SKA Hybrid Review:
Three Aperture Arrays + Small Dishes

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Review questions and answers

Please summarize the hybrid configuration proposed.

The proposal has four components

- 2500 12-m dishes operating from 0.5 to 25 GHz (36 GHz reduced sensitivity) with and A/Tsy 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.

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

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

Table 2 from hybrid proposal: SKA AA+SD Hybrid Sensitivity

			LFA		MFA		HFA		SD	Total
Freq (GHz)	T_{sky} (K)	T_{rec} (K)	*Aeff/Tsys* ($m^2 K^{-1}$)	T_{rec} (K)	*Aeff/Tsys* ($m^2 K^{-1}$)	T_{rec} (K)	*Aeff/Tsys* ($m^2 K^{-1}$)	T_{rec} (K)	*Aeff/Tsys* ($m^2 K^{-1}$)	*Aeff/Tsys* ($m^2 K^{-1}$)
0.1	990	200	1010							1010
0.17	255	40	4070							4070
0.22	132	50	6600	30	4600					6600
0.53	18			30	15600	30	12500	22	5000	33100
0.65	12			30	17800	30	14300	22	5800	37900
0.8	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

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 show 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^2K^{-1} rather than the 28,200 m^2K^{-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^2K^{-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. The field of view is reduced from 200 sq degrees to 90 sq degrees. The survey speed is proportional to $(\text{Aeff/Tsys})^2 \times$ 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.

What is the cost of the hybrid?

The cost of the hybrid is given in the table below. 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.

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

The 12-m small dishes are a symmetrically-fed Gregorian reflector design which is cheaper to construct than the previous offset fed 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 [USSKA consortium 2002]

The low-frequency aperture tile arrays appear are based on the high-frequency component of LOFAR and the estimated cost is $60 per feed element, 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 x 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 is similar but the feed element separation is 27cm.

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 element for beamforming is 400 MS/S x 1700 beams x 16875 inputs x 8 operations per input x 200 stations divided by 108e6 feed elements is equal to ~170 Gigaoperations/sec. With the high-frequency array costing $270M the cost per feed element is $2.5. This cost must cover

- a feed 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 element, control wiring and connectors for the phase shifters, the 1.7 x 1.7m water and electromagnetically tight box and a ~100 Gigabit fibre connection per box. The reviewers feel that a detailed justification of $2.5 cost per feed element is needed, especially in the light of the $60 cost per feed element estimated for the low-frequency array.

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 no increase in survey speed as the total number of beams is reduced.

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.

Further Discussion

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 ~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.

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?

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 element 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 element. The reviewers feel that the low cost of the mid and high-frequency aperture tile array needs justification.