CSIRO - Australia Telescope National Facility

The 1kT - Application of Phased Array Technology (Part 2)

A. Some general considerations, and

B. Possible use of secondary-focus phased-array technology for steerable Cassegrain antennas.

1. Introduction

From the technical workshops held to date (1,2), it would appear that two of the greatest challenges from the "RF design" point-of-view (which then impacts on the "digital design") are:

- the array element [1] designed to provide adequate efficiency over a nominated area of sky, and
- the effectiveness of interference excision, which itself will be a function of the array element design.

The aspects of array element design, efficiency of sky coverage and effectiveness of interference excision are all inter-related, and should be researched first for a wide range of array element types. As the "distant scene" (which currently appears to be quite murky) becomes clearer, detailed aspects can be researched intensively and cost considerations introduced.

In this File Note, the first stage of a study of phased array technology forming part of the array element is reported. At the same time, it is hoped that the series of File Notes to be issued in this area will stimulate input, particularly in regards to other aspects of the system performance and design. Such aspects may include:

- antenna aperture efficiency versus bandwidth and sky-coverage;
- sidelobe performance for: (a) arraying as an interferometer, and (b) interference excision (including LNA non-linearity effects);
- multibeaming (if actually required from an array element point-of-view);
- overall methods of implementing interference excision;
- TBD

It is also hoped that studies such as those being proposed here, together with like studies on other aspects of the system, will help to consolidate a useful and meaningful set of specifications somewhat related to reality.

2. Some Issues Relating to Performance Specifications

An initial report on the trade-off in regards to antenna efficiency versus elevation (sky) coverage has been given in (3). Fig. 2.1 is an excerpt from this, and demonstrates the compromises which may have to be made in specifying a fixed-cost system.

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[1] The "array element" is here defined as a stand-alone antenna approximately 100m in size, which can be arrayed with a number of like elements to form the 1kT interferometer.

Other related factors include the necessary maximum sidelobe levels, particularly for interference excision. This specification will particularly impact on the design of a fixed planar array, where wide bandwidth is generally incompatible with a wide scan-angle because of high-level grating lobes.

It is currently considered that interference excision will take place at the array-element. This may be done at two "levels":

- through sidelobe minimisation at directions where very strong signals may occur, eg, from satellites (geostationary or non-geostationary) and close-by ground-based signals, and
- through signal correlation and signature recognition techniques (utilising dual-polarisation). Such techniques are currently under investigation by the ATNF in collaboration with R. Fisher, NRAO (Greenbank).

3. *Use of Phased Array Technology*

To date, a number of proposals have incorporated phased arrays as a solution for or forming part of the solution of the array element of the 1kT. Although yet to be verified, use of phased-array technology in one of its forms may well be an important aspect for assisting in the implementation of interference excision, eg through the ability to shift beams, sidelobes and minima for beam comparisons and/or direct interference reduction.

Table 3.1 summarises five possible array-element configurations which employ phased-array technology in one form or another. The remainder of this report is devoted to the Cassegrain antenna using a phased-array feed at the secondary focus. Other concepts will be investigated later, so that the performance characteristics described in Section 1 can ultimately be compared and evaluated.

4. *A Cassegrain Antenna with a Phased-array Feed at the Secondary Focus*

4.1 Introduction

This antenna type was chosen in this initial study of array elements because:

a) it maintains constant gain and beam circularity over the full range of elevation and azimuth angles determined by the mechanical design,
b) it can give a low side-lobe solution, a potentially important factor for interference excision,
c) the focal-plane array, given a solution for achieving a wide band sub-element (or tile) will have the following advantages:-

  - it will give a near-optimum illumination of the sub-reflector over the operational bandwidth situated within the frequency coverage of the feed sub-element;
  - it could give the capability to steer the feed-beam, and hence the antenna beam, side-lobes and minima of the array-element, but only within a restricted range of angles;
  - by using pure Cassegrain optics (ie "unshaped"), a number of separate phased-array feeds can be used to achieve a very wide band for the antenna;
  - at the higher frequencies where the feed array is relatively small, additional elements can be included, so as to compensate for a reduced-cost "floppy" back-up structure.

In the implementation of such an antenna, the cost of the structural and mechanical aspects of the antenna, the phased-array feed-system(s), and the method of implementation of interference excision are critical issues. This last factor, along with the element design, is the most important factor which need to be addressed.

The technical aspects of a possible configuration for the Cassegrain will be discussed in the following sections.

4.2 The Optics

Fig. 4.1 shows the general optics: a paraboloidal reflector, diameter (D) 70m with a Cassegrain sub-reflector, diameter 10m. The f/D is 0.35 and the maximum operating frequency for design purposes is 2 GHz.

The feed sub-element (or tile) is a critical component, and finding a practical solution for this is just as critical for this concept as it is for other possible array element solutions using wide-band elements. Possible configurations and performances of the secondary focus phased-array feeds are given in Sec. 4.4.

Another important aspect, particularly from a cost point of view, is the implementation of a low-cost structural design including that for the main paraboloidal reflector and the hyperboloidal sub-reflector. Some preliminary aspects are considered in the next section.

4.3 Main and Sub-reflectors: Structural Aspects

Assume that the two reflectors will be of gore construction to minimise cost, ie the reflectors will be ribbed with wire mesh stretched between the ribs (4). However, there are a number of issues which need to be considered in a final design:

- the loss through the approximation of using quasi-flat mesh to approximate a paraboloidal surface;
- the higher sidelobes introduced by the periodicity of the structure;
- the periodicity of the sub-reflector relative to the main reflector, and the relative angular displacements of the ribs making up the two reflectors;
- the specification of the wire mesh for the two reflectors to reduce leakage to an acceptable level;
- the specification for the rigidity of the ribs forming the main reflector. Note that the specifications can be relaxed somewhat by using the focal-plane array to partially compensate for first-order distortions at the higher-frequencies where the array size is relatively small (5). This technique could be introduced using the second focal-plane array shown in Fig. 4.1, ie above 800 MHz.

Initial calculations show that the main reflector could require 48 ribs (gore loss ≈ -1.2 dB at 2GHz), and a mesh of 1.2 mm dia wires with a spacing of 12 mm (gives -15 dB transmission at 2 GHz). However, as mentioned above, a study of the increased level of sidelobes due to the surface periodicity is required. An acceptable sub-reflector configuration also needs to be considered.

In regards to major distortions in the ribs over the elevation-angle range, assume that the uncompensated distortion is equivalent to one-cycle of error (5) with a zero-to-peak value of β. Further, if we allow β to be 0.075λ, then at 800 MHz, this is 28 mm giving 1.7 dB loss. However, at 2 GHz such a distortion would yield a loss of approximately 10 dB. To maintain the loss at better than 1.7 dB for frequencies above 800 MHz, it is proposed that the higher frequency focal-plane array should be increased in size beyond that required only to provide the correct illumination of the sub-reflector. This aspect will be considered in the next section.

Finally, there is a need to consider the random component of error (eg. small scale rib distortions, reflector mesh distortions, etc.). Assuming an initial rms value for this component of 7mm total, the corresponding gain loss will be 1.5 dB at 2 GHz, decreasing to 0.25 dB at 800 MHz.

4.4 The Feed Array:

4.4.1 The feed-array element

(a) Some limitations for phased-arrays:

The ideal characteristics for an element of an array will depend on the angle of scan required for the array. A wide scan-angle would ideally require a fairly broad element pattern; however this requirement would be inconsistent with the lack of attenuation of the grating lobes which will appear as the frequency is increased, thus limiting the useful bandwidth. For a small scan-angle system, it is an advantage to have an element for which the beamwidth decreases as the frequency increases, so that grating lobes are attenuated. This would then give wide-band performance. (Note: the above description is consistent with the general statement that the "scan-angle-bandwidth" factor for a phased array tends to be approximately constant.)

For the phased-array feed for the Cassegrain antenna, the angle of scan is negligible, so wide bandwidth should, in principle, be possible.

(b) Element types under consideration:

The elements to be used in the feed array have yet to be researched and developed in detail, and as mentioned in Sec. 4.2, it is a necessary and challenging area of research where phased-array technology is to be used for the 1kT.

In this general consideration of the element types, two alternatives are considered:

- square waveguide using a crossed wide-band driven element to obtain two polarisations. Ideally, it is very desirable to be able to cover two bands, and
- wide-band "microstrip" technology (horizontal and/or vertical). Here again, at least two bands are essential.

The elements are shown diagrammatically in Fig. 4.2 (3).

The method using square waveguide is likely to restrict the two bands in the ratio of 2 to 1. The bandwidth covered by each band will depend on the ability to achieve an adequate match, and minimum excitation of higher order modes (particularly the TE_{02} mode) at the higher frequencies for bandwidth ratios approaching 2:1.

In addition, the aperture distributions along the two major axes are not generally identical, the field in the H-plane of the aperture being tapered, and that in the E-plane being uniform. This in turn will yield different pattern bandwidths, and at the high frequency end, sidelobe levels (if present).

The use of "microstrip" (or equivalent) technology may be more flexible if methods of "stacking" the elements to achieve dual-banding can be achieved, eg using a band separation of 3:1. The other critical factor which requires further research is the ability to achieve a wider bandwidth than that currently available.

(c) Alternative array types:

The two array types which have been considered to date are as follows:

i) Waveguide technology (bandwidth, f_{max}/f_{min}, for each band is assumed to be 2.03), using two arrays with frequency coverage as follows:

Array 1: 200 - 407 MHz (Band A), and
400 - 810 MHz (Band B);

Array 2: 800 - 1700 MHz (Band C)

ii) "Microstrip" technology (bandwidth ratio 1.7), giving a frequency coverage as follows:

Array 1: 200 - 352 MHz (Band A), and
600 - 1056 MHz (Band C);

Array 2: 345 - 607 MHz (Band B), and

Array 3: 1035 - 1820 MHz (Band D).

Note that, in principle, Arrays 2 and 3 could be combined into a single array similar to that for Array 1.

Fig. 4.3 illustrates (i) above, and Fig. 4.4 illustrates (ii). The following section will consider only the array type shown in Fig. 4.3. The array elements will be assumed to be square waveguide with a minimum size and spacing of 810 mm for Array 1, Band A. The minimum size is therefore 0. 54λ and maximum 1.10λ.

4.4.2 The feed configuration

(a) The optimum illumination:

As a first approximation to the Cassegrain optics in Fig. 4.1 the illumination of the equivalent paraboloid with a semi-angle of 12.4° is assumed.

Two types of array distributions have been considered:

i) a tapered distribution according to Jo (r/a B), where B=2.40, a is the radius of the array to be used at a given frequency and o < r < a. Fig. 4.5(b) shows that for a main reflector edge-taper of -13 dB at 12.4°, ka sin 12.4° = 4.0, or $2a/\lambda = 5.93$. For Band A, the array size must therefore be 8.9 m, which is determined by the minimum frequency of 200 MHz. Similarly at the maximum frequency (407 MHz), the size illuminated reduces to 4.4m. For Array 2, the minimum size is 2.2m (800 MHz).

ii) a distribution to give quasi-uniform main reflector illumination for high efficiency. Here the array amplitudes are adjusted according to the "main-lobe" and first negative "side-lobe" of the function J1(U)/U so as to approximate the corresponding focal-plane Airy distribution. The pattern approximates that of a two-hybrid-mode horn. However, the need for a large array to produce the required distribution probably precludes its use in practice except for perhaps the high frequency array (Array 2).

Note however, that the patterns of the reflector will be different for the two distributions (a) and (b) above since the first tapered illumination will give a wider beamwidth and lower sidelobes than the more uniform distribution in (b), similar to cases (b) and (a) respectively in Fig. 4.5. Some small degree of null steering is therefore possible by altering the feed illumination.

In practice, there will be a need to operate the antenna over a finite or "instantaneous" bandwidth. In this case, the optimum illumination of the reflector would normally be achieved at the centre of the band, with "over-illumination" at the bottom of the desired band, and "under-illumination" at the top of the band. Further work needs to be done to determine the maximum desirable (instantaneous) bandwidth.

(b) Array size:

In Fig 4.3 the array sizes for the two lower bands is determined by the lowest frequencies (200 and 400 MHz) in each case. The higher-frequency array (400-800 MHz) may be extended to cover the full diameter to provide beam steering, the optimum diameter at a given frequency being "moved" electronically in the desired lateral direction to achieve the desired beam shift.

The array covering the highest frequency (800-1700 MHz) is twice the optimum size required at 800 MHz to enable partial compensation for major reflector distortions. The array can be readily extended (because of its small size) to permit beam steering at the lower frequencies. The array as it stands will currently permit steering at the upper frequencies.

c) Optimising the feed-element layout:

Taking Array 1, Band A (200 to 407 MHz) as an example, the far-out sidelobe structure was studied, particularly as the frequency is increased, since partial grating lobes, and then grating lobes appear. The feed array element was assumed to be a square waveguide.

For the lower frequencies (200-300 MHz), an "ordered" element arrangement (eg where each consecutive row of elements is staggered by half the pitch) appears to be optimum.

However, as the frequency is increased, the grating lobes increase to high levels (-13 dB). By introducing some irregularity in the element layout near the centre of the array where there will be greatest impact at the high-frequency end, it is possible to reduce the level of the grating lobes. Fig. 4.6 shows the "compromise" element layout which has enabled the major grating lobe to be reduced by 6 dB at 350 and 407 MHz. At 300 MHz however (element spacing 0.81λ) the major far-angle lobe is increased in level by 5dB as shown in Table 4.1 below.

Table 4.1

Change in level in far-out (grating) lobes by an altered feed element* layout.

Frequency (MHz)	Element Spacing (λ)	Worst Case Far-out Sidelobe **(dB)	
		Staggered Configuration	Array: Fig. 4.6
200	0.54	-	-
250	0.68	-	-25
300	0.81	-28	-22.5
350	0.95	-13.6	-19.3
407	1.1	-11.3	-17.6

* Elements are assumed to be square waveguides.
** This is the sidelobe level of the feed, not the entire antenna.

4.5 Use of feed-array in interference excision

Further consideration needs to be given to the use of the focal-plane array for interference excision. For example, perhaps correlation techniques in association with the outer ring of elements of a feed-array, appropriately phased, to sample the interference in the annular space defined by the antenna aperture, can be used. Alternatively, small dedicated array(s) placed on the rear of sub-reflector to implement interference excision including nulling may be a possibility.

4.6 Some general comments on use of phased-array technology for 1kT

This preliminary study does tend to indicate that if an overall bandwidth ratio of near to 10:1 is to be achieved, then it may be necessary to have two separate arrays, with each array covering two bands (not necessarily adjacent bands). The pattern of the elements is critical in relation to any grating lobe suppression. This also leads to an important question which will impact back on the overall design: how low must sidelobes, including grating lobes, be for a (100m) array-element? Perhaps the relative performance of different interference excision techniques in suppressing interference, particularly coming through high-level sidelobes, will play a major part in the array-element design.

Bruce MacA Thomas
1 May 1997

References:

1. Notes of the Workshop: "SKAI Antennas and Architectures", held at Delft, 9 and 10 September 1996. A workshop hosted by the Netherlands for Research in Astronomy.
2. Notes of the Workshop: "The 1kT International Project; Australian Participants Technical Workshop No.1", held at Sydney, 20 and 21 January 1997. A workshop hosted by the Australia Telescope National Facility.
3. B. MacA. Thomas: "The 1kT Array: (a) Some thoughts on the overall antenna specifications, and (b) Concepts for and performance of a (100m) phased-array element", a CSIRO ATNF discussion paper, 3 February 1997. (AT file No. 43.16/015, AT Tech. Doc. No. 39.3/063)
4. W.V.T. Rusch and R.D. Wanselow: "Boresight gain loss and gore-related sidelobes of an umbrella reflector", IEEE Trans AP-30, pp 153-157, Jan 1982.
5. A.R. Cherrette, R.J. Acosta, P.T. Lam and S.W. Lee: "Compensation of reflector antenna surface distortion using an array feed", IEEE Trans AP-37, pp 966-978, Aug. 1989.

Table 3.1

Array Element Solutions Utilising Phased-Array Technology

Array Element Type	Description	Elevation Angle Coverage	Gain Characteristics	Other Characteristics	Progress and Comments
Planar Fixed Array - wide band	A current popular choice	Grating lobes increase with scan angle, θ (θ is angle from normal)	Gain ∝ Element (θ). Cos θ	Beam ellipticity increases with θ	"Thinned" array techniques for grating-lobe intensity reduction over wide bandwidths is a key area for investigation.
Planar Fixed Array - narrow band	Use of multitude of relatively narrow-band elements	Scannable in "N-S" direction with broad-beam in "E-W" direction	As for planar array above	Beam ellipticity increases as θ	"Honeycomb Wire" antenna suggested as a sub-element (2). Requires further work to establish scanning method and elevation range, and arraying method to form the array element.
Mechanical: "restricted-scan" array	Planar-array on mechanical mount (see Fig. 3.1)	Determined by mechanical design of mount-potential for full coverage	Independent of elevation	Circular beam	This concept was proposed as a comparison with the fixed planar array above. It is not being pursued (see alternative option below).
Mechanical: Cassegrain	Secondary-focus phased-array feed (see Sec. 4)	As above	As above	Limited main-beam electronic scanning possible. Circular beam.	An initial report is provided in Sec. 4
Mechanical/ Electronic scan	Two planar arrays, 45° to vertical for elevation scan; az. scanned mechanically. See Fig.3.2	± 40° electronic scan in elevation around 45°	Restricted scan range gives low gain loss	Beam ellipticity is minimal	Under investigation

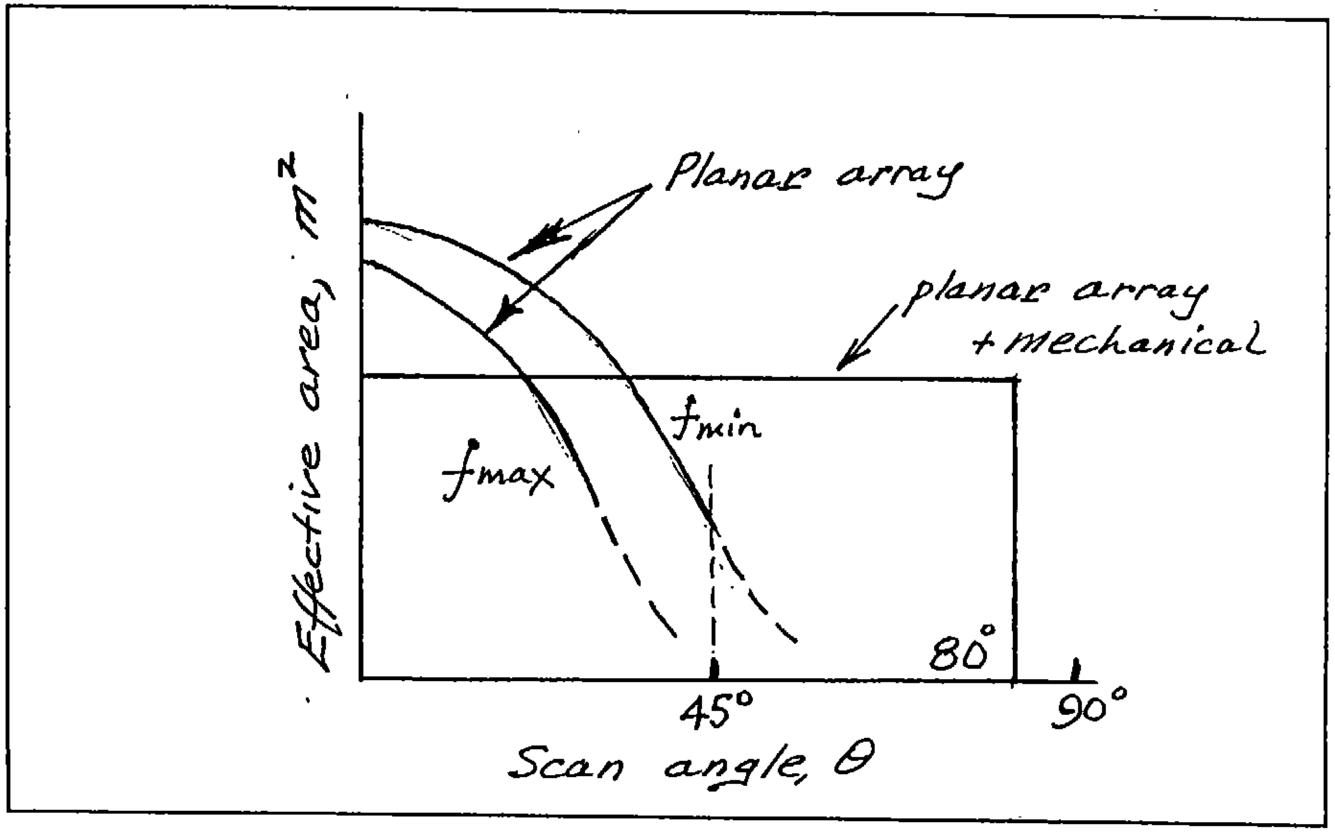
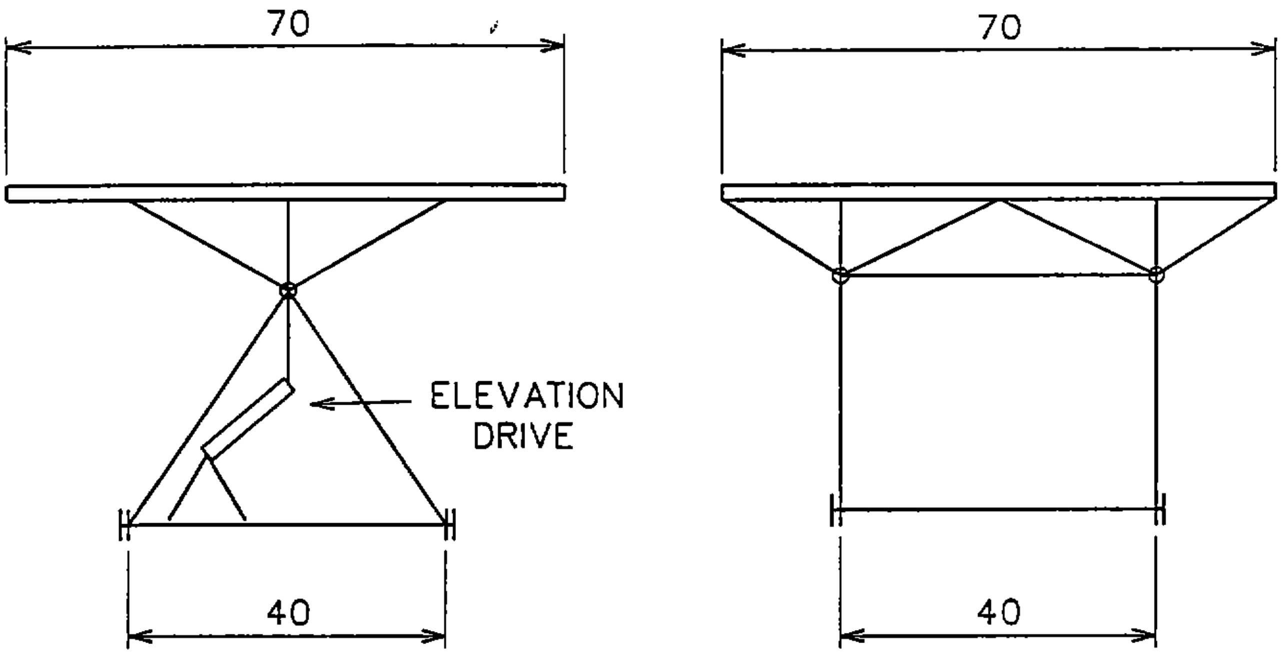


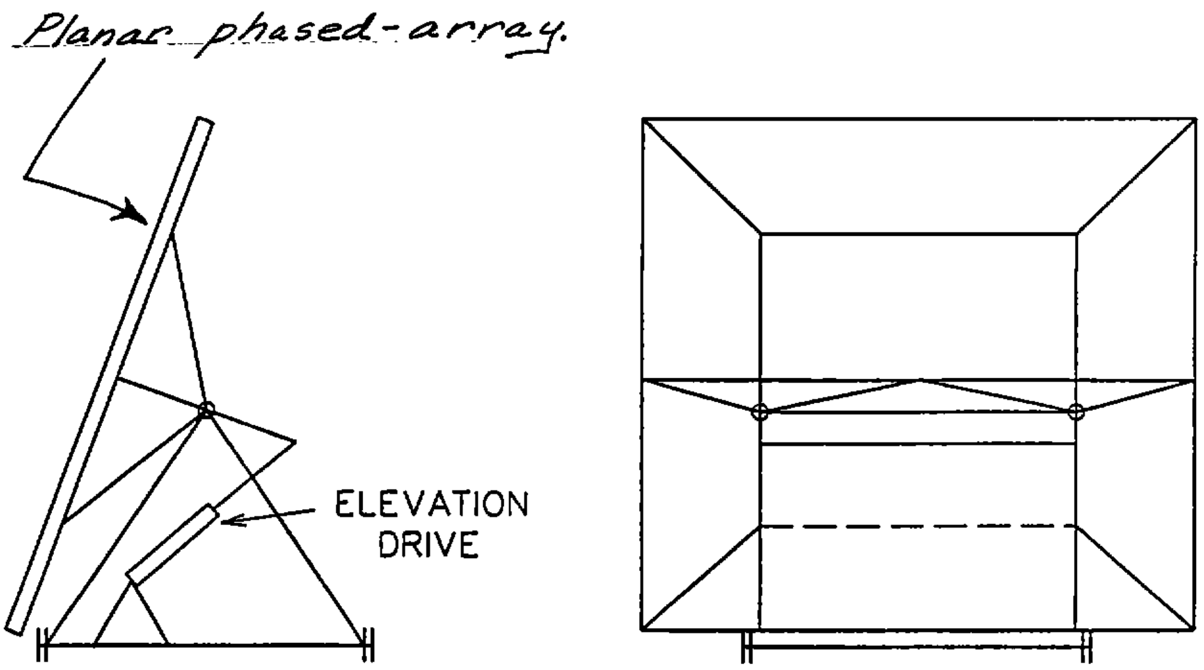
Fig.2.1: An illustrative example comparing different (100m) array-element technologies. Characteristic: effective area versus elevation angle for a fixed cost.

Fig. 3.1: THE 1kT ?

—Limited-scan phased-array on simple mount.



ELEVATION = 90°

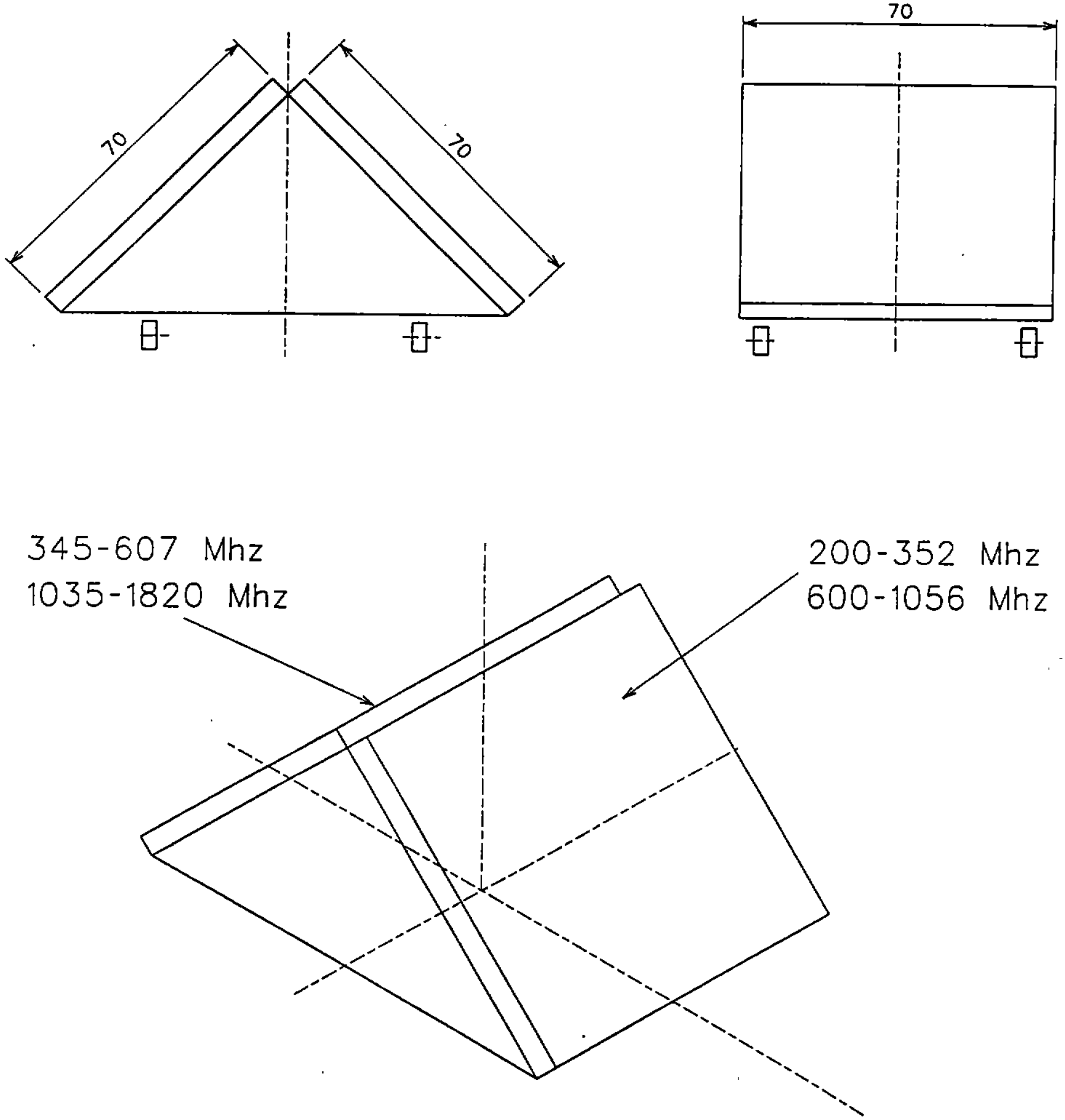


ELEVATION = 20°

FIG. 3.2: THE 1kT ?

Azimuth- Mechanical.

Elevation- Electronic Scan, ±40° about normal



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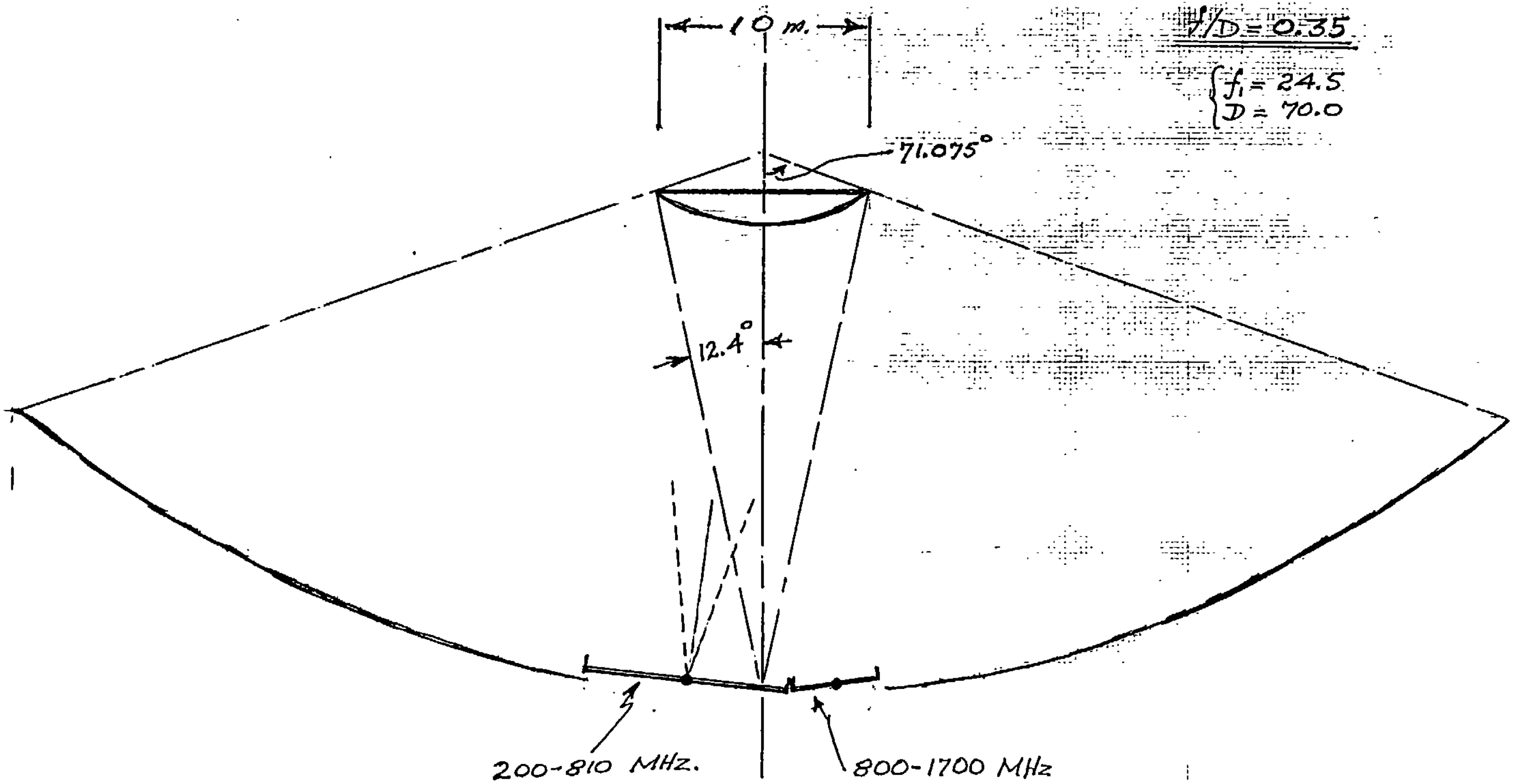

Fig. 4.1: The Cassegrain Optics.

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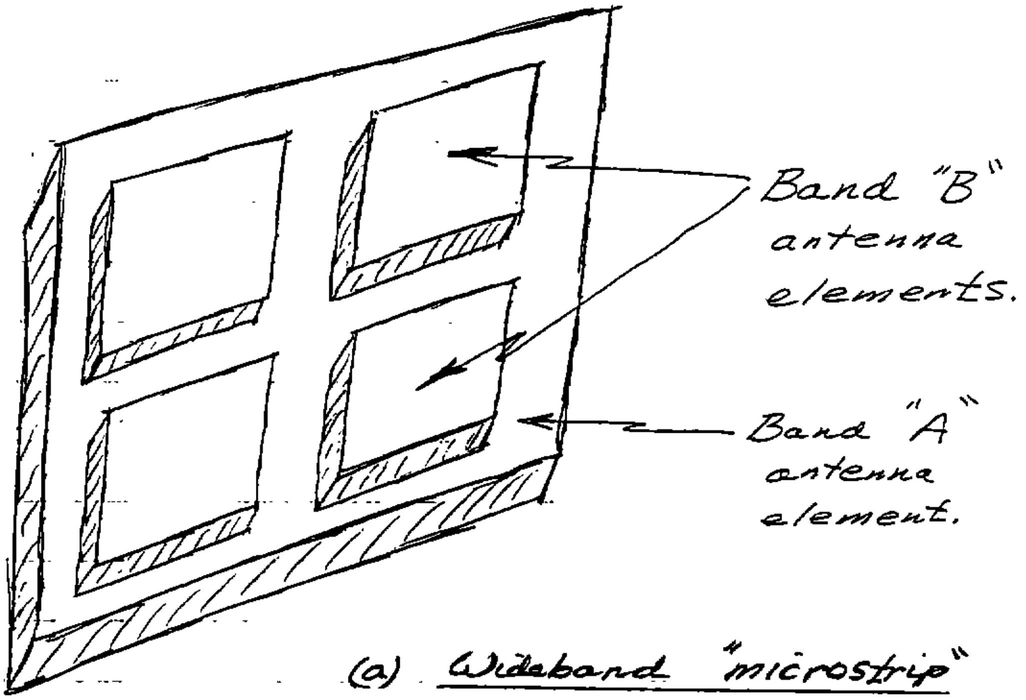
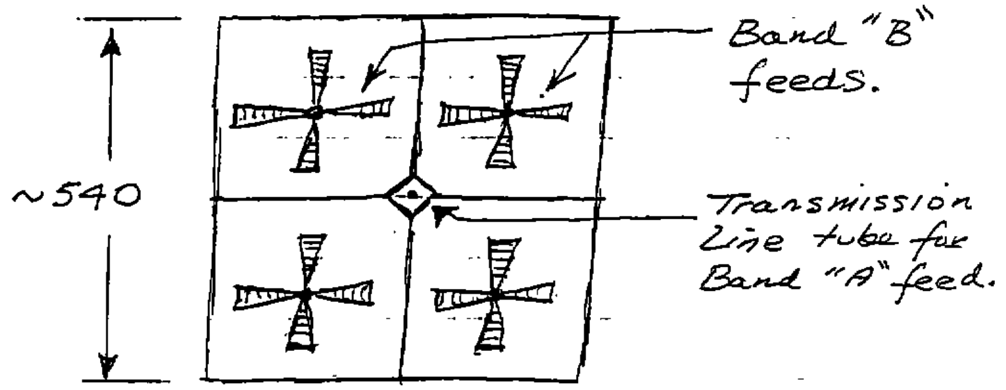
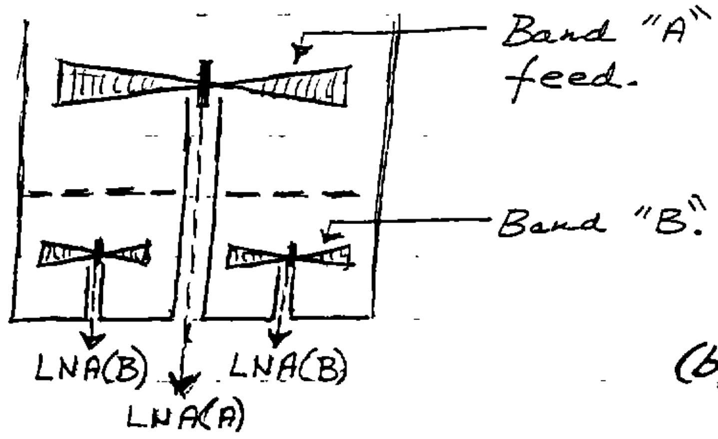
FIG. 4.2 : CONCEPTS FOR THE "TILE"

(Diagrammatic Only)



(a) Wideband "microstrip" technology (horizontal and/or vert^{l}).





(b) Square-Waveguide Technology.

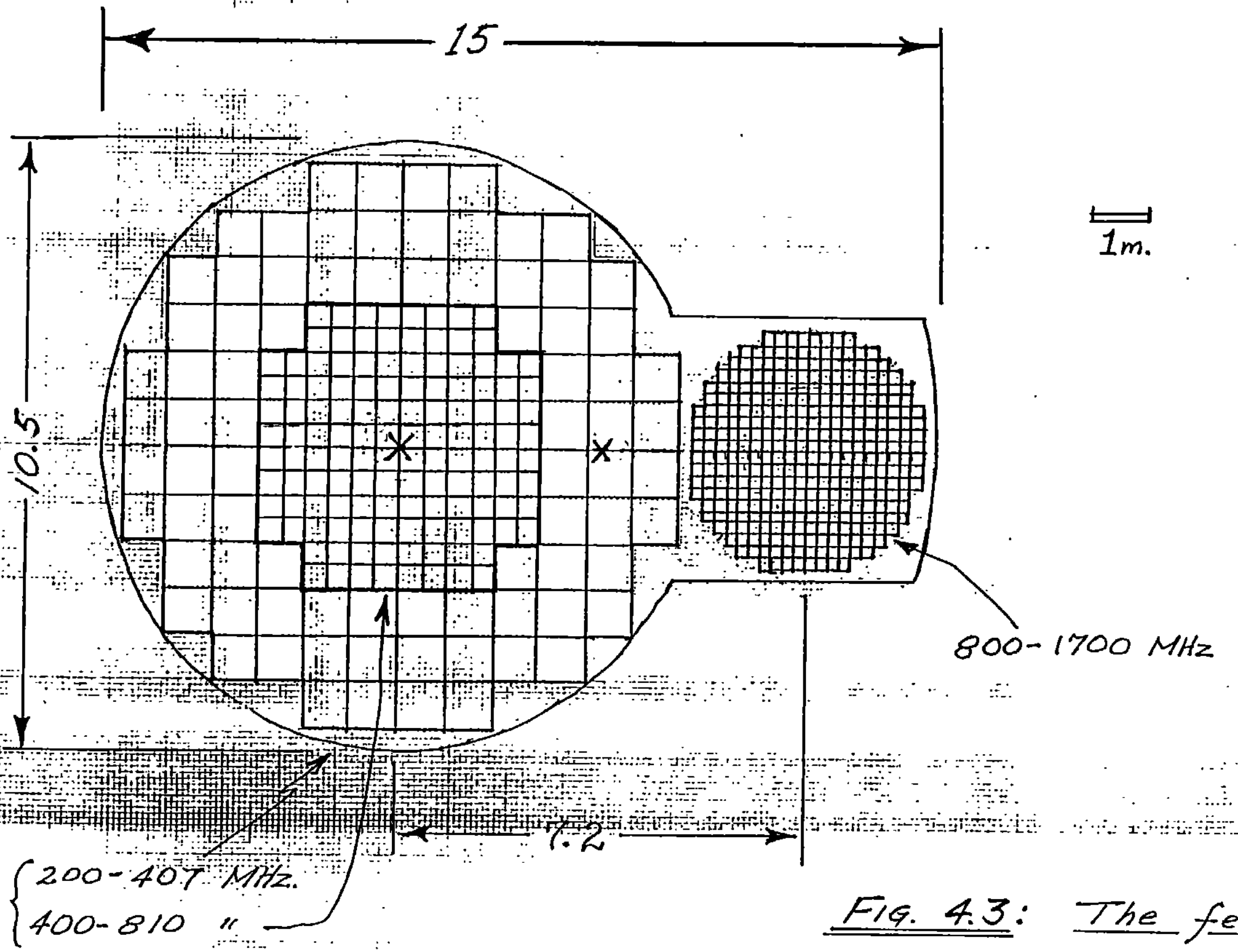


Fig. 4.3: The feed array.

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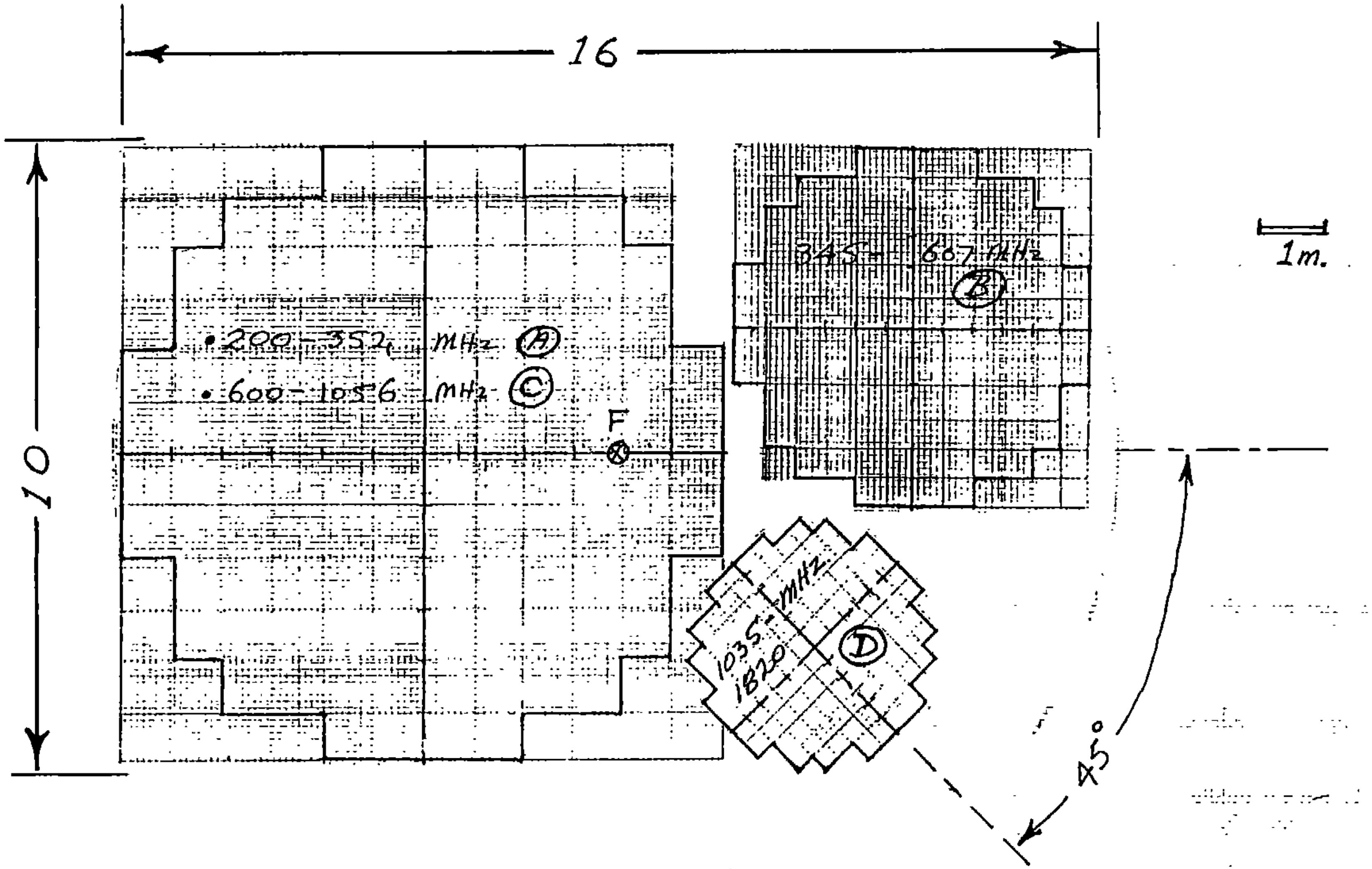

Fig. 4.4: An alternative feed array.

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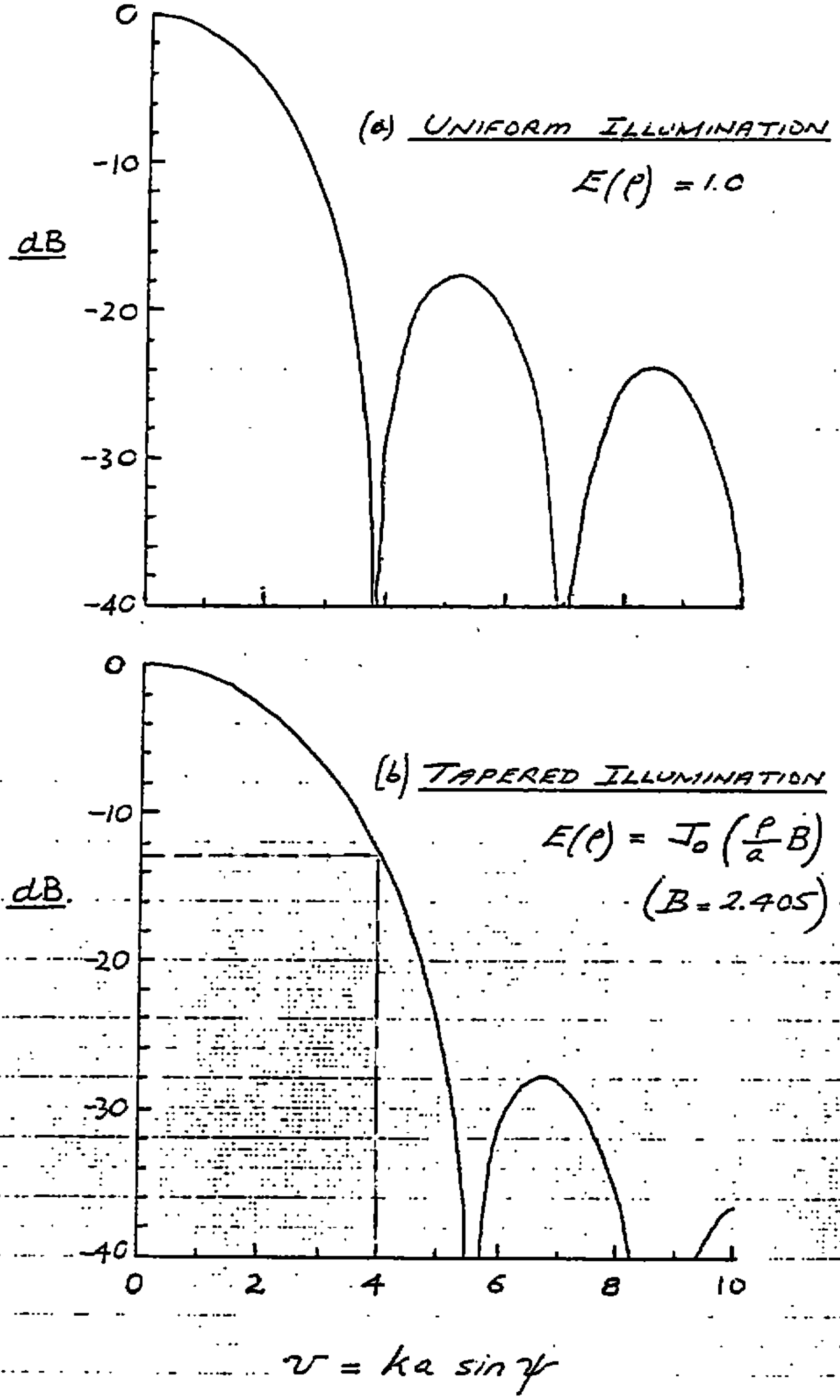

FIG. 4.5: Theoretical patterns of circular apertures.

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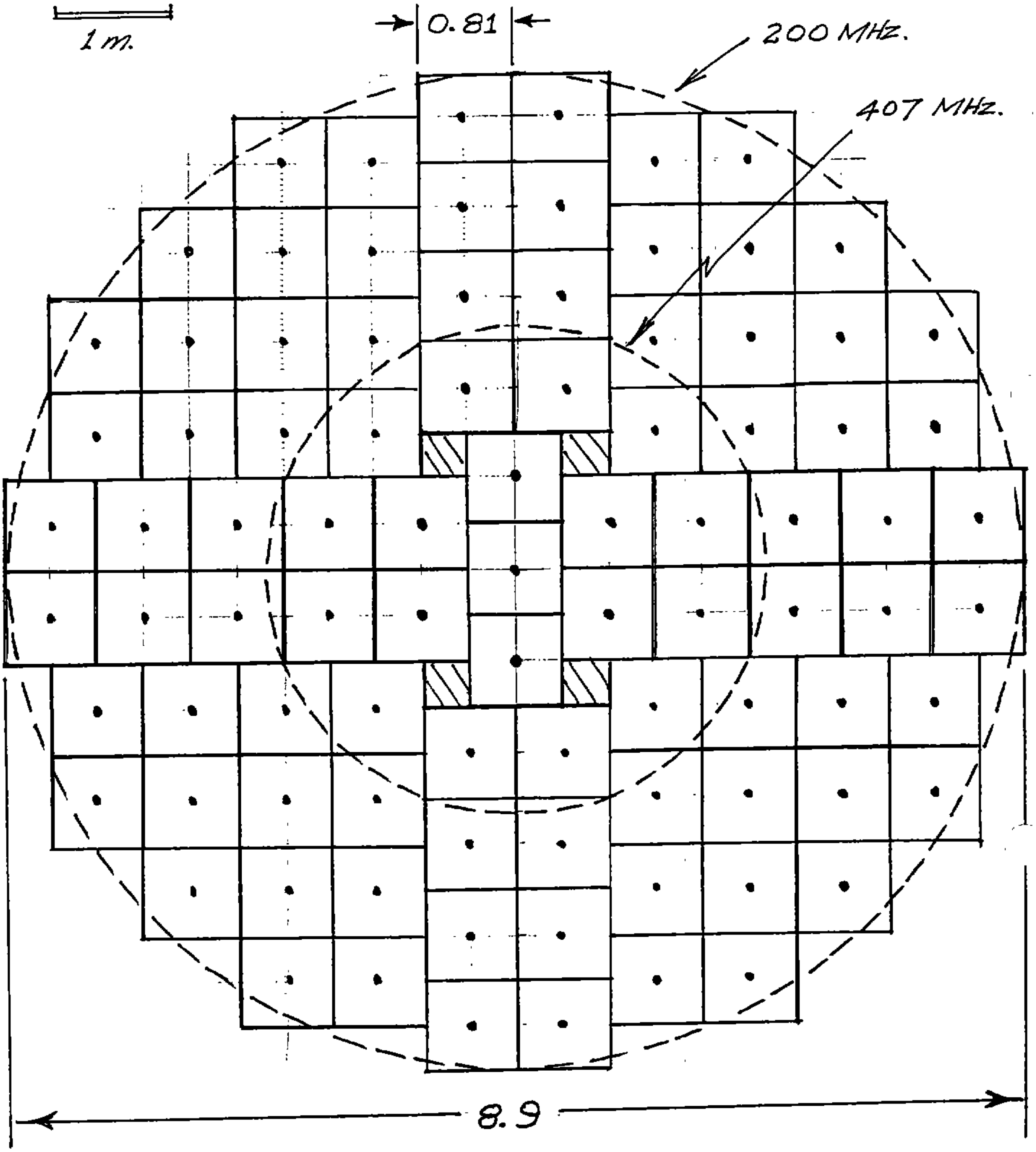

FIG. 4.6: Feed array configuration for reduced sidelobes.