SKA station cost comparison

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Introduction

Current SKA white papers and updates present cost in a variety of ways which makes direct comparisons difficult. To a first approximation the major difference between the proposals is the cost of the antenna stations. These costs have been extracted from the white papers and updates and an attempt has been made to bring them all to a common metric: cost per square metre of physical collecting area.

Together with the aperture efficiency and Tsys these data allow the cost of antenna stations for a full sensitivity SKA to be estimated. While such a metric cannot include the unique strength and weakness of each concept, it does allow a comparison on economic grounds. Furthermore, with hybrid SKA solutions now a on the horizon the frequency dependent aspect of the analysis should provide useful discussion material relating to the optimum hybrid form.

In addition, at a given maximum frequency the A/Tsys for a fixed cost is estimated as a function of frequency. This allows the relative performance of the different concepts to be compared over the full range of operating frequencies.

Background

To allow the various concepts to be compared it is assumed that the cost of moving structure varies as the cube root of frequency. This approximation takes into account the higher precision and rigidity needed at higher frequencies and is derived from data presented in Appendix 1 of the cylindrical reflector white paper [4]. In the white paper parabolic dish costs ranging from the 160MHz Culgoora Radioheliogragh through to the 100 GHz GBT where compared. Using the cube root scaling brought all parabolic dish costs to within ±15% range. As a comparison a square root scaling in frequency would make the relative cost of the GBT half that of Parkes and a third of the Radioheliograph.

Another assumption made is that the LNA noise figure remains constant at the 1.4GHz value. In practice it will probably double or triple at 30GHz, but there is currently insufficient data to model this variation for all concepts. Other assumptions are presented in the text below. Note, all costs are in 2010 US dollars ($), all areas are physical areas and frequency is in GHz. Aperture efficiency is used converted physical area to effective aperture.

In addition to the uncertainty in the above assumption there is the uncertainty inherent in the estimates given in the white papers and in their interpretation. In addition, it does not include some smaller costs that are implementation dependent. These included correlators where large filled aperture antenna are cheaper and signal transport cost where filled aperture antenna are cheaper. Thus the following discussion should not be considered definitive. It is, however, very useful in highlighting general trends.

LAR

Estimated costs for LAR are from "Draft White Paper the Large Adaptive Reflector Concept" by The LAR Group, page 25 [1]. The reflector for a 22GHz LAR is \$8.7M. The aerostat, tethers, focus support and fibre transmission to the ground cost \$8.3M and it assumed this is independent of frequency. LAR needs a number of separate feeds systems each covering approximately a 3:1 frequency range. Three of these cost \$15M and the maximum frequency is 22GHz. At a maximum frequency of 7.3 GHz the feed system covering the 7-22 GHz band is not needed and the cost reduces to \$10M. Reducing the maximum frequency to 2.44GHz reduces the cost to \$5M. As a function of maximum frequency in GHz (fmax) this cost variation can be modelled as

$$\$4.55M * \max[0,\ln(fmax/2.44)] + \$5M.$$

The log of frequency is appropriate here because it models a fixed cost being added for each octave of frequency coverage, the minimum cost is \$5M indicating at least one feed system is needed. In practice the cost will be more granular but here a smooth variation is assumed.

The physical area of the reflector is 31415m^2 and this gives a cost per square metre at 1GHz of

Reflector	\$100/m^2 . fmax$^{0.33}$
Feeds	\$145/m^2 . [1.1+ max(0,ln(fmax/2.44)]
Aerostats, focus & transmission	\$264/m^2

KARST

Kilometer-square Area Radio Synthesis Telescope KARST, by Nan et al [2] quote a \$850M price for a SKA with an area of one square kilometre. Little detail is provided on the breakdown of costs. Here it is assumed that that half the cost is in the towers, cables, focus cabin and feeds. It is assumed that this cost is fixed. The 5GHz reflector accounts for the other half of the \$850M.

Reflector	\$249/m^2 . fmax$^{0.33}$
Towers, cables, focus cabin and feeds	\$425/m^2

Luneburg Lens

The data for the Luneburg lens proposal is found in "Eyes on the Sky: A Refracting Concentrator Approach to the SKA" Editor Peter Hall [3]. For a total physical collecting area of 2 square kilometres the cost was \$617M of which \$92M was for the single feed arm and the rest for the lenses. As the lens does not move it is assumed that its cost is independent of frequency. The feed arms were designed to operate up to 10GHz[1] and their cost is frequency dependent. In the current design there are two feeds per feed arm and each feed costs \$310. As their cost is small it will be assumed their cost is constant with frequency. For station electronics and DSP a figure of \$5231 per antenna is quoted for a system with a processing bandwidth of 7.5GHz. Thus each GHz of processing bandwidth costs \$697 per feed arm with a high and low band feed. This is then multiplied by the processing bandwidth specified for the SKA: 0.5 +fmax/5. With each lens having a diameter of 7m and an area of 38.5 m^2 the costs are

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[1] The original concept went to 5GHz however the feed arm design was specified to operate at 10GHz [15]

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Lens	\$264/m^2
Feed arms	\$21/m^2. fmax$^{0.33}$
Feeds per arm	\$8/m^2
Antenna electronics and DSP	\$18/m^2 . (0.5 + fmax/5)

Cylindrical Reflector

The original data for the cylindrical reflector proposal is found in “Cylindrical Reflector SKA” J.D. Bunton, C.A. Jackson and E.M. Sadler [4]. The costs were significantly updated in the 2003 submission “Panorama of the Universe: a Cylindrical Reflector SKA”, editor J.D. Bunton [11]. The reflector cost is unchanged at \$10.9k for 100m^2 of 11.3m reflector. Scaling this up to the proposed 15m reflector gives a cost of \$133/m^2 at a 1GHz operating frequency. In the update the cost of the 1GHz linefeed hardware is given as \$115/m, the 1GHz linefeed LNA and RF beamformer as \$115/m and the linefeed electronics as \$162/m. At 1 GHz the bandwidth of the linefeed electronics is 0.7 GHz making the linefeed electronics cost \$231/m per GHz of output bandwidth. The optical link to the beamformer is estimated to cost \$200/m per GHz of output bandwidth. Each antenna has an area of 1650m^2 and has a 100m long linefeed. Thus the cost metre must be divided by 16.5 to give the cost per square metre. The output bandwidth is 0.5 + fmax/5 GHz. The cost of the reflector and line feed hardware is assumed to proportional to fmax$^{0.333}$, the cost of the LNA and beamformer is proportional to fmax and the electronics and optical link cost are proportional to output bandwidth. Cost of the station beamformer is not given in the update but using data from the original submission it was \$480/m/GHz. With a five time reduction for the use of ASICs this gives a cost of \$5.8/m^2/GHz. These data give the cost estimates shown below

Reflector	\$133/m^2 . fmax$^{0.33}$
Linefeed hardware	\$7/m^2. fmax$^{0.33}$
Linefeed LNA and RF beamformer	\$7/m^2. fmax
Linefeed electronics	\$14/m^2. (0.5 + fmax/5)
Linefeed optical link	\$12.1/m^2. (0.5 + fmax/5)
Station beamformer	\$5.8/m^2. (0.5 + fmax/5)

12m LNSD Reflectors

The data for the US 12m reflector proposal is found in “The Square Kilometer Array Preliminary Strawman Design Large N - Small D” prepared by the USSKA Consortium [5]. The cost of a 32GHz 12m reflector, area 113m^2, is \$150k and the cryogenically cooled receivers are \$39k each. It is assumed that the cost of cryogenic cooling will be independent of frequency. The \$39k does include an LO and IF system but not include digitising the signal, signal transport and station beamforming. As component is similar design to the Luneburg lens its data will used, which is scaled down by a factor of four due to the difference in area. This gives the following approximation to the cost per square metre

Reflector	\$418/m^2 . fmax$^{0.33}$
Cryogenics and feed	\$345/m^2
Antenna electronics	\$4.5/m^2 . (0.5 + fmax/5)

12m Preloaded Reflectors

The data for the Indian 12m reflector proposal is found in "Preloaded Parabolic Dish Antennas for the Square Kilometer Array" Govind Swarup [6]. The cost of the 12m reflector is \$60k and it performance is quoted up to 10GHz. However, the performance is seriously degraded at this frequency. Good performance is maintained up to ~5GHz. The receivers use pulse tube cooling and are estimated to cost \$7k. The 12m LNSD cost will be used for antenna station electronics. This gives the following approximation to the cost per square metre

Reflector	\$310/m^2 . fmax$^{0.33}$
Pulse tube cooled feeds	\$62/m^2
Antenna electronics	\$4.5/m^2 . (0.5 + fmax/5)

Aperture Array

The data for aperture arrays is found in "The European Concept for the SKA: Aperture tile arrays" [7]. There are two major cost components. One is associated with the feed element, LNA, beamforming, signal conditioning and A/D conversion. This was costed at 448.4M Euro for 79.3M dual polarisation feed elements, which gives a cost per element of 5.65 Euro each. Each square metre of collecting area, assuming a $\lambda/2$ spacing, needs 44. fmax^2 feed elements. The second cost is associated with the tile including mechanical, LO, signal and beamforming electronics, interconnections and manufacture. This was costed at 316M Euro for 3.5 square kilometres of tiles, giving a cost of 90 Euro/m^2. Using a conversion factor of 1.15 US dollars to the Euro gives the following cost estimates

Feed elements and associated costs	\$285/m^2 . fmax^2
Tile related costs	\$104/m^2

The above costs are for a single aperture array that covers a single 3:1 frequency range. For a true comparison additional arrays are needed as the maximum frequency increases. In the white paper design these implemented with 2:1 frequency spacing. The frequency bands are 0.12-0.3, 0.27-0.67 and 0.6->1.5GHz. This doubles the tile related costs at ~0.5GHz and triples the cost at ~1.1GHz. This cost increase can be approximated by using the multiplicative factor [1 +max(0, ln(fmax/0.16))] which gives a tripling of tile related cost at 1.1GHz. Note the same functional form as that for the LAR focal plane array is used. In both a fixed cost is added for each octave of added frequency range. For the feed elements the cost in different arrays scales by a factor of ~4 four for each successive array. As the feed cost does not dominate at low frequencies a high frequency approximation is appropriate. This adds ~25% to the cost. Thus the cost estimates for a multi-array system is

Feed elements and associated costs	\$356/m^2 . fmax^2
Tile related costs	\$104. [1 +max(0, ln(fmax/0.16))] /m^2

System Temperature and Aperture Efficiency

The above data allows the cost of the physical aperture to be calculated. To convert this to effective aperture it must be multiplied by the aperture efficiency. Dividing by the system temperature Tsys allows the cost for a given A/Tsys to be calculated. The values for these parameters are presented for the various concepts in the table below.

	Tsys (K)	Reference	Aperture efficiency	Reference
LAR	25	[1] Section 1	0.6 . 0.8#	[1]Section 7.1
KARST	25	[2]Section 6	0.65	[2]Table 5.1
12m LNSD	18	[5] Table B.1	0.60-0.75 (0.7 used)	[12]p.31
12m Preloaded	30	[6] Table 2	0.64	[6]Table 2
Luneburg Lens	29 −6 +15 + 6K/GHz	[3] Table 8.1 [10] p.3 + LNA [3] Fig 8.1*	0.65	[3]Table 5.3
Cylindrical Reflector	35	[11] 1.3	0.69 . 0.9#	[4] K.1
Aperture Array	35	[7] 4.3.9	0.8	[7] 4.3.6

References [1] to [7] are from the original 2002 white paper for the concept and references [8] to [14] from 2003 updates
Average scan loss for cylinder estimated at 0.9 and 0.8 for LAR and Aperture Array.
* Dielectric loss in lens

For the Luneburg lens the situation is a little complicate. In the original white paper Tsys less LNA and lens loss is 29K. In the update this is reduced by 6K to 23K. The lens loss is approximately 6K/GHz although reduced values are anticipated in the update and the update also specifies 15K for the LNA.

Comparison at Maximum Frequency

In this section the cost of the antenna station to achieve an A/Tsys of 20,000 is calculated. Note that a cost at any one frequency does not necessarily indicate the relative A/Tsys at frequencies less than the maximum frequency. This will be presented for a limited number of cases in the next section. The results below are derived from the above data, after galactic noise and water vapour emission is added to Tsys. Water vapour is assumed to add 20K to the noise at 22.5GHz and the galactic noise is 16K at 500MHz and scales with frequency with an $f^{-2.55}$ law.

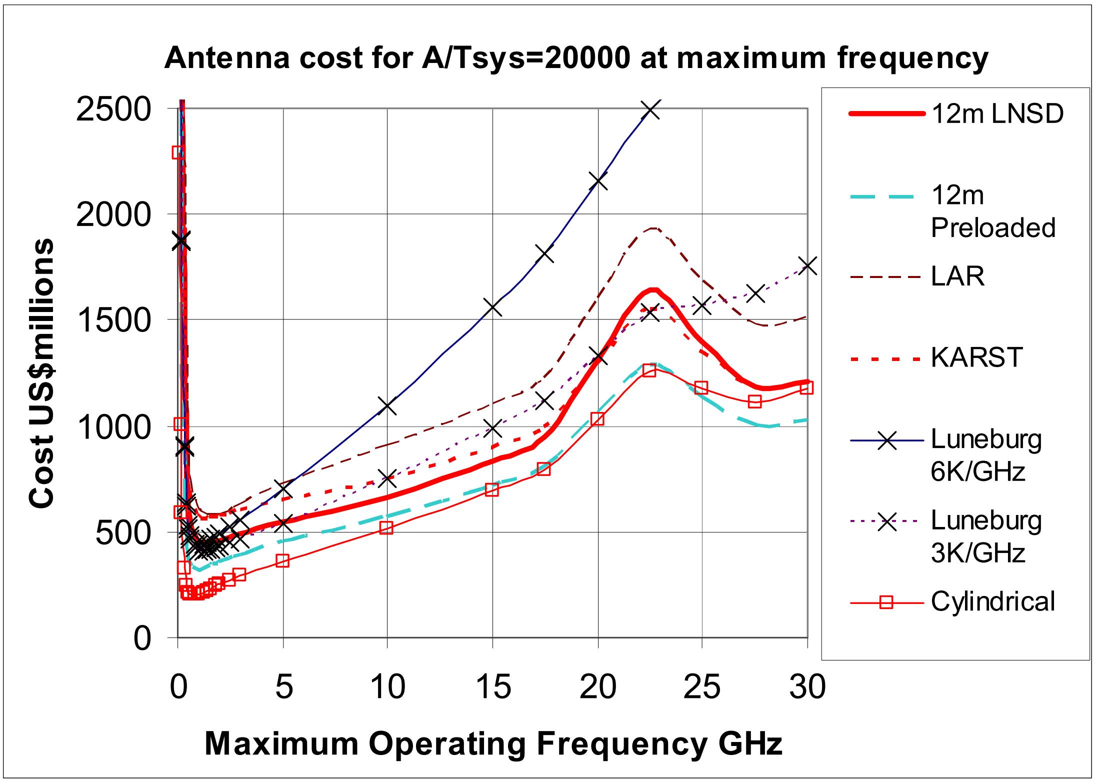

Figure 1 High Frequency comparison, total SKA antenna station cost for given performance at the maximum frequency

Above is shown the cost of all concentrator based concepts up to a maximum frequency of 30GHz. The two 12m parabolic dish proposals have track each other over the frequency range 0.5 to 15 GHz. At 22 GHz the higher noise preloaded proposal is less affect by water vapour noise. The 12m preloaded proposal has been extrapolated to 30GHz. However, as a mesh surface is used, it is unlikely that it could reach this frequency. Instead the 12m preloaded proposal could be seen as a low frequency implementation of 12m parabolic reflectors. Compared with the Luneburg lens the 12m LNSD dish is more sensitive to noise added due to water vapour, the cost increase is 110% at 22.5GHz as compared to a 10-20% increase for the lens. As the absolute noise is low the 12m LNSD antenna will be more adversely affected by all noise external to the antenna, such as water vapour, sky noise away from zenith and galactic noise.

The two large diameter designs, LAR and KARST, have similar costs at lower frequencies. Both have large fixed cost for feed support. In the KARST design this leads to a slower increase in cost with increasing frequency when compared to 12m reflectors. However to achieve a field of view comparable to other concepts more needs to spent of feeds and electronics. Thus final cost should be higher. In the case of LAR feed cost are fully factored in. The large f/D ratio of the reflector requires each focal plane array to be an order of magnitude larger than that needed for a short f/D reflector. Additional focal plane arrays are needed as frequency increases, which causes the cost to increase more steeply than KARST or 12m reflectors. In both cases it appears that the large diameter designs do not have a cost advantage compared to the 12m proposals, particular at low frequencies where the large fixed costs limit possible cost reductions.

The two large/multi field-of-view high frequency concepts are the Luneburg lens and the Cylindrical Reflector. In both these concepts the cost increases more rapidly with frequency than the 12m reflector concepts. For the Luneburg lens the cost increase is due to lens loss. In the white paper and the update the loss is equivalent to 6K/GHz. Thus at 10GHz the total collecting area must be double the 1.4GHz area to compensate. Significantly, this extra area will translate into improved low frequency performance. The update also indicates that it may be possible to reduce the lens loss. As shown halving the lens loss to 3K/GHz significantly reduces the cost of a Luneburg lens implementation at high frequencies, making it more competitive. In the case of the cylindrical reflector the added cost is due to the line feed. At low frequencies the linefeed cost is small but at 20-30GHz it becomes comparable to that of the reflector. Even with this added cost the cylindrical reflector is still competitive at high frequencies. At lower frequencies the cheapness of the reflector makes it cheaper than the other concepts.

At low frequencies (<500MHz) the system noise is dominated by galactic noise and the cost to achieve a given A/Tsys increases rapidly. This is shown below in Figure 2. The only way to achieve the required A/Tsys is to have a large collecting area. The lowest noise concept, 12m LNSD, has the smallest total area and hence a high relative cost for low frequency implementations. For the other small diameter concentrator designs higher Tsys leads to larger collecting areas and better performance at low frequencies. Of these the cylindrical reflector has a significant cost advantage at low frequencies due to the low reflector cost. The large area concentrator concepts LAR and KARST are both expensive in a low frequency implementation because of the high fixed cost.

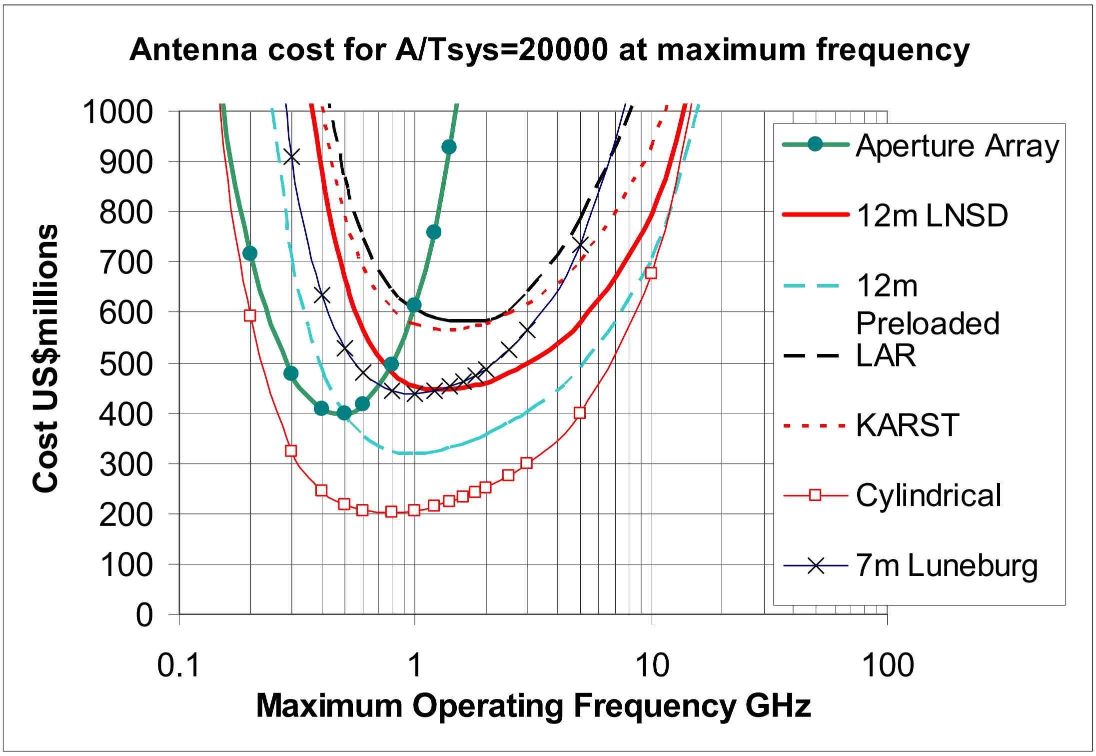

Figure 2 Low frequency comparison, total SKA antenna station cost for given performance at the maximum frequency

At low frequencies aperture arrays are also a viable solution. There are two main cost components: the tile and the feed elements. At low frequencies the cost is dominated by the tile which must provide a water and radiation tight enclosure for the electronics. To a first approximation this is fixed cost per square metre and, in a sense, is directly comparable to the surface of a reflector, as both must have an area equal to the total collecting area. Thus at low frequencies the aperture array cost will track that of a reflector. However, there appears to be scope to further optimise the costs at low frequencies, possibly by reducing the electronics enclosure size or by implementing a hybrid concept that falls somewhere between the aperture array concept and the sparse arrays of LOFAR. At high frequencies the cost of feed elements dominates. This cost increases in a quadratic manner and is responsible for the increasing cost above 500MHz.

The above comparison is not fair to aperture arrays because they can simultaneous support four separate and independently targeted observations. This gives the concept four times as much observing time, which is equal to a two fold increase in sensitivity or half the cost for the same performance. The Luneburg lens can also provide simultaneous independently targeted observations. However, this comes at the cost of extra feed arms, feeds and electronics.

For the cylindrical reflector the situation is not so clear cut. It has an imaging field of view FOV that is 4 to 30 times that of a 12m parabolic reflector. When surveying full use can be made of the imaging FOV, giving the concept an approximately ten times speed advantage or a three times increase in sensitivity. With targeted observing the speed increase is less as only one fully independent observation can take place at any one time. Thus the speed increase will be less than the 4 to 30 achieved when surveying. Estimation of the true speed and sensitivity improvement will need simulations done with a realistic observing program. In the interim a reasonable guess in needed. First, note the area of sky in which beams can be formed, the antenna FOV, is 24 to 100 times that of a 12m parabolic reflector. It is this that limits the usefulness of the cylindrical reflector in targeted observing. The relationship between antenna FOV and speed is unknown but, for arguments sake, if the speed increased as the cube root of FOV then the cylindrical reflector would be 2.9 to 4.6 times faster. Assuming an average speed increase of four for a mix of survey, targeted and opportunistic observing then the cylindrical reflector's sensitivity is improved by a factor of two. This is shown below. For comparison purposes the 12m preloaded concept is also plotted as it is the cheapest of the single FOV concepts.

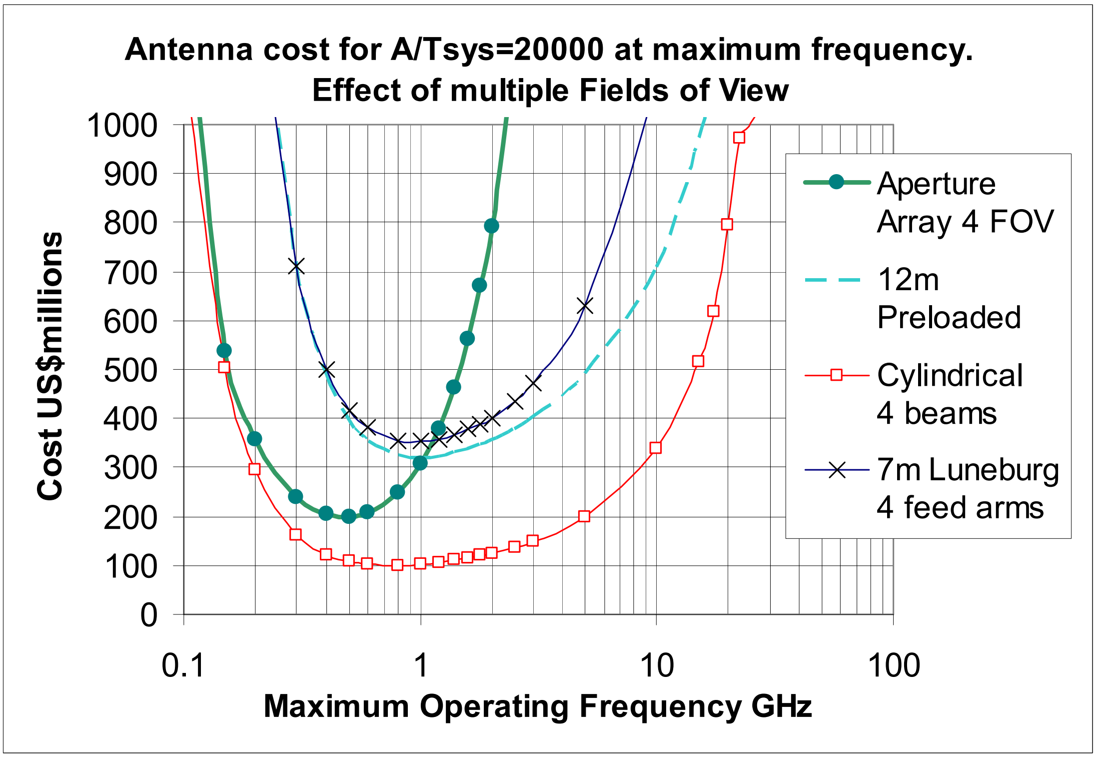

Figure 3 Cost reduction due to speed improvement with multiple FOVs

The aperture array, Luneburg lens and cylindrical reflector all have a four times speed increase. However the reduction in Luneburg lens cost is less because adding beams requires additional hardware in the form of feed arms, feeds and electronics.

Comparison over Operating Range

The above comparisons are useful in estimating how the cost varies as a function of maximum frequency but for a complete comparison it is necessary to compare designs over their operating range. To do this the A/Tsys per million dollars is calculated. The plots shown above give the cost at a given maximum frequency (fmax) for A/Tsys =20,000. This cost in millions of dollars will be signified by the parameter $C_at_fmax. For each design Tsys is a function of frequency. Thus the A/Tsys per million dollars as a function of operating frequency (f) can be calculated using the formula:

A/Tsys per $M at frequency f = (20,000/$C_at_fmax) * (Tsys(fmax)/Tsys(f))

These estimates for systems with maximum operating frequencies of 5, 10 and 22.5 GHz are plotted on the following page. Except for the Luneburg lens all the designs have a similar variation with frequency, with A/Tsys per $M (performance per dollar) being roughly constant from 1 to 15GHz. Importantly variations in this metric reflect variation in Tsys with frequency. A doubling of Tsys in any one band halves the performance per dollar in that band but leaves the results for all other frequencies unchanged. This is seen as a drop in A/Tsys per $M due to galactic and water vapour noise.

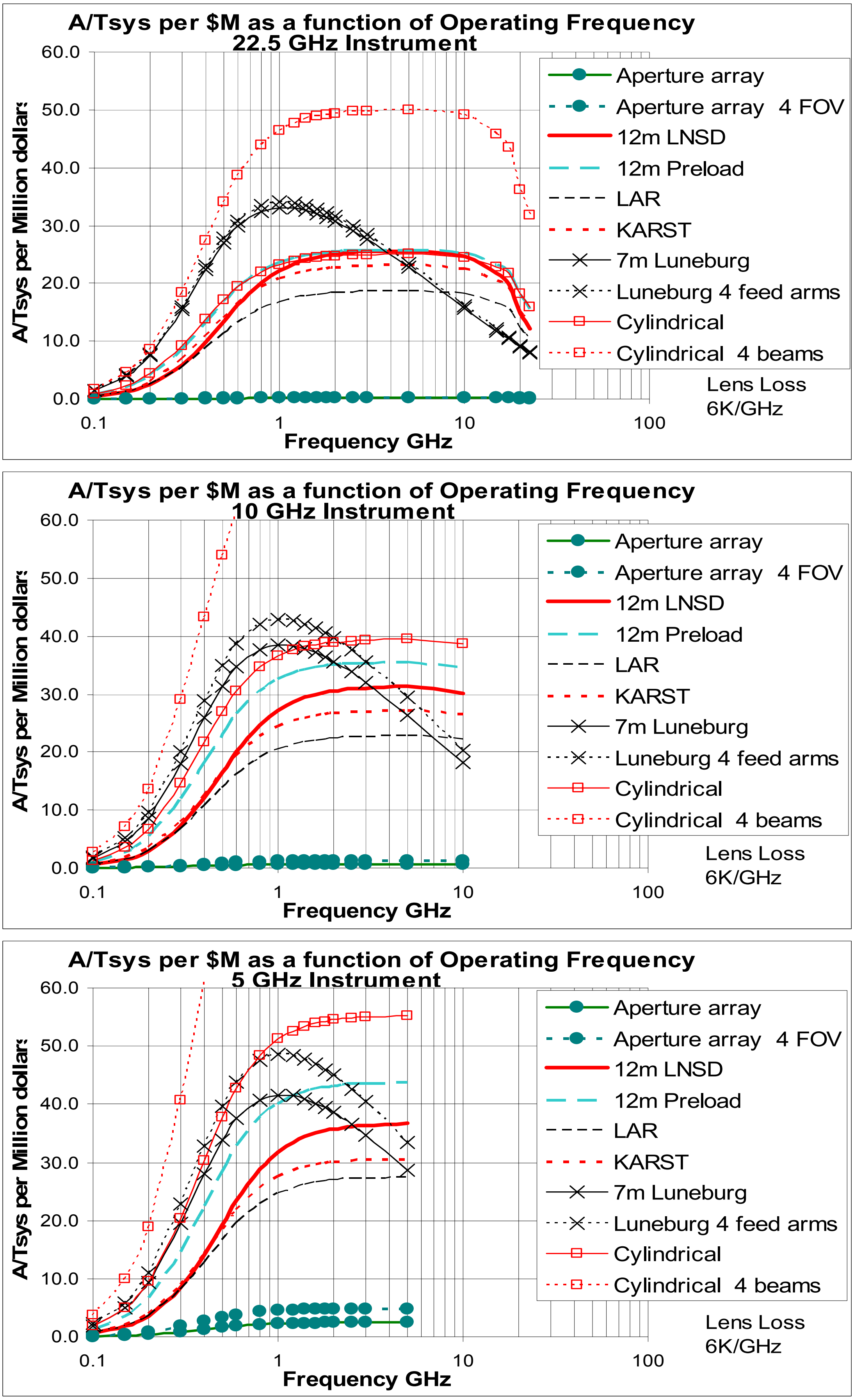

Figure 4 Variation in A/Tsys as a function of frequency for 5, 10 and 22.5GHz designs

At 22.5GHz the performance per dollar is very similar for most designs. The greatest variation is at low frequencies where the small collecting area of the 12m LNSD reflectors degrades its performance. In contrast, the Luneburg lens has very good performance per dollar at low frequencies. This degrades with increasing frequency due to the increasing lens loss, with the crossover point being ~5GHz. The effect of multiple FOVs is also shown. For the Luneburg lens increasing the number feed arms from one to four almost doubles the cost of a 22.5GHz instrument leading to a small improvement in performance per dollar. The decision to use multiple feed arms is more a tradeoff between absolute sensitivity in one beam against flexibility and higher speed. Note there is no loss of survey sensitivity. Also some observations do not need a sensitivity of 20,000 m^2/K. These also benefit from a multi feed arm implementation. This improvement in the relative worth of the Luneburg lens has not yet been factored in.

For the cylindrical reflector the large FOV is part of the design and if this large FOV and its multiple beams gives a fourfold speed increase then performance per dollar doubles as show. Interestingly if the Luneburg lens had no lens loss then it performance per dollar would be very similar to the cylindrical reflector with four effective beams. Finally the aperture array has an estimated cost of $250 billion for a 22.5 GHz SKA. Thus, as is shown, the performance available per million dollars is very small.

The middle figure shows the performance per million dollars for designs with a 10GHz maximum frequency. As they don't have large fixed costs small diameter reflector designs have improved relative to the large diameter design and Luneburg lens. In the case of the Luneburg lens the lens itself is a fixed cost. However if multiple feed arms are added to the Luneburg lens their relative cost is less and there is an improvement in performance. The design to benefit most is the cylindrical reflector due to the large reduction in linefeed costs. These general trends continue if the maximum frequency is reduced to 5GHz. At this frequency assuming a fourfold speed increase due to the large antenna FOV and multiple beams the cylindrical reflector has an A/Tsys per $M equal to ~100 over the frequency range 1 to 5GHz. In all cases shown aperture arrays have high cost. The maximum frequency needs to decrease to ~1GHz before they becomes competitive.

LNA at high frequencies

At frequencies of 10GHz or more it is expected that noise contributed by the receiver will increase due to noisier LNAs and increased coupling, feed and window losses. This variation is not well covered in the white paper and updates so for purposes of a comparison it is assumed that this is modelled by linearly increasing LNA temperature for frequency above 5GHz, with the temperature doubling at 22.5GHz. Estimated LNA noise temperatures at 1.4GHz are:

12m LNSD	5K
LAR, KARST and 12m preloaded	8K
Luneburg, Cylinder and Aperture Array	15K

Using this approximation and frequency scaling gives the A/Tsys per million dollars shown below

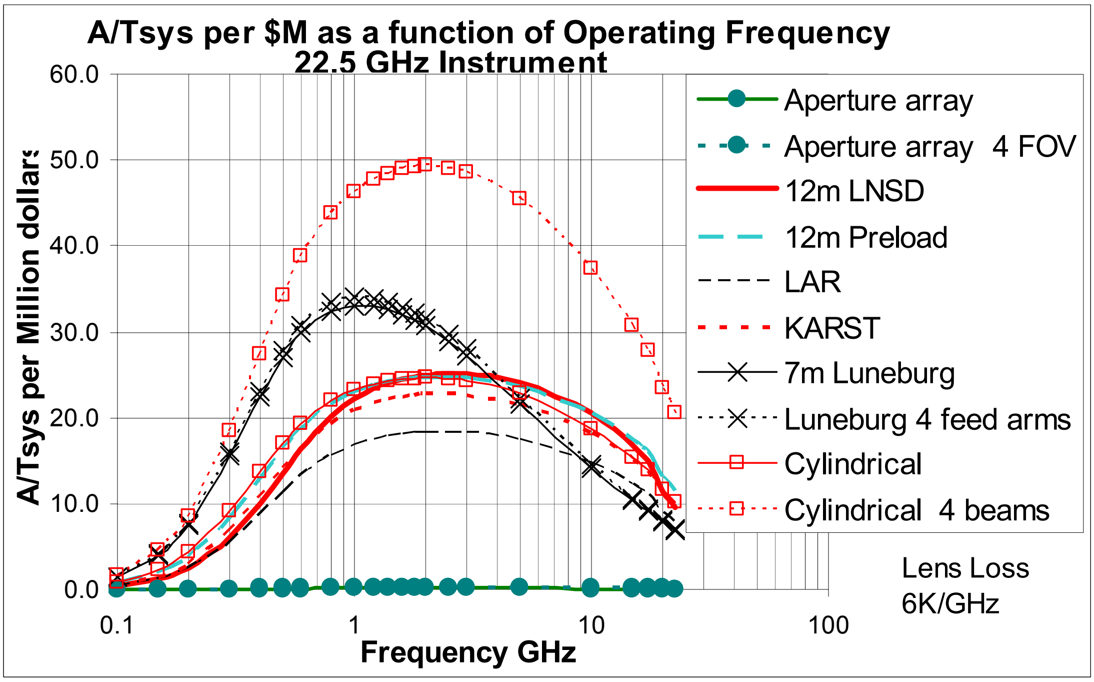

Figure 5 A/Tsys per million dollars with LNA noise temperature doubling at 22.5GHz

It is seen that there is no change at low frequencies. This is to be expected as there is no change in Tsys. At high frequencies the Luneburg lens is affected very little because its system temperature is already high. For the other concepts the loss of A/Tsys is ranges from 20% for the 12m LNSD reflector to 35% for the cylindrical reflector.

Conclusion

Estimated costings, aperture efficiencies and system temperature have been obtained from the white papers and updates for all seven SKA concepts. These have been used to calculate the cost to achieve the SKA target of A/Tsys equal to 20,000 m^2/K. Also derived is the A/Tsys per million dollars as a function of operating frequency. These results allow some useful comparisons to be made between the concepts. However, the results are by no means definitive. The costs are only estimates and gross assumptions have been made as to variations of cost with frequency. Further many factor have not been properly accounted for, such as degraded performance of small diameter designs at frequencies approaching 100MHz.

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All SKA memos and white papers (references 1 to 14) are found at
http://www.skatelescope.org/ska_documents.shtml

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