EWG Reviews of SKA Hybrid Proposals

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1 Introduction

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After the first SKA convergence meeting in Cape Town, South Africa (January 2004) [5], several groups were invited to provide descriptions of possible hybrids. Those concepts were:

- ▷ Aperture array + small dishes hybrid,
- ▷ Cylinder + small dishes hybrid.

Hybrids using Luneburg Lenses were also invited, but as Australia has withdrawn that concept from consideration as an SKA concept, hybrid concepts involving Luneburg were also withdrawn. In addition, the Large Adaptive Reflector (LAR) group was asked to provide a proposal since the LAR can, in principle, cover the full frequency range desired for the SKA (that being one of the key limiting factor with many concepts). Thus the LAR provided a comparison reference. The hybrid proposals have been reviewed by members of the Engineering Working Group and are presented here. Also in this document (Section 5) is a summary of the discussions held in Penticton immediately prior to the International SKA meeting (see Appendix A).

To guide the review process and to ensure some degree of consistency, Bruce Veidt and Peter Hall drafted a set of questions which were given to the reviewers. That set of questions was in two parts: first a set specific to the concept under review, and second, a set of general questions that was to be applied to the overall idea of an SKA composed of several different types of element designs. The questions are reproduced below in sections 1.1 and 1.2.

1.1 Specific questions

Please summarize the hybrid configuration proposed.

Is the hybrid concept capable of achieving a significant fraction of the key science goals of the SKA? Which (if any) of the science goals cannot be met with this hybrid?

What is A_{eff}/T_{sys} across the total frequency range of the hybrid? (Please select enough points to give a reasonable impression of the performance over the full frequency range, including points at band edges, maxima and minima.)

What is the cost of the hybrid? If possible, please break up the cost into:

- ▷ components,
- ▷ infrastructure,
- ▷ computing, and
- ▷ operations.

To what degree is the infrastructure shared between the components?

What are the advantages of this hybrid configuration? What are the shortcomings? Are there any synergisms?

Have the components making up the hybrid been optimized for operation in a hybrid system? If not, what are the savings if this is done? For example, the frequency range of a component in a hybrid will be narrower than it would be if it was a single-component SKA concept, likely reducing the cost.

If this hybrid solution is selected, what would be the most effective scheduling of construction of the different components: serial or parallel? What are the advantages and disadvantages of either schedule from an engineer's point-of-view and from an astronomer's perspective?

1.2 Global questions

Are there major issues of hybrid description still outstanding? Did the proponents tell us what we asked? (See hybrid concept request memo, Peter Hall, 8 March 2004.)

Have the submissions and ensuing reviews added to our understanding of whether a hybrid concept is desirable in a $1b SKA?

Can we afford a hybrid at all - what are the perils of multiple technologies from the construction and operation viewpoint?

Are there any new hybrid solutions requiring attention? Has anything been overlooked?

How much can be gained by optimising the component specifications towards operation within a hybrid as compared with a non-hybrid solution?

Are there aspects of hybrid design which cannot be well addressed via first-round demonstrators? For example, frequency hybrids operating in the band of frequency overlap may have very different station beams, and the problem of image formation with dissimilar beams would not normally be addressed by the demonstrator of each component.

Should any large-area international demonstrator be a hybrid? Has the existing descriptive process reached a useful conclusion?

How should the design convergence process proceed?

2 Cylindrical Reflectors + Small Dishes

Concept authors:	John Bunton, CSIRO
	Joseph Lazio, NRL
Reviewers:	Ralph Spencer, JBO
	Parbhu Patel, ASTRON

2.1 Summary of the hybrid configuration proposed

A two-component parabolic cylinder array forms the low frequency sub-array, with a Large- Number-Small-Dish (LNSD) array forming the high frequency sub-array [3].

The low frequency cylinders cover 0.1 to 0.7 GHz, the high frequency cylinders cover 0.1 to 2 GHz, extendable to 5 GHz, and the LNSD array covers 0.47 to 24 GHz.

2.2 Questions

Is the hybrid concept capable of achieving a significant fraction of the key science goals of the SKA? Which (if any) of the science goals cannot be met with this hybrid?

The proposed hybrid fails the SKA sensitivity goals at 100 MHz and below, and also above 2 GHz, though it is better than specification at 0.4–2 GHz. Therefore the science goals Epoch of Re-ionisation and Cradle of Life may be compromised.

The report pays some attention to the central core of the array, where a high filling factor is needed for key science projects such as Dark Energy, the Strong-field Test of Gravity and the Cradle of Life. They point out the need for 2 cores due to shadowing limitations, with a suggested separation of around 1 km.

What is Ae /Tsys across the total frequency range of the hybrid? (Please select enough points to give a reasonable impression of the performance over the full frequency range, including points at band edges, maxima and minima.)

The sensitivity of the array is maximum when the two cylindrical arrays can be combined, giving 40000 m^2/K at $\sim$0.6–0.9 GHz. This optimises searches for HI emission at redshifts around 1. The sensitivity becomes 30000 m^2/K between 1 to 2 GHz where the small dishes and cylinders combine, falling to 10000 m^2/K above 3 GHz where the small dishes operate on their own.

The low frequency performance drops to 14700 m^2/K at 0.3 GHz, and to 1400 m^2/K at 0.1 GHz.

The high frequency performance drops to 5200 m^2/K at 22.5 GHz and to 1800 m^2/K at 36 GHz.

What is the cost of the hybrid? If possible, please break up the cost into:

- ▷ *components,*
- ▷ *infrastructure,*
- ▷ *computing, and*
- ▷ *operations.*

See Table 1.

Table 1: Cost Table for Cylinders + Small Dishes.

Components	
2500 small dishes	493 M
600 low frequency cylinders	140 M
600 high frequency cylinders	226 M
	859 M
Infrastructure:	
Small dish core	38 M
Cylinder core	38 M
96 stations	48 M
Central office/processing centre	20 M
System engineering/NRE etc.	60 M
	204 M
Computing etc.:	
Computing	130 M
Signal processing	80 M
	210 M
Total	$ 1273 M

To what degree is the infrastructure shared between the components?

There is little opportunity for sharing costs in the core since two cores are required. Outside the core and in the stations the infrastructure costs can be shared, except for extra fibres and power requirements. The low frequency cylinders only add about 10% to the overall cost of the project and small dishes add extra 50%.

What are the advantages of this hybrid configuration?

The advantages are in the possibility of multi-beam forming capability at low frequencies, and the extra sensitivity for redshifted hydrogen.

What are the shortcomings? Are there any synergisms?

The presence of two cores could lead to imaging difficulties when the two are combined. The proposed feeds (Ingersen and Kildal feed) appear not to provide good match over the wide bandwidth and therefore the efficiency assumed (70%) in the calculation of A_{eff}/T_{sys} may be difficult to achieve. There is NO detailed information provided for the linefeeds for the cylinders except a list of options for the radiators. Synergies come about due to combined effort in feed design (e.g. using Ingerson or Kildal designs), in receiver development and in data link design, as well as in signal processing, computing, and civil work.

Have the components making up the hybrid been optimized for operation in a hybrid system? If not, what are the savings if this is done? For example, the frequency range of a component in a hybrid will be narrower than it would be if it was a single-component SKA concept, likely reducing the cost.

There may be potential for cost saving if the low and high frequency cylinders can be incorporated into one cylinder. However the problems of wide-band feed design may preclude this as being an option, and the design overcomes the low frequency limitation of both dishes and high frequency cylinders. If this hybrid solution is selected, what would be the most effective scheduling of construction of the different components: serial or parallel?

What are the advantages and disadvantages of either schedule from an engineer's point-of-view and from an astronomer's perspective?

This depends on which science project has the highest priority. For instance if HI studies were considered urgent then the high frequency cylinders should be constructed first. The use of separate cores and therefore separate infrastructure means that the infrastructure build can also be scheduled accordingly. However the stations share infrastructure so there is no point in a separate infrastructure build there.

2.3 Global questions

Are there major issues of hybrid description still outstanding? Did the proponents tell us what we asked? (See hybrid concept request memo, Peter Hall, 8 March 2004.)

A fairly full description for the Cylinders + Small Dishes hybrid has been given. Outstanding issues — like detailed feed design for both the cylinders and dishes, receiver performance, beam forming, data link specifications, correlator specification etc. — can only be answered by further study, much of which is in common with other proposals. Until these are done the costing can only remain approximate.

Have the submissions and ensuing reviews added to our understanding of whether a hybrid concept is desirable in a $1b SKA?

There are at least two hybrids the Cylinders + Small Dishes and Aperture Arrays + Cylinders. The relative costs therefore can be compared:

- ▷ Cylinders + small dishes: $1273 M
- ▷ Aperture Arrays + small dishes: $ 1450 M

Although cost of AA + Dishes is greater than Cylinders + Dishes, it is difficult to compare the performance exactly as AA has much to offer in terms of multi-beaming capability plus significant cost reduction for the future. Also the components of the hybrid concepts are at different level of development.

Can we afford a hybrid at all—what are the perils of multiple technologies from the construction and operation viewpoint?

We need to be wary of hybrids which merely add together two quite different technologies. There needs to be advantages gained by common technology development.

Are there any new hybrid solutions requiring attention? Has anything been overlooked?

The Aperture Array + Small Dishes hybrid certainly needs further investigation.

LAR + Small Dishes should perhaps be looked at if there are potential cost savings.

As mentioned above, two completely different technologies does not offer much in the way of synergy in technologies and therefore we probably cannot expect much in terms of cost reduction, as the technologies for each component of the hybrid needs to be developed separately. To achieve the required cost reduction, we need to identify common technologies and develop them so that it can be used in both components of the hybrid.

Also, we should closely look at other demonstrators to see if there is a low cost design but it is not considered as a hybrid, e.g. the Preloaded Parabolic dish from the Indian concept for producing low cost reflectors.

How much can be gained by optimising the component specifications towards operation within a hybrid as compared with a non-hybrid solution?

Yes within the science goals. Each solution will impose its own parameters on the optimum science.

Are there aspects of hybrid design which cannot be well addressed via first-round demonstrators? For example, frequency hybrids operating in the band of frequency overlap may have very different station beams, and the problem of image formation with dissimilar beams would not normally be addressed by the demonstrator of each component.

This is a problem, not only restricted to hybrids—e.g. there could be varying size beams in any of the concepts (e.g. if the terrain dictates the size or number of antennas at a station).

Should any large-area international demonstrator be a hybrid?

At the moment the demonstrators are at different physical locations, so a direct combination would be difficult. However it should be possible to combine data sets to investigate the qualities of a combined images.

Has the existing descriptive process reached a useful conclusion?

See below.

How should the design convergence process proceed?

There are still a lot of unknowns, which hopefully will be answered by the demonstrators. There is obviously scope for more discussion, highlighting issues, but we do need more concrete information in many areas.

3 Aperture Arrays + Small Dishes

Concept authors: Arnold van Ardenne, ASTRON
Joseph Lazio, NRL
Reviewers: John Bunton, CSIRO
Bruce Veidt, NRC

3.1 Review questions

Please summarize the hybrid configuration proposed.

The proposal [4] has four components

- ▷ 2500 12-m dishes operating from 0.5 to 25 GHz (36 GHz reduced sensitivity) with and A/Tsys equal to half the SKA specification.
- ▷ high frequency multi-beam aperture array covering 0.53 to 1.25 GHz (1.7 GHz reduced sensitivity); total effective area 0.6 km^2(0.8 km^2 physical area)
- ▷ mid-frequency multi-beam aperture array covering 0.22 to 0.56 GHz (0.8 GHz reduced sensitivity); total effective area 0.75 km^2(1 km^2 physical area)
- ▷ low-frequency multi-beam aperture tile array covering 0.1 to 0.22 GHz; total effective area 1.2 km^2(1.6 km^2 physical area)

The proposal states that “within the central 1 km, the elements are packed so closely that separate regions are needed for the various elements.” This would imply four separate regions, which does not match well with Figure 1. This figure shows a 1-km region for the small dishes and a separate region with an annulus for the aperture arrays. This needs clarification. Outside the 1-km regions the components may be arranged into 154 antenna stations consisting of four separate components:

- ▷ 13 small dishes,
- ▷ a 72-m diameter high frequency aperture array,
- ▷ an 81-m diameter mid frequency aperture array,
- ▷ and a 101-m diameter low frequency aperture array.

Is the hybrid concept capable of achieving a significant fraction of the key science goals of the SKA? Which (if any) of the science goals cannot be met with this hybrid?

This hybrid should be able to meet the science goals of the SKA as it covers the full frequency range and has good sensitivity in all bands. It has less than full SKA sensitivity above 1.7 GHz, which has the potential to reduce the science throughput at these frequencies. But it is noted that this is counterbalanced by the independent operation of the various components. In a single-component concept high and low frequency observations compete for time. In hybrid concepts this does not occur and the amount of time devoted to high frequency science is at least doubled, bring the effective sensitivity of the small dishes up to about 80% of the SKA specification.

Table 2: SKA AA+SD Hybrid Sensitivity

		LFA		MFA		HFA		SD		Total
Freq GHz	T_{sky} K	T_{rec} K	$\frac{A_{eff}}{T_{sys}}$ m^{2}K^{-1}	T_{rec} K	$\frac{A_{eff}}{T_{sys}}$ m^{2}K^{-1}	T_{rec} K	$\frac{A_{eff}}{T_{sys}}$ m^{2}K^{-1}	T_{rec} K	$\frac{A_{eff}}{T_{sys}}$ m^{2}K^{-1}	$\frac{A_{eff}}{T_{sys}}$ m^{2}K^{-1}
.1	990	200	1010							1010
.17	255	40	4070							4070
.22	132	50	660	30	4600					6600
.53	18			30	15600	30	12500	22	5000	33100
.65	12			30	17800	30	14300	22	5800	37900
.8	6			30	13700	30	16700	22	7100	37500
1.2	4					30	17600	15	10600	28200
1.45	4					30	17600	15	10600	28200
1.7	4					30	12900	15	10600	23500
2	3							15	11200	11200
5	3							15	11200	11200
10	4							15	10600	10600
11	4							29	6100	6100
20	16							29	4480	4480
22.5	23							29	3880	3880
24	16							29	4480	4480

What is Aeff/Tsys across the total frequency range of the hybrid?

The Aeff/Tsys of the four components is given in table 2 of the proposal, which is reproduced below in Table 2.

The figures in this table are consistent with the given effective areas, receiver and sky noise and for the aperture tiles the $1/\lambda^2$ dependence of Aeff when the feed element separation exceeds 0.58λ. This data is also given in Figure 3, but the table and figure are not entirely consistent. For example, Figure 3 in the proposal shows the high frequency aperture tiles with no drop off in Aeff/Tsys from 1.45 to 1.7 GHz where the table shows a decrease. It would appear that the Figure 3 has some errors.

The individual components of this hybrid match the SKA sensitivity over the frequency range 0.2 to 1.7 GHz. The specification is hard to meet below 200 MHz as area needs to increase as $\lambda^{2.6}$ and the aperture arrays are a constant area concept. This comment applies to all SKA design concepts proposed to date. Above 1.7 GHz only the small dishes are available, they have 55% of full SKA sensitivity. As noted previously the effective sensitivity is higher because of the increased observation time available.

Each component has a separate correlator. When operated in this manner the combined Aeff/Tsys is not equal to the sum of the Aeff/Tsys for the two components instead it is the RMS sum. For example at 1.45 GHz the combined sensitivity of the small dishes and high-frequency aperture array is 20,500 m^{2}K^{-1} rather than the 28,200 m^{2}K^{-1} quoted. Combined operation of the components is only proposed for mid and high-frequency arrays from 0.53 to 0.8 GHz, with a peak Aeff/Tsys of 32,100 m^{2}K^{-1} at 0.65 GHz. In doing this the number of beams is reduced from 2200 to 1000 (mid frequency array). The beam size of the mid-frequency array is 20% smaller than that of the high-frequency array. Thus the field of view is reduced from 200 square degrees to 90 square degrees. The survey speed is proportional to (Aeff/Tsys)$^2\times$ FoV and it is found that the survey speed of the combined arrays is no faster than that of the two arrays operating separately. As much of the science at 0.7 GHz depends on survey speed extra correlator capacity is needed to take advantage of the overlap in the frequency coverage of the mid and high frequency arrays.

Table 3: Cost Table for Aperture Arrays + Small Dishes.

2500 small dishes	$490 M
276k high-frequency tiles	270 M
390k mid-frequency tiles	140 M
138k low-frequency tiles	130 M
Infrastructure cost	150 M
Signal processing	80 M
Computing	130 M
System engineering/NRE	60 M
TOTAL	$1450 M

What is the cost of the hybrid?

The cost of the hybrid is given in Table 3. It is seen that the cost are approximately equal divide between the small dishes, aperture tile arrays and other costs. Of these the aperture tile arrays at $540M, is the largest cost component.

The 12-m small dishes are a symmetrically-fed Gregorian reflector design which is cheaper to construct than the previous offset feed design. The change leads to a ∼10% reduction in construction cost allowing the dishes to achieve 55% of SKA sensitivity at 2–5 GHz. The cost of the small dishes is $490M or $196,000 each including foundations and cryogenically cooled receivers. This is actually a little higher than the costs in the original design concept white paper [6].

The low frequency aperture tile arrays appear are based on the high frequency component of LOFAR and the estimated cost is $60 per feed, which is in agreement with the LOFAR estimate (excluding antenna station digital receivers and beamformers). Much of this cost is in the metal work of the antennas and electronics chassis, and the cables and connectors so use of current costs is considered reasonable. It appears that the cost of the digital beamformer is balanced against a reduced cost RF beamformer for the SKA: 4 inputs for the SKA and 16 for LOFAR.

The high frequency aperture array consists of 276,000 tiles each 1.7m $\times$ 1.7m, the feed separation is 12cm ($\lambda/2$ spacing equivalent to 1.25 GHz). The Vivaldi feed system accepts both polarisations making total number of Vivaldi feeds in the array is 108 million. To increase flexibility each array incorporates dual beamformers. The mid frequency array uses is similar but the feed separation is 27 cm.

Each high frequency array station beamformer has 16875 200-MHz inputs and the total number of beams generated is ∼1700. The average compute cost per feed for beamforming is 400 MS/S $\times$ 1700 beams $\times$ 16875 inputs $\times$ 8 operations per input $\times$ 200 stations divided by 108×10^6 feeds is equal to ∼170 Gigaoperations/sec. With the high frequency array costing $270M the cost per feed is $2.5. This cost must cover

- ▷ a feed element with LNA
- ▷ dual phase only RF beamforming,
- ▷ water and electromagnetically tight box for the electronics,
- ▷ signal transport of one sixteenth of two 200 MHz beams: 25 MHz of bandwidth,
- ▷ one eighth of a downconversion and digitisation system and
- ▷ ∼170 Giga digital arithmetic operations per second in the beamformer.

With current FPGA digital signal processing costs estimated at ∼$10 per Giga operation/s, it would appear that Moore's law needs to provide at least 1000 times reduction, estimated to take 15 years or beyond the start time of the SKA. Then there is the cost of the feed structure, an LNA per feed, control wiring and connectors for the phase shifters, the 1.7 $\times$ 1.7m water and electromagnetically tight box and a $\sim$100 Gigabit fibre connection per box. The reviewers feel that a detailed justification of $2.5 per feed cost is needed, especially in the light of the $60 per feed cost estimated for the low frequency feed.

To what degree is the infrastructure shared between the components?

There will be some infrastructure shared (roads, power, and fibre optic networks) resulting in some cost savings. However, since the central core for each band is offset from those of the other bands ("overlapping core" concept), the area of the core region (and the length of power and data cables and of roads) will be larger. Outside the core at remote stations there will be a higher degree of sharing.

There will be little infrastructure sharing for signal processing since the plan is to have separate correlators for each band. The mid and high frequency arrays may be combined but the combined correlator capacity results in a reduction in the total number of beams and no increase in survey speed.

Have the components making up the hybrid been optimized for operation in a hybrid system?

In this proposal there appears to be more accommodation (such as by modification of the core layout to accommodate the other concept) than optimisation. This is illustrated in the frequency/sensitivity table that shows that as many as three observing bands overlap. Although this is still a debatable point, there is a strong argument that an optimised frequency-hybrid telescope will have minimal overlap of frequency bands particularly if there is little combined use of the overlap.

If this hybrid solution is selected, what would be the most effective scheduling of construction of the different components: serial or parallel? What are the advantages and disadvantages of either schedule from an engineer's point-of-view and from an astronomer's perspective?

There is no strong argument for either serial or parallel deployment of the components of the hybrid. Each component in this proposal is nearly independent of the others so construction could proceed at a convenient pace once roads, power, and fibre-optic networks are in place.

3.2 Further discussion

3.2.1 Phase only beamforming

The mid and high frequency arrays use densely packed Vivaldi feed elements. These are phase only beam formed over 16 feed elements. Assuming a 4 by 4 array the total phase change across the array is $\sim$300 degrees. With 200 MHz signals the fractional bandwidth is 36% at 0.56GHz. With this bandwidth there will be significant gain loss in the phase-only beamformer away from the band centre.

3.2.2 Grating lobes

The aperture arrays have a large FoV. For the MF array there are two 800 sq degrees RF beams at 0.56 GHz coming from the antenna array, reducing to 500 sq degrees at 0.7 GHz. These are digitally beamformed at the antenna station to generate 200 sq degrees FoV at 0.7 GHz. It is noted that RF beamforming followed by digital beam forming can lead to grating lobes. To limit this, the beam area that is digitally beamformed should be well within the -1dB area of the RF beam.This would reduce the available field of view to less than 125 square degrees per RF beams. With two beams the 200 sq degree FoV is meet but there may still be significant grating lobes. It would be useful if the authors could give the grating lobe levels at the edge of the FoV.

At the highest frequency of operation the aperture tile arrays have a 0.68λ separation. How does this affect the sky coverage?

3.3 Summary

This proposal is for a $1.45B hybrid system essentially consisting of four separate components: low, mid and high frequency aperture tile arrays, and 12-m small parabolic dishes. In their frequency bands the aperture tile arrays meet SKA specification up to a frequency of 1.45 GHz. Above 1.7 GHz only the small dishes are available and these have a sensitivity that 55% of the SKA specifications. However each system can operate simultaneously allowing up to four times the observing time of a non-hybrid SKA system. When this is considered the small dishes come close to meeting the SKA specifications for effective sensitivity and the aperture tile arrays exceed it.

There is considerable frequency overlap between the various components of the hybrid. However, only combined use of the mid and high frequency aperture tile arrays is contemplated. When this is done only the correlator resources of the individual arrays is available so the to generate all cross correlations the field of view is more than halved. For other combinations of components no inter-component correlation are envisage. Hence the Aeff/Tsys of the components cannot be added, as shown in table 2. In addition table 2 and figure 3 do not entirely agree.

The mid and high frequency aperture tile arrays use phase only RF beamforming. This will lead to gain loss at the band edges. This is followed by digital beamforming. Quantisation of the phase slope by the RF beamformer will lead to grating lobe problems which need to be addressed.

Costing of the small dishes and low frequency aperture tile arrays appears reasonable. The mid and high frequency aperture tile arrays are 13 and 24 times cheaper than the low frequency aperture arrays, with the cost per feed of high frequency aperture tile array being $2.5. This $2.5 cost includes feed, LNA, beamforming, signal transport, and all other cost associated with the feed. The reviews feel that the low cost of these components of the hybrid needs justification.

4 LAR as a Hybrid Option

Concept authors:	The LAR Group, NRC
Reviewers:	Graeme James, CSIRO
	Larry D'Addario, NRAO

The LAR concept presented in the LAR hybrid proposal [1] is the same as earlier descriptions and is no sense a new hybrid proposal. Therefore the hybrid review questions set out are somewhat redundant to this essentially non-hybrid proposal. The LAR concept has been reviewed extensively at previous SKA meetings [7, 8].

In the LAR Group report of 1 June 2004 [1] there seems to us to be little new information that has not already been presented elsewhere. The curve in Fig. 1 is worth repeating to remind us of the potential frequency coverage of LAR. What they do not address is the new FoV spec with its considerable increase in instantaneous coverage.

Aside from the general mechanical/environmental/practicality concerns of LAR we reiterate the following two points.

The feed Like the cylindrical reflector proposal, all the effort with LAR appears to have gone into the reflector optics and configuration. This is fine as far as it goes, but in any reflector antenna the feed is the most critical element and the one, which in the end, will limit the overall performance. However all we seem to get is a vague mention of focal plane arrays with a specific tilt at the Vivaldi array. That one of the most crucial aspects of the overall system has essentially been ignored is of real concern. Indeed, there are many feed issues to address for the requirements of their focal plane array: cost, complexity, power requirements, size of array (especially with the extended FoV spec), bandwidth performance and so on. Thus, aside from any other issues regarding LAR, until the feed problem is addressed seriously with demonstrable feed elements, it is difficult to see how it can be seen as a viable option for the SKA.

Cross-polar performance The single offset configuration of LAR has inherently poor cross-polar performance particularly as the scan angle moves away from zenith. This is acknowledged in the LAR concept white paper of May 2003 [9] with one solution to do a correction via the focal plane array. Again, it seems this issue has not been addressed further and would seriously detract from the proposal if it could not be solved adequately.

5 EWG Comments on Hybrids

Compiled and presented by: Bruce Veidt, NRC

5.1 Introduction

- ▷ EWG met July 2004 and discussed hybrids and the process of convergence
- ▷ Considered following concepts:
  - ▷ Large Adaptive Reflector (LAR) as a hybrid substitute [1],
  - ▷ Aperture Array + Small Dishes (AA+SD) [4],
  - ▷ Cylinders + Small Dishes (CYL+SD) [3],
  - ▷ also introduced to wide-field dishes with focal-plane arrays [2].
- ▷ This document is a summary of that meeting and was presented by Bruce Veidt at the Concept Convergence Workshop, part of the SKA2004 Conference on 22 July 2004.

5.2 Why Consider Hybrid Configurations?

- ▷ Does *not* reduce the risk of reaching cost or performance goals
- ▷ Expands some of the capabilities of the SKA
- ▷ Changes "trajectory" through parameter space
- ▷ But probably have a higher cost and/or lower A_{eff}/T_{sys}
- ▷ Should we be using expensive high-frequency capable aperture at low frequencies where a much lower-cost solution is available?
- ▷ Figure 1 shows the sensitivity of a generic frequency hybrid in comparison to the specified SKA sensitivity.

5.3 LAR—An Alternative to Hybrids [1]

Figure 2 shows that the LAR has high aperture e□ciency over a wide frequency range. Low-frequency operation is limited by the size of the feed in comparison to the size of the focal spot, and at the high-frequency end, by phase errors from the flat panels making up the surface.

5.3.1 LAR—Phased-Array Feeds

- ▷ Only two experiments (NRAO and ASTRON) involving a phased-array feeds have been performed to date.
- ▷ Phased-array feeds are essential for the LAR so that the feed pattern matches the elliptical profile of the reflector and so that a wide field-of-view is obtained.
- ▷ Uncooled LNAs may be adequate to ∼2 GHz and cooled LNAs required above.
- ▷ How confident will we be in 2008 that high-performance phased-array feeds can be built for the LAR?
- ▷ How confident will we be in 2008 that high-performance *cooled* phased-array feeds can be built for the LAR?

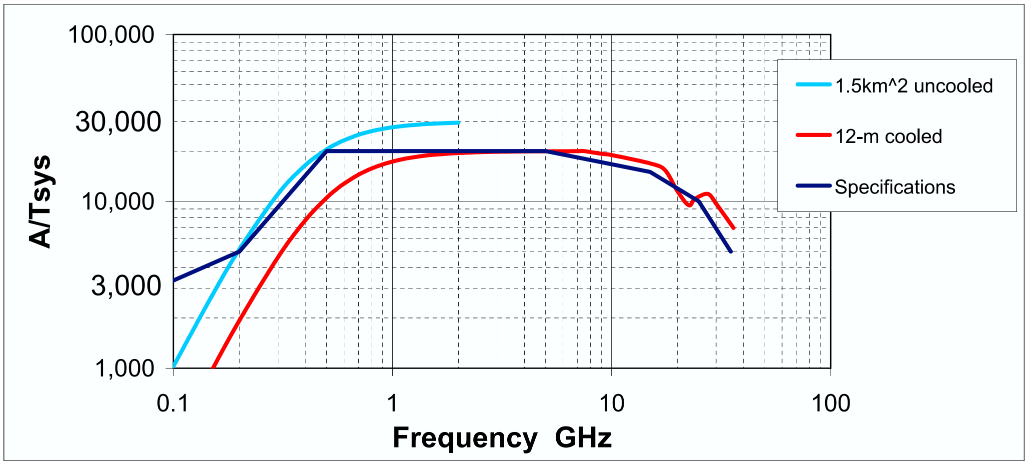

Figure 1: Generic frequency-hybrid sensitivity.

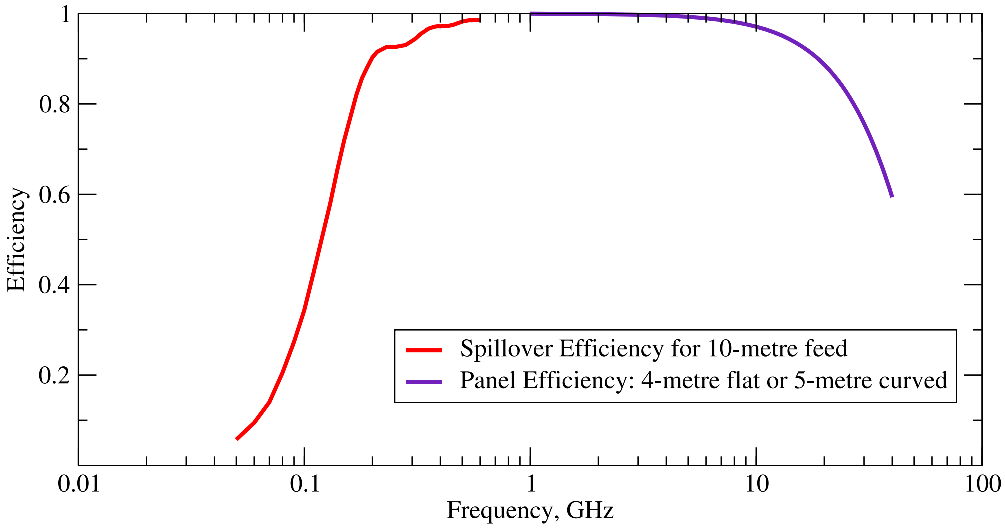

Figure 2: LAR aperture efficiency.

5.3.2 LAR—Low-Frequency Performance

- ▷ Latest SKA spec calls for 200 square degrees field-of-view at 0.7 GHz
  - ▷ LAR has a field-of-view limited by focal-package size (∼10m)
- ▷ Specification calls for widely-separated field-of-views, either by sub-arrays or phased-array techniques
  - ▷ Small-n arrays will have poor performance in sub-array observing modes

5.4 Small Dishes + Focal Plane Array — Another Alternative [2]

- ▷ SD could be either Indian PPD or US hydroformed dish
- ▷ US SD meets high-frequency spec's
- ▷ SD cannot provide multiple, widely-spaced beams on the sky without sub-arrays
- ▷ Recently proposed that wide-field specification be meet with a focal-plane array
  - ▷ to get 200 sq. deg. need field width $\sim 15°$
  - ▷ how large will aberrations be this far off axis?
  - ▷ earlier concerns on focal-plane array development apply here too

5.5 Cylinder + Small Dishes [3]

- ▷ Figure 3 shows the sensitivity of CYL+SD as a function of frequency.
- ▷ Offers very wide field-of-view at low frequencies
- ▷ Does not provide independent widely-spaced beams
- ▷ Wide-band line feed yet to be demonstrated
- ▷ Again, dependent upon phased-array feed technology
- ▷ Although many beams within a large field-of-view are available, only the central beam can be pointed independently...how will these other beams be used?
- ▷ Requires more thorough investigation of fabrication cost of cylinders

5.6 Aperture Array + Small Dishes Hybrid [4]

- ▷ The sensitivity of AA+SD is shown in Figure 4.
- ▷ *Heavily* dependent upon low-noise phased arrays
- ▷ Construct much more than a square kilometre because each receiving band has a separate aperture
- ▷ Have a huge number of receivers ⇒ need very low-cost
  - ▷ scepticism concerning cost extrapolations
  - ▷ Moore's Law helps electronics, but not radomes etc.
- ▷ Although EMBRACE will be completed by 2008, there will be very little operational experience

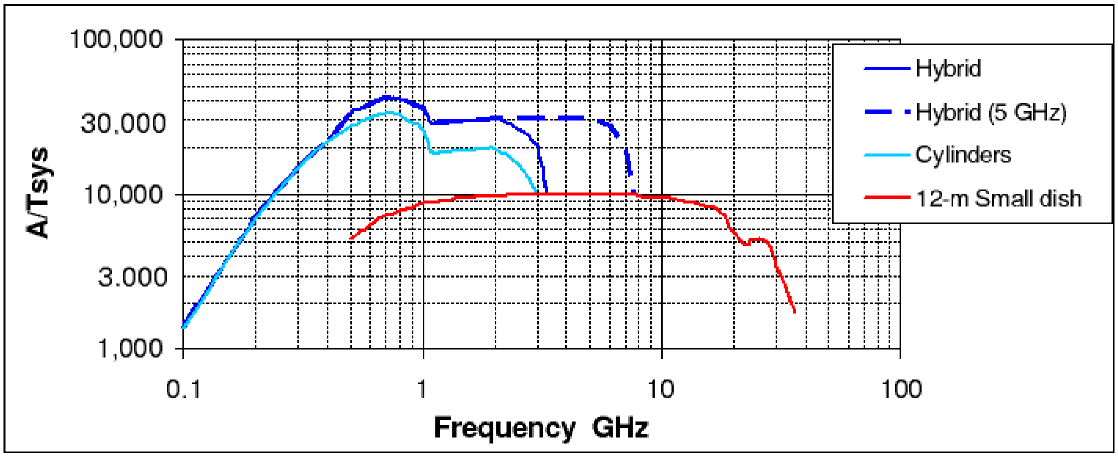

Figure 3: Sensitivity of CYL+SD.

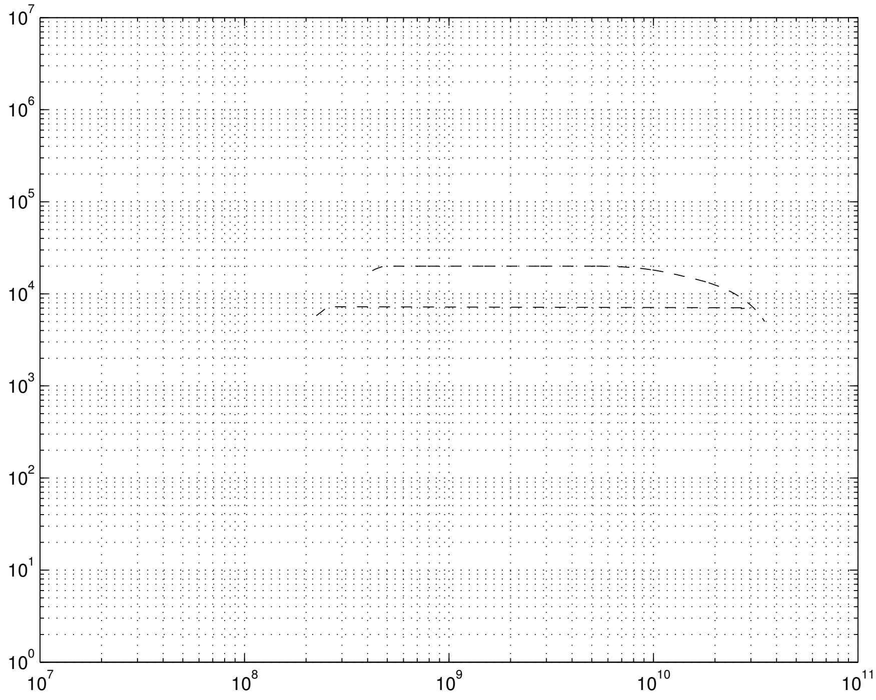

Figure 4: Sensitivity of AA+SD hybrid.

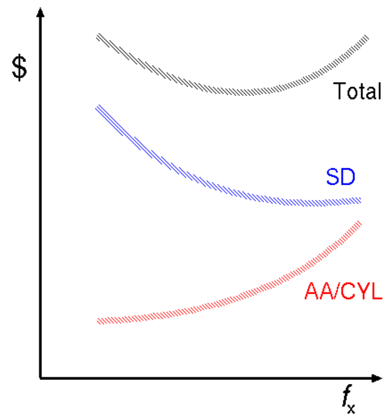

Figure 5: Sketch of component cost as a function of cross-over frequency.

5.7 Are hybrids affordable?

- ▷ $1.2–1.4 billion
- ▷ Hybrids will have 2×NRE
- ▷ Added operational expenses
- ▷ Jaap Bregman has an interesting optimization procedure that should be looked at carefully. He has done a high-level economic analysis that estimates that money should be spent in these ratios:

collecting area	:	receiver	:	correlator	observation type
6	:	2	:	1	single field
3	:	2	:	1	survey

5.8 Should There be Any Frequency Overlap?

- ▷ Can be argued that one way to optimize components in hybrid (performance/cost) is to minimize frequency overlap. See Figure 5. This shows that as SD is made to work at lower frequencies the cost rises, and as AA or CYL is made to operate at higher frequencies, their cost also rises. An optimum can be found with no overlap (minimum of upper curve). Starting from that point, if a frequency overlap is allowed the total cost will rise since for either component this requires an increase of cost.
- ▷ Also concerns that wide-field imaging will be very difficult with different concepts because of dissimilar beams (may not be a problem for non-imaging applications)
- ▷ Counter-argument is that overlap is a way to boost sensitivity: if we have the concentrator area, use it as much as we can.
- ▷ Hybrid demonstrator probably not needed if there will be no frequency overlap.

5.9 Strawman Hybrid

- ▷ Have used AA+SD as a strawman
- ▷ Should not be viewed as an expression of preference
- ▷ Strawman is to be viewed as a target
- ▷ Should be seen as something to try to surpass

5.10 Discussion of Risk

- ▷ Presently highly subjective
- ▷ Probably relative risk, not absolute
- ▷ US Decadal Review forces 2008 concept selection date, making it di□cult to reduce risk because of time constraints
- ▷ Take the point of view of a reviewer in 2008, what is the risk of missing cost and/or performance targets?

5.10.1 Risk of Possible Components

Concept	Freq	Cost Risk	Performance Risk
LAR	$<$ 22 GHz	High	High[2,3]
KARST	$<$ 2 GHz	High	Medium–High[2]
CYL	$<$ 2 GHz	Medium	Medium[2]
AA	$<$ 2 GHz	High	Medium
SD	$>$ 1 GHz	Low[1]	Low
PPD	$<$ 5 GHz	Low[1]	Medium[2]

[1] Technology risk is low but computing cost uncertainty may increase to medium

[2] Low-frequency FPA unproven

[3] Cooled FPA yet to be developed

5.11 Where do we go from here?

- ▷ Cost calculator will help in costing hybrids and with optimization
- ▷ AA+SD deserves further study
- ▷ Suggested that SD+LAR be investigated
- ▷ Indian dish design + FPA interesting concept for wide-field low-frequency observing
- ▷ "Year in the life of" studies to better understand how the hybrids will be used?
- ▷ Begin a more formal risk analysis

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A Request for Hybrid Concept Documents

Additional Material For Hybrid Concept Documents
P. J. Hall, 8 Mar 2004.

To allow the next-stage IEMT evaluation, and to streamline entry of parameters into the emerging cost/performance calculator, the following information should be provided. (Some of the numerical information is redundant in final calculations but is requested to aid reviewers of written documents). Note that "component" means a constituent array of the hybrid SKA.

1. The total frequency range covered by the hybrid, with the design range for each component specified explicitly.
2. A sketch of the arrangement of component collecting areas within stations and central arrays.
3. Any updated costing information on the hybrid concept.
4. $A_{effective}/T_{sys}$ for each component of the hybrid at centre frequencies and band edges (also specify explicitly component and total SKA sensitivities at 1.4 GHz).
5. The type of antenna elements used in each component, and the dimensions of any concentrators.
6. The number of independent, widely placeable, fields-of-view provided by each component of the hybrid array.
7. Parameters for each component, including: equivalent number of stations, station FOV, number of antennas per station, physical area per station, effective area per station, station dimensions and antenna shadowing limits (if applicable).
8. A broad indication of the array configuration, the total bandwidth transmitted in representative distance regimes, and the total entity (station or antenna) FOV at chosen spot frequencies (including 1.4 GHz). An example table for one component might be:

SKA Diameter Regime	% of Area	Bandwidth (GHz)	Total FOV@1.4GHz (square degree)
0 - 5 km	50	5	1
5 - 150 km	25	5	1
150 - 3000 km	25	0.5	0.1

9. The nature of the feeds employed (single or phased array), phased array tile dimensions or the level of RF beamforming employed (if applicable), and the domain scale in any aperture array component (see http://www.skatelescope.org/documents/SKA_EUR_CONCEPT_IntegratedApertureArrayPanels_17072002.pdf , page 15 for terminology).
10. The physical temperature of receivers used in each component (15K, 80K and 300K might be standard choices).
11. The quantization accuracy at the receiver output (1/2/4/8 bits might be standard choices).
12. The accuracy at the correlator input (1/2/4/8 bit choices).
13. The scale of the proposed correlator and the field-of-view able to be processed, given observing bandwidths consistent with SKA science goals.
14. Comments on the amount of station and central infrastructure (civil, signal processing and distribution, computing) likely to be shareable between components, and an estimate of the amount of new infrastructure needed to support the hybrid SKA.
15. Comments on non-imaging or new operational modes (e.g. simultaneous observing at widely separated frequency bands) supported by the hybrid SKA.