SKA Antenna Selection – Economics and the Field of View

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Introduction

In designing a radiotelescope there is always a conflict between performance and economics. This poster shows that feed numbers are a major constraint in limiting the field of view. Using this constraint leads to a flow chart, which shows possible paths to a practical solution.

A full version of this paper available at http://www.atnf.csiro.au/SKA/techdocs/Antenna_selection.pdf

Theory

For any antenna the maximum effective aperture A_{em} in m^2 and the beam solid angle Ω_A in steradians are related to the wavelength λ in metres by:

$$\lambda^2 = A_{em}\Omega_A$$

(can be derived by squaring Beamwidth = wavelength/diameter)

If the SKA were made of N identical antennas then each would have an effective area of 1,000,000/N square metres. The above relationship can be rewritten as:

$$\left(\frac{0.3}{f}\right)^2 = \frac{1{,}000{,}000}{N}.\Omega_A \quad \text{with } f \text{ in GHz}$$

$$\Omega_A = \frac{N}{11{,}100{,}000\, f^2} \text{ steradians}$$

The beam solid angle is approximately equal to the product of the half power beam width in the two principle planes θ_{HP} and φ_{HP}. The field of view FOV_{HP} is equal to the area of the ellipse defined by θ_{HP} and φ_{HP}. This gives:

$$FOV_{HP} \approx \frac{\pi\theta_{HP}\varphi_{HP}}{4} \approx \frac{\pi.\Omega_A}{4} = \frac{N}{14{,}100{,}000\, f^2} \text{ steradians}$$

And if the total instantaneous field of view is FOV then:

Number of feeds per antenna $\approx$ FOV/FOV_{HP}

$\approx$ $14{,}100{,}000\ FOV.f^2/N$

Multiplying this by the number of antennas N shows that

Total number feeds in the SKA $\approx$ 14,000,000 FOV.f^2

This result is independent of antenna technology and at 1GHz full sky coverage requires 88,000,000 feeds growing to 8,800,000,000 at 10GHz. It would seem full instantaneous sky coverage is not possible at GHz frequencies, thus:

At GHz frequencies economics dictate that the SKA have a restricted Field of View

FOV is the area of sky where the SKA can have high sensitivity instantaneously, about 10,000 deg^2 for phased arrays and about 1 deg^2 for small parabolic reflectors at 1 GHz. Later beamforming can reduce this total. N specifies the number of primary receptors each consisting of an LNA and feed

Astronomy and Field of View

The scientific impact of the SKA can be improved not only by increasing its A_e/T_{sys} but also by increasing its field of view. A good example of this is the Parkes Multibeam, which increased the field of view of the Parkes dish by a factor of 13, allowing a survey to be completed in an order of magnitude less time. The extreme in increasing field of view is the phased array, which can allow any part of the sky to be accessed. With sufficient backend processing 100's or 1000's of observations can be conducted simultaneously. In terms of astronomy throughput a 10 independent beam instrument is equivalent to a single beam instrument that has A_e/T_{sys} three times higher.

In general, the number of useable beams that can be achieved with a given antenna technology is proportional to the field of view which leads to the conclusion:

To maximise the astronomy throughput it is desirable that the SKA maximise the Field of View

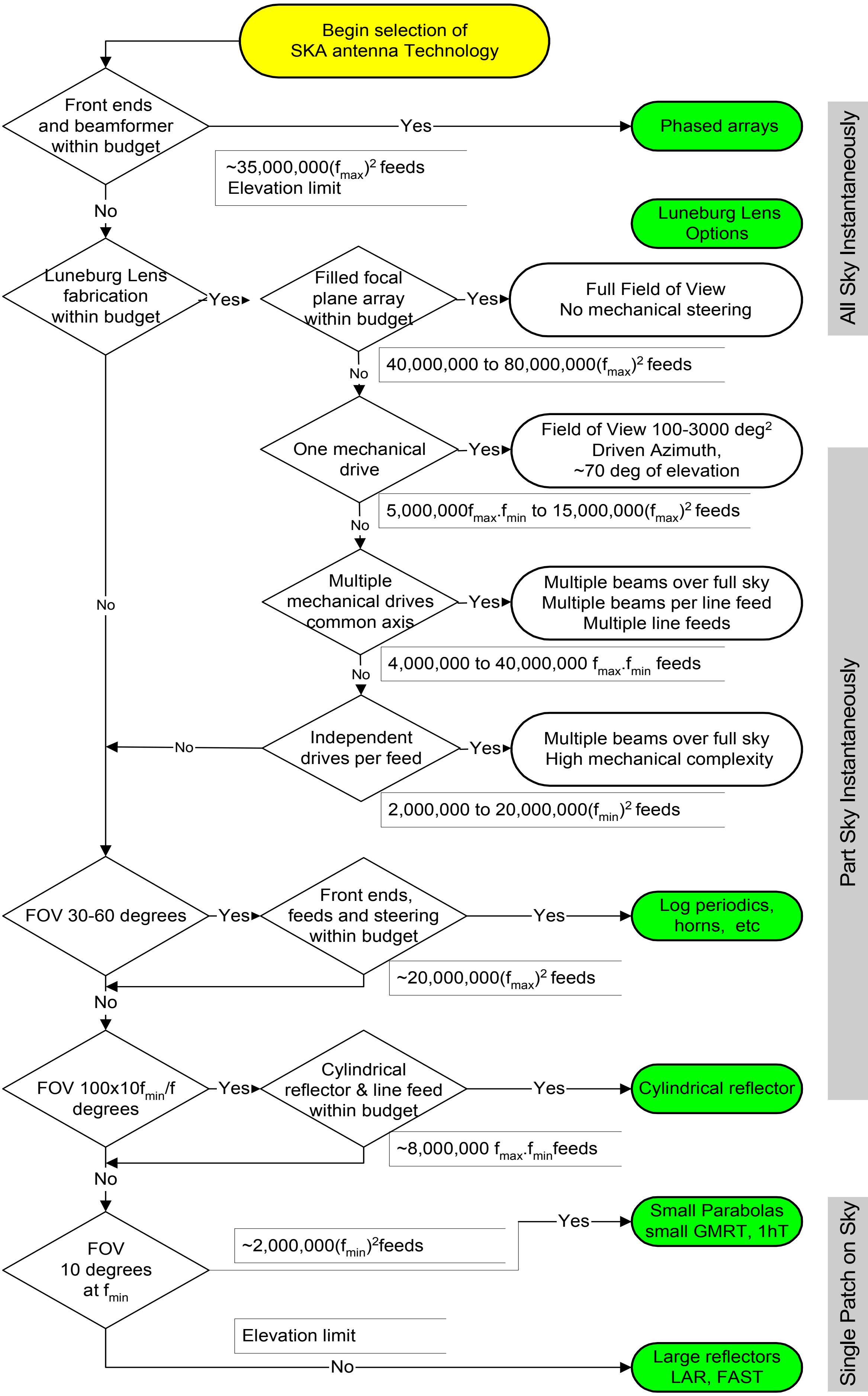
But this conflicts with feed number limitations. These two conflicting requirements leads to the Flow chart shown below which systematically explores options for maximising the field of view while at the same time keeping in mind many of the economic constraints imposed by the various antenna technologies.

The major contenders for full field of view are phased arrays and Luneburg lenses. These are followed by designs with a large field of view such as log periodic antennas and cylindrical reflectors, which with suitable beam forming can provide multiple beams over a 1000 square degrees area of the sky. Finally there are the parabolic/spherical reflector designs. The small parabolic reflectors typically have a single useable beam. The large reflectors will use a focal plane array but even so the total field of view will be smaller than that of the small reflector. Typically all parabolic/spherical reflector designs will support only a single user at a time. The other designs can support multiple users.

The flow chart below describes possible paths to a practical solution

The chart includes feed numbers for the phased arrays these are proportional to maximum frequency squared. For parabolic designs the size is inversely proportional to the minimum frequency leading to a minimum feed number that is proportional to minimum frequency squared. A cylindrical reflector antenna is part reflector and part phased array so the feed numbers are proportional to the product of maximum and minimum frequency. This also applies to a Luneburg Lens with line feed.

Antenna Selection Flow chart



Conclusion

Phased arrays are too expensive at GHz frequencies but are the design of choice at lower frequencies. At higher frequencies, the Luneburg lens would form the basis of an ideal instrument because of its extreme flexibility in forming a field of view. Its major problem is dielectric loss which limits its maximum frequency and the unknown costs and technical challenges in building and supporting the lens.

Cylindrical reflector antennas are also a good choice as a large field of view is desirable in maximising the astronomy throughput of the SKA although the 100 by 1 degree FOV at 1GHz is less than ideal. Cylindrical reflectors have become a viable option, at this time, because Moore's Law has made the implementations of a full beamformer cost effective. The reflector is low cost and designs such as the Doublet (see paper these Proceedings) are very robust and can be made very rigid. This allows operation at very high frequencies.

At present no work is being conducted into the feasibility of non-reflector reduced-field-of-view antennas such as log-periodic, horn or helical antennas. However, the degree of field of view reduction they can give is not great. This probably makes them uneconomic, at high frequencies, due to the high antennas numbers needed to give the required collecting area.

Small parabolas and the Canadian Large Adaptive Reflector have fields of view of about 1 deg^2 at 1GHz which probably limits these designs to a single astronomy program at any one time. But when the instrument is dedicated to imaging the throughput will be similar to the imaging beam of a multibeam instrument. Current correlator costs possibly precludes full imaging on multiple beams at any one time.

All large reflectors have elevation limits caused by foreshortening in the case of the Canadian LAR and blockage in the case of the Chinese FAST proposal. For a complete sky coverage both these instruments would probably require a Northern and Southern hemisphere instrument. Phased arrays also have elevation limits, which could be overcome by building paired instruments inclined at complementary angles.