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SKA: MATCHING THE SPECIFICATIONS AND ANTENNA TECHNOLOGIES

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Abstract

The challenges of meeting the required specifications for the antenna technology for the Square Kilometre Array (SKA) are discussed from first principles. In particular, aspects dealing with the realisation of planar antennas having both wide bandwidth and a wide field-of-view are considered.

1. Introduction

The current accepted thinking is that to cover the full desired frequency range of say 100 or 150 MHz to around 22 GHz for a new radio telescope with a collecting area significantly greater than any existing facility, the antenna/radio-frequency design should be separated into two distinct frequency ranges with a frequency break near 1GHz.

It is also commonly accepted that the astronomical requirements in the high-frequency range (HF-SKA) could be met by an array of small reflector antennas using wideband feed systems.

However, the desirable requirements for the low-frequency facility (Mid-SKA) are a lot harder to achieve. The current requirements are:

- "Whole-of-sky" field of view
- Simultaneous multi-beams in field of view
- Near constant collecting area with maximum at the lowest frequencies.
- Dual polarisation

To meet these requirements, it would appear that planar-array technology should be used.

It will be assumed that an SKA array consists of a large number of (up to 1,000) array-stations, where an array-station is a compact collection of basic antenna elements tied as a phased array using time-delay networks.

In this paper the basic antenna requirements and relative characteristics at array-station level are addressed for both HF-SKA and Mid-SKA. In particular the difficulties of meeting all desirable characteristics for Mid-SKA, and some compromises, are discussed.

Part A: Some general considerations

2. Some key requirements

Consideration of the requirements for the Square Kilometre Array (SKA) leads to the general conclusion that the antenna technologies for an array-station should satisfy the characteristics listed below in Table 1.

Table 1 - Antenna Major Requirements: Array-station

Facility name	*Frequency range (nominal)*	*Field-of-view requirements*	*General antenna technology being proposed.*
HF-SKA	1-22 GHz	~1° at 1.4 GHz	Reflector
Mid-SKA	100-1500 MHz	Whole-of-sky No. of simultaneous beams: say 10 minimum	Planar array

The frequency break near 1GHz for the two facilities is based on the concept that it represents a reasonable compromise between the two antenna technologies currently proposed.

However, the need for a "whole-of-sky" field of view for the Mid-SKA adds an additional "dimension" to the antenna requirements which have to be met, and intuitively one feels that compromises may have to be made in regards to other properties of the antenna, such as a need to restrict bandwidth for example.

3. Collecting area

A study undertaken at the ATNF of the costs of existing and proposed radio telescope facilities consisting of reflector antennas shows that for a given collecting area, a 30-fold increase in the maximum frequency-limit results in a ten-fold increase in cost. For example using the Atacama Large Millimetre Array (ALMA) as a benchmark at an assumed total cost of US$600M, a collecting area of 2×10^5 m^2 should be possible for HF-SKA at the same cost, although the desire is that the available collecting area would be increased through novel low-cost technologies. For the sake of discussion, let us assume that an initial collecting area for HF-SKA of 2×10^5 m^2 (which is a fifteen-fold increase in collecting area of the VLA) would represent a significant facility.

For the Mid-SKA facility however, there appears to be a strong demand for very large collecting areas at the lower-frequencies, so that the original request for 10^6 m^2 collecting area across the design band may not necessarily be a realistic requirement. It is therefore suggested that a more practical collecting area function for Mid-SKA may be one that has a maximum value at the low-frequency limit (say 100 or 150 MHz) and which decreases (according to the antenna technology used) as the frequency increases (this aspect will be covered in more detail in Sec.6). However, in the specification of both Mid-SKA and HF-SKA, it may be desirable to have approximately equal collecting areas at the "break" frequency (maximum frequency of Mid-SKA, minimum frequency of HF-SKA), which will be assumed to be a variable at this stage, dictated partly by the technical factors.

4. Array station size for HF-SKA

One of the major requirements for the HF-SKA is for the field-of-view to be about 1° at 1.4 GHz. Given that it is assumed that reflector antennas will be used, this specification implies an antenna size of about 12m.

Assuming that when the facility is operating in the "imaging" mode, and also to achieve the maximum number of different baselines for the entire array, a single antenna itself would form an array-station. For a total collecting area of 2 x 10^5 m^2 (a useful minimum size), approximately 2,000 antennas (array-stations) would be required and therefore need to be correlated. By increasing the antenna size to 17m, this number of antennas (array-stations) reduces to about 1,000, with a field-of-view of 0.7° at 1.4 GHz. This would appear to be a reasonable compromise.

Part B: Antenna challenges for Mid-SKA

For HF-SKA, the challenges for the antenna design will be to develop low-cost steerable reflector antennas with high reliability, and complex feed systems required to cover the wide bandwidth and anymultibeaming at the array-station level.

For Mid-SKA, the antenna challenges are perhaps at least an order of magnitude greater, and because of the uncertainty in how to realise a planar antenna with very wide-band, wide-angle steerable beams, the overall cost is an unknown factor. However, there are considerable benefits to be had from a facility capable of producing multiple beams steerable to any direction in the sky and capable of operating over a wideband. In the following sections, some of the basic antenna issues for Mid-SKA are addressed in order to see where compromises may be necessary.

5. Basic planar array systems

Let us consider two types of planar antenna systems at the array-station level: a "compact" array in which the basic elements are closely packed, and a "thinned" array in which the basic elements are widely spaced to form a "randomised-element" array (for characteristics see box below). In the case of the "compact" array, it is assumed that the antenna elements are spaced at intervals of about $\lambda/2$ at the highest frequency of operation to avoid high-level grating lobes. However, as the frequency decreases, limitations (such as mutual coupling effects) play an increasing role in the array performance. These limitations and their effect on overall performance (including effective collecting area) are the subject of further fundamental study.

General Characteristics of Thinned Arrays:

- For a given number of elements N, the peak gain, G is independent of the antenna element distribution.
- The beamwidth and the beam efficiency decreases as the overall diameter D enclosing the elements increases. The energy contained in the sidelobe region therefore increases.
- A periodic array will give high-level grating lobes, but if the elements are randomly spaced, the sidelobe energy is smeared nearly uniformly in space.
- In the limit of a highly thinned array, the average sidelobe level L, normalised to the main beam peak, is approximately 1/N.

  For example, $L \cong -37\text{dB}$ if $N = 6{,}250$

We will now consider some basic idealised antenna element characteristics, which will be used later to indicate general trends in performance when used in a planar array.

6. Basic antenna element characteristics

Let us consider two well-known antenna element types, antennas having constant effective-area (Ae) and those having constant beamwidth (HPBW) with frequency (see Table 2). There are also antennas (eg fin-line and flared horn end-fire elements), which we will call "compromise" antenna elements, that have Ae and HPBW characteristics which fall roughly between the two types. It is interesting that the paraboloidal reflector fed with a log-periodic feed is almost a "matched" wideband system, except that the phase centre of a typical log-periodic antenna does not remain fixed (at the focal-point) with frequency.

Table 2 - Characteristics of some Basic Isolated Antenna Elements

Element type	*Example*	*Effective area (Ae)*	*HPBW*
Constant-Ae	Paraboloid	Constant	$\propto\lambda$
Constant-HPBW	Log-periodic	$\propto\lambda^2$	Constant
"Compromise"	Flared "end-fire" structures	$\propto\lambda$	$\propto\sqrt{\lambda}$

For a planar array, we ideally require a constant-HPBW element to achieve constant sky-coverage independent of frequency. The idealised array will therefore tend to have an effective area proportional to λ^2, although in practice this will only apply in the case of a thinned array. For a compact array, the effective area of each antenna element tends to decrease as the frequency decreases. This gives a more constant effective area characteristic but at a significant cost of reduced effective area at low frequencies where a high value is most important!

It is also useful to consider the approximate relationship between gain and effective collecting area for elements having particular coverage (field-of-view) expressed as HPBW, see Table 3. (Note that for reference, a dipole has a gain of 2dB and an effective area, Ae/λ^2 of 0.12). The relationships between the different parameters are given by the following idealised basic formulae for simple antenna elements:

$$G = \frac{35{,}000}{(\mathrm{HPBW})^2}\ , \text{ and } \ \frac{Ae}{\lambda^2} = \frac{G}{4\pi}$$

where G is the antenna element gain, and the HPBW is expressed in degrees.

Table 3 - Effect of Antenna Element Beamwidth

HPBW	*G(dB)*	*Ae/λ^2*	*# per array-station* ^*	*Total # of elements **
150°	2	0.12	4,000	4,000,000
100°	5	0.25	2,000	2,000,000
75°	8	0.50	1,000	1,000,000
55°	10	0.80	625	625,000

* Ae for SKA = 2x $10^6 m^2$ @ 150 MHz

^ assumes there are 1000 array-stations

7. Implications

Table 3 shows that in the ideal case of "isolated" (low mutual coupling) antenna elements, 4 million elements with the appropriate time-delay networks at an array-station level (where there could be 4,000 elements) would be necessary if an all-sky coverage is required. Also, the question of specifying the antenna element type which maintains a very wide beamwidth over a decade bandwidth needs to be addressed. If the elements are placed in a "compact" configuration, the effect of mutual-coupling on the performance has to be determined. If the elements are configured as a "thinned" array the effect of the smaller beamwidth at array-station level needs to be considered in the overall design. It is interesting that if the "randomisation" of the elements of each of the array-stations is different, the overall sidelobe performance of the SKA array may be improved.

Table 3 also shows that if the instantaneous field-of-view is restricted (say to 55°) the number of elements decreases dramatically. In this case, a steerable high-gain log-periodic antenna could be used. Note however that such elements with constant beamwidth have an effective area which decreases as λ^2 (see Table 2). Another option may be to use an antenna element which has a "compromise" pattern (see Table 2), so that the effective area does not decrease as rapidly as a "constant-HPBW" element. However the HPBW does slowly decrease with frequency, which may not be an acceptable compromise.

Figure 1 illustrates, on an effective collecting area basis, the use of "constant-HPBW" and "compromise" elements for Mid-SKA. It also shows that if HF-SKA has an effective collecting area of 2×10^5 m^2, then there may be a need to revisit the value of the "break" frequency between the Mid-SKA and HF-SKA. In the figure, this is around 600 MHz. This would imply using reflector technology above 600 MHz for example, and permit a relaxed antenna bandwidth specification for Mid-SKA (say 100-600 MHz). However, one disadvantage of this scheme is that a wide-angle field-of-view would not be available for frequencies above 600 MHz.

8. The search for a "magic carpet"

Many other aspects and compromises relating to the realisation of planar arrays (either compact or thinned) capable of producing scanned beams over a wide field-of-view and over very wide bandwidths, still need to be investigated.

However, the need to search for an ideal surface, the so-called "magic carpet", is still a challenging issue. It is interesting that antenna developments compared to electronic digitisation of signals is relatively devoid of significant break-throughs. Antenna engineers continue to use discrete elements ("digital" elements) which do not fit comfortably with wideband planar array applications. Perhaps a true "magic carpet" is, in reality, an "analog" or "continuous" absorbing surface upon which effective phase shifts can be placed??

9. Acknowledgments

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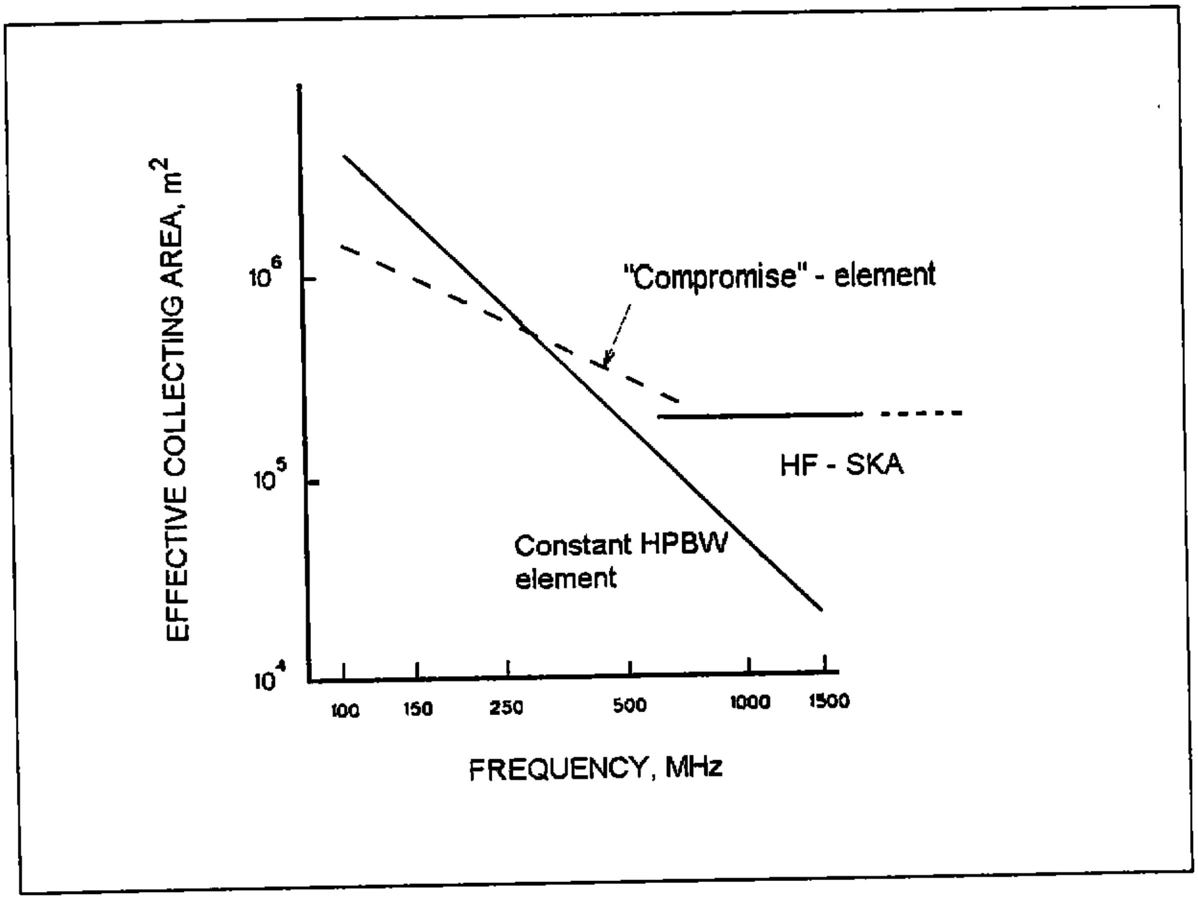

Fig 1: The collecting area versus frequency for Mid-SKA for two types of antenna elements are shown. For comparison, an HF-SKA is also shown.

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