20</td>
<td>2.6 Potential combined concepts with KARST (Bo Peng)</td>
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<td>11:40</td>
<td>2.7 HIFAR (Brian Boyle)</td>
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<tr>
<td>12:00</td>
<td>3. Contributions from design teams to other concepts if their design is not chosen (please come prepared!)</td>
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<tr>
<td>12:30</td>
<td>Lunch</td>
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<tr>
<td>13:30</td>
<td>4. Comments on feasibility of hybrid concepts (IEMT)</td>
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<td>Preliminary costing (Peter Hall)</td>
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<td>Scientific utility of the hybrids (Steve Rawlings)</td>
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<td>14:30</td>
<td>5. Discussion</td>
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<td>5.1 Open discussion of feasibility and scientific utility of proposed hybrid concepts, and their place in the engineering demonstration process</td>
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<td>5.2 Activities and schedule leading toward convergence</td>
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<tr>
<td>15:30</td>
<td>Coffee/tea</td>
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<tr>
<td>16:00</td>
<td>6. Open discussion on how to maintain the continuity of the radio astronomy communities around the world in the pre-SKA and SKA eras</td>
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<tr>
<td>17:00</td>
<td>7. Presentation from Rudolph Gouws on “The strategic and economic future of South Africa” (part of the “Industry Day” programme from the day before)</td>
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<td>17:30</td>
<td>End</td>
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Annex 2: Documents included in SKA Memo 48

J. Lazio “SKA Hybrids using the US LNSD Concept”
P. Wilkinson “Hybrid solutions – A European perspective”
B. Veidt “Hybrid solutions for the Square Kilometre Array: perspectives from the LAR”
R. Ekers, J. Bunton “A cylinder plus 12-m dish hybrid”
P. Hall, A. Chippendale “A multi-fielding SKA covering the range 100 MHz to 22 GHz”
B. Peng “Potential combined concepts with KARST”
B. Boyle “HIFAR”
A. Van Ardenne “Hybrids; a combined concentrator for high frequency observing”
A. R. Thompson and B. Veidt “Comments on Hybrid-System Documents”