CSIRO - Australia Telescope National Facility

Focal-plane arrays - some basic characteristics and an application to HF-SKA

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Summary

The RMIT University, Melbourne, is carrying out research which is applicable to focal-plane arrays for reflector antennas, particularly for the HF-SKA radio telescope which we currently assume will operate at a frequency of 1 GHz and above (to possibly about 20 GHz).

The RMIT university research covers the following aspects:

- Wide-band patch elements with a VSWR bandwidth ratio of 1.8,
- Future research dealing with "double-stacked" patch elements where there would be a small number of higher-frequency elements above a single lower-frequency element.
- Wide-band time-delay optic-fibre component development.

In this report, the requirements of the reflector optics for an HF-SKA application which uses a focal-plane array are discussed, and a preliminary design proposed. In particular, the case where the focal-plane array is used to form multi-beams at the Nyquist spacing is considered. If the research currently being carried out at the RMIT University in producing an antenna element with two wide frequency bands is successful, it will be possible to achieve multiple beams across a given angular region of the sky over say four bands. If "double-stacking" of a basic element is not possible, this report shows that the multiple beams could be achieved across two adjacent bands, where the total bandwidth ratio is 1.8.

1. Introduction

The general advantages of focal-plane arrays are seen to be:

- Multi-beaming at Nyquist spacing
- Higher aperture efficiency due to ability to capture more focal-plane energy (on transmission, this equates to producing a more uniform aperture illumination)
- Increased field-of-view due to ability to implement near-optimum amplitude and phase focal-plane distribution.
- Ability to compensate for large-scale reflector distortions.

However, these advantages may come at a cost of considerable complexity, and like most compact arrays, at possible restricted bandwidth characteristics.

A useful paper on the principle of focal-plane arrays and related processing aspects is given in [1], although the application is restricted to an antenna with a semi-angle θ_0 of 48°, which reflects the optics of the particular antenna used as a test-bed. Some preliminary considerations for feeding large-diameter Cassegrain antennas is included in [2].

In this report, it will be assumed that the antenna optics is not pre-determined, but that there is a desire to utilise a given antenna element having a wide bandwidth forming the focal-plane array.

Following an overview of some of the key issues that need to be addressed in designing focal-plane arrays, a preliminary specification of a focal-plane array for HF-SKA (assumes a minimum frequency of 1 GHz) which has potential wide bandwidth and is capable of producing multi-beams at the Nyquist rate, is described.

2. General restrictions on parameters

One of the major parameters in designing a focal-plane array is the relationship between bandwidth and reflector semi-angle. Let us assume that the semi-angle of feed illumination of the main reflector (or equivalent semi-angle in the case of a dual-reflector system) is θ_o. To avoid the incidence of grating lobes in real space the element spacing must be less than the following [1]:

a) Square grid: $\frac{d_\square}{\lambda} \leq \frac{1}{1+\sin\theta_o}$, or

b) Hexagonal grid: $\frac{d_H}{\lambda} \leq \frac{1}{\cos 30^\circ(1+\sin\theta_o)}$

Table 1 illustrates these relationships for reflectors of different semi-angles (or equivalent semi-angle for a dual-reflector antenna).

To achieve a moderate antenna bandwidth, Table 1 shows that the equivalent semi-angle of the dish should be small. This implies that such focal-plane arrays are best used with Cassegrain antennas (typically "large" reflectors) or offset geometry (typically "small" antennas) where blockage of the array is eliminated. A typical antenna geometry is shown in Fig. 1, where the illumination semi-angle is 25°.

Table 1
Restrictions on maximum element spacing and bandwidth ratio

Equivalent reflector Semi-angle	**Maximum element spacing (λ)**		**Maximum bandwidth* ratio**	
	$d_\square$	d_H	$d_\square$	d_H
10°	0.85	0.98	1.70	1.96
15°	0.80	0.91	1.60	1.82
20°	0.74	0.86	1.48	1.72
25°	0.70	0.81	1.40	1.62
30°	0.66	0.77	1.32	1.54

* *The bandwidth ratio assumes that at the lowest frequency of operation, the element spacing is 0.5 λ.*

3. An application to HF-SKA

Perhaps one of the most general future applications of focal-plane array technology is for multi-beam applications at or near the Nyquist sampling interval. It should be noted that reflector antennas using a cluster of single conventional feeds can only sample at approximately twice the Nyquist sampling interval (see Table 2).

By using a phased array which uses relatively wide-band elements (say 1.8 bandwidth ratio), it is possible to have a collection of elements with say a minimum spacing of $\lambda/2$, combined in phase to form an effective single feed.

In Table 2, the following parameters are defined for a given reflector semi-angle θ_o:

- Approx equivalent feed diameter ($2a/\lambda$) formed from a cluster of antenna elements
- Beam-deviation factor (BDF) for reflector
- Nyquist spacing, (d_N/λ).

Where the feed is formed by a cluster of elements, the amplitude should be tapered according to a $J_o(u)$ Bessel function. Consequently the amplitude weights must be able to be varied.

Table 2
Nominal feed diameter and Nyquist spacing

Reflector Semi-angle (θ_o)	**Equivalent f/D**	**Reflector BDF**	**Feed dia ($2a/\lambda$)**	**Nyquist spacing** (d_N/λ)**
10°	2.86	1.0	7.3	3.4
15°	1.90	1.0	4.9	2.3
20°	1.42	1.0	3.7	1.7
25°	**1.13**	**1.0**	**3.0**	**1.35**
30°	0.93	1.0	2.5	1.1
35°	0.83	1.0	2.2	1.0
40°	0.69	0.95	2.0	0.87
50°	0.54	0.92	1.6	0.70
60°	0.43	0.86	1.5	0.60
63°	0.41	0.85	1.4*	0.57

* Experimental value for Parkes is approx. 1.1.

** It can be shown that the Nyquist spacing is given by:

$$\frac{d_N}{\lambda} \sim \frac{1.2\,(f/D)}{BDF}$$

where BDF is the Beam Diameter Factor of a symmetric paraboloidal antenna.

The results in Table 2 show the following:

- That the Nyquist spacing is approx. half the required effective feed diameter, as expected.
- That if a minimum element spacing of 0.5λ is chosen, then for a wideband system (say 1.8 bandwidth ratio, where the element spacing increases to $0.9\ \lambda$ at the highest frequency), there is a need to use a reflector with a relatively small semi-angle θ_o. This requirement is also consistent with Table 1.

4. Choosing some initial parameters

Let us assume that the antenna diameter is approximately 10 m and that offset primary optics (or equivalent) is used, where the semi-angle is 25° to permit high feed-system bandwidth to be achieved.

Also, for our initial study, let us assume the following:

- A hexagonal array of elements is used where the basic element spacing is 0.5 λ at the lowest frequency (see Fig. 2).
- The antenna element frequency range is 1.8:1, which, by way of example, is broken down into two RF system bands, see Table 3.

Table 3
Some preliminary array specifications: test-bed

Parameter	Band A	Band B
Minimum frequency (GHz)	1.0	1.4
Mean frequency (GHz)	1.2	1.6
Maximum frequency (GHz)	1.4	1.8
RF System bandwidth (MHz)	400	400
Approx. aperture diameter (mm) (see Table 2)	~750	~560
Minimum array grid spacing (mm)	150	150
Maximum array grid spacing (mm)	260	260
Nyquist spacing (mm) - mid band	337	253
Nyquist spacing (mm) - upper band	290	225

Note that the wide antenna-element bandwidth ratio of 1.8 may be stretching the array performance requirements (due to incidence of wide-angle sidelobes (quasi grating-lobe response)), and depending on the antenna element pattern characteristics with frequency (assumed to be $\cos^2 \theta$ at higher frequencies), it may be necessary to restrict the total antenna element bandwidth ratio to 1.7 or even 1.6. Alternatively, it may be necessary to decrease the reflector semi-angle θ_o (as indicated by Table 1). If the total element bandwidth ratio were restricted to say 1.6, the RF system bandwidth would then be 300 MHz for the example given in Table 3.

Some preliminary calculations of feed pattern shape using a hexagonal configuration have been made. Indicative sets of element amplitudes for the two bands (centre-frequencies of 1.2 and 1.6 GHz) and for two specific element layouts are given in Fig. 2. Further computation needs to be done to fine-tune the element amplitudes to give acceptable (compromise) feed-pattern illumination and spillover over each band. The pattern calculations for the layouts giving the adjacent Nyquist beams also need to be optimised.

5. Adding additional bands

Additional bands may be added to cover the higher frequencies by placing similar arrays besides the lower frequency one. However, this does not give beams which overlap. An alternative antenna-element being researched by RMIT University, Melbourne, relates to double stacking of say four high-frequency elements on a single low-frequency element. If achievable, this would give dual antenna-element bandwidth, with multiple-beam coverage at Nyquist spacing over the same area of sky.

6. References

[1] J.R. Fisher, "Phased array feeds for low noise reflector antennas", Private Communication, NRAO, Green Bank, W.Va, 30 January, 1996.

[2] B. MacA Thomas, "The 1kT-application of phased array technology (Part 2)", AT Techn.Doc. No. 39.3/064, 1 May 1997.

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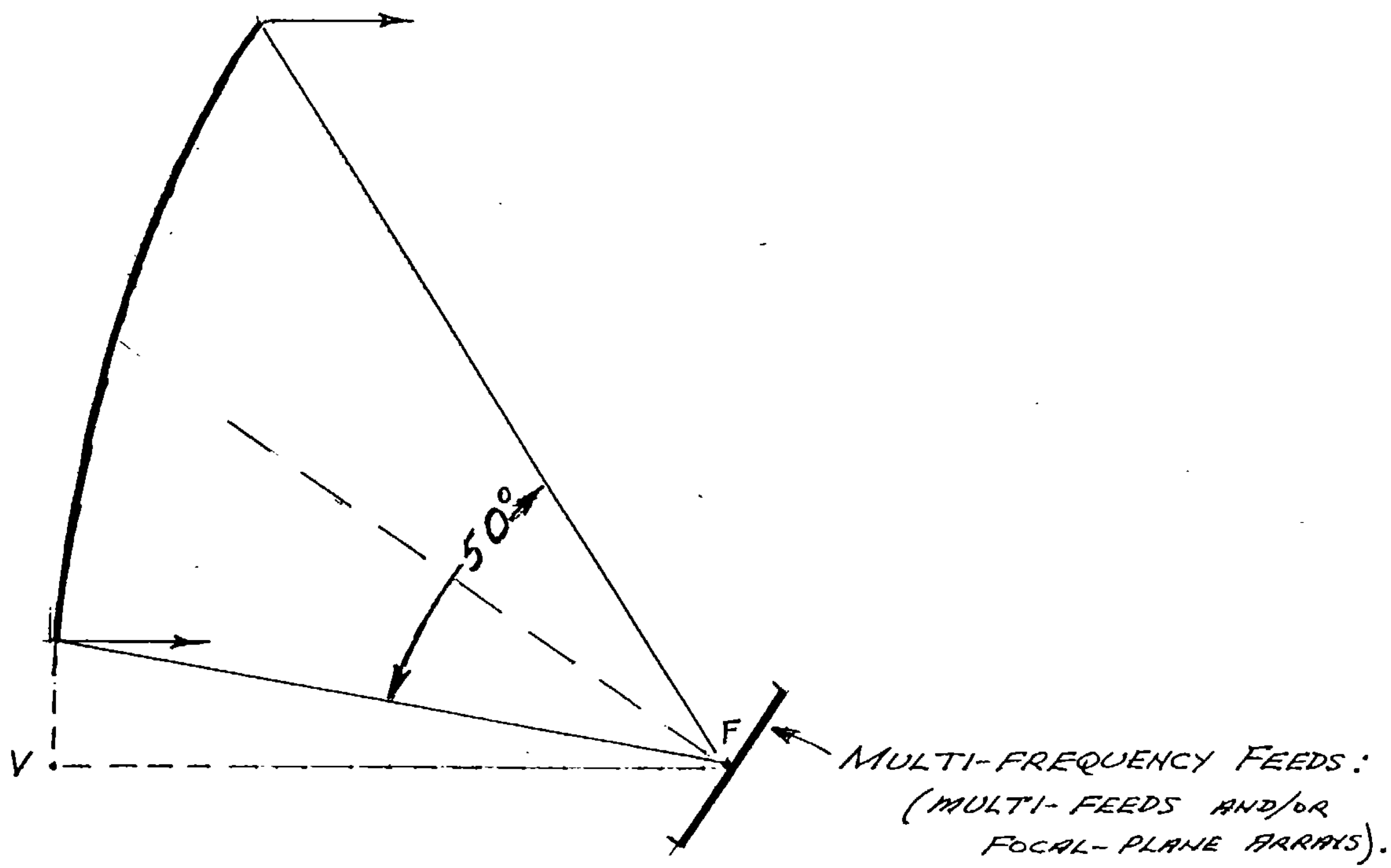

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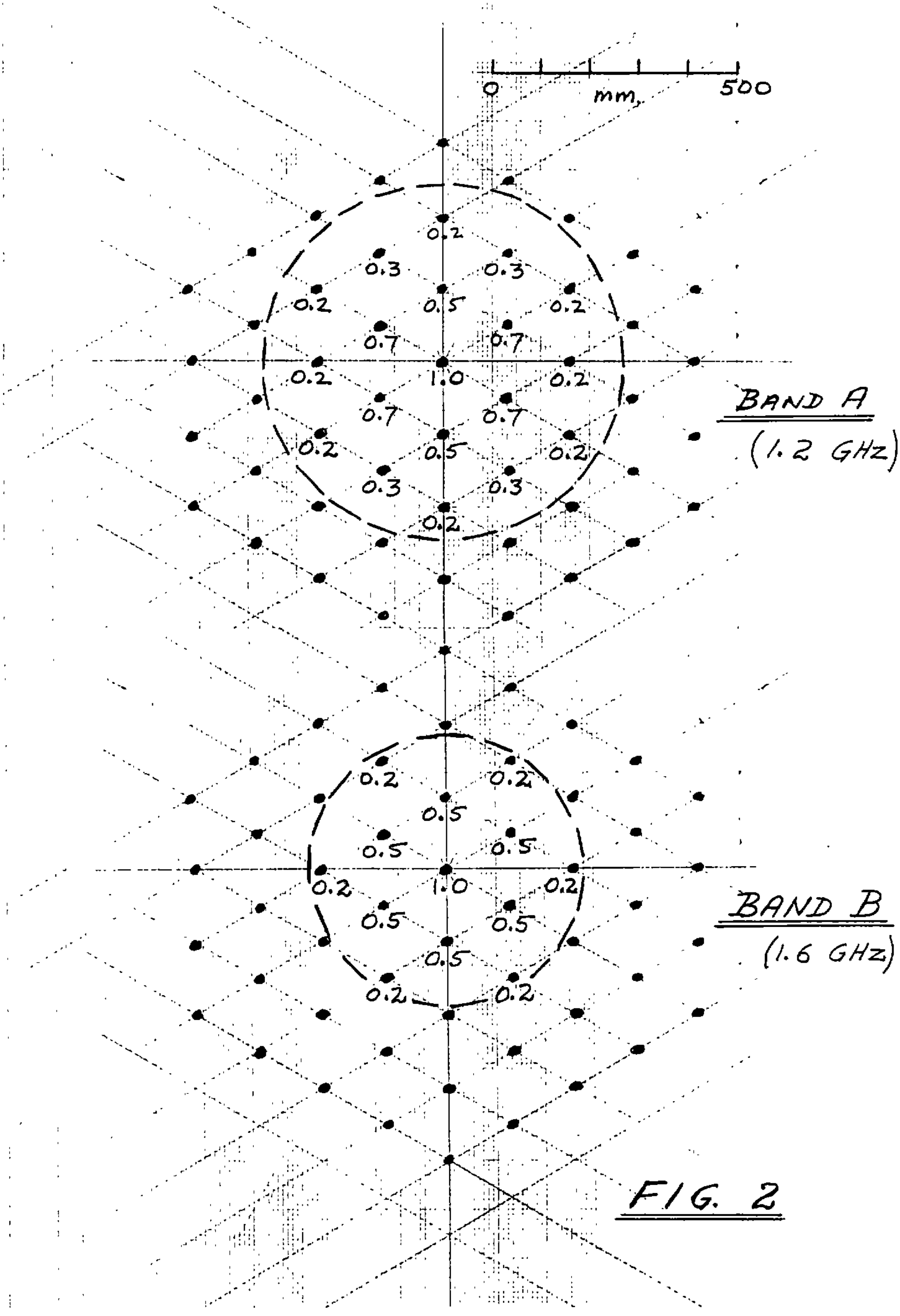
FIG. 1.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BAND A
(1.2 GHz)
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0.5
0.5
0.2
0.2
BAND B
(1.6 GHz)

FIG. 2