O. Roscoe

RCA

Technical Report

(2)

FEASIBILITY STUDY OF A 4 FREQUENCY BAND SPACECRAFT ANTENNA SYSTEM

Prepared for

Department of Communications
Ottawa, Ontario.

Contract No: IPL36100-5-0596
Serial No: OPL5-0063

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Printed in Canada
August 23, 1975

Proj. No.: 3500-T/6
Rev. No.: 0

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1.0 INTRODUCTION

This study is the continuation of a series of studies sponsored by the Department of Communication under Contract No. IPL36100-5-0596, Serial No. OPL5-0063 to investigate the feasibility of including additional UHF frequency bands into the antenna system of a hybrid UHF - 4/6 GHz spacecraft antenna system.

According to the specification, a total of 4 frequency bands must be covered:

a) 275 - 420 MHz
b) 880 - 890 MHz
c) 3700 - 4200 MHz
d) 5925 - 6425 MHz

The coverage area for most of the above frequency bands must correspond to the large part of Canada, thus representing a minimum of $2^{\circ} \times 8^{\circ}$ angular coverage. The desired edge gains in the various frequency bands are:

a) 19 dB
b) 25 dB
c) 27 dB
d) 27 dB

Since the gain requirements have to be met simultaneously and an interaction between practically feasible gains exists among various frequency bands, some priorities among the frequency bands have to be established. For the purpose of the present study, these priorities were set in this sequence: c, d, a, b.

The following investigation centers around the basic concept of using a single deployed 13 Ft. diameter paraboloid reflector for all frequency bands. As a fall back position, a separate array is used for frequency band b, but even in this configuration, the array is mounted into the focal plane of the paraboloid.

First of all, it is assumed that there should be very little sacrifice in the 4/6 GHz gain after the UHF feeds have been incorporated into the same antenna. Hence, blockage and other scattering effects have to be minimized to achieve the desired 27 dB edge gain in the 4/6 GHz bands for Canadian coverage. It is also noted that with the available aperture, an edge gain of 19 dB over the required coverage represents a 75% efficient antenna at 275 MHz. Such an efficiency is difficult to achieve even under the normal ideal feed conditions. It is therefore clear that the design of such an antenna is by no means straightforward.

The following study is an effort to produce a reasonable design to come close to the design objectives within given contraints. It does not necessarily represent the best solution to the problem, bearing in mind that other design approaches are always available for future considerations.

2.0 MECHANICAL RESTRAINS

The present discussion is limited to the case of a 13 Ft. deployable parabolic reflector. It is deemed best to have the central part of the reflector made solid and rigid to achieve low rms surface error, while the outer portion of the reflector deploys once on station. This mechanical design approach has been considered in a previous report[1]. The deployable web and rib portion of the reflector has a higher rms surface error than the central solid portion. Certain minor modifications of this basic design may have to be introduced to produce a slightly better rms surface error in certain parts of the outer deployable annulus portion. The reason behind this modification will become clear when the electrical design is being discussed.

One major parameter critical to the mechanical design is the focal length of the reflector. A compromise is being sought to produce a focal length amenable to mechanical as well as to electrical solutions. Here, again the UHF feeds become the constraints.

3.0 ELECTRICAL CONSIDERATIONS

Typical f/D ratios for microwave antennas are between 0.25 and 1.0. For the present case, the focal length can range from 39 inches to 156 inches. For the 4/6 GHz antenna, a 39 inch focal length is just about the optimum since only a part of the reflector is being used. However, at UHF frequencies, the feeds will have to have hemi-spherical radiation patterns. It is possible to design feeds to approximate such patterns and, physically, these structures are small compared with the wavelength. Since the focal region is occupied by the 4/6 GHz feed horns, the UHF feeds will have to be placed around the 4/6 GHz feed horns. Two design difficulties are now encountered. Ignoring the interfering effects of the 4/6 GHz feed horns with the UHF feeds, it is observed that at 39 inches away, the reflector is not quite in the far field of the UHF feed. A quick analysis will confirm this fact. It can be shown that the induction and the radiation fields are respectively proportion to $1/r^2$ and $2\pi f/rc$, where r is the distance, c the velocity of light and f the frequency. For these two fields to have equal strengths

$$1/r^2 = 2\pi f/rc$$

$$\text{or} \quad r = \lambda/6.$$

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(1) Final Report: UHF Communications Payload Implementation Study. DSS Contract Ref. PL36100-4-2008, RCA, July 1975.

At 275 MHz this distance is about 7 inches. Thus, at the reflector, the induction field is only 15 dB down from the radiation field. An exact analysis becomes formidable since analysis based on geometric optics does not apply anymore. The second design difficulty comes from the fact that the 4/6 GHz feed horns have already occupied the focal region. It is estimated that the size of the 4/6 GHz feed at 39 inches is a rectangular aperture approximately 9.2" x 4.7". The UHF feed structures will have to be displaced from the focal region to clear the 4/6 GHz feed horns. Such a displacement results in beam deviation (minimum about 7.5^{o}) which in turn means a loss of gain. The remedy for this situation is to use two UHF feeds on either side of the 4/6 GHz horns (an orthogonal pair will provide the circular polarization needed). This pair of feed structures forms a broadside array feeding the reflector. It appears that at this point the problem is under control. However, on closer examination, it is discovered that the array factor has undesirable influence on the primary pattern thrown on the reflectors. A computer program was written to analyse the primary pattern with emphasis on the array factor. It is now known that nulls can appear on the reflector if the spacing of the two UHF feed structures are spaced above a certain distance. The minimum spacing of the UHF feed structures is dictated by the size of the 4/6 GHz horns. In this particular aspect, the 880 - 890 MHz band presents a problem. A computer program (GLORL2) was written to calculate the array factor for a two element array (on the focal plane) taking the space attenuation factor into account. The output of this program multiplied by the element pattern gives the distribution on the reflector from which the far field pattern can then be calculated. A second computer program (GLOFL2) calculated the array edge taper versus various focal lengths and its output for three UHF frequencies of 275 MHz, 420 MHz and 890 MHz are shown respectively in Figures 1, 2 and 3. From these parametric curves, the focal length for any one of the three frequencies can be optimized. The obvious choice is to optimize the gain for the lowest frequency while maintaining a feasible physical separation of the array elements for the higher frequencies. It is observed that at 890 MHz, the 4/6 GHz horns will always be in the way of the array and it is also impossible to place the 890 MHz elements in front of the 4/6 GHz feeds without interfering with the 4/6 GHz horn patterns. The conclusions from such calculations indicated that two possible feed configurations can be used for the 880 - 890 MHz bands: a) a third (separate) array structure not utilizing the available reflector, b) a slot array feed illuminating the reflector.

Looking at Figure 1, the near optimum focal length for 275 MHz is approximately 45 inches. With this focal length, the array factor together with the space attenuation factor results in an edge taper of 8 dB if the spacing is kept around 11 or 12 inches. The final edge taper would be higher than this value since the element pattern has to be taken into account. The actual value will depend on the type of structure used. This brings about the discussion of the UHF feed structures.

With all the available information so far gathered, it is obvious that three feed structures are necessary, one for the 4/6 GHz bands of which a design is readily available and two for the UHF frequencies. It has been mentioned that the 880 - 890 MHz band should have its own separate antenna or feed. A compact antenna at such a frequency is a 6 - helix array. Past experiences[2] have shown that a boresight gain of about 25 dB is available from such a structure if the helices are positioned at the corners of squares of sides 1.4λ in length. The remaining structure will have to cover the frequency band of 275 MHz to 420 MHz. For such a wide bandwidth, the favourable candidate at UHF frequencies is the log periodic structure, in particular the type proposed by Isbell[3]. Figure 4 shows the approximate physical configuration and the type of patterns from this configuration for the band of 275 MHz to 420 MHz. It can be seen that the E-plane pattern has an appreciable taper while the H-plane pattern is much broader. This assymetry in E and H-plane patterns is actually favourable since the log periodic arrays are stacked in the H-plane and the array factors calculated above are multiplied by the H-plane pattern to form the H-plane illumination pattern on the reflector.

The preferred arrangement would be a combination of four such log periodic arrays in a turnstile fashion to produce the required circular polarization. The entire feed reflector arrangement is shown in Figure 5. A side view sketch of the feeds and part of the 880 MHz antenna is shown in Figure 6.

Because of the blockage in the focal region, it is necessary to off-set the 4/6 GHz portion of the reflector to clear the blockage caused by the 6 - helix array and the 4/6 GHz feed horns (See Figure 5). With the 4/6 GHz portion of the reflector extending into the deployable section, it is necessary to improve the rms surface accuracy in that area so that there is a minimum loss of gain in the 4/6 GHz communication bands. This may require additional ribs in that area to form a more accurate surface.

4.0 GAIN & PATTERN CALCULATIONS FOR SYSTEM CONFIGURATIONS USING SEPARATE 885 MHz ARRAY

The preferred focal length for the reflector was chosen to be 45 inches. The gain and the far field pattern are then calculated for several frequencies to check the design. The feed configuration is as shown in Figure 6. In these computations, the reflector is assumed to be perfect and that blockage is ignored. With the log periodic arrays, there is a certain amount of backward radiation (about - 17 dB)

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(2) See for example, J.D. Kraus "Helical Beam Antennas for Wide Band Application" Proc. IRE, Oct. 1948, pp. 1236 - 1242.

(3) "Log Periodic Dipole Arrays", D.E. Isbell, IRE Trans. AP-8, May 1960, pp. 260 - 267.

not intercepted by the reflector. All these secondary effects are taken care of in the gain table in a separate calculation. Figures 7, 8, 9, 10, 11 and 12 show the gain and pattern calculation of the frequencies 275 MHz, 420 MHz, 3720 MHz, 3950 MHz, 4200 MHz and 6175 MHz, these calculations have already included the aperture efficiency and the spillover loss.

The gain of the 6-helix array has been established by previous RCA Limited experience. It is known that a single eight-turn helix produces approximately 17 dB gain and each doubling of helices spaced the optimum spacing will increase the gain by 3 dB. Based on measured results (see Figure 13) it can be shown that the boresight gain of a 6-helix array is 24.95 dB. The gain can be further increased by additional helices, only at the expense of the gain of the lower frequencies. Since the gain at 275 MHz is already below expectations, additional helices with the associated ground plane can only cause more blockage and scatter. Thus, the 885 MHz antenna is also somewhat short of the design goal of 25 dB. It should be mentioned that the ground planes of the top four helices are actually used to reduce the back radiation of the log periodic turnstile. At the same time, the six-helix array is actually placed independently of the focus of the main reflector to achieve minimum or zero blockage of the 4/6 GHz. The final location of the 6-helix array can be chosen such that the 4/6 GHz elliptical reflecting area of the reflector can be shifted towards the center of the reflector to minimize mechanical problems.

In conclusion, there are several important comments regarding this particular design. Firstly, the N-S dimension of 4/6 GHz elliptical reflecting area can be reduced and compensated for by an equivalent increase of the E-W dimension. The loss is insignificant, but the mechanical problem becomes easier. In the above analyses, the scattering of the energy at 400 MHz due to the 4/6 GHz feed horns has not been analyzed. The increase in the E-W dimension of the 4/6 GHz reflecting area results in a smaller E-W dimension of the 4/6 GHz feed horns. Qualitatively, this will reduce the scattering problem. However, it requires further study or even experimentation to determine the magnitude of the problem.

From the gain Table 1, it is obvious that there is no sacrifice in the 4/6 GHz performance. However, the gains are below expectations at 275 MHz and 885 MHz. The margin available in the 420 MHz gain will probably disappear once scattering is accounted for. In conclusion, the feed design has been fairly difficult and the gain expectation of 19 dB from 275 MHz to 420 MHz and also the gain of 25 dB at 880 MHz are somewhat optimistic with this approach.

Table 1.

Characteristics For Various Frequency Bands

(885 MHz Band is Covered by Separate Array)

	275 MHz	420 MHz	885 MHz	3720 MHz	6175 MHz
Boresight Gain	19.03	21.93	24.95	29.85	31.09
Computed Edge Gain E-W Edge Gain N-S	($3^{\circ} \times 9^{\circ}$) 18.78 18.98	($3^{\circ} \times 9^{\circ}$) 21.2 21.8	($4^{\circ} \times 8^{\circ}$) 22.82 22.82	($2^{\circ} \times 8^{\circ}$) 28.55 28.55	($2^{\circ} \times 8^{\circ}$) 31.12 28.95
Phase Error and Surface Error Loss	0.60	0.57	N/A	0.40	0.45
Blockage	0.36	0.41	0.0	0.0	0.0
Back Radiation	0.17	0.11	N/A	N/A	N/A
Thermal and Pointing	0.10	0.12	0.05	0.32	0.35
Cable and Feed Loss	0.12	0.15	0.22	0.30	0.35
Mismatch	0.20	0.20	0.10	0.05	0.05
Reflector Loss	0.08	0.10	N/A	0.18	0.20
Total Loss	1.63	1.66	0.37	1.25	1.50
After Loss Edge Gain E-W Edge Gain N-S	($3^{\circ} \times 9^{\circ}$) 17.15 17.35	($3^{\circ} \times 9^{\circ}$) 19.54 19.60	($4^{\circ} \times 8^{\circ}$) 22.45 22.45	($2^{\circ} \times 8^{\circ}$) 27.30 27.30	($2^{\circ} \times 8^{\circ}$) 29.62 27.45

The gain at 275 MHz cannot be increased much further, but the gain at 880 MHz can be increased at the expense of the gains at the lower frequencies. A variation of the arrangement discussed in this section is shown in Figure 14, where the 4/6 GHz is fed offset in the E-W direction.

In this case, the outer part of the reflector is contributing less or at the extreme nothing to the 4/6 GHz band reflector. This greatly reduces the mechanical design problems associated with the improved accuracy requirements of the 4/6 GHz band part of this reflector section. The mechanical simplification is achieved at the expense of some frequency dependency in the EW pointing of the 4/6 GHz band patterns. Although no detailed computer analysis was done for this case withing the limited scope of this program, RCA Limited's past experience indicates that the frequency dependent EW squint of the pattern may amount to about $.15^{\circ}$, causing an edge gain variation for the given Canadian coverage in the order of .5 dB. (Note that the N-S offset described earlier has only about half of this squint. Furthermore, the squint has no practical effect on the edge gain for the given Canadian contour since the edge gain limitation is presented by the E-W plane.)

A subalternative for the location at the 4/6 GHz aperture is to keep the N-S offset configuration, but pull it back further towards the middle of the reflector. In this case, the compromise is between mechanical complexity of the reflector design and the blockage caused by the corporate feed. For a compromise location, when the 4/6 GHz aperture is offset fed by quarter of the N-S aperture dimension, the center of the corporate feed is at the -3 dB point of 4/6 GHz aperture distribution. For this case, a 10% geometrical optical blockage will cause approximately .5 dB reduction of edge gain relative to the figures given for the 3720 MHz column and approximately .4 dB reduction for the 6175 MHz column in Table 1.

The feed horn configuration for the 4/6 GHz frequency band is assuming a 3 horn design. This is a slightly different feed from the one previously investigated [1)] but it has slightly better edge gain performance and its central horn can be readily used for the generation of a C-band spot beam. (More detailed performance characteristics for this feed configuration are presently being computer analyzed by RCA Limited for another program and the results will be available shortly.) The feed network of this 3 horn configuration for one frequency band consists of two hybrids and two branchline couplers.

5.0 CHARACTERISTICS OF A CONFIGURATION USING THE AVAILABLE REFLECTOR AT 885 MHz

This configuration offers a solution to improve the gain at 885 MHz for a small sacrifice in gain of the 4/6 GHz. Only an approximate analysis will be given for this case. Figure 15 shows: a) the 4/6 GHz horn array and b) the developed version of the 4/6 GHz horn array to incorporate a slot radiator 885 MHz feed.

The three stacked horns of the 4/6 GHz array are now moved slightly apart to allow a slot or folded dipole to be inserted in place. An orthogonal pair is placed at the top and the bottom of the horns to provide a near circular polarization. If LP is preferred, the orthogonal pair of dipoles is not necessary. The individual folded or slot dipoles must be cavity backed to provide an almost hemispherical pattern in the H-plane. The stacking provides the edge taper in the H-plane. The E-plane pattern is that of a normal $\lambda/2$ dipole. The unequal stacking distances of the orthogonal pair of dipoles will result in slightly unequal E and H-plane beamwidths which in turn will give rise to a non-perfect axial ratio. The feasibility of such an arrangement is totally dependent on the performance of the cavity backed dipoles. This problem cannot be adequately analyzed analytically. The best proof of the validity of the design assumptions is by actual experiments. If such an arrangement is successful, the far field pattern is a nearly symmetrical pencil beam without shaping. The required $4^{\circ} \times 8^{\circ}$ shaped beam is still not achieved, however, the edge gain at 8° beamwidth is calculated to be about 25 dB assuming an overall efficiency factor of 55%. An extension of such an arrangement to achieve a partially shaped beam is to incorporate two additional slot folded dipoles at the edge of the horns in Figure 16.

The power dividing network now becomes a little more complicated and a good axial ratio of the CP wave is hard to maintain over the entire beamwidth. However, the E-W edge gain is better with such a feed, for the 885 MHz band. At the same time, the blockage for the lower frequencies (275 - 420 MHz) are reduced. The gain for these frequencies improves by about 0.25 dB.

The present blockage and weight calculations assume that no antenna coverage is provided for the 420 - 880 MHz band. However, there is no inherent limitation in the investigated log periodic antenna structure which excludes the extension of frequency band into the 420 - 880 MHz region. Such extension increases the blockage caused by the feed thus a gain reduction in the order of .3 dB occurs on that account. Furthermore, this part of the feed will be somewhat defocussed. Assuming that the extended feed covers the 420 - 800 MHz band, the antenna efficiency will be about .5 dB lower at 800 MHz than at 420 MHz.

The 4/6 GHz antenna configuration is essentially unchanged relative to the situation described in Section 4. One minor modification is the slight separation among horns in order to allow the presence of the 885 MHz slot radiators. This has the effect of slightly widening the E-W beamwidth in the 4/6 GHz band and reducing the gain at the saddle point in the middle of the coverage.

6.0 WEIGHT ESTIMATES (For the separate 885 MHz array described in Section 4) *

Table 2 summarizes the estimated weight of the antenna components required in the overall antenna system.

TABLE 2

Summary of Estimated Antenna Weight

1)	4 and 6 GHz Subsystem	Lbs.	
	Main reflector	22	
	Support tower and bracket	12	
	Feed horns	2	
	Coax cables	2	
	Orthocouplers (2 off)	2	
	Underdeck waveguide components	6	
	Thermal hardware	3	
		49	Subtotal
2)	UHF Subsystem	Lbs.	
	Extendible booms	4	
	Reflecting mesh	3	
	Feed system and wiring	4	
	Support bracket at tower	3	
	6-helix array	4	
	Springs, hinges and shock absorbers	3	
	Pyrotechnics controls and strings	3	
		24	Subtotal
	Grand Total	73 Lbs.	

* The weight is approximately .5 lbs. less for the configuration described in Section 5.

7.0 CONCLUSION

1. It is feasible to incorporate the desired additional frequency bands into one single paraboloid antenna design with some reduction of efficiency in the UHF frequency bands.

2. No compromise is necessary in the 4/6 GHz frequency band performance but a part of the reflector has to be constructed more accurately which causes some increase of weight and deployment complexity. Over 27 dB edge gain is feasible for this band.

   When the 4/6 GHz band aperture is located closer to the center of the paraboloid, the edge gain may drop to 26.5 dB.

3. An edge gain of 17 dB is feasible at 275 MHz.

4. An edge gain of approximately 25 dB seems to be possible at 885 MHz, but final verification of this performance requires some experimental work on an integrated 885 MHz and 4/6 GHz feed. If this approach fails, an edge gain of 22.5 dB is feasible with a separate 6 helix array which can be mounted in the focal plane of the paraboloid.

5. An additional frequency band coverage between 420 MHz and 800 MHz can also be provided at the expense of some reduction of the 275 - 420 MHz band edge gain and some increase in the antenna weight.

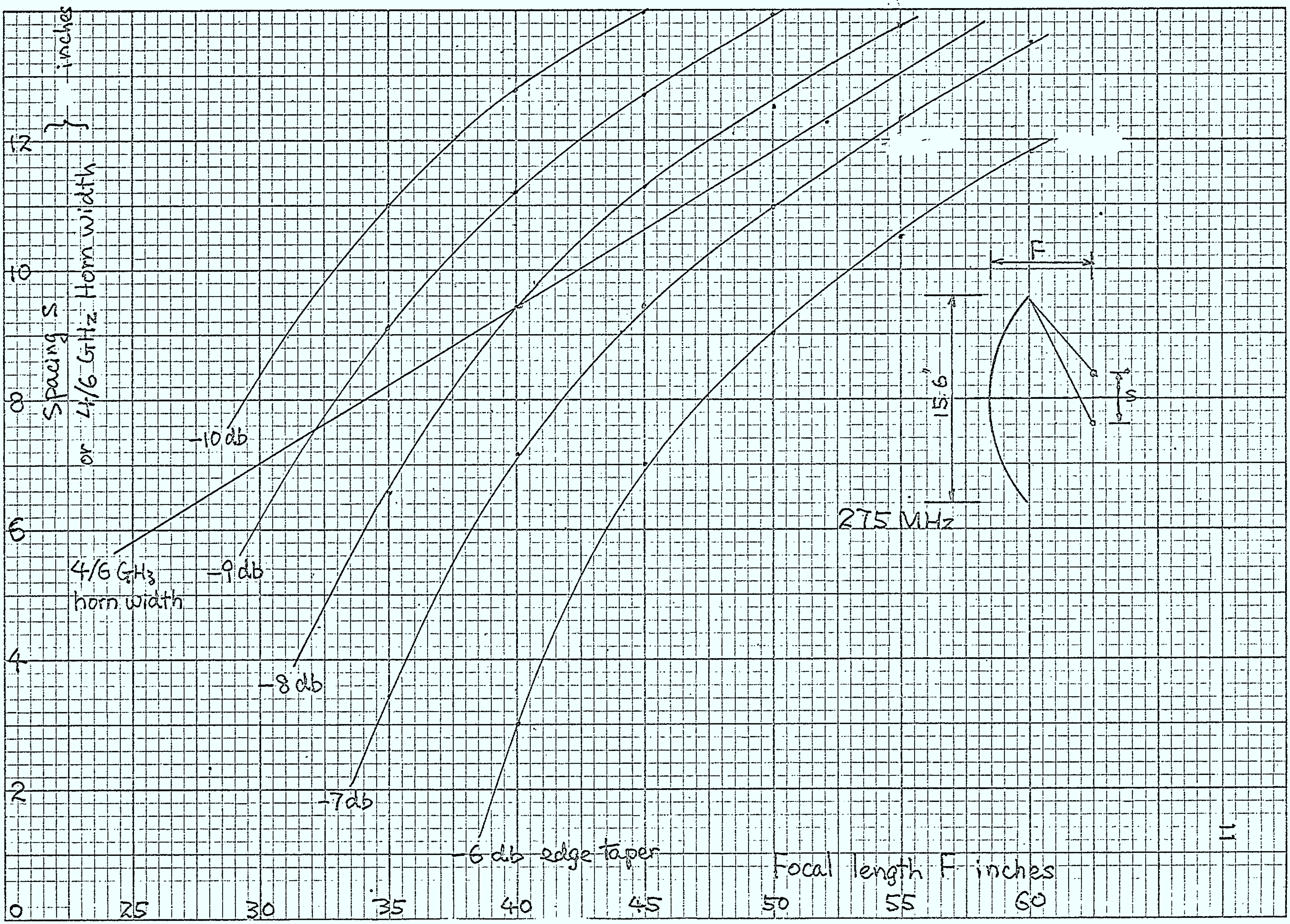


Fig. 1 Spacing vs. edge taper due to array factor.

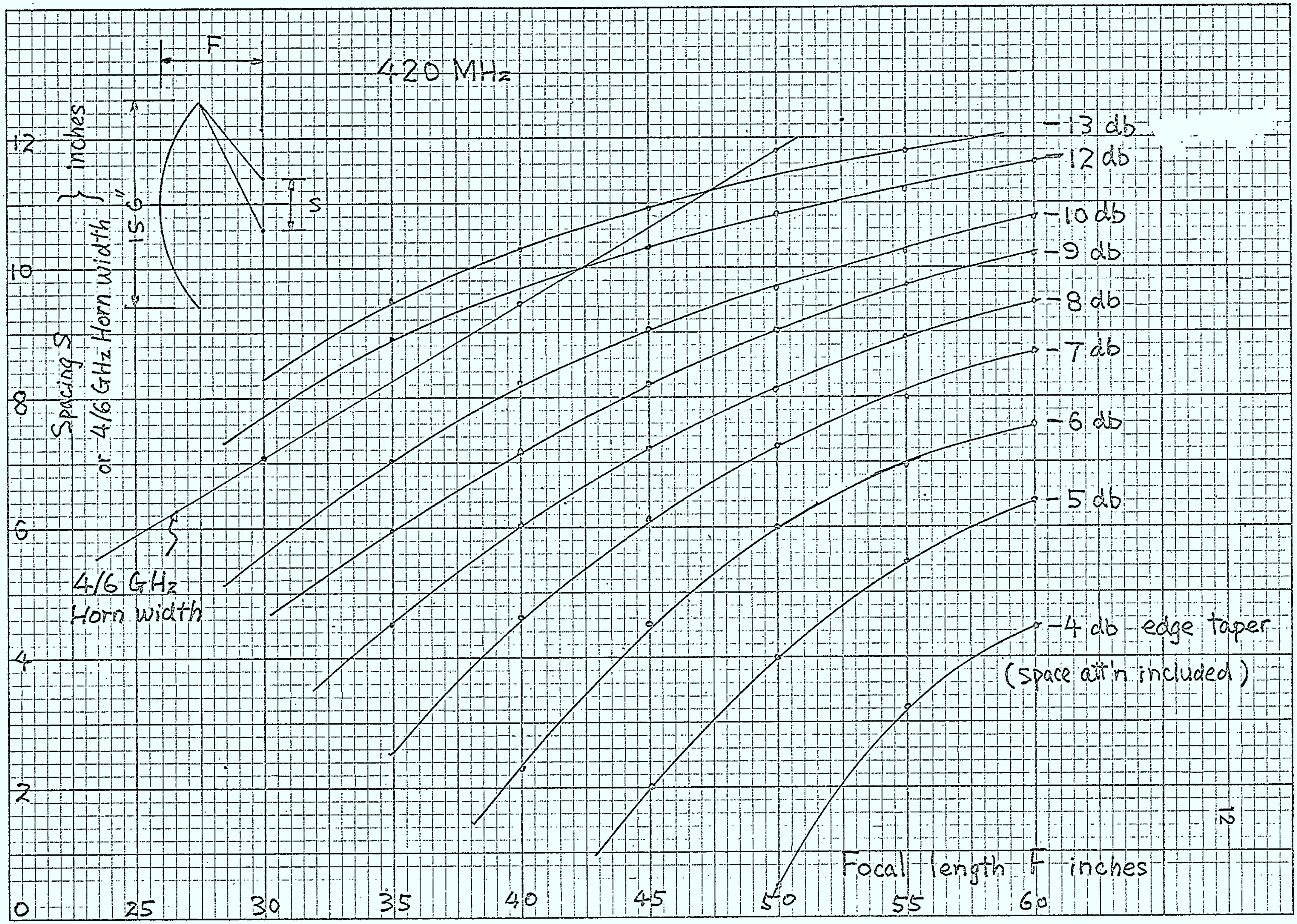


Fig. 2 Spacing vs. edge taper for two element array.

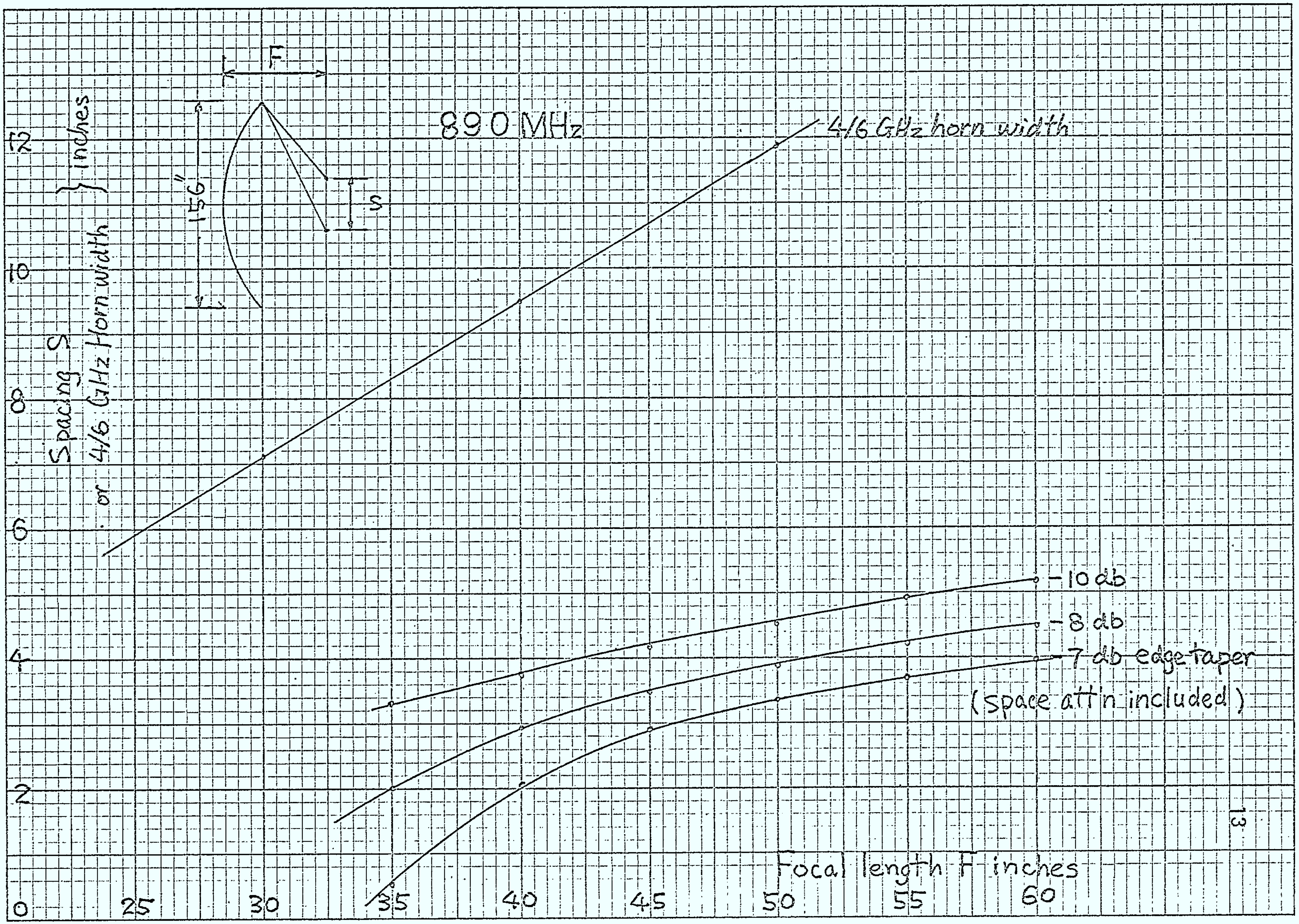
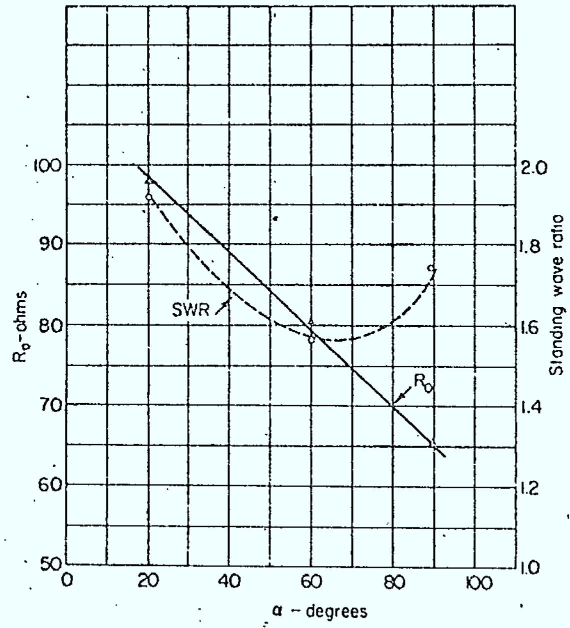
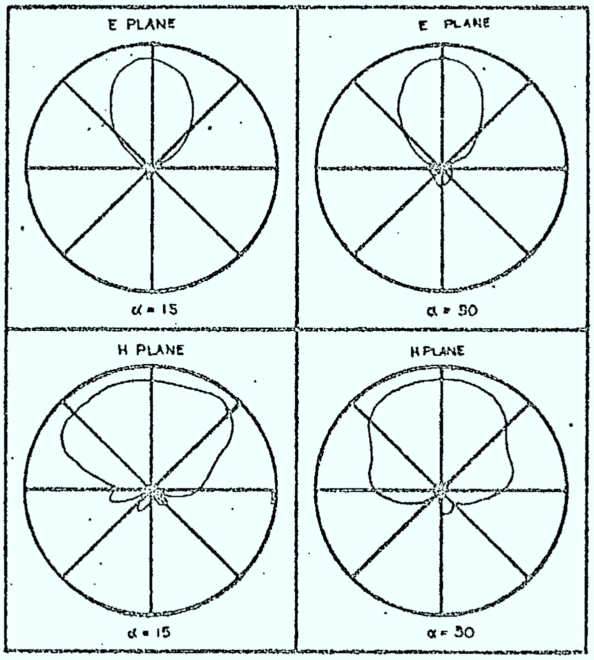


Fig. 3 Spacing vs. edge taper for two element array factor.



Input impedance $\tau = 0.81$



—Typical patterns; $\tau = 0.81$.

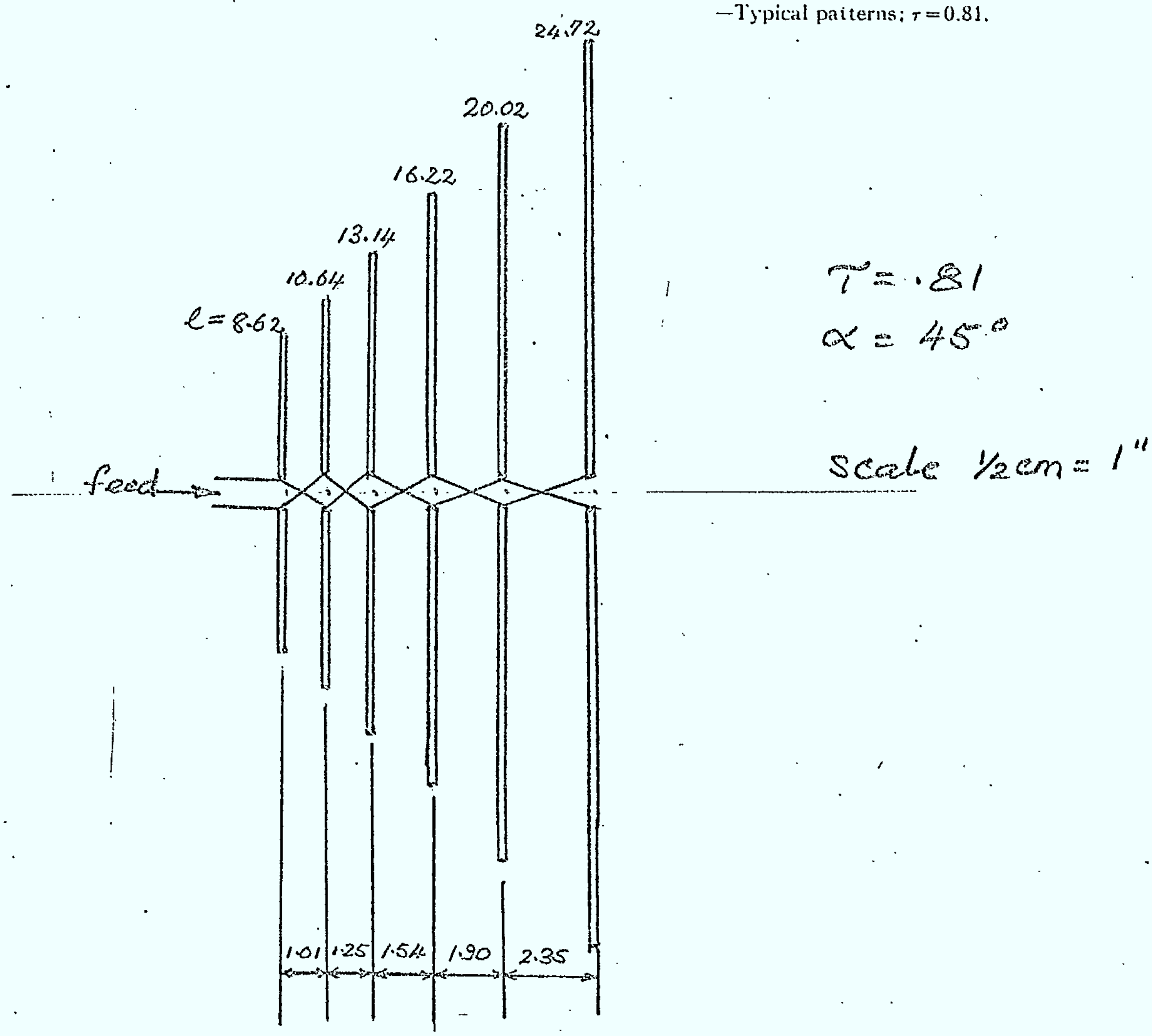


Fig. 4 Basic characteristics of the log periodic feed array.

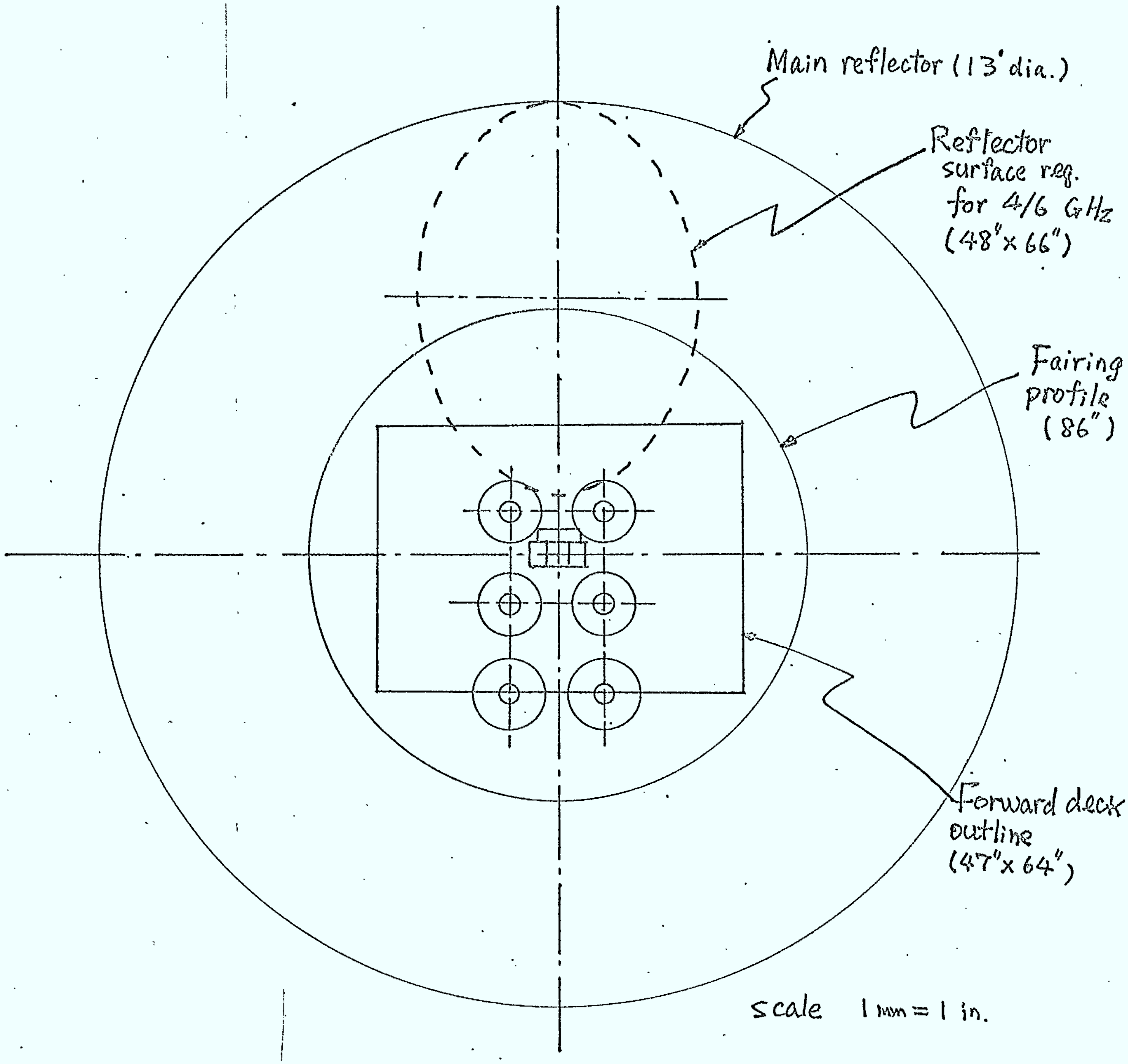


Fig. 5 Overall antenna configuration using separate 885 MHz antenna mounted in the middle of reflector.

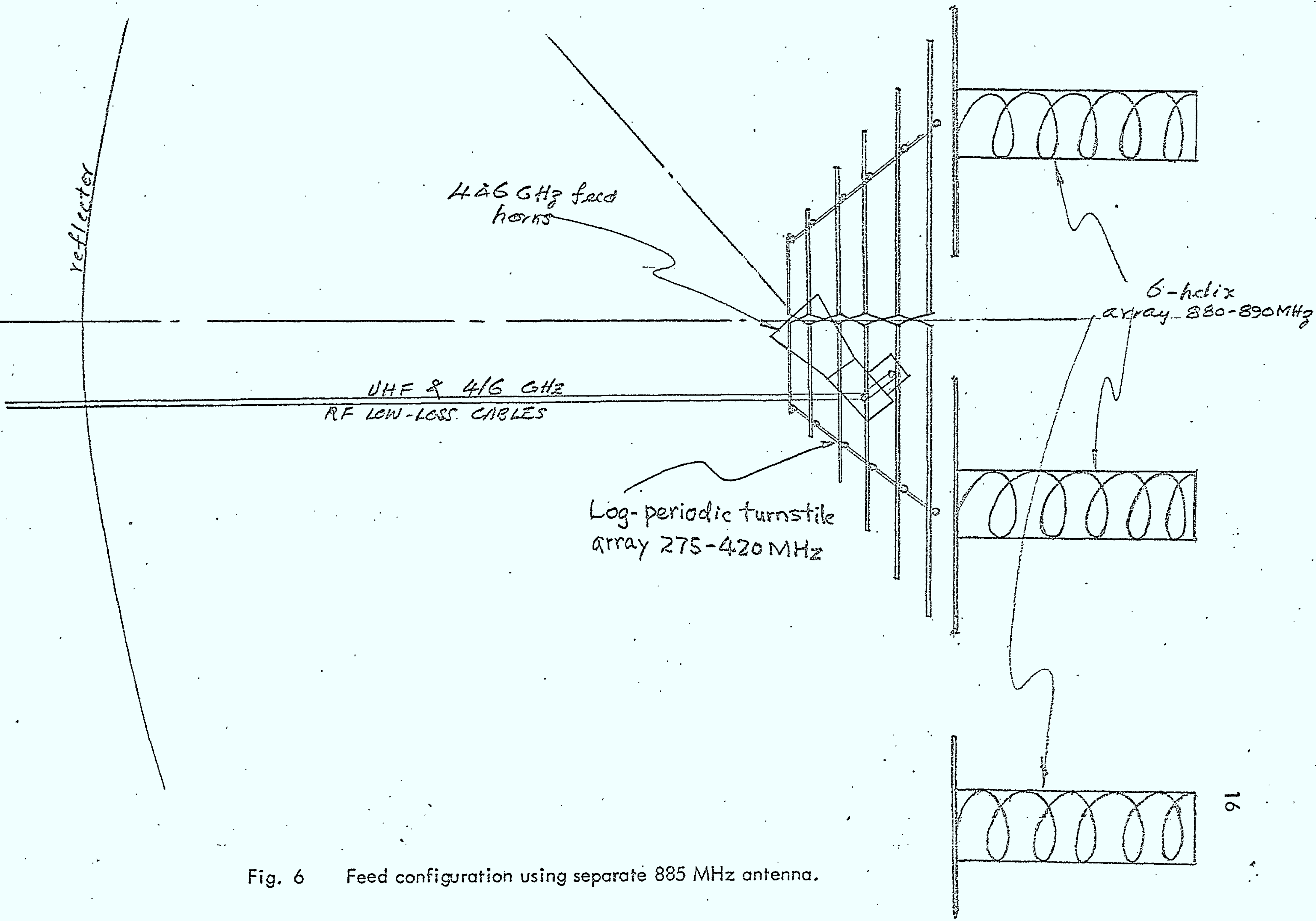


Fig. 6 Feed configuration using separate 885 MHz antenna.

1.) HORIZONTAL GAIN

Elevation (Degrees)	AZIMUTH (DEGREES) -10.00	-8.00	-6.00	-4.00	-2.00	0.00	2.00	4.00	6.00	8.00
10	15.694	16.089	16.394	16.611	16.740	16.783	16.740	16.611	16.394	16.08
8	16.449	16.862	17.182	17.411	17.545	17.592	17.545	17.411	17.182	16.86
6	17.038	17.466	17.798	18.031	18.174	18.220	18.174	18.031	17.798	17.46
4.	17.459	17.896	18.234	18.477	18.621	18.669	18.621	18.477	18.234	17.89
2.	17.712	18.155	18.499	18.744	18.891	18.938	18.891	18.744	18.499	18.15
0	17.796	18.242	18.587	18.833	18.979	19.031	18.979	18.833	18.587	18.24
-2.	17.712	18.155	18.499	18.744	18.891	18.938	18.891	18.744	18.499	18.15
-4	17.459	17.896	18.234	18.477	18.621	18.669	18.621	18.477	18.234	17.89
-6.	17.038	17.466	17.798	18.031	18.174	18.220	18.174	18.031	17.798	17.46
-8	16.449	16.862	17.182	17.411	17.545	17.592	17.545	17.411	17.182	16.86
-10	15.694	16.089	16.394	16.611	16.740	16.783	16.740	16.611	16.394	16.08

Fig. 7a Computed gain values of antenna at 275 MHz.

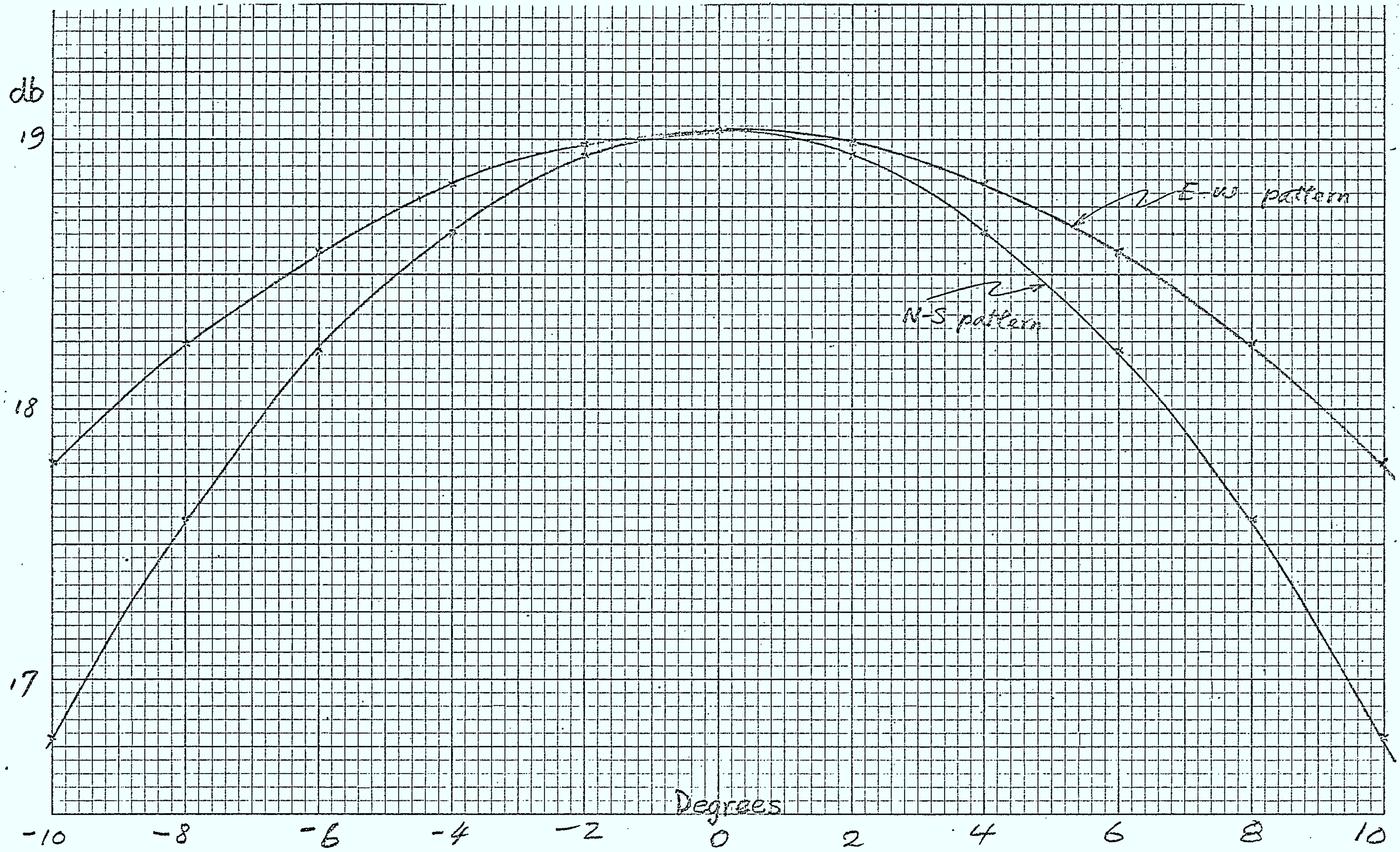


Fig. 7b EW and NS patterns of antenna at 275 MHz.

1.) HORIZONTAL GAIN

Elevation (Degrees)	AZIMUTH (DEGREES) -10.00	-8.00	-6.00	-4.00	-2.00	0.00	2.00	4.00	6.00	8.00
10	14.360	15.350	16.100	16.620	16.934	17.029	16.934	16.620	16.100	15.35
8	15.750	16.851	17.694	18.233	18.634	18.753	18.634	18.283	17.694	16.85
6	16.885	18.068	18.975	19.617	19.999	20.126	19.999	19.617	18.975	18.06
4	17.721	18.960	19.912	20.585	20.989	21.122	20.989	20.585	19.912	18.96
2	18.232	19.500	20.480	21.173	21.587	21.724	21.587	21.173	20.480	19.50
0	18.401	19.687	20.670	21.370	21.786	21.929	21.786	21.370	20.670	19.68
-2	18.232	19.500	20.480	21.173	21.587	21.724	21.587	21.173	20.480	19.50
-4	17.721	18.960	19.912	20.585	20.989	21.122	20.989	20.585	19.912	18.96
-6	16.885	18.068	18.975	19.617	19.999	20.126	19.999	19.617	18.975	18.06
-8	15.750	16.851	17.694	18.283	18.634	18.753	18.634	18.283	17.694	16.85
-10	14.360	15.350	16.100	16.620	16.934	17.029	16.934	16.620	16.100	15.35

Fig. 8a Computed gain values of antenna at 420 MHz.

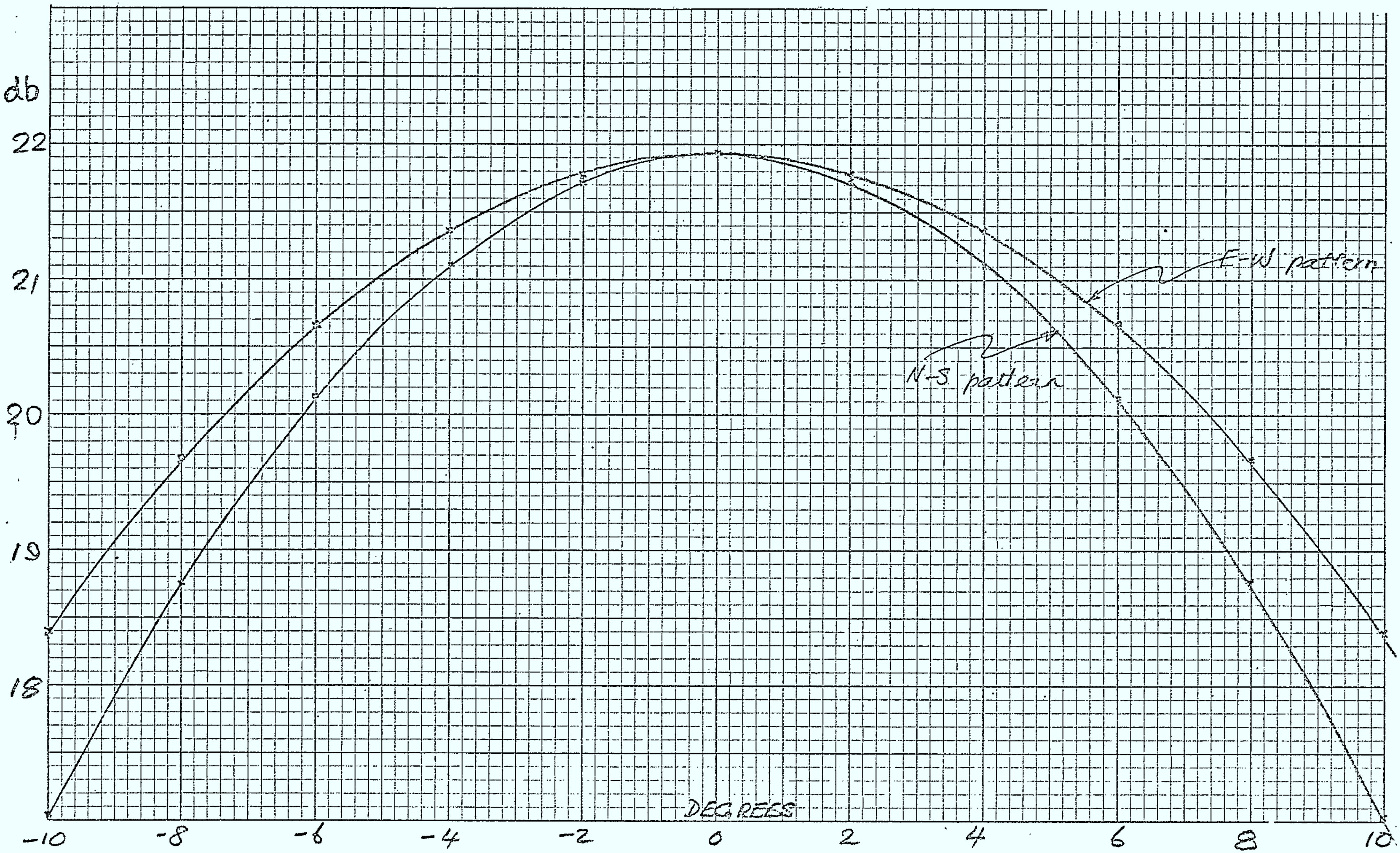


Fig. 8b EW and NS patterns of antenna at 420 MHz.

1.) HORIZONTAL GAIN

Elevation (Degrees)	AZIMUTH (DEGREES) -5.00	-4.00	-3.00	-2.00	-1.00	0.00	1.00	2.00	3.00	4.00
2.0	20.370	23.410	25.088	25.533	25.172	24.418	24.190	24.584	24.724	23.96
1.5	22.993	25.857	27.415	27.896	27.551	26.892	26.612	26.812	26.801	25.96
1.0	24.731	27.469	28.972	29.446	29.149	28.551	28.261	28.354	28.24[illegible]	27.35
.5	25.716	28.401	29.873	30.345	30.075	29.519	29.232	29.274	29.100	28.17
0.0	26.041	28.710	30.172	30.645	30.385	29.847	29.570	29.596	29.387	28.40
-.5	25.710	28.411	29.882	30.349	30.081	29.540	29.279	29.318	29.091	28.06
-1.0	24.707	27.477	28.977	29.437	29.134	28.564	28.324	28.405	28.153	27.09
-1.5	22.954	25.857	27.410	27.847	27.472	26.833	26.629	26.793	26.596	25.42
-2.0	20.350	23.448	25.074	25.481	24.970	24.192	24.027	24.338	24.180	22.89

Fig. 9a   Computed gain values of antenna at 3720 MHz.

Fig. 9b EW and NS patterns of antenna at 3720 MHz.

1.) HORIZONTAL GAIN

Elevation (Degrees)	AZIMUTH (DEGREES) -5.00	-4.00	-3.00	-2.00	-1.00	0.00	1.00	2.00	3.00	4.00
2.0	19.954	23.047	24.817	25.396	24.982	24.220	24.086	24.604	24.780	23.95
1.5	22.873	25.830	27.486	28.020	27.663	26.964	26.733	27.026	27.050	26.15
1.0	24.774	27.644	29.239	29.754	29.433	28.783	28.512	28.688	28.617	27.67
.5	25.829	28.662	30.237	30.747	30.445	29.827	29.549	29.672	29.537	28.55
0.0	26.144	28.988	30.558	31.066	30.774	30.172	29.901	30.006	29.838	28.81
-.5	25.748	28.637	30.225	30.735	30.433	29.827	29.573	29.692	29.507	28.43
-1.0	24.613	27.598	29.224	29.737	29.398	28.760	28.524	28.683	28.502	27.36
-1.5	22.685	25.806	27.495	27.994	27.582	26.865	26.649	26.894	26.734	25.50
-2.0	19.807	23.131	24.915	25.385	24.831	23.936	23.725	24.122	24.013	22.65

Fig. 10a Computed gain values of antenna at 3950 MHz.

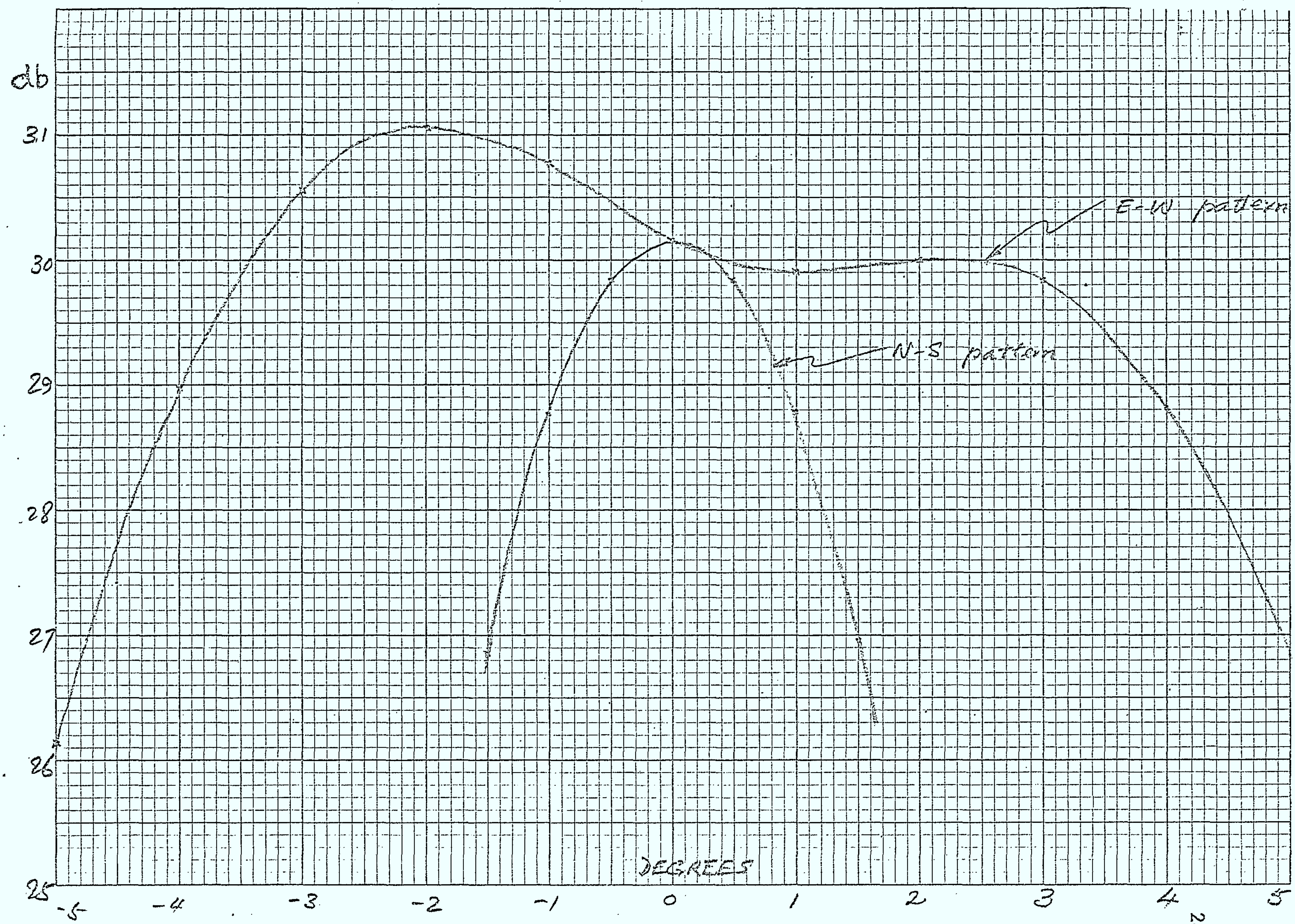


Fig. 10b EW and NS patterns of antenna at 3950 MHz.

1.) HORIZONTAL GAIN

* *

Elevation (Degrees)	AZIMUTH (DEGREES) -5.00	-4.00	-3.00	-2.00	-1.00	0.00	1.00	2.00	3.00	4.00
2.0	19.709	22.609	24.359	24.961	24.587	23.909	23.919	24.530	24.726	23.85
1.5	22.782	25.712	27.406	27.962	27.634	26.963	26.805	27.183	27.225	26.29
1.0	24.827	27.739	29.389	29.936	29.624	28.972	28.738	28.983	28.939	27.96
.5	25.982	28.885	30.516	31.060	30.758	30.117	29.856	30.035	29.933	28.92
0.0	26.329	29.250	30.885	31.429	31.125	30.487	30.217	30.374	30.243	29.18
-.5	25.894	28.869	30.524	31.069	30.754	30.096	29.830	29.997	29.854	28.75
-1.0	24.647	27.716	29.411	29.961	29.608	28.905	28.650	28.861	28.723	27.56
-1.5	22.515	25.713	27.479	28.022	27.599	26.801	26.547	26.844	26.737	25.50
-2.0	19.348	22.709	24.564	25.098	24.542	23.557	23.265	23.715	23.660	22.32

Fig. 11a Computed gain values of antenna at 4200 MHz.

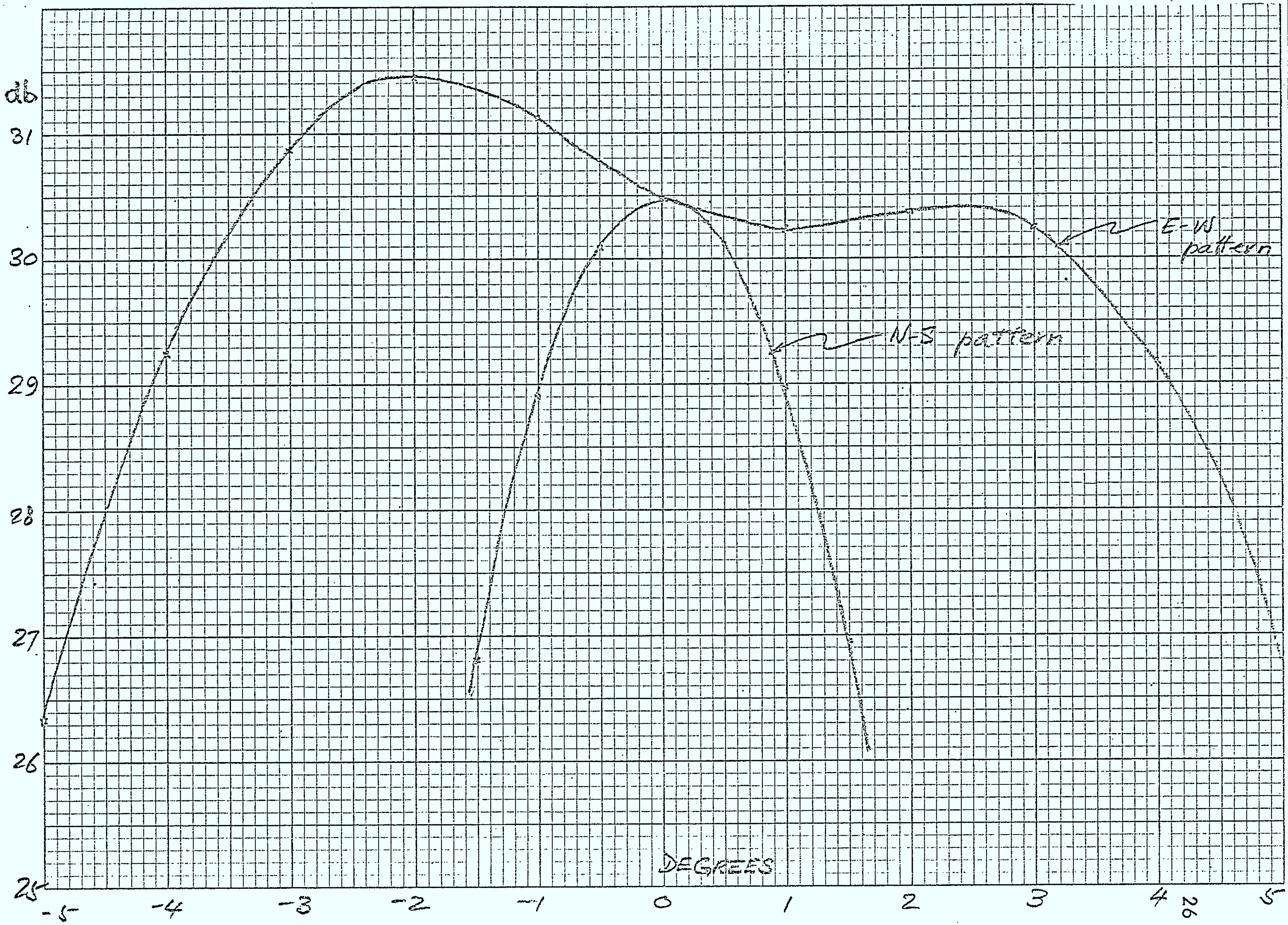


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Fig. 11b EW and NS patterns of antenna at 4200 MHz.

1.) HORIZONTAL GAIN

Elevation (Degrees)	AZIMUTH (DEGREES) -5.00	-4.00	-3.00	-2.00	-1.00	0.00	1.00	2.00	3.00	4.00
2.0	21.896	23.886	24.403	23.849	22.656	22.010	22.656	23.849	24.403	23.88
1.5	24.697	27.239	28.065	27.708	26.805	26.300	26.805	27.708	28.065	27.23
1.0	26.620	29.479	30.456	30.210	29.455	29.053	29.455	30.210	30.456	29.47
.5	27.724	30.751	31.805	31.619	30.945	30.594	30.945	31.619	31.805	30.75
0.0	28.017	31.133	32.225	32.056	31.420	31.092	31.420	32.058	32.225	31.13
-.5	27.442	30.596	31.686	31.512	30.885	30.570	30.885	31.512	31.686	30.59
-1.0	25.916	29.038	30.088	29.866	29.230	28.922	29.230	29.866	30.088	29.03
-1.5	23.346	26.323	27.236	26.934	26.286	25.996	26.286	26.934	27.236	26.32
-2.0	19.681	22.234	22.860	22.391	21.787	21.563	21.787	22.391	22.860	22.23

Fig. 12a Computed gain values of antenna at 6175 MHz.

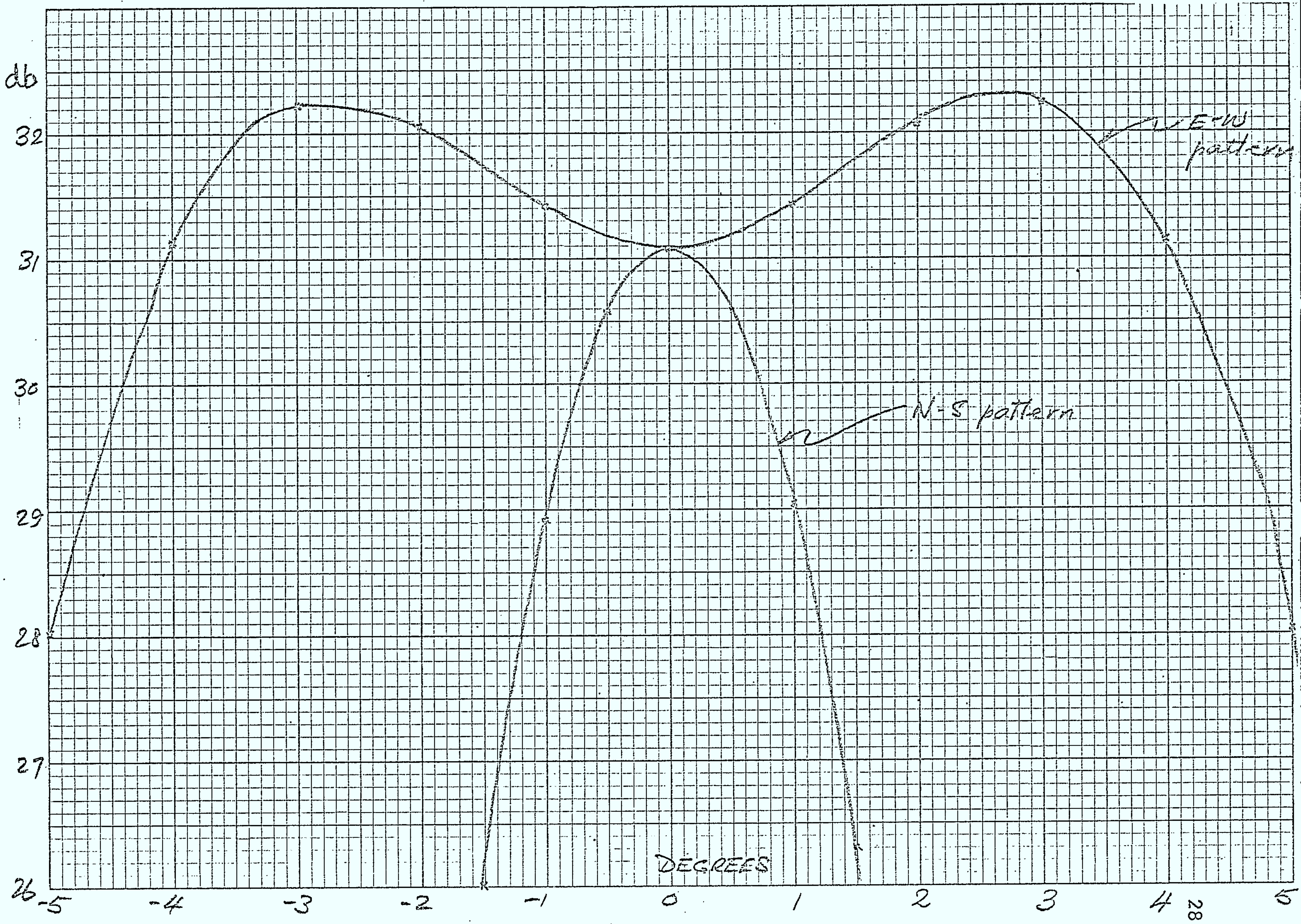


Fig. 12b EW and NS patterns of antenna at 6175 MHz.

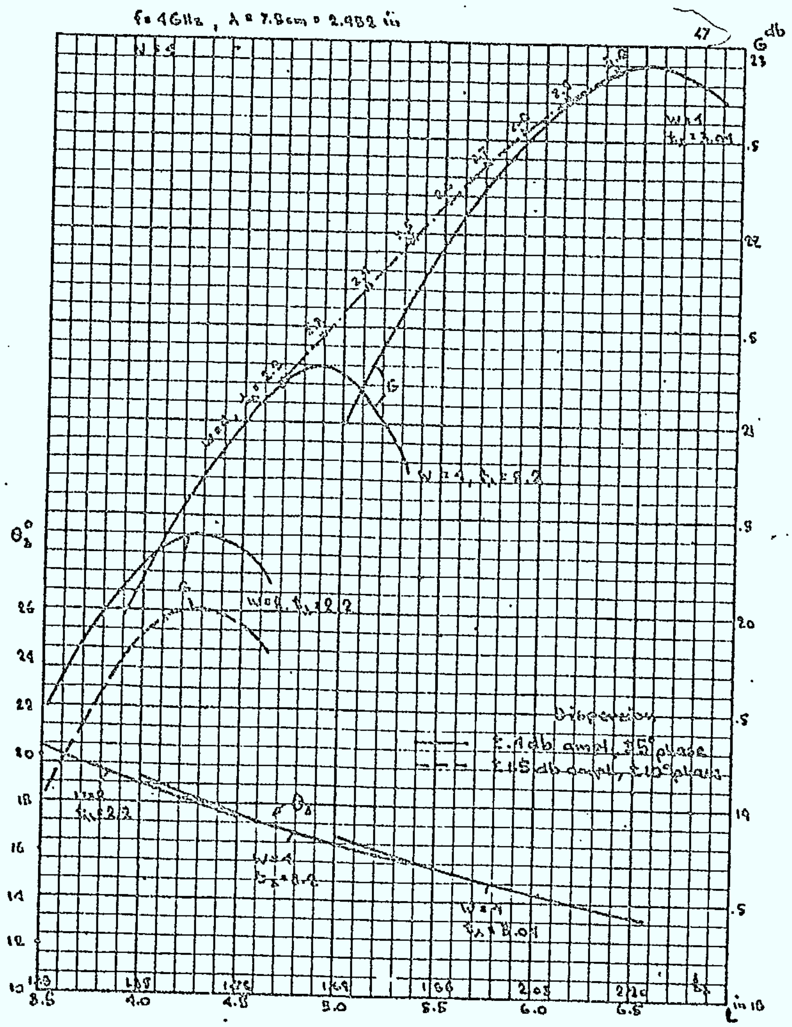


Fig. 13 Measured gain and Θ_3 for 4 element arrays of multiwinding helices vs. element separation.

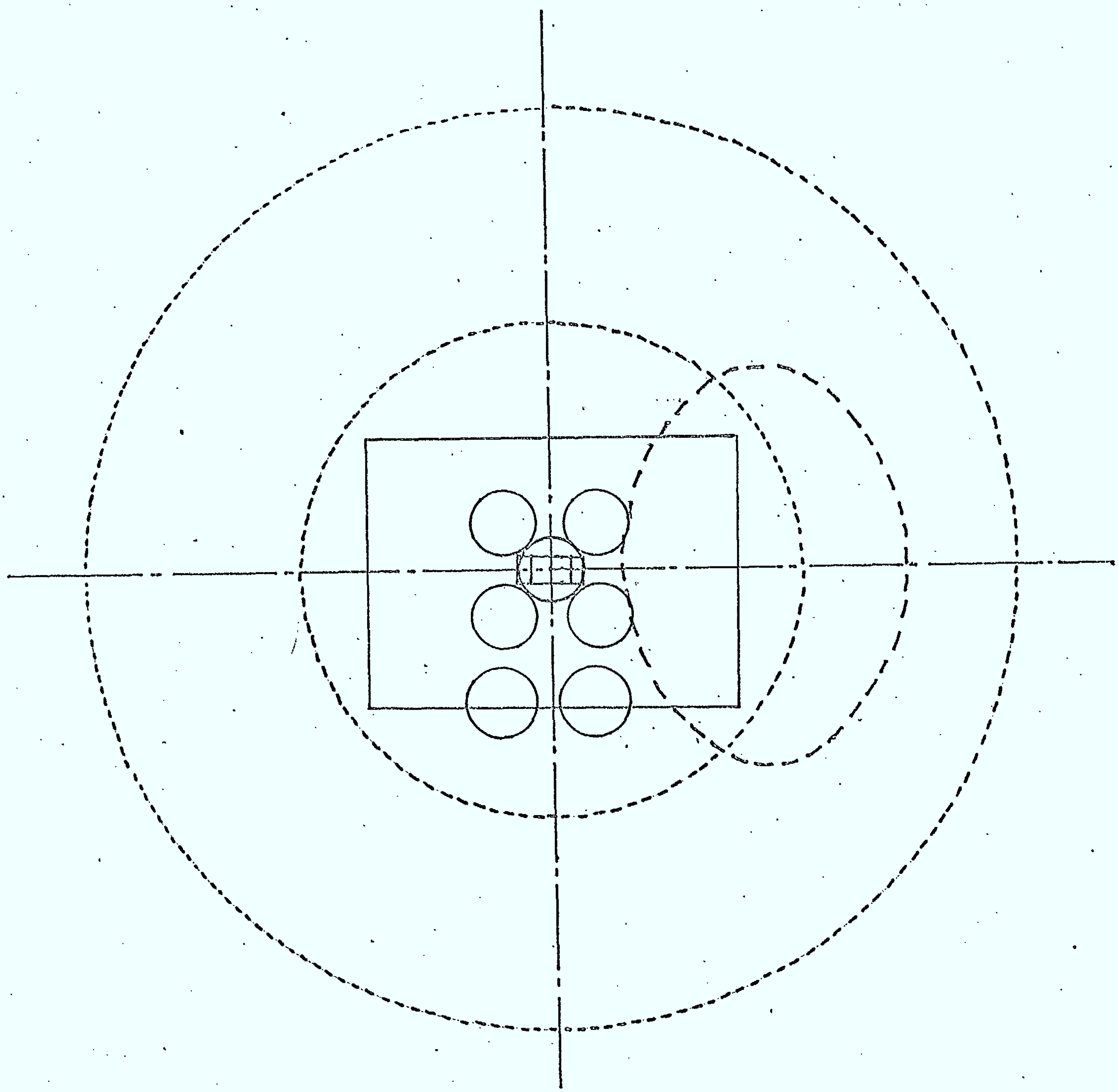
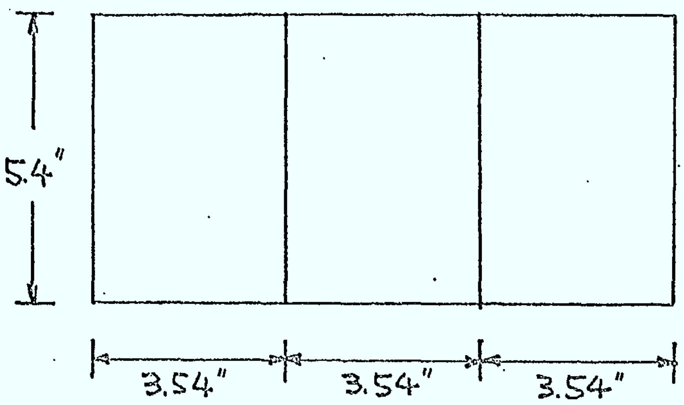
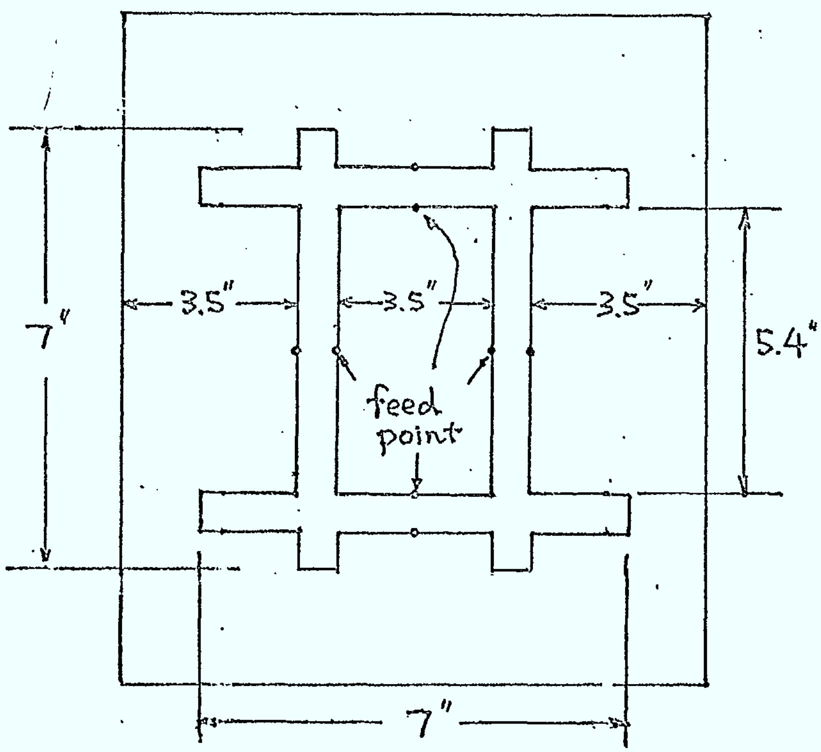


Fig. 14. Antenna configuration using EW offset for 4/6 GHz reflector.



(a) 4/6 GHz horn array front view



(b) 4/6 GHz horn array with cavity back dipoles for 885 MHz

Fig. 15 Combined 4/6 GHz and 885 MHz feed.

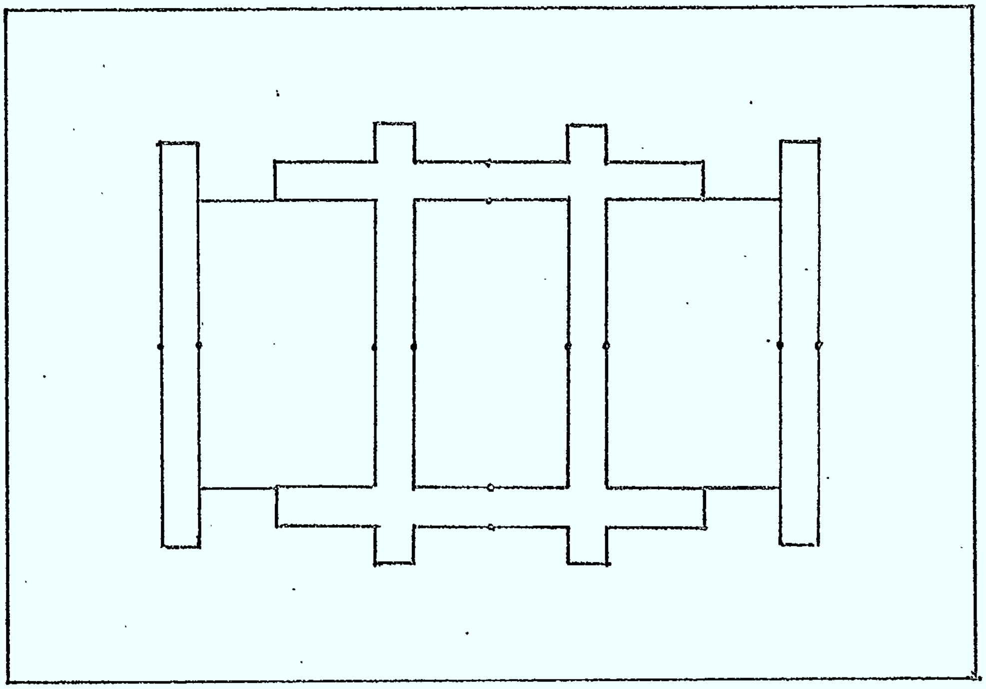


Fig. 16 Improved version of 885 MHz slot array feed.