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ANTENNA BEAMSHAPING

STUDY

for the

UHF MULTIPURPOSE SATELLITE

NADIAN ASTRONAUTICS LIMITED

CANADIAN ASTRONAUTICS LIMITE

42 Gould St., Ottawa, Ontario K1Y 2P4
(613) XXXXXXXXX 829-2025

ANTENNA BEAMSHAPING STUDY for the UHF MULTIPURPOSE SATELLITE

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1.0 INTRODUCTION

The UHF multipurpose satellite as presently conceived (Refs (1),(2)) provides communication services from synchronous orbit at UHF and one of the following SHF frequency combinations: 4/6 GHz; 12/14 GHz; 7/8 GHz; 7/8 GHz plus L-Band. These SHF combinations are arranged in approximately descending order of priority. The SHF antenna coverage required depends on the configuration model in question but generally speaking there is a requirement for transmit/receive SHF coverage of the entire Canadian land mass and/or reception via a single, narrow, spot-beam aimed in the region of the Prairies. The intent of the narrow spot-beam receive mode is to reduce vulnerability of the system to potential SHF uplink jamming, primarily from the Atlantic and Pacific offshore regions.

In the design of a communications satellite, the performance of the antenna is of paramount importance since it has a 'multiplier effect' which propagates through nearly all the various spacecraft subsystems. For example, a 2 dB increase in antenna gain means that in order to meet a specified EIRP requirement, the D.C. power requirement is reduced by 35% with appropriate reductions in solar array and battery weight. These in turn can be reflected in reductions in structure, RCS, wiring harness, apogee motor, etc. weight. Alternatively the total weight can be kept constant and the saving can be traded for some other feature such as a number of channels, EIRP, reliability, additional payloads and the like.

It will be shown later in this study that for spacecraft antenna structures of moderate dimensions (i.e. 15 feet or less), the diffraction limited antenna beamwidth at UHF is so large that for Canadian and near offshore coverage, it is not practical to attempt shaping of the beam. Consequently this study will be aimed primarily at beam shaping in the 4/6 and 12/14 GHz bands. While it is technically possible to implement planar arrays with complex and variable beamshapes, such techniques are not under consideration at present and this study will be confined to parabolic reflector type antennas.

For the purposes of this study, the Canadian coverage is assumed to be defined as coverage of all the land area of the Canadian Provinces and Territories from which the satellite can be seen with an elevation angle greater than zero degrees. It is also assumed that the antennas will be required to operate from a fairly small range of orbital arc (i.e. ±5 degrees) in the region of 109 degrees West. 28 dB will be taken as the minimum acceptable gain at 4 GHz and 27 dB as the minimum at 6 GHz.

2.0 STUDY OBJECTIVES

The initial statement of work for this study called for an analysis of beamshaping techniques and performance for UHF and all four potential SHF bands and for antenna diameters in the range 10 to 16 feet.

During the course of the work it became apparent from discussions with the contract project officer that the 7/8 GHz and L-Band options were becoming less important as potential configurations and that the UHF plus 4/6 GHz configuration had highest priority. Consequently the effort to be spent on 7/8 GHz and L-Band was deleted. The effort on 4/6 GHz and 12/14 GHz was expanded to include review and evaluation of antenna configurations developed by other contractors who were responsible for investigating communications subsystem payloads. The modified objectives of the study are therefore:

1. Review and evaluate the performance of certain proposed antenna configurations developed by other contractors at 4/6 GHz and 12/14 GHz
2. Estimate the achievable edge of coverage gains and coverage patterns achievable by means of alternate antenna configurations primarily at 4/6 GHz and 12/14 GHz.

The results obtained from the second task are not necessarily intended to represent the optimum antenna configuration. They are however intended to present some near optimum configurations and the performances which can be achieved from them. Further work would undoubtedly refine the performance obtainable but the effort involved is not warranted until an actual spacecraft program is implemented. Similarly, this report is not intended to be a treatise on antenna theory. Rather it is intended to develop some useful concepts and data on shaped beam antennas for use by systems engineers.

3.0 ANTENNA PRINCIPLES

3.1 Introduction

Countless texts have been written on the theory of antennas. It is not the intent of this chapter to reiterate the detailed analysis which can be found in the literature (e.g. Refs (3), (4), (5)). Rather, it is to present the systems engineer with some useful concepts and data with which he might not be otherwise familiar. The report will be restricted to parabolic type antennas.

3.2 The Parabola

Parabolic reflectors are generally used in microwave antenna work because of a simple geometric feature of a paraboloid. In Figure 3.2.1, the distance from any point on a plane normal to the paraboloid axis. to the paraboloid focus via the paraboloid surface is a constant, irrespective of the position on the plane. Consequently the energy from a point source of electromagnetic radiation at the focus illuminating the reflector is transformed into a coherent plane wavefront across the reflector aperture. The propagation of this wavefront is determined by its dimensions, measured in terms of the wavelength of the radiation. If the reflector aperture is a circle and is uniformly illuminated with radiation, the resulting wave propagates outwards in a slightly divergent beam, with a divergence angle of $\theta \simeq 1.22\ \lambda/d$. This divergence angle is limited by the properties of electromagnetic radiation and will be referred to as the diffraction limited beam width. Most of the energy in the radiated beam is contained within this angle but some energy (known as sidelobe energy) is present at greater angles.

3.3 Beam Shaping

At any point in the far field of a transmitting reflector antenna, the electric field vector is the integral of the electric field contributions from a large number of small current elements in the reflector surface. The shape of the far field

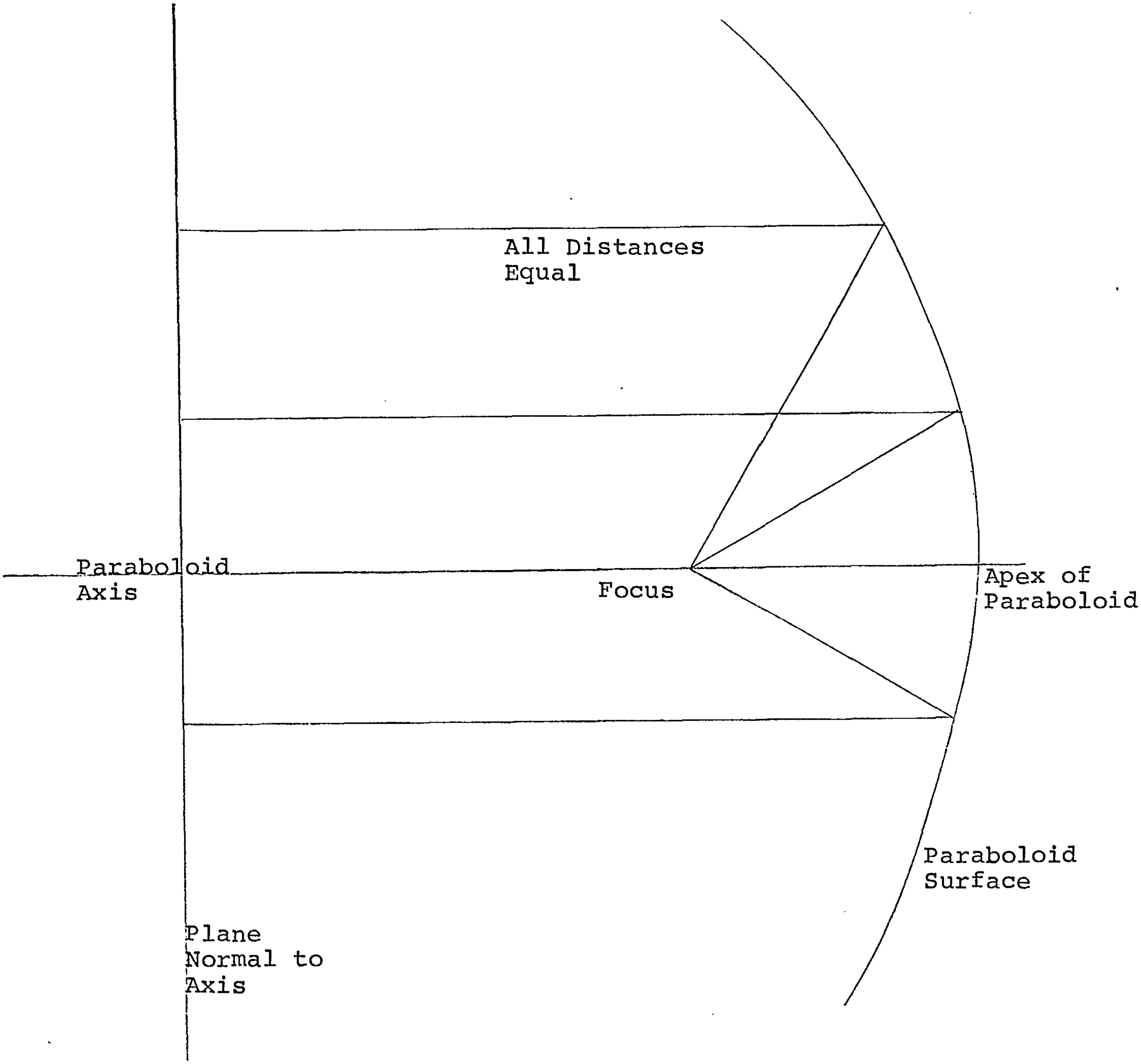


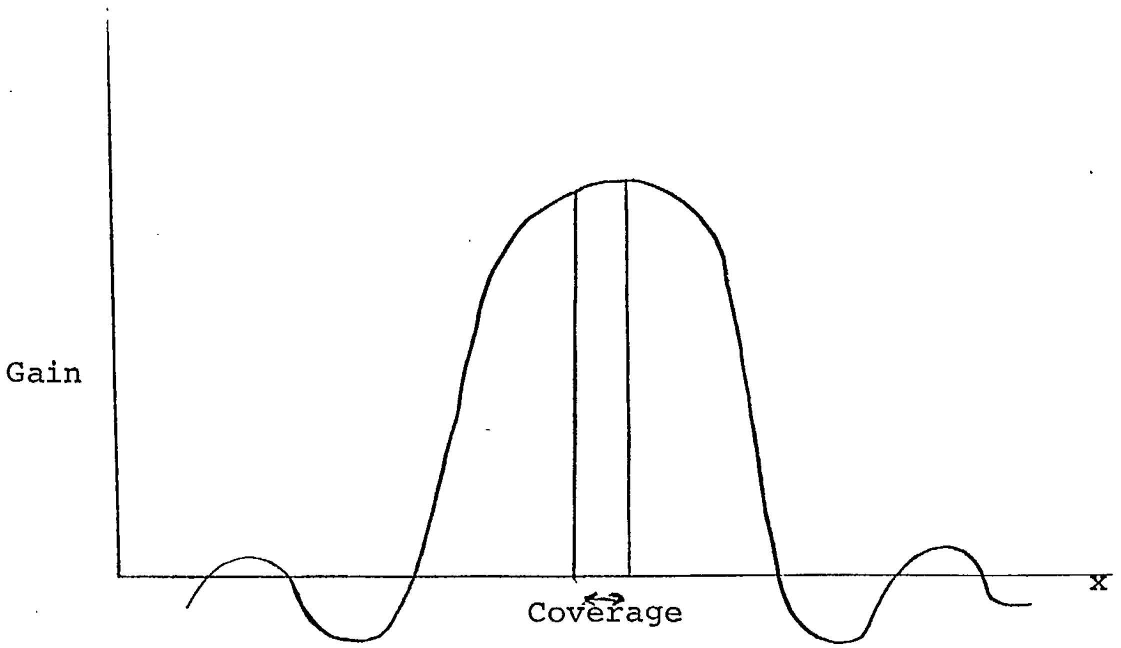
Figure 3.2.1 Paraboloid Geometry

pattern is determined by the distribution of these currents. A uniform distribution (such as might be produced by reflector illumination from a point source feed) will result in the well known sin(x)/x diffraction pattern shape for the far field pattern. This shape has the sharpest possible main beam but suffers from a high sidelobe level. The width of the main beam of the radiation from a uniformly illuminated reflector will be referred to as the diffraction limited beamwidth of the antenna.

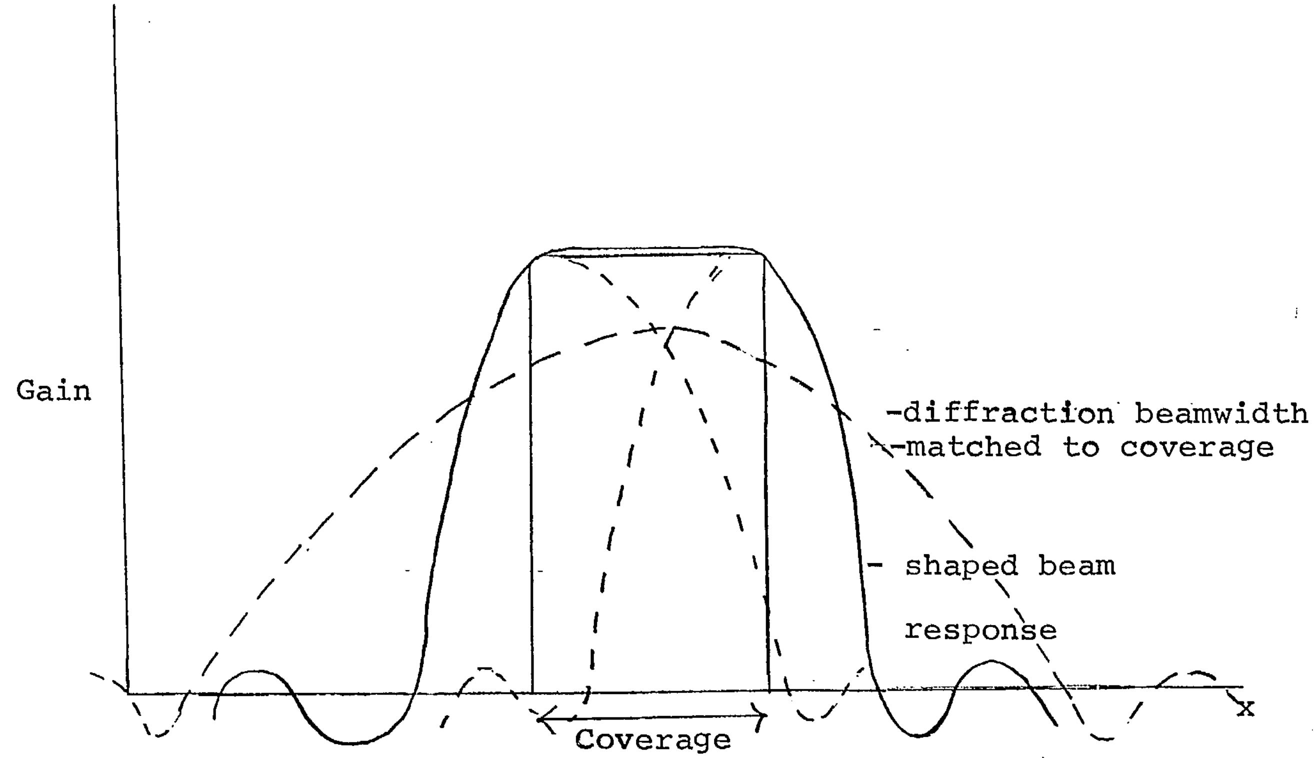
The technique of beam shaping is a means whereby the energy radiated from the antenna reflector can be distributed more uniformly over the target area than can be achieved with a diffraction limited beam. One can envisage the technique as involving the superposition of a large number of sin(x)/x type beams to cover the area in question. From this, it follows that the beam shaping concept can only be applied in situations where the area to be covered is comparable to or larger than the diffraction limited beamwidth. Figure 3.3.1 provides a conceptual illustration of the technique in one dimension. In Figure 3.3.1(a) the area to be covered is much less than the diffraction beamwidth, and any attempt to shape the beam can only result in more radiated energy falling outside the desired area, with consequent reduction in net gain. In Figure 3.3.1(b) on the other hand, a single diffraction beamwidth would obviously not provide coverage over the required area whereas superposition of many beams provides near uniform coverage. The diffraction beamwidth (determined by the reflector size in wavelengths) determines the rate at which the response cuts off at the edge of the desired coverage area and hence determines the amount of energy wasted outside the coverage zone.

The normal non shaped beam technique is also illustrated in Figure 3.3.1(b). Here the antenna reflector size has been reduced in order to increase the diffraction beamwidth to match the coverage area. In this situation, for the same edge of ceverage EIRP, the diffraction limited beam puts more power in the centre of, and off the edge of the coverage zone, i.e. the edge gain is reduced and more RF power is required. As a rule of thumb, a diffraction limited beam is optimum when the edge gain is about -4 dB relative to the peak whereas a shaped beam usually has an edge taper of about -2 dB.

The normal technique for beam shaping involves the use of multiple feed horns, each of which can be thought of as generating separate 'beams' which overlap to give uniform coverage. Such a feed shaping process obviously involves the displacement of the individual feed horns from the paraboloid axis. The effect of feed displacement is to cause an odd order phase perturbation of the wavefront emerging from the aperture - i.e. ttthe phase front contains linear, cubic etc. phase errors. To a



(a) Area to be covered less than diffraction Beamwidth



(b) Area to be covered greater than diffraction Beamwidth

Figure 3.3.1 One-Dimensional Beam Shaping Principle first order, the main result is a displacement of the antenna main beam. The beam angular displacement is usually less than the feed angular displacement by the 'beam deviation factor'. This factor depends on the ratio of focal length to reflector diameter. Silver(3) contains a tabulation of this factor. The effect of the cubic and higher order phase errors is to cause asymmetries in the displaced beam pattern. In particular, a small sidelobe on the paraboloid axis side of the main beam (called a coma lobe) appears.

Displacement of the feed along the paraboloid axis causes a defocussing of the beam. For small displacements of the feed the main effect is to broaden the beam but larger displacements result in a more flat topped or humped beam. This technique has a number of promising features particularly simplicity but obviously requires a shaped reflector with unequal focal lengths in the Azimuth and Elevation directions. In view of the requirement for a focussed UHF beam, this technique was not pursued further in this study.

In the theoretical limit, if the reflector is made large enough, the diffraction beamwidth approaches zero and it becomes possible to distribute energy uniformly over the target area and nowhere else. This situation is analogous to the optical imaging condition where the 'image' has the same shape as the 'object', or, in antenna terms, the pattern has the same shape as the feed. Therefore, as the reflector size is increased, the feed structure can be expected to resemble more and more closely the shape of the coverage area. In the perfect illumination condition of the coverage area, the antenna gain is given by:

$$G = 4\pi/\Omega$$

where Ω is the solid angle subtended by the coverage area at the antenna. For Canada from synchronous orbit, this angle is approximately 0.003 steradians giving a maximum potential Canada coverage gain of about 36 dB. To achieve this gain, the gain contour lines would have to follow exactly the projected outline of Canada with no pointing error margin.

3.4 Transmit-Receive Equivalence

It is customary in the literature on antennas to describe the various phenomena and characteristics using the basic assumption that the antenna is radiating energy. It can be shown from a theoretical basis that, assuming the absence of non reciprocal devices such as circulators etc. an antenna has the same pattern and gain in the receive mode as in the transmit mode at the same frequency. With a shaped beam, it is fairly simple to visualize how the beam is formed in the transmit mode, but this is sometimes difficult to do considering the receive mode. One useful concept is to consider the diffraction 'image' at the feed horns produced by a single point source located in the far field of the antenna. This 'image' will be a sin(x)/x type diffraction pattern with a size determined by the dish aperture size and the dish focal length. This diffraction pattern has the beamwidth corresponding to a uniformly illuminated aperture. If the feed system were able to usefully absorb all of the energy present in the diffracted image the antenna efficiency would be 100%. However the response characteristics of a feed horn are not necessarily matched to the pattern. A pyramidal horn for example has a constant field distribution in the E plane and a (approximately) cosine distribution in the H plane. The energy entering the horn is therefore represented by the correlation of the electric field distribution in the diffraction pattern with the response of the feed horn. The energy which is not accepted by the feed horn is reflected back towards the dish and energy which falls outside the horn is the equivalent of 'spillover loss' in the transmit mode.

Figure 3.4.1 is an illustration of the antenna in the receive mode. In the normal situation with a diffraction limited beam, the main lobe of the diffraction image is slightly larger than the feed horn. If the horn is made larger, it begins to intercept an increasing proportion of image sidelobe energy which, being out of phase with the main lobe energy, begins to effectively subtract from the response. Thus the gain is a maximum when the feed is large enough to capture most of the energy in the main lobe but not large enough to capture the out of phase sidelobe energy. (N.B. Complex feeds can be constructed for high gain, spot beam situations. In these, the portion of the feed which intercepts sidelobe energy is made to reverse the phase of the energy thereby adding to the main lobe output instead of subtracting.)

3.5 Feed Systems

As described in section 3.3, a highly shaped beam using a parabolic reflector can be expected to have a feed structure shape similar to that of the coverage area. Referring to Figure 3.4.1 again it can be seen that a shaped beam antenna (in the receive mode) is one in which the feed system intercepts energy

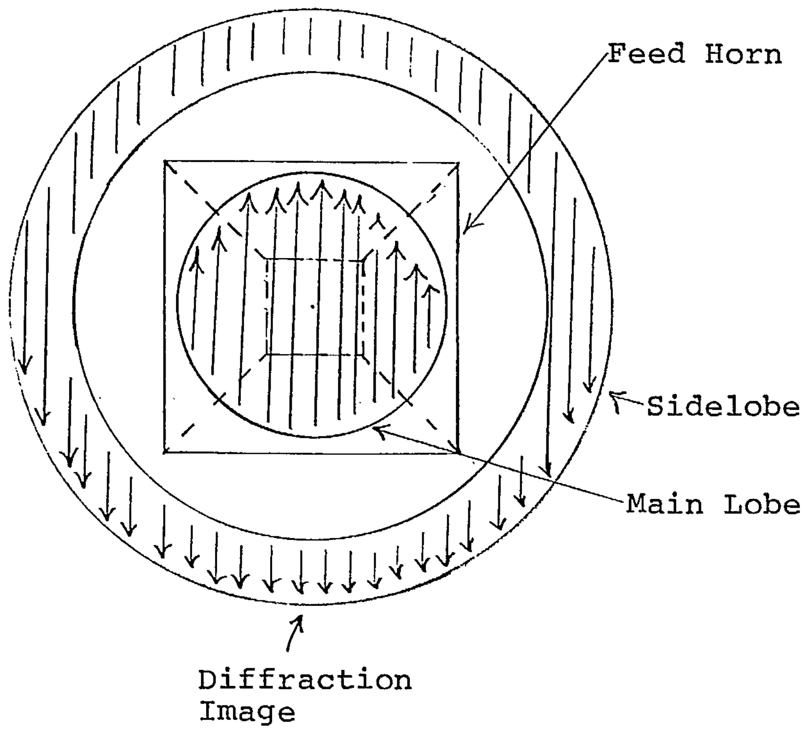


Figure 3.4.1 Diffraction Image Falling Onto Feed Horn

in the main lobe of the diffracted image for all source locations within the coverage zone. Ideally the intercepted energy is constant for all source locations in the coverage area and is zero for all source locations outside the coverage area. To achieve this requires that the diffracted image be very small compared to the feed size - i.e. the dish diameter is large and the feed is large.

The output of a shaped beam antenna in the receive mode is thus a correlation of the diffraction image electric field distribution and the electric field response of the feed system. The electric field response of a pyramidal horn is approximately uniform in the E plane. Therefore variation of gain with E plane horn dimensions can be approximated by the integral of the sin(x)/x function. Although the physical situation is two dimensional rather than one dimensional and the diffracted image is assumed to be in the centre of the horn, some useful insights may nevertheless be gained. Figure 3.5.1 shows diagrammatically the behaviour of this integral. As the horn size is increased, the gain increases (corresponding to reduced spillover loss) up to a maximum when the horn intercepts nearly all of the main lobe energy. As the size increases further the gain decreases and then increases again as the alternately in and out of phase diffraction sidelobes are intercepted.

With the larger horns it is fairly obvious that the output will be less dependent on the position of the diffracted image and hence less dependent on the source location than is the case for a small horn - i.e. the receive beam coverage is increased. This is again assuming that the image size is less than the feed size.

As the size of the horn is increased, the diffraction pattern becomes an increasingly poor 'match' to the horn mouth. An increasing proportion of the received energy is reflected back from the horn and the gain is reduced but the coverage area is increased. The horn can be considered to act as a two way transducer and in the receive mode only that proportion of the received diffraction pattern which correlates with the electric field distribution across the horn mouth in the transmit mode contribute to received energy emerging at the horn throat.

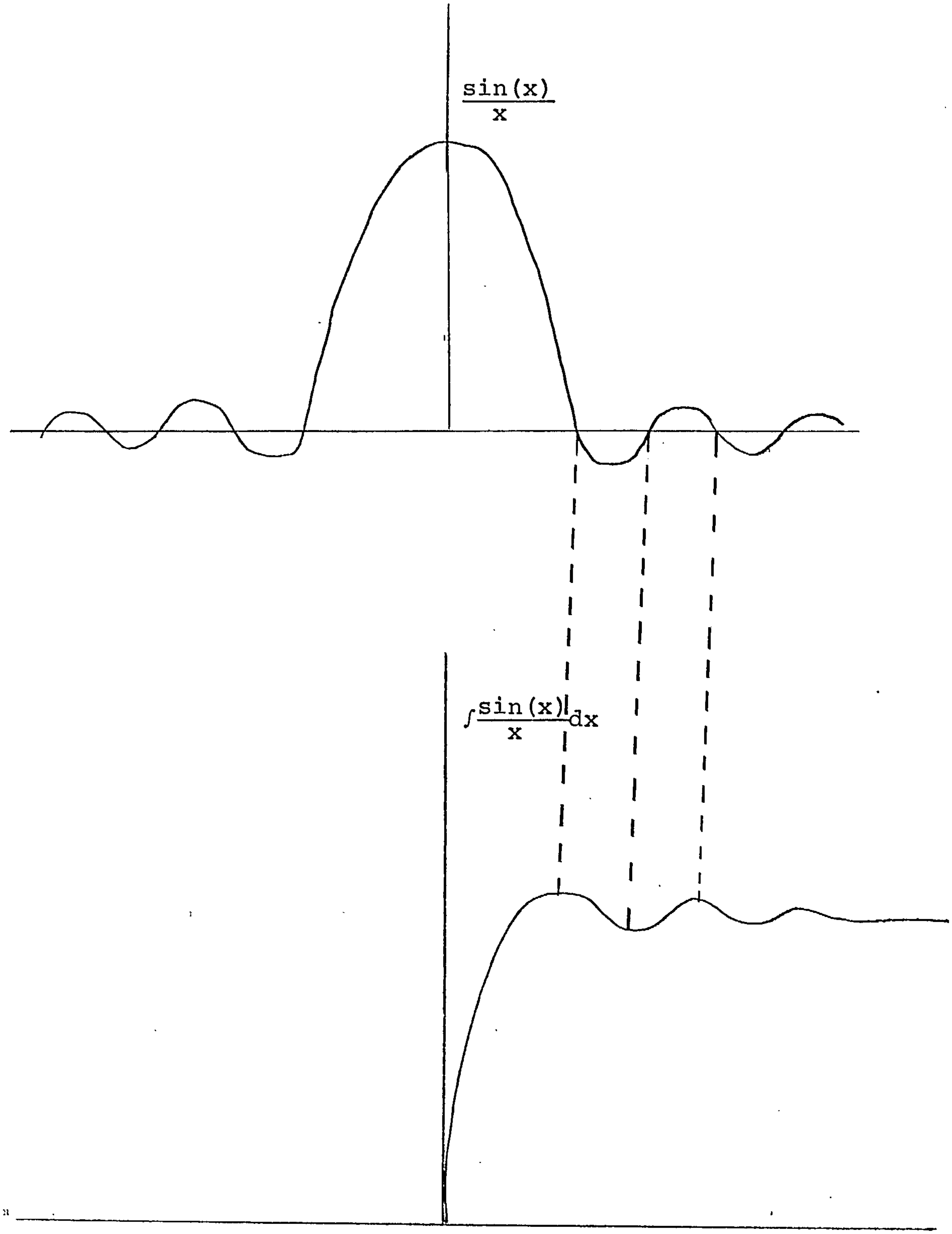


Figure 3.5.1 Behaviour of sin(x)/x and ∫(sin(x)/x)dx

3.6 Reflector Systems

A parabolic reflector is generally employed in reflector type antenna systems. This is because of the on axis focussing properties of a paraboloid i.e. an incoming plane wave along the paraboloid axis is focussed onto a point (within the limits of diffraction) at the paraboloid focus. This property is true of all parts of the paraboloid and it is not necessary for the paraboloid axis to coincide with the centre of the antenna aperture. For such offset arrangements the mean arrival direction for the energy at the focus will be from the approximate centre of the aperture, as in Figure 3.6.1.

In the transmit mode the feed illuminates the paraboloid with a desired distribution of electric field and phase and in the receive mode the feed collects the energy concentrated at the focus. In the transmit mode the radiated energy from the feed transforms into a pattern of circulating currents in the reflector surface. Each of these circulating currents re radiates, and the far field signal is the resultant of the radiating currents, summed over the dish surface.

The paraboloid is an imperfect transducer. Except for points on the paraboloid axis of a symmetrical reflector, some of the energy from the horns is transformed in polarization. Also, the focussing property is only truly valid for points on the paraboloid axis. For the normal antenna situation where on axis operation only is required this is no limitation. However for shaped beams, it may be that other shapes are preferable but such an investigation is outside the scope of this study.

As an alternative to the use of multiple feeds for beam-shaping, it is possible to shape the reflector in such a way as to cause the same end result. The shaped reflector type of arrangement has the advantage that it requires only one feed horn but has the fundamental disadvantage that it lacks bandwidth, since the reflector shaping must be carefully calculated for a specific wavelength. This nullifies the inherently aperiodic properties of the parabolic reflector. For this reason, and also because one of the requirements is for a spot beam capability, the shaped reflector concept was not considered in this study.

3.7 Antenna Modelling

Ideally it would be desireable to start out with some desired antenna beam shape and to be able to convert this shape directly into an implementable configuration. Unfortunately the present state of the art does not permit this to be done. Such

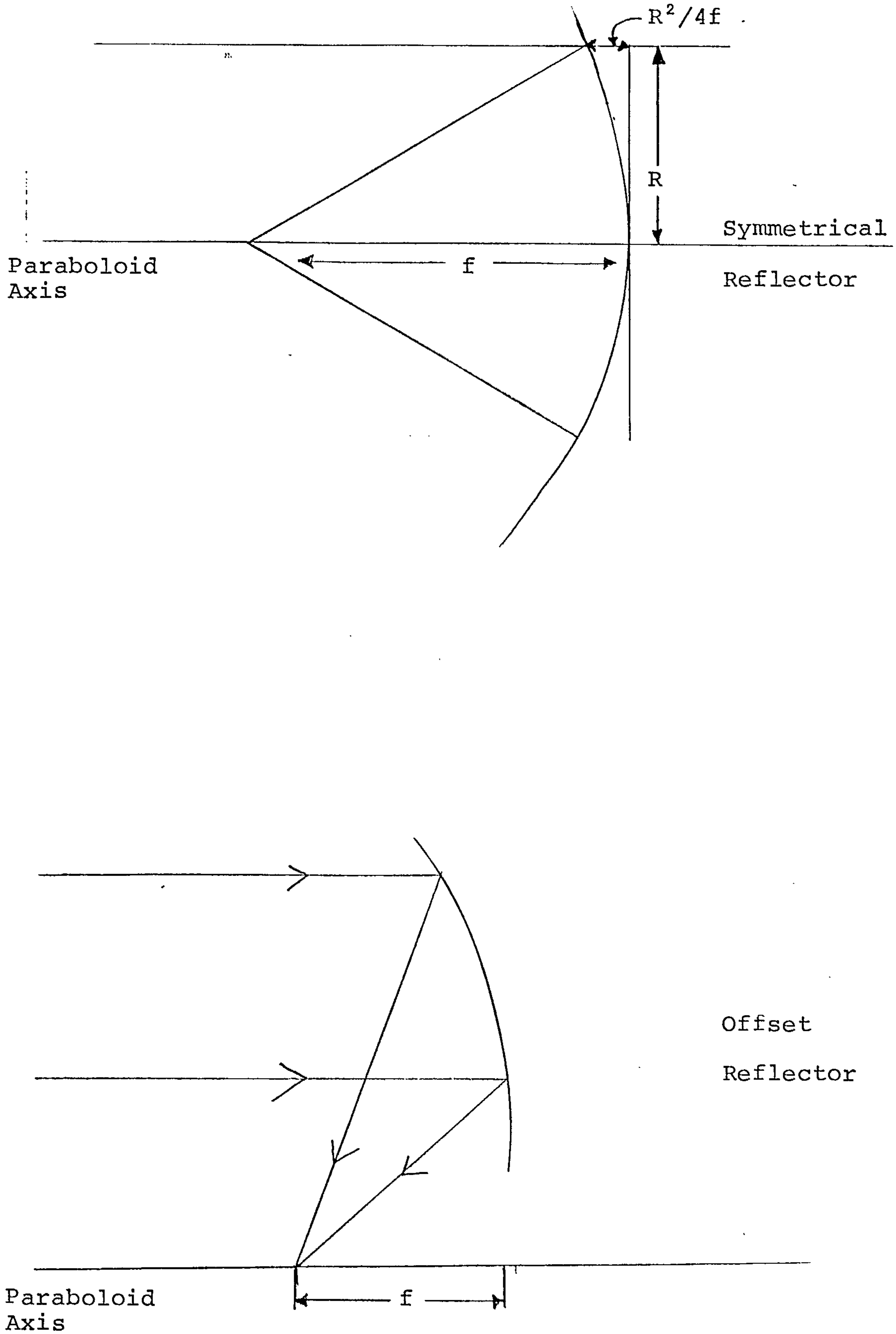


Figure 3.6.1 Parabolic Reflector Goemetry

an approach may not even be theoretically possible since some patterns shapes may not be achievable with physically realizable components. The approach must therefore be iterative. This involves starting with a desired shape, deriving a configuration which might work and then determining the actual pattern resulting from the chosen configuration and the shape can be re evaluated.

Chapter 5 contains an account of the steps involved in generating a Canada coverage shaped beam antenna for 4/6 GHz, given certain constraints on antenna size, feed construction etc.

Throughout chapters 4 and 5, extensive use is made of a numerical technique for the prediction of microwave antenna patterns. This technique is a straightforward modelling of an antenna in the transmit mode. Given the location, orientation and power distribution of the feed horns, it is possible to calculate the value of the RF current at any point on the reflector surface. The reflector is divided up into a large number of elements (typically 200 - 400) in a rectangular grid and the current is calculated at each element. These currents are then stored. The electric field contribution of each current element at a particular azimuth and elevation angle in the far field is calculated and the contributions from all the elements are summed to obtain the antenna gain. The integration is performed over a matrix of far field points and the resultant gains are stored in this matrix. A contour plotting routine then performs an inverse quadratic interpolation of the gain values taken three at a time along an elevation cut of the far field pattern. For Canada coverage antennas, the gain matrix normally contains 99 points, covering an azimuth range of -5 degrees to +5 degrees in steps of 1 degree and -2 to +2 degrees in steps of 0.5 degrees in elevation. For a conceptual study such as this, it was not considered necessary to manually interpolate and plot the gains. Consequently the contours presented are machine interpolated and plotted to a resolution of ±.05 degrees using a teletype machine as a plotting mechanism with a scale of 1 inch = 1 degree.

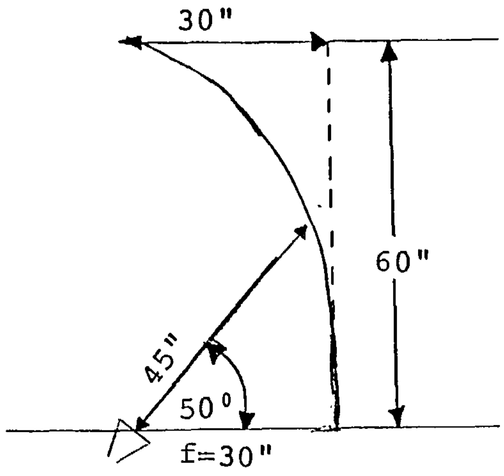
In order to facilitate evaluation of prototype antenna patterns, a transparency map of Canada has been prepared and is found at the back of this report. This map was generated by transforming points of Canada in the earth centred latitude and longitude coordinate system into an antenna centred azimuth and elevation coordinate system. The transformation was performed for the azimuth elevation coordinate system centred at geostationary altitude (zero orbit inclination) and with the coordinate axis elevated 'up' by 7.6 degrees and skewed east by 1.58 degrees relative to the earth centre line. The transparency should be laid over the antenna pattern to be evaluated and the locations of the various contours can be read off. N-S and E-W pointing errors can be simulated by moving the map up and down or side to side by the appropriate amounts.

3.7.1 Model Validation

In order to validate the antenna model and to provide a basis for comparison, an analysis was made of an antenna configuration believed to be similar to that employed on the Anik series of satellites built by Hughes Aircraft for Telesat Canada. Figure 3.7.1 shows the configuration analysed. It should be noted that the dimensions and arrangements shown are derived from published information and some common sense deductions and do not necessarily represent in detail the actual configuration used by Hughes.

The Anik reflector is an offset paraboloid circular aperture. The diameter of the circle is 60 inches and the focal length of the paraboloid is 30 inches. The tip of the dish is therefore directly over the paraboloid focus, where the feed structure is located. The diffraction limited beamwidth of a 60 inch aperture at 4 GHz is about 4 degrees - i.e. much greater than the N-S width of Canada but less than the E-W width of Canada as seen from synchronous orbit. It follows from earlier in this chapter that there is no particular advantage to the use of N-S beamshaping so the optimum N-S horn dimension is that which fully illuminates the reflector. The H plane horn dimension which gives a 90 degree beamwidth to the first null is 3.9 inches at a frequency of 4 GHz (Silver(3)). In the E-W direction, the maximum angle subtended by the dish at the feed is just under 90 degrees and from Silver(3) the E plane horn mouth dimension with a beamwidth of 90 degrees is about 2.6 inches at 4 GHz. The three horns are fed with approximately equal power in a +60, 0, -60 degree phase relationship. The N-S locations of the three horns can be estimated using the Canada coverage projection map and the beam deviation factor referred to earlier in this chapter.

Figure 3.7.2 shows the horizontally polarized transmit gain contour obtained at 4 GHz using the configuration shown in Figure 3.7.1. A peculiarity of the Anik antenna and feed is that the phase relationship between the horns reverses between odd and even channels. This results in a slight Easterly or Westerly bias depending on whether the channel is odd numbered or even numbered. Figure 3.7.3 shows the pattern at the same frequency but with the phase reversed. Excellent correlation with published data is observed (Ref (6)).



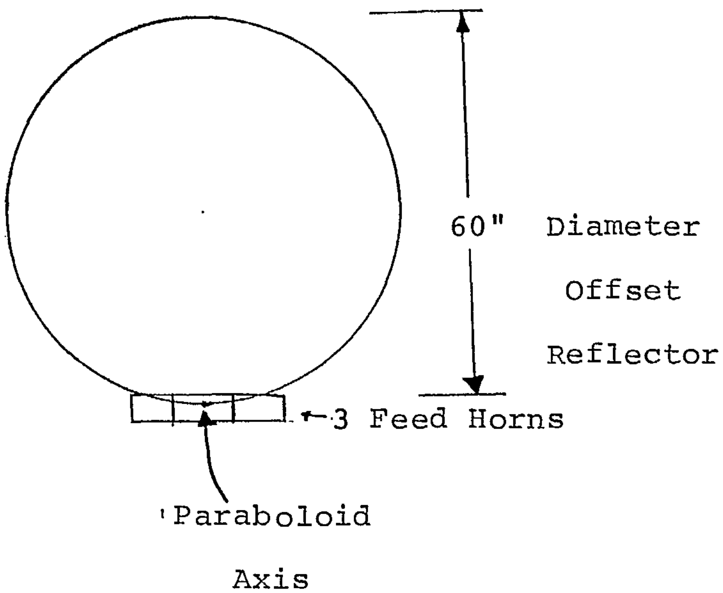


Figure 3.7.1 Anik - type antenna Configuration

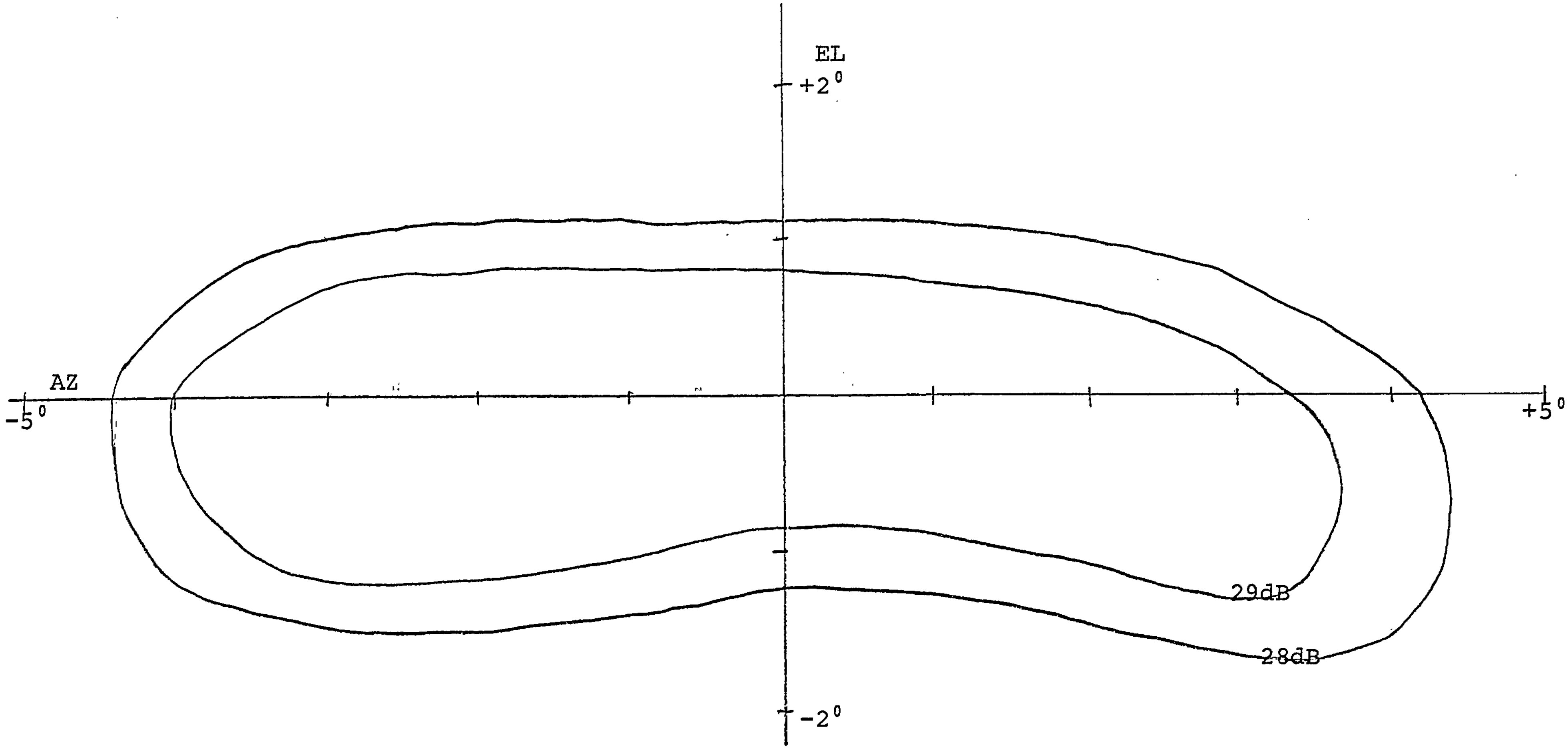


Figure 3.7.2 'Anik' Type Configuration, 4 GHz Transmit

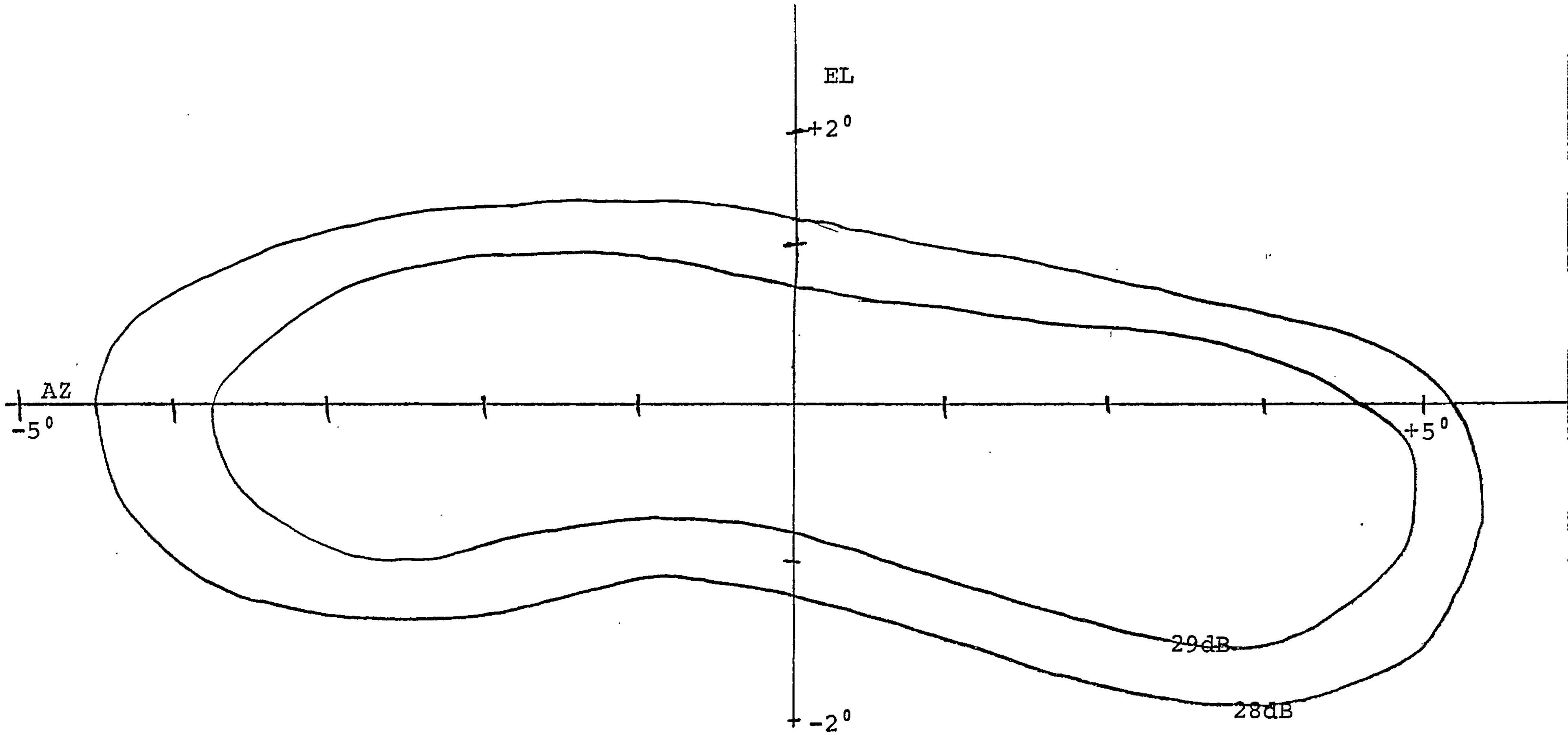


Figure 3. 7.3 'Anik' Type Configuration, 4 GHz Transmit Reversed Phasing

The patterns shown in figures 3.7.2 and 3.7.3 were computed with the reflector divided into about 300 elements. The patterns were recomputed with the dish divided into about 500 elements. In the main beam, the difference betwwen the two runs was about 0.02 dB and in the sidelobes about 0.05 dB. It is therefore concluded that numerical and sampling effects are insignificant when the reflector is divided into about 300 elements.

When the previous configuration is analysed as a three horn, vertically polarized, in phase system at 6 GHz, the resulting pattern shows three distinct 'beams' with substantial nulls between them. The size of the point diffraction image at the feed at 6 GHz is estimated to be about 1.8 inches (or less) in diameter. This is considerably less than the 2.6 inch width of the feed horns and the gain is considerably weighted by the cosine function response of the horn in the H plane. It is understood that the feed horns are in fact compensated by means of a vertical septum in the centre of each horn mouth. This has the effect of turning the E-W response of the entire feed structure at 6 GHz from a 3 cosine response into a 6 cosine response. When this is correlated with the sin(x)/x diffraction image the result is a much more uniform total E-W response. Thus, the antenna would function as a three horn system for horizontal polarization (4 GHz) and a six horn system for vertical polarization (6 GHz).

Figure 3.7.4 shows the resultant patterns based on a six horn equivalent representation. Again, good correlation is obtained between the results and published data. It is interesting to note that in the elevation plane (N-S) the pattern cuts are nearly 'flat topped', and slightly doublehumped in some cases. This is due to the large size of the feed horns in the E plane (N-S) dimension. Correlation of the 1.8 inch size of the diffraction image with the uniform horn response over the 3.9 inch E plane dimension would be expected to produce such a gain response.

The gain values quoted include such effects as spillover loss, cross polarization loss, scanning loss etc. but do not include 'hardware' effects such as reflector dissipation loss, reflector transparency, reflector shape distortions etc. These factors could all be included but this is not considered worthwhile at the conceptual stage.

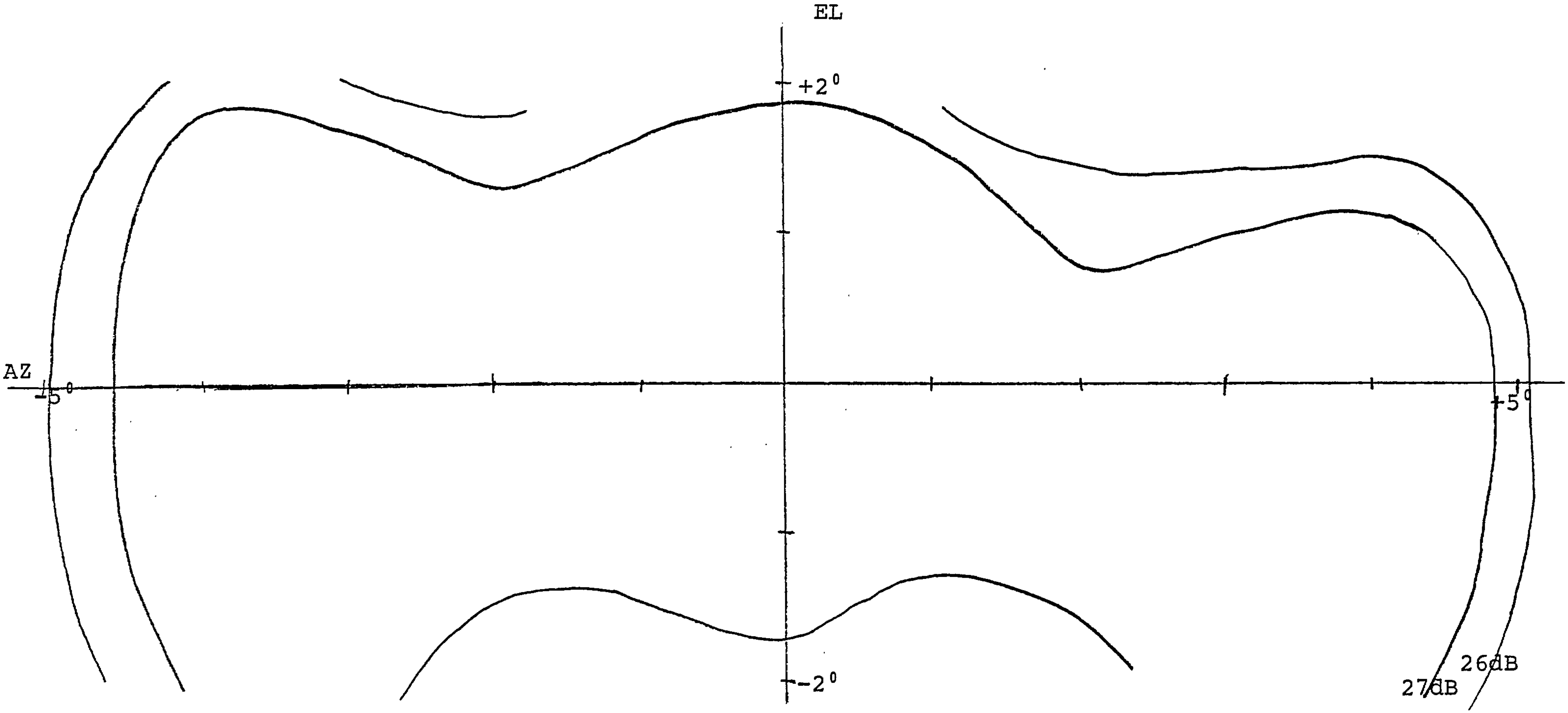


Figure 3.7.4 'Anik' Type Configuration, 6 GHz Receive

4.0 EVALUATION OF CANDIDATE ANTENNA CONFIGURATIONS

4.1 Introduction

A major part of the effort in this study was spent in evaluation various antenna designs proposed by other contractors on the UHF program. This chapter contains a summary of these evaluations and some comments on the performances achieved.

4.2 Mark I Configuration - 4/6 GHz, 2 Horns

This proposed configuration employs a hybrid reflector system to exploit the polarization selective properties of horizontal and vertical gridded reflectors. This causes the apparent reflector size to change depending on the signal polarization. The configuration is shown in Figures 4.2.1 and 4.2.2. This configuration was analysed four times based on the following combinations of assumptions:

(a) Assuming that the gridded part of the reflector reflects horizontal polarization
(b) Assuming that the gridded part of the reflector reflects vertical polarization
(c) The two horns are fed in phase at 4 and 6 GHz
(d) The two horns are fed in quadrature at 4 GHz and in phase at 6 GHz.

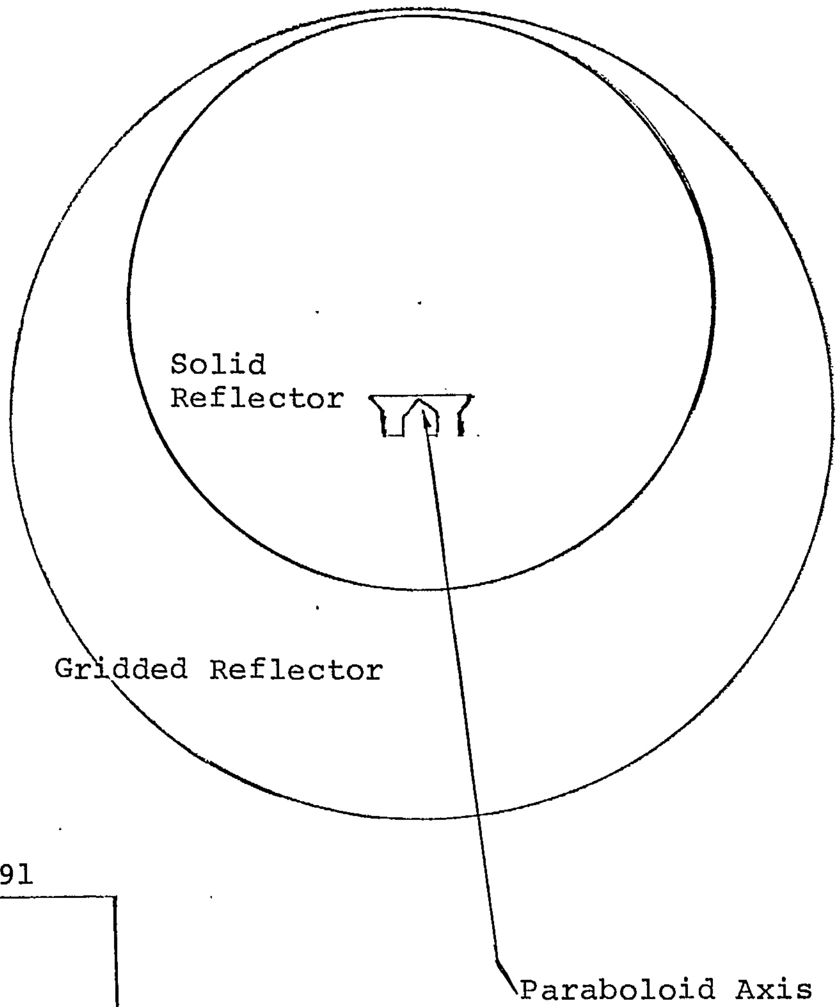
This polarization flexibility was present to permit the polarization of 6 GHz spot beam receive mode to be selected.

The following subsections evaluate the configuration using assumptions (a) and (b) above respectively, then assuming in phase feeds (assumption (c)) followed by an analysis assuming quadrature feed at 4 GHz (assumption (d)). Section 4.2.4 contains an analysis of the spot beam performance of this configuration.

4.2.1 Mark I Configuration, Horizontal Gridding

Assuming the reflector is gridded to reflect <u>horizontal</u> polarization, then the effective reflector diameter is 84 inches at 4 GHz and 60 inches at 6 GHz. The patterns obtained are as in Figures 4.2.3, 4.2.3(a), 4.2.3(b) and 4.2.4. Figure 4.2.3 shows the pattern obtained without taking into account feed

Reflector



Horns

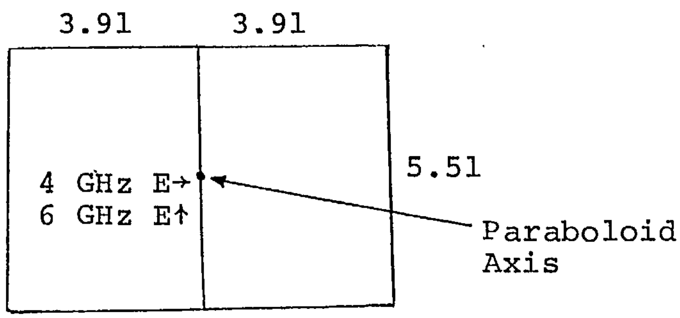


Figure 4.2.1 Mark I 4/6 GHz configuration

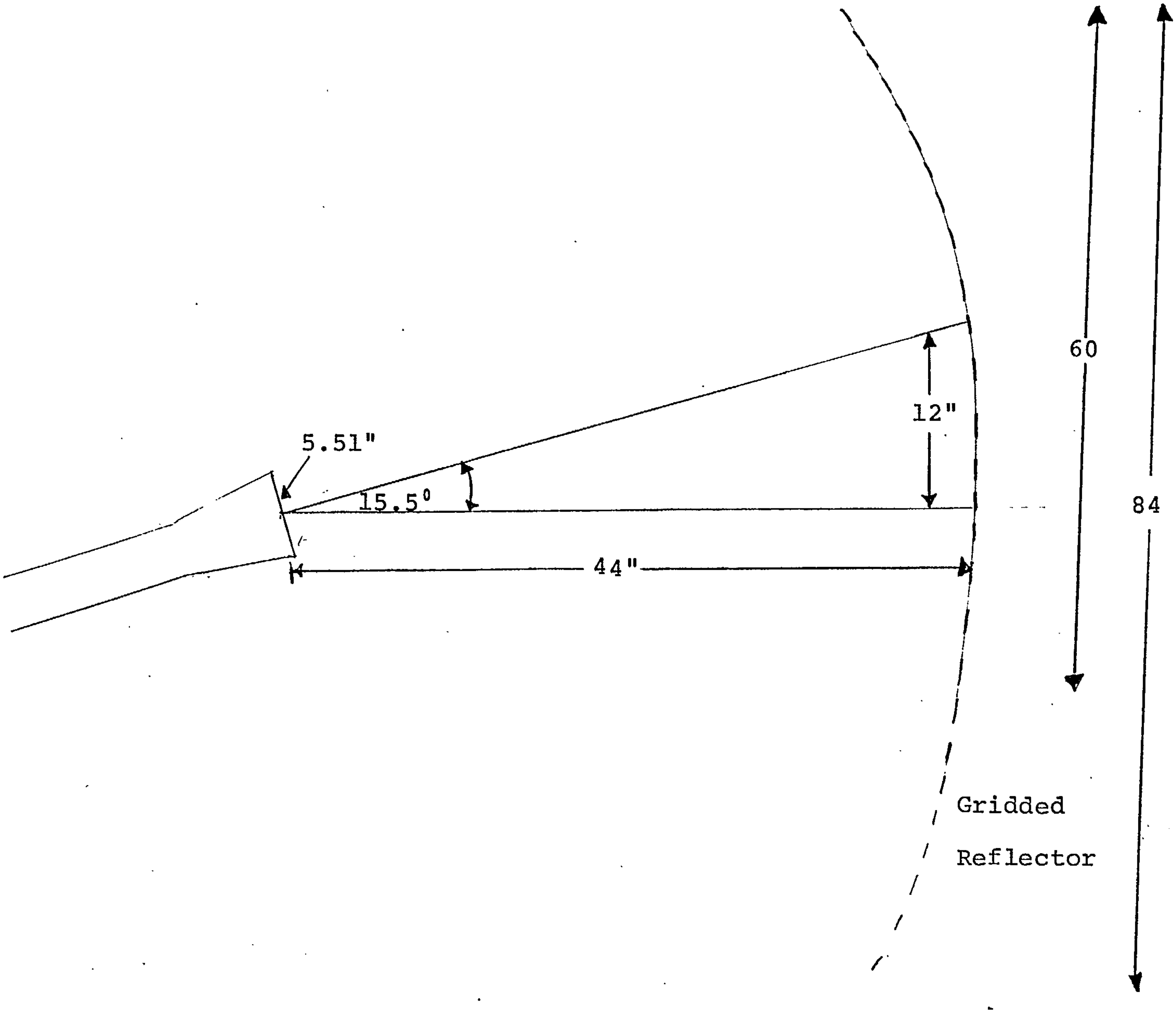


Figure 4.2.2 Mark I 4/6 GHz Configuration

blockage. The 4 GHz patterns are reasonably good with the 28 dB gain contour covering Canada with a reasonable pointing error margin. A small additional gain could be obtained by twisting the feed slightly to 'dip' the right hand side of the pattern. Figure 4.2.3(a) shows the effect of blockage by the 4/6 GHz horns. The pattern is still just adequate and would be more so with a clockwise twist. The general effect is a gain reduction of about 0.5 dB, although the shape is changed slightly. Figure 4.2.3(b) shows the effect of a 20 by 20 inch blockage such as might be caused by a large UHF feed structure. The resulting pattern does not appear to be usable.

Figure 4.2.4 shows the 6 GHz pattern for the horn configuration described, but with a 60 inch reflector effective diameter. The pattern appears to consist of two distinct beams (one from each horn) with a double humped response in the N-S direction. This double humped response is interpreted as being due to the large E plane dimension of the horns i.e. 5.51 inches or 2.8 wavelengths at 6 GHz. The primary horn pattern thus has a 10 dB beamwidth of about 35 degrees and a 3 dB beamwidth of 20 degrees (S. Silver(3), P. 346). The solid part of the dish subtends an angle of about 70 degrees at the horns. In contrast, the E plane dimension at 4 GHz is only 0.81 λ giving an E-W primary horn beamwidth of 50 degrees at 3 dB and 75 degrees at 10 dB, which is a good 'match' to the dish size.

4.2.2 Mark I Configuration, Vertical Gridding

Assuming the mesh reflector is gridded to reflect <u>vertical</u> polarization, the effective reflector diameters are 60 inches at 4 GHz and 84 inches at 6 GHz. As in case 1, the 6 GHz pattern (Figure 4.2.6) appears unusable due to excessive 'double humping'. The 6 GHz pattern was repeated for 90 degree and 180 degree phasing of the horns but no improvement resulted. The 4 GHz pattern is again quite promising, with, interestingly, no central 'waist' in the pattern (Figure 4.2.5). Again a small clockwise twist would improve the coverage slightly. The 4 GHz pattern with the 60 inch dish is not quite as good as with the 84 inches, due partly to higher spillover loss (0.2 dB) and power wastage over the midwestern U.S. and off the top righthand limb of the earth.

4.2.3 Mark I Configuration, Quadrature Feed at 4 GHz

With the 84 inch effective reflector diameter a small 'waist' or 'dip' in the pattern was just noticeable (Figure 4.2.6). The result of quadrature feed of the 4 GHz horns is to increase the depth of the 'dip' in the centre of the pattern.

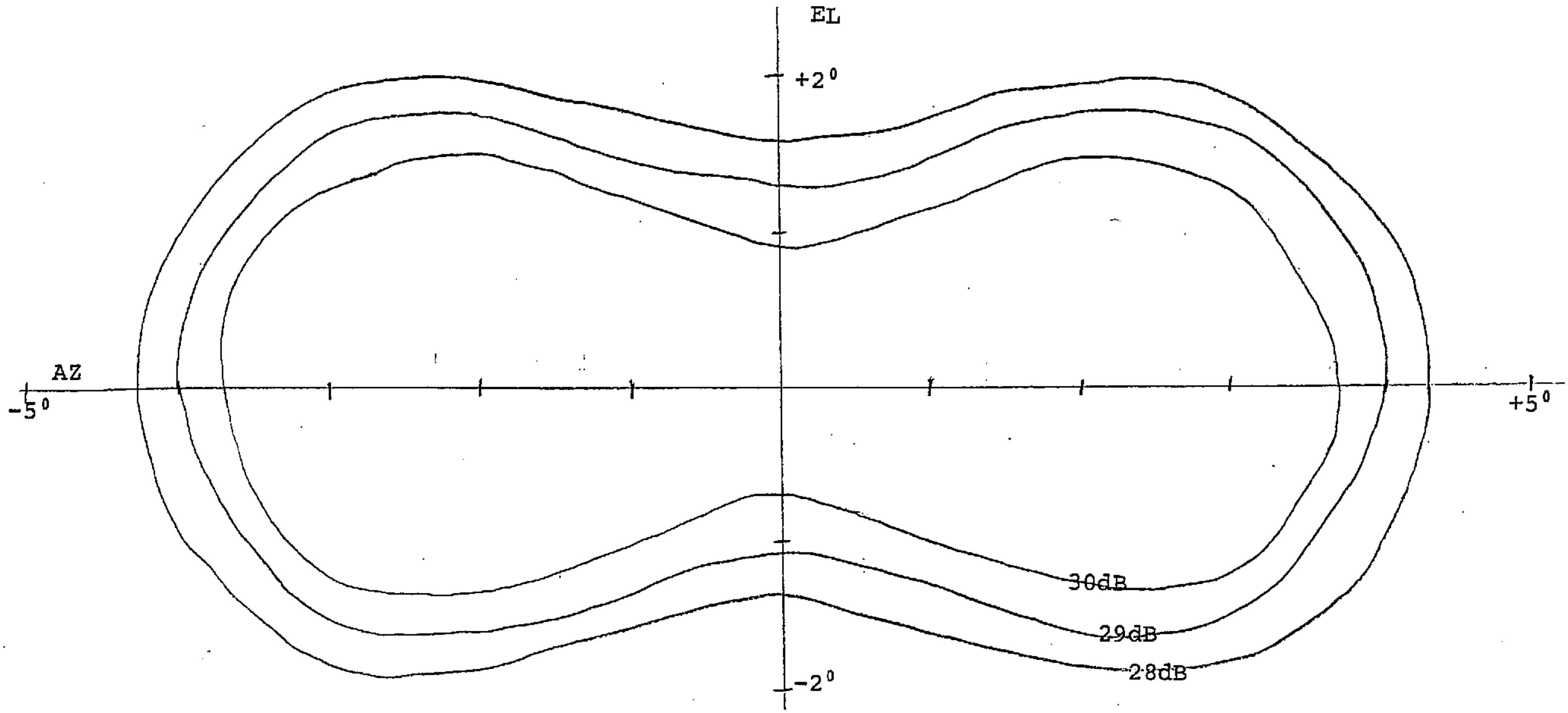


Figure 4.2.3 Mark I Configuration, 4 GHz Transmit, 84" Reflector, No Blockage

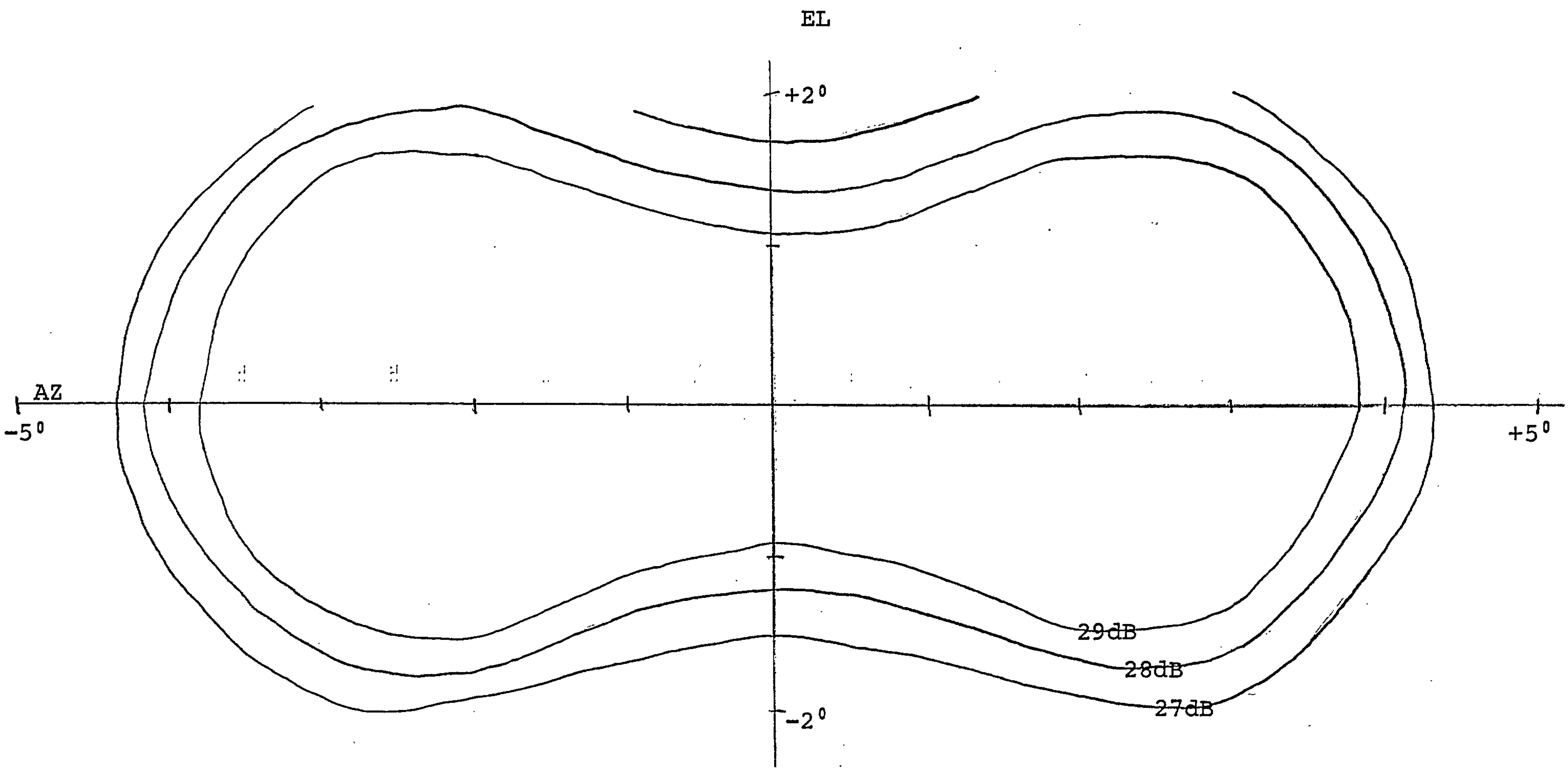


Figure 4.2.3(a) Mark I Configuration, 4 GHz Transmit, 4/6 Feed Blockage

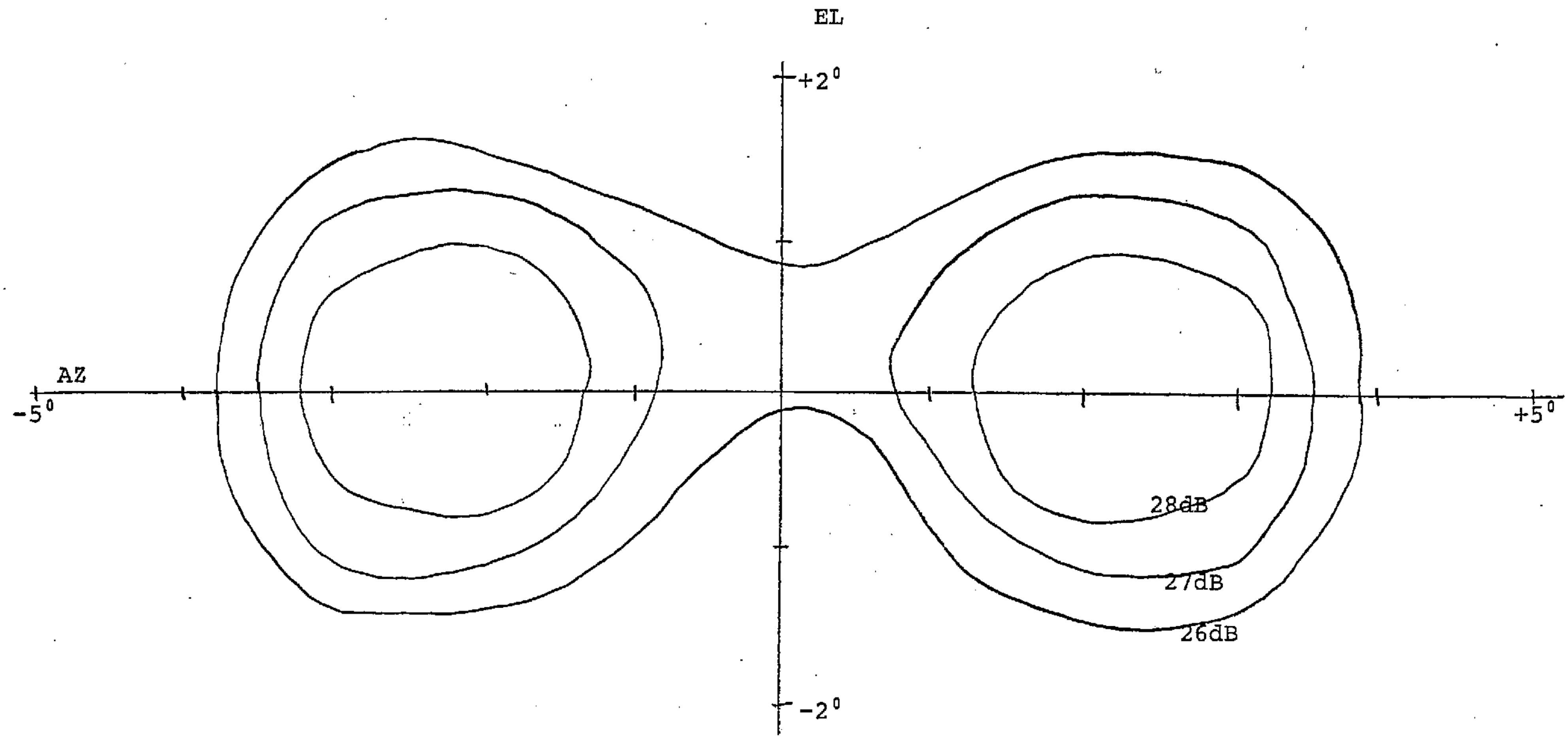


Figure 4.2.3(b) Mark I Configuration, 4 GHz Transmit, 20" x 20" Blockage

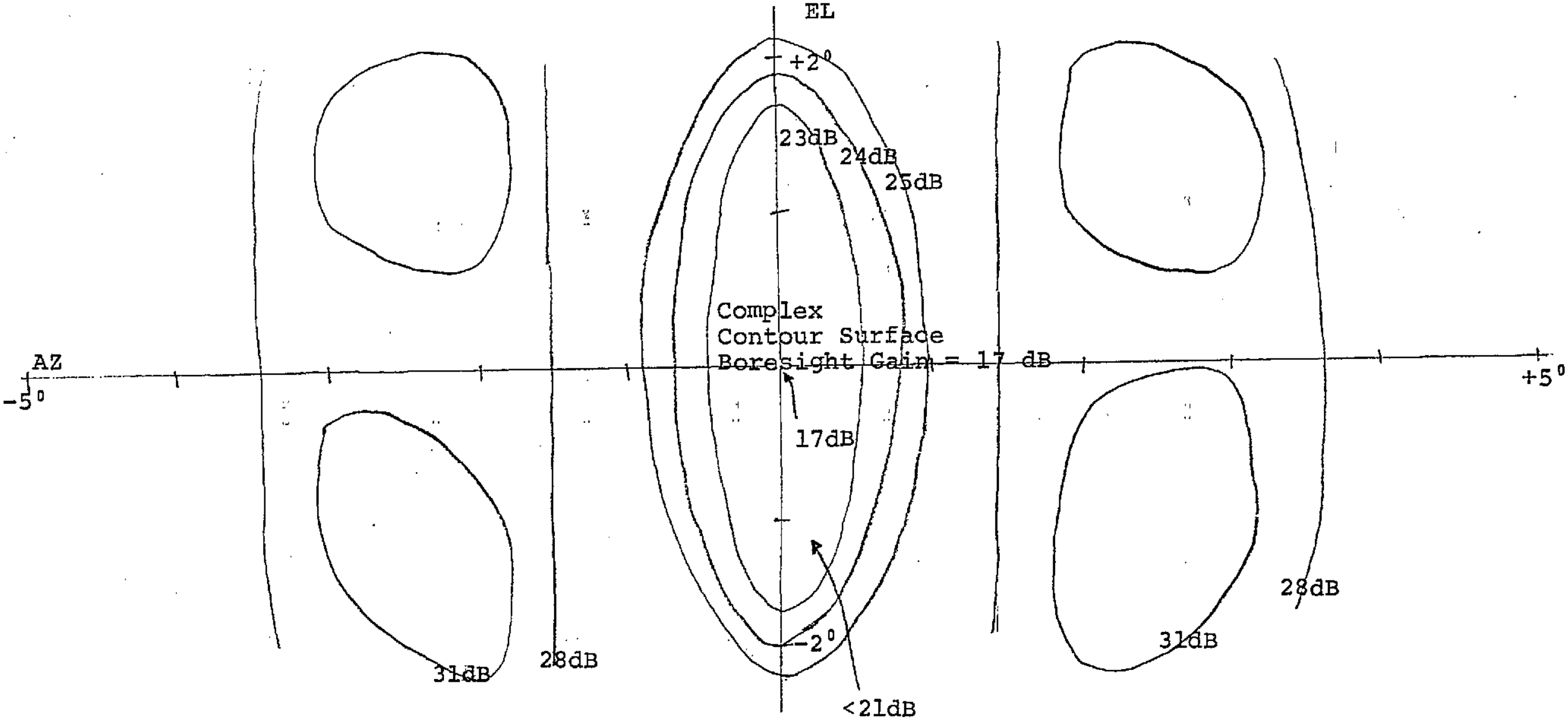


Figure 4.2.4 Mark I Configuration, 6 GHz Receive, 60" Reflector

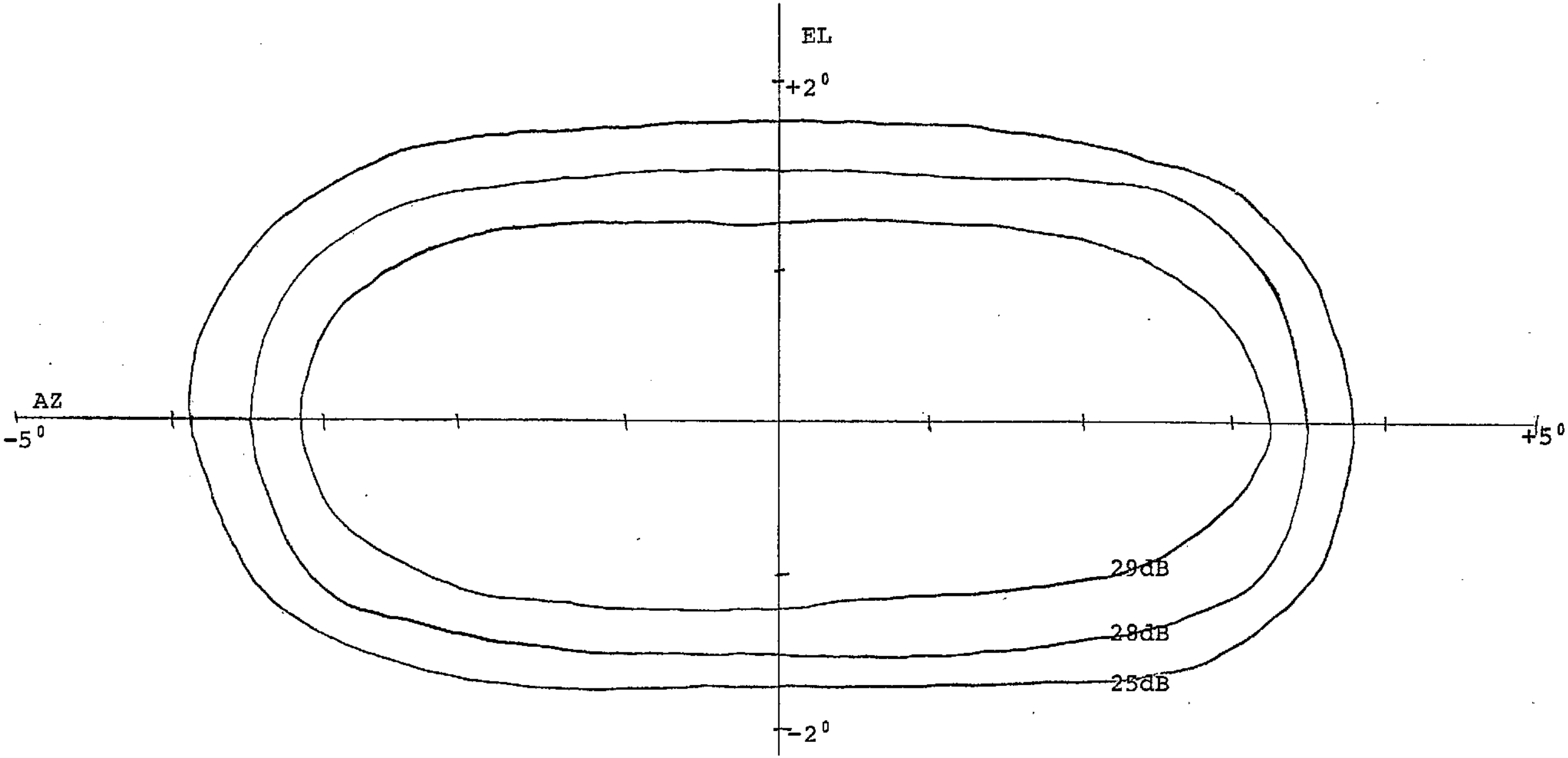


Figure 4.2.5 Mark I Configuration, 4 GHz Transmit, 60 " Reflector

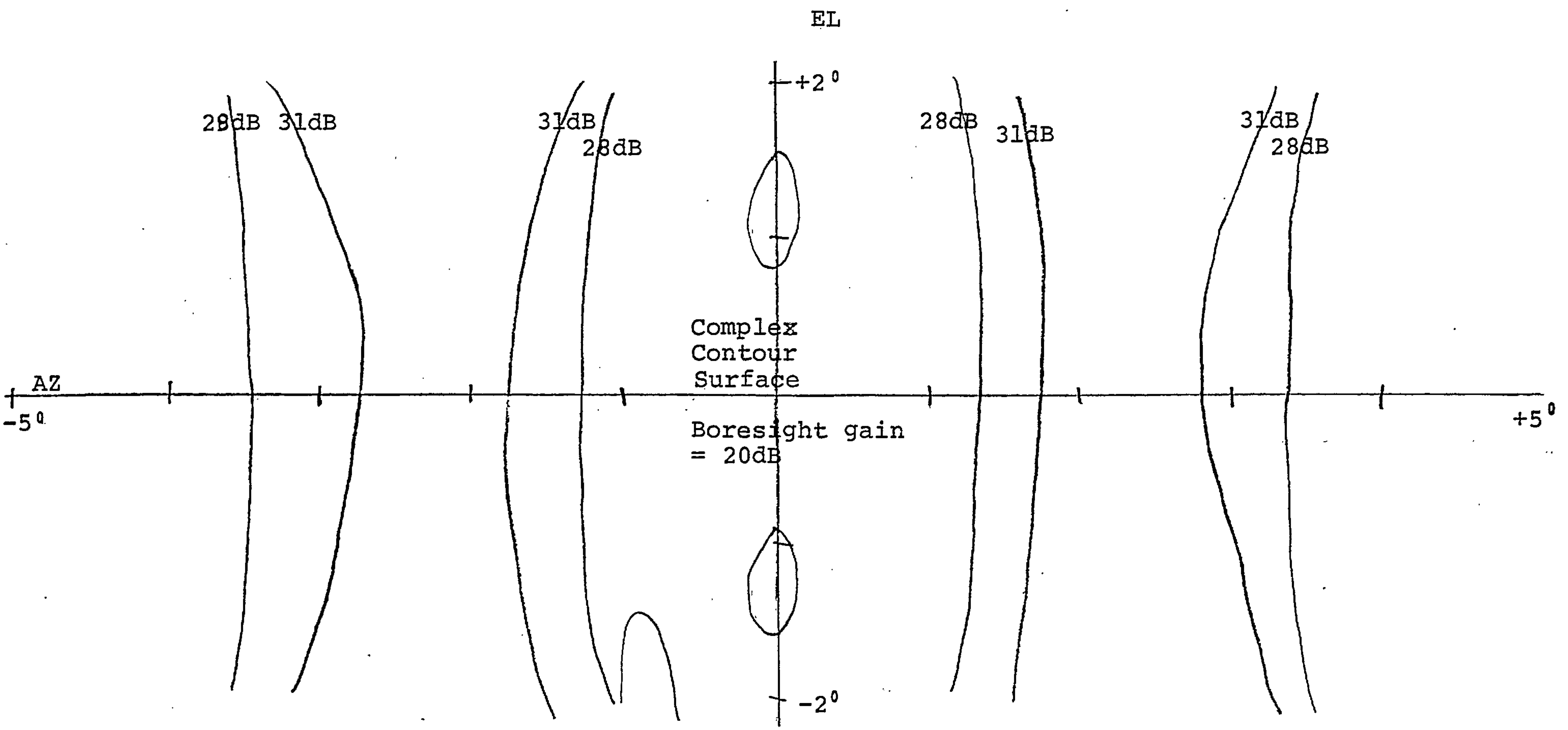


Figure 4.2.6 Mark I Configuration, 6 GHz Receive, 84" Reflector

The increased dip is a result of the fact that, on axis, the total electric field vector is $1/\sqrt{2}$ times the total electric field vector with in phase horns, resulting in an on axis gain drop of about 3 dB.

Figure 4.2.7 shows the resulting pattern for a 60 inch equivalent dish diameter (vertical gridding on non solid part of dish) and Figure 4.2.7(a) shows the result including 4/6 GHz feed blockage.

The pattern of Figure 4.2.7 is just usable but the blockage effects makes the pattern of 4.2.7(a) unusable for a minimum gain requirement of 28 dB.

Figure 4.2.8 shows the effects of an 84 inch equivalent dish diameter coupled with the quadrature feed. The 3 dB on-axis gain reduction makes the pattern unusable for 28 dB gain Canadian coverage.

4.2.4 Mark I Configuration, Spot Beam at 6 GHz

One proposed configuration for the 6 GHz spot beam horn is shown in Figure 4.2.9. The analyses show that the resulting beam is approximately circular and is elevated at about 3.5 degrees relative to the paraboloid axis (antenna boresight). The peak gain is about 41 dB (no blockage). The large elevation angle makes the spot beam fall off the surface of the earth, well above the North pole. Elementary geometry shows that a 3 inch horn displacement at 44 inch focal length produces a feed horn angular offset of 3.9 degrees relative to boresight. The beam deviation factor for an 84 inch diameter, 44 inch focal length dish is 0.92 (Silver, P. 488) resulting in a final beam displacement of 3.58 degrees. This is consistent with the computer generated result.

4.3 Mark IA Configuration

This proposed configuration is similar to the Mark I concept except that the feed system is defocussed away from the reflector and the horns are fed in quadrature. Two defocussing values were used, namely 4 inches and 2 inches. With a defocussing value of 4 inches outwards along the paraboloid axis the resulting pattern exhibited a downward tilt of about 1 degree (due to the slightly offset nature of the feed) and developed

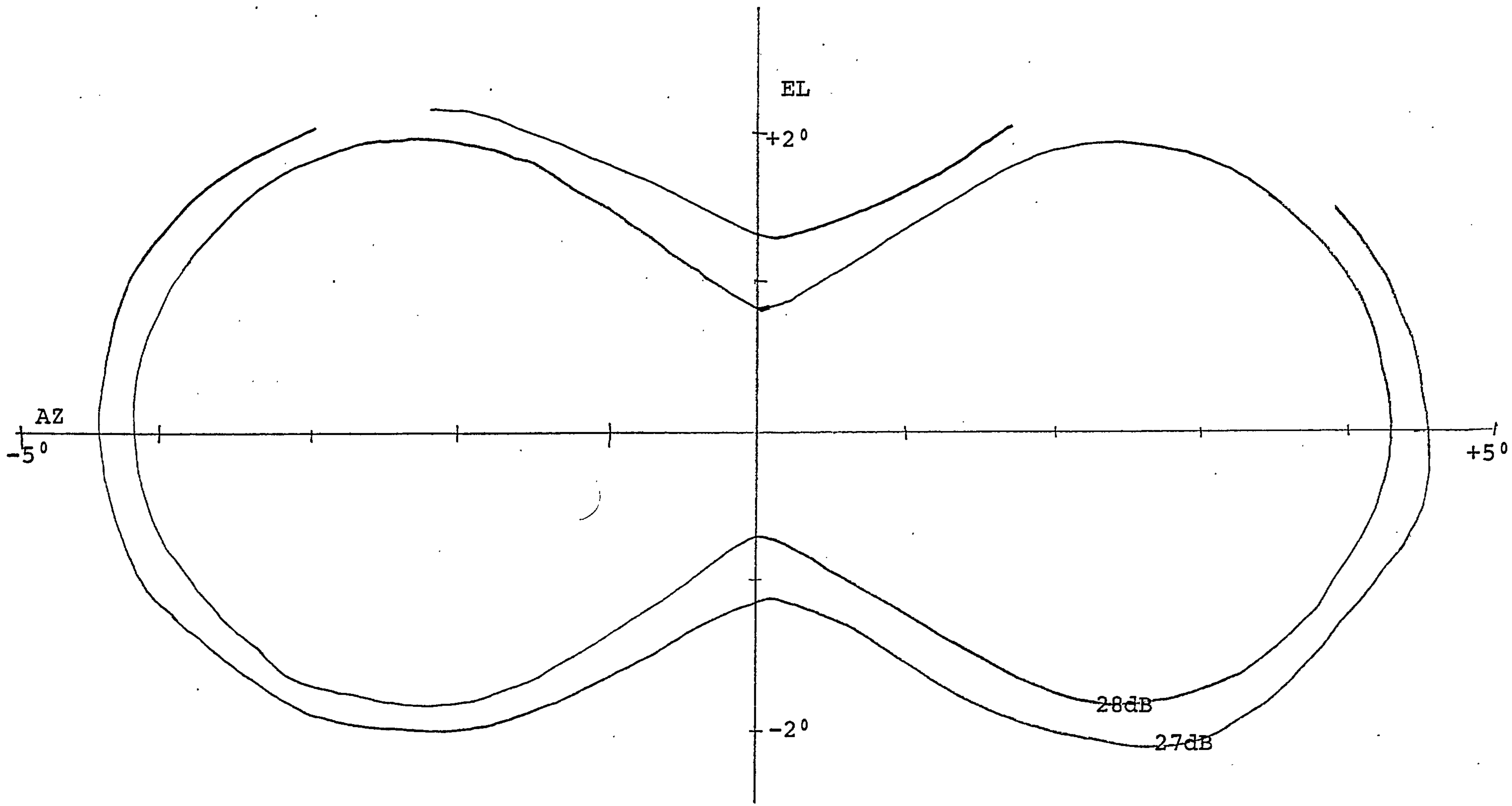


Figure 4.2.7 Mark I Configuration, 4 GHz Transmit, 60" Reflector, Quadrature Feed

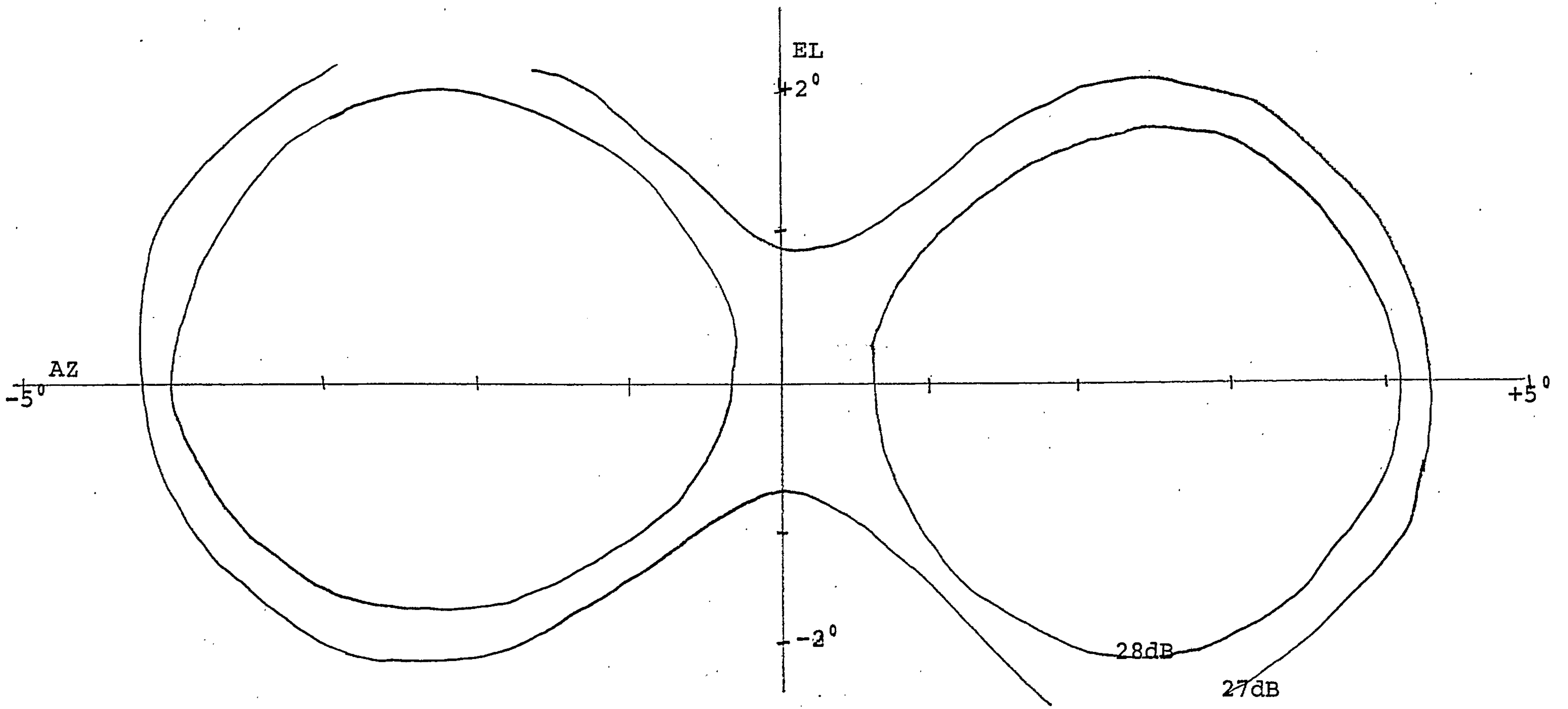


Figure 4.2.7(a) Mark I Configuration, 4 GHz Transmit, 60" Reflector, Quadrature Feed, Feed Blockage

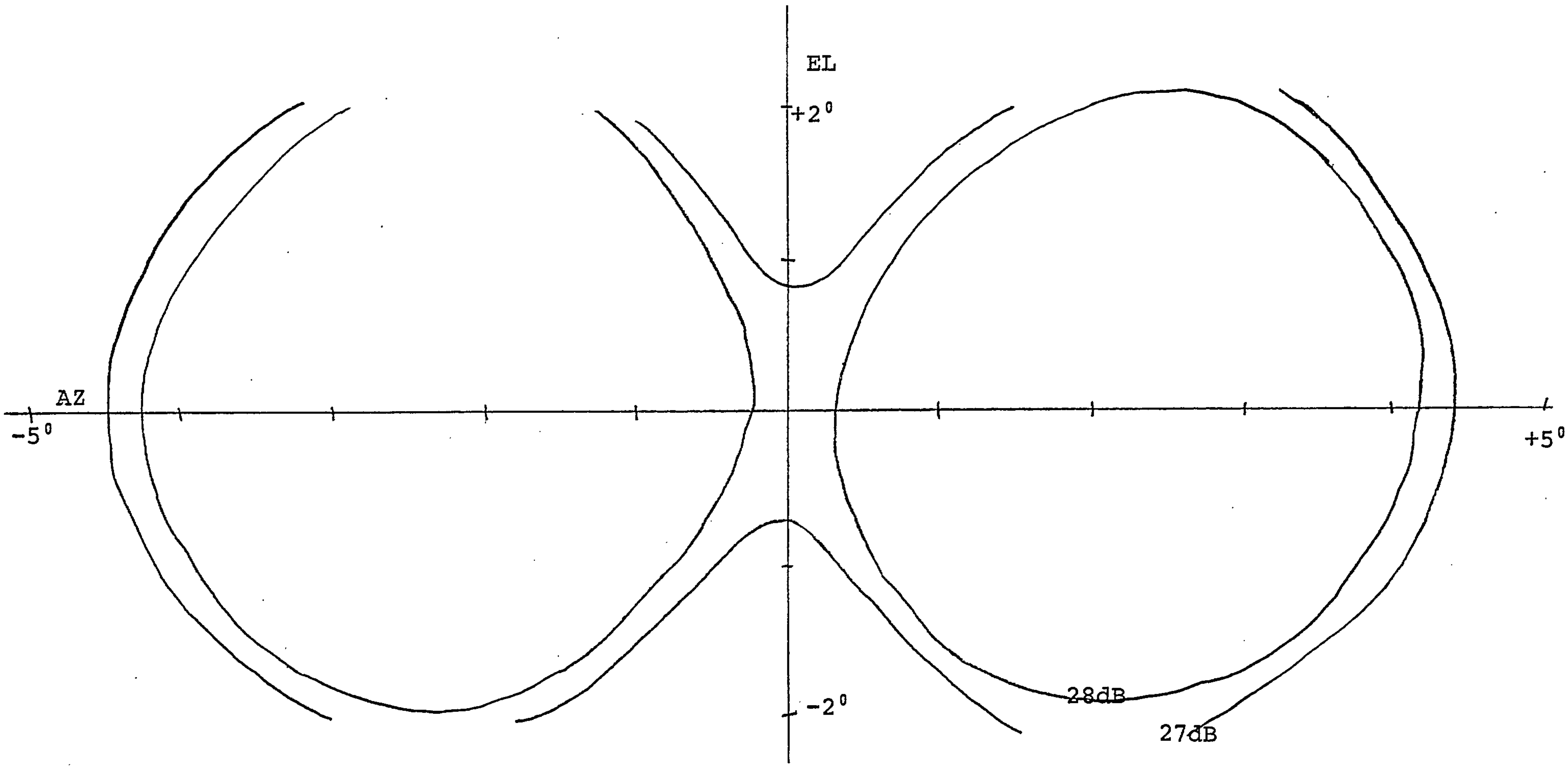


Figure 4.2.8 Mark I Configuration, 4 GHz Transmit, 84" Reflector, Quadrature Feed

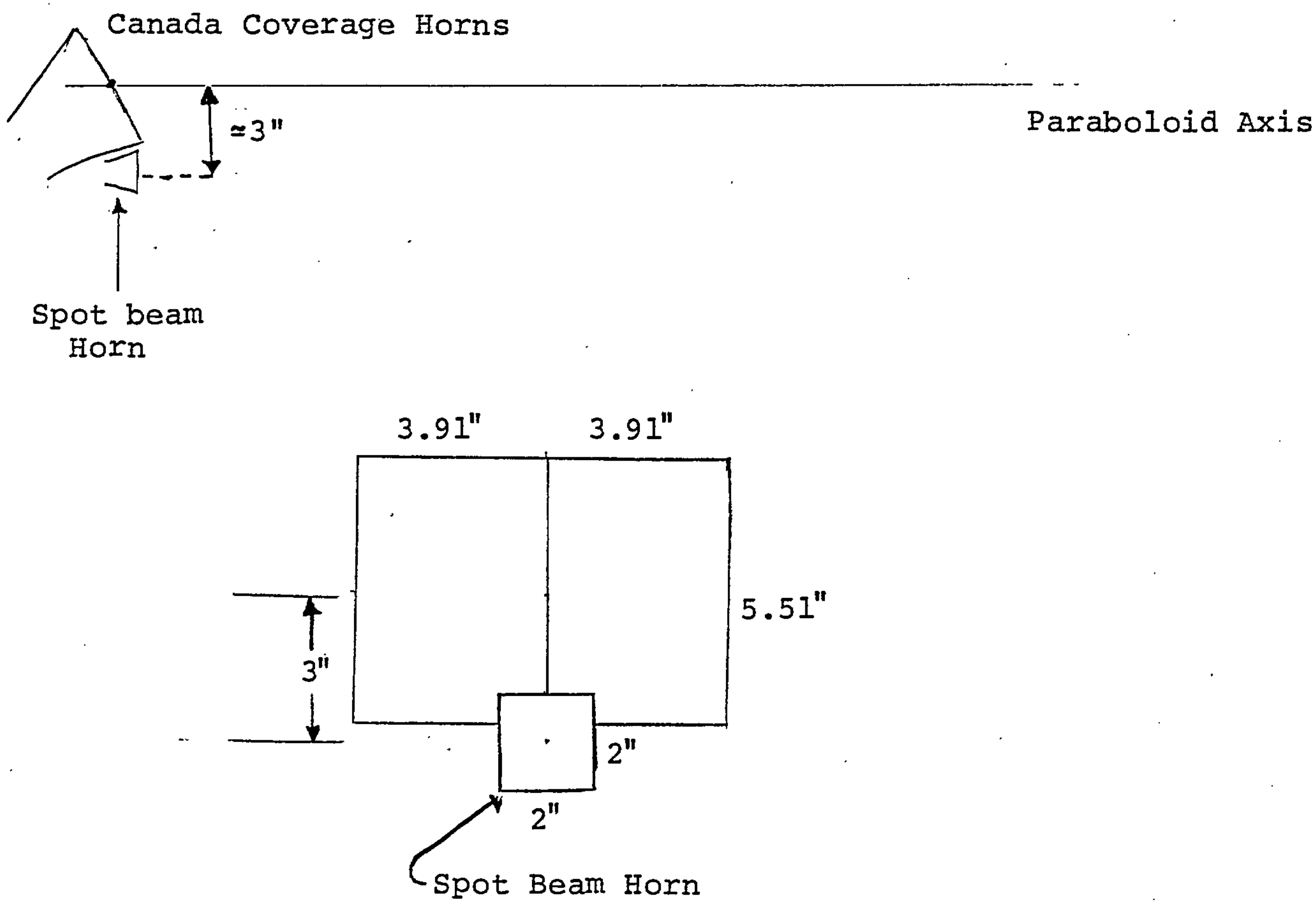


Figure 4.2.9 Mark I configuration 6 GHz spot beam

more than 3 dB of asymmetry. There was also a very pronounced 'waist' in the pattern in the overlap region between the horns. The achievable Canada coverage gain with this configuration was less than 26 dB and so it was not pursued any further.

A feed defocussing of 2 inches again resulted in a downward tilt of the beam. This was corrected by maintaining the same defocussing value and displacing the feed downward slightly (by 1 inch) to bring the beam back near the antenna axis. The resulting pattern is shown in Figure 4.3.1. Due to the smaller defocussing the asymmetry is reduced to 2 dB or less but the 'waist' is again very pronounced, as it was in the undefocussed case. The achievable Canada coverage gain is between 27 and 28 dB. Figure 4.3.1 was computed on the assumption that the gridded section would be arranged to reflect vertical polarization, i.e. the effective dish diameter is 60 inches. A larger dish would be expected to increase the centre 'waisting' effect.

At 6 GHz, the pattern separates into two distinct beams (with no asymmetry since the feeds are in phase at 6 GHz) even with a 60 inch effective dish diameter. The achievable Canada coverage gain is about 25 dB, which is considered unacceptable.

4.4 Mark 2 Configuration - 4/6 GHz, 2 Horns

This proposed configuration resembles the Mark I in that it uses two horns and a solid/gridded reflector system. The horns are, however, smaller and the solid part of the reflector is also smaller. The horns are also 'staggered' to cause a clockwise rotation of the antenna pattern to improve the 'match' to the shape of Canada. This configuration is shown in Figure 4.4.1. The horn 'stagger' shown, and the 6 GHz spot beam horn dimensions were scaled from a drawing of the feed assembly and may therefore contain some slight inaccuracies. The large horns are tilted 'up' by 15.5 degrees to aim at the centre of the solid section. The small 6 GHz spot beam horn is aimed at the centre of the aperture.

One aspect of the proposed configuration involved tilting part of the gridded reflector to bring the 6 GHz spot beam 'up' from the position it would otherwise occupy over the midwestern U.S. This could not be simulated without rewriting some of the computer analysis routines. In view of the effort involved and the marginal utility of having just one extra configuration analysed in detail, the dish was assumed to be not split. The

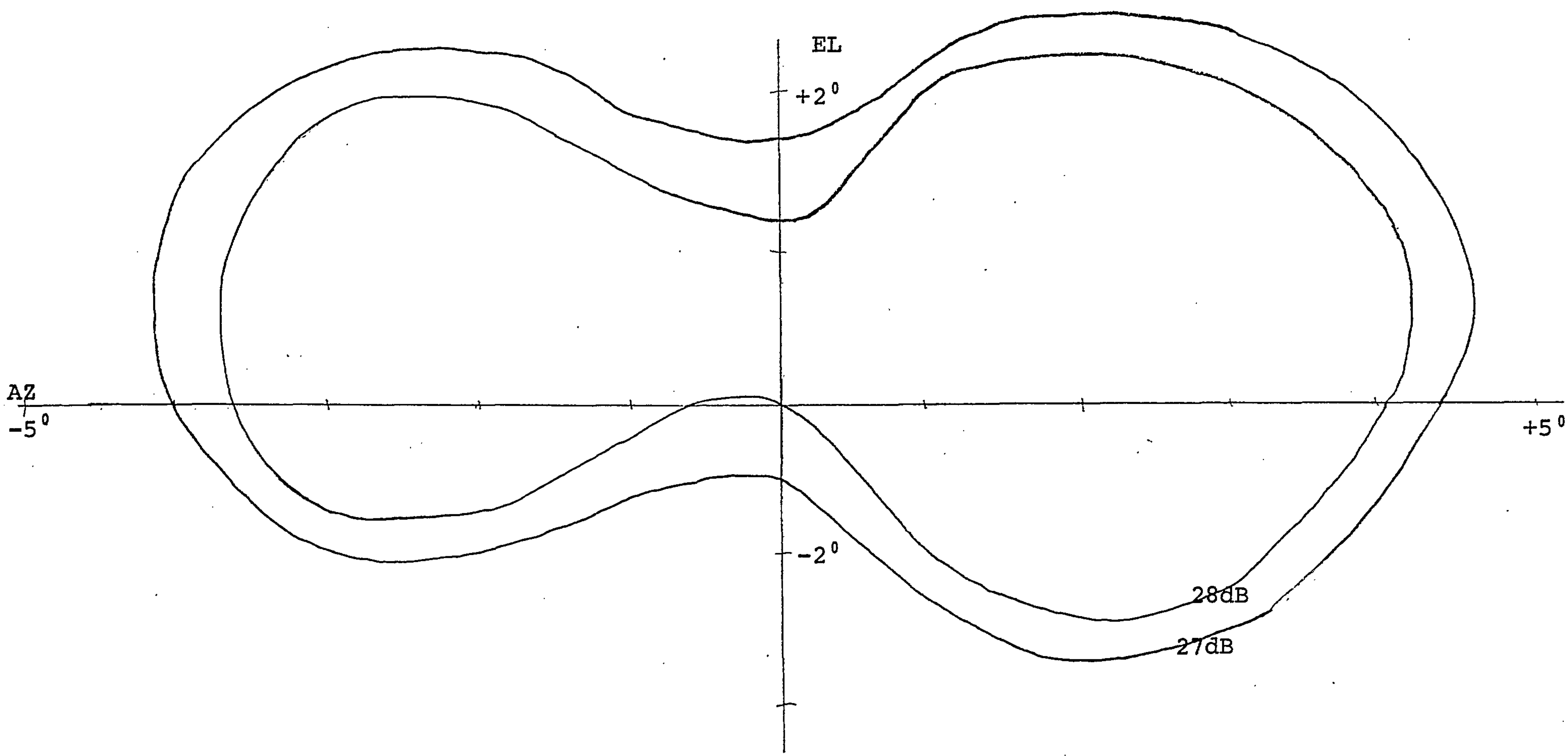


Figure 4.3.1 Mark IA Configuration, 4 GHz Transmit, Quadrature feed, 2" feed defocussing

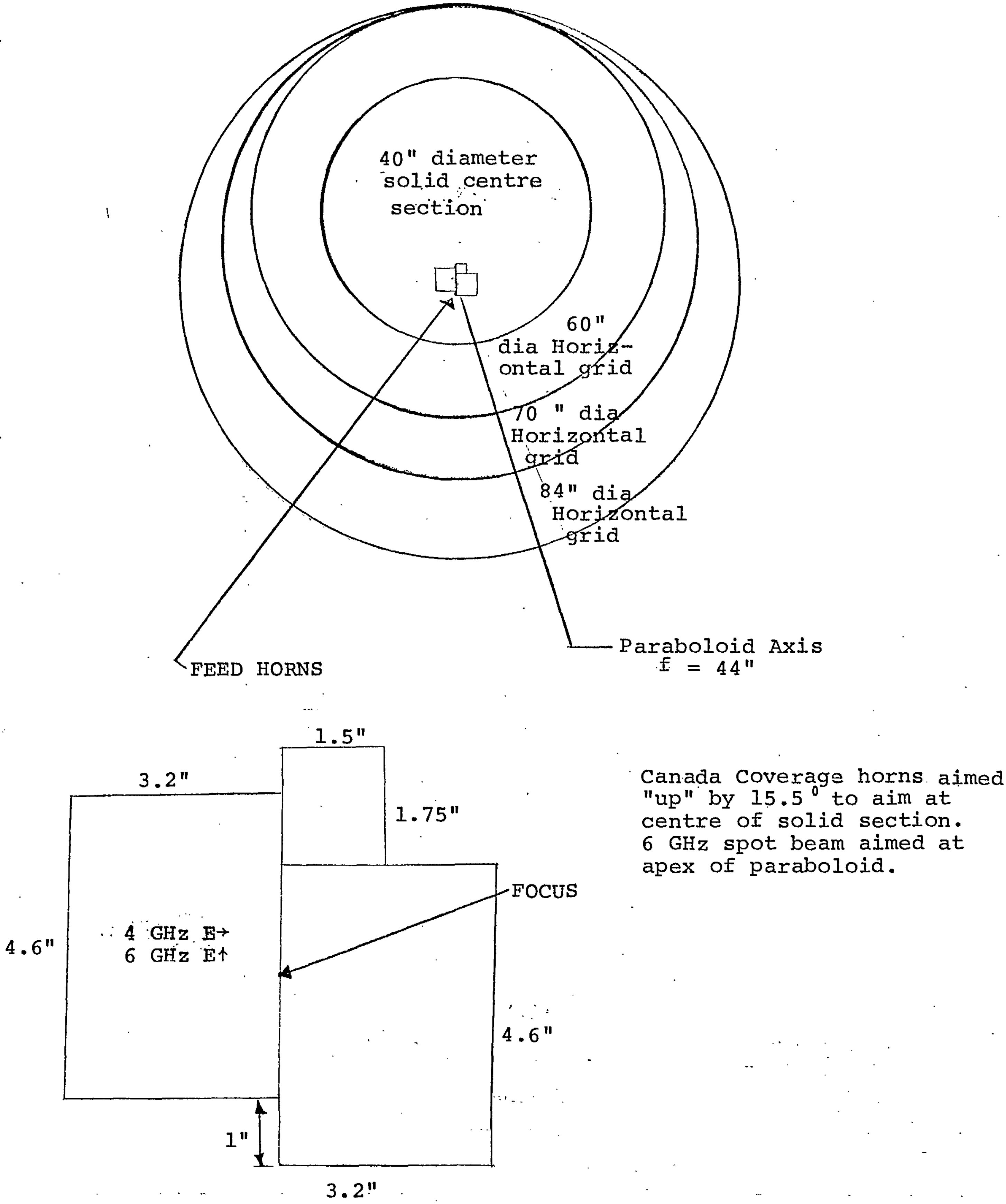


Figure 4.4.1 Mark 2 Configuration

proposed split focus technique is in any case considered undesireable since, to a first approximation, its main effect is to create different N-S and E-W focal lengths for the paraboloid. This leads to a defocussing effect for the 4 GHz and/or UHF beams with a possible reduction in gain.

The Mark 2 configuration proposed to utilise a 60 inch reflector diameter at 4 GHz by use of the 40 inch diameter centre section of the dish plus the 60 inch diameter gridded section. However, the other horizontally gridded sections are obviously still present and will affect the pattern to some extent. In the actual configuration proposed, the density of gridding on the outer section was lower than on the inner sections to reduce spot-beam sidelobes. This feature could not be modelled and so the configuration was analysed at 4 GHz based on the assumptions of a 60 inch and then an 84 inch reflector. The results for the 84 inch reflector configuration however represent the most likely pattern to be obtained in practice.

4.4.1 Mark 2 Configuration, 60 inch Reflector at 4 GHz

Figure 4.4.2 shows the 4 GHz pattern assuming a 6.4 inch by 4.6 inch blockage on the paraboloid axis. It is readily apparent that the 'stagger' of the feed horns is excessive and the pattern is much too twisted clockwise. A reduced 'stagger' (probably about 0.4 inches rather than 1 inch) would rotate the pattern back to a more optimum coverage orientation. This would however push the spot beam horn further away from the effective pattern axis. The effects of a reduced stagger on coverage can be simulated by rotating the Canada map clockwise and gauging the proper orientation by eye. Doing this, the edge gain in the Yukon and Newfoundland is 27 dB with zero pointing errors. The gain slope is however quite large and 29 dB gain can be obtained outside of the Yukon and Newfoundland. (The target value in the reference material was 28.94 dB.) The large gain slope within the nominal coverage area makes the pattern quite sensitive to pointing errors.

4.4.2 Mark 2 Configuration, 84 inch Reflector at 4 GHz

In the proposed configuration, the horizontally gridded area outside the nominal "4 GHz transmit" portion of the reflector, can be expected to influence the horizontally polarized transmit pattern. The 2 horn configuration was reanalyzed assuming that the effective dish diameter for 4 GHz horizontal

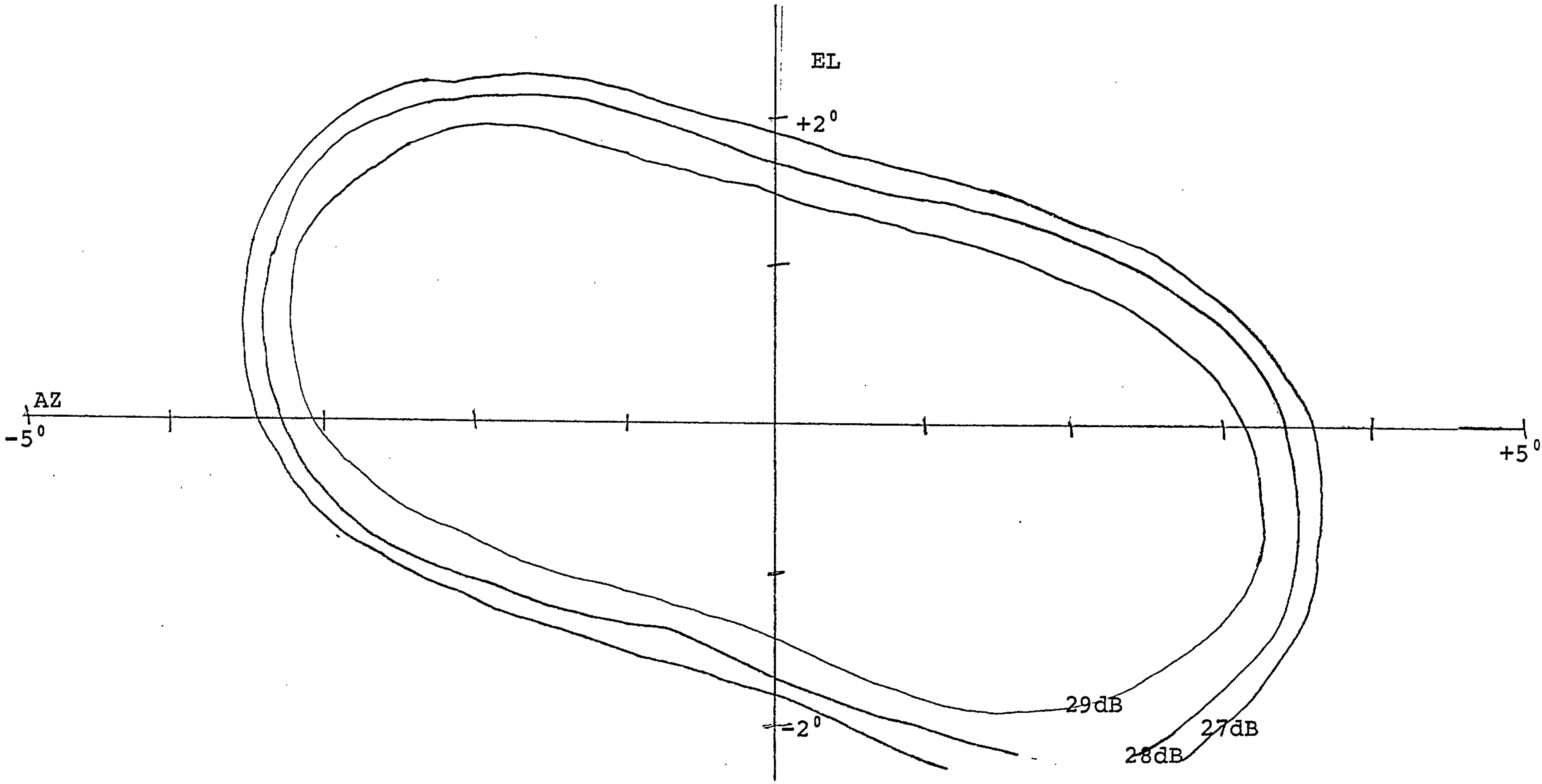


Figure 4.4.2 Mark 2 Configuration, 4 GHz Transmit, 60" Reflector

radiation is 84 inches. Figure 4.4.3 shows the resulting pattern (including feed blockage effects). The obvious effect is a slight dog-boning due to the anti phase horn sidelobe energy falling on the dish. Since the pattern is very generous in the N-S direction the 'waist' in the pattern does not constrain coverage and the overall performance is the same as the 60 inch effective diameter, i.e. 27 dB minimum gain, 29 dB over most of Canada.

4.4.3 Mark 2 Configuration, 6 GHz Canada Coverage

Figure 4.4.4 shows the pattern for 6 GHz Canada-coverage receive. Again the excessive 'stagger' causes too much clockwise twist. Realignment by eye shows that the achievable 6 GHz gain is 26 dB (no pointing errors) over all of Canada and 28 dB over most of Canada. The target value was 28.34 dB. The shape is very similar the the 4 GHz pattern and similar comments apply.

As mentioned previously the 6 GHz spot beam pattern was not analyzed owing to the difficulty of representing the 'split dish' configurations without a program rewrite. Without the split dish, the result is a fairly predictable spot beam aimed towards the midwest of the United States.

4.5 Mark 3 Configuration - 12/14 GHz, 4 Horns

The coverage requirements for 12 and 14 GHz are different from those at 4/6 GHz. In the 14 GHz receive band Canada coverage is required with horizontal polarization. In the 12 GHz transmit band, full Canada coverage is required on one channel only. Other channels require transmit coverage via four 'regional' beams to Eastern Canada (Maritimes), Central Canada (Ontario, Quebec), the Prairies and Western Canada. Other channels require coverage to the Western half of Canada (Prairies and Western) and to the Eastern half (Central and Eastern) of Canada. The proposed configuration is depicted in Figure 4.5.1. For multiple horn excitation at 12 GHz, power combining is performed in the transponder rather than in the antenna subsystem.

Flexibility is again available with respect to the polarization of the gridding outside the solid portion of the reflector. The configuration was therefore initially analyzed using both possible assumptions of grid direction. At 12 GHz

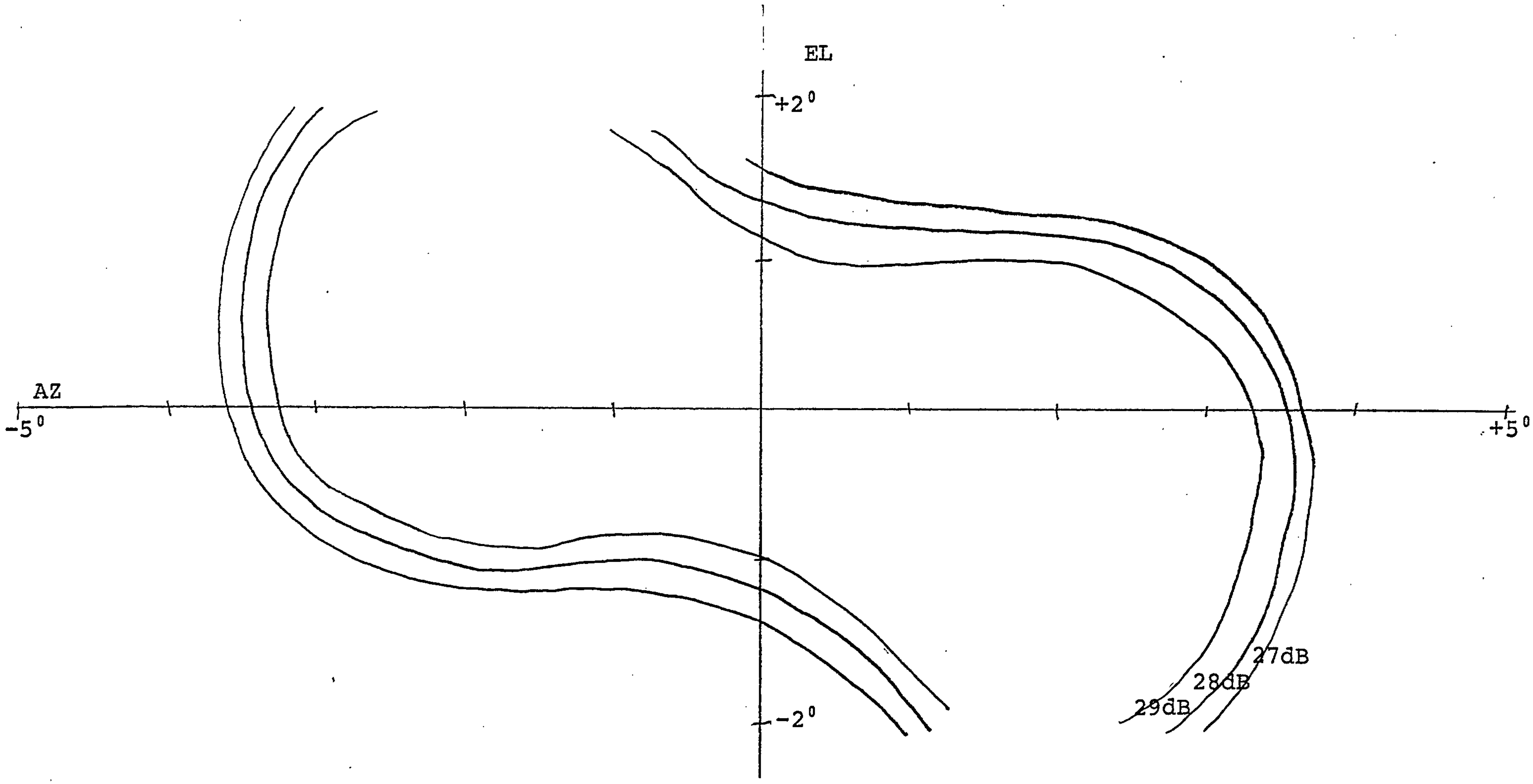


Figure 4.4.3 Mark 2 Configuration, 4GHz Transmit, 84" Reflector

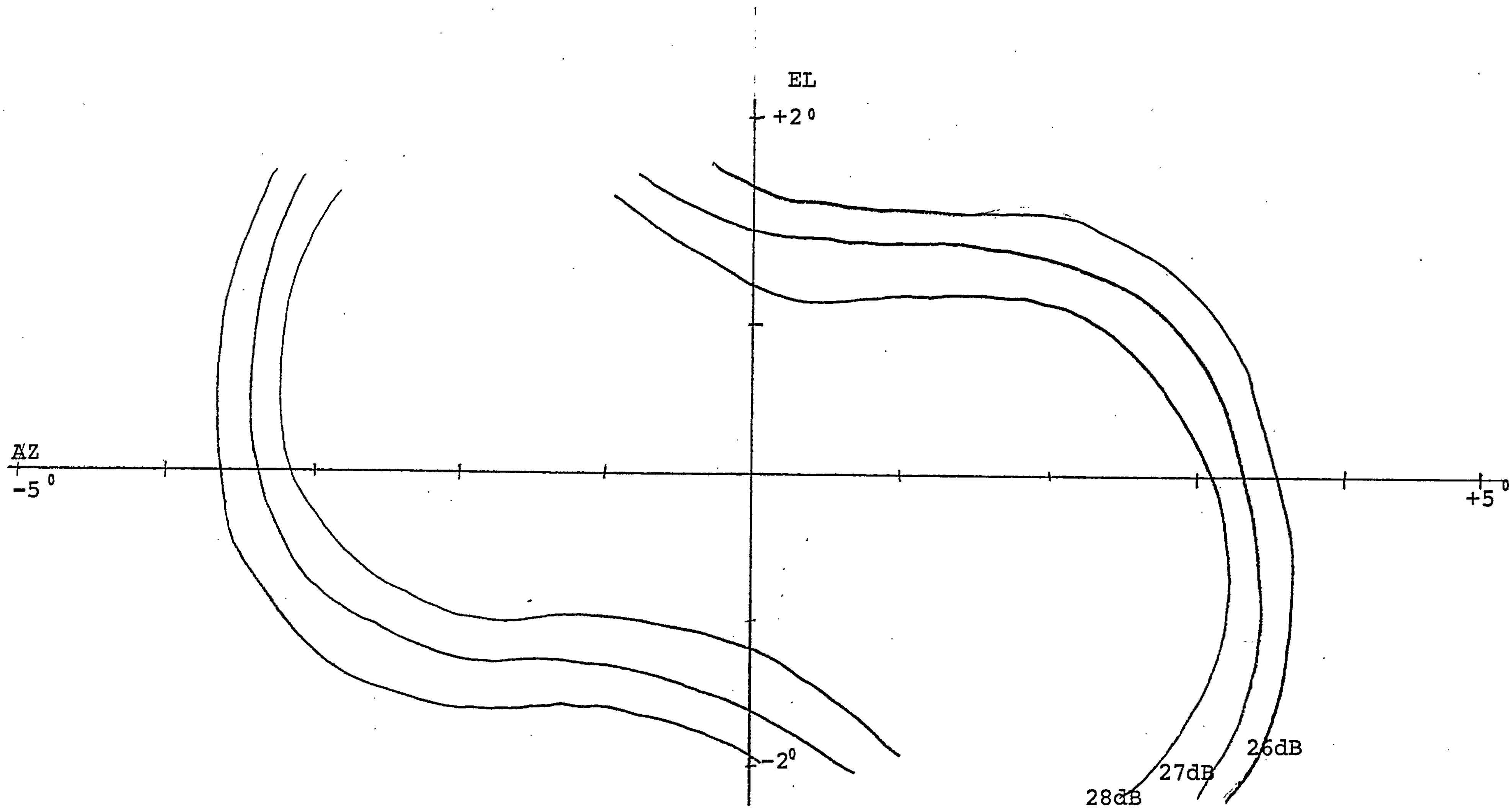


Figure 4.4.4 Mark 2 Configuration, 6 GHz Receive, 60" Reflector

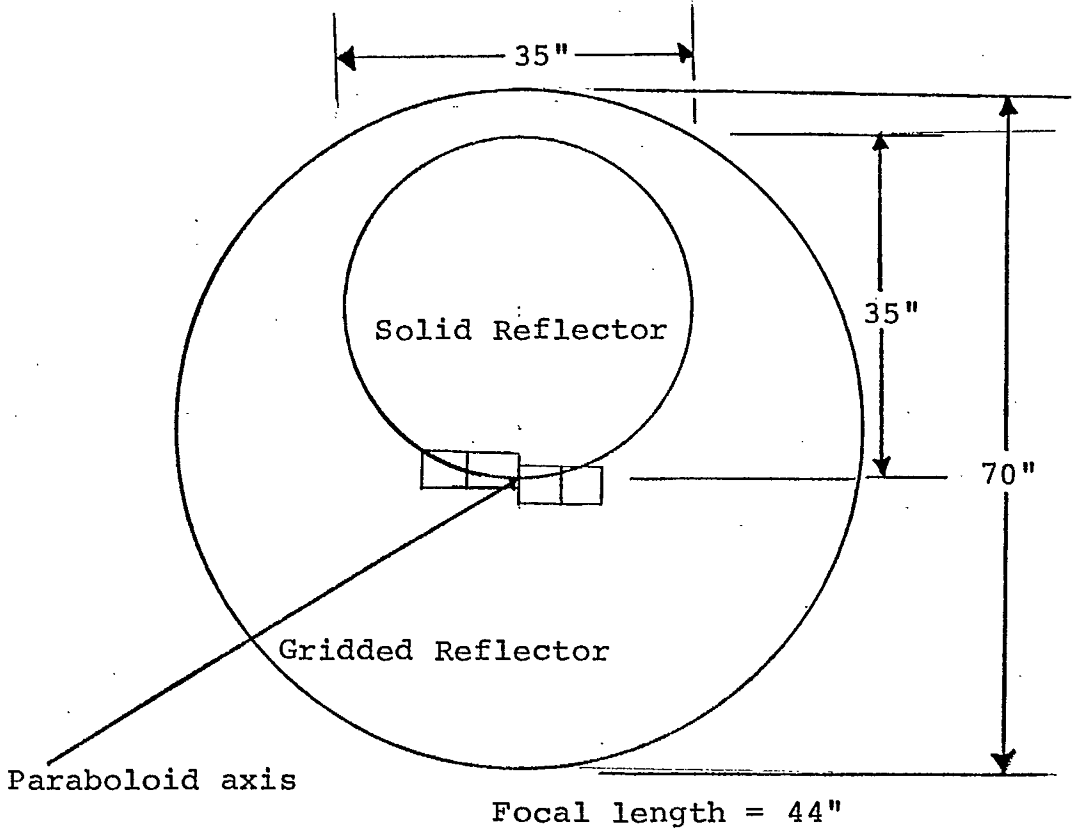
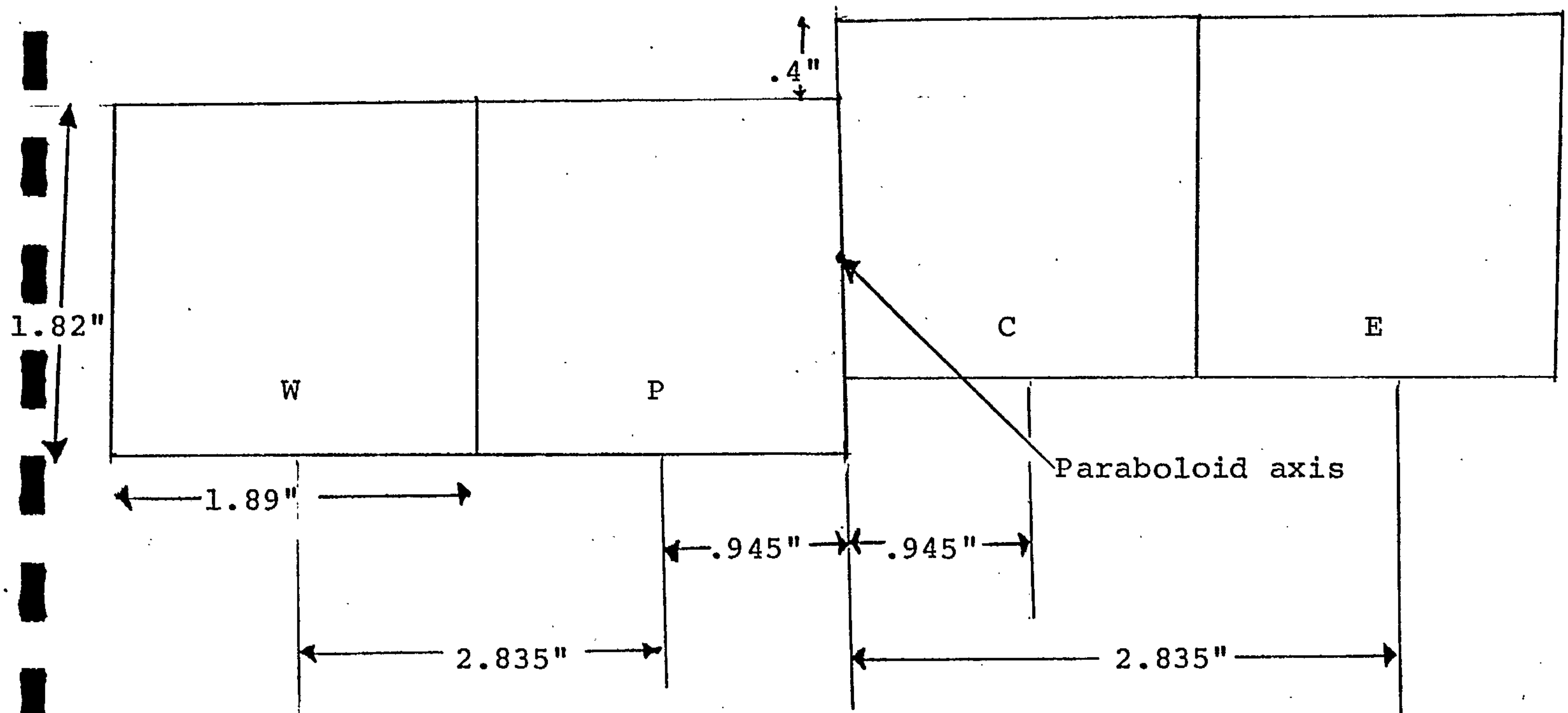


Figure 4.5.1 Mark 3, 12/14 GHz Antenna Configuration



Feed structure is tilted 'up' at 22 degrees to aim at centre of solid reflector.

the vertically polarized pattern with a 70 inch equivalent dish diameter is shown in Figure 4.5.2. The pattern forms two distinct 'beams' and is strongly double humped in the N-S plane. It is therefore unsuited for Canada coverage. With a 35 inch dish size however, Figure 4.5.3 results. In this pattern the smaller dish size has removed significant quantities of horn sidelobe energy from the far field pattern resulting in a much more uniform coverage. Since 12 GHz Canada coverage is a requirement, a 35 inch equivalent dish size was assumed for all subsequent 12 GHz patterns.

For 14 GHz Canada coverage receive, the pattern corresponding to a 70 inch equivalent dish diameter is shown in Figure 4.5.4. While the coverage is continuous, the N-S beamwidth is very narrow, resulting in very large gain slopes near the edge of Canada with poor tolerance to pointing errors.

In order to broaden the 14 GHz N-S beam slightly, the 14 GHz Canada coverage receive mode was recomputed assuming a 35 inch equivalent dish diameter.

Figures 4.5.3 and 4.5.5 show the 12 and 14 GHz Canada coverage patterns for a 35 inch diameter dish. At 12 GHz, a gain of 28 dB is achievable over all of Canada (no pointing errors) if the pattern is given a slight clockwise twist. 30 dB is obtainable over most of Canada but the N-S gain slope is high.

At 14 GHz the pattern is similar to that at 12 GHz. 28 dB gain is just achievable (no pointing errors) and 30 dB is obtainable over most of Canada. Again the N-S gain slope is quite high and the E-W pattern is a little too wide.

Figure 4.5.6 shows the single zone performance of the four 12 GHz horns energized individually with the patterns superimposed. Figure 4.5.7 shows the performance with combined Central plus Eastern and Prairie plus Western horn configurations. The patterns are again superimposed for convenience.

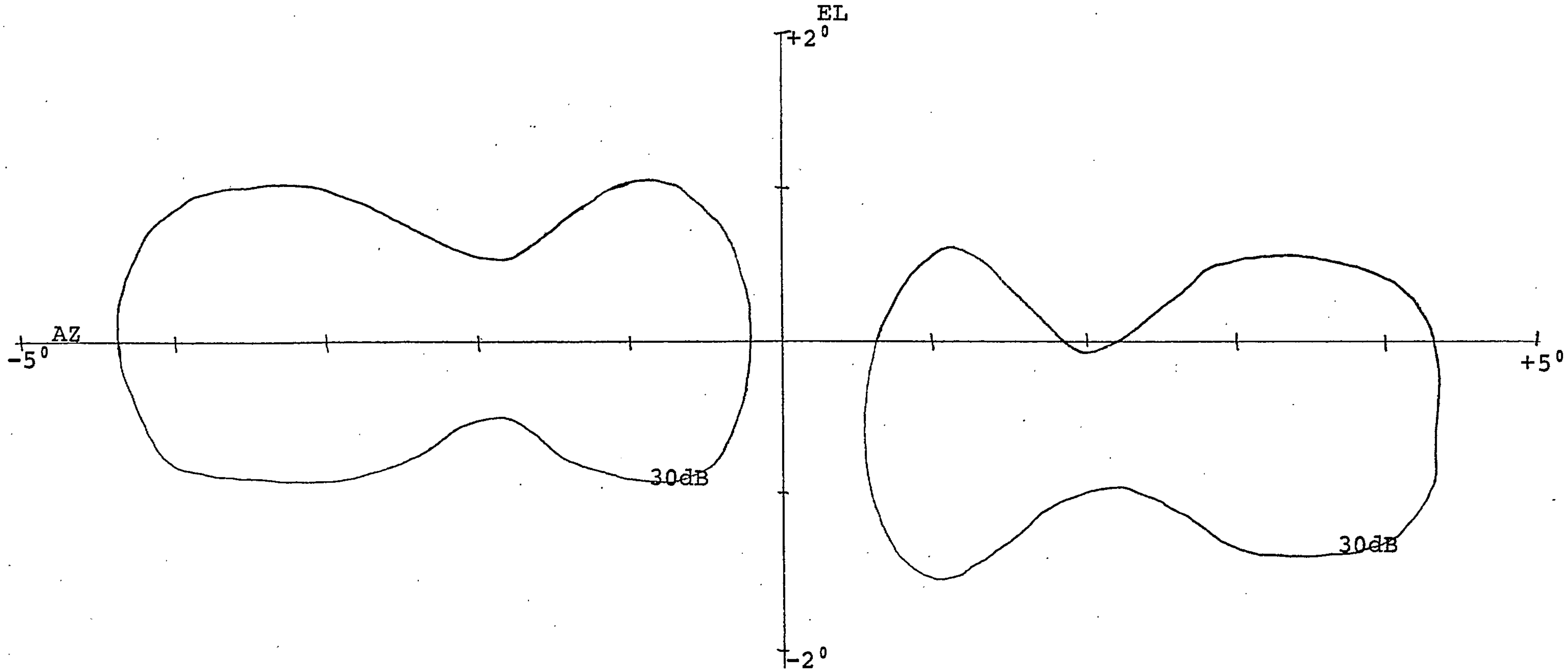


Figure 4.5.2 Mark 3 Configuration, 12 GHz Transmit, 70" Reflector

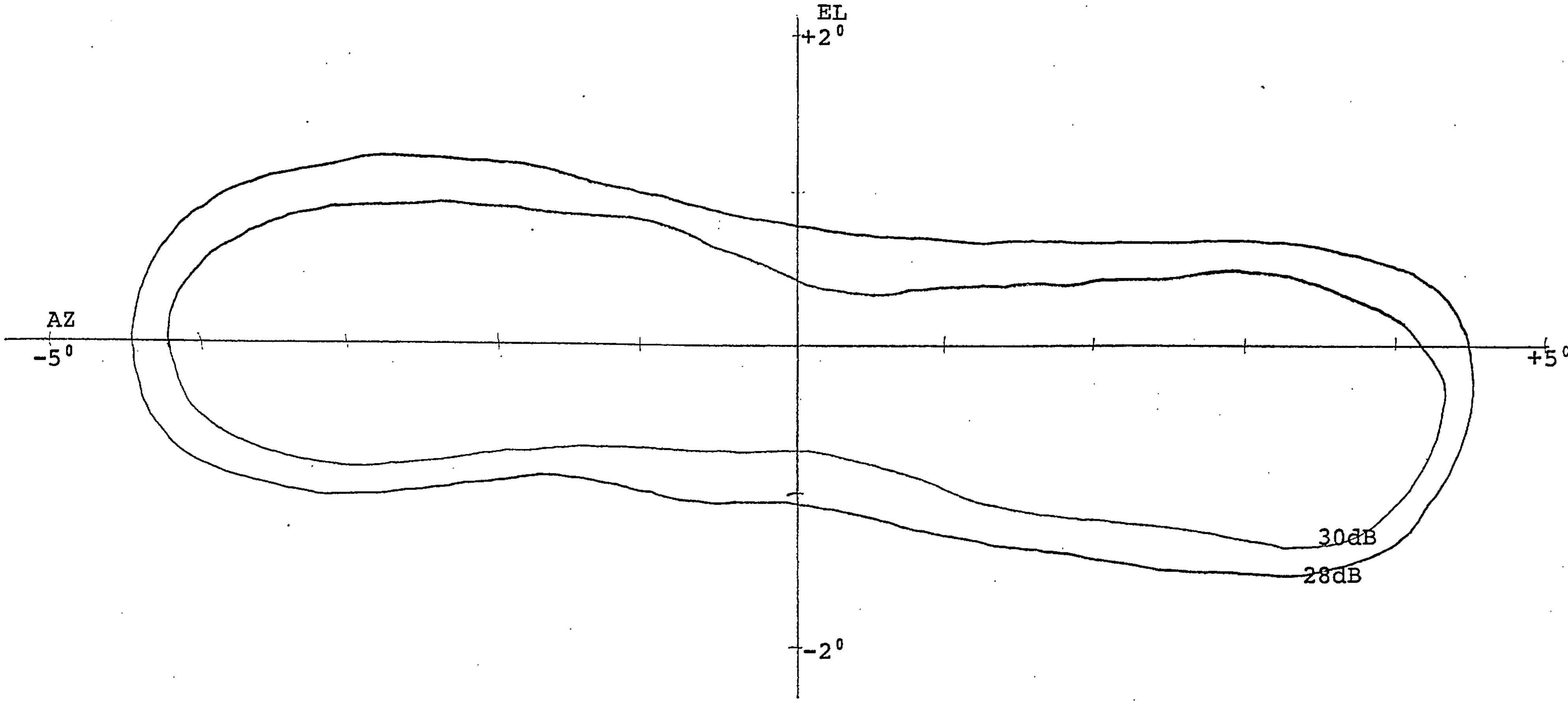


Figure 4.5.3 Mark 3 Configuration, 12GHz Transmit, 35" Reflector

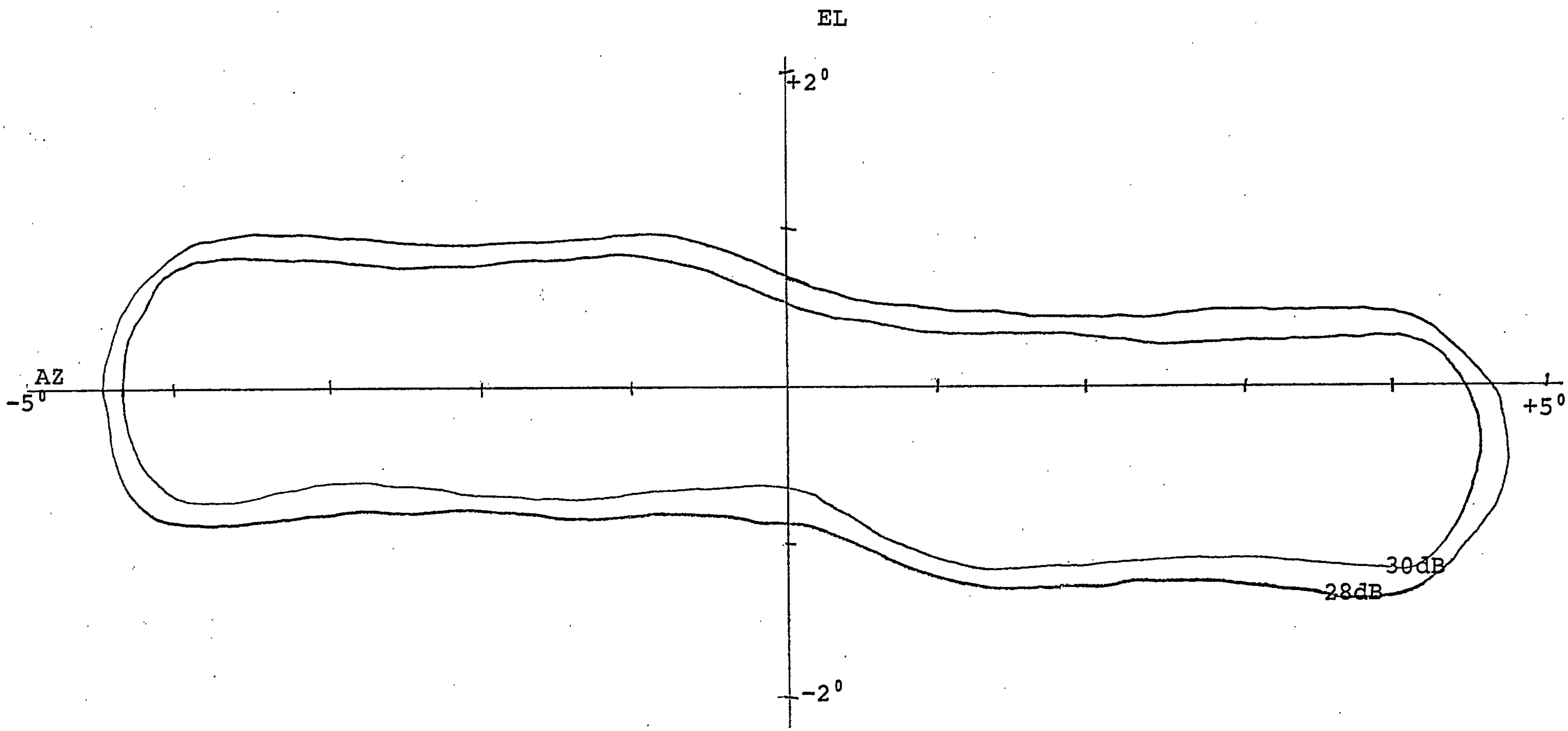


Figure 4.5.4 Mark 3 Configuration, 14 GHz Receive, 70" Reflector

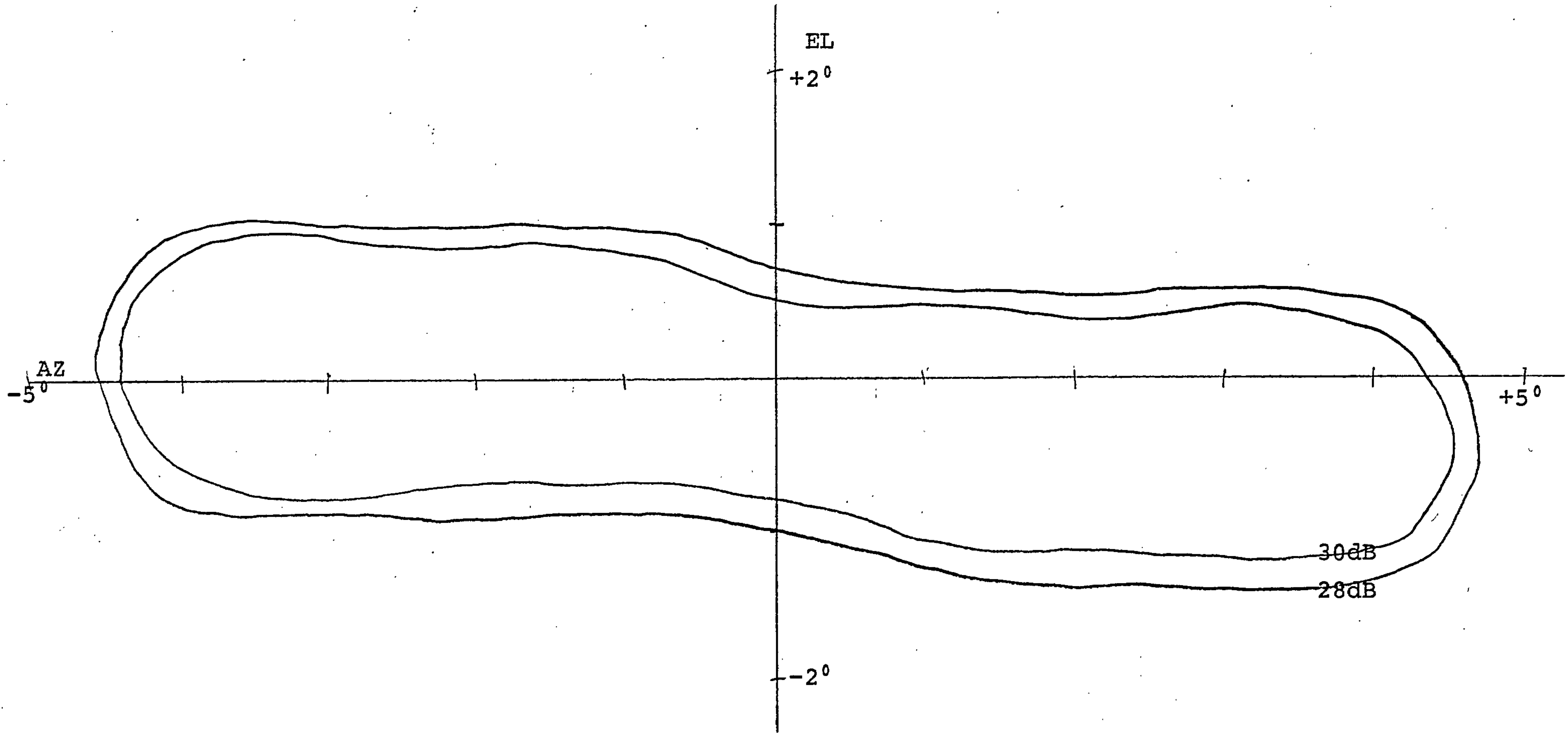


Figure 4.5.5 Mark 3 Configuration, 14 GHz Receive, 35" Reflector

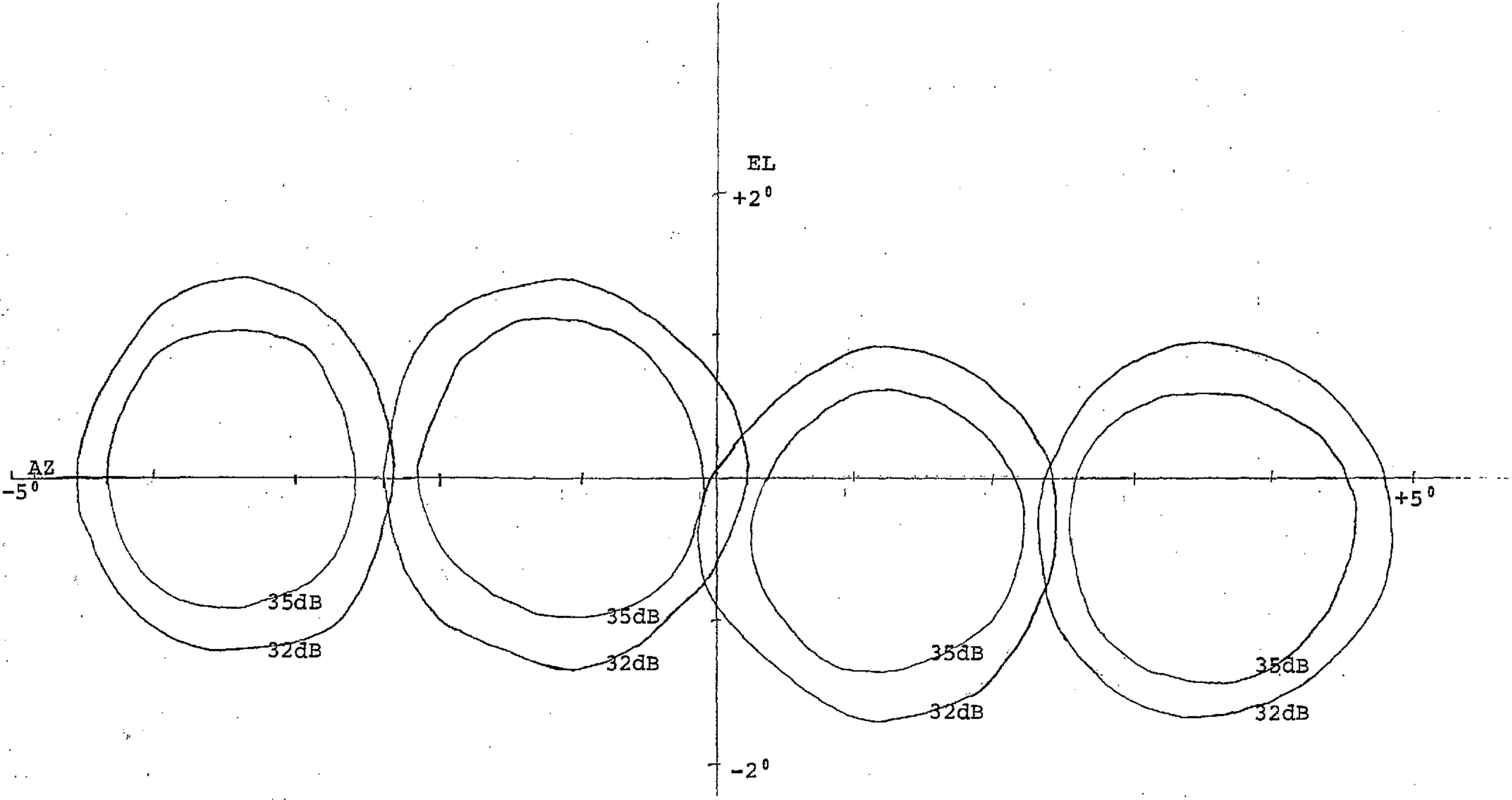


Figure 4.5.6 Mark 3 Configuration, 12 GHz Transmit, Single Zone Beams

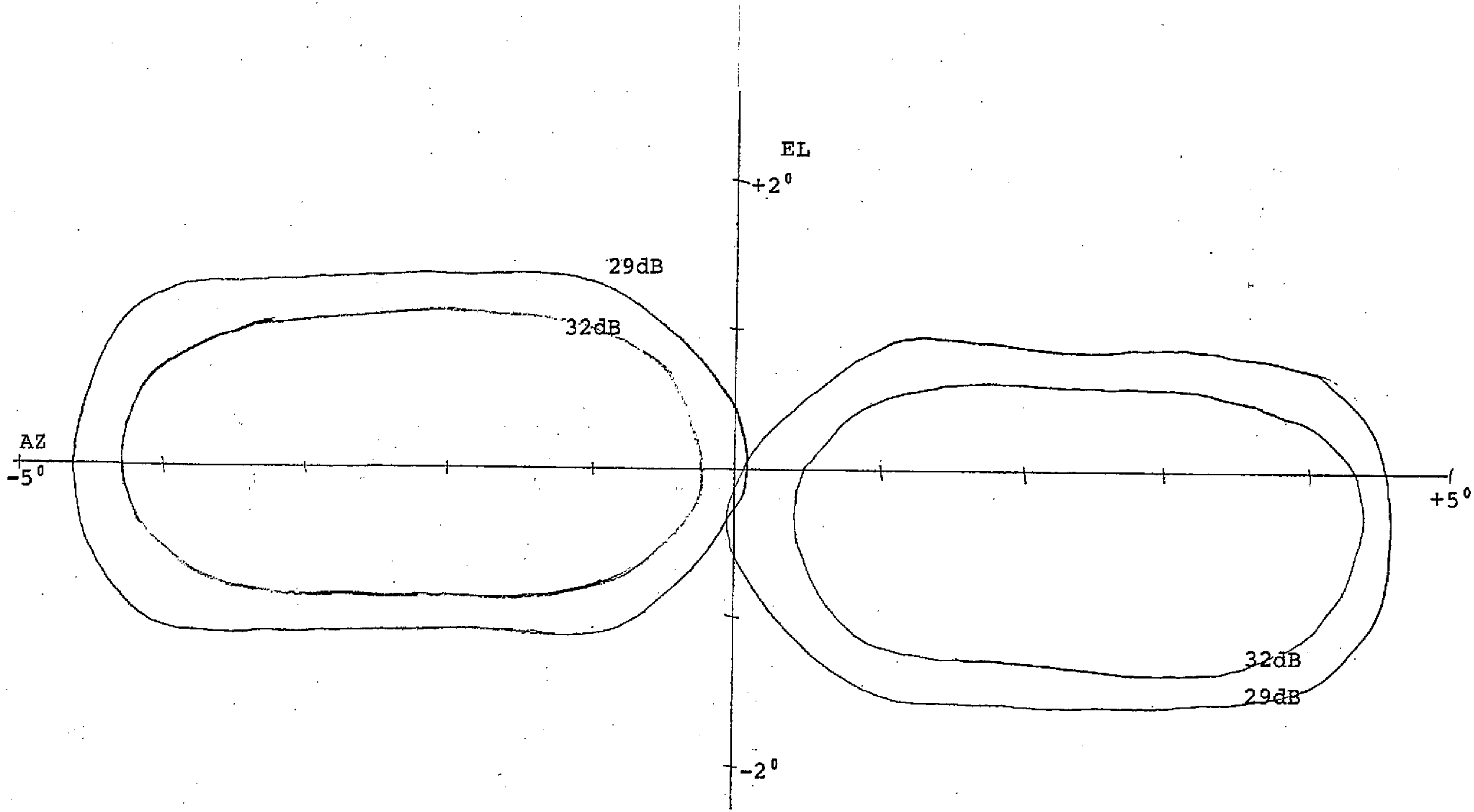


Figure 4.5.7 Mark 3 Configuration, 12 GHz Transmit, Double Zone Beams

5.0 ALTERNATE ANTENNA CONFIGURATIONS FOR 4/6 GHz

5.1 Introduction

In this chapter a design rationale will be developed whereby a desired antenna pattern shape can be generated with a minimum number of iterations. The desired coverage area will be assumed to be all of Canada from a narrow (±5 degrees) range of synchronous orbit locations around 110 degrees West longitude.

It is assumed that the 4/6 GHz antenna system will be able to share all or part of a large reflector used for UHF operation. The reflector is assumed to be a deployable dish consisting of a 7 foot diameter solid centre section and a folding mesh outer section up to 13 - 16 feet diameter. It is also assumed that the inner portion of this folding mesh section will be accurate enough to permit operation at 4 and 6 GHz. The normal dish tolerance criteria do not in any case apply in this instance since the 4/6 GHz energy falling on the mesh portion is small and the effects of surface errors are not as great on a shaped beam antenna as on a pencil beam antenna.

The configurations developed have not been checked for mechanical feasibility. Once the mechanical constraints are fully known, any necessary reconfigurations can be made. It is, however, considered unlikely that any major performance penalties will result. Indeed, it may prove that another iteration can cause a small performance increase.

In the 4/6 GHz communications satellite application, the most critical aspect of antenna performance is the 4 GHz transmit gain and coverage. Consequently, this mode will be optimized first and the 6 GHz receive mode adapted to the 4 GHz configuration.

Canada subtends an angle of about 1.5 - 1.7 degrees in the N-S plane at synchronous orbit. Allowing, say, ±0.1 degrees for N-S pointing errors, the N-S beamwidth at 4 GHz should be in the region of 1.7 - 1.9 degrees. This requires a N-S aperture size in the region of 9 to 10 feet. This size is probably achievable as a small mesh extension of the 7 foot diameter solid centre section of the antenna referred to earlier.

Two design approaches are presented in this chapter. One covers a 3 horn configuration using just the solid 7 foot diameter centre section of the main dish for 4/6 GHz operation. The outer portion is assumed to be made of coarse mesh which would be nearly transparent to 4/6 GHz radiation. Good performance is achievable with this design but it requires a special power combiner/divider network to distribute the power available from the odd/even channel transponder output multiplexers to the three feed horns. While this would represent a new development in Canada, it is conceptually simpler than that demonstrated on the Anik spacecraft. The other approach uses a 4 horn feed and exploits a small part of the deployable mesh for 4 GHz operation (the inner part of the deployable UHF mesh would obviously have to be overlaid with a finer mesh for SHF reflection). This four horn configuration offers a performance advantage and does not require a special 2-3 combiner.

5.2 3 Horn Configuration

5.2.1 Design Rationale, 3 Horn Configuration at 4 GHz

The angle subtended by a 7 foot diameter, 44 inch focal length reflector at the focus is about 100 degrees. At 4 GHz, the N-S beamwidth of the feed horn should therefore be of the order of 100 degrees in order to fully illuminate the dish. If the horn design beamwidth is made slightly less than 100 degrees, this would permit a slight reduction in spillover loss and would place a small amount of sidelobe energy on the dish, leading to a very small amount of N-S beamshaping. A N-S horn dimension of 1.3 wavelengths was therefore selected, giving a horn height of 3.9 inches. In the E-W direction, a similar set of criteria lead to a horn width of 2.6 inches. Criteria of shape matching with the Canada coverage map lead to the same horn configuration as was analyzed for the Anik in Chapter 3. The main difference is that at 4 GHz with the 84 inch dish, the width of the 'beams' from each horn is about the same as the beam spacing so that the beams overlap at the 3 dB points, giving approximately uniform E-W coverage. Thus, the horns must be fed in phase to avoid dips in the beam overlap regions.

With a centre fed aperture, the most intensely illuminated part of the reflector is the region directly in the line of the feed. Unfortunately this is the region which is normally blocked out by the feed structure. In order to reduce blockage effects it is desireable to implement some degree of offset into the feed/reflector system. For a 3 axis stabilized spacecraft such as is envisaged for the UHF satellite system, a fully offset reflector system (such as is used on Anik) is not practical due to deployment and launch vehicle shroud constraints.

Also, the cross polarization performance of a highly offset antenna is very poor. As a compromise it was assumed that it would be possible to configure the circular reflector so that the centre of the circular reflector is 12 inches away from the apex of the paraboloid of which the circular dish is a part. This requires that the feeds be tilted 'up' 15.5 degrees in order to still fully illuminate the circular aperture area. Figure 5.2.1 shows the selected configuration.

5.2.2 Design Evaluation, 3 Horn Configuration at 4 GHz

Calculation of the 4 GHz horizontally polarized transmit pattern showed excellent coverage characteristics with a good agreement between the desired beam shape and the actual beam shape.

The centre portion of the pattern was however a little narrower than expected. This was assumed to be due to coma and/or sidelobes of the beams from the two outer horns subtracting from the centre horn power. This was overcome by rearranging the power split so that the centre horn received about 1 dB more power than the outer horns. The resulting 4 GHz transmit pattern is shown in Figure 5.2.2. A gain of 29 dB with more than ±0.1 degree pointing error margin is achievable over all of Canada and 30 dB everywhere except the tip of Newfoundland and the Western extremities of the Yukon. The beam edge gain slopes are not high. It is also apparent that the pattern could be slightly reshaped to advantage by putting slightly more power in the centre horn and pointing the Eastern 'beam' slightly further south, and the Western one slightly further north.

5.2.3 Design Rationale, 3 Horn Configuration at 6 GHz

The horn configuration for 4 GHz was evaluated for the 6 GHz vertically polarized receive mode and for several E-W dish sizes. The results were not satisfactory, primarily due to the narrow E plane beamwidth of the 3.9 inch horns at 6 GHz. This caused excessive first sidelobe energy to fall on the reflector, resulting in a pronounced 'double hump' N-S pattern cut.

Two solutions to this problem were implemented. The first was to reduce the effective dish diameter for vertical polarization to 56 inches by the use of selective vertical gridding

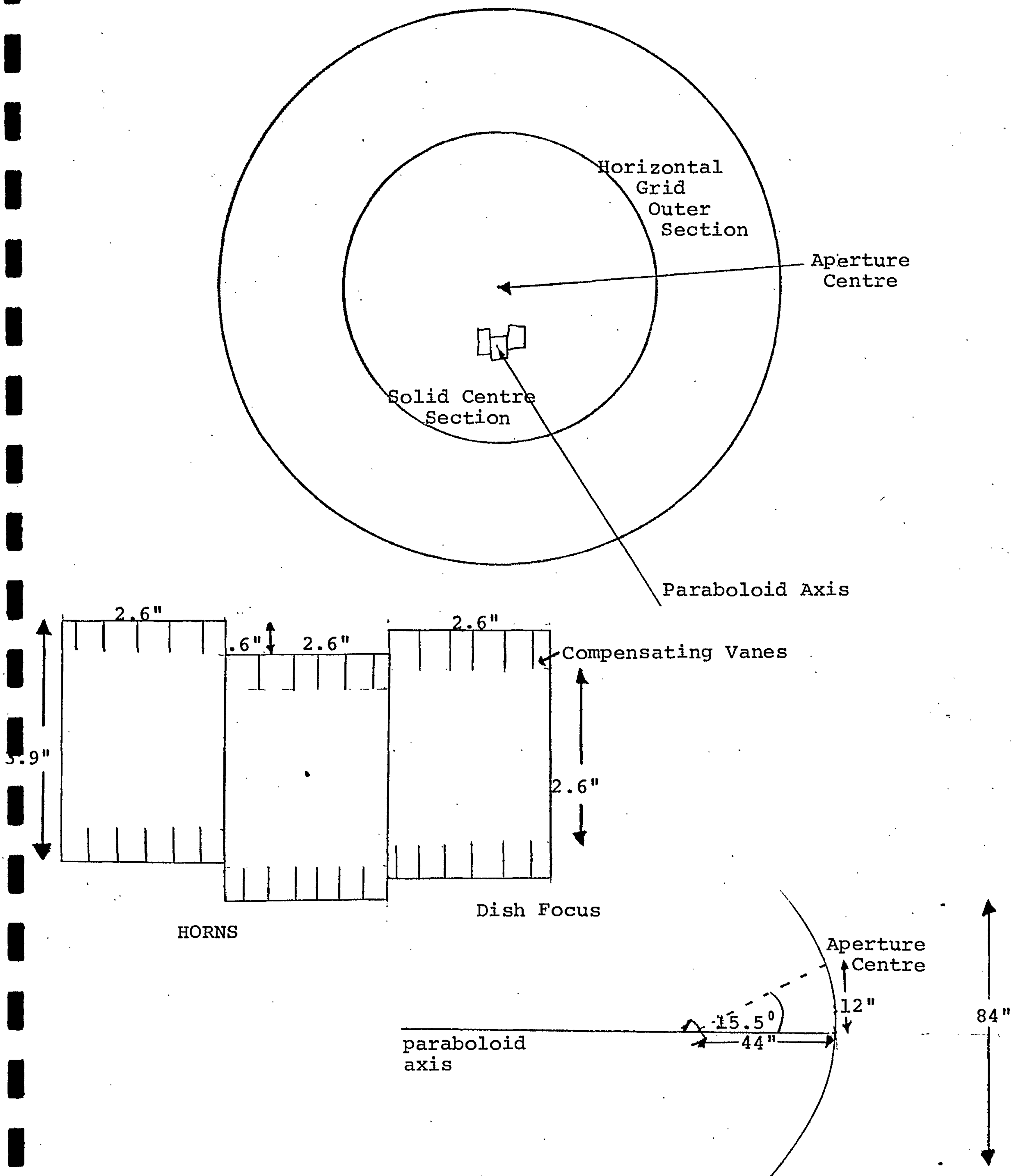


Figure 5.2.1 Three-horn configuration

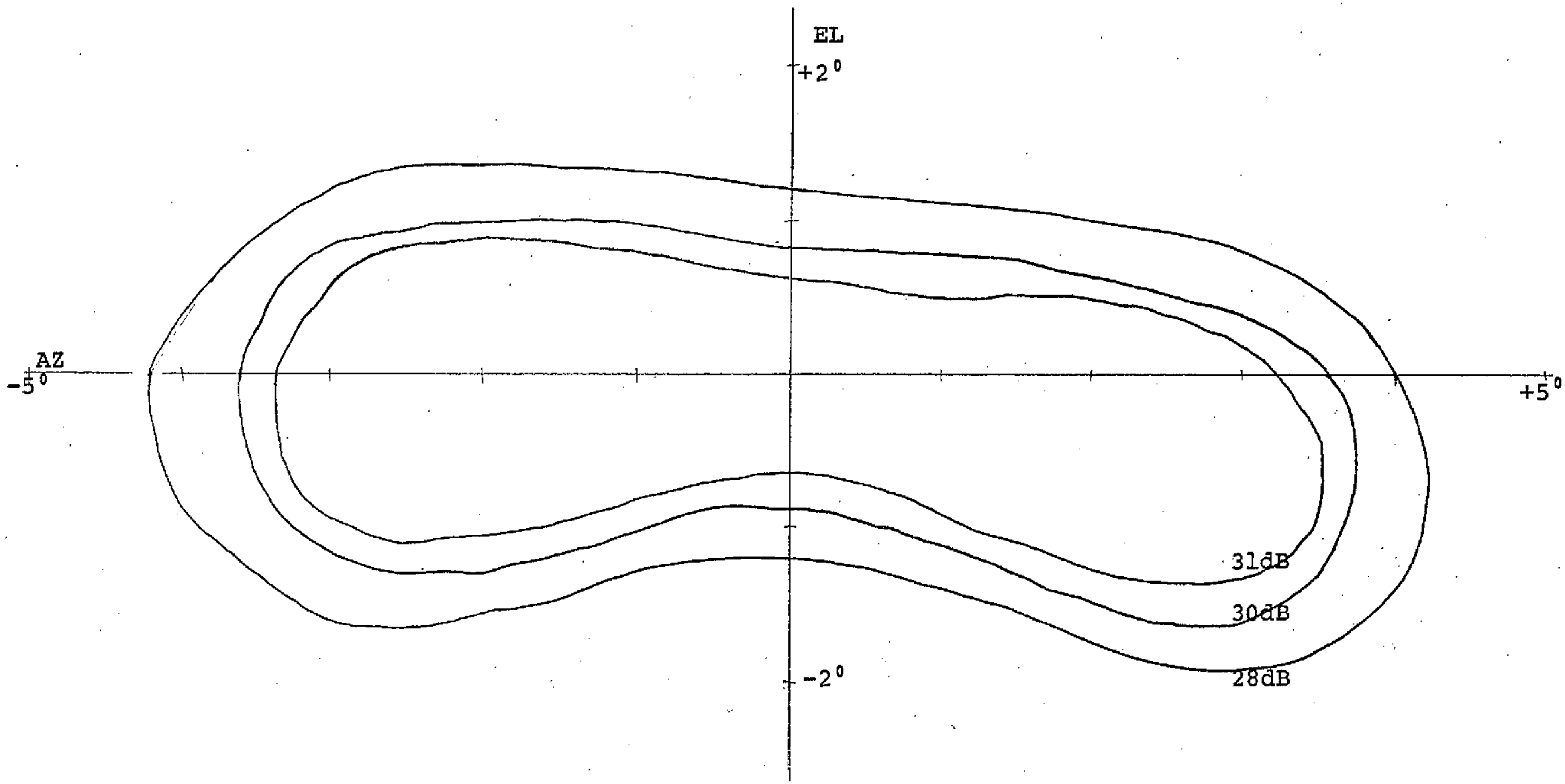


Figure 5.2.2 3 Horn Alternate Configuration, 4 GHz Transmit

on the reflector. A 56 inch reflector at 6 GHz results in the same diffraction beamwidth as an 84 inch reflector at 4 GHz. The second solution was to reduce the effective height of the horns at 6 GHz by the use of compensating vanes in the horn mouth (as shown in Figure 5.2.1). These vanes have little or no effect on the horizontally polarized electric vector at 4 GHz but reduce the effective E plane horn mouth size for the vertically polarized electric vector at 6 GHz. The vanes are cut so that the effective horn height at 6 GHz is equal to the horn width, resulting in a superior match of N-S beamwidth to reflector size. One additional advantage of this technique is that changing the relative sizes of the top and bottom vane sets permits the N-S pointing of the 6 GHz pattern to be trimmed independently of the 4 GHz pattern.

5.2.4 Design Evaluation, 3 Horn Configuration at 6 GHz

Incorporation of the modifications described previously produces the 6 GHz pattern shown in Figure 5.2.3. 29 dB gain is just achievable over all of Canada (no pointing error margin) and 28 dB is obtainable with generous N-S and E-W pointing margins.

For 6 GHz spot beam operation a directional coupler with low insertion loss couples a small fraction (-20 to -30 dB) of the centre horn output to a separate spot beam receiver. Since the purpose of the spot beam is for jamming resistance, a situation in which high ground station EIRP's will be used, the directivity of the spot beam is more important than the gain. Consequently the loss via the directional coupler is unimportant. Figure 5.2.4 shows the 6 GHz vertically polarized spot beam pattern without the directional coupler loss. This central beam does not give good rejection in the Hudson's Bay area but is quite good off the East and West coasts where the response is about 20 dB down relative to the peak. The spot beam gain and directivity could be improved by use of horizontal polarization for this mode but this would require a more complex coupling arrangement to the centre horn.

5.2.4 Power Combining for 3 Horn Configurations

It is common practice in satellite transponders to separate odd and even channels into groups in order to ease the design of channel filters and output multiplexers. One requirement

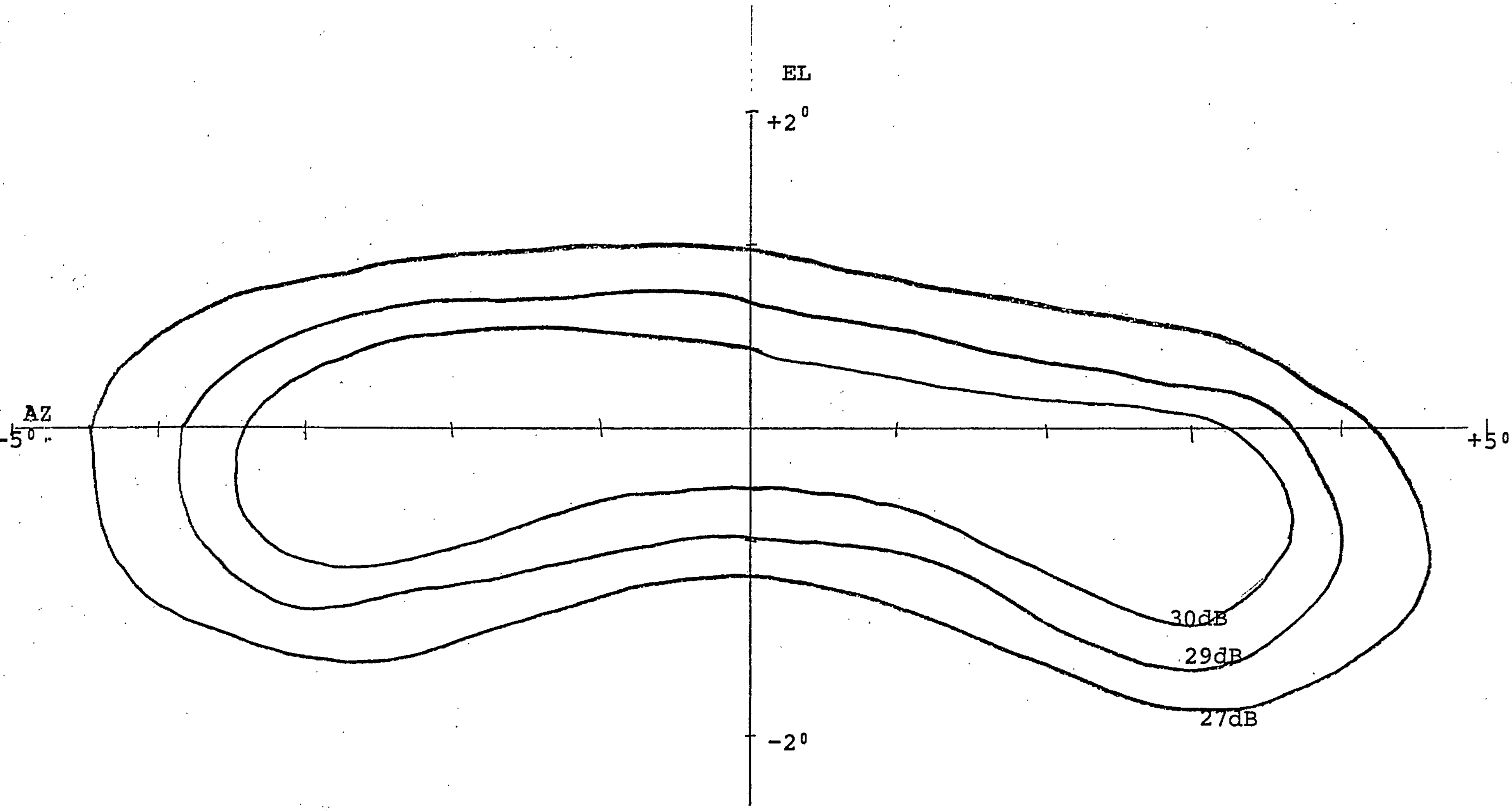


Figure 5.2.3 3 Horn Alternate Configuration, 6 GHz Receive

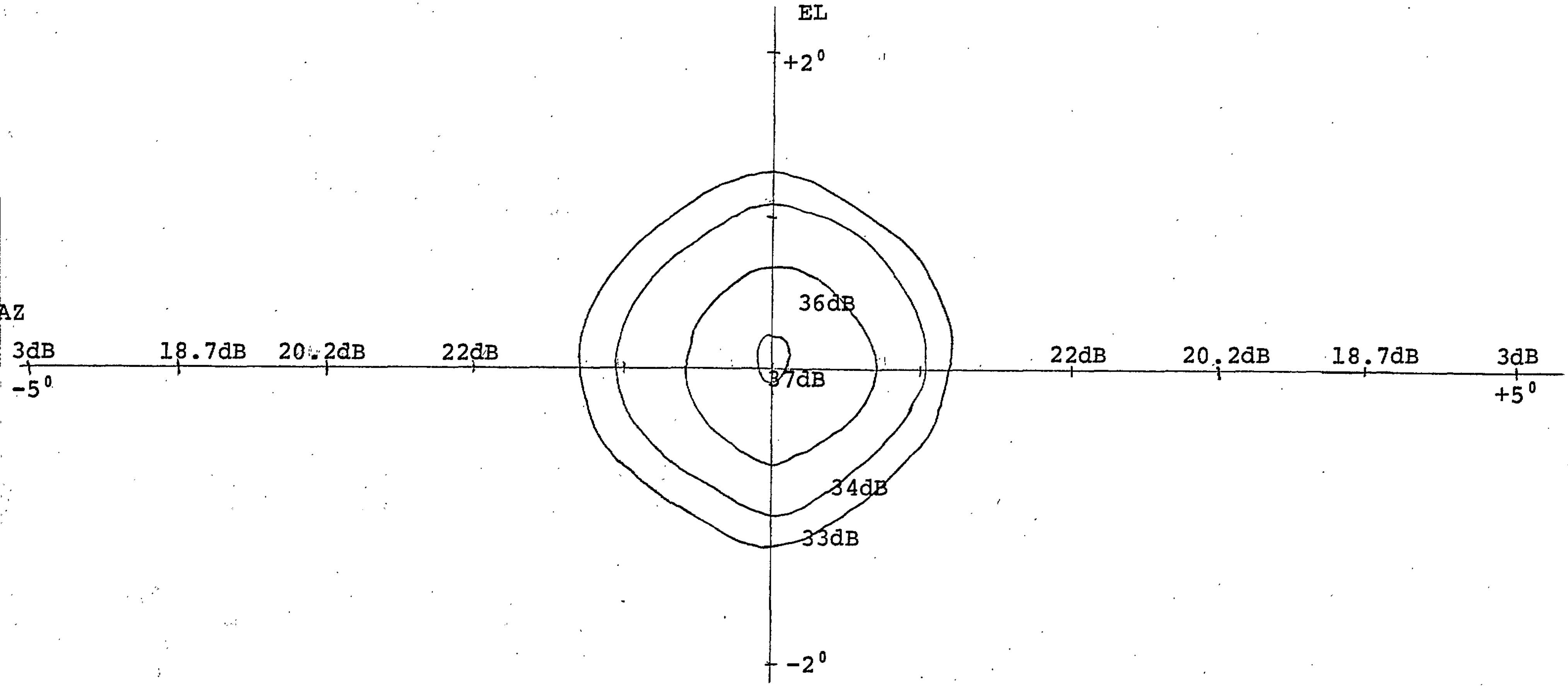


Figure 5.2.4 3 Horn Alternate Configuration, 6 GHz, Vertically Polarized Spot Beam

for good performance is that good isolation must exist between the outputs of the odd and even channel multiplexers. This can be accomplished by using the isolation properties of a magic Tee to combine the two multiplexer outputs. The two output arms of the Tee then each carry half of the power from each multiplexer. Poor isolation between multiplexers would then result from mismatches in either of the two transmission chains connected to the Tee output arms and isolators may be necessary on the multiplexer outputs.

For a 3 horn configuration antenna, the problem is to combine the outputs from the Tee in a low loss, well matched combiner and to redivide the power into 3 roughly equal parts. Such a device has been described by Houterman(6) for application in the Anik antenna. For the Anik application the combiner also has to provide the necessary phase shifts to transfer from two equal power quadrature phase inputs to three equal power 60 degree phase outputs. The voltage transfer matrix for this device is:

$$\begin{vmatrix} E \\ C \\ W \end{vmatrix} = \begin{vmatrix} .789 & -.211 \\ .577 & .577 \\ -.211 & .789 \end{vmatrix} \begin{vmatrix} V_1 \\ \\ V_2 \end{vmatrix}$$

where E, C and W are the voltages fed to the three horns and V_1 and V_2 are the quadrature voltages in the two port input. For this application, the transfer matrix can be much simpler since the input voltages can be in phase and the outputs are in phase. The matrix

$$\begin{vmatrix} E \\ C \\ W \end{vmatrix} = \begin{vmatrix} .7874 & 0 \\ .4359 & .4359 \\ 0 & .7874 \end{vmatrix} \begin{vmatrix} V_1 \\ \\ V_2 \end{vmatrix}$$

provides three in phase outputs, with the centre output 1 dB higher than the others when energized with equal in phase inputs. Figure 5.2.5 shows a diagrammatic representation of the device.

Figure 5.2.6 shows one possible implementation of a 6 GHz feed coupling arrangement. Vertically polarized outputs from the feed horns (obtained using ortho made couplers or other devices) are combined with a magic Tee and an unequal power combiner to provide a 1 dB 'boost' to the centre horn. A -20 dB directional coupler on the centre horn provides an output to the spot beam receiver.

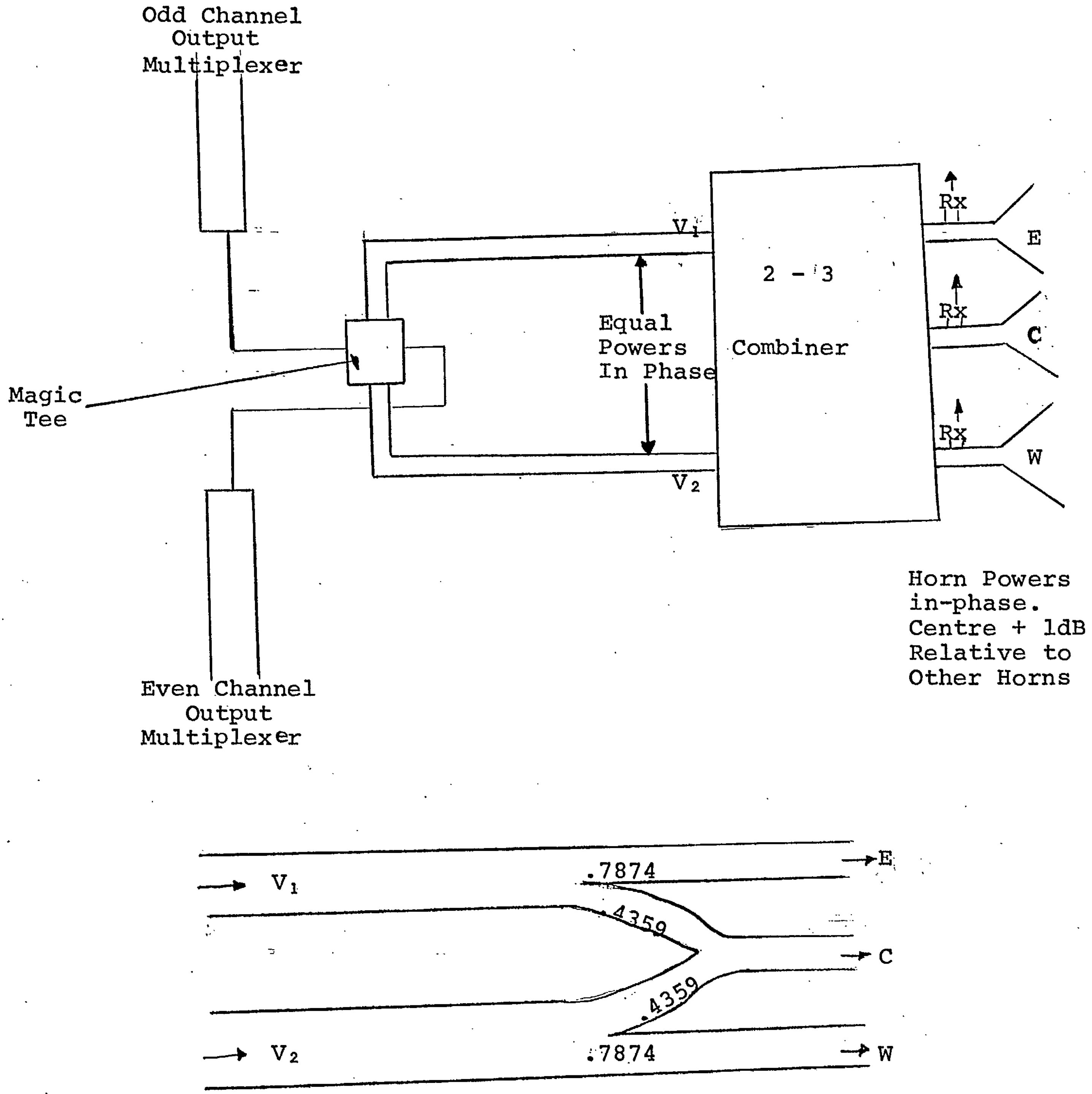


Figure 5.2.5 3 Horn Feed Arrangement for 4 GHz

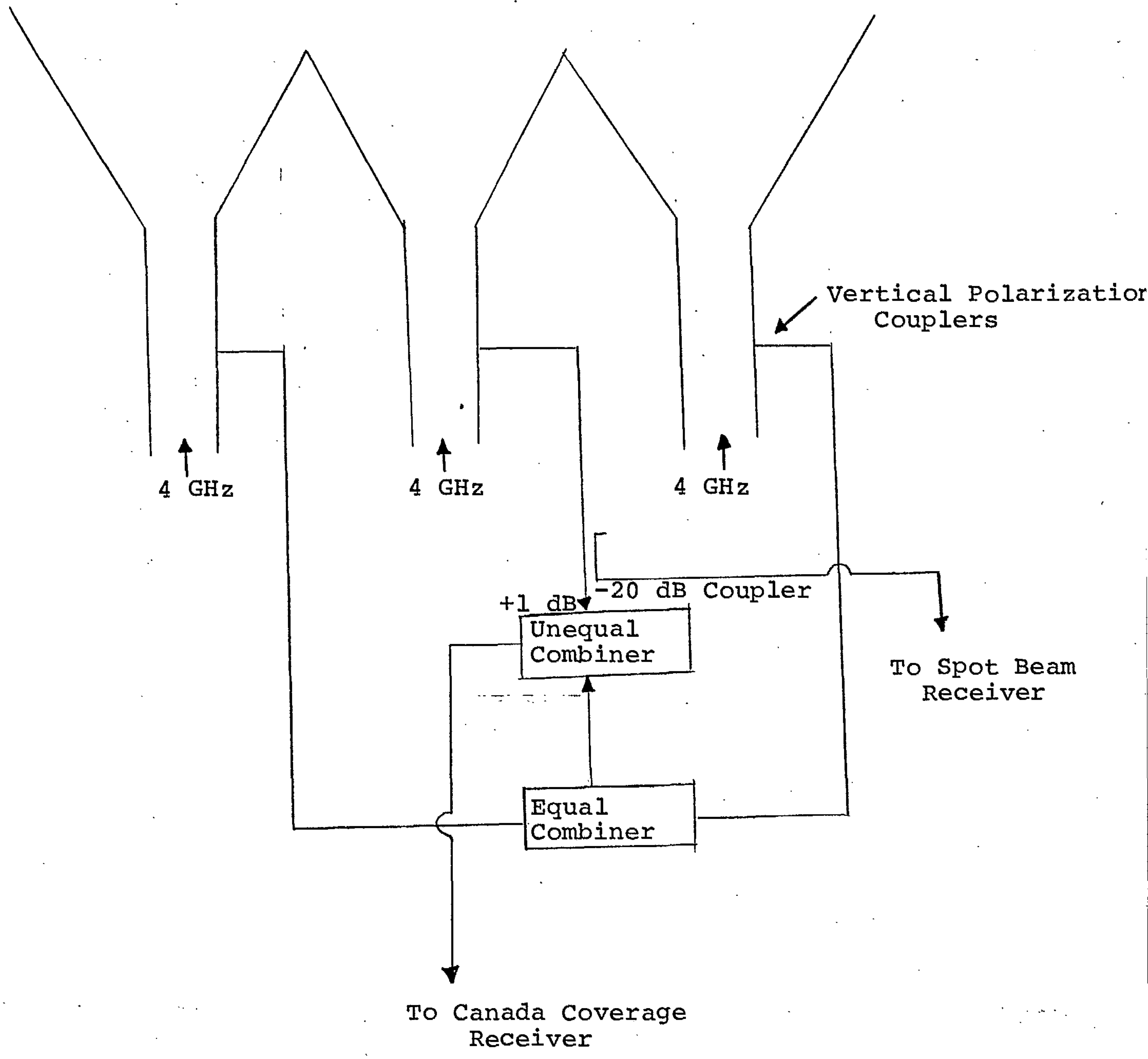


Figure 5.2.6 3 Horn, 6 GHz Feed Combination

5.3 4 Horn Configuration

5.3.1 Design Rationale, 4 Horn Configuration at 4 GHz

In view of the potential problems with a 3 horn configuration, a more advanced design using 4 horns and a larger effective reflector size was investigated. As stated earlier, a 9 foot diameter reflector at 4 GHz permits a modest amount of beamshaping in the N-S direction. In order to increase the amount of first sidelobe energy on the top and bottom of the dish, the horn size was increased slightly to 4 inches in height and the reflector height was increased to 9 feet.

In the E-W direction, the entire feed structure must be about the same width as for the 3 horn design. A feed system width of 8 inches divided into four horns of 2 inches each was selected for the initial iteration. The locations of the four horns in the N-S direction was determined by drawing a set of 2 degree diameter circles on the Canada coverage map and choosing the horn locations so that the four beams fell at the circle centres. As in the 3 horn design, a slightly offset reflector system was chosen to reduce feed blockage effects. Figure 5.3.1 shows the configuration selected.

A preliminary set of 4 GHz computations showed the same phenomenon as obtained with the 3 horn configuration - i.e. the gain at the centre of the pattern was lower than expected. Again this was assumed to be caused by outer horn coma or sidelobe effects. Again, the power in the centre horns was increased by 1 dB relative to the outer horns in order to alleviate the problem.

5.3.2 Design Evaluation, 4 Horn Configuration at 4 GHz

Figure 5.3.2 shows the 4 GHz pattern for the 4 horn configuration. At 4 GHz, 30 dB gain is achievable over all of Canada (zero pointing error) and 31 dB over most of Canada. It is important to note that with such highly tailored beam shapes the achievable gain becomes quite sensitive to the range of orbital slots from which a single antenna must be designed to work.

5.3.3 Design Rationale, 4 Horn Configuration at 6 GHz

Computing the 6 GHz pattern produced by the array of four 4 inch by 2 inch horns produced similar results to the 3 horn

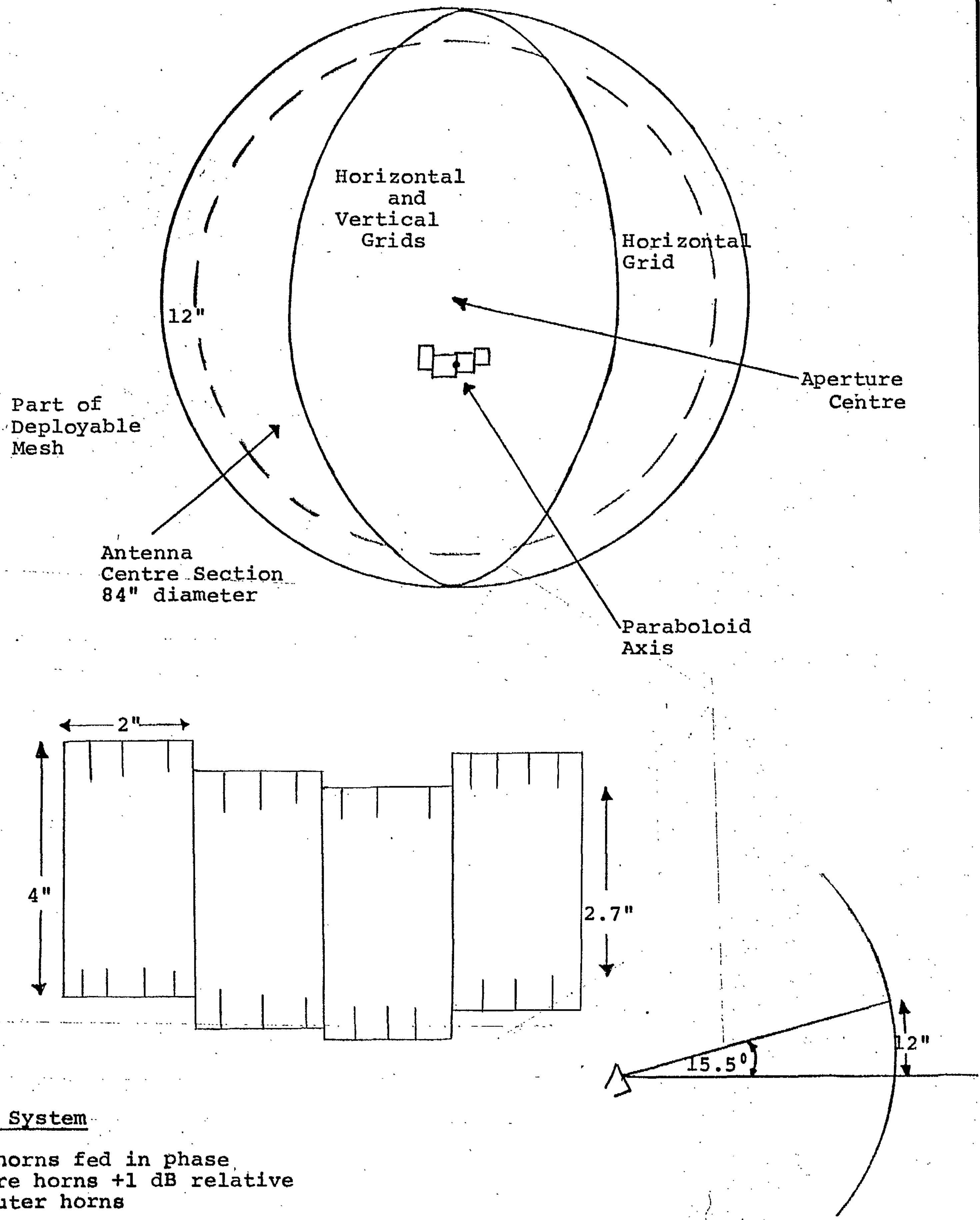


Figure 5.3.1 4 Horn Antenna Configuration

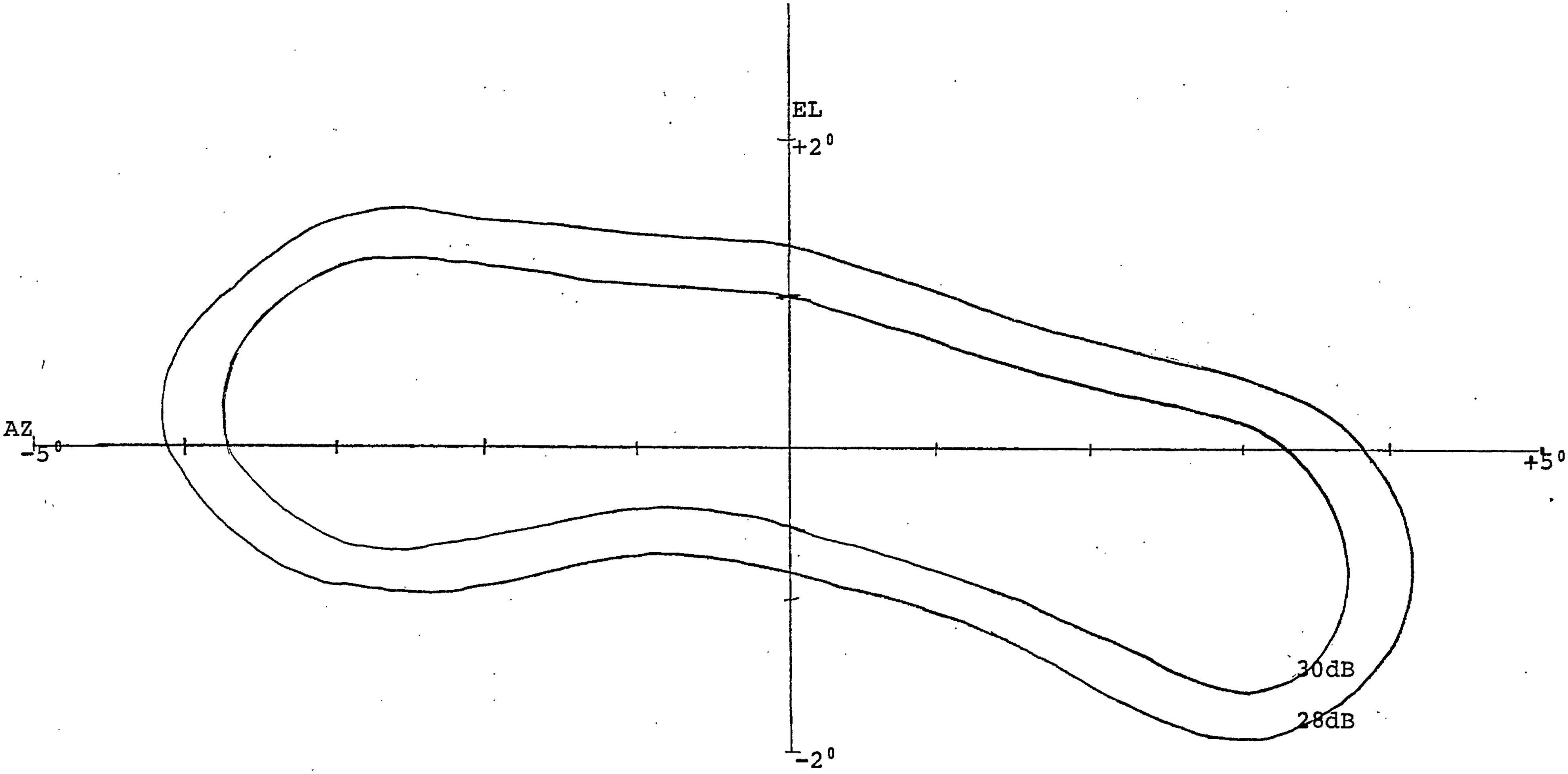


Figure 5.3.2 4 Horn Alternate Configuration, 4 GHz Transmit

case. There was excessive double humping in both N-S and E-W planes. The N-S double humping was removed by compensating the feed horn with vanes, as in the 3 horn case. The selected equivalent horn height of 2.7 inches at 6 GHz gave a small useful measure of N-S beamshaping which coupled with the 9 foot N-S aperture. The pattern still had excessive ripple in the E-W plane. This ripple was assumed to be due to the size of the diffraction image being less than the H plane width of the horns. While it might have been possible to further compensate the horns with a vertical septum, it was decided instead to increase the width of the diffraction image to match the E-W horn size. This was accomplished by reducing the effective width of the reflector at 6 GHz, so making the all reflecting part of the reflector elliptical in shape with a width of 60 inches as shown in Figure 5.3.1. It was also found necessary to increase the power of the centre horns by 1 dB as in the 4 GHz case, to compensate for outer horn coma and sidelobes.

5.3.4 Design Evaluation, 4 Horn Configuration at 6 GHz

Figure 5.3.3 shows the 6 GHz pattern obtained for this configuration. The achievable gain is 29 dB over all of Canada with zero N-S pointing error margin and ±.1 degree E-W margin. The N-S pointing error margin could be improved by a small realignment of the feed horn compensating vanes.

The spot beam is again generated by means of a -20 dB coupler connected to the 'Prairie beam' feed horn. Figure 5.3.4 shows the pattern obtained, withour the coupler loss, for a vertically polarized 6 GHz spot beam. Spot beam performance could again be improved by use of horizontal polarization but at the expense of a more complicated coupling arrangement.

5.3.5 Power Combination for 4 Horn Configuration

Figure 5.3.5 shows a possible layout for the power transfer chain from output multiplexers to antenna feeds for 4 GHz and from feeds to receiver at 6 GHz. With this configuration, multiplexer isolation is more easily obtained since the two outputs from the magic Tee combiner are independent and never 'see' each other. The 4 GHz magic Tee and the unequal power dividers can be located either in the satellite body (requiring four waveguide runs to the horns) or adjacent to the feed horns (requiring only two runs). Similarly, the 6 GHz outputs can be combined adjacent to the horn and the resulting output (coaxial cable or waveguide) run adjacent to the transmit waveguides. Coaxial cable can be used for the spot beam output, since absolute gain is not important in this mode.

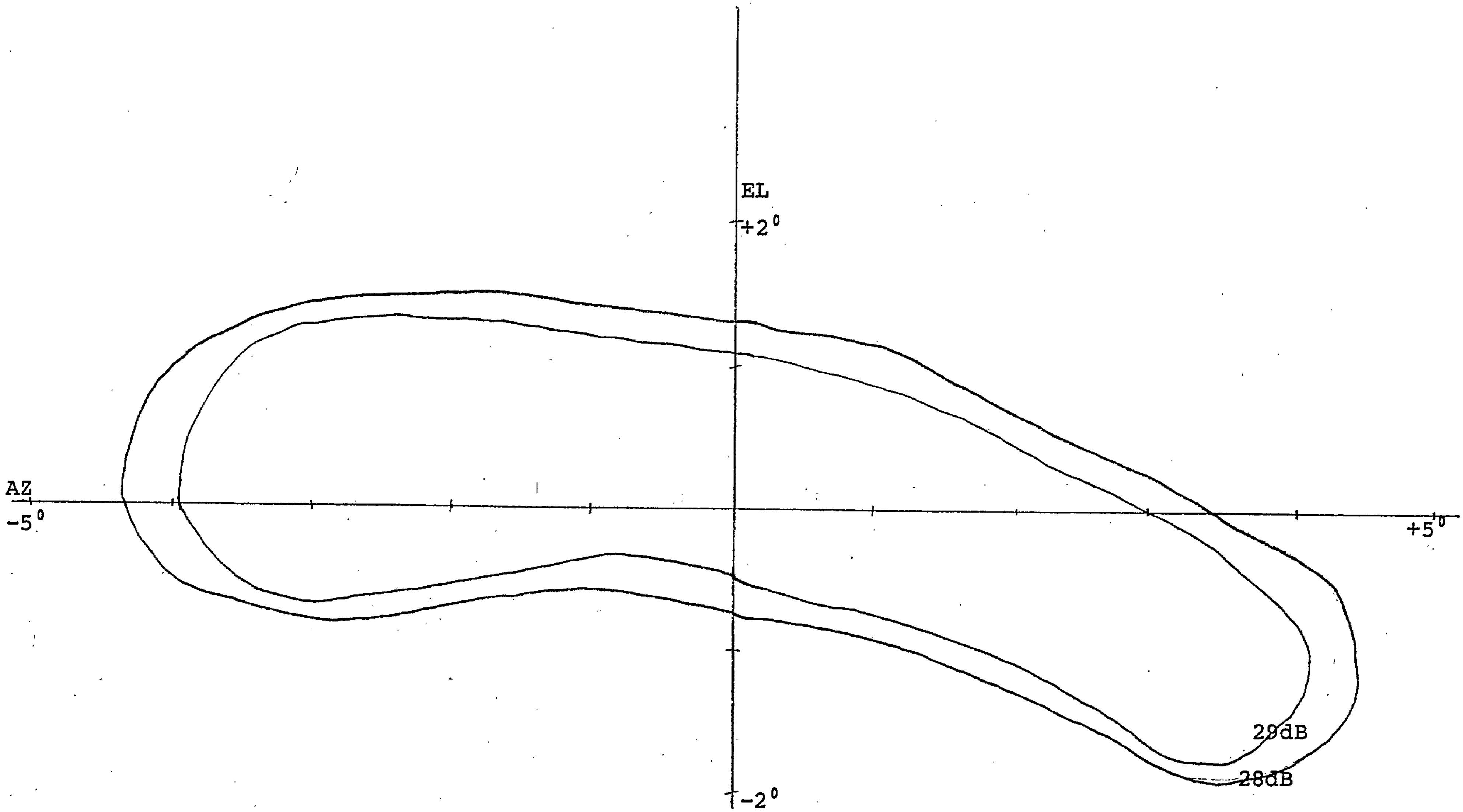


Figure 5.3.3 4 Horn Alternate Configuration, 6 GHz Receive

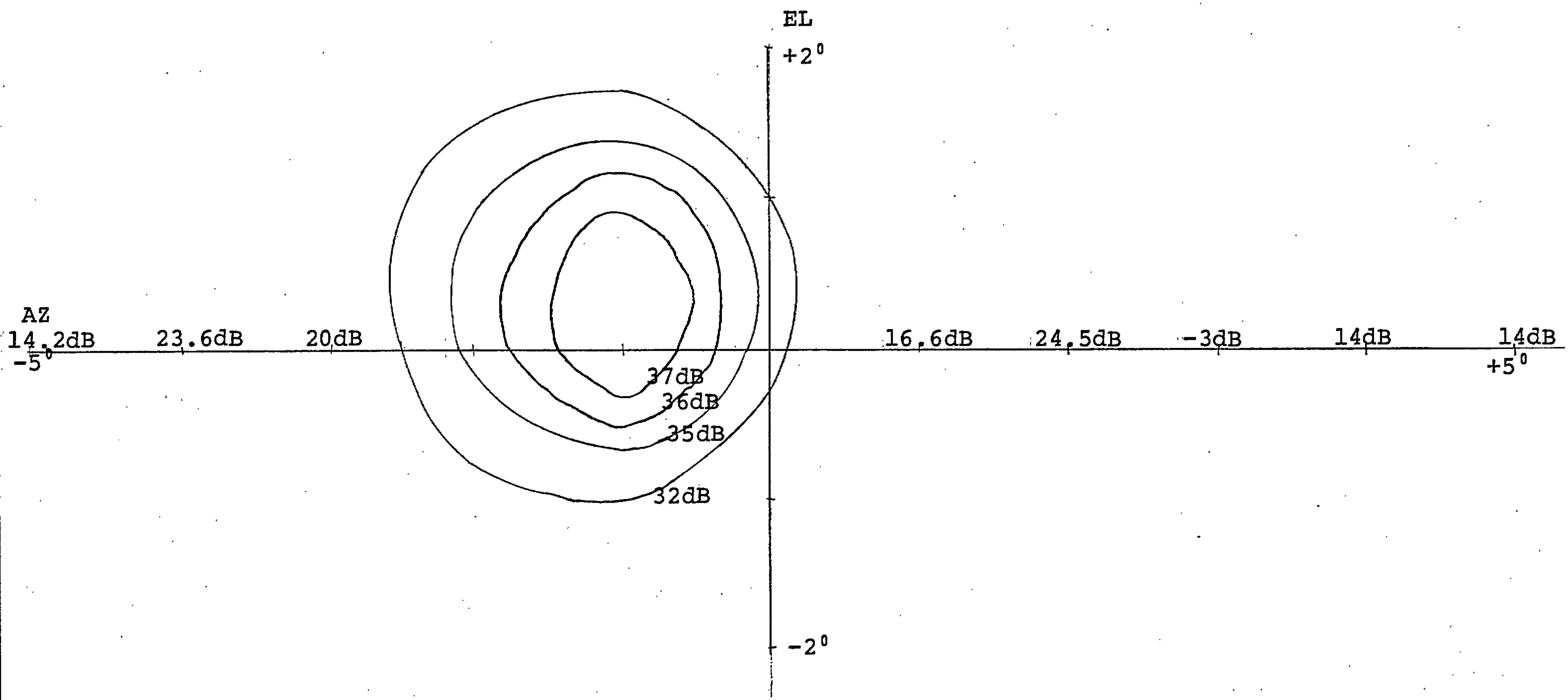


Figure 5.3.4 4 Horn Configuration, 6 GHz Vertically Polarized Spot Beam

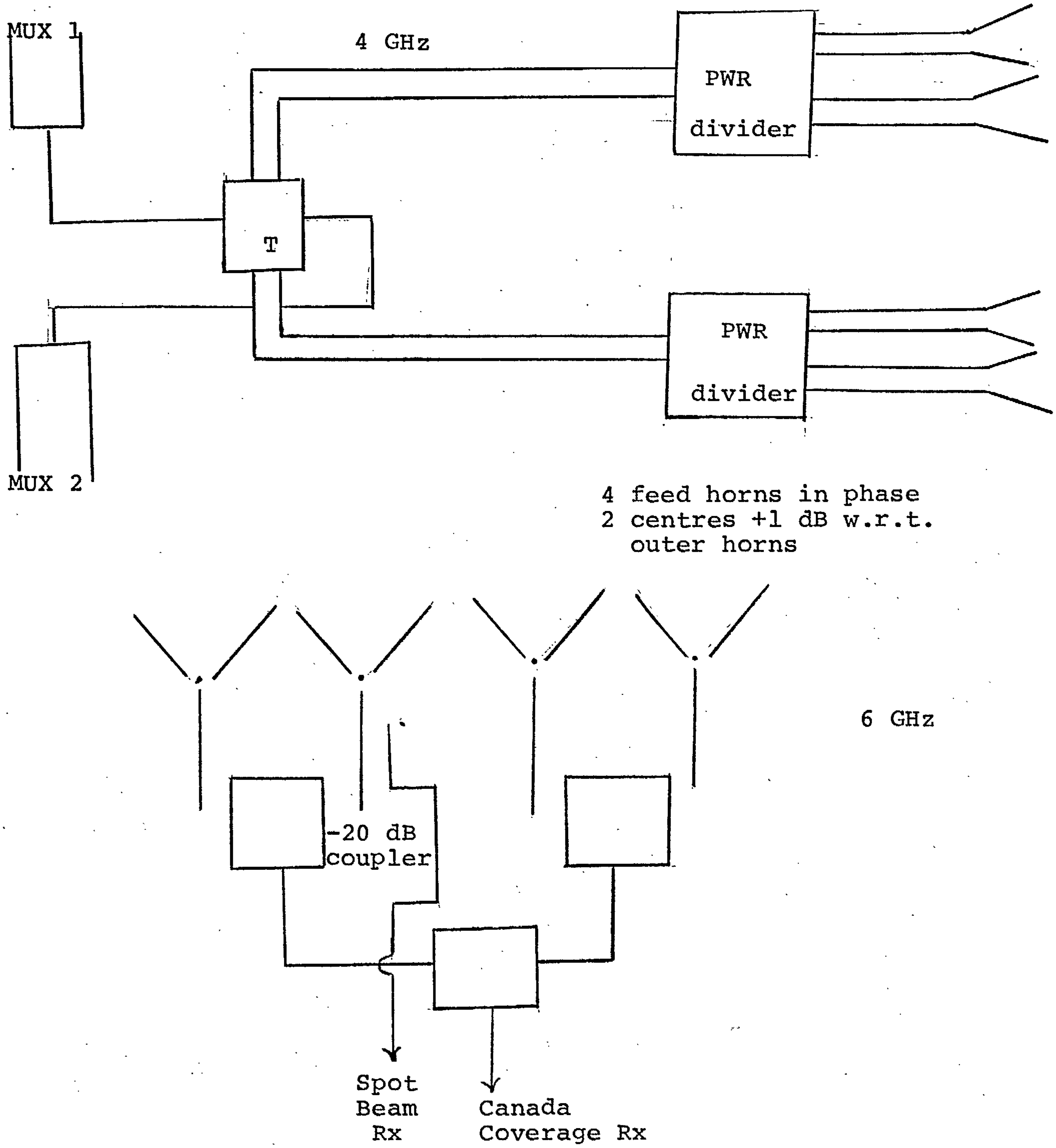


Figure 5.3.5 Feed Combination for 4 Horn Configuration

6.0 UHF ANTENNA PERFORMANCE ESTIMATES

As mentioned in an earlier section of this study, it is not possible within the constraints of reasonable antenna size to improve coverage at UHF frequencies by the use of beamshaping techniques. It is however possible to use the numerical prediction technique to estimate the achievable gain at various locations.

The available software did not directly treat the primary radiation pattern from candidate UHF feeds such as a quadrifilar helix or a full wave square loop plus reflector. However the main criteria which apply to illumination of the dish by a horn also apply to illumination by other types of feed. For example, the feed beamwidth must be designed as a compromise between spillover loss and full utilization of the reflecting surface. The shape of the primary radiation pattern from a small aperture horn can be regarded as similar to that from a short helix or full wavelength loop. In any case, the on axis gain is not a very sensitive function of the detailed power distribution characteristics across the dish.

The UHF feed was therefore approximated by illuminating the reflector from a large horn which was designed to comply with all the normal criteria for an on axis/peak gain antenna such as about 10 dB edge illumination taper. The antenna blockage used however was that appropriate to a smaller UHF feed. Using these approximations, patterns were generated over the Canada coverage area for different sizes of reflectors. The patterns are nearly circular symmetric and the gains are nearly constant over Canada. Table 6.2 shows the variation of gain with distance from boresight value for a frequency of 315 MHz. The 4 degrees off boresight value can be used as a basis for estimating edge of coverage gain. For operation in the offshore regions, the 5 degrees off axis value can be used.

Reflector Diameter	Focal Length	dB Gain vs Degrees off axis					
		0^0	1^0	2^0	3^0	4^0	5^0
10'	44"	17.9	17.9	17.8	17.7	17.5	17.3
14'	44"	20.2	20.1	20.0	19.7	19.4	18.9
16'	55"	21.4	21.4	21.2	20.9	20.4	19.8

Table 6.1 UHF Antenna Performance at 315 MHz

7.0 CONCLUSIONS

(a) The two-horn Canada-coverage configurations analysed provide performance which is acceptable, but barely so. While the 4 GHz performance of a two horn system may be capable of further improvements, it is difficult to achieve good simultaneous 6 GHz performance. The estimated performance limit at 4 GHz is 27 - 28 dB edge of coverage gain for two horn systems.

(b) Three horn configurations can provide an antenna pattern more closely matched to the shape of Canada than two horn designs. The resulting gain increase can provide an edge of coverage gain of 28 - 29 dB at 4 GHz. Horn compensation techniques permit good simultaneous 6 GHz performance to be achieved. Three-horn configurations may however require unusual power combiner/divider techniques to feed the horns properly.

(c) Four horn configurations can eliminate the power combining/dividing problems of three horn designs and can provide a useful performance improvement. Edge of coverage gains of 29 - 30 dB appear achievable over all of Canada at 4 GHz. Good 6 GHz performance is also achievable by the use of horn compensation and polarization selective reflectors.

(d) At 12/14 GHz the smaller wavelength, in conjunction with readily available reflector sizes, permits the beam shapes to be even more closely tailored to the coverage area. Some extra performance over that at 4/6 GHz should be obtainable although the configurations analysed did not full exploit the potential extra performance. It is estimated that at 12/14 GHz, about 1 dB or so more performance could be achieved compared with that at 4/6 GHz, assuming comparable reflector sizes.

(e) For readily available spacecraft antenna sizes, the UHF diffraction beamwidth is so large that there is no particular advantage in beamshaping for Canada coverage applications. Consequently, UHF antennas should be designed for maximum on-axis gain. Estimated edge of coverage gains at UHF range from 17.5 dB for a 10 foot reflector to 20.4 dB for a 16 foot reflector.

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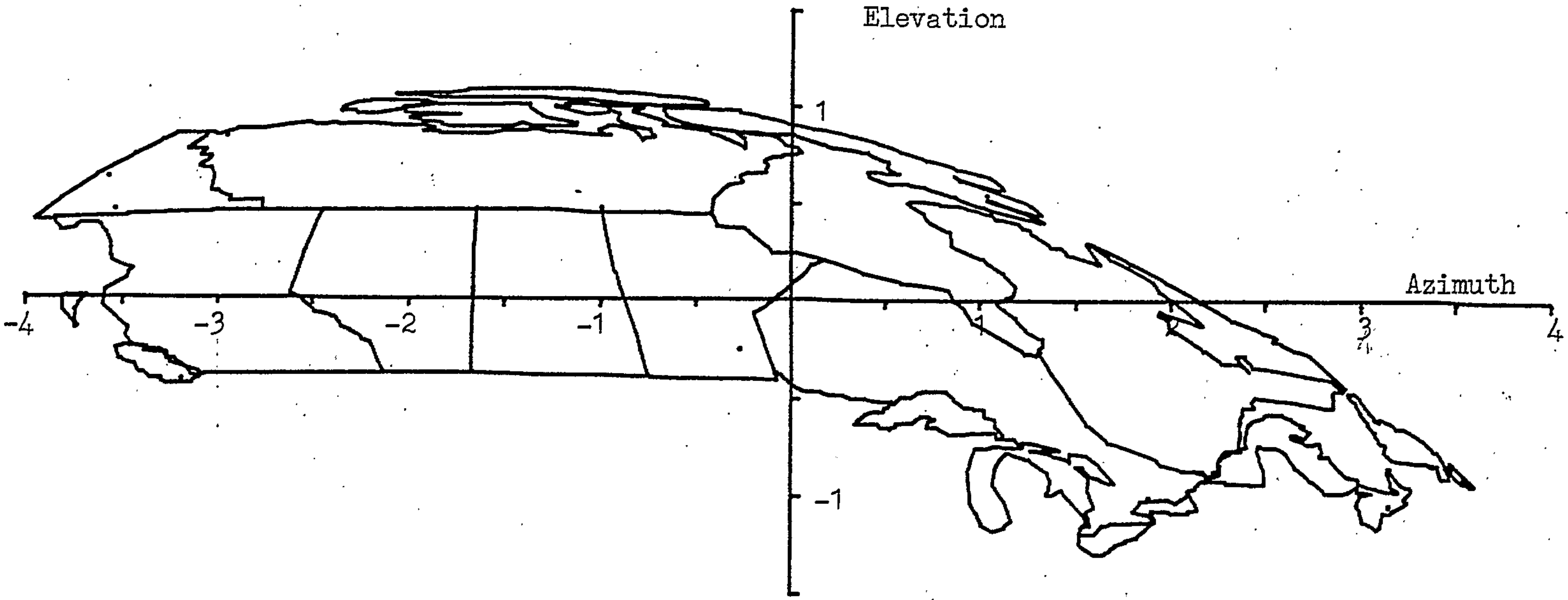

Canada Coverage Projection from Geostationary Orbit, 109°W Longitude