A Cylinder plus 12-m Dish Hybrid

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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, eg a simple dipole at 30 MHz has an area of about 10 m^2
- 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 (m^2). Cylinder, lens and dish diameter 10 m.

	Dipole	Cylinder	Lens or Dish
0.1 GHz	1	30	100
0.3 GHz	0.1	10	100
1 GHz	0.01	3	100
3 GHz	0.001	1	100
10 GHz	0.0001	0.3	100

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 m^2 compared to 700,000 m^2 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 Tsys of 18K and assuming 70% aperture efficiency, the number of antennas needed for A/Tsys of 20,000 is 4551. Total cost for these antennas is US$860M and the effective area is 360,000 m^2.

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.

	Cost at 5 GHz (US$/m^2)	Cost at 0.5 GHz (US$/m^2)
Reflector	228	105
Linefeed hardware	13	6
LNA and RF beamformer	38	4
Downconversion and A/D	24	3
Line feed to beamformer	32	5
Total cost per m^2	335	123

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.

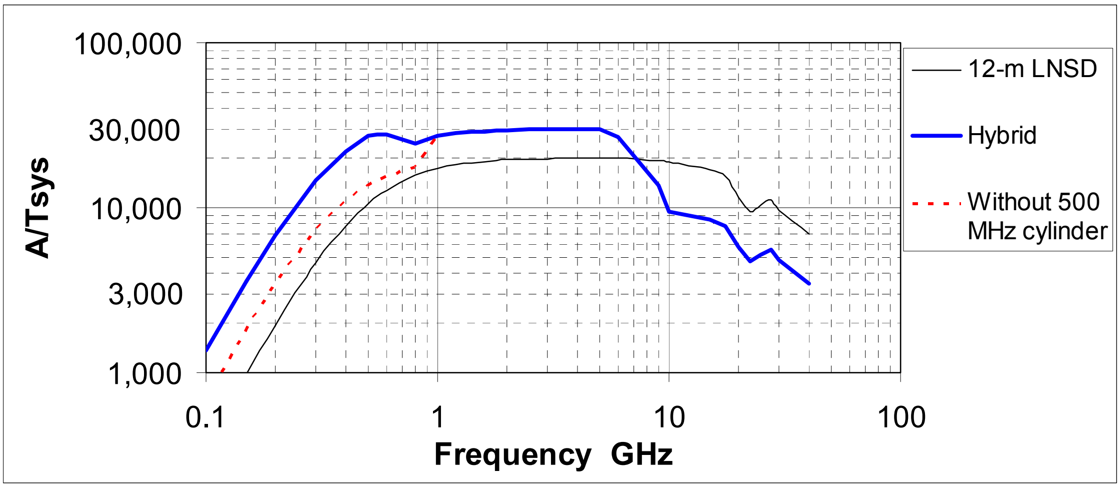

Figure 1 Sensitivity for dual cylinder plus 12-m hybrid

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 m^2/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 m^2/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.

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