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Lockheed

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A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION

SUNNYVALE, CALIFORNIA

MULTIBEAM ANTENNA STUDY

PHASE I - FINAL REPORT
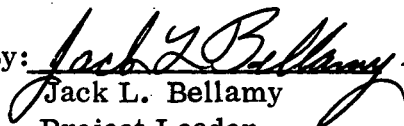
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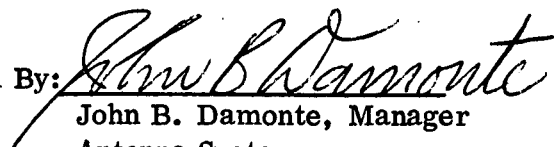
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Preface

The objective of the Multibeam Antenna Study is to develop an antenna concept for point-to-point communications between any two points within the continental United States using a synchronous orbit satellite. The objective of the Phase I effort reported herein has been to select a suitable antenna concept for the aforementioned application. The performance of the selected antenna concept is to be demonstrated in the Phase II effort.

The scope of the Phase I effort included establishing appropriate criteria for selecting the preferred candidate antenna concept, defining candidate systems for study, evaluating candidates against the criteria, and selecting the most promising concept. In this effort a special management decision making process (KTA Decision Analysis Techniques) was used to handle the comparison efficiently and to provide documentation of the process. The major portion of the effort dealt with the analysis of candidate systems to determine how well they met specified performance standards.

Out of 48 candidate antenna concepts considered in detail, the two-antenna, circular aperture, artificial dielectric lens system was considered to be the most promising candidate for the intended application. Primary reasons for this are that it offers the best promise of providing a high degree of isolation between any two pairs of beams, while providing the same coverage obtainable from the any of the other candidates considered.

It is recommended that the Phase II effort be undertaken to demonstrate the performance of the lens system experimentally.

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1.0   INTRODUCTION

1.1   Summary

This is the final report on the Phase I effort under contract number NAS 5-21711 performed by Lockheed Missiles and Space Company, Incorporated, for the Goddard Space Flight Center of the National Aeronautics and Space Administration.

The purpose of the Multibeam Antenna Study is to develop an appropriate antenna concept for providing spot beam coverage on the contiguous 48 states. The study has two phases. Phase I, which will be described herein, is concerned with the selection of a suitable antenna concept for the multibeam application. Phase II is to be an experimental evaluation of the antenna concept selected in the Phase I study.

The Phase I study commenced with the establishment of criteria for judging the suitability of various candidate antenna approaches. These criteria were divided into two groups, absolute requirements or "Musts" and desirable characteristics or "Wants". Three separate analyses were made. The Step I analysis considered 48 candidate antenna systems and determined that 15 of these were of sufficient promise for further consideration. In the Step II analysis, which was more thorough and detailed than the Step I analysis, the 15 candidates were compared and 4 basic concepts were selected for the final comparison. In the Step III analysis, the remaining 4 basic concepts with variations were subjected to further review.

The final analysis indicated that the preferred antenna concept is a dual-antenna, circular artificial dielectric lens. A detailed description of the preferred concept is given in Section 8.

We have attempted to make this report complete by reprinting much of the material which has appeared in the monthly progress reports. In the

interest of making the text more readable, we have departed from the format used earlier and have placed much of the detailed discussion in appendices.

In the remainder of this section the objectives of the Phase I study are discussed and a description of the analytical methods is presented. A discussion of the absolute requirements placed on the antenna concepts will be found in Section 2. A discussion of the desired characteristics as originally established will be found in Section 3. The preliminary or Step I Decision Analysis is discussed in Section 4 and is further described in Appendix A. In Section 5 we present the results of a comparative analysis of reflector antenna off-axis beam performance which was completed as preparation for the Step II Decision Analysis. The Step II and Step III analyses are discussed in Sections 6 and 7, respectively, with further details in Appendices B and C.

The description of the preferred approach together with a plan for evaluating this candidate experimentally will be found in Section 8. The summary and final conclusions appear in Section 9.

1.2   Objectives of the Phase I Study

The objective of the Phase I study effort was to select an antenna systems concept for point-to-point communications between any two points within the continental United States using a synchronous orbit satellite in the 1974 to 1976 time frame.

By the terminology "antenna systems concept" we mean a practical embodiment of a particular antenna type. We must not only determine the appropriate type of antenna (such as lens, reflector, or array) but also the number of antennas, the aperture sizes, the number of beams to be provided, and all other parameters needed to define the antenna--short of performing a detailed design. By "system" we mean to include all associated hardware which must be included if the candidates are to be compared on a common basis.

The study was limited to the point-to-point communications problem. Certainly any concept which can provide complete point-to-point communications coverage within a specific geographical area will have some capability of providing area coverage of geographical subdivisions of the primary service area. But generally the requirements for a point-to-point system and for an area coverage system are different and to a certain extent incompatible. In the point-to-point communications problem we seek a practical compromise between high beam-to-beam crossover levels and high isolation between various pairs of beams. In the area coverage case we are not so much concerned with the isolation between the component beams which are used to synthesize an area coverage beam; we are only concerned with isolation between different service areas. Also for the area coverage problem we would avoid too high a crossover level between adjacent individual or component beams. The reason for this is that when two or more beams are used to synthesize an area beam, there is

"fill-in" between adjacent beams and if this effect is ignored and the crossover levels are set too high, the uniformity of coverage within a service area will suffer. Finally, in the point-to-point case we would logically use polarization diversity to help reduce interference between adjacent spot beams, while in the area coverage case one would normally use a common polarization for a particular service area (composite beam) and use polarization diversity to provide isolation between adjacent service areas.

Thus we are considering only the point-to-point communications problem with its critical compromise between coverage and isolation. Area coverage can be provided by channel and beam selection in the system, but these areas will in general not conform to particular political or geographical areas.

We consider the continental United States to include the 48 contiguous states and to exclude Alaska and Hawaii. In the analysis, however, we have given some consideration to how these two detached areas could be covered with various candidate antenna systems.

The study is limited to systems which employ a synchronous orbit satellite. Furthermore, it is assumed that the satellite is stabilized in three axes. Our studies have indicated that with small spot beams emanating from a synchronous satellite the stabilization must be extremely accurate and it is quite likely that a tracking system must be employed to hold the beams in position, but since this is common to all antenna types it was not a factor in determining the most suitable candidate antenna.

Finally, the antenna system must be available as hardware for use in the 1974 to 1976 time frame. Therefore, only a moderate amount of development can be performed to obtain a practical design. This does not, however, limit the choice to "state-of-the-art" designs.

1.3   Analysis Methods

1.3.1   KTA Decision Analysis

We have used the Kepner-Tregoe Associates (KTA) Decision Analysis[1] procedure to select the preferred candidate during the study. A detailed description of this technique as it applies to this effort will be found in the proposal[2]. For the sake of completeness, a brief description of the method is included here.

Generally in comparison studies, the selected or preferred candidate is presented together with its advantages and strong points while rejected alternatives are discussed in terms of weaknesses and disadvantages. The final report thus tends to justify the choice rather than to present an overview of all candidate approaches in perspective. The reader has little assurance, sometimes, that the choice has been made on a fair basis.

The KTA Decision Analysis procedure helps guarantee the fairness and objectivity of the comparison. First, it requires that all candidates be measured against a common standard. Second, it makes the entire comparison process visible in perspective so that any bias which may creep in is trackable. No procedure can eliminate the use of judgement or engineering opinion in making a comparison of alternatives. But the KTA Decision Analysis procedure will improve the accuracy of the evaluation by breaking the big decision (which is the best candidate?) down into a number of smaller decisions (which has the best coverage, isolation, etc. ?) which can be handled more easily and more accurately.

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[1] Kepner, Charles H. and Tregoe, Benjamin B., "The Rational Manager", New York: McGraw-Hill Book Company, 1965.

[2] LMSC/A989189, "Technical Proposal for a Study of Multibeam Antennas for Advanced Multi-Function Communication Satellites" dated 3 May 1971, Section 3.1.

The KTA Decision Analysis procedure is very efficient because it is formalized and direct. There is no wasted effort in unimportant digressions and there is a positive flow toward the final decision. The efficiency of KTA Decision Analysis was emphatically demonstrated during the Phase I study where 48 candidates were compared to arrive finally at one preferred candidate. Three analyses were made and, once the required background information had been collected, none of these analyses required more than two days time.

Finally, the documentation and visibility provided by the procedure enables the reader to make his own evaluation if he disagrees with the conclusions reached during the study. All the relevant technical information is available in the documentation. If the reader wishes to, he may make whatever changes in the technical judgements, the weightings, or the scoring he feels are necessary and then he can determine what effect such changes have on the choice.

The tasks to be performed in the KTA Decision Analysis are as follows:

1. Prepare A Decision Statement

This is simply making a statement of the purpose of the analysis. This statement should be as specific and detailed as possible so as to eliminate irrelevant considerations at the outset. The Decision Statement for all the analyses performed during the Phase I study is identical with the objective of the Phase I study contained in the first paragraph of Section 1.2 above.

2. Establish a List of Musts and Wants

Musts are absolute requirements, such that if an alternative does not satisfy a Must, it would be rejected immediately no matter what other characteristics are offered. A want, on the other hand, is a desirable characteristic which can be satisfied to a degree.

3. Weight the Wants

Each of the Wants must be weighted on a scale of 1 to 10. It is not necessary to weight the Musts, since measuring the competing concepts against the Musts is a go-no go proposition. The most important Want is given a weighting of 10. Other Wants are individually compared against the most important wants to determine relative weighting.

4. Evaluate Candidates Against the Must List

All competing concepts are evaluated to see if they satisfy the Musts. Any candidate failing to satisfy even one of the Musts is immediately discarded. Following this elimination step, all candidates which remain are acceptable solutions (in that they satisfy minimum requirements), but in the remaining steps some will be found to be better solutions than others.

5. Evaluate Candidates Against the Want List

Each of the competing concepts is analyzed to determine how well it satisfies each of the Wants. This task constitutes the bulk of the Phase I study effort. In some cases an evaluation could be made quickly using experience and engineering judgement. In other cases it was necessary to perform analyses or to search the literature for relevant information. Once all the needed information is obtained, the analysis chart is completed by making a comment thereon concerning how well each concept satisfies each particular Want.

6. Score the Candidates

Once the analysis chart is completed, the concepts are scored. For each Want the candidate offering the best performance is given a score of 10, the next best concept receiving a lower score and so on. The scores need not cover the entire range from 10 to 0, however. The relative scores should reflect the significance of differences in performance. Once the candidates

have all been scored for each Want, the scores are multiplied by the weightings
to find the weighted scores. The weighted scores for each candidate are added
to determine the total weighted score.

7. Assess Possible Adverse Consequences

Normally the candidates would rank in relation to their total weighted
scores, the candidate having the highest score being the one which most nearly
satisfies the criteria established. There may, however, be other factors which
would make the selection of the highest scoring candidate an imprudent choice.
To prevent this, "possible adverse consequences" are evaluated for several of
the highest ranking candidates.

To evaluate possible adverse consequences, we ask for each candidate
what adverse consequences might occur if that particular candidate were selected.
As an example, an undue amount of development risk might be involved. Or
perhaps projected performance might be based on unconfirmed information which
might later turn out to be erroneous. Such possibilities are assigned a probability
factor from 0 to 10 and a seriousness factor from 0 to 10. For each adverse
consequence the product of the probability factor and the seriousness factor is
calculated. The sum of these products for each candidate is the risk factor
associated with that particular candidate.

8. Select the Preferred Concept

The final step is to evaluate the results of the comparison. First,
the concepts are ranked in descending order of their total weighted scores.
Next, we examine score differences to see if they are truly significant. And
finally, we compare risk factors for the leading candidates to determine if
the ranking should be modified.

As an example, consider the scores 642, 637, 619, 575, 570, 392
and 160. The analysis is not considered significant enough to distinguish between

the first two candidates. The five point difference in their scores is not significant when one considers that a change of 1 in the weighting or the scoring of a highly weighted Want might reverse the ranking of the two candidates. Thus, the first two candidates must be considered to be essentially equal in performance. The difference between the first and third candidates is, indeed, open to some question regarding significance. But as we progress through the list the differences become numerically larger and more and more significant.

We now examine the effect of the risk factor on the ranking. If the first two candidates have significantly different risk factors, the one with the lower risk factor would be ranked first. But if the third candidate had an even lower risk factor by a wide margin, we might place it first, since the third candidate is not that far behind the first two in performance.

The important point here is that the Decision Analysis process does not result in a hard and fast ranking based strictly on numerical scores. The results must be interpreted in terms of the significance of score differences and the rankings can be modified as a result of considering relative risk.

For reference, the eight tasks in a Decision Analysis process are listed here as follows:

1. Prepare a decision statement
2. Establish a list of Musts and Wants
3. Weight the Wants
4. Evaluate candidates against the Must list
5. Evaluate candidates against the Want list
6. Score the candidates
7. Assess possible adverse consequences
8. Select the preferred concept.

1.3.2   Analysis Sequence

During the Phase I study it was necessary to consider a very large number of possible candidate antenna systems. After the list of Musts had been generated and the generic antenna types had been evaluated against this list, 48 candidate antenna systems remained in contention. Evaluating all of these candidates against the 10 Wants required 480 assessments.

In the interests of efficiency, we elected to perform the Decision Analysis in three successive steps. In Step I all 48 candidates were compared against the 10 Wants. In this evaluation if the required information necessary to make one of the 480 assessments was not readily available, a consensus of engineering opinion or judgement was used to make the assessment. While there is some probability that some of these judgements could be erroneous, at least to some degree, we can expect that on the whole the assessments will be sufficiently accurate for preliminary purposes if qualified, experienced personnel participate in the analysis. During the Step I analysis only a limited amount of detailed analytical work was performed.

At the completion of the Step I analysis, 15 candidates were considered as being sufficiently promising to warrant further consideration. During the Step II analysis these candidates were again evaluated against a Want list which had been revised to reflect more accurately the desires of NASA GSFC. The Step I Analysis had highlighted certain areas where a detailed theoretical investigation would be needed and this investigation was completed in conjunction with the Step II analysis. Thus the Step II analysis was a more thorough re-examination of the 15 candidates remaining after Step I. This resulted in reducing the number of candidates to four.

In the Final Step III analysis various embodiments of the four candidates remaining from the the previous analysis were examined in still more detail. This resulted in the selection of a single antenna concept as the preferred candidate, namely, the two-antenna, circular aperture, artificial dielectric lens system.

A Step IV analysis was attempted to determine the most appropriate type of artificial dielectric to be used, but this analysis was not successful in accomplishing this objective.

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2.0   ABSOLUTE REQUIREMENTS OR MUSTS

2.1   General

Musts are absolute requirements. They are absolute in the sense that any candidate failing to satisfy even one Must is automatically eliminated, regardless of any other attribute offered. Conversely, any candidate which meets all the Musts is an acceptable solution, in that it meets minimum requirements.

The list of Musts was agreed upon at a conference between LMSC representatives and the NASA GSFC technical monitor at the Goddard Space Flight Center on 5 April 1972. As noted in the following, there were some minor modifications to the Musts which occurred during the program.

2.2   Definition of Musts

Eight Musts were established as follows:

1. Each candidate must provide coverage of the contiguous 48 states above the -10 dB level.

All of the land area within the contiguous 48 states must be illuminated by antenna beams in such a way that the gain at any point within the service area is no more than 10 dB below the peak gain of the beam. This defines a minimum relative pattern coverage level. Providing for higher level coverage was considered a Want (Want #4).

2. Each candidate must be capable of providing 15 to 25 beams covering the service area.

Each candidate must be capable of providing at least 15 beams covering the 48 contiguous states. However, we were not required to consider any configuration of a candidate concept which provided more than 25 beams within the service area.

3. __It must be possible to operate simultaneously on all beams.__

This in effect requires that each beam be available at a separate port. For this Must, only simultaneous accessibility is considered and not such performance characteristics as beam-to-beam isolation.

4. __The antenna system must be capable of handling 100 watts of cw power per antenna beam.__

5. __The antenna system must be capable of providing an rf bandwidth of 12.4 percent centered at 12.475 GHz.__

The bandwidth requirement was the most critical must and was modified during the course of the Phase I study. The above statement of this must does not represent the original or the final form of this must but instead the form used throughout the study.

Originally, the Must was stated as requiring the antenna to have a 500 MHz rf bandwidth per beam. This would be sufficient to cover the 11.7 to 12.2 GHz Satellite-to-Ground link and the 12.75 to 13.25 GHz Ground-to-Satellite link if, and only if, separate antennas were used for transmitting and receiving. In fact, reducing the bandwidth per antenna seems to be the only argument for dividing the beams between two antennas in this way.

Since utilizing two antennas involves additional weight and complexity, it is important to achieve maximum benefit to compensate for this penalty. For concepts involving two antennas instead of one (and this can be extrapolated to more than two antennas) it seems clear that the beams should be divided according to polarization between the two antennas. The conclusion was reached to use polarization diversity with the beams of one polarization interlaced with those of the other so as to make maximum use of the isolation provided by polarization. By dividing the beams between two antennas so that all beams on each antenna have a common polarization, we have more flexibility in setting the cross-over

levels between beams since the beam-to-beam spacing for each antenna is increased. Also, to improve the beam-to-beam isolation, we may, if necessary consider concepts which involve the use of polarization grids to reduce coupling between adjacent beams of the system which are coupled through their cross-polarized energy.

Thus, in view of these considerations for multiple antennas and also to provide for single antenna versions of the various candidate antenna types, this Must was modified from its original form of 500 MHz rf bandwidth per beam to include the range from 11.7 to 13.25 GHz as stated above.

At the conclusion of the Phase I study, the Ground-to-Satellite frequency band was redefined as the 14.0 to 14.5 GHz band. This would cause modification of the Must to reflect a total band from 11.7 to 14.5 GHz unless separate antennas are used for transmitting and receiving. This modification was necessary to comply with frequency allocations for this purpose. Although this is a more stringent requirement, it would not have caused the elimination of any of the 48 candidates considered in the first (Step I) analysis.

6. <u>The antenna system must be designed for X-band operation.</u>

The limits of X-band for the purposes of this Must are the frequencies mentioned above. Originally, there was a K_u band requirement (17.7 to 19.7 GHz), but this was eliminated at the outset by the NASA GSFC Technical Monitor.

7. <u>The antenna system must have a port-to-port isolation greater than 30 dB.</u>

Port-to-port isolation is the passive isolation between ports in the multiple beam system. Good port-to-port isolation is necessary for proper repeater operation and would be measured by exciting one port and measuring the output at another.

8. The antenna system must have an overall efficiency greater than 25 percent.

The efficiency referred to here relates to all factors which tend to reduce gain, such as attenuation in transmission lines, spillover, illumination efficiency, and mismatches.

2.3   Evaluation of Candidate Concepts

Eight generic types of antennas were evaluated as to their ability to satisfy the foregoing lists of musts. These eight antenna types were:

1. Multiple feed paraboloidal reflectors
2. Multiple feed spherical reflectors
3. Butler arrays
4. Phased arrays
5. Multiple feed waveguide lenses
6. Multiple feed dielectric lenses
7. Multiple feed artificial dielectric lenses
8. Luneberg Lenses.

It was found that all of these antenna types could be designed to satisfy all of the musts with the exception of the bandwidth requirements.

Coverage at the –10 dB level can be obtained for all of the antenna types considered, although it may (or may not) be more difficult with one kind of antenna than it is with another. Beam footprints for a 16 beam case and a 23 beam case are shown in Figures 1 through 6. The –4, –6, and –8 dB contours for the 16 beam case are shown in Figures 1, 2 and 3, respectively, and the corresponding contours for the 23 beam case are shown in Figures 4, 5, and 6. As can be seen from these figures, the cross-over levels for these beam arrangements are of the order of –4 and –5 dB. Examination of Figure 3 and Figure 6 shows that coverage of the contiguous 48 states at the –8 dB level is virtually complete and
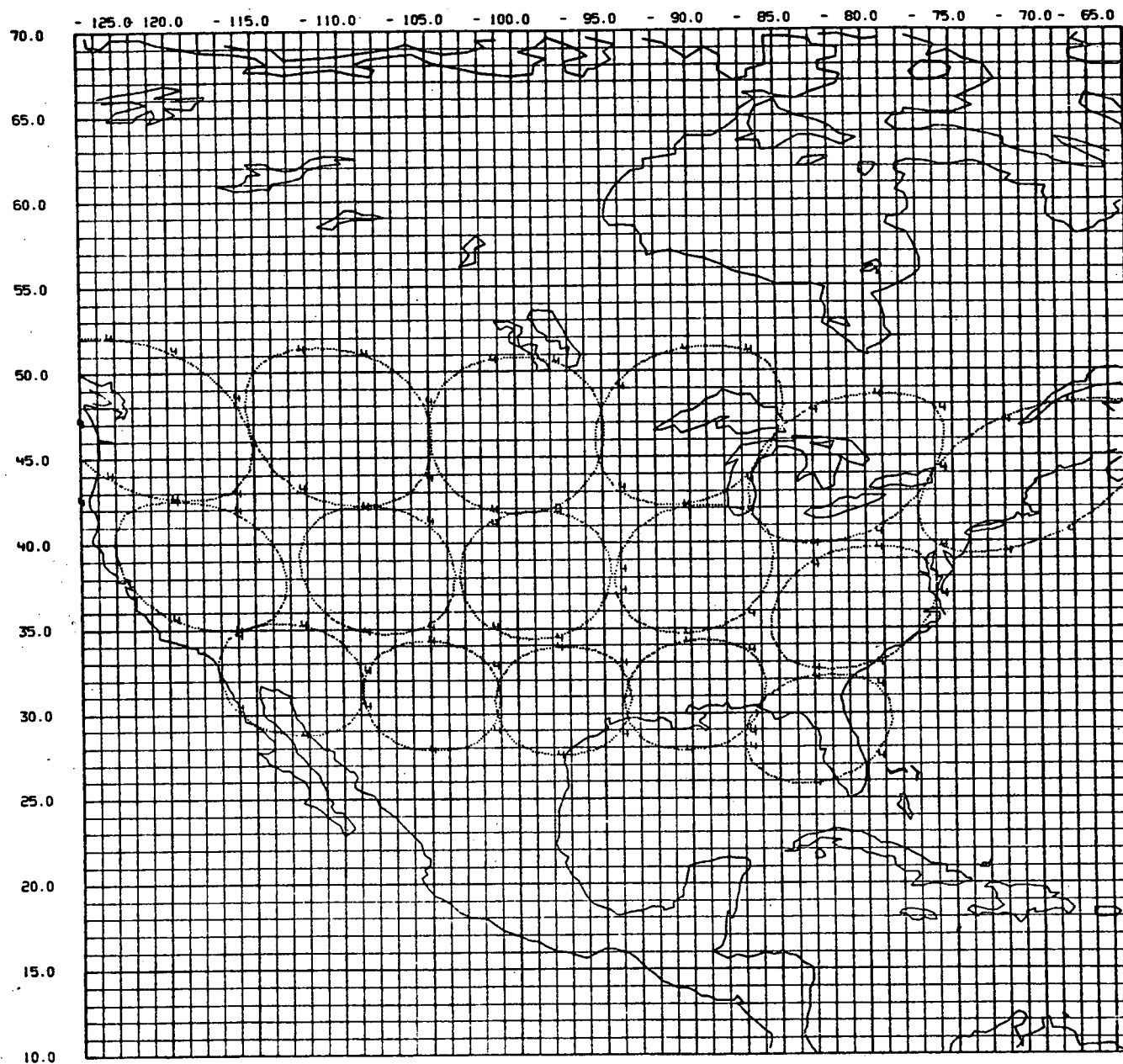
XMIN	XMAX	YMIN	YMAX
-125.0000	-65.0000	10.0000	70.0000
XBIGO	SLAMB	SDEL	SIGMA
	1.0000	.0000	.0000
XPHI	AMU	BONS	BOEW
-100.0000	.0000	*90*	*7d*
ALTS	A3		
19323.0000	.0000		

CONTOUR VALUES

-4.0000

BLONG	BLAT
-121.0000	47.0000
-110.0000	46.5000
-100.0000	46.0000
-90.3000	46.5000
-81.5000	44.0000
-71.0000	43.5000
-118.0000	38.6000
-108.0000	38.3000
-99.0000	38.0000
-90.0000	38.3000
-81.0000	36.0000
-113.0000	32.0000
-105.0000	31.0000
-97.5000	30.7000
-90.0000	31.0000
-83.0000	29.0000

$$\frac{(D/\lambda)_{NS}}{(D/\lambda)_{EW}} = \frac{80}{62} = 1.29$$

16 Beams

$$\frac{(D/\lambda)_{NS}}{(D/\lambda)_{EW}} \text{ CORRECTED} = \frac{1.13 \times 80}{1.13 \times 62} = \frac{90}{70} = 1.29$$

FIG.1   -4 dB CONTOURS, 16 BEAM CASE

XMIN	XMAX	YMIN	YMAX
-125.0000	-65.0000	10.0000	70.0000

XBIGD	SLAMB	SDEL	SIGMA
	1.0000	.0000	.0000

XPHI	AMU	BONS	BDEW
-100.0000	.0000	80.0000	62.0000

ALTS	A3	90	70
19323.0000	.0000		

CONTOUR VALUES

-6.0000

BLONG	BLAT
-121.0000	47.0000
-110.0000	46.5000
-100.0000	46.0000
-90.3000	46.5000
-81.5000	44.0000
-71.0000	43.5000
-118.0000	38.6000
-108.0000	38.3000
-99.0000	38.0000
-90.0000	38.3000
-81.0000	36.0000
-113.0000	32.0000
-105.0000	31.0000
-97.5000	30.7000
-90.0000	31.0000
-83.0000	29.0000

FIG.2   -6 dB CONTOURS, 16 BEAM CASE

XMIN	XMAX	YMIN	YMAX
-125.0000	-65.0000	10.0000	70.0000

XBIGD	SLAMB	SDEL	SIGMA
	1.0000	.0000	.0000

XPHI	AMU	BDNS	BDEW
-100.0000	.0000	90	70

ALTS	A3
19323.0000	.0000

CONTOUR VALUES

-8.0000

BLONG	BLAT
-121.0000	47.0000
-110.0000	46.5000
-100.0000	46.0000
-90.3000	46.5000
-81.5000	44.0000
-71.0000	43.5000
-118.0000	38.6000
-108.0000	38.3000
-99.0000	38.0000
-90.0000	38.3000
-81.0000	36.0000
-113.0000	32.0000
-105.0000	31.0000
-97.5000	30.7000
-90.0000	31.0000
-83.0000	29.0000

FIG.3   -8 dB CONTOURS, 16 BEAM CASE

FIG.4   -4 dB CONTOURS, 23 BEAM CASE

XMIN	XMAX	YMIN	YMAX
-125.0000	-65.0000	10.0000	70.0000

XBIGO	SLAMB	SDEL	SIGMA
96 -25.0000	1.0000	.0000	.0000

XPHI	AMU	BDNS	BDEW
-100.0000	.0000	.0000	.0000

ALTS	A3
19323.0000	.0000

CONTOUR VALUES
-6.0000

BLONG	BLAT
-122.8000	46.0000
-114.5000	45.8000
-107.0000	45.6000
-100.0000	45.5000
-92.9000	45.5000
-85.5000	45.7000
-68.0000	46.0000
-121.5000	38.6000
-114.8000	38.4000
-108.4000	38.3000
-102.2000	38.2000
-96.0000	38.2000
-89.5000	38.3000
-82.7000	38.5000
-75.3000	40.0000
-117.0000	32.2000
-110.8000	32.0000
-104.7000	31.5000
-98.7000	31.3000
-92.7000	31.5000
-86.7000	31.9000
-80.3000	33.4000
-82.0000	27.4000

$D/\lambda = 96$

FIG.5   -6 dB CONTOURS, 23 BEAM CASE

XMIN	XMAX	YMIN	YMAX
-125.0000	-65.0000	10.0000	70.0000
XBIGD	SLAMB	SDEL	SIGMA
%.0000	1.0000	.0000	.0000
XPHI	AMU	BONS	BDEW
-100.0000	.0000	.0000	.0000
ALTS	A3		
19323.0000	.0000		

CONTOUR VALUES

-8.0000

BLONG	BLAT
-122.8000	46.0000
-114.5000	45.8000
-107.0000	45.6000
-100.0000	45.5000
-92.9000	45.5000
-85.5000	45.7000
-68.0000	46.0000
-121.5000	38.6000
-114.8000	38.4000
-108.4000	38.3000
-102.2000	38.2000
-96.0000	38.2000
-89.5000	38.3000
-82.7000	39.5000
-75.3000	40.0000
-117.0000	32.2000
-110.8000	32.0000
-104.7000	31.5000
-98.7000	31.3000
-92.7000	31.5000
-86.7000	31.9000
-80.3000	33.4000
-82.0000	27.4000

$D/\lambda = 96$

FIG. 6 -8 dB CONTOURS, 23 BEAM CASE

we can conclude that the -10 dB coverage requirement can be met provided the beam placements shown are physically realizable.

The beam placements indicated are certainly realizable in multiple antenna versions of the basic concepts where the beams have been divided in such a way as to maximize feed spacing. Generally beam crossovers in the -4 and -5 dB range are considered practical in multiple feed single antenna versions, although in some instances dielectric feed loading may be necessary to achieve the proper feed spacing. In cylindrical versions of reflectors and lenses there is some restriction on feed placement, due to the fact that all the beams associated with a single linear feed are constrained to lie in a certain plane making the beam placement shown in the figures impossible to achieve. However, without detailed analysis, it was not possible to rule out cylindrical antennas (and some arrays) on the basis of the coverage must, since even though there may not be complete freedom in the placement of beams, the -10 dB coverage requirement conceivably could be met. We therefore concluded that the coverage must could not be used to rule out any of the candidate concepts.

There appears to be no difficulty in providing 15 to 25 beams with a separate output port for each for any of the basic antenna concepts except for the phased array. All of the lenses and reflectors have multiple feeds and the Butler array has a separate port for each beam. Phased array configurations can be designed (but not easily visualized) to provide multiple beams with separate output ports. Thus, Musts 2 and 3 can be met with any of the basic antenna concepts.

Meeting the power requirement is not a problem.

There is no inherent difficulty in designing any of these antenna types for X-band operation (as compared with other bands).

Port-to-port isolation in multiple feed reflector and lens systems depends on the direct coupling between feeds and to a certain extent on feed-reflector or feed-lens interaction. In array systems this isolation is primarily dependent on the directivity of hybrids and other circuit elements. Although it appears to be relatively more difficult to achieve the required 30 dB isolation in an array system over a broad bandwidth, we cannot conclude that it cannot be achieved.

A 25 percent overall efficiency figure may be marginal in the case of lenses, based on reported results, but there does not appear to be a fundamental limitation which would preclude the possibility of improving on these results.

Thus, we can conclude that except for the bandwidth problem which we have yet to discuss, all of the basic antenna types can be designed to meet all of the other Musts. If not, we at least have insufficient grounds for eliminating any candidate for failing to satisfy a Must.

All of the eight basic antenna types were evaluated with respect to meeting the bandwidth requirement. The parabolic reflector bandwidth is basically limited by the bandwidth of the feed and no problem was anticipated in designing for the 12.4 percent bandwidth. The spherical reflector is more sensitive than its parabolic counterpart, since the departure of the sphere from the equivalent paraboloid measured in wavelengths (instead of inches) is a function of frequency. Preliminary evaluation indicated that this frequency sensitivity could be tolerated, assuming that the inherent phase error itself can be tolerated. Luneberg lenses and dielectric lenses have the same frequency band limitations as does the parabolic reflector.

For the artificial dielectric lens, the bandwidth requirement can be met provided the lens is designed to operate at frequencies sufficiently removed from the resonant frequency of the particles. For waveguide lenses the bandwidth

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may be improved by zoning and by using long focal lengths to reduce thickness. There will be a problem in achieving appropriate bandwidth with the waveguide lens, but the bandwidth requirement does not eliminate the waveguide lens as a possible candidate. (NOTE: As will be seen later, the bandwidth problem proved very difficult for the waveguide lens when analyzed during the Step III analysis and consequently the only admissible version of the waveguide lens proved to be a two-lens system where one was used for transmitting and the other for receiving).

It is not easy to visualize phased array systems capable of providing a large number of beams. They are possible, however, using the cross-guide arrangements dicussed in the proposal. We can also configure a multiple antenna system which utilizes several antennas having a few beams each to form a multibeam system. Generally, configuring a multibeam array system with complex waveguide circuitry would undoubtedly lead to delicate impedance relationships which would be very sensitive to frequency because of the dispersive nature of waveguide.

Probably the simplest form of multiple beam array is, of course, the Butler array. A two dimensional form of Butler system could be constructed by tiering linear Butler matrices in two dimensions. Such a configuration would result in an ordered beam arrangement with fixed cross-over levels and known (but inadequate) beam-to-beam isolation.

In addition to the two dimensional multibeam array, the linear array that provides several beams must also be considered. The linear multibeam array can be used as a feed element for cylindrical lenses and reflectors to achieve certain desirable results.

All of the arrays have serious bandwidth problems which can be illustrated by considering the relative phasing of a row of discrete radiators as a function of frequency. It is possible to obtain broad bandwidth for a broadside

array (i.e., one which radiates in a direction normal to the array aperture plane). If the elements are fed in a family tree or corporate structure arrangement and are fed with equal path lengths, then the beam will be normal to the aperture plane and the beam will be stationary as frequency changes over the range of bandwidth for which the power dividing circuit components are designed. Since the path length from the input terminal to each of the radiating elements is the same, the frequency characteristics of the lines feeding the elements compensate for each other and the beam does not move. This is a complex and heavy way to feed a large array -- but that is another matter. With this type of feeding, which will provide broad bandwidth, we are constrained to a single beam per array and thus a 15 to 25 beam antenna system would require 15 to 25 arrays -- a trivial case.

When more than one beam is radiated by a single antenna in a multibeam array system, at least one -- in fact, all but one -- of the beams must be offset from the normal to the array aperture. The frequency sensitivity of a squinted beam causes the problem. For illustrative purposes, consider a single beam linear array with the beam offset from the broadside condition. If the array is fed from one end of the line the beam position is given by

$$\sin \theta = \frac{\lambda}{\lambda_g} - \frac{\lambda}{2d}$$

where θ is the angle off broadside, λ is the wavelength in free space, λ_g is the wavelength in the transmission line, and d is the interelement spacing. The above equation assumes that there are (geometric) phase reversals between adjacent elements; if not, the second term is omitted. Power handling and attenuation dictate the use of waveguide transmission lines at these frequencies. Note that we are limited to spacings less than one wavelength to prevent spurious lobes from forming for desired beam offsets at small angles off broadside.

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FIG. 7

Sectioned
Array

Length = 7 ft
32 Sections

FREQ. = 11.725 GHz

12.475 GHz

13.225 GHz

RELATIVE GAIN (DB)

ANGLE OFF BORE SIGHT (DEGREES)

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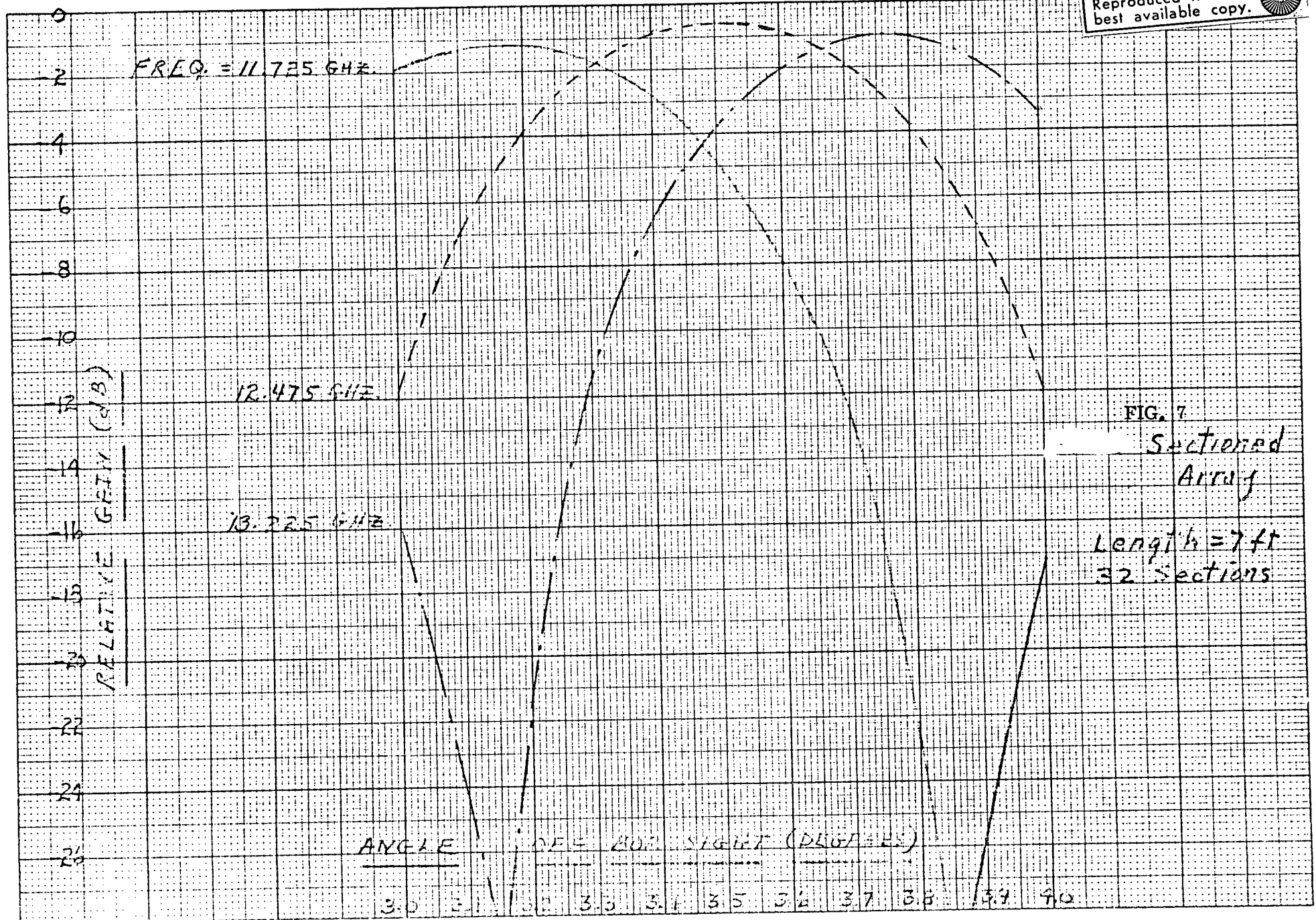
Also d should be greater than a half wavelength for practical reasons.

When the above equation is evaluated for a 12.4 percent bandwidth, for typical waveguides, and for offsets of the order of 3.5 degrees (needed for the coverage of the eastern and western seaboards), it can be seen that the beam will swing significantly ($\pm$ one or two beamwidths) over the required band. It can be concluded that this type of array will not provide the required bandwidth.

Sectioning an array will improve its bandwidth. The array factor for combining sections together controls the position of the beam, and the variation of the beam position of each individual section has less and less effect as the number of sections increases. The possibilities of using sectioning to improve bandwidth was investigated for the case of a 7 foot array designed to operate at 12.475 GHz with a 3.5 degree offset from broadside. Waveguide having an internal width of 0.622 inch was considered.

Without sectioning, the beamwidth is about 0.53 degrees. Within this beamwidth centered at 3.5 degrees off broadside, the beams at $\pm$ 750 MHz are shifted so as to provide only side lobe radiation. When the array is sectioned into 32 sections (about 2.6 inches/section), the array factor for the 32 sections shifts about $\pm$0.3 degree or just over $\pm$0.5 beamwidths over a $\pm$750 MHz band. This is illustrated in Figure 7. This is intolerable since it puts a null close to the desired area. Bear in mind that the frequency band required is actually broader than the 12.4 percent stated in the Must and that the band edges, not the center, are the main portions of the band. In effect, at the edges of the offset beam there would be an 18 or 19 dB difference in gain between transmitted and received gain due to the frequency sensitivity of the array. (Note that dividing a 7 foot array into 32 sections represents a very high degree of complexity).

This case is not proved by the above example which merely illustrates the effect. We investigated other choices of waveguide in the practical range of

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parameters without achieving the desired bandwidth characteristics. In fact, if we presume that a frequency-compensated feeding network can be built, we find that the sensitivity of the interelement spacing to frequency is such as to cause intolerable beam shifts. In this case the change in offset is proportional to the change in wavelength or inversely proportional to the change in frequency, amounting to about 0.2 to 0.3 degree as before.

Thus we concluded that phased arrays, Butler arrays, and cylindrical antennas which utilize linear array feeds do not meet the bandwidth requirement of 12.4 percent for the offset beams and therefore can be eliminated from further consideration. The only possibility, it appears, for using array systems would be to revise the Must so that a 500 MHz bandwidth is required, which eliminates all single antenna array concepts and requires separate antennas for transmitting and receiving.

In summary, all generic antenna types satisfied all the Musts except for phased arrays, Butler arrays, and cylindrical antennas utilizing linear array feeds, which failed to satisfy the bandwidth requirement.

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3.0 DESIRED CHARACTERISTICS OR WANTS

During the successive analyses (Steps I through III) the list of desired characteristics or Wants was revised. We shall define the Wants here as originally established for the Step I analysis and discuss revisions later as they applied to the Step II and III analyses.

1. <u>Provide coverage of Alaska above the -10 dB level.</u>

The primary service area is considered to be the contiguous 48 states. However, in any domestic system it is desirable to provide coverage for outlying portions of the United States. In satisfying this Want, one considers how easily this coverage can be provided including the penalties on weight and complexity and the impact on performance in the primary service area. One also considers how well the area can be covered. The weighting for this Want was assigned a value of 2 for the Step I analysis.

2. <u>Provide coverage of Hawaii above the -10 dB level.</u>

This is similar to the above Want, except that the principal islands of the Hawaiian group are to be covered. This Want had a weighting of 2 for Step I.

3. <u>Minimize spillover outside of the primary service area.</u>

This Want had to do with reducing spurious radiation outside of the primary service area. Of particular concern is radiation which falls upon Canada and Mexico. This Want received a weighting of 3 for the Step I analysis.

4. <u>Minimize the area within the contiguous 48 states where the gain provided is between 6 and 10 dB below the peak gain.</u>

This Want is related to Must #1. Any candidate meeting the Must will provide gain at least at the -10 dB level throughout the primary service area. This constitutes minimum acceptable performance. To improve performance we wish to minimize those areas for which the relative gain is below the -6 dB level. (All relative gain levels refer to the peak gain within the service area). The areas

of concern are generally in the vicinity of the common crossover point of three and four beam clusters and around the outside edge of the service area. Satisfying this Want implies high crossover levels between adjacent beams. This Want had a weighting of 10 for Step I.

5. <u>Minimize areas where the beam-to-beam isolation is less than 30 dB.</u>

Since contiguous co-polarized beams cannot be avoided (except in a trivial case), beam-to-beam isolation will be zero at the crossover region of such beams and will fall below the 30 dB level for some region near the cross-over point. In such regions where the isolation is inadequate, only frequency diversity can be used to prevent interference. The geographical extent of such regions where the isolation is inadequate should be minimized to maximize the service area for which interference-free reuse of frequencies can be employed. If this is applied to any two beams and not to just adjacent pairs of beams, then it is unnecessary to have a separate Want relating to side-lobe levels. This Want also received a weighting of 10 for Step I.

6. <u>Maximize the number of users on a worst case basis.</u>

Because contiguous co-polarized beams are unavoidable, it follows that there will also be some areas where isolation is inadequate. The occurrence of interference will then depend upon whether or not the ground terminal is located within one of the zones where isolation is inadequate and upon whether or not the same channel is being used in the adjacent co-polarized beam. The only way to guarantee interference-free operation (that is, operation with at least 30 dB isolation with respect to interfering signals) is to eliminate the probability aspects and assign a limited number of frequency channels to each beam in the system. This assignment is made on the basis of not using the same channel on two contiguous co-polarized beams.

This Want is stated as maximizing the number of users on a "worst case" basis because it assumes a high traffic condition and an unfavorable set of locations for the ground terminals. If we rely on the probability aspects of the problem, we are assuming a random or uniform distribution of ground terminals and are presuming moderate to light traffic volume. The relative weighting of Wants 5 and 6 is predicated on some presumptions about the intended application and the traffic conditions relevant thereto. This Want (#6) received a weighting of 8 in the Step I analysis.

In evaluating candidates in relation to this Want, the pertinent factors are the number of beams provided by the candidate and the arrangement of these beams within the geographical service area. There is some difference in the number of users which can be accommodated with the "box" and "billiard ball" beam arrangements.

7. Maximize overall antenna efficiency.

We naturally want to maximize the gain provided over the service area. The coverage Want (#4) applies only to the relative gain within the service area, that is, the gain variation within the service area. Maximizing the absolute gain as well is important since it reduces power requirements on the vehicle and/or eases requirements placed on the ground terminals. The use of the word "efficiency" in this Want was undoubtedly a bad choice, although it was not apparent at the time that the Step I analysis was performed. For one thing, we are concerned about gain efficiency in terms of beamwidth (dB gain for a given beamwidth) and not aperture efficiency (dB gain/square foot of aperture). This is because the coverage requirements dictate certain beamwidths and we can use whatever aperture is needed to obtain that beamwidth. The two viewpoints are not the same, since some tapered illuminations give better gain for a given beamwidth than does a uniform illumination which maximizes the aperture efficiency. For

example, a 7 foot circular aperture antenna illuminated with a distribution function of the form $(1-r^2)^2$ where r is the normalized radius, will have a gain of 45.91 dBi at X-band (56% aperture efficiency). A uniformly illuminated aperture of 59.29 inches will produce the same beamwidth and a gain of 45.25 dBi (100% aperture efficiency). Distinctions of this type were considered generally beyond the scope of the Step I analysis.

In the Step I analysis we did not compare candidates which offered different numbers of beams within the primary service area. This did not occur until the Step III analysis, and at that time it became apparent that maximizing gain was a better choice of words. The reason, of course, is that if one antenna provides 25 beams and the other only 15 beams in covering the same geographical area, the former will provide higher gain in the service area as a result of the narrower beamwidth and the larger aperture used and may or may not be more efficient than the latter antenna.

For the Step I analysis this Want received a weighting of 3.

8. Minimize complexity.

Complexity is difficult to define, even though it is easy to recognize a simple antenna and a complex antenna. The more complex an antenna is, the harder it is to manufacture and adjust and the more likely it is to fail. Complexity in a sense contains the elements of the risk factor. Probably one method of handling the complexity problem would have been to assess complexity factors as part of the evaluation of adverse consequences, but including the minimization of complexity as a Want seemed more direct.

In evaluating candidates against this Want, we agreed to set down any comment which related to an antenna being more complex and then to score on the basis of how serious that comment seemed to be. Since no probability factor is involved, including this as a Want (instead of as an adverse consequence) is an acceptable procedure.

In the Step I analysis, this Want had a weighting of 7.

9. <u>Minimize weight.</u>

This refers to the total weight of the antenna system back to an interface that permits comparison of candidates on a common basis. A weighting of 5 was assigned to this Want for the Step I analysis.

10. <u>Provide for growth to more beams.</u>

One way to increase the utility of a multibeam system is to provide more beams within a fixed geographical service area. This permits the system to handle more users and more traffic. Another way to accomplish the same thing is to expand the bandwidth of the system to provide more channels. The latter was not considered a realistic future requirement in view of the projected over-crowding of the spectrum. Providing more beams is a potential requirement, however, since it provides more traffic without increasing the use of spectrum.

The purpose of including growth potential as a Want was to introduce a factor to consider that would help avoid a "dead end" design. This Want had a weighting of 2 for the Step I analysis.

4.0   STEP I DECISION ANALYSIS

4.1   Candidate Antenna Concepts

On June 7 and 8, 1972, the NASA GSFC Technical Officer visited LMSC to review the progress on the multibeam study. During his visit, a list of candidate antenna concepts to be used in the Step I analysis was generated. This list consisted of variations of the basic antenna types which had previously survived the test of satisfying the absolute requirements or Musts of the decision analysis procedure.

The candidate antenna list consisted of twelve different types of antennas and four variations of each. The twelve basic antenna types are as follows:

I. <u>Circular Paraboloids.</u> This antenna is a circular aperture paraboloidal reflector antenna with multiple, point-source feeds, one for each beam. The paraboloidal reflectors were to have a diameter of the order of 7 feet.

II. <u>Circular Dielectric Lens.</u> This antenna is a circular aperture, solid dielectric lens with an f/D ratio of the order of 1.5. Point-source feeds would be used to illuminate the lens.

III. <u>Circular Artificial Dielectric Lens.</u> This is a circular aperture, artificial dielectric lens similar to the circular dielectric lens (II).

IV. <u>Circular Waveguide Lens.</u> This is a circular aperture waveguide lens similar to antenna II.

V. <u>Elliptical Paraboloid.</u> This is an elliptical aperture paraboloidal reflector antenna with multiple point source feeds. One dimension of the aperture was to be approximately 7 feet, the other larger by a factor of not more than 2:1. No decision was made regarding whether the major axis was to be oriented north-south or east-west, although the former seemed preferable.

VI. <u>Spherical Reflectors.</u> This antenna is a circular aperture spherical reflector with multiple point-source feeds. The diameter of the reflector was set

at 8 feet to provide a 7 foot aperture plus an allowance for scanning. The feeds were not assumed to be corrected for the phase error of the reflector. The justification for this is that it seems a very complex task to attempt to provide broadband phase correction in a multiple feed system. If the spherical reflector were selected as the preferred candidate, more consideration would be given to phase correction possibilities.

VII. <u>Luneberg Lens.</u> This is a standard spherical Luneberg lens with multiple point source feeds. The aperture diameter is approximately 7 feet.

VIII. <u>Parabolic Cylinder.</u> This is a cylindrical reflector having a square aperture of 7 feet by 7 feet. Feeds were pillbox line source feeds 7 feet long, each containing one or more exciters to provide multiple primary beams. At least one and not more than three pillbox feeds would be needed to illuminate the cylindrical reflector.

IX. <u>Offset Parabolic Cylinder.</u> This is the same as the Parabolic Cylinder (VIII) except that the pillbox feed and reflector are configured in the "offset" arrangement to eliminate secondary aperture blockage.

X. <u>Cylindrical Dielectric Lens.</u> This is a cylindrical solid dielectric lens with 7 foot by 7 foot aperture dimensions. The lens is fed by pillbox feeds as discussed above for the cylindrical reflector (VIII).

XI. <u>Cylindrical Artificial Dielectric Lens.</u> This is the same as antenna X except that an artificial dielectric is used.

XII. <u>Cylindrical Waveguide Lens.</u> This is the same as antenna X except that the lens is a waveguide lens.

For each of the above twelve antenna types four variations were considered. These are:

A. <u>Single antenna.</u> In this variation all beams were to be obtained from a single lens or reflector by multiple feeds. Generally this represents the minimum aperture, minimum weight case for each antenna type. The feeds are configured for each antenna type to provide interlaced beams of two polarizations so as to maximize beam-to-beam isolation.

B. <u>Dual antennas.</u> In this variation two antennas are used. All the beams of one polarization are on one antenna and all those of the orthogonal polarization are on the other antenna. The beams of the two antennas are interlaced, so that the closest adjacent beams are cross-polarized.

C. <u>Four antennas.</u> This variation evolves from the dual antenna by dividing the beams of the dual configuration among four antennas in such a way as to maximize the beam-to-beam spacing in each antenna.

D. <u>More than Four antennas.</u> This category represents all other combinations of multiple antennas exceeding 4 in number and less than N, where N is the number of beams to be provided. No attempt is made to fix the number of antennas, the comments and scoring only serving to indicate relative changes as more antennas are used. For some antennas this category might be 6 antennas, for others 8 antennas, and so on.

In referring to the various antenna candidates we shall generally use a nomenclature which consists of combinations of the underlined words in the above two lists. For example, one combination would be "Offset Parabolic Cylinder: Two Antennas". A shorthand notation for this same antenna type would be a combination of the Roman numeral and the letter as in "IX-B". The latter is less descriptive and will be used only where referral to the above lists is unnecessary.

Thus, if all possible combinations are considered, there are 48 candidates ranging from I-A through XII-D. This list represents all of the candidate antenna concepts discussed with the Technical Officer during the June, 1972, meeting.

4.2   Other Candidate Antennas.

It was permissible to add to the list given above and during the course of the Step I analysis we considered doing so. Naturally, there was a reluctance to increasing the number of candidate antennas to be considered as it would tend to work against the main purpose of the Step I analysis. In this section we shall mention some of the additional candidates we discussed and the reasons we had for not adding them to the list. Note that each additional antenna type adds four more candidates to the list.

First, flexibility in the aperture dimensions could have been considered. Except for the Elliptical Paraboloids (V-A through V-D), all of the antenna types considered were deemed to have equal aperture dimensions in two perpendicular dimensions. Configurations I through IV and VI through VII were all circular aperture antennas and configurations VIII through XII were all square apertures.

Therefore, except for the Elliptical Paraboloid (V) and the Luneberg Lens (VII), elliptical or rectangular aperture configurations could have been considered. This would have added 9 additional antenna types with four variations each for a total of 36 additional candidates or a grand total of 84 candidates altogether.

The logic for not adding the additional 36 candidates was that the elliptical aperture or rectangular aperture case is represented in general by the pair of the Circular Paraboloid (I) and the Elliptical Paraboloid (V). By considering this couplet, we were evaluating what the performance potential improvement would be for the paraboloid if we are permitted to adjust the ratio of the north-south/east-west aperture dimensions. We concluded then that by implication we were also evaluating what this freedom of choice or design option would mean for the other antenna types. Thus we did not add any other elliptical or rectangular aperture candidates at this point.

Second, we could have added a cylindrical version of the Spherical Reflector (VI). This would be a reflector having a surface which is a portion of a right circular cylinder. The feeds would be pillboxes as have been mentioned before. Having the spherical reflector in the candidate list shows the relationship of the spherical reflector to the circular paraboloid. Generally the spherical reflector trades poorer beam performance near the axis for wider offset capability. As above, then, comparing the Spherical Reflector (VI) with the Circular Paraboloid (I) by implication compares the cylindrical version of the former with the Parabolic Cylinder (VIII). Thus we did not add a cylindrical derivative of the Spherical Reflector at this point.

Third, we considered adding a cylindrical version of the Luneberg Lens. This would be formed by a cylindrical stack of shaped parallel plate regions, an array of geodesic Luneberg lenses. The cylindrical lens would be fed by pillbox feeds. Without detailing this analysis, it appeared that this configuration would be heavier than any of the other cylindrical lenses (except the solid dielectric version-X) and would not offer any material performance advantages with respect to the most highly weighted Wants. Furthermore, we anticipated difficulties in developing a configuration which would allow us to use the polarization diversity feature, at least in the A or single antenna form. An artificial dielectric embodiment of the Luneberg principle could be employed, but offhand this seemed to be heavier than the Cylindrical Artificial Dielectric Lens (XI) without offering any strong advantages. Thus we did not add any cylindrical form of the Luneberg Lens to the candidate list.

Notice that both the Spherical Reflector and the Luneberg Lens antenna types are suited to wide angle scanning. The decision not to include cylindrical versions of the antennas was influenced markedly by the fact that for 15 to 25 beams a "wide-angle" capability is not really required. The maximum offset

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for the application at hand is of the order of 2 to 3 beamwidths and the degradations thus experienced are not very serious. In fact, any of the lens concepts can be designed for some wide-angle capability to improve on the paraboloidal reflector or uncorrected lens capability out to about 10 to 15 beamwidths of offset. Had we been considering more beams in one of the two directions (such as many beams in the east-west direction) consideration of cylindrical versions of spherical reflectors and Luneberg Lens could have been more easily justified.

The aforementioned antenna concepts were considered informally and in some detail, but it appeared unnecessary to expand the scope of the analysis from that established during the June, 1972, meeting. Other candidates not mentioned above could have been generated and evaluated, but the main argument against doing so was that the 48 candidates selected are representative candidates and further search for likely candidates would have delayed arriving at a Step I decision.

4.3   Beam Arrangements

The circular aperture antenna candidates utilize point source feeds. Except for the limitations of physical interference, the feeds may be moved around to position the beams as desired. (Of course, performance will suffer if the beams are too close together or too far removed from the axis).

With the cylindrical versions of the same antennas, there is an additional restriction on the locations of the beams in that all beams emanating from a single line source must lie in a common plane.

To compare all candidate forms of antennas on a common basis, we defined the main area to be covered as being a 3 by 6 rectangular arrangement of beams. This crude model of the contiguous 48 states was used primarily to determine how the beams would be split up among several antennas and how weight grows in going from A to B to C to D. In the evaluation process comments

were made to relate the crude model to the actual case and to define exceptions and distinctions (in particular, the problems relating to coverage of New England and Florida).

For a single antenna the crude model of beam arrangements is shown in Figure 8. This is the "box-beam" arrangement as discussed in the proposal. In evaluating the capability of maximizing the number of users on a worst case basis, the capability of a candidate system providing the billiard ball beam arrangement is commented upon, where applicable. Note that dual polarization is used to maximize beam-to-beam isolation. The 2 polarizations in this and other figures is indicated by solid and dashed circles. Note also that the beam arrangement of Figure 8 is the beam arrangement to be achieved for multiple antenna versions of the same candidate.

As mentioned before, in going to the dual antenna version we always place one polarization on one antenna and the complementary polarization on the other. This maximizes the average beam-to-beam spacing for each of the two antennas and allows the designer to use polarization grids to purify the polarization of each of the two antennas. The beam arrangement for the dual antenna case is shown in Figure 9. Polarization is indicated as in Figure 8 and antenna numbers are indicated in the circles.

If a very large number of beams were needed so that there is some serious degradation of the peripheral beams due to lateral defocussing, the beams in the dual antenna case might be split into a "western" half and an "eastern" half. This would minimize the offset required from the antenna axis and would improve performance. Since large lateral offsets are not required to achieve the number of beams needed here, we chose to divide the beams according to polarization for the reasons given above.
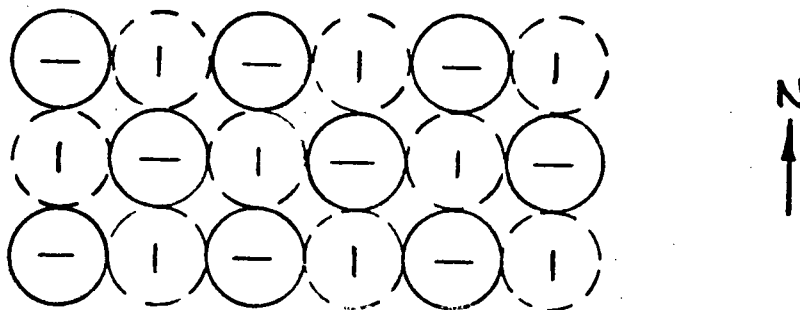
FIGURE 8   SINGLE ANTENNA BEAM ARRANGEMENT
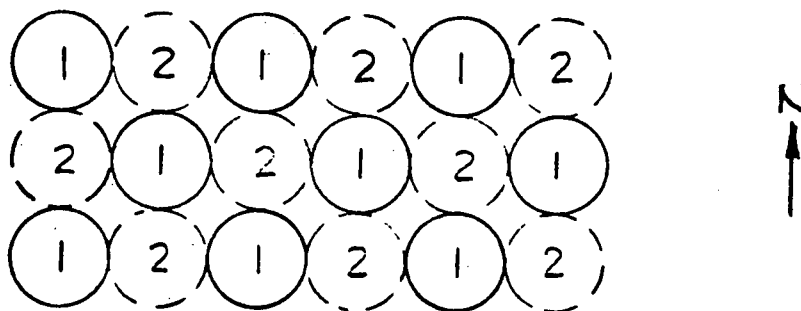
FIGURE 9   DUAL ANTENNA BEAM ARRANGEMENT
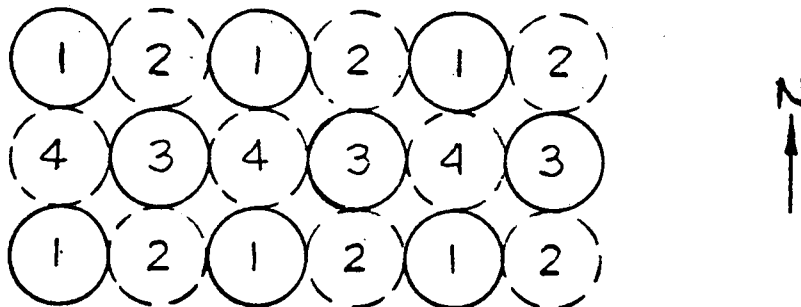
FIGURE 10   FOUR ANTENNA BEAM ARRANGEMENT

Note in Figure 9 that if the beams are to be achieved by any cylindrical versions of the candidate antenna concepts, the focal axis of the cylinder must be oriented in the left-right or east-west direction. This requires the minimum number of pillbox feeds, namely three for the cases of Figure 8 or Figure 9. If the focal axis of the cylinder is oriented in the north-south direction, six pillbox feeds are required which has several disadvantages. First it doubles the feed weight. Second, for the parabolic cylinder reflector it doubles the aperture blockage. Third, for the offset parabolic cylinder it worsens the axial defocussing which must occur. (These problems will be considered in more detail later). Therefore, when considering cylindrical antenna concepts the east-west orientation of the focal axis was chosen.

In going to the dual antenna configuration of Figure 9, the minimum spacing between beams in a single antenna has been increased by a factor of $\sqrt{2}$. That is, the closest pair of beams in each antenna would lie along the diagonal (NW-SE or NE-SW) while in the single antenna case the closest pair would lie in the N-S or E-W direction. The dual antenna version of circular aperture antennas will have the same number of feeds as will the single antenna version. For the cylindrical versions of the antennas, there will be twice as many pillbox feeds in the dual antenna version--that is, 6 pillboxes.

The four-antenna beam arrangement is shown in Figure 10. The principle employed here is to divide the beams on each antenna in the dual case so as to improve the minimum beam-to-beam spacing. Here the minimum spacing has been increased by a factor of 2 over the single antenna case. While the same number of feeds is required for 1, 2 or 4 antenna configurations of circular antennas, the cylindrical case will again require twice the number of pillboxes needed for the single case (the same as the dual case). As shown the two middle feeds have been moved to the two additional reflectors or lenses.

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The reader may imagine how additional antenna apertures might be used to arrive at configurations in the "more than four" category. For example, for the cylindrical versions six might be the next logical step so as to provide a separate aperture for each pillbox. By this procedure lateral defocussing could be eliminated in the N-S direction for all six antennas by placing the pillboxes on axis and reorienting the lenses or reflectors. There still would be E-W lateral defocussing for two of the beams in each pillbox, however. There does not appear to be an easy way to make a major improvement in the minimum beam spacing with only a few more antennas. The next major improvement for all beams would require almost as many antennas as beams. We might divide beams of Figure 10 into east-west halves to arrive at 8 antennas. Thus, going to more than four antennas does not seem to improve the beam-to-beam spacing for all beams but would probably tend to minimize lateral defocussing. Probably the only strong argument for more than four antennas is to provide better coverage of Florida and New England for the cylindrical antenna types.

4.4   Selection of Preferred Candidates

Each of the 48 candidate antenna concepts was evaluated against each of the 10 Wants applicable to the Step I analysis. The actual worksheets used together with a detailed explanation of the assessments made are included in Appendix A. This departure from the format previously used in the monthly reports has been made in the interests of preserving the continuity of the report.

The scoring of the individual candidates against the Want list resulted in a relative ranking of the 48 individual candidates. By inference some conclusions can be drawn about other candidates not actually included in the list. This analysis produced some interesting results concerning the candidates when considered by classes. It also indicated important areas where study was needed to prepare for the Step II analysis. The results of the scoring are given in Table 1.

TABLE 1   Total Weighted Scores, Step I

		A	B	C	D
		1	2	4	> 4
I	Circular Paraboloid	419	436	406	387
II	Circular Dielectric Lens	363	370	356	349
III	Circular Artificial Dielectric Lens	423	430	398	368
IV	Circular Waveguide Lens	418	425	388	358
V	Elliptical Paraboloid	435	442	412	388
VI	Spherical Reflector	415	417	387	363
VII	Luneberg Lens	302	318	321	321
VIII	Parabolic Cylinder	311	348	341	320
IX	Offset Parabolic Cylinder	319	362	339	311
X	Cylindrical Dielectric Lens	305	326	317	303
XI	Cylindrical Artificial Dielectric Lens	321	350	334	313
XII	Cylindrical Waveguide Lens	316	345	329	308

The above table can be revised to show relative rankings. This is shown in Table 2 where ties are indicated by an asterisk.

TABLE 2   Relative Ranking – Step I

		A	B	C	D
		1	2	4	>4
I	Circular Paraboloid	7	2	12	16*
II	Circular Dielectric Lens	20*	18	24	26
III	Circular Artificial Dielectric Lens	6	4	13	19
IV	Circular Waveguide Lens	8	5	14*	23
V	Elliptical Paraboloid	3	1	11	14*
VI	Spherical Reflector	10	9	16*	20*
VII	Luneberg Lens	48	39	34*	34*
VIII	Parabolic Cylinder	43*	27	29	37
IX	Offset Parabolic Cylinder	38	22	30	43*
X	Cylindrical Dielectric Lens	46	33	40	47
XI	Cylindrical Artificial Dielectric Lens	34*	25	31	42
XII	Cylindrical Waveguide Lens	41	28	32	45

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The KTA Decision Analysis procedure does not provide a hard ranking based on the actual numerical scores. Score differences of only a few points can and should be neglected. Wider differences can be given more importance in proportion to the magnitude of the score difference. To simplify Table 2 the numerical scores of Table 4 have been grouped together to eliminate insignificant differences. This grouping is based on all scores within the group being within 20 of the top score. The groups are as follows:

1	442-423
2	419-406
3	398-387
4	370-356
5	350-334
6	329-311
7	308-302

Using this definition of the groups, Table 2 can be revised as shown in Table 3.

TABLE 3 Group Ranking – Step I

		A	B	C	D
		1	2	4	> 4
I	Circular Paraboloid	2	1	2	3
II	Circular Dielectric Lens	4	4	4	5
III	Circular Artificial Dielectric Lens	1	1	3	4
IV	Circular Waveguide Lens	2	1	3	4
V	Elliptical Paraboloid	1	1	2	3
VI	Spherical Reflector	2	2	3	4
VII	Luneberg Lens	7	6	6	6
VIII	Parabolic Cylinder	6	5	5	6
IX	Offset Parabolic Cylinder	6	4	5	6
X	Cylindrical Dielectric Lens	7	6	6	7
XI	Cylindrical Artificial Dielectric Lens	6	5	5	6
XII	Cylindrical Waveguide Lens	6	5	6	7

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Table 3 reflects the ranking of the various candidates with the ability of the analysis to distinguish between candidates taken into account. Actually some candidates at the bottom of one group may be insignificantly different from candidates at the top of the next lower group, so we shall have some use for Table 1 later on.

First of all, there is at least a 100 point difference between the leading candidate (V-B) and the candidates in groups 6 and 7. To make an error of this magnitude would mean gross misjudgments in evaluating and scoring the candidates or perhaps a large number of smaller errors. Thus all candidates in groups 6 and 7 can be eliminated from further consideration on the basis of being relatively less attractive than the remaining 31 candidates.

Notice that there is a natural break in the scores between groups 3 and 4. The gap is 17 points, the largest interval between any two groups in the table. Moreover, groups 4 and 5 are at least 72 points behind the leading candidate. This difference, though not as good as the 100 point difference discussed above, is nevertheless significant. We can, therefore, eliminate groups 4 and 5.

Of the 17 candidates remaining in groups 1, 2, and 3, the maximum point spread is 55 points. This maximum difference is itself significant, but further reductions on the basis of point scores can only be made with less and less confidence. Notice, however, that two of the group 3 candidates (I-D and V-D) are the only "D" candidates (more than four antennas) remaining and incidentally have the lowest scores of the remaining candidates (387 and 388, respectively). It is unlikely that these two candidates on reevaluation in Step II could ever overtake the leading candidate. Furthermore, the "more than four" category itself does not actually represent a candidate specifically but instead the extrapolation to all conceivable configurations of more than four antennas and less than 1 antenna per beam. The D category provides a means of assessing the merits of any extrapolation

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which could provide a benefit. Since the D category did not produce a <u>better</u> candidate than fewer antennas of the same type for the 12 types considered, we concluded that considering more than four antennas serves no useful purpose and eliminated I-D and V-D from the list.

Thus the remaining candidates which were the subject of the Step II evaluation are those shown in Table 4.

TABLE 4   Step II Candidates

		A	B	C	A	B	C
		1	2	4	1	2	4
I	Circular Paraboloid	419	436	406	2	1	2
III	Circular Artificial Dielectric Lens	423	430	398	1	1	3
IV	Circular Waveguide Lens	418	425	388	2	1	3
V	Elliptical Paraboloid	435	442	412	1	1	2
VI	Spherical Reflector	415	417	387	2	2	3

Notice that we retained candidates in the C version (specifically IV-C and VI-C) which have the same scores as candidates I-D and V-D which were eliminated. In fact there could be good argument against considering any of the C versions which in every case are 30 points behind the dual antenna versions (B). But, it is not too difficult to extrapolate from 2 to 4 antennas for any of the antenna types. Therefore, all five C versions were retained for the Step II analysis. Primary emphasis would be placed on single and dual antenna versions and four antenna versions would be deduced from the performance of dual antenna versions.

4.5 · Analysis of Results

One important conclusion of the Step I analysis was that in general the cylindrical versions of the antennas failed to satisfy the Wants as well as the circular versions did. The reason for this needs to be examined.

One of the primary contributors is the weight problem. The pillbox feeds were estimated to have a weight of 20 lbs. a piece when constructed of 0.050 inch wall thickness magnesium. In most cases this represents 60 lbs. of feed per antenna used and is a sizeable fraction of the total weight of the system. A feed-in-face type of pillbox could be constructed for less than 10 lbs., but there would be some relative degradation of the off-axis beams with this f/D ratio.

But weight is not the whole story. To illustrate this, we recomputed the total scores assuming the weight of the antenna was inconsequential. This resulted in the scores shown in Table 5.

TABLE 5 Scores Without Want #9 - Step I

		A	B	C	D
		1	2	4	>4
I	Circular Paraboloid	369	391	366	352
II	Circular Dielectric Lens	343	360	356	349
III	Circular Artificial Dielectric Lens	383	400	373	353
IV	Circular Waveguide Lens	383	400	373	353
V	Elliptical Paraboloid	385	397	372	358
VI	Spherical Reflector	365	372	347	333
VII	Luneberg Lens	302	318	321	321
VIII	Parabolic Cylinder	276	318	316	300
IX	Offset Parabolic Cylinder	284	332	314	291
X	Cylindrical Dielectric Lens	285	321	317	303
XI	Cylindrical Artificial Dielectric Lens	291	325	319	303
XII	Cylindrical Waveguide Lens	291	325	319	303

The spread of points has been reduced, but the dominance of the circular antennas over the cylindrical ones can be illustrated by groupings as we did before. The groups are:

1	400-383
2	373-356
3	353-343
4	333-314
5	303-276

The relative ranking by groups is shown in Table 6.

TABLE 6   Relative Ranking by Groups Without Want #9 – Step I

		A	B	C	D
I	Circular Paraboloid	2	1	2	3
II	Circular Dielectric Lens	3	2	2	3
III	Circular Artificial Dielectric Lens	1	1	2	3
IV	Circular Waveguide Lens	1	1	2	3
V	Elliptical Paraboloid	1	1	2	2
VI	Spherical Reflector	2	2	3	4
VII	Luneberg Lens	5	4	4	4
VIII	Parabolic Cylinder	5	4	4	5
IX	Offset Parabolic Cylinder	5	4	4	5
X	Cylindrical Dielectric Lens	5	4	4	5
XI	Cylindrical Artificial Dielectric Lens	5	4	4	5
XII	Cylindrical Waveguide Lens	5	4	4	5

Between the leading candidate (III-B and IV-B) and groups 4 and 5 is a point difference of at least 67 points. This has just about as much significance as the minimum 72 point difference used above to eliminate groups 4, 5, 6, and 7 from Table 3. This is particularly true when we remember that there is one less Want (having a maximum weighted score of 50). Thus, even if weight is not considered, the Luneberg Lens and all of the cylindrical antenna candidates would be eliminated.

The technical reasons to support this are related to the problems of the feed. The cylindrical configuration constrains us to an ordered beam arrangement where the beams emanating from each pillbox lie in a line. The limitation of the freedom of placing the beams may have serious impact on the ability to meet the coverage Want (#4, weighting of 10), particularly with respect to the tip of New England and to Florida. We have the choice of failing to provide the required coverage or adding extra pillboxes (which then incurs more blockage and more weight). This is one of the reasons that the multiple antenna versions of the cylindrical antennas are better than the A or single antenna versions in Table 5. Having extra antennas allows us to provide the extra pillbox needed to improve coverage without blocking the aperture for all beams.

Another way that the feeds contribute to the relatively poor position of the cylindrical antennas is in the complexity aspects of the problem. For the single antenna version of the cylindrical antennas we have a relatively poor rating with regard to "minimizing complexity" due to the fact that both polarizations will have to be supported within a single pillbox feed without cross coupling. This represents a fair development and design risk (more properly evaluated as a "possible adverse consequence") and we do not have the ability to purify the polarization at the pillbox aperture (as we do in dual and other multiple antenna versions of the cylindrical antennas). On the other hand, the multiple antenna versions of the cylindrical antennas suffer in complexity due to the fact that for

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at least half of the pillboxes (parallel polarization) we probably could not count on having a deployable design that would maintain plate spacing accurately enough to provide uniform phase over the pillbox aperture. With several rigid pillboxes, the problems of packaging for launch grow more complex.

Thus the feeds, in addition to the weight they contribute, add to the complexities of the problem and hamper the efforts to achieve adequate gain coverage. These two areas tend to offset the improvement in polarization isolation obtained in the cylindrical antenna versions. Substantially the same purity of polarization can be obtained by using polarization grids in conjunction with dual antenna versions of the circular antenna types, even if it is necessary to cover the entire radiating apertures.

An interesting pattern can be observed in Table 5. For each of the circular aperture antennas (except the Luneberg Lens), the versions rank in order B, A, C, D. For the cylindrical antennas the ranking is B, C, D, A. When weight is considered, the order for cylindrical antennas (except the parabolic cylinder) changes to B, C, A, D. The relatively poor showing of the single antenna version is caused by the feed problems of the cylindrical antennas. We expect the scoring for weight and complexity to decrease generally as we go from single to mutliple antennas. To offset this scoring trend we hope to get a corresponding increase in performance. With the cylindrical antennas, the coverage is much poorer for the single antenna version because of the difficulties of covering Florida, New England, Hawaii and Alaska. For the single antenna the improved weight and complexity (moderately weighted wants) is more than offset by the coverage problems (highly weighted Wants).

For the circular antennas (except the Luneberg Lens) coverage is better to start with and improves only slightly by going to multiple antennas. The major bulk of the improvement occurs by going from one to two antennas. The same can

be said of the isolation want (also highly weighted). Thus for the circular antennas the order in either Table 1 or Table 5 becomes B, A, C, D.

Admittedly, the differences which establish the orders given above are not always significant. In fact, more often than not, the first place version B does not score more than 10 points or so better than the second place version (A or C). Thus while the dual antenna version is always better, its edge over the second place version of the same antenna type is not significant enough to separate the two. The only thing worthy of consideration in this respect is the consistency with which the dual antenna version places first. This indicates the dual antenna concept is at least as good as the single antenna concept and perhaps that we were consistent in our scoring.

The Luneberg Lens fails to fit these patterns. Generally going to more antennas seems to improve the situation. The primary reason is that there are performance improvements in going to multiple antennas, but there is no counter-acting trend (in the scoring) due to greater complexity and weight. This statement is only true when the Luneberg is compared against lighter and simpler antennas. If only the four Luneberg versions were compared, weight and complexity would grow by leaps and bounds and the final order would probably be A, B, C, D or B, A, C, D. But when compared with the other antenna types the weight and complexity of the single antenna version is already so bad as to result in a very low score for those two Wants and the decrease accompanying the increase in the number of antennas has an insignificant numerical impact.

The Luneberg Lens type considered is the compressed foam spherical shell type of construction. The required variation of refractive index is achieved by controlling the density of material in successive shells. This admittedly is the heaviest method of construction. If an artificial dielectric is used, losses increase and the weight problem is alleviated, but otherwise the performance

characteristics and problems of complexity remain the same. The relative position of the artificial dielectric type of Luneberg is fairly represented in Tables 5 and 6 which do not consider weight. Actually the position of the artificial dielectric Luneberg Lens would be somewhat worse than shown in these two tables because of the losses and because of heavier weight compared to, say, the circular paraboloid.

4. 6   Comparison of the Preferred Candidates

The candidates retained for the Step II analysis were those shown in Table 4. The Step I analysis had indicated a general preference for two-antenna versions of circular aperture lenses and reflectors. In preparation for the Step II analysis, we examined the results of the Step I analysis to determine where the most profitable investigations could be conducted to upgrade our technical information.

The two circular lense retained for Step II (Artificial Dielectric Lens, III, and Waveguide Lens, IV) were judged in the Step I analysis to have essentially the same characteristics. The difference in scoring is attributible to the difference in weight. The coverage, isolation, and gain performance characteristics were judged to be the same for both types of lens. One task marked for Step II was therefore to evaluate methods of constructing both types of lens and then to simply discard the heavier type -- if the performance characteristics were found on closer scrutiny to be truly equivalent. Actually, we did not compare these two lenses in detail until the Step III analysis, and when we did so, the presumption of equivalent performance was not entirely verified due to the bandwidth problem discussed in Section 2.3.

For the Step II analysis we could have also included elliptical aperture versions of the lenses and of the spherical reflector. At the conclusion of the Step I analysis we found that there was no apparent advantage in using an elliptical aperture instead of a circular one, other than a presumed possibility of better

off-axis performance for the case of the elliptical paraboloid. This advantage of the elliptical aperture would disappear entirely for the spherical reflector which has the same characteristics (essentially) for all beam angles within its scanning range. It would be almost non-existent for lenses designed for a wide-angle capability for the few beamwidths of offset involved here. Thus while the elliptical aperture version of the paraboloid would be retained for the Step II analysis as a separate candidate, there would be no point to adding elliptical aperture versions of the lenses or of the spherical reflector. Of course, we need not feel restricted to circular apertures and can employ an elliptical aperture lens or spherical reflector if it allows us to cover the service area more completely.

In this respect, it was decided that a secondary task to be performed during the Step II analysis would be to configure specific beam arrangements for both circular and elliptical apertures. Basically this is in compliance with the philosophy that the Step II analysis should be more thorough and detailed than the Step I analysis. Knowing aperture sizes, number of beams, beam positions, and so on would permit us to compare candidates on a more exact basis.

The three basic antenna types, lenses, paraboloidal reflectors, and spherical reflectors, are capable of providing essentially the same coverages, although there may be some difference between the one-antenna and two-antenna versions of each. Weight, complexity and most other factors for the three generic types of antennas are about the same. There will be some relatively minor impact, of course, due to blockage and loss factors when comparing lenses and reflectors. But the primary difference in the above three basic antenna types will be in their off-axis scan properties. While we can do something about cross-polarization coupling, the basic coma lobe and side lobe performance of these antennas for off-axis beams will be the determining factor in satisfying the highly-weighted beam-to-beam isolation Want.

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Accordingly, the results of the Step I analysis showed a real need for a detailed investigation of the off-axis performance characteristics of lenses and reflectors. First of all, we had assumed that the elliptical aperture paraboloid would have better off-axis beam characteristics due to the absence of localized areas of high phase distortion. This had to be evaluated to see (1) if it were true and (2) if any difference found was of significant magnitude. Second, we had estimated that the coma lobe problem would not be too serious because of the limited beam offset required for the intended application. This needed verification. We also needed to obtain performance figures for the spherical reflector approach. Finally, the off-axis beam performance for lenses with and without wide-angle coma correction needed study.

Thus, it was decided that a detailed investigation of the off-axis performance as it relates to beam-to-beam isolation was needed as preparation for the Step II analysis. This investigation is reported in the next Section.

5.0   COMPARISON OF OFF-AXIS PERFORMANCE OF REFLECTORS

5.1   Theory

Of the five generic antenna types considered in the Step II analysis, three were reflectors. These are the circular aperture paraboloid, the elliptical aperture paraboloid, and the spherical reflector. A primary performance factor considered in the evaluation of the candidate antennas is the beam-to-beam isolation which is dependent on the location, extent, and level of coma lobes and side lobes. A theoretical analysis of relevant pattern characteristics and gain performance was made for the three reflector candidates using the current distribution method.

The current distribution method involves the integration of the surface current distribution on the surface of the reflector to find far field pattern characteristics. This method has been used extensively in the development of the Flex-Rib reflector at LMSC to set design parameters and to predict performance. Often a theoretical function is used to simulate the feed pattern. The analytical function used commonly predicts a gain 1.5 to 1.7 dB higher than obtained in practice. If other parameters relating to the antenna configuration are changed, the method predicts the corresponding change in performance with good relative accuracy and this has been verified by experiment. On the other hand, if an experimental feed pattern is used in the computations and if appropriate care is used in measuring the far field pattern characteristics of the reflector, correlation between the theoretical value and the actual experimental gain figure is very accurate. LMSC's experience shows that the correlation is normally within 0.1 to 0.3 dB, based on experience with the ATS F and G antenna and others.

The accuracy of the current distribution suffers primarily from the failure to account for modifications of the primary feed patterns as a result of the presence of feed support structure. Blocking, spillover, surface contour irregularities, feed-reflector interaction (VSWR), and the like can all be taken into account.

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During the time available for the Step II analysis, it was not possible to perform experimental measurements on the three types of reflectors to ascertain relative performance. The next best thing seemed to be to analyze the performance of the three reflector types using the same methods (which had been proven in other cases) and to base decisions on the theoretical results. Because it was necessary to use the analytical function to describe the feed, only relative accuracy can be expected. Actual gain figures will be somewhat lower than predicted by the analysis and we can expect the side lobes to be somewhat higher than predicted due to practical matters such as blockage.

The basic vector integral to be evaluated is of the form

$$I = \int_S \frac{\sqrt{G_f(\psi, \xi)}}{\rho} \left[\bar{n} \times \left(\bar{i}_\rho \times \bar{e} \right) \right] e^{-jk\rho \left(1 - \bar{i}_\rho \cdot \bar{i}_R \right)} dS$$

where $G_f(\psi, \xi)$ is the gain function of the feed, ρ is the distance from the feed to a point (ρ, ψ, ξ) on the reflector surface, $\bar{n}$ is the unit vector normal to the reflector surface at the point (ρ, ψ, ξ) $\bar{i}_\rho$ is the unit vector in the ρ direction, $\bar{e}$ is a unit vector defining the polarization of the feed, k is $2\pi/\lambda$ (where λ is the wavelength, and $\bar{i}_R$ is the unit vector pointing toward the far field observation point. The integration is performed over the reflector surface S. The feed is assumed to be located at the origin of the coordinate system.

The reflector surface is described in terms of the coordinates ρ, ψ, ξ and the far-field observation point is located in terms of the coordinates R, θ, ϕ. It can be shown that the gain function of the reflector antenna can be found from

$$G = \eta \frac{\bar{I}_T \cdot \bar{I}_T^*}{\lambda^2}$$

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where η is the radiation efficiency (total radiated power/total input power), where $\bar{I}_T$ is the component of $\bar{I}$ perpendicular to the direction of propagation, and where * indicates the complex conjugate.

The current distribution method allows us to calculate the field in any direction and to determine cross-polarization components. Had more time been available, we could have directly calculated the beam-to-beam isolation predicted as a function of angle for any two beams in a multibeam system. In the event the reflector candidates had been found more suitable for the multibeam application the requisite expense and effort to do so might be justifiable. In an effort to be cost-effective, we chose to limit our computations to the plane of scan which, for the case of the paraboloid, contains the coma lobe and which (unfortunately) has no cross-polarized component.

In these computations the gain function of the feed was assumed to be the form

$$G_f(\psi,\xi) = 2(m+1)\cos^m\psi \qquad 0\leq\psi\leq\frac{\pi}{2}$$

$$G_f(\psi,\xi) = 0 \qquad \frac{\pi}{2}<\psi\leq\pi$$

where m is adjusted so that the feed pattern is 10 dB below the peak value in the direction of the reflector edge for the on-axis beam except as noted. The same value of m was used for all other offset positions.

5.2   Results

In Figure 11 the offset beam patterns for an 84 inch diameter circular paraboloid are shown. The parameter is the angle α, the angle that the feed is offset from the reflector axis. The focal length of the reflector is 42 inches and the feed is set 42 inches from the vertex. The operating frequency is 12.475 GHz. It can be seen that the first side lobe increases from -26.8 dB to -13.6 dB and

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ANGLE

RELATIVE POWER ONE WAY db

4°   3°   2°   1°   0°

α=3.6   2.88   2.16   1.44   .72   0

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FIG. 11   Patterns For
Circular Paraboloid
Dia = 84"
F = 42"
Freq = 12.475 GHz.
EDT = -10dB

40

30

.20

12
72

6
36

0
0

6
36°

12°
72°

18°
108°

10
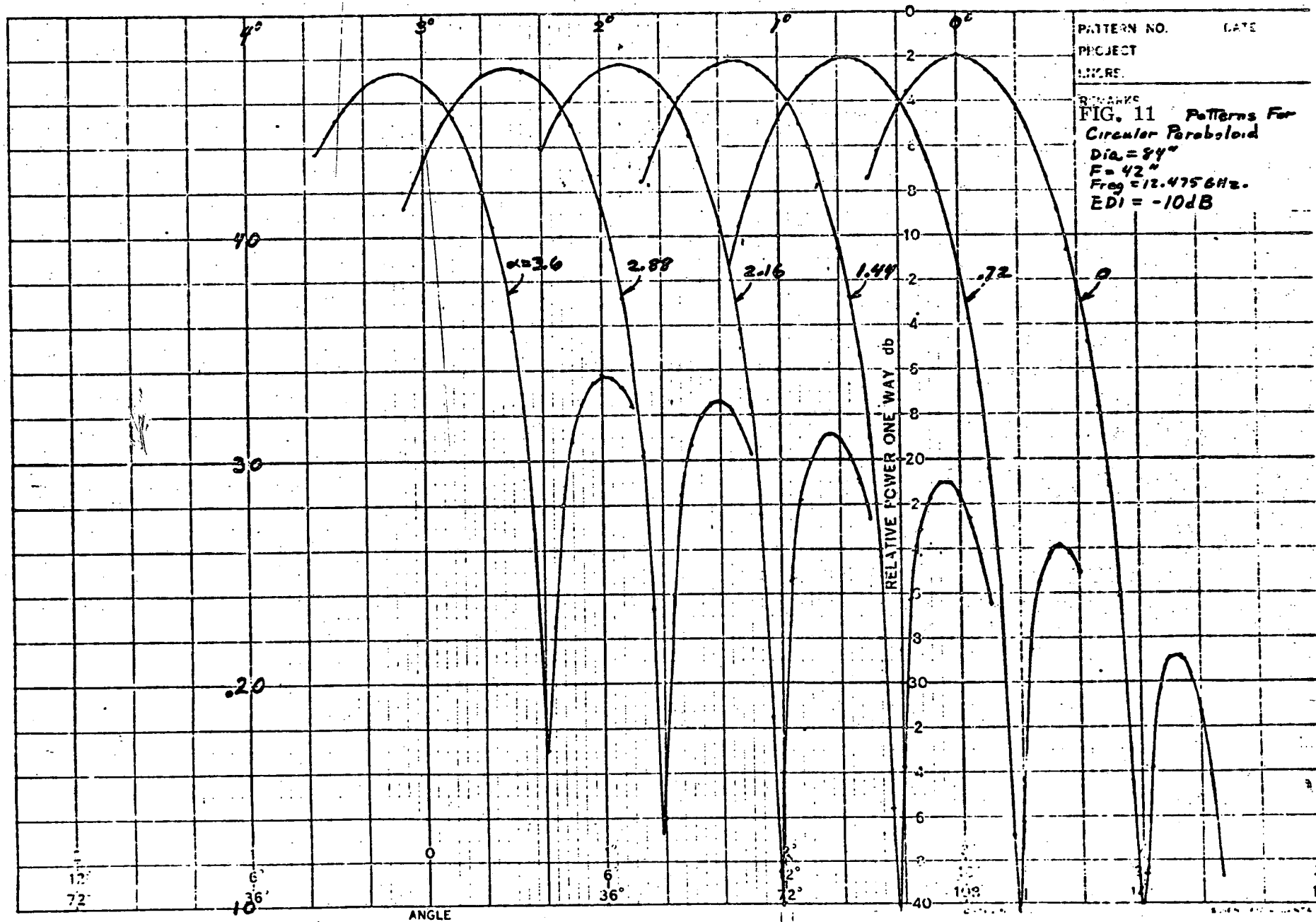
that the gain has decreased from 48 dB to 47.3 dB.

If we maintain the aperture dimension in the plane of scan at 84 inches and maintain the focal length at 42 inches but increase the aperture dimension in the perpendicular plane to 126 inches (an aspect ratio of 1.5:1) we obtain the curves of Figure 12. For these computations the feed pattern was adjusted so that for the on-axis case the relative intensity in the direction of the edge was -10 dB. This makes m a function of the reflector surface coordinates (but not of the feed offset angle). The feed gain was adjusted to account for the change in feed pattern shape. In Figure 12 notice that the peak gain is higher (due to the larger aperture), the gain degradation is more severe, but the coma lobe increase is not as serious.

In Figure 13 the configuration in the plane of scan is maintained but the cross-plane aperture dimension has been reduced to 56 inches, corresponding to an aspect ratio of 2:3. Here the gain is lower due to reduced aperture area, the gain degradation is less, but the coma lobe degradation is now more severe.

The results of these three series of computations are summarized in Figures 14, 15, and 16. Figure 16 also includes the level of the second side lobe just beyond the coma lobe for the circular aperture.

The conclusion which can be reached as a result of these computations is that the elliptical aperture does improve some characteristics of off-axis performance while at the same time degrading others. In one case the gain performance is improved at the expense of coma lobe performance and in the other case just the reverse is true. Generally, neither improvement nor degradation is sufficient to be of any benefit or serious harm. Moderate elliptical apertures cannot be used to improve coma lobe to the point where the paraboloid would provide acceptable beam-to-beam isolation in the 30 dB range.

FIG. 12 Patterns for Elliptical Paraboloid 84" X 126" F = 42" Freq = 12.475 GHz EDL = -10 dB

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FIG. 13   Patterns for
Elliptical Paraboloid
84" x 56"
F = 42"
Freq = 12.475 GHz
EDI = -10 dB

$\alpha = 3.6$ 2.88   2.16   1.44   .72   0°

0°   1°   2°   3°   4°

0
2
4
6
8
-10
2
4
6
8
-20
2
4
6
8
-30
2
4
6
8
-40

RELATIVE POWER ONE WAY (db)

ANGLE

0   2°   6°   12°   18°   24°
       6°   12°   72°   108°
       36°   72°

40

30

20

10

CHART NO. 121
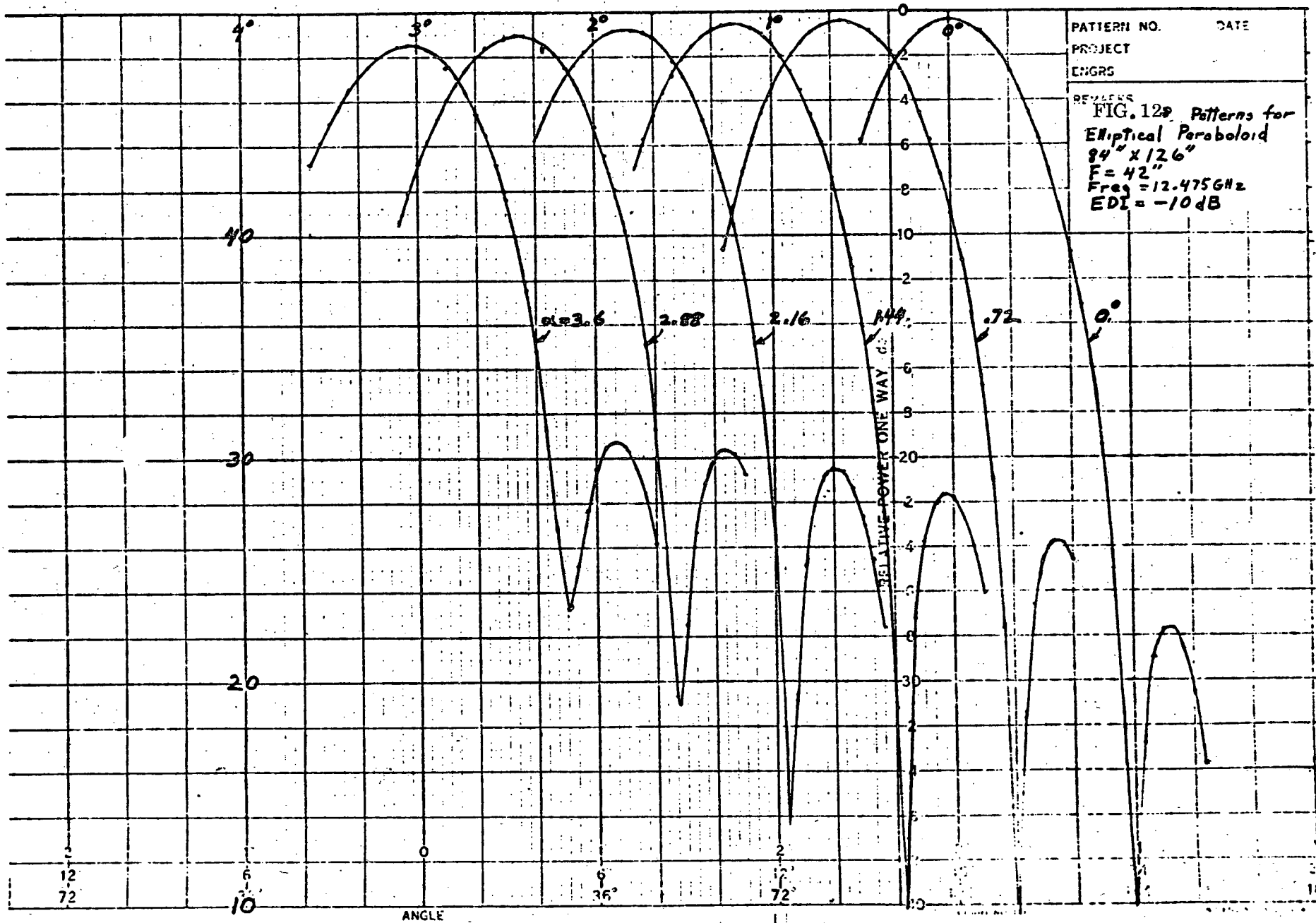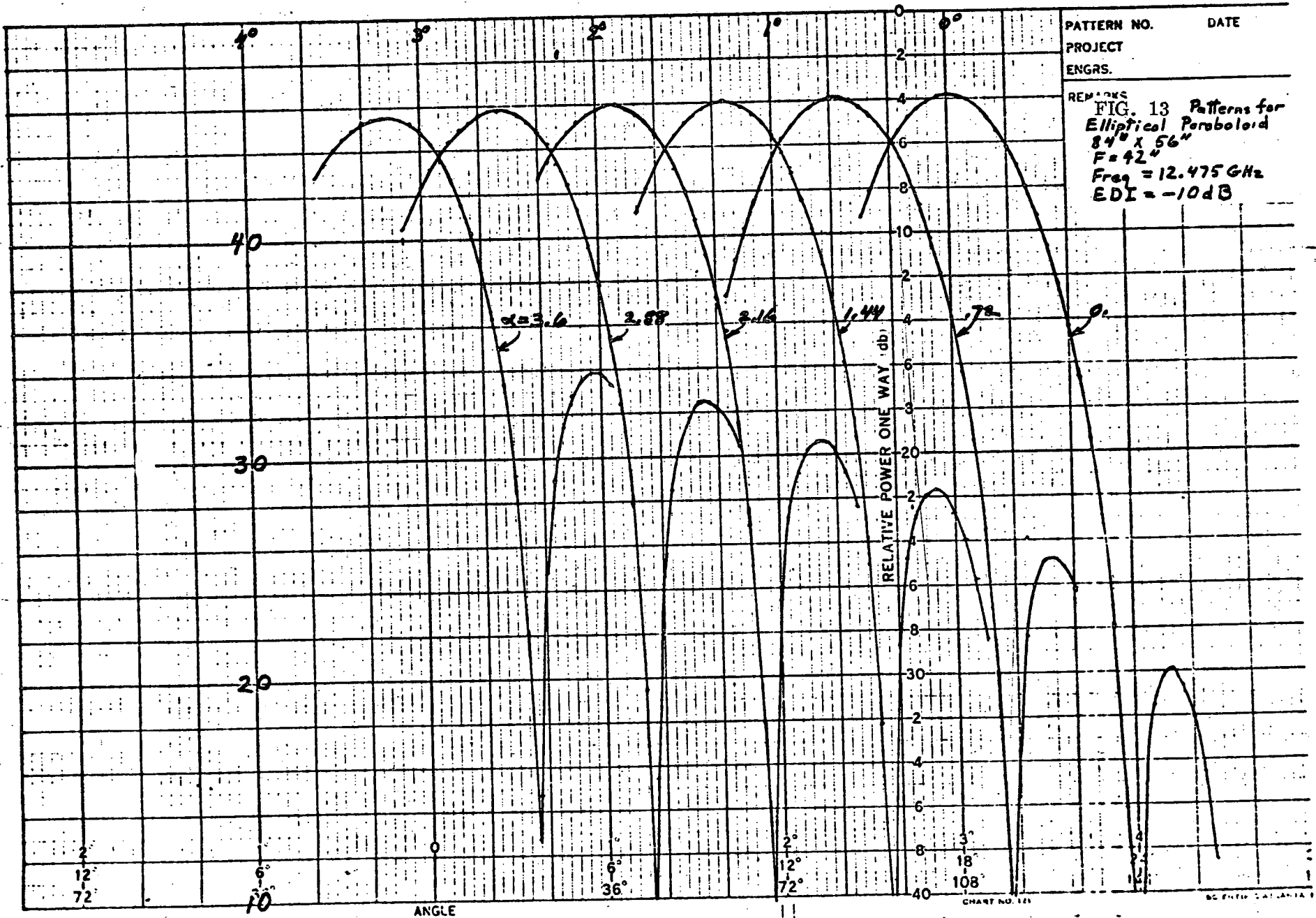
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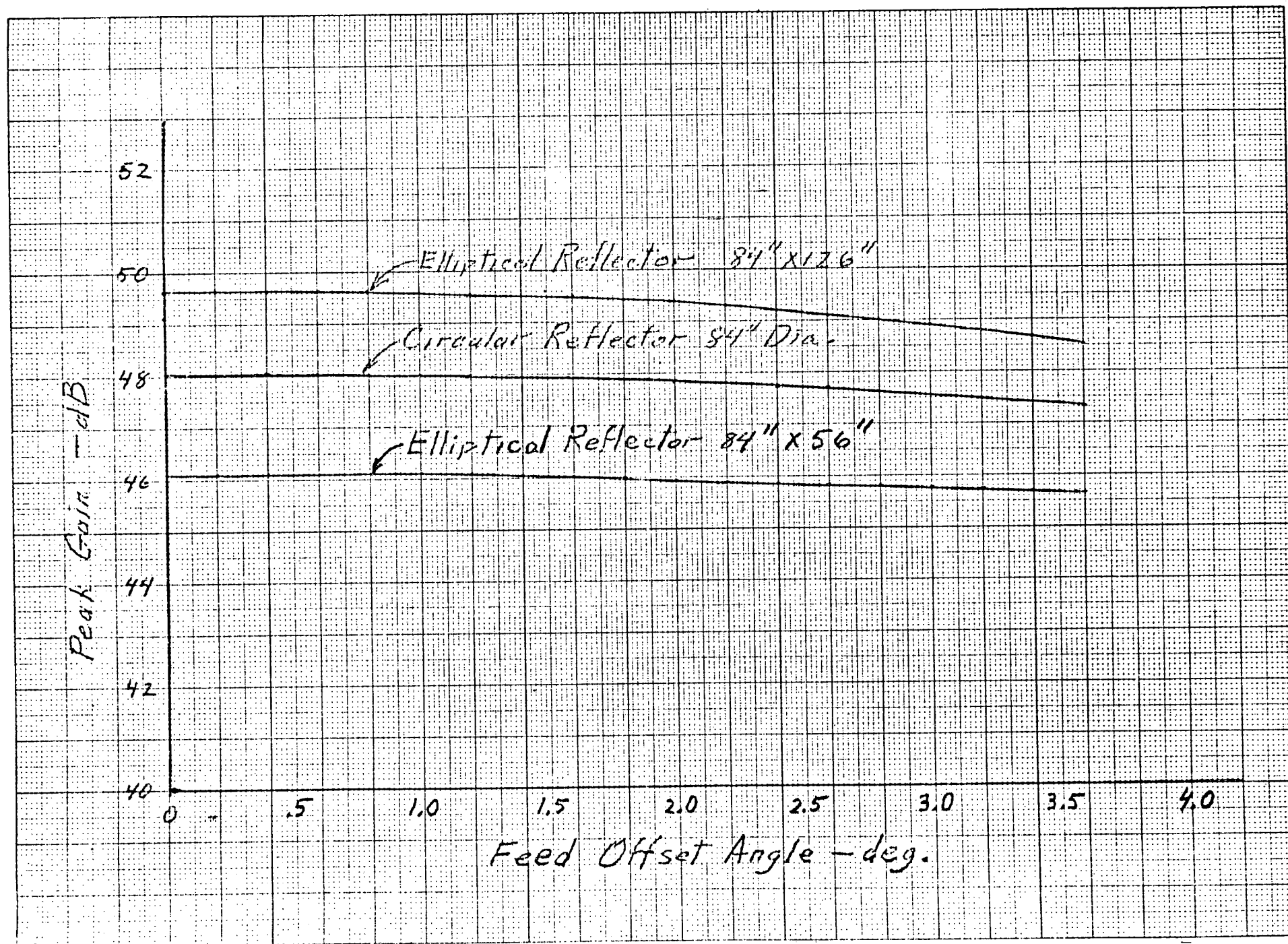
FIGURE 14   PEAK GAIN VS. FEED OFFSET ANGLE

The graph shows Relative Gain — dB (vertical axis, from 0 to -5) versus Feed Offset Angle — deg. (horizontal axis, from 0 to 4.0).

Curves labeled:
- Elliptical Reflector 84" X 56"
- Elliptical Reflector 84" X 126"
- Circular Reflector 84" Dia.

Freq = 12.475 GHz
Focal length = 42"
Edge (directed) illum. = -10 dB
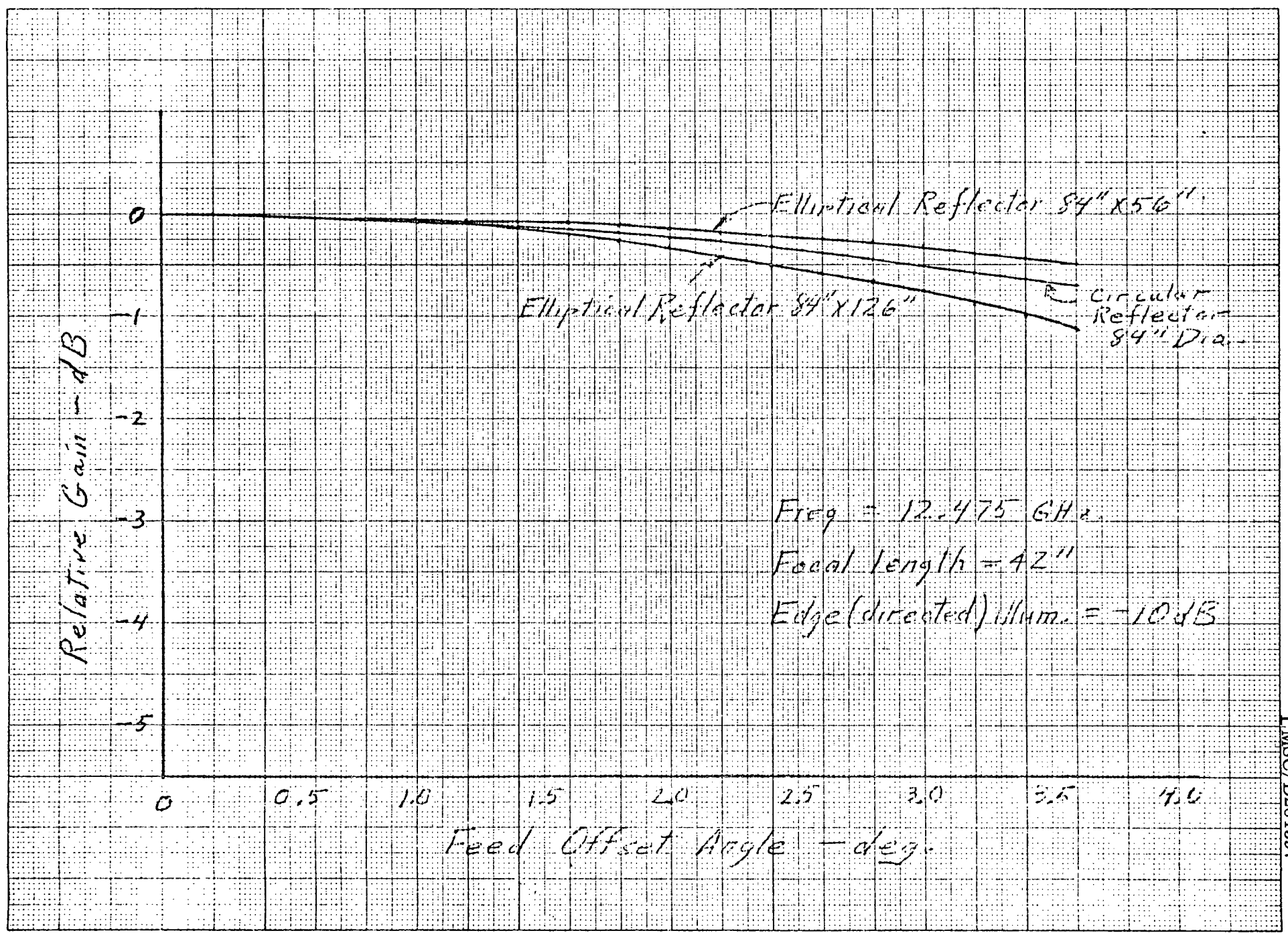
FIGURE 15   RELATIVE GAIN VS. FEED OFFSET ANGLE

Side Lobe Level ~dB (vertical axis)

Elliptical Reflector 84" x 56"

Circular Reflector 84" Dia.

Elliptical Reflector 84" x 126"

Circular Reflector 84" Dia., Second Lobe

Freq = 12.475 GHz.
Focal length = 42"
Edge (directed) illum. = -10 dB

Feed Offset Angle ~deg.

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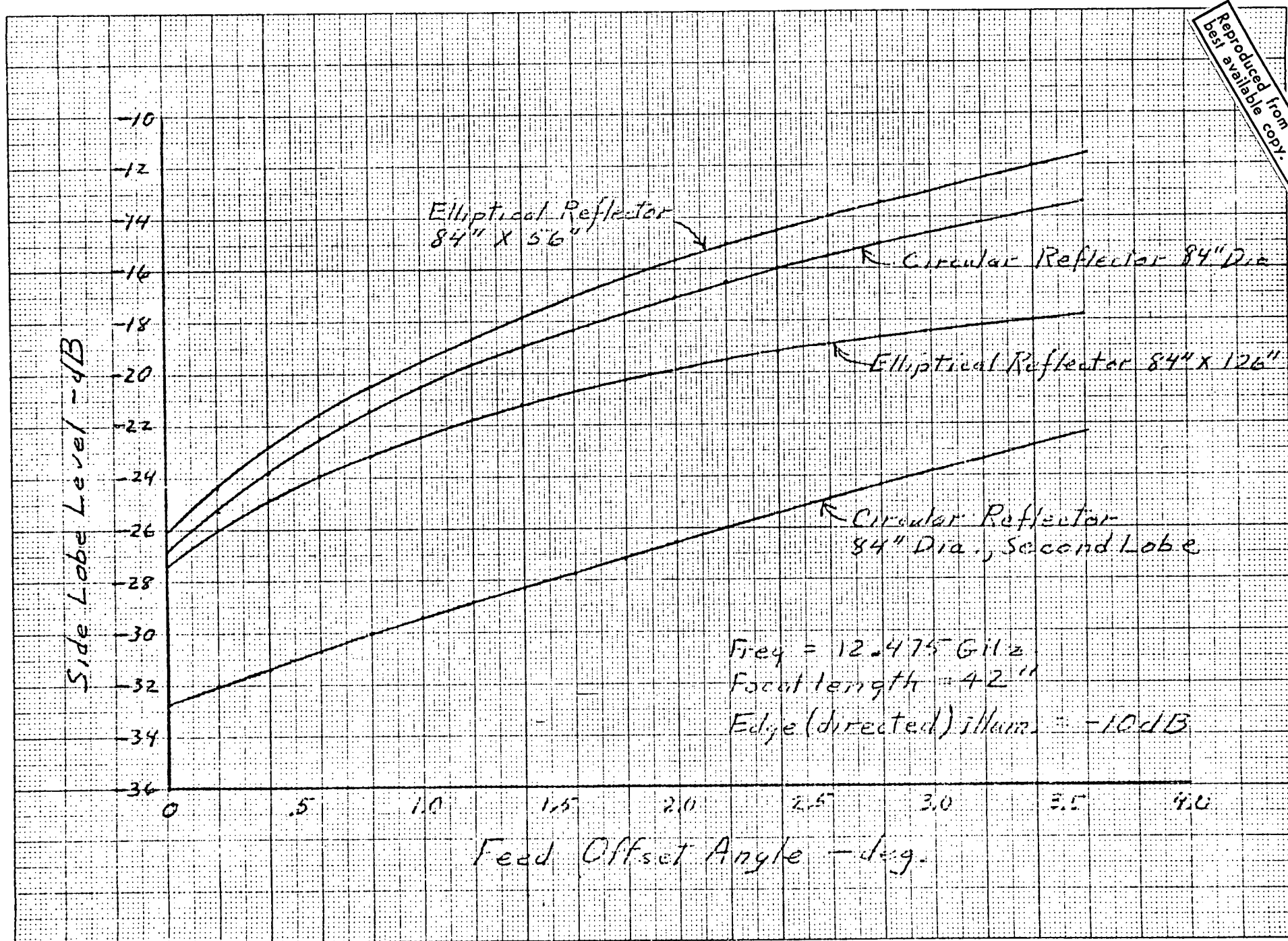
FIGURE 16   SIDE LOBE LEVEL VS. FEED OFFSET ANGLE

The fundamental conclusion then is that for practical purposes we can ignore the off-axis scan differences associated with elliptical apertures and assume they are substantially the same as those of a circular aperture. This is particularly true when it is remembered that all offsets are not in the plane of major and minor axes of the reflector aperture.

In an effort to determine how sensitive the coma lobe performance of the circular aperture paraboloid was to other parametric changes, we investigated the change for a 3.6 degree feed offset with varying focal length. The feed pattern was appropriately modified to provide a -10 dB edge directed illumination. The results are shown in Figures 17, 18 and 19 for an 84 inch reflector with focal lengths of 28, 63, and 84 inches respectively. It can be seen that while there is much variation in the first side lobe for the on-axis beam, the coma is still too high for our purposes at the extreme beam offset. Naturally, the degradation is less serious for the longer focal lengths. In the more detailed computations performed for the 42 inch focal length with both the circular and the elliptical apertures it was found that the first movement off the axis provides the most serious degradation of the coma lobe, with successive movements causing smaller and smaller increases in the coma lobe level.

In another effort to solve the coma problem we reduced the edge directed illumination to the -17 dB level. The result is shown in Figure 20. While the first side lobe for the on-axis case is below the -36 dB level, the coma reaches an unacceptable level at the extreme beam offset. With the more pronounced aperture illumination taper it was necessary to increase the aperture diameter to 93 inches to maintain the same beamwidth.

Spherical reflector patterns are shown in Figures 21 and 22. The pattern is, of course, symmetrical and the lobe and fill-in seen in the figures will appear all around the beam. For Figure 21 the pattern for an 84 inch aperture at

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FIG. 17 Patterns for
Circular Paraboloid
84" Dia.
F = 28"
Freq. = 12.475 GHz.
EDT = -10 dB

α = 3.6°

α = 0°

RELATIVE POWER ONE WAY (db)

ANGLE

LMSC/D28459

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FIG. 18 Patterns for Circular Paraboloid 84" Dia. F = 63" Freq = 12.475 GHz. EDI = -10dB

FIG. 19 Patterns for Circular Paraboloid 84" Dia. F=84" Freq = 12.475 GHz EDt = -10 dB

α=3.6°

α=0°

RELATIVE POWER ONE WAY (db)

ANGLE
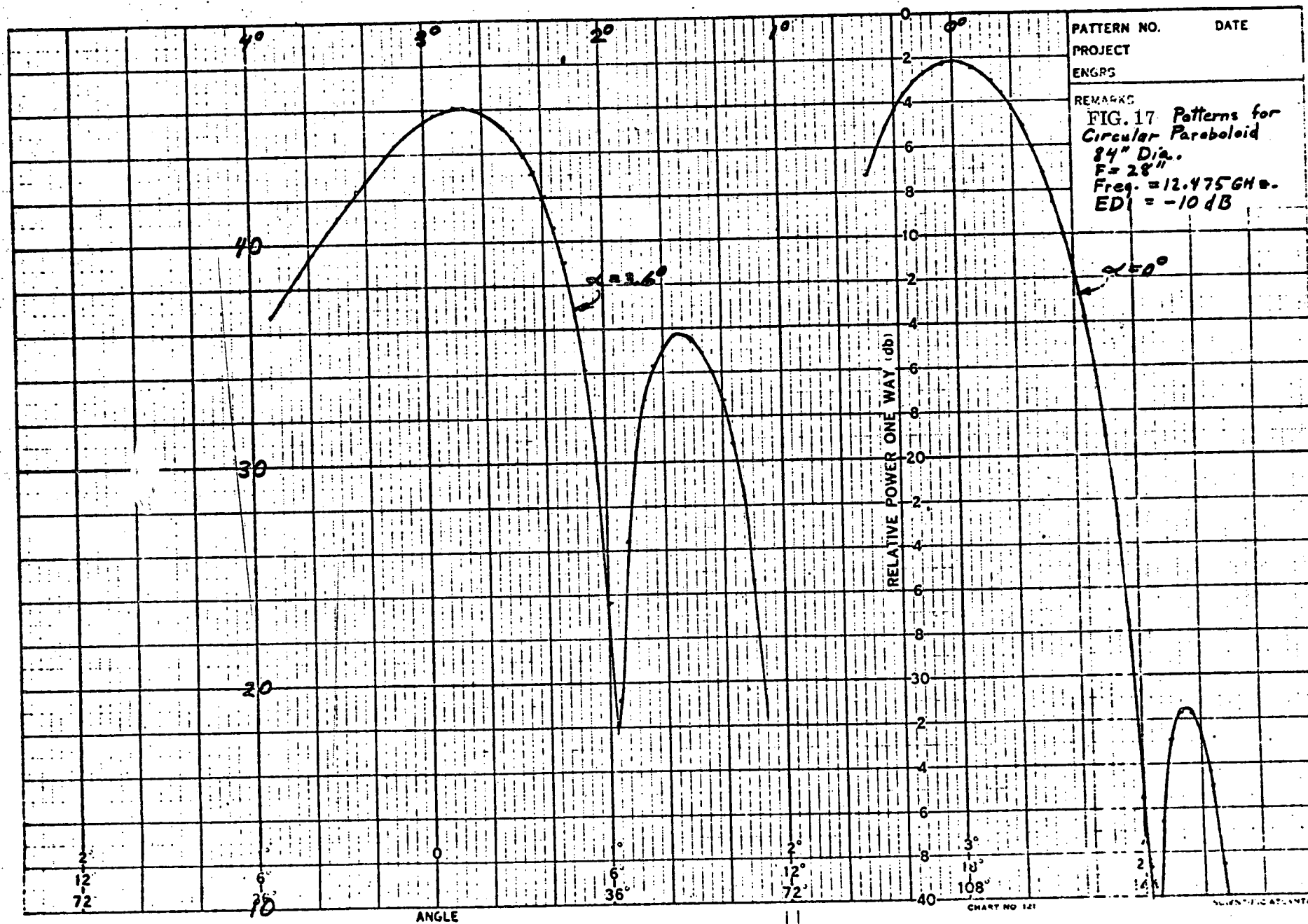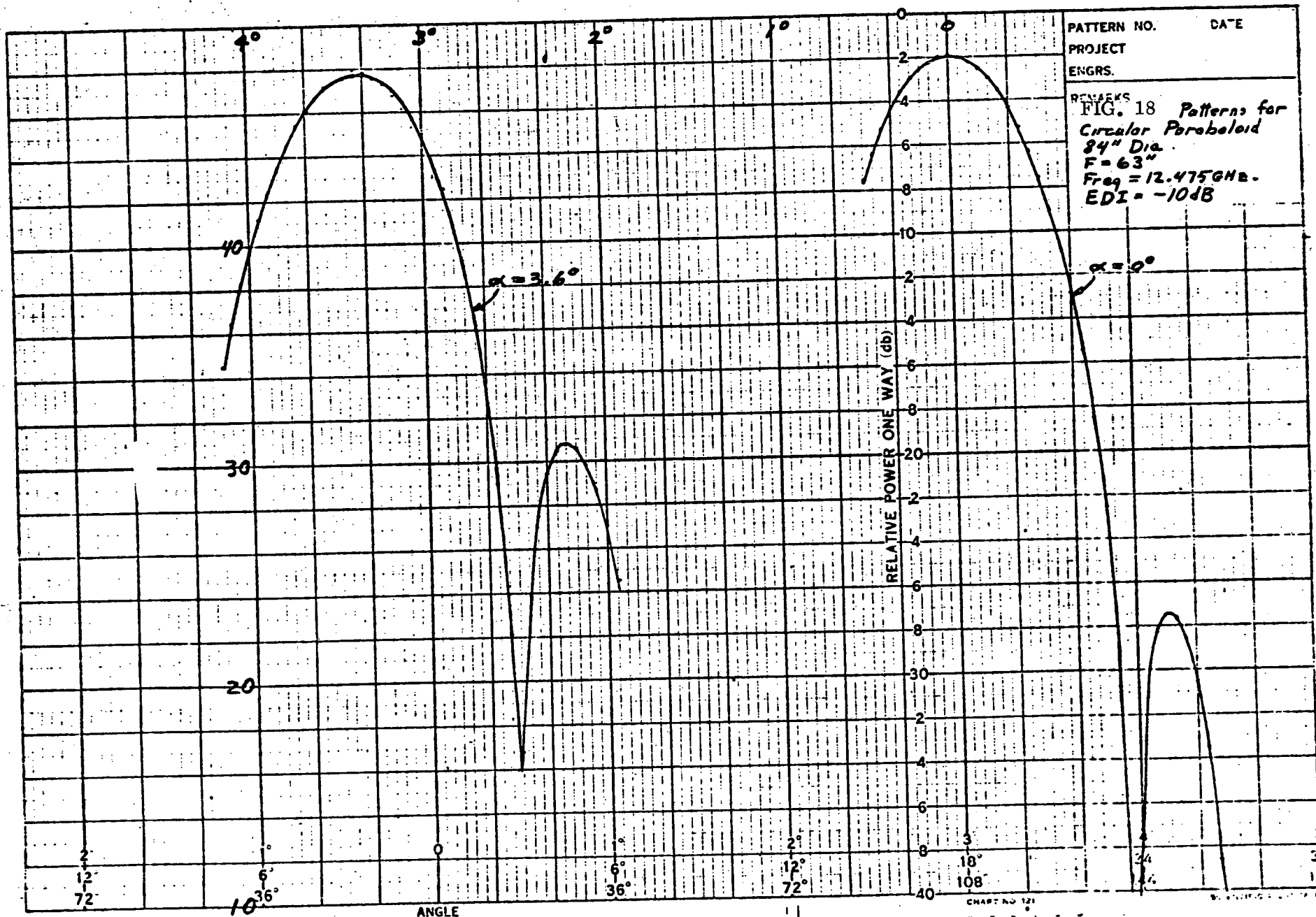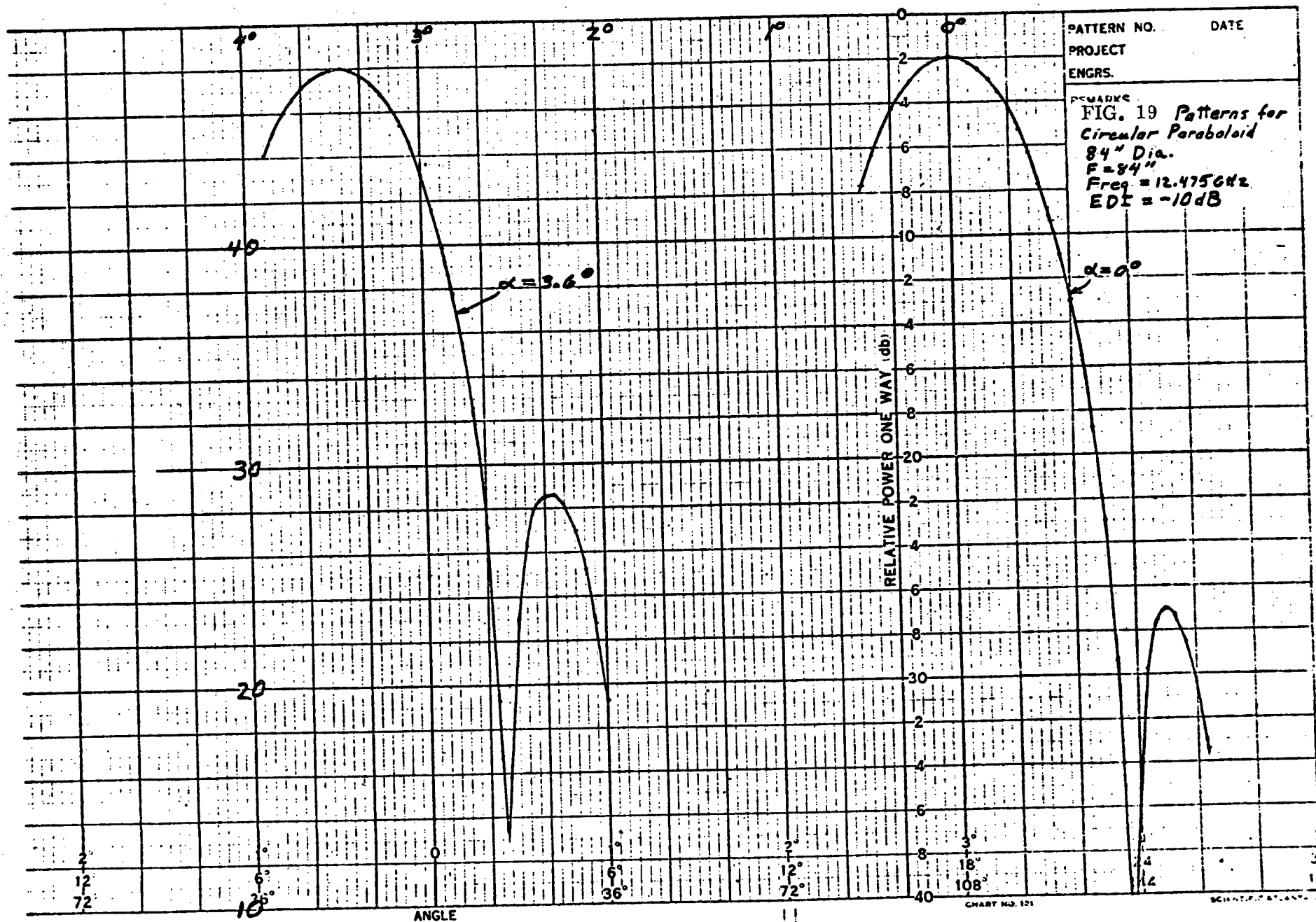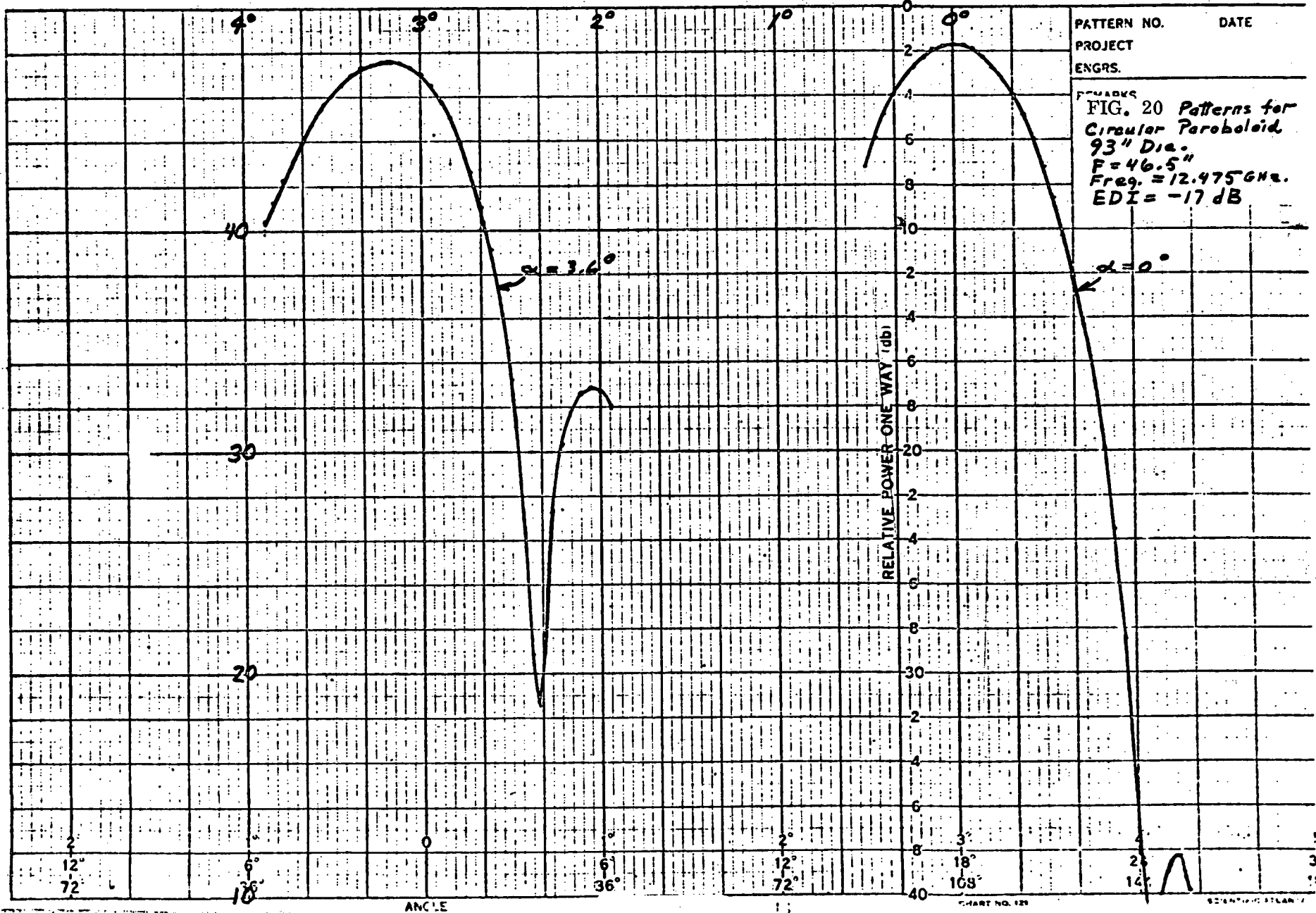
FIG. 20 Patterns for Circular Paraboloid 93" Dia. F=46.5" Freq. =12.475 GHz. EDI = -17 dB

α=3.6°

α=0°

RELATIVE POWER ONE WAY (db)

ANGLE

PATTERN NO.   DATE
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ANGLE

RELATIVE POWER ONE WAY (db)

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PROJECT
ENGRS
REMARKS

FIG. 21 Patterns for
Spherical Reflector
84" Dia.
84" Radius of Curvature
F = 39.6325"
Freq = 12.4756Hz

α = 3.6°

α = 0°
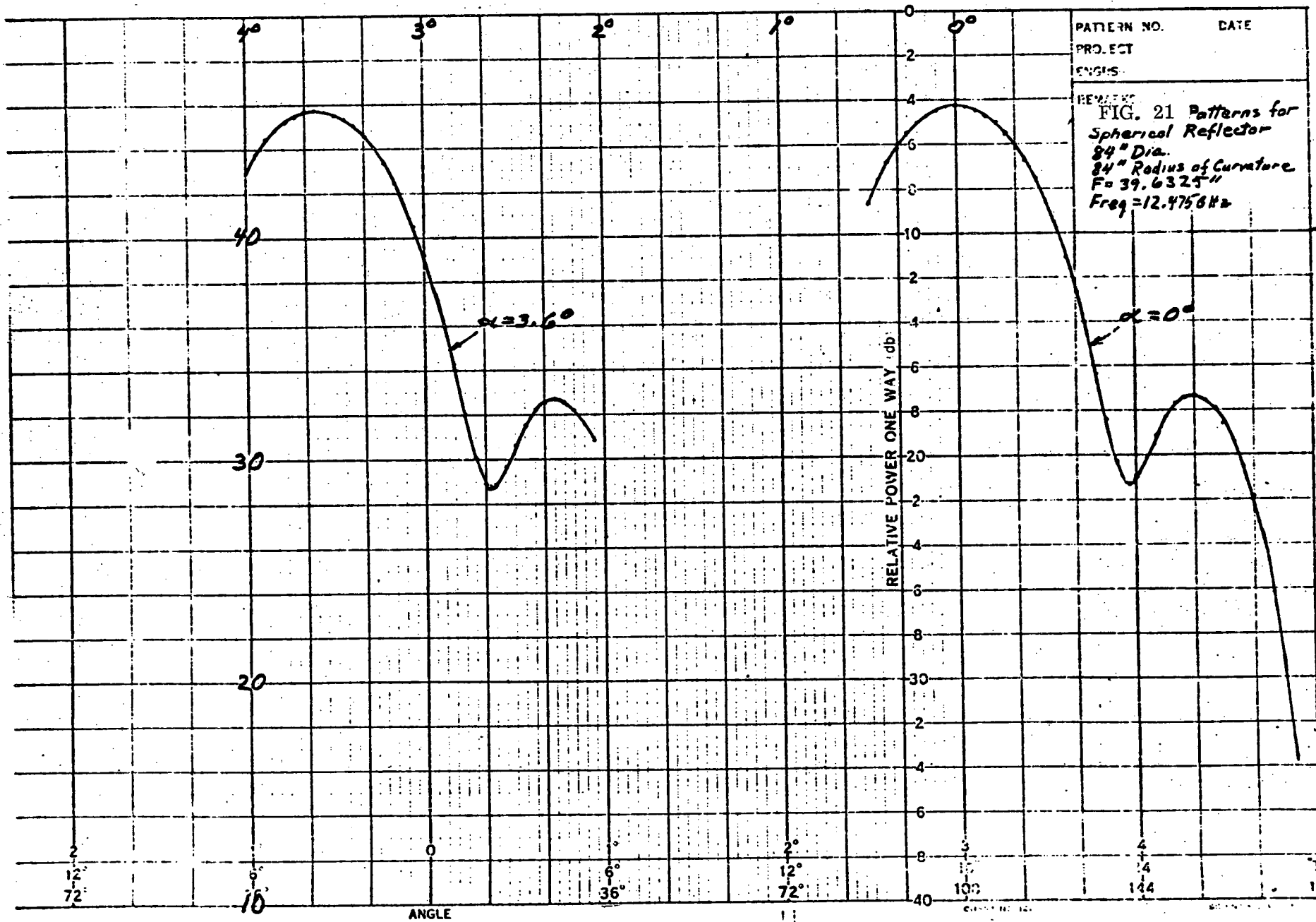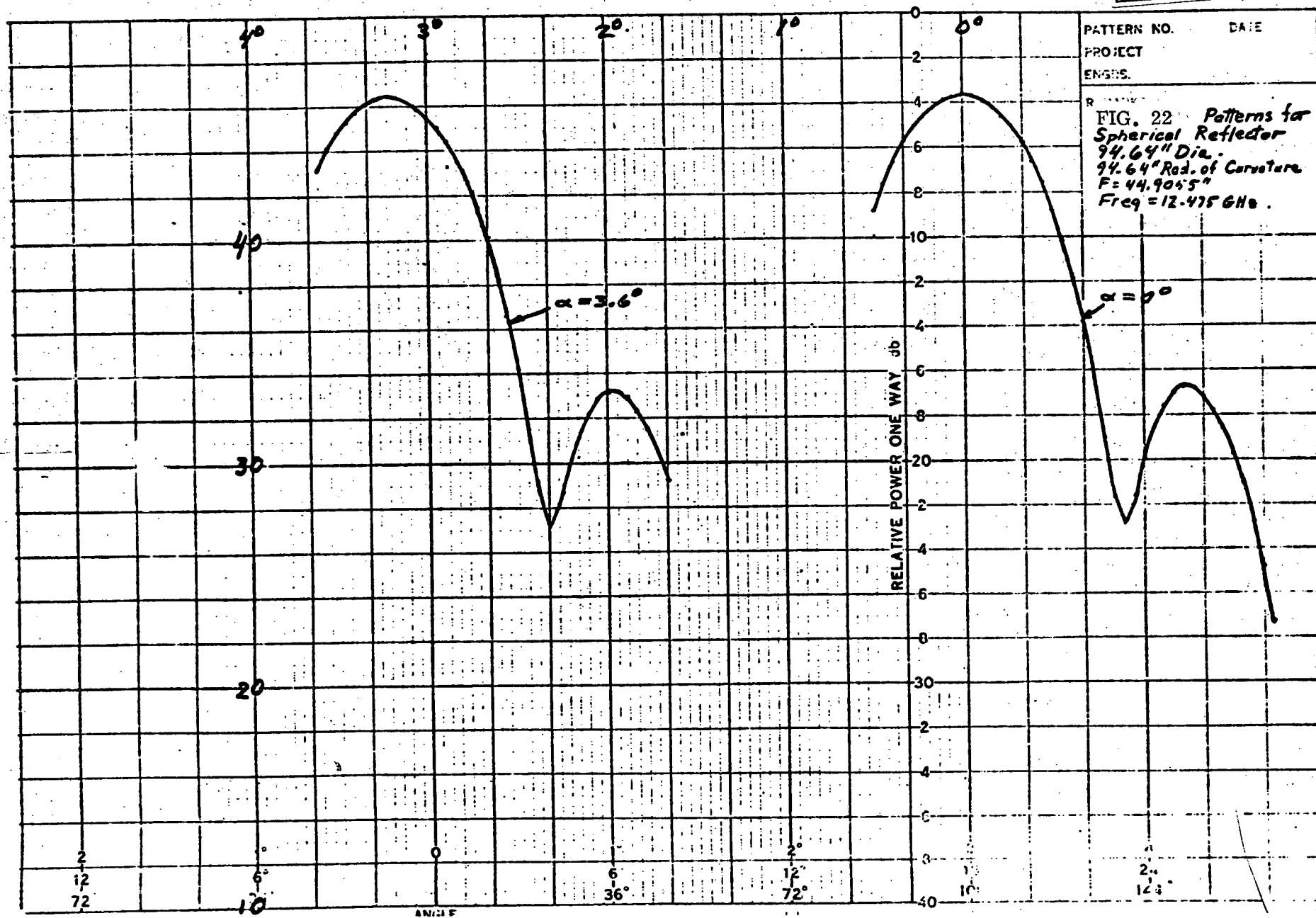
FIG. 22 Patterns for
Spherical Reflector
94.64" Dia.
94.64" Rad. of Curvature
F = 44.9055"
Freq = 12.475 GHz.

α = 3.6°

α = 0°

RELATIVE POWER ONE WAY, db

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12.475 GHz is shown. In Figure 22, the aperture diameter has been adjusted to 94.64 inches to obtain the same beamwidth obtained with a circular paraboloid.

These patterns indicate that the spherical reflector with an uncorrected feed is not an acceptable candidate for obtaining good beam-to-beam isolation. Correcting the feed for the aberrations of the reflector will make the system frequency sensitive.

To determine the beam-to-beam isolation attainable, we need to consider not only the level of the coma lobes and side lobes, but also their position and extent. In Figures 23 and 24 the patterns for one half of a symmetrical sector are shown. The beams and side lobes co-polarized with beam A are shown in Figure 23 and those co-polarized with the adjacent beam are shown in Figure 24. The cross-over level of adjacent beams is assumed to be -3 dB and the focal length-to-diameter ratio of the reflector is set at 0.5. Notice that the outboard skirts of the offset beams are distorted, in addition to the coma lobe problem appearing on the inboard side of the beam. This distortion causes some interference with co-polarized beams further outboard. Beams near the center are subject to lower levels of interference, but because there are more side lobes present there is a greater probability of interference occurring.

The beam-to-beam isolation resulting from the situation depicted in Figure 23 and Figure 24 is shown in Figure 25. Beam-to-beam isolation is found by taking the relative level of the highest interfering lobe at any given angle. Edge beams have better isolation because there are no lobes beyond them to cause coma lobe interference. The interference for the edge beams comes from the distortion of the outboard skirts of interior beams. Beginning with Sector C we see the effect of the coma lobe on beam-to-beam isolation; the coma lobes appear at the outboard cross-over region in each sector from there to the axis.

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Fig 23
-3 dB cross over
Lobes co-polarized
with beam A
f/D = .5
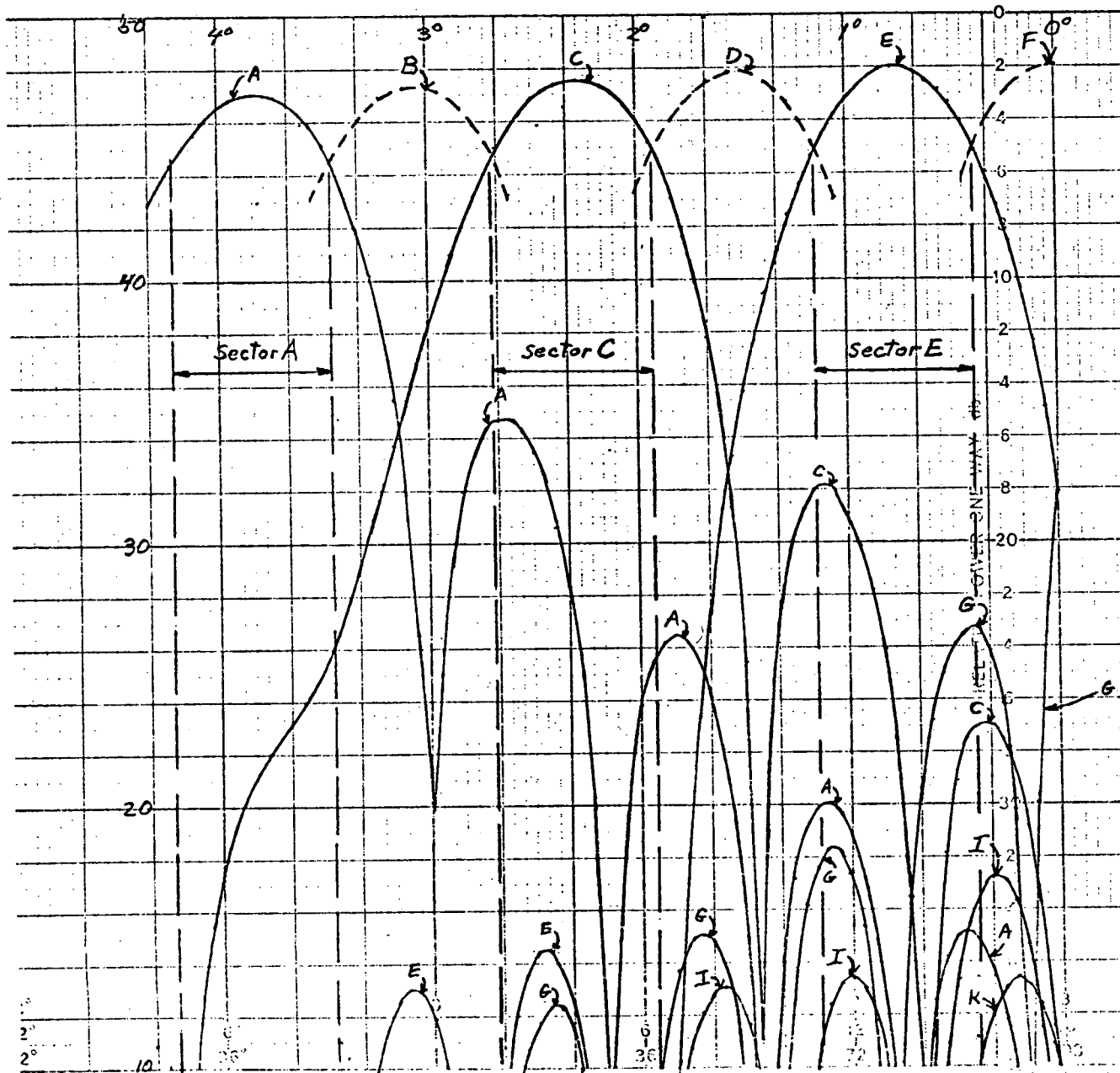
FIG. 24
-3 dB crossover
Lobes copolarized
with beam B
f/D = .5

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PROJECT
ENGRS.
REMARKS FIG. 25
Beam-to-beam
        isolation
-3 dB crossover
f/D = .5

Sector A   Sector B   Sector C   Sector D   Sector E   Sector F

RELATIVE POWER ONE WAY db

ANGLE
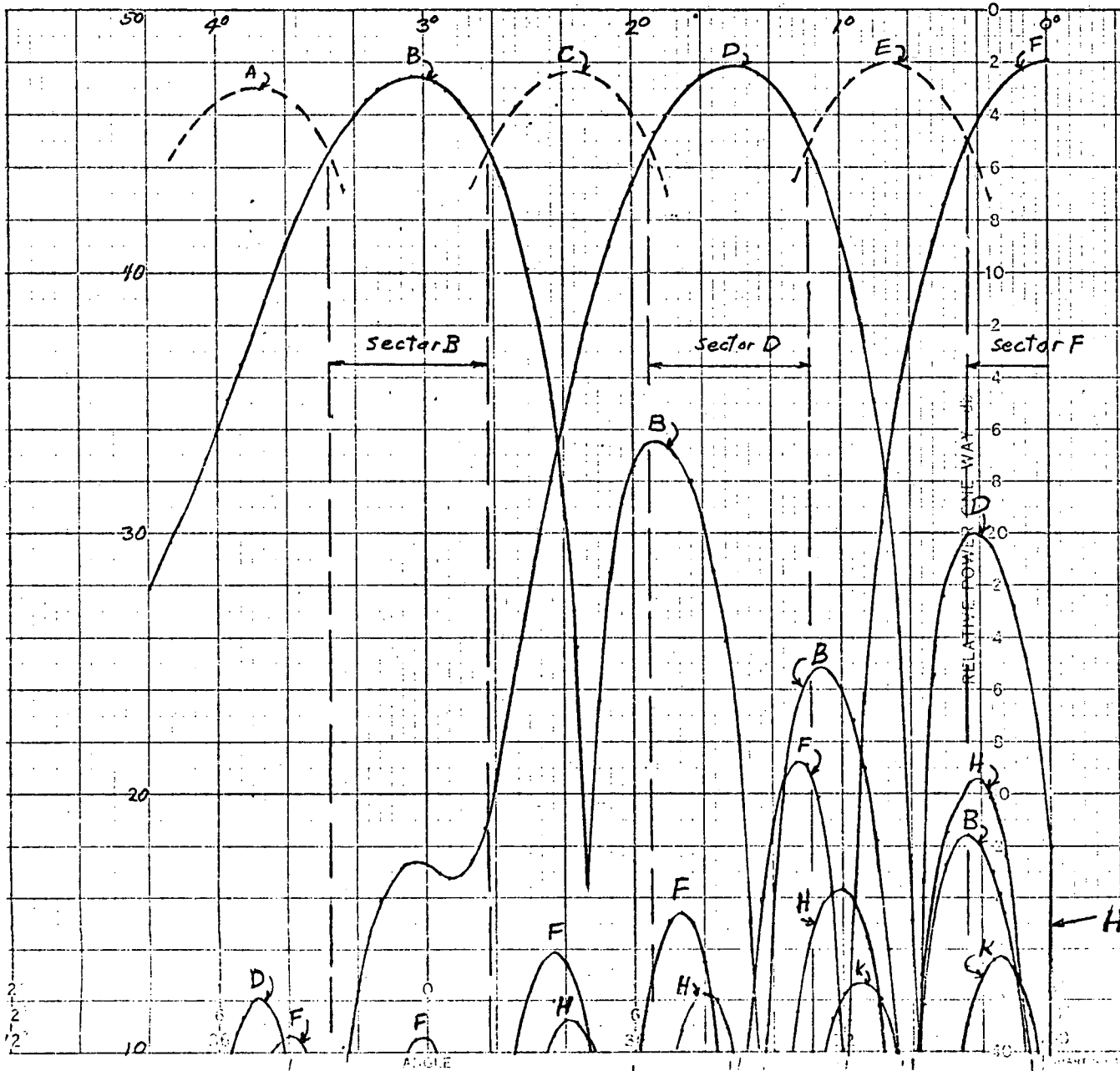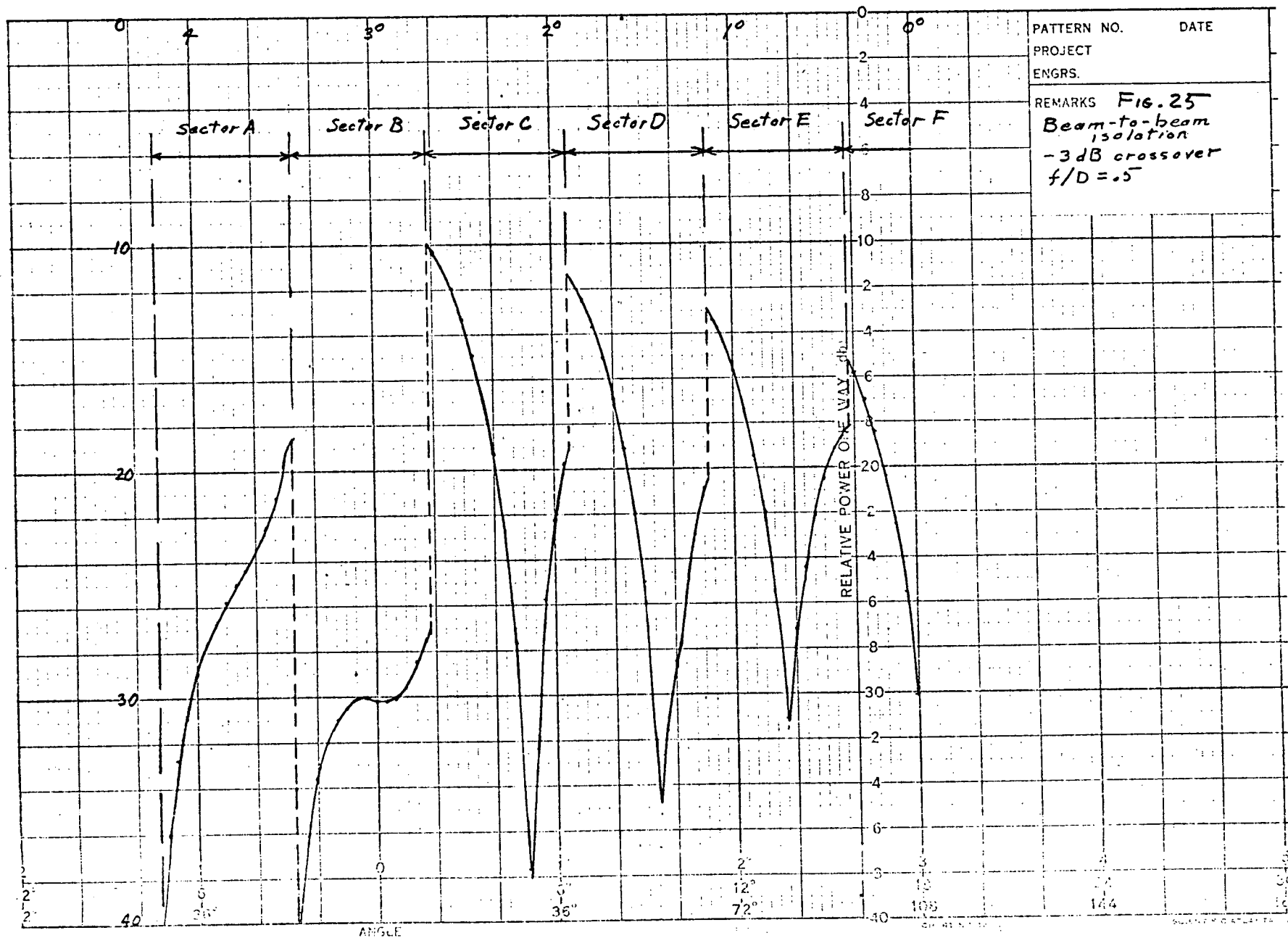
The effect of reducing the cross-over level to -5 dB is shown in Figure 26 for the same f/D ratio. The effect of the coma lobes has been reduced, but the second side lobe begins to have more of an effect. Generally, isolation has been improved at the expense of coverage.

To attempt to achieve 30 dB isolation the patterns were recalculated with the focal length-to-diameter ratio adjusted to 1.0. The isolation for the -3 dB cross-over case is shown in Figure 27. It is difficult to say whether isolation has been improved over the case shown in Figure 26 when both extent and level of interference are considered. The improvement over the shorter focal length case for the same crossover level is obvious, however.

Finally, in Figure 28 the case for a -5 dB crossover level and an f/D ratio of 1.0 is shown. Except for limited areas the isolation is almost 30 dB. This improvement is obtained at the expense of coverage. This particular case appears almost good enough to be considered, not as meeting the isolation Want, but as coming close to satisfying it. It must be remembered, however, that the theoretical patterns shown here should be degraded by a few dB to account for the problems encountered when one attempts to reproduce these results in a practical antenna. The very long focal length requires larger feeds and thus more blockage to spoil the results theory predicts. We cannot count on these side lobes being at theoretical levels or even at the predicted positions. The isolation is particularly sensitive to coma lobe position since the spikes in Figure 28 are the skirts of coma lobes.

Generally, it was concluded that none of the reflector approaches offer strong promise for achieving a 30 dB beam-to-beam isolation. A 20 dB isolation figure could probably be attained. Should a reflector approach be selected, it would be necessary to in effect "pull out all the stops" to achieve good beam-to-beam isolation. This means that we would have to use long focal lengths and strongly tapered aperture distributions and would have to design for lower cross-over

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LOCKHEED MISSILES & SPACE COMPANY

Sector A   Sector B   Sector C   Sector D   Sector E

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ENGRS.
REMARKS   *Fig. 26*
Beam-to-beam
   isolation
-5 dB crossover
f/D = .5

RELATIVE POWER ONE WAY (db)

0°   4°   3°   2°   1°   0°   0°
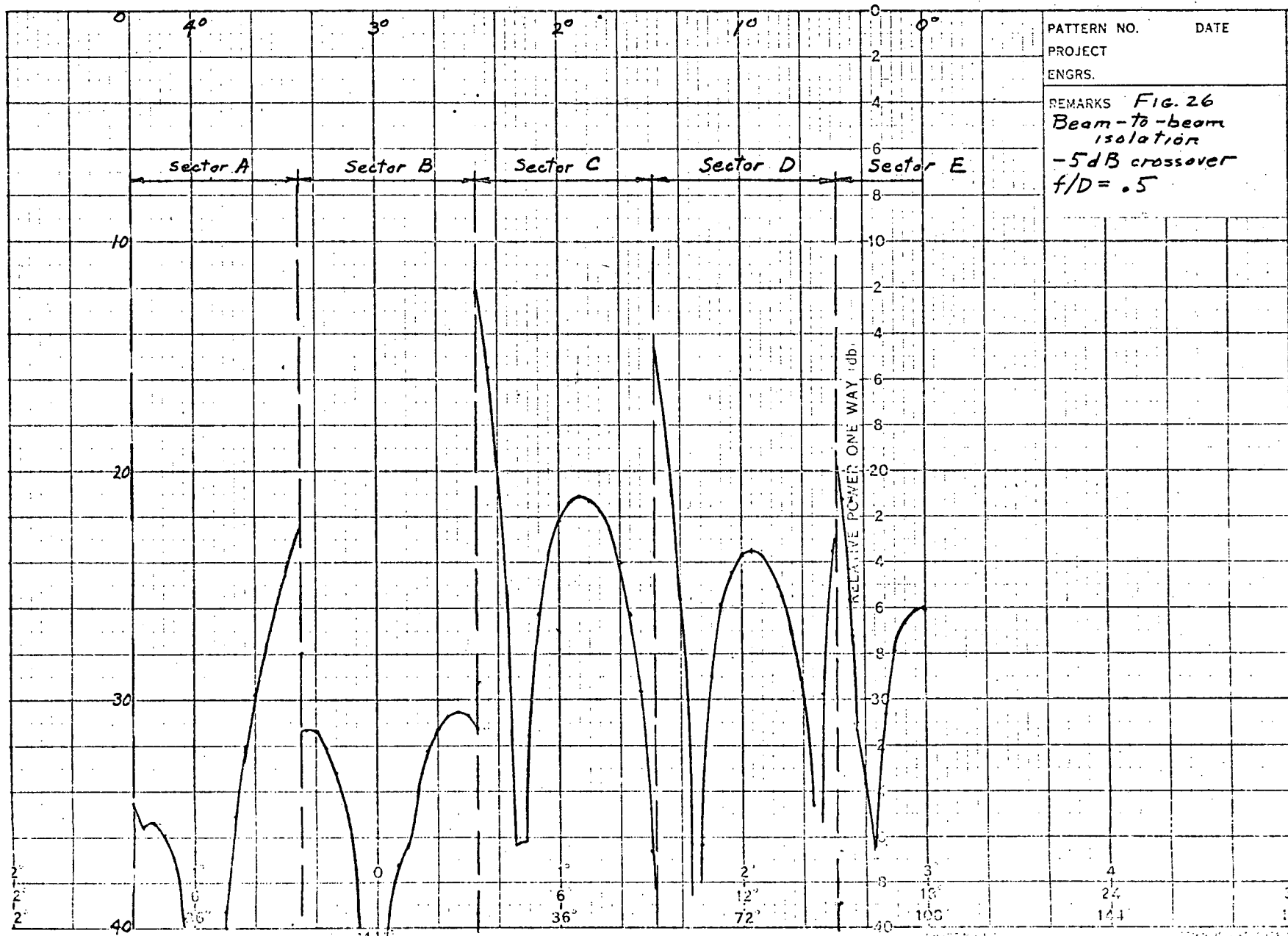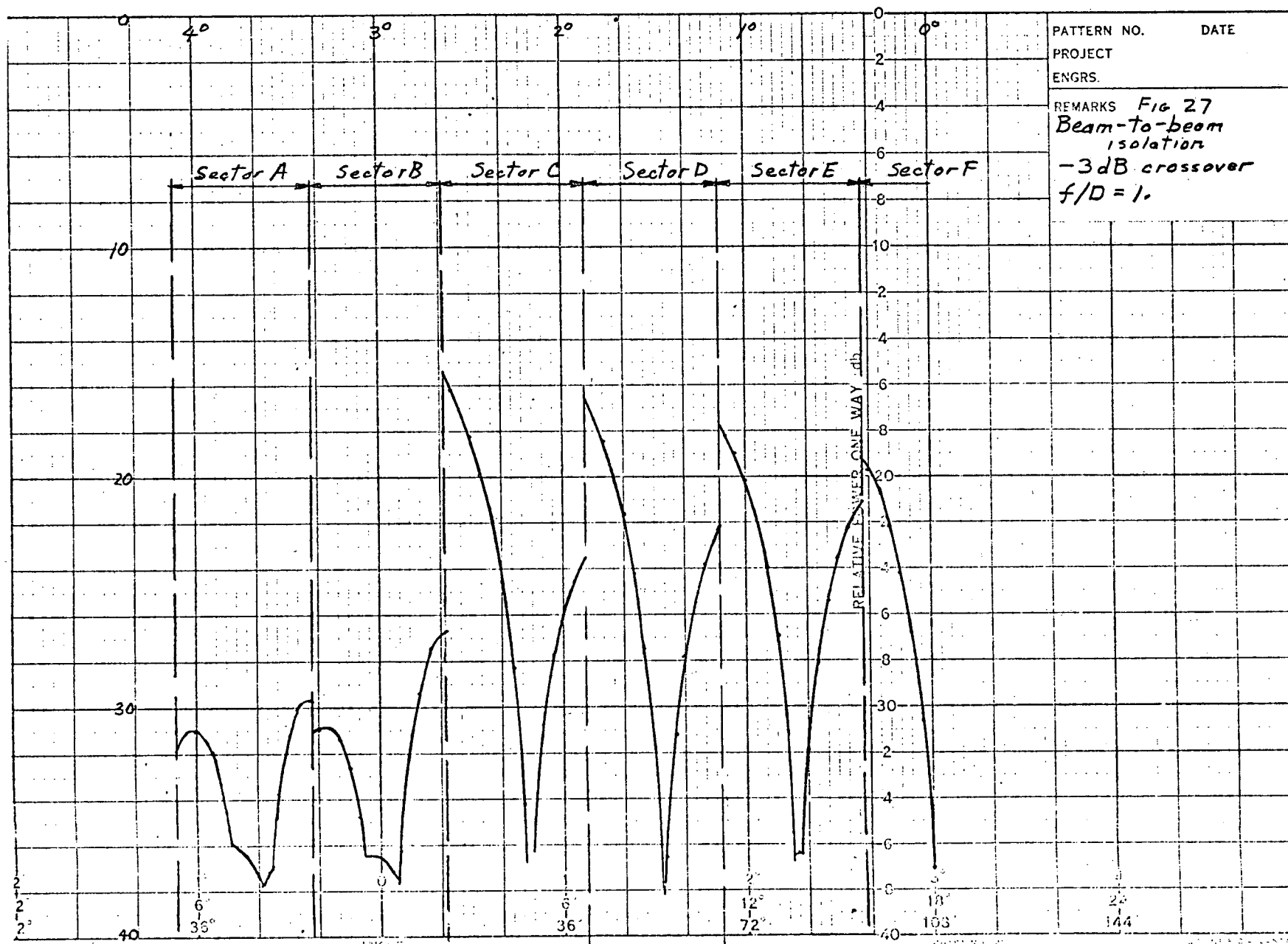
PATTERN NO.	DATE
PROJECT	
ENGRS.	

REMARKS *FIG 27*
Beam-to-beam
isolation
−3 dB crossover
f/D = 1.

Sector A   Sector B   Sector C   Sector D   Sector E   Sector F

0
10
20
30
40

RELATIVE POWER ONE WAY db

6°   6°   12°   18°   2?°
36°   36   72°   108   144

Fig. 28 Beam-To-beam isolation -5 dB crossover f/D = 1.
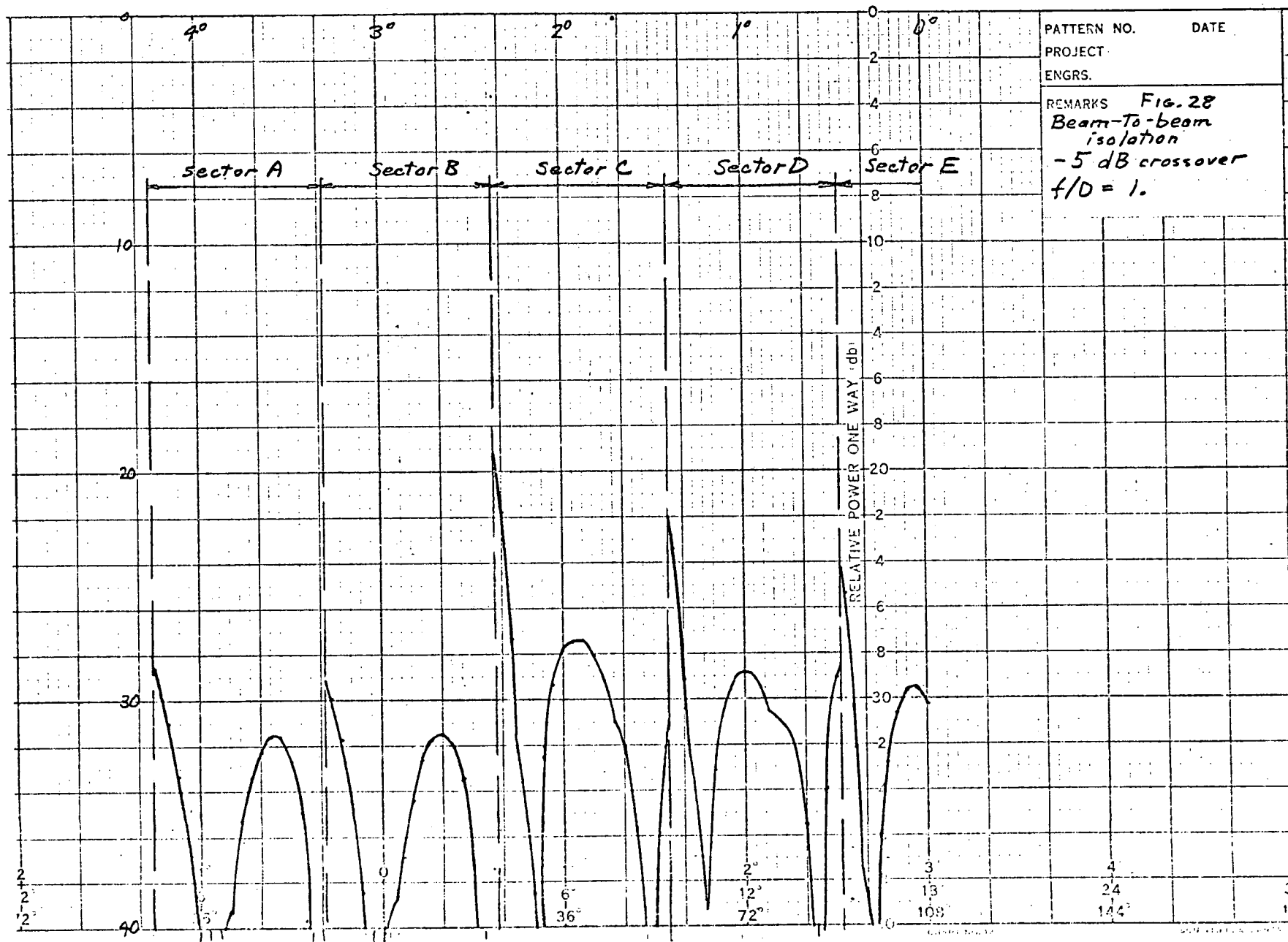
levels to trade coverage for isolation. Even though the offsets required are small for this case, the coma lobe problem is quite serious in view of the 30 dB isolation goal.

It was not possible to perform a similar analysis for lenses, due to the fact that analytical methods for predicting lens pattern performance need some development. The results of this study on reflectors, however, would indicate that the lenses will occupy a favorable position in the final standings because they offer possibilities of correcting for coma which has turned out to be a serious problem even for small offsets. We can achieve improvement in isolation by increasing the focal length, but on a reflector we cannot carry this to an extreme without seriously blocking the aperture. In the lens we could achieve longer focal lengths if we can solve the feed design problems. So while we have not settled the question of whether to use a long focal length, uncorrected lens or a moderate focal length lens with coma-correction, it seems that some kind of lens will provide better isolation.

6.0   STEP II DECISION ANALYSIS

6.1   The Criteria of Comparison

At the meeting held with the NASA GSFC Technical Monitor at LMSC on August 3, 1972, the Wants used in the Decision Analysis Process were discussed and some modifications were made. These decisions will be discussed in detail here.

Want #5: Maximize Beam-to-Beam Isolation

In the Step I analysis this Want had a weighting of 10. In discussing this Want in preparation for the Step II analysis, general agreement was reached that this is the single most important Want and that other Wants should be derated in comparison. The intended application will likely have high traffic volume with many users accessing the system at any one time. In such situations a candidate system which does not provide adequate beam isolation is really no good at all. If there is high traffic and poor isolation, there will be a large amount of interference between users and there is no other solution to this problem except to use different communications channels which limits the number of users.

The same is not true of the two other performance characteristics referred to in the Want list. If efficiency of the antenna system is lower than we desire or if the coverage patterns have areas where inadequate gain is provided on ground, we may increase transmitter power on the satellite or use larger antennas at the ground terminals. Admittedly, it is not desirable to do either of these things but they are solutions. With low traffic density, interference would be a probability situation and a user experiencing difficulty could conceivably arrange to use another channel. With high traffic density, however, other channels will not generally be available and there is consequently no solution to the interference problem except to provide good isolation in the antenna patterns in the first place.

Thus, because this is critical to providing high traffic volume, the beam-to-beam isolation Want was considered to be the most important factor in the evaluation.

Want #5: Minimize Inadequate Gain Areas

This Want relates to the uniformity of coverage within the 48 contiguous states. A correlated Must establishes that all areas within the contiguous 48 states must be covered at a level not more than 10 dB below the peak gain. This Want is to minimize those areas where the gain is between 6 and 10 dB below the peak gain.

In the Step I analysis, this Want had a weighting of 10. Because it appeared that the beam-to-beam isolation Want was critical, this Want was reduced in weighting to 9 for the Step II analysis to place more emphasis on the isolation Want.

Want #6: Maximize the Number of Users

Satisfaction of this Want depends on the number of beams provided and the arrangement of the beams within the service area. In determining the number of users for this Want, worst case conditions are assumed so that the same communications channels cannot be used on adjacent co-polarized beams. This Want was reduced in weighting from 8 in the Step I analysis to 6 in the Step II analysis to reflect the increase in importance attached to the beam isolation Want.

Want #8: Minimize Complexity

This Want was reduced from a weighting of 7 in the Step I analysis to 5 in the Step II analysis to reflect the increased importance attached to the beam isolation Want.

Want #9: Minimize Weight

This Want was reduced in weighting from 5 in the Step I analysis to 3 in the Step II analysis to reflect the increased importance attached to the beam isolation Want.

Want #7: Maximize Overall Efficiency

This Want relates to the absolute gain level provided over the service area. The efficiency is to be maximized in relation to the gain obtained when a fixed beamwidth is provided and not to the gain obtained in terms of the aperture used.

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This Want was weighted 3 in the Step 1 analysis and it was decided to retain this weighting in the Step II analysis. Reduced gain may impact satellite system design by requiring a larger transmitter, greater power consumption and more weight. Or it may impact the design of ground terminals by requiring larger ground antennas or more sophisticated transmitting and receiving systems. Poorer satellite antenna gain performance tends to work against the important objective in future systems of being able to service small user terminals on the ground.

Therefore, this Want retained its original weighting of 3 because of the importance of having high link gain.

Want #3: Minimize Spillover

This Want relates to the ability to confine the radiation to within the geographical service area without spilling over into foreign countries. On reconsideration of this Want it was decided that inclusion of this Want in the analysis would not aid in separating the candidate systems. All candidates have relatively the same ability to isolate foreign countries. There are some differences in aperture size, but as a practical matter the differences are insignificant when measured against the effectiveness of suppression of unwanted radiation in terms of population (particularly with respect to Canada). The solution of the international problem appears to be in obtaining international cooperation in the selection of polarization and frequency bands. Therefore, this Want was eliminated from the Step II and all subsequent analyses.

Want #2: Provide Coverage of Hawaii

Want #1: Provide Coverage of Alaska

These two Wants, originally weighted at 2 each, were combined into a single Want with a weighting of 1. Having these as separate Wants effectively doubles the importance attached to the capability of covering remote areas with additional feeds. In view of the increased importance attached to the beam

isolation Want, combining these two Wants and reducing the weighting to 1 seems justified.

Want #10: Provide Growth to More Beams

The objective of including this Want in the Step II analysis is to consider growth possibilities during the selection process so that we would not select a candidate system solely on its capabilities to meet current needs without giving some consideration to growth possibilities. It was decided, however, that this could better be accomplished, if necessary, by considering the inability to extrapolate a candidate system to a "more-beam, more-user" configuration as a possible adverse consequence. Therefore, this Want was eliminated from the Step II and subsequent analyses.

These modifications to the Want List were made with the aid and consent of the technical monitor. The revised Want list is as follows:

#	Want	Weighting
5.	Maximize Beam-to Beam Isolation	10
4.	Minimize Inadequate Gain Areas	9
6.	Maximize Number of Users	6
8.	Minimize Complexity	5
9.	Minimize Weight	3
7.	Maximize Overall Efficiency	3
2.	Provide Coverage of Hawaii and Alaska	1

6.2 Candidate Antenna Concepts

As a result of the Step I analysis performed during the month of June, the original list of forty-eight candidate antenna systems was reduced to fifteen candidates to be reevaluated in the Step II analysis. This list, with relative ranking from the Step I analysis, is as follows:

1. Elliptical Paraboloid (2 Antennas, V-B)

2. Circular Paraboloid (2 Antennas, I-B)

3. Elliptical Paraboloid (1 Antenna, V-A)

4. Circular Artificial Dielectric Lens (2 Antennas, III-B)

5. Circular Waveguide Lens (2 Antennas, IV-B)

6. Circular Artificial Dielectric Lens (1 Antenna, III-A)

7. Circular Paraboloid (1 Antenna, I-A)

8. Circular Waveguide Lens (1 Antenna, IV-A)

9. Spherical Reflector (2 Antennas, VI-B)

10. Spherical Reflector (1 Antenna, VI-A)

11. Elliptical Paraboloid (4 Antennas, V-C)

12. Circular Paraboloid (4 Antennas, I-C)

13. Circular Artificial Dielectric Lens (4 Antennas, III-C)

14. Circular Waveguide Lens (4 Antennas, IV-C)

15. Spherical Reflector (4 Antennas, VI-C)

Originally we had given some thought to expanding the candidate antenna list to include variations in aperture size or shape for all of the basic types and to include several different beam arrangements, such as a 15 beam and a 25 beam case. Attempting to do so with 15 candidates in the basic list resulted in a list of more than forty candidate systems to evaluate. This would have hindered our efforts to make the Step II analysis on a more precise and detailed basis. Accordingly, we decided to perform the Step II analysis on the 15 candidates which survived the Step I analysis and to consider parametric variations of the basic types only in the Step III analyses.

Originally, in the Step I analysis we used the ground rule that in going from one antenna to two antennas we would divide the beams between the two antennas so that all beams of one polarization were on one antenna and those of the

complementary or orthogonal polarization were on the other. This ground rule was retained for the Step II analysis. On the other hand in the Step I analysis we used the ground rule that the beams of each polarization of the two antenna case would be divided between two antennas so that maximum separation of beams within a given antenna would occur. The objective here was to reduce mutual interaction of feeds so that better performance could be obtained. In making the studies of comparative off-axis performance in preparation for the Step II analysis, it became apparent that it was more appropriate to divide the beams among the four antennas into two polarizations and into East and West service areas. This minimized the offset required and would therefore contribute to better beam-to-beam isolation. Thus, using the 18 beam model we used in the Step I analysis, the beam assignment shown in Figure 29-a was considered a possible alternative to the beam assignment used in Step I for the 4 antenna case. The latter is shown in Figure 29-b. Solid and dashed circles indicate different polarizations and the numbers indicate the different antennas in the four antenna case.

6.3   Beam Arrangements

During the Step II analysis a study was made of beam arrangements which could be used to cover the service area. These beam arrangements are applicable to any of the fifteen remaining candidate antennas of the Step II analysis. Two configurations evolved as having appropriate coverage, one a 23-beam arrangement with each beam being circular and the other a 16-beam arrangement with each beam having an elliptical cross-section of aspect ratio 1.29:1 with the major axis aligned in the north-south direction. Four, six and eight dB contours of the 16-beam case are shown in Figure 1 through Figure 3 and corresponding contours for the 23-beam case are shown in Figure 4 through Figure 6.
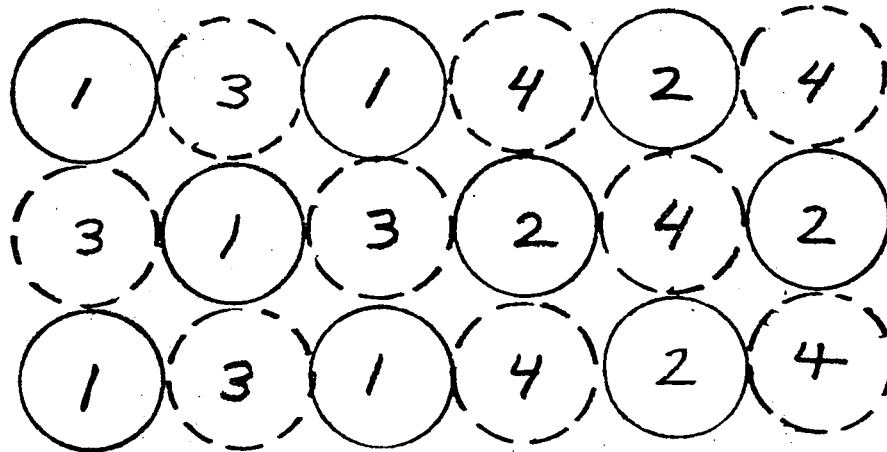
FIG. 29a   Four Antenna Case - Beam Assignment to
            Minimize Offset.
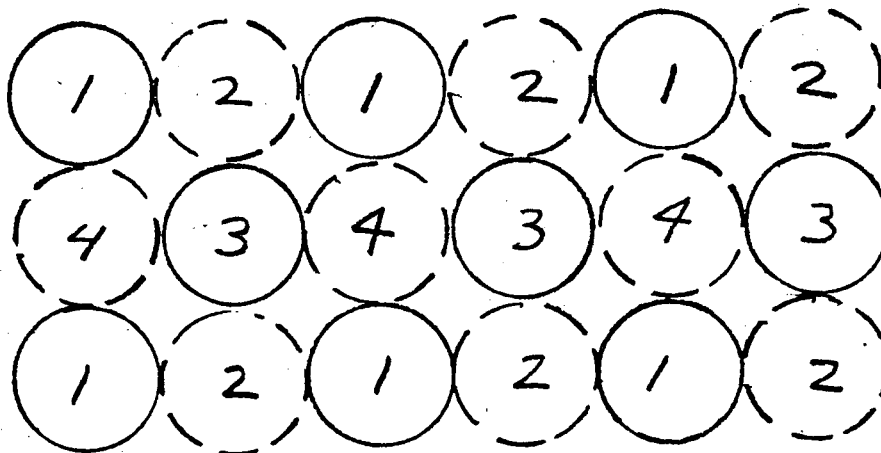
FIG. 29b   Four Antenna Case - Beam Assignment to
            Maximize Feed Spacing.

In carrying out the Step II analysis we did not double the number of candidates so that each antenna concept had a 16 and a 23 beam case. We dealt instead with generic types which could be adapted to either the 16 or 23 beam configuration. The beam arrangements shown in the accompanying figures were used in analyzing beam-to-beam isolation characteristics, since position of coma and side lobes with respect to co-polarized beams is important.

We did not recompute the beam footprints for the two-antenna cases where higher cross-over level is obtained. For the two-antenna cases, the same plots can be used except that the -4, -6, and -8 dB contours should be read as the -2, -4, and -6 dB contours respectively. This was sufficiently accurate for the purposes of the Step II analysis.

6.4   Selection of the Preferred Candidates

The 15 candidates retained after the Step I analysis were evaluated using the revised Want list. The worksheets used together with a detailed explanation of the assessments made are included in Appendix B. The total weighted scores of the fifteen candidates are shown in Table 7.

In the Step II analysis the maximum range from the best to the worst of the 15 candidates was almost 100 points which can be considered significant enough to separate candidates. The natural break point comes between the eighth and ninth candidates where there is a difference of 21 points. Retaining only the candidates above this break point would eliminate all reflectors except the single circular and elliptical paraboloids (I-A and V-A). The strength of the lens candidates in the Step II analysis is evident from an inspection of Table 8.

The first three candidates (III-B, III-A, and IV-B) are within an 11 point spread and are essentially indistinguishable in their ability to satisfy the Wants. Candidate number four (IV-A) is not far behind. Reflector characteristics

TABLE 7

Total Weighted Scores – Step II

	A	B	C
Number of Antennas	1	2	4
I Circular Paraboloid	274	250	231
III Circular Artificial Dielectric Lens	306	312	291
IV Circular Waveguide Lens	293	301	277
V Elliptical Paraboloid	271	247	228
VI Spherical Reflector	249	235	215

The relative ranking of the 15 candidates is shown in Table 2.

TABLE 8

Relative Ranking – Step II

	A	B	C
Number of Antennas	1	2	4
I Circular Paraboloid	7	9	13
III Circular Artificial Dielectric Lens	2	1	5
IV Circular Waveguide Lens	4	3	6
V Elliptical Paraboloid	8	11	14
VI Spherical Reflector	10	12	15

are very well known, due largely to the experience background available plus the detailed analyses performed on specific problems related to the proposed multiple beam application. If the estimate of lens performance characteristics is verified in closer analyses, we could proceed with the selection of one of the lens candidates as the preferred antenna type both for the Phase II effort and for the eventual system.

Accordingly, a decision was reached to retain the four top lens candidates for the final Step III analysis. The Technical Monitor concurred in this decision.

In accordance with KTA Decision Analysis procedures, the highest ranking candidates were examined for possible adverse consequences which might influence the selection of the preferred candidate. It was concluded that no significant adverse consequences exist for these candidates.

The four candidate antenna systems selected for further study in the Step III analysis were:

1. Circular Artificial Dielectric Lens (2 Antenna, III-B)
2. Circular Artificial Dielectric Lens (1 Antenna, III-A)
3. Circular Waveguide Lens (2 Antenna, IV-B)
4. Circular Waveguide Lens (1 Antenna, IV-A).

The preference for the lens candidates over the reflector candidates is traceable primarily to the fact that the lenses may be corrected for coma. The coma and sidelobe problems with the reflectors were found to be sufficiently serious as to prevent the achievement of satisfactory beam-to-beam isolation levels.

7.0   STEP III ANALYSIS

7.1   The Criteria of Comparison

The Wants and weightings used for the Step II analysis were used without modification for the Step III analysis.

7.2   Candidate Antenna Concepts

The basic antenna concepts studied in the Step III analysis were listed in Section 6.4. When the Step III analysis was started, it became evident that from the viewpoint of simplicity and ease of implementation, the TEM mode or parallel plate lens, which is a special case of an artificial dielectric lens, should be considered on its own merits. This resulted in a revision of the list of candidate concepts, as follows:

Designation	Type	Number of Beams
III-A-1/16	One artificial dielectric lens	16
III-A-1/23	One artificial dielectric lens	23
III-B-1/16	Two artificial dielectric lenses	16
III-B-1/23	Two artificial dielectric lenses	23
III-B-2/16	Two TEM/parallel path lenses	16
III-B-2/23	Two TEM/parallel path lenses	23
IV-B/16	Two TE waveguide lenses	16
IV-B/23	Two TE waveguide lenses	23

In the above the Roman numeral and the upper case letter identify the generic class and number of antennas as in previous analyses. The ordinary artificial dielectric lens is identified by "-1" while the TEM parallel path type is identified by "-2". The number of beams is indicated by "/16" or "/23".

It can be seen that with three basic types of lens, single and dual antenna versions of each, and 16 and 23 beam case of each, 12 possible candidates could be considered. Four of these can be eliminated at the outset to result in the list given above. We shall briefly discuss here the various candidates.

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III-A-1 - One Artificial Dielectric Lens

This candidate is a single artificial dielectric lens of the "ordinary" type with either 16 or 23 beams. All of the 16 or 23 feeds illuminate the same lens which supports both polarizations. There is no problem in obtaining the required bandwidth.

III-B-1 - Two Artificial Dielectric Lenses

This concept uses two artificial dielectric lenses of the "ordinary" type. Half of the feeds with one polarization feed one of the lenses and the remaining half with the orthogonal polarization feed the other lens. All feeds have the full required bandwidth.

III-A-2 - One TEM Parallel Path Lens

This is not an admissible case in a dual polarization system.

III-B-2 - Two TEM Parallel Path Lenses

This concept utilizes two TEM mode parallel plate lenses, each capable of supporting only one linear polarization. Half of the feeds illuminate each of the two lenses and all feeds must have the full bandwidth.

IV-A - One TE Mode Waveguide Lens

With this type of lens, it is very difficult to obtain a broad operating bandwidth. Our analysis showed that, even with zoning, we could not expect to achieve the full transmit/receive bandwidth in a single lens. Accordingly, this candidate was eliminated as failing to satisfy the bandwidth Must.

IV-B - Two TE Mode Waveguide Lenses

With proper design we could expect to achieve either the transmit or the receive bandwidth in a single waveguide lens with zoning. A dual antenna version of the waveguide lens would therefore be possible if one were a transmitting lens and the other a receiving lens. However, each lens would have to support both

polarizations in a system utilizing polarization diversity to improve beam-to-beam isolation. Thus the main advantage of the two-antenna concept is lost. The foregoing comments are summarized in Table 9.

TABLE 9

Step III   Candidates For 16 And 23 Beams

Type	1 Lens	2 Lenses
ARTIFICIAL DIELECTRIC	All feeds full bandwidth lens – Two polarizations	1/2 feeds per lens - All feeds full bandwidth - One polarization per lens
TEM PARALLEL PLATE	Not applicable due to single polarization capability only	1/2 feeds per lens – All feeds full bandwidth – One polarization per lens
TE WAVEGUIDE	Not applicable due to frequency bandwidth limitations	All feeds per lens – Feeds narrow-band – Two polarizations per lens

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To develop some physical parameters which could be used in the evaluation, we chose a plano-convex design for the artificial dielectric lens and a plano-concave design for the TE mode waveguide lens. The pertinent facts on each are summarized in Figures 30, 31 and 32.

7.3   Selection of Preferred Candidates

The detailed discussion of the evaluation of the candidate concepts will be found in Appendix C. The results of the scoring in the Step III analysis is shown in Table 10.

TABLE 10

Total Weighted Scores - Step III

| | Number of Beams | |
Candidate	16	23
One artificial dielectric lens (III-A-1)	290	296
Two artificial dielectric lenses (III-B-1)	331	337
Two TEM parallel path lenses (III-B-2)	331	337
Two TE mode waveguide lenses (IV-B)	273	284

The relative ranking of the 8 candidates is shown in Table 11.
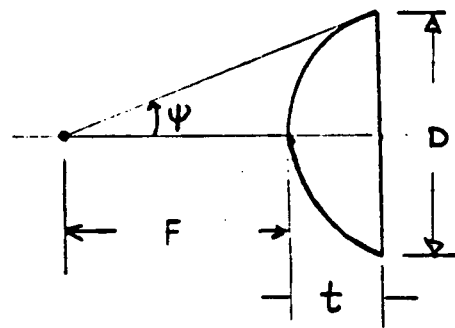
$$m = 1.6 \qquad D = 96''$$

F/D	0.5	1.0
t	18"	11"
ψ	36°	24°

FIGURE 30 ARTIFICIAL DIELECTRIC LENSE
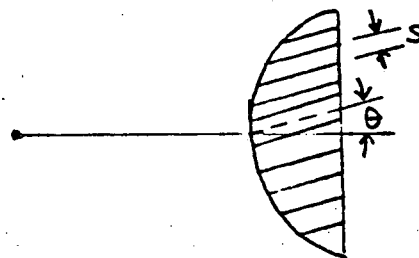
$$n = \frac{1}{\cos\theta} = 1.6$$

$$S = 0.4''$$

PLATE THICKNESS = 0.030"

FIGURE 31 TEM MODE OR PARALLEL PLATE LENSE

$m = 0.5 \qquad D = 96''$

$F/D = 1.0 \qquad t = 33''$

$\psi = 55°$
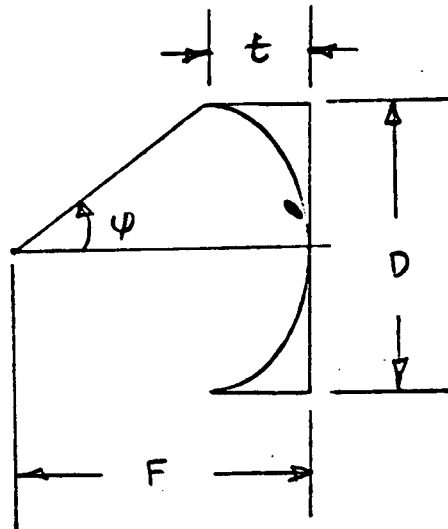
WAVEGUIDE CROSS-SECTION
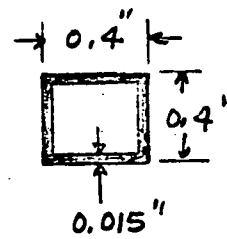
TE_{10} MODE

FIGURE 32 WAVEGUIDE LENS PARAMETERS

TABLE 11

Relative Ranking – Step III

Candidate	Number of Beams	
	16	23
One Artificial Dielectric Lens (III-A-1)	4	3
Two Artificial Dielectric Lenses (III-B-1)	2	1
Two TEM Parallel Path Lenses (III-B-2)	2	1
Two TE Mode Waveguide Lenses (IV-B)	6	5

The Step III analysis has clearly identified the two-antenna artificial dielectric lens system as the most promising candidate in terms of satisfying the design objectives. Because of the lack of practical data on the TEM parallel path lens, it is not certain that this particular form of artificial dielectric is necessarily the optimum choice.

The two-antenna artificial dielectric lens configuration won out over the other candidate primarily because of poorer beam-to-beam isolation obtainable with the single antenna artificial dielectric lens (III-A-1) and because of the complexity and weight problems of the waveguide lens configurations (IV-B).

Thus, we can conclude that the Phase I study has resulted in the selection of a two-antenna, circular aperture, artificial dielectric lens system as the most promising concept for the multibeam application. This system may be designed for 16 to 23 beams.

8.0   PHASE II PLAN

8.1   General Approach

The original plan for the Phase II effort was to demonstrate the performance of the selected antenna approach. This involved the design and fabrication of sufficient hardware so that pertinent performance characteristics could be measured. The experimental test program was to include both coverage and isolation measurements. In quoting and planning the Phase II effort, we assumed that the selected approach would be a paraboloidal reflector antenna, since we had no way of knowing what the final selection would be.

Had a reflector system been selected, the modelling phase could have been undertaken with a great deal of confidence and a minimum of risk. This is due to the relatively well-developed hardware capability associated with reflector systems for space applications and to the wealth of experience in handling such systems analytically.

With artificial dielectric lenses, the situation is different. We can expect all types of artificial dielectric lenses to have substantially the same overall performance characteristics. The choice of the most suitable method of simulating the effect of a dielectric medium is a design decision and not a conceptual one, but it is critical to the successful completion of an experimental demonstration of the complete system. We attempted to make a "Step IV" analysis to select a particular type of artificial dielectric for the Phase II effort, but we were unsuccessful in this effort. The crucial information which was lacking was experimental data on various artificial dielectric materials with insight into weight, dimensional tolerances, uniformity of dielectric constant, anisotropy, losses and so on.

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We surveyed the pertinent literature sources to obtain the needed information to make a final selection of the appropriate artificial dielectric material. Published work on lenses has always been a relatively insignificant proportion of the total antenna technology literature and experimental work on the artificial simulation of dielectric materials is even more scarce. Lens design work enjoyed its (relative) high point between World War II and the middle or late 1950's. It was during this period that the mathematics for wide angle lens optics was developed. Artificial dielectric materials having dielectric constants significantly different from unity (so as to be suitable for lens design) were developed during this period primarily (presumably) for the purpose of simulating the Luneberg lens in light-weight versions. But since 1962, with a few exceptions, there seems to have been little work on the practical applications of lenses. This state of affairs is in sharp contrast to array and reflector technologies where both hardware and analytical experience is available in abundance for applications which include spacecraft antennas.

Accordingly, we are faced with two options regarding a general approach to be followed in completing the multibeam antenna study. One is to investigate artificial dielectric materials thoroughly before attempting to model and test a complete system. In addition the analytical tools should be developed to predict lens performance as accurately as we can predict reflector antenna performance before committing ourselves to a specific design. The advantages of this approach are that it reduces the development risk and works toward an optimum simulation of a flight system. The disadvantages are that it would cause delays in completion of the experimental demonstration and would incur additional cost.

The second option is to use an available artificial dielectric material and continue with the program as planned. A delay will be involved in this approach to procure the artificial dielectric material from the manufacturer.

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We can complete this effort within the original cost. The disadvantages of this approach are that (1) to hold costs within the original figure we must make certain design concessions relative to coverage and number of beams to avoid a costly feed design effort, (2) we shall not have sufficient time to optimize the design as we would like to, and (3) we take a certain amount of risk that the available artificial dielectric material will perform according to expectations.

Between these two extremes there are certain options which can be added which will eliminate risk and permit some optimization of the lens design.

We have no authority to plan a Phase II effort beyond the original monetary scope of the contract. Therefore, we shall present here a plan for a Phase II effort based on using a commercially available artificial dielectric material to model the lens antenna system. We will, however, include our recommendations for three additional options which may be added to the basic program.

8.2   Description of the Preferred Candidate

The antenna system to be evaluated in the Phase II effort consists of two artificial dielectric lenses. Each lens will be fed by an arrangement of multiple feeds, approximately half of the beams emanating from one lens with one polarization and the remainder emanating from the other with the orthogonal polarization. The lenses will each have a circular aperture of approximately seven feet in diameter and a focal length-to-diameter ratio of the order of unity.

Certain design decisions still must be made. Among these are the exact aperture size to be used, the choice of focal length, the number of beams to be provided, the choice of lens contour (conventional or wide-angle), the cross-over level to be provided, and the choice of whether or not to add polarization grids. These decisions may in some cases differ for an operational system and for the modelling to be accomplished in the Phase II effort.

The operational system, for example, would undoubtedly be designed to provide the largest number of beams feasible and to achieve the highest possible crossover level. To attempt to achieve a high cross-over level in the demonstration model would require a feed design program which we believe could not be accomplished within present funding. A 25 beam system, for example, will require a larger aperture than a 16 beam system and therefore a thicker lens. This will affect the thickness of the blank from which the lens is to be machined and will therefore affect cost. The use of a long focal length lens will reduce thickness of the lens but may cause feed design problems. While we may expect that an operational system can be designed to provide 25 beams with a crossover level in the range from -3 to -4 dB, cost considerations relevant to the Phase II dictate that we simulate a 16 beam system with a crossover level in the range of -4 to -5 dB.

This concession will not devalue the information we expect to obtain from the experimental tests to be conducted in Phase II. The essential performance characteristics to be evaluated experimentally are the factors which relate to beam-to-beam isolation from the lens system. Tests will be performed during Phase II that will demonstrate the polarization purity of the patterns obtained from the lens and that will show what the coma lobe and side lobe performance will be. We can extrapolate performance to the larger apertures needed for more beams. Our tests will also indicate to some degree what the deleterious effects of multiple feed interaction will be in a multibeam lens system.

Probably the most important difference between the demonstration system and the operational prototype will be in the selection of the refractive index of the lens. The only lightweight lens material available has a relative dielectric constant of 2 which results in a lens what is thick and therefore heavy compared to lens using a higher dielectric constant. Furthermore, should it be

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desirable to use a coma-corrected surface the lower dielectric constant will result in a convex-convex contour while an appropriate higher dielectric constant would result in a contour very nearly plano-convex (which is easier to machine). The materials manufacturer would need additional experimentation to have the necessary confidence that he can supply a material with a dielectric constant of the order of 2.5 which would be more suitable for our purposes. Thus the Phase II modelling will not accurately simulate the weight or the geometry of the flight type system. Since generally lens losses increase as the dielectric constant is increased, we will not obtain an accurate simulation of efficiency, but the difference is not expected to be large.

The lens to be constructed for the Phase II effort will be approximately 7 feet in diameter with a focal length of the order of 7 feet. It will be manufactured from an available artificial dielectric material having a relative dielectric constant of approximately 2.0. Eight feeds will be provided which can be arranged in two different configurations to simulate the 16 beams of the two antenna system. The lens material has a bulk density of about 2 pounds per cubic foot.

8.3   Detailed Plan for the Phase II Effort

The Phase II effort compatible with present funding has been planned to include the following tasks:

(1) Materials Procurement. A cylindrical block of artificial dielectric material having a dielectric constant of 2 will be procured from Emerson and Cuming, Inc. The material is a plastic foam loaded with metallic particles. The manufacturer has had experience in producing this particular material and can provide it on order with a 60 day delivery. The dimensions of cylindrical lens blank are 100 inches in diameter and 30 inches thick.

(2) Lens Fabrication. An 84 inch plano-convex lens will be fabricated from the lens blank. General Electric (Syracuse) will probably perform this task for LMSC, since they have appropriate tooling and have had experience in machining this type of loaded foam.

(3) <u>Feed Design and Fabrication.</u> LMSC will design and fabricate 8 feeds for the lens.

(4) <u>Antenna Tests.</u> LMSC will evaluate the lens performance by making impedance measurements and by recording radiation patterns to simulate the 2 antenna 16 beam configuration. The beam crossover level will be approximately -4.5 dB.

(5) <u>Final Report.</u> LMSC will prepare and submit a final report on the Phase II effort.

No additional funding is required to perform the program as outlined above. To allow sufficient time for the procurement of the lens material and for the machining of the lens by outside contractors, the end date of the contract must be extended from 3 April to 3 July 1973. In addition it should be recognized that there will be little activity on the program while the lens is being fabricated. A program schedule is shown in Figure 33.

8.4   Other Options

Several options can be added to the basic program outlined in the foregoing paragraphs. All of these would require additional funding which in some cases is minimal. Also each would require an extension of the contract.

8.4.1   Two Dimensional Modelling

To optimize the design we need to select the proper focal length and to decide whether or not to use a coma corrected contour. Feed design and lens mounting considerations would dictate the use of short focal lengths whereas lens weight considerations and coma lobe performance would dictate longer focal lengths. If satisfactory coma lobe performance can be obtained without using a coma-corrected lens contour, it is preferable to do so, since the plano convex contour is easier to machine. Additionally, there may be some modification of the aperture distribution in a coma-corrected lens which would tend to work against the objective of obtaining low side lobes.

SCHEDULE PLAN

MODEL	PLAN	TITLE Fig 33 NASA - GODDARD PHASE II	PREPARED BY: P.J. BYRNES	DATE 10-2-72
ISSUE NO.	REFERENCE	MULTIPLE BEAM ANTENNA STUDY	APPROVED BY:	DATE

FIGURE 33	1972			1973						
	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY
PREPARE SPEC FOR EMERSON + CUMING	▭									
FAB ARTIFICIAL DIELECTRIC CYL.			▭							
DESIGN LENS		▭								
DESIGN FEEDS		▭								
DESIGN LENS/FEED SUPPORT		▭								
PREPARE SPEC FOR G.E.										
CONFERENCE - DESIGN REVIEW			△							
FAB LENS					▭					
FAB FEEDS				▭						
FAB LENS/FEED SUPPORT				▭						
TEST FEEDS					▭					
ASSEMBLE AND TEST LENS							▭			
CONFERENCE - PELIMINARY							△			
FINAL REPORT - DRAFT									▭	
CONFERENCE - FINAL REPORT									△	
FINAL REPORT - FINAL										▭

The choice of focal length and lens contour will be critical in achieving the desired results. Analytical tools are not available for predicting pattern performance of lenses with arbitrary contours with the same accuracy that we have for reflectors. Some valuable insight regarding final performance can be obtained by making a two-dimensional simulation of the lens in a parallel plate region. Pattern measurements for offset feeds would show the coma lobe performance of the selected lens contour and would thus allow us to optimize the choice of focal length and to evaluate the need for coma-correction. Cross-polarization effects and astigmatism (the dominant aberration in rotationally symmetric coma-corrected lenses) would not be evaluated.

This effort would not require much additional funding and could be accomplished during the waiting period while the lens blank is being manufactured. Completion of this task before the lens is cut to contour would greatly reduce the risk involved in the Phase II effort.

8.4.2   Lens Modelling With a New Dielectric

The basic program defined in Section 8.3 would use a commercially available artificial dielectric material with a dielectric constant of 2.0. This results in a thicker and heavier lens than would one utilizing a material with a higher dielectric constant. Although Emerson and Cuming expects to be able to make the same kind of material with higher dielectric constants, some development and evaluation tests are required to confirm this. A dielectric constant of about 2.5 is considered more suitable for the lens system. This figure is a compromise between the size and weight considerations on the one hand and estimated losses on the other. In either the conventional or the wide angle design, this dielectric constant would result in a lens contour with one face which is plane or nearly so, reducing the problems of lens manufacture.

This option would have six tasks, as follows:

(1) <u>Material development</u> Emerson and Cuming would be asked to develop and test an artificial dielectric material having a dielectric constant of 2.5.

(2) <u>Two dimensional modelling</u> The new material and the design lens contour would be checked in a two-dimensional sample as described in Section 8.4.1.

(3) through (6) These four tasks would be the same as the four tasks in the planned Phase II effort described in Section 8.3, except that the new dielectric material would be used.

Additional funding would be required and the end date of the contract would have to be extended to 3 August 1973.

8.4.3   New Phase II plus a Phase III

The breadboard lens antenna fabrication and test as outlined in Section 8.3 would be designated as Phase III. The dielectric material used in Phase III would be selected in a new Phase II. The new Phase II would include the following effort:

(1) <u>Materials analysis</u> Various types of artificial dielectric materials would be analyzed in terms of their ease of fabrication, applicability to spacecraft environment, and electrical performance. Types considered would be metal strip, discs or rods immersed in low dielectric constant foam, metallic foil discs or strips on thin dielectric sheets, and metal plate TEM regions.

(2) <u>Evaluation of commercially available materials</u> The possibility of making the commercially available loaded foam artificial dielectric in an appropriate range of dielectric constants would be evaluated with the help of the manufacturer. Characteristics needing evaluations are uniformity, anisotropy, dielectric constant tolerance, frequency characteristics and losses.

(3) <u>Sample fabrication</u>   Samples of the more promising candidates evaluated in the Materials analysis task will be fabricated. Samples of any suitable commercial material will be procured.

(4) <u>Sample evaluation</u>   The samples will be evaluated experimentally to determine their relevant electrical and physical properties.

(5) <u>Selection of a preferred approach</u>   A preferred method of simulating the dielectric medium for the Phase III testing will be selected.

(6) <u>Two dimensional Modelling</u>   Using the preferred approach, a two dimensional model will be constructed and tested to verify the focussing properties of the material and the lens contour.

(7) <u>Performance Analysis</u>   An analysis will be performed to predict the final performance of the lens. This will be comparable to the corresponding analysis of reflector properties described earlier in this report. This analysis will permit the optimization of various design parameters in the lens.

(8) <u>Phase III Planning</u>   The work of the Phase III effort will be planned in detail.

(9) <u>Phase II Final Report</u>   A final report will be prepared detailing all of the work accomplished during the new Phase II.

Additional funding will be required for the Phase II effort outlined in the foregoing paragraphs. The remaining funding is sufficient to cover the Phase III effort. The end date of the contract would have to be extended to 3 October 1973.

9.0   SUMMARY AND CONCLUSIONS

The Phase I effort has been concluded. As a result, a two-antenna, circular aperture artificial dielectric lens configuration has been selected as the most suitable candidate for providing the coverage, beam-to-beam isolation, and other desirable characteristics of the multiple beam application.

A Phase II effort has been planned to demonstrate the performance of the lens approach. This effort utilizes a commercially available artificial dielectric material and offers an opportunity of providing a good evaluation of the multibeam lens concept within the existing contract funds. This effort is described in Section 8.3.

From an engineering viewpoint a more comprehensive evaluation is recommended. This effort, which is described in Section 8.4.3, would involve a detailed evaluation of artificial dielectric materials before starting the modelling of the lens system. Additional funds would be required for this option, however. Other options for augmenting the planned Phase II effort at minimal cost are also described.

APPENDIX A

EVALUATION OF CANDIDATE ANTENNAS

STEP I ANALYSIS

A -1 (a)

Evaluation of Candidate Antennas - Step I Analysis

Introductory Remarks

The actual KTA Decision Analysis worksheets used in the Step I analysis are to be found in this appendix. Because the space provided on the form is limited, it is not possible to detail the comments on each candidate with respect to each want and fragmentary comments are used. We have included the actual worksheets and will discuss each assessment in detail in the text. Each want will be considered individually with respect to all 48 candidates. This will be done in descending order of importance or weighting.

WANT #4: Minimize Inadequate Gain Areas

This can be interpreted in the broad sense as the desire to achieve high beam crossovers.

I Circular Paraboloid

For the circular paraboloid we expect to be able to achieve a -6 to -8 dB compound crossover (between diagonal beams) in the single antenna (I-A) case, although this may tend to be optimistic when interaction problems are taken into account. However, when two antennas are used (I-B), the interbeam spacing is increased by a factor of $\sqrt{2}$ (because adjacent beams are located on a diagonal). If we reduce the aperture to broaden the beamwidth, we should be able to realize the same crossover on diagonal beams in the dual antenna case as we could achieve on the north-south beams in the single antenna case, probably in the neighborhood of -4 dB. Going to 4 or more antennas (I-C and I-D) improves the beam-to-beam spacing and makes attainment of -3 or -4 dB crossover levels easier, since there would be less interaction.

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II   Circular Dielectric Lens

III   Circular Artificial Dielectric Lens

IV   Circular Waveguide Lens

The comments applicable to the circular paraboloids are also applicable to the circular lenses.

V   Elliptical Paraboloid

In general the attainment of a specific crossover level will be about the same for the elliptical paraboloid as for the circular paraboloid. There could be some problems in utilizing dielectric loading of the feeds to provide closer feed spacing, since loading would tend to sharpen the primary beams in both planes. Problems need to be investigated, but the initial assessment was that there is negligible difference between the elliptical and the circular paraboloid cases.

VI   Spherical Reflector

With the proper adjustment in aperture size and without considering the other performance characteristics, the ability to achieve a specified beam crossover with spherical reflectors is considered comparable to that associated with the circular paraboloid.

VII   Luneberg Lens

Theoretically, the variation of refractive index in the Luneberg lens tends to cause crowding of the energy toward the periphery of the lens aperture. This places an inverse taper to the aperture illumination, tending to cause narrower beam widths. This in turn makes it difficult to achieve high beam crossovers. Practical approximations to the theoretical Luneberg lens tend to de-emphasize this crowding effect and thus may permit the attainment of better crossover levels than theory would predict. In addition, with circular paraboloids and other types of lenses, dielectric end plugs may be used with the feeds to reduce the feed

aperture sizes so that close beam spacing can be obtained. In the Luneberg Lens we probably could not use this endfire feed technique. For these reasons, the single Luneberg (VII-A) is rated a little lower than the circular paraboloid (I-A).

For the multiple antenna versions of the Luneberg (VII-B, VII-C, VII-D) the difference between the circular paraboloid and the Luneberg tends to diminish due to the flexibility of setting feed spacing in multiple antennas.

VIII   Parabolic Cylinder

For the single parabolic cylinder (VIII-A) the beams must be in rows corresponding to the orientation of the line source feeds. This is a limitation of design freedom and may cause problems in minimizing inadequate gain areas, since we are trying to cover an irregularly shaped ground area and not a symmetrical solid angle. Additionally, there will be difficulty in achieving adequate gain coverage for New England and Florida unless additional feeds are added for these regions (which increases blockage, weight and so on). Thus achieving minimum inadequate gain areas with a single parabolic cylinder is considered to be quite a problem.

With dual antennas (VIII-B) the situation is alleviated by the increased beam spacing, but there is still a problem with New England and Florida.

As the number of antennas is increased (VIII-C and VIII-D) the spacing becomes larger--as with the paraboloid--and an added feed blocks fewer of the beams. In the case of VIII-D the additional antennas (beyond 4) could be special antennas just to provide the New England and Florida coverage.

IX   Offset Parabolic Cylinder

This case is very much like the parabolic cylinder for all four versions. Blockage would not be a factor, but the same difficulties exist because of the constraint on beam placement.

A-3

X   Cylindrical Dielectric Lens

XI   Cylindrical Artificial Dielectric Lens

XII   Cylindrical Waveguide Lens

These cases are similar to the parabolic cylinder because of the constraint on beam placement. There is a problem in obtaining New England and Florida coverage.

WANT #5: Maximize Beam-to-Beam Isolation

This Want relates to the interference between beams on the ground. Basically two types of coupling must be considered. One is side-lobe coupling between co-polarized beams and the other is cross-polarization coupling between beams which are nominally cross-polarized. This Want has a weighting of 10, equal to the weighting applied to obtaining adequate gain coverage.

I   Circular Paraboloid

A single circular paraboloid is only a fair performer for closely spaced beams with respect to fulfilling this objective. The reflector tends to cause cross-polarization problems which may be intensified for offset feeds and for multiple feed cases where there would be interaction. Also, side lobes tend to increase when there is feed interaction. (NOTE: The severeity of the coma lobe problem with reflectors was not fully evaluated at this juncture).

Multiple antenna versions (I-B, I-C, and I-D) tend to have better side lobes because the feeds interact less. Since the feed spacing is larger, the feed may be designed to provide better reflector illumination. Furthermore the deleterious effects of blockage are reduced because the number of feeds per reflector is reduced in the multiple antenna case. Polarization effects can also be controlled better in the multiple antenna versions, because polarizing screens may be added to purify beam polarization if necessary.

A-4

II   Circular Dielectric Lens

III   Circular Artificial Dielectric Lens

IV   Circular Waveguide Lens

The lens configurations do not suffer the effects of blockage on side lobes and on cross-polarized energy. Furthermore, the lenses can be designed to compensate for coma. The same general comments apply relative to multiple antenna versions. Thus the lens antennas are somewhat better in isolation than would be the paraboloidal reflector.

V   Elliptical Paraboloid

When the beam is directed off the axis of a circular paraboloid, phase distortion occurs resulting in coma. The areas on the reflector surface where the major portion of this phase distortion occurs are at four points around the reflector periphery at 45 degrees to the plane of offset. In an elliptical paraboloid these troublesome portions of the reflector are not present for at least some of the beams and so it was believed that some improvement beneficial to obtaining better isolation might occur. The single elliptical paraboloid (V-A) was judged to be at least as good as the single circular paraboloid (I-A) with respect to beam-to-beam isolation, but not by any significant margin.

For multiple antenna versions (V-B, V-C, and V-D) we can expect less beam-to-beam coupling for the same reasons cited for the circular paraboloid.

VI   Spherical Reflector

For the single antenna (VI-A) we can expect poorer beam-to-beam coupling than we would obtain from the circular paraboloid because the spherical reflector does not provide uniform phase across the aperture and would have higher side lobes. Multiple antenna versions (VI-B, VI-C, and VI-D) should each be correspondingly worse than the circular paraboloid counterpart.

VII   Luneberg Lens

The single Luneberg Lens (VII-A) should have higher first side lobes than the corresponding circular paraboloid antenna due to the illumination problem discussed previously. The wide angle side lobes probably will fall off at a more rapid rate compared to the circular paraboloid. Thus while wide angle coupling on co-polarized beams will be less than obtained with the circular paraboloid, the coupling to the nearest co-polarized beam (the beam located on the diagonal) should be higher.

Since the coupling on the diagonal beams is the determining factor, multiple antenna versions (VII-B, VII-C, and VII-D) should be about the same as the single antenna case.

VIII   Parabolic Cylinder

In the single antenna version (VIII-A) both polarizations must exist in the same pillbox feed. There is a high probability that problems will exist in obtaining two pure polarizations orthogonal to each other within the feed itself. The reflector, being cylindrical, will not have any depolarizing effect on the feed radiation. The single antenna, then, could have less polarization coupling than the corresponding circular paraboloid antenna (I-A).

For multiple antenna versions (VIII-B, VIII-C, and VIII-D) both polarizations do not exist in any single feed. Pure feed polarizations should be relatively easy to obtain and, if necessary, simple polarization grids can be placed over the pillbox feed apertures. Since the reflector will not depolarize the feed radiation, multiple antenna versions of the parabolic cylinder should have superior cross-polarization characteristics.

IX   Offset Parabolic Cylinder

X   Cylindrical Dielectric Lens

XI   Cylindrical Artificial Dielectric Lens

XII   Cylindrical Waveguide Lens

These antennas should have the polarization characteristics of the Parabolic Cylinder.   There may be some slight improvement over the Parabolic Cylinder due to the fact that there is no blocking problem which could cause deterioration of side lobes.

WANT #6: Maximize the Number of Users

This Want refers to the fact that certain beam arrangements will provide more users than others under the worst possible conditions.

I   Circular Paraboloid

II   Circular Dielectric Lens

III   Circular Artificial Dielectric Lens

IV   Circular Waveguide Lens

V   Elliptical Paraboloid

VI   Spherical Reflector

VII   Luneberg Lens

These antenna configurations have maximum freedom in the placement of beams and therefore best fulfill the Want.   Either box or billiard ball beam arrangements can be configured.

VIII   Parabolic Cylinder

IX   Offset Parabolic Cylinder

X   Cylindrical Dielectric Lens

XI   Cylindrical Artificial Dielectric Lens

XII   Cylindrical Waveguide Lens

Either box or billiard ball beam arrangements can be configured with the cylindrical antennas. However, because the beams are produced by line source feeds, there are some limitations on the design freedom. In certain situations additional pillbox feeds may be required to achieve a particular beam arrangement adding to weight and causing other problems. Thus the cylindrical antennas are considered slightly less desirable with respect to this Want.

WANT #8: Minimize Complexity

Complexity is a general, abstract term. In evaluating candidates against this Want, comments are made about any aspect of the candidate configuration which tends to make it complex. Scoring then reflects a judgment as to how serious the problem is.

     I   Circular Paraboloid

For the single antenna version (I-A) the major problem is routing 15 to 25 waveguides from the feed area to the back of the reflector. Multiple antenna versions (I-B, I-C, and I-D) will have a less complex waveguide routing problem, but they will require precise alignment between antennas to interlace the beams properly and there will be increasing problems of packaging the antennas during the launch.

     II   Circular Dielectric Lens

For the single antenna case (II-A) the waveguide routing problem is simpler because the feeds are in the back of the lens. This lens cannot be unfurled, however, causing some problems in stowing it for launch. For multiple antennas (II-B, II-C, and II-D) alignment problems exist and the fact that the antennas are not furlable leads to serious packaging problems.

     III   Circular Artificial Dielectric Lens

     IV   Circular Waveguide Lens

These antennas have simpler waveguide routing problems than those

A-8

associated with the Circular Paraboloid. Deployment problems are not as yet fully evaluated. Multiple antenna versions (III-B, III-C, III-D, IV-B, IV-C, and IV-D) have the alignment problems referred to above.

V   Elliptical Paraboloid

This antenna type should have the same problems as the circular paraboloid.

VI   Spherical Reflector

The spherical reflector antennas should have larger physical apertures than the corresponding circular paraboloids due to the lower efficiency and the extra aperture required to provide for the offset beams. Otherwise the complexities are similar to those of the paraboloid.

VII   Luneberg Lens

The Luneberg Lens cannot be furled and furthermore is difficult to support. The dual antenna (VII-B) version would be difficult to package for launch in a 10 foot shroud (except by stacking along the vehicle axis). The other multiple antenna versions (VII-C and VII-D) do not seem at all practical considering the complications of packaging and deployment. All multiple versions have the problem of alignment.

VIII   Parabolic Cylinder

The major complication for the single antenna case is that the three feeds required must each support both parallel and perpendicular polarizations (with respect to the top and bottom pillbox walls). It is a touchy problem to preserve the polarization purity of the two modes. Another problem relates to the fact that pillboxes are difficult to configure in a deployable form, particularly when plate spacing must be preserved for the parallel polarization modes. Thus the pillbox feeds probably would not be deployable and would represent a packaging problem during launch. For the multiple antenna versions (VIII-B, VIII-C, and VIII-D)

the problems of supporting two independent polarization modes in a single pillbox do not exist, but we still have the requirement to hold plate spacing in close tolerance for the parallel polarization mode pillboxes. Alignment for proper interlacing and packaging problems are associated with the multiple antenna versions.

IX   Offset Parabolic Cylinder

The feed problems for the offset parabolic cylinders are the same as for the Parabolic Cylinders. For the single antenna case (IX-A) the packaging and deployment is simpler (compared with VIII-A) because the reflector may be folded up against the pillbox and be deployed simply by a hinge arrangement. For the Parabolic Cylinder the entire pillbox must be brought out in front of the reflector. For the dual antenna version (IX-B) the second reflector may be folded out from the other side of the pillbox feeds with little increase in packaging problems and with better alignment capabilities than any other configuration. The other multiple antenna versions (IX-C and IX-D) represent serious packaging and complexity problems.

X   Cylindrical Dielectric Lens

The cylindrical dielectric lens in all versions has the problems mentioned above relating to pillbox feeds. The single antenna version (X-A) is more complex in packaging than the comparable circular version of the same antenna. Multiple versions of the cylindrical dielectric lens (X-B, X-C, and X-D) become increasingly more complex.

XI   Cylindrical Artificial Dielectric Lens

XII   Cylindrical Waveguide lens

These antennas have all the feed problems common to the cylindrical antenna versions and the alignment and packaging problems associated with

A-10

multiple antennas (as compared with single antennas).

WANT #9: Minimize Weight

No detailed weight analysis has been performed. Preliminary estimates of antenna system weight have been made for each candidate. The basis for these estimates will be given here.

I   Circular Paraboloid

The single antenna version would weigh about 18.9 pounds. Using 0.25 lbs/square foot of aperture area (based on ATS F and G figures), the reflector would weigh 9.6 lbs. Allowing 1 lb. for the feed support and 8.3 lbs. for the feeds brings the total to 18.9 lbs. The dual antenna version (I-B) would require a second reflector (9.6 lbs.), a second feed support (1 lb.), and additional supporting structure to position the two antennas relative to each other (1 lb.) for a total of 30.5 lbs. The four antenna version (I-C) would add 2 reflectors, 2 feed supports, and 2 antenna support booms for a total of 53.7 lbs. A 100 lb. weight was assigned to the "more than 4" version (I-D).

II   Circular Dielectric Lens

Using 3M6098 material which has a relative dielectric constant of 2.4 $\pm$ 2% a 6-foot unzoned lens (f/D = 1.5) would weigh about 1500 lbs. A zoned version would weigh about 300 lbs. In comparison with these figures weight of feeds and other structure was neglected.

The dual antenna version (II-B) would weigh 600 lbs. zoned. The four antenna configuration (II-C) would weigh 1200 lbs. The remaining multiple antenna version (II-D) would be over a ton.

III   Circular Artificial Dielectric Lens

For the single antenna version (III-A) the lens itself would weigh around 60 lbs. Allowing 8.3 lbs. for feed and a pound or so for support structure

LMSC/D284597

brings the total to around 70 pounds. The other three versions (III-B, III-C, and III-D) figure out to 132, 256, and 450 lbs. respectively.

IV   Circular Waveguide Lens

For this type of antenna the lens weight is taken as 100 lbs., although there may be some possibilities of weight reduction below this value. Thus, the four versions IV-A, IV-B, IV-C, and IV-D, have estimated weights of 110, 212, 416, and 700 lbs. respectively.

V   Elliptical Paraboloid

This is similar to the circular paraboloid with an allowance of about 4 pounds for the extra reflector weight. The four versions, V-A, V-B, V-C, and V-D have estimated weights of 23, 38.5, 65.7 and 150 lbs. respectively.

VI   Spherical Reflector

This is the same as the circular paraboloid except that the reflector would probably weigh around 13 lbs. Thus the weight for the four versions, VI-A, VI-B, VI-C, and VI-D, are 22, 37, 67 and 125 lbs. respectively.

VII   Luneberg Lens

From the average density of commercial Luneberg Lenses, the weight of a single 5 foot lens was computed to be 1340 lbs. For a 7 foot lens the weight turns out to be 3600 lbs. Some reduction in diameter is possible due to the relatively sharp beams we should have with this type of lens, but even at the lower figure the Luneberg is still a heavy antenna. For the dual antenna version (VII-B) the weight should range from 1 to 4 tons. The four antenna version (VII-C) would range from 2 to 8 tons. More than four antennas (VII-D) would probably not be a feasible approach.

VIII   Parabolic Cylinder

For the reflector a weighting factor of about 0.5 lb/square foot of aperture

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was assumed. This is about twice that required for the Flex-Rib type of a circular paraboloid used for the ATS F and G, but it reflects the weight necessary to provide a stable backbone for the cylindrical surface.

The pillbox weight was determined by computing the weight of the top and bottom plates of the pillbox 7 feet wide and 3.5 feet deep, assuming a 0.050 inch wall thickness. The metal chosen was magnesium. The weight per pillbox comes out about 20 lbs.

With 25 lbs. of reflector, 60 lbs. of pillboxes, and 4 pounds of structure, the estimated weight for a single antenna (VIII-A) is 89 lbs. For the multiple antenna versions, VIII-B, VIII-C, and VIII-D, the estimated weights are 178, 236, and 320 lbs. respectively.

The pillbox weight is a significant contributor to the total weight of the parabolic cylinder antennas and will also be significant in the cylindrical lens configuration XI and XII. Undoubtedly, some careful design may permit some weight reduction. For example, a reduction in wall thickness to 0.040 inch would reduce the feed weight by 20 percent to about 16 lbs. But, in contemplating weight reductions two factors must be taken into consideration. First, since there will be several feeds in each pillbox, a long focal length pillbox is required to provide good performance for offset beams. Changing focal length to 1.75 ft. (f/D = 0.25) would reduce plate surface area and would result in a pillbox weight of about 8 lbs. There would be problems with multiple beam excitation and off-axis performance. Second, since half of all of the feeds in any particular antenna version must support parallel polarization of the electric field, the plate spacing must be maintained accurately throughout the parallel plate region to preserve phase uniformity. If the plate thickness is reduced, additional stiffeners would probably be required to keep the plates flat. Thus the 20 lb. weight estimate for each pillbox may not be too pessimistic.

IX   Offset Parabolic Cylinder

The weight estimates for this antenna are the same as for the Parabolic Cylinder (VIII).

X   Cylindrical Dielectric Lens

For the cylindrical versions of the lens we assume that the weight of the lens itself would be $4/\pi$ times the weight of the circular lens.

For the single antenna configuration (X-A) one lens and three pillbox feeds are needed, bringing the weight to over 1500 lbs., unzoned, and 300 lbs., zoned. The dual antenna version (X-B) is in the 3000 lb. unzoned/600 lb. zoned weight class. These figures are doubled for the four antenna version (X-C). The last multiple antenna version (X-D) appears impractical from a weight viewpoint.

XI   Cylindrical Artificial Dielectric Lens

For this antenna type we estimated a single lens weight of 75 lbs. Thus the single antenna version (XI-A) with 3 pillbox feeds and support structure would weigh 139 lbs. For the multiple antenna versions, XI-B, XI-C, and XI-D, the estimated weights are 278, 436, and 625 lbs. respectively.

XII   Cylindrical Waveguide Lens

For this antenna we estimated the lens weight to be 133 lbs. Thus the weights for the four versions, XII-A, XII-B, XII-C, and XII-D are 197, 394, 668, and 825 lbs. respectively.

In scoring the various candidates relative to the weight objective, it is important not to use a numerical formula for finding the score. The scores are assigned according to how much impact it would have on a typical vehicle design situation. The paraboloid has the lowest weight in a flight configuration and, of course, receives the maximum score of 10. Other weights under 100 lbs. received scores of 7 to 9. When the weight was in hundreds of pounds, this was considered unattractive and warranted a low score. Tons warrant scores of 0.

WANT #7: Maximize Overall Efficiency

In the Step I analysis, we were mainly looking for losses of one type or another. Principal loss sources are blockage, dielectric losses, phase errors, and defocussing.

I   Circular Paraboloid

The principal losses for the single antenna version (I-A) are the blockage of 25 feeds and the small amount of lateral defocussing for the off-axis beams. Multiple antenna versions (I-B, I-C, and I-D) will have less blockage loss as the number of feeds per antenna is reduced. Lateral defocussing will be about the same in the multiple antenna versions.

II   Circular Dielectric Lens

Blockage is not a factor in this case, but dielectric losses become important. With similar aperture distributions, we expect the lens to be 25 percent efficient compared to 50 percent for the circular paraboloid. Multiple antenna versions (II-B, II-C, and II-D) are the same as the single antenna case.

III   Circular Artificial Dielectric Lens

This type of antenna should be a little better than the dielectric lens. Although there are no dielectric losses as such, there may be internal losses in the lens. Multiple antenna versions are the same as the single antenna case.

IV   Circular Waveguide Lens

This antenna type has about the same losses as the Artificial Dielectric Lens.

V   Elliptical Paraboloid

This antenna type has about the same losses as the Circular Paraboloid.

VI   Spherical Reflector

This antenna should have an efficiency of about the same order of magnitude as the lens. In addition to the blockage loss, there will be a loss due to the

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imperfect phase distribution across the aperture (quadratic phase error). For
the dual antenna (VI-B) there will be some improvement due to reduced blockage,
but for the remaining multiple antenna versions, the loss due to phase error
should dominate.

VII   Luneberg Lens

This antenna type will have dielectric losses. If loaded foam is used to
reduce the weight to something sensible, these losses will become more severe.
The illumination of the aperture may tend to reduce the available gain for a
prescribed beam width as mentioned above, but this needs more study to determine
the magnitude of this effect. The multiple antenna versions (VII-B, VII-C, and
VII-D) have the same losses as the single antenna version.

VIII   Parabolic Cylinder

The parabolic cylinder has two different kinds of blockage. First, the
pillbox feeds will block the secondary aperture of the cylindrical reflector.
Second the multiple feeds in each pillbox will block the pillbox aperture. Both
of these blocking effects are linear or cylindrical blocks which tend to be more
severe than circular or rotational blocks. For example, if the feeds in a single
pillbox occupy 8.4 inches of 84 inch width of the pillbox, the feeds would block
ten percent of the aperture area of the pillbox. On the other hand, if a feed
cluster 8.4 inches in diameter blocks the secondary aperture of a circular
reflector 84 inches in diameter, the blockage amounts to only 1 percent of the
aperture area. Blockage of the cylindrical reflector aperture by the three
pillboxes is also a "linear" type of block. In effect, with the two blockages the
radiating aperture of the cylindrical reflector will be divided into four parts.
The blockage caused by the three pillboxes will divide the aperture into north
and south halves and the blockage of the pillbox apertures will divide each half
into east and west quarters. Thus blockage effects with the parabolic cylinder

will be more serious than with the circular paraboloid.

With the dual antenna version (VIII-B) roughly the same primary and secondary aperture blockage will occur as with the single antenna case (VIII-A). With four (VIII-C) or more than four (VIII-D) antennas, there will be some reduction in blockage, though not to an appreciable extent.

IX   Offset Parabolic Cylinder

To alleviate the secondary aperture blockage problem, the offset parabolic cylinder was considered. It should be noted that this attempts to solve only half the problem, since the blockage of the pillbox apertures would still occur with the offset parabolic cylinder. The price paid for eliminating blockage of the secondary aperture is the introduction of axial defocussing in the multibeam antenna case. To illuminate the reflector properly, the feeds (pillboxes) must be tilted so that some feeds are offset in an axial sense as well as a lateral sense.

Because of the defocussing problem with the offset parabolic cylinder, both the single (IX-A) and dual (IX-B) antenna versions would be only a little better than the Parabolic Cylinder (VIII-A). The other multiple beam versions (VII-C and VII-D) will be more efficient in those cases where only one pillbox is needed per antenna.

The problem of blockage of the pillbox aperture can be helped by using a slice of a cylindrical lens between parallel plates or an offset parabolic configuration for the pillbox. With the cylindrical lens concept the feeds are behind the pillbox aperture and do not block pillbox radiation. Although a f/D ratio of about 0.5 could be used, the lens type of pillbox will be just as heavy and perhaps heavier than the reflecting pillbox due to the additional weight of the lens and it will have lens losses. The offset configuration ("hoghorn") type of pillbox feed would weigh about twice as much as the simple centered pillbox and in addition would suffer from axial defocussing effects.

X   Cylindrical Dielectric Lens

XI   Cylindrical Artificial Dielectric Lens

XII   Cylindrical Waveguide Lens

The same comments can be made here about lens losses as were made previously for the circular versions of the same antenna types. In addition, the lenses will also suffer from primary aperture (pillbox) blockage. There will be no blockage, of course, of the secondary (lens) aperture.

WANT #3: Minimize Spillover

In this analysis we were not considering design variations of particular antennas which would offer a material difference in the ability to minimize spillover. In the preliminary analysis phase (Step I) we concluded that all candidates would have about the same spillover or spurious radiation into foreign countries. Therefore, all candidates were scored 10 for this Want. This Want is weighted 3.

WANT #2: Coverage of Hawaii

This Want, which has a weighting of 2, relates to the difficulty required to provide coverage of the main Hawaiian group of islands in the basic antenna and to the kind of performance that would be provided. (NOTE: The subsatellite position must be chosen so that Hawaii is visible).

I   Circular Paraboloid

For the single antenna version (I-A) coverage of Hawaii could be provided by adding another feed. There would be some gain degradation due to the fact that Hawaiian coverage requires a larger beam offset. The multiple antenna versions (I-B, I-C, and I-D) are essentially the same as the single antenna case.

II   Circular Dielectric Lens

Hawaiian coverage could be provided by a single separate feed. Blockage would not be increased (as it is in the circular paraboloid case). There would be less gain degradation applicable to the Hawaiian beam if the lens is designed for wide angle optics. Multiple antenna versions (II-B, II-C, and II-D) are the same as the single antenna case.

III   Circular Artificial Dielectric Lens

IV   Circular Waveguide Lens

These configurations have the same characteristics as the Circular Dielectric Lens (II).

V   Elliptical Paraboloid

The elliptical paraboloid is similar to the circular paraboloid.

VI   Spherical Reflector

For all versions of the spherical reflector, Hawaiian coverage can be provided by adding a separate feed. This produces a small increase in blockage. The Hawaiian beam is as good as any other beam, if sufficient aperture is available.

VII   Luneberg Lens

This is the best configuration for providing coverage of outlying areas. It requires a separate feed, no additional blockage occurs, and the Hawaiian beam is not degraded.

VIII   Parabolic Cylinder

To provide Hawaiian coverage on the single antenna (VIII-A) requires a separate pillbox, since Hawaii lies at a more southern latitude than any point within the contiguous 48 states. This adds 20 pounds of extra weight and increases the blockage.

In the multiple antenna versions (VIII-B, VIII-C, and VIII-D) the effect of increased blockage is felt on fewer and fewer beams.

IX   Offset Parabolic Cylinder

For this configuration coverage of Hawaii for all four versions requires the addition of a single pillbox and a weight penalty of 20 pounds. There are no blockage problems. There would be more axial defocussing for the Hawaiian beam leading to degraded performance.

X   Cylindrical Dielectric Lens

XI   Cylindrical Artificial Dielectric Lens

XII   Cylindrical Waveguide Lens

For all four versions of all three lenses the problem of providing Hawaiian coverage is simply the additional weight of the extra pillbox. There are no blockage or axial defocussing problems. If the lenses are designed for wide angle optics, there would be little degradation of the Hawaiian beam.

WANT #1: Coverage of Alaska

This Want has a weighting of 2.

Exactly the same comments apply to Alaskan Coverage as applied to Hawaiian coverage, except, of course, that Alaska lies at a more northernly latitude.

Generally, coverage of Alaska will not be as good as the coverage of Hawaii because the main Hawaiian islands cover an area smaller than the beams whereas Alaska, as viewed from the satellite, will be stretched out along the horizon.

WANT #10: Provide for Growth to More Beams

This Want measures the potential of providing more beams within the contiguous 48 states. We have postulated an increase in aperture diameter of up to 2:1. This Want is weighted 2.

I   Circular Paraboloid

The single antenna version (I-A) will be limited by the degradation experienced due to the lateral offset of the feeds from the main axis of the reflector. With the single antenna version the aperture size could be increased to provide a 4 x 7 arrangement of beams (instead of 3 x 6) and might even be increased enough to provide a 5 x 8 beam arrangement without too much degradation. Extra blockage will occur.

The dual antenna version (I-B) will have the same capability, roughly, as the single antenna version. The other multiple antenna versions (I-C and I-D) may be reconfigured to divide the beams into east and west halves (and into the two polarizations as well) and so are capable of providing growth to more beams.

II   Circular Dielectric Lens

III   Circular Artificial Dielectric Lens

IV   Circular Waveguide Lens

There are no problems of increased blockage with these lens configurations. The lenses could be designed for wide angle optics and so have the capability of providing a significantly larger number of beams. The penalty is the additional weight which increases in proportion to the number of antennas used and which is dependent on the type of lens selected. For four or more antennas of any of the lenses, we may reconfigure the beam arrangement as indicated above to minimize the beam offset per lens and obtain a slight improvement in performance.

V   Elliptical Paraboloid

Because of the elliptical aperture, the elliptical paraboloid will initially have more beams than the comparable circular paraboloid which has an aperture diameter equal to the minor axis of the elliptical paraboloid. Growth, however, would be similar to the circular paraboloid case.

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VI   Spherical Reflector

This antenna has very good potential for providing more beams. There is a slight problem in scaling to a larger size (so as to illuminate the same geographical area with more beams) in that the phase error is dependent on wavelength and doubling the aperture size would seem to double the phase error. Actually the effective radius of "uniform" phase is dependent both on size and wavelength, primarily on the former, and while doubling the diameter of the reflector does not exactly double the effective aperture, we can make adjustments and design for the larger aperture and for more beams.

The penalty for achieving more beams within the service area is an increase in weight which, of course, becomes progressively worse as the number of antennas is increased.

VII   Luneberg Lens

Because the increase in weight associated with the Luneberg Lens is a volumetric growth of the worst kind, Luneberg Lens candidates were deemed to have little possibility of providing growth to more beams.

VIII   Parabolic Cylinder

For the parabolic cylinder there are complications in providing growth to more beams. It will be recalled that the pillbox weight was comparable to the reflector weight for the reference case and three pillboxes were required for the single antenna version (VIII-A). In going to larger apertures so that more beams can be used within the service area, the pillbox size and weight must grow along with the reflector size and more of the larger pillboxes would be required. This then places the Parabolic Cylinder in a poor position compared to the circular paraboloid, for example, where the feeds are rather simple and the dominant weight penalty is the increased reflector weight.

IX   Offset Parabolic Cylinder

The weight penalty attributed to providing more beams is the same in this case as it was for the Parabolic Cylinder (VIII). The offset parabolic cylinder will have an additional problem with increased axial defocussing as more pillboxes are added.

X   Cylindrical Dielectric Lens

This type of antenna has not only the weight penalty associated with larger and more pillboxes but also a severe weight growth rate associated with the dielectric lens itself. This candidate in all versions was, therefore, considered to have very little potential for growth to more beams.

XI   Cylindrical Artificial Dielectric Lens

XII   Cylindrical Waveguide Lens

These two candidates have the same pillbox weight penalty as associated with other cylindrical concepts (VIII, IX, and X). The growth rate of weight associated with the lens itself is not nearly as severe as it would be for the dielectric lens (X).

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Decision Analysis Worksheet

Decision Statement: I Circular Paraboloid

OBJECTIVES	WT	A 1 antenna		B 2 antennas		C 4 antennas		D >4 antennas	
MUST (— Is it absolutely essential? / — Is it measurable?)		INFO	GO/NO	INFO	GO/NO	INFO	GO/NO	INFO	GO/NO

WANT (— All objectives that are not "musts" / — "musts" we wish to minimize or maximize)

WANT	WT	INFO (A)	SC	WT·SC	INFO (B)	SC	WT·SC	INFO (C)	SC	WT·SC	INFO (D)	SC	WT·SC
4 Minimize inadequate gain areas	10	Comp to orig., more flex in placing feeds -6 → -8dB comp. Xover	7	70	Better than A 3 → -4 dB x over ½ spacing	9	90	Better than B 2 times spacing	10	100	Better but need to go to 12 to imp. spacing for all beams	10	100
5 Maximize beam-to-beam isolation	10	some coma, side lobe coupling, pol. coupling.	5	50	Less interaction Better than A in s.L. + pol. coupling	7	70	Maybe a little better than B	7	70	not much better than C	7	70
6 Maximize number of users	8	Best flexible beam placement	10	80	like A	10	80	like A	10	80	like A	10	80
8 Minimize complexity	7	Routing 15-25 wave guides to back, not bad at 12 GHz	10	70	less complex W.G. Have alignment problem. Seg. dep.	7	49	W.G. ↓ Alignment same Pack worse	2	14	Pack worse than C, etc	0	0
9 Minimize weight	5	9.6 # Ref, 1# sup, 8.3 # feeds ≥18.9 #	10	50	A+9.6+1+1 for boom ≤ 30.5 #	9	45	B+2×9.6+2×1+2×1 ≤ 53.7 #	8	40	100 #	7	35
7 Maximize overall efficiency	3	blockage of 25 feeds off-axis deg ½dB	9	27	slightly better than A	10	30	not much better than B	10	30	like C	10	30
3 Minimize spillover	3	—	10	30	—	10	30	—	10	30	—	10	30
2 Provide coverage of Hawaii	2	separate feed some gain degrad.	7	14	like A	7	14	like A	7	14	like A	7	14
1 Provide coverage of Alaska	2	same as Hawaii	7	14	like A	7	14	like A	7	14	like A	7	14
10 Provide growth to more beams	2	limited by offset possibly 30-35	7	14	30-35	7	14	50	7	14	> 50	7	14
		TOTAL WT·SC		**419**			**436**			**406**			**387**
				(#7)			(#2)			(#12)			(#16)

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ecision Statement: **II Circular Dielectric Lens**

What are we trying to decide?
What is the decision to be made?
What decisions must have already been made?

─────────── ALTERNATIVES ───────────

OBJECTIVES

IST (– Is it absolutely essential?)
(– Is it measurable?)

3M 6098
$\epsilon_r = 2.4 \pm 2\%$
6' 1.5 f/D = 1480# unzoned
296# zoned

ANT (– All objectives that are not "musts" – "Musts" we wish to minimize or maximize)	WT	A 1 INFO	SC	WT/SC	B 2 INFO	SC	WT/SC	C 4 INFO	SC	WT/SC	D >4 INFO	SC	WT/SC
4 Minimize inadequate gain areas	10	like air pol	7	70	like I-B	9	90	like I-C	10	100	like I-D	10	100
5 Maximize beam-to-beam isolation	10	can corr. for coma, anyhow feed prob. like air. pol.	6	60	prob. better than A or I-B	8	80	better than B	8	80	not much better than C	8	80
6 Maximize number of areas	8	like I-A	10	80	like I-B	10	80	like I-C	10	80	like I-D	10	80
8 Minimize complexity	7	Waveguide routing better than air pol. bad stowage & dep.	6	42	not furlable worse than A	3	21	worse than B	1	7	worse than C	0	0
9 Minimize weight	5	1500# unzoned 300# zoned.	4	20	3000/600	2	10	6000/1200	0	0	!!!	0	0
7 Maximize overall efficiency	3	Dielectric losses Eff may be as low as 75%	7	21	like A	7	21	like A	7	21	like A	7	21
3 Minimize spillover	3	—	10	30	—	10	30	—	10	30	—	10	30
2 Provide coverage of Hawaii	2	separate feed, less degrad.(than I-A) of wide angle	8	16	like A	8	16	like A	8	16	like A	8	16
1 Provide coverage of Alaska	2	same as Hawaii	8	16	like A	8	16	like A	8	16	like A	8	16
10 Provide growth to more beams	2	can be wide & bad weight	4	8	like A except not worse	3	6	worse wt, better perf. than A	3	6	worse wt, better perf. than C	3	6
			TOTAL WT/SC	363			370			356			349
				(#20)			(#18)			(#24)			(#26)

WEIGHTING
– Which of our "Want" objectives is the most important? (10)
– What is the relative importance of all other "Want" objectives?
– Does the weight assigned to each objective accurately indicate the contribution that the objective should make in the ultimate decision?

SCORING
– How well do all alternatives under consideration satisfy each specific objective?
– Which alternative provides the greatest satisfaction? (10)
– What is the relative satisfaction provided by all other alternatives?

Decision Statement: III Circular Artificial Dielectric Lens

- Why are we trying to decide?
- What is the decision to be made?
- What decisions must have already been made?

OBJECTIVES

MUST (— Is it absolutely essential? — Is it measurable?)

ALTERNATIVES

	A 1 antenna		B 2 antennas		C 4 antennae		D > 4 antennas	
	INFO	GO/NO	INFO	GO/NO	INFO	GO/NO	INFO	GO/NO

WANT (— All objectives that are not "musts" — "Musts" we wish to minimize or maximize)

	WT	A INFO	SC	WT/SC	B INFO	SC	WT/SC	C INFO	SC	WT/SC	D INFO	SC	WT/SC
4 Minimize inadequate gain area	10	like cir. param.	7	70	like I-B	9	90	like I-C	10	100	like I-D	10	100
5 Maximize beam-to-beam isolation	10	like air. diel. lens	6	60	like II-B	8	80	like II-C	8	80	like II-D	8	80
6 Maximize number of users	8	like air param.	10	80	like I-B	10	80	like I-C	10	80	like I-D	10	80
8 Minimize complexity	7	better wg routing than I, unknown deployment prob.	10	70	worse than A	7	49	worse than B	2	14	worse than C	0	0
9 Minimize weight	5	60# lens + 8.3# feeds + extra struct wg = 70#	8	40	+60#+2# =132#	6	30	+2×60#+2×2# 256	5	25	450#	3	15
7 Maximize overall efficiency	3	maybe better than II may have int. loss	7	21	like A	7	21	like A	7	21	like A	7	21
3 Minimize spillover	3	—	10	30	—	10	30	—	10	30	—	10	30
2 Provide coverage of Hawaii	2	like II-A	8	16	like II-A	8	16	like II-A	8	16	like II-A	8	16
1 Provide coverage of Alaska	2	like II-A	8	16	like II-A	8	16	like II-A	8	16	like II-A	8	16
10 Provide growth to more beams	2	wt. grows could be wide ∠	10	20	worse wt. wide ∠	9	18	better than A but worse wt	8	16	better than C worse wt	8	16
				423			**430**			**398**			**368**

TOTAL WT/SC ► (#6) TOTAL WT/SC ► (#4) TOTAL WT/SC ► (#13) TOTAL WT/SC ► (#19)

WEIGHTING
- Which of our "Want" objectives is the most important? (10)
- What is the relative importance of all other "Want" objectives?
- Does the weight assigned to each objective accurately indicate the contribution that the objective should make in the ultimate decision?

SCORING
- How well do all alternatives under consideration satisfy each specific objective?
- Which alternative provides the greatest satisfaction? (10)
- What is the relative satisfaction provided by all other alternatives?

FORM LMSC 2698 B (FRONT)

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Decision Statement: IV Circular Waveguide Lens

- What are we trying to decide?
- What is the decision to be made?
- What decisions must have already been made?

ALTERNATIVES

OBJECTIVES

MUST (– Is it absolutely essential? – Is it measurable?)

	A 1 antenna	B 2 antennas	C 4 antennas	D > 4 antennas
	INFO / GO/NO	INFO / GO/NO	INFO / GO/NO	INFO / GO/NO

WANT (– All objectives that are not "musts" – "Musts" we wish to minimize or maximize)

Objective	WT	A INFO	SC	WT·SC	B INFO	SC	WT·SC	C INFO	SC	WT·SC	D INFO	SC	WT·SC
4 Minimize inadequate gain areas	10	like cir para	7	70	like I-B	9	90	like I-C	10	100	like I-D	10	100
5 Maximize beam-to-beam isolation	10	like cir diel lens	6	60	like II-B	8	80	like II-C	8	80	like II-D	8	80
6 Maximize number of users	8	like cir para	10	80	like I-B	10	80	like I-C	10	80	like I-D	10	80
8 Minimize complexity	7	like cir art diel lens	10	70	like III-B	7	49	like III-C	2	14	like III-D	0	0
9 Minimize weight	5	100# lens +10# / 110#	7	35	+102# =212#	5	25	416#	3	15	700#	1	5
7 Maximize overall efficiency	3	slightly better than or same as AD Lens	7	21	like A	7	21	like A	7	21	like A	7	21
3 Minimize spill over	3	—	10	30	—	10	30	—	10	30	—	10	30
2 Provide coverage of Hawaii	2	like cir diel lens	8	16	like II-A	8	16	like II-A	8	16	like II-A	8	16
1 Provide coverage of Alaska	2	like cir diel lens	8	16	like II-A	8	16	like II-A	8	16	like II-A	8	16
10 Provide growth to more beams	2	like cir art diel lens	10	20	like III-B	9	18	like III-C	8	16	like III-D	5	10
TOTAL WT·SC				418			425			388			358
				(#8)			(#5)			(#14)			(#23)

WEIGHTING
- Which of our "Want" objectives is the most important? (10)
- What is the relative importance of all other "Want" objectives?
- Does the weight assigned to each objective accurately indicate the contribution that the objective should make in the ultimate decision?

SCORING
- How well do all alternatives under consideration satisfy each specific objective?
- Which alternative provides the greatest satisfaction? (10)
- What is the relative satisfaction provided by all other alternatives?

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FORM LMSC 2696 B (FRONT)

Decision Statement: I Elliptical Paraboloid

OBJECTIVES

MUST (— Is it absolutely essential? / — Is it measurable?)

ALTERNATIVES

A 1 antenna	B 2 antennas	C 4 antennas	D >4 antennas
INFO / GO/NO	INFO / GO/NO	INFO / GO/NO	INFO / GO/NO

WANT (— All objectives that are not "musts" / — "Musts" we wish to minimize or maximize)

WANT	WT	A INFO	SC	WT SC	B INFO	SC	WT SC	C INFO	SC	WT SC	D INFO	SC	WT SC
4 Minimize inadequate gain area	10	like air para. maybe better, maybe not	7	70	Better than A	9	90	better than B	10	100	not much better than C	10	100
5 Maximize beam-to-beam isolation	10	cut off bad part of dish for offset feed.	6	60	Better than A on both S.L. & pol.	7	70	maybe a little better than B	7	70	not much better than C	7	70
6 Maximize number of users	8	like air para	10	80	like I-B	10	80	like I-C	10	80	like I-D	10	80
8 Minimize complexity	7	like air para	10	70	like I-B	10	70	like I-C	7	49	like I-D	2	14	0	0
9 Minimize weight	5	air para + 4# = 23#	10	50	38.5 #	9	45	65.7 #	8	40	150 #	6	30
7 Maximize overall efficiency	3	like air para	9	27	like I-B	10	30	like I-C	10	30	like I-D	10	30
3 Minimize spillover	3	—	10	30	—	10	30	—	10	30	—	10	30
2 Provide coverage of Hawaii	2	sep. feed, maybe less degradation than air para.	8	16	like I-B	8	16	like I-C	8	16	like I-D	8	16
1 Provide coverage of Alaska	2	same as above	8	16	like I-B	8	16	like I-C	8	16	like I-D	8	16
10 Provide growth to more beams	2	more beams better than air para	8	16	better than I-B	8	16	better than I-C	8	16	better than I-D	8	16
TOTAL WT SC				435 (#3)			442 (#1)			412 (#11)			388 (#14)

WEIGHTING
— Which of our "Want" objectives is the most important? (10)
— What is the relative importance of all other "Want" objectives?
— Does the weight assigned to each objective accurately indicate the contribution that the objective should make in the ultimate decision?

SCORING
— How well do all alternatives under consideration satisfy each specific objective?
— Which alternative provides the greatest satisfaction? (10)
— What is the relative satisfaction provided by all other alternatives?

A-28

FORM LMSC 2006 B (FRONT)

LOCKHEED MISSILES & SPACE COMPANY

Decision Analysis Worksheet

Decision Statement: VI Spherical Reflector (approx. 8' diam)

Decision Analysis Worksheet

- What are we trying to decide?
- What is the decision to be made?
- What decisions must have already been made?

A-29

FORM LMSC 2698 B(FRONT)

LOCKHEED MISSILES & SPACE COMPANY

MUST (—Is it absolutely essential? —Is it measurable?)

ALTERNATIVES

OBJECTIVES	A 1 antenna		B 2 antennas		C 4 antennas		D >4 antennas	
	INFO	GO/NO	INFO	GO/NO	INFO	GO/NO	INFO	GO/NO

WANT (—All objectives that are not "musts" —"Wants" we wish to minimize or maximize)

OBJECTIVES	WT	INFO	SC	WT SC	INFO	SC	WT SC	INFO	SC	WT SC	INFO	SC	WT SC
4 Minimize inadequate gain areas	10	comparable to cir para	7	70	comp to I-B	9	90	comp to I-C	10	100	comp to I-D	10	100
5 Maximize beam-to-beam isolation	10	poorer side lobes than cir para	4	40	worse than I-B	5	50	worse than I-C	5	50	worse than I-D	5	50
6 Maximize number of users	8	like cir para	10	80	like I-B	10	80	like I-C	10	80	like I-D	10	80
8 Minimize complexity	7	bigger reflector but like cir para	10	70	like I-B	7	49	like I-C	2	14	like I-D	0	0
9 Minimize weight	5	13# refl, 1 amp, 8.3 feeds 22#	10	50	+13+1+1 37#	9	45	+2×13+2×1+2×1 67#	8	40	125#	6	30
7 Maximize overall efficiency	3	lower than cir para order of loss	7	21	phase error dominant factor	7	21	like B	7	21	like B	7	21
3 Minimize spillover	3	—	10	30	—	10	30	—	10	30	—	10	30
2 Provide coverage of Hawaii	2	separate feed good as any beam	9	18	like A	9	18	like A	9	18	like A	9	18
1 Provide coverage of Alaska	2	same as above	9	18	like A	9	18	like A	9	18	like A	9	18
10 Provide growth to more beams	2	wt growth 50 beams, very good	9	18	wt worse like A	8	16	wt worse same as B	8	16	same as B	8	16
		TOTAL WT SC		**415**			**417**			**387**			**363**
				(#10)			(#9)			(#16)			(#20)

WEIGHTING
- Which of our "Want" objectives is the most important? (10)
- What is the relative importance of all other "Want" objectives?
- Does the weight assigned to each objective accurately indicate the contribution that the objective should make in the ultimate decision?

SCORING
- How well do all alternatives under consideration satisfy each specific objective?
- Which alternative provides the greatest satisfaction? (10)
- What is the relative satisfaction provided by all other alternatives?

Decision Statement: VII Luneberg Lens
- What are we trying to decide?
- What is the decision to be made?
- What decisions must have already been made?

OBJECTIVES

MUST (—Is it absolutely essential? —Is it measurable?)

ALTERNATIVES

A 1 antenna	B 2 antennas	C 4 antennas	D >4 antennas
INFO GO/NO	INFO GO/NO	INFO GO/NO	INFO GO/NO

WANT (—All objectives that are not "musts" — "Musts" we wish to maximize or minimize)

OBJECTIVE	WT	A INFO	A SC	A WT·SC	B INFO	B SC	B WT·SC	C INFO	C SC	C WT·SC	D INFO	D SC	D WT·SC
4 Minimize inadequate gain areas	10	Prob. very hard to get high f over due to crowding	6	60	Better than A, but not quite as good as I-B	9	90	Better than B	10	100	Better than B	10	100
5 Maximize beam-to-beam isolation	10	should have high front side lobes	5	50	like A	5	50	like A	5	50	like A	5	50
6 Maximize number of users	8	like air para	10	80	like I-B	10	80	like I-C	10	80	like I-D	10	80
8 Minimize complexity	7	cannot be furled hard to hold	3	21	diff to be corrected on 10' shroud except stacked axially	1	7	not feasible	0	0	not feasible	0	0
9 Minimize weight	5	1340# at 5' Diam 3600# at 7' (20.5#/f²)	0	0	1-4 tons	0	0	2-8 tons	0	0	!!	0	0
7 Maximize overall efficiency	3	dielectric losses high illumination	7	21	like A	7	21	like A	7	21	like A	7	21
3 Minimize spillover	3	—	10	30	—	10	30	—	10	30	—	10	30
2 Provide coverage of Hawaii	2	Best, sep. feed	10	20	like A	10	20	like A	10	20	like A	10	20
1 Provide coverage of Alaska	2	Best, sep feed	10	20	like A	10	20	like A	10	20	like A	10	20
10 Provide for growth to more beams	2	enormous wt penalty	0	0	more wt	0	0	worse	0	0	worse yet	0	0
TOTAL WT·SC				**302**			**318**			**321**			**321**
				(#48)			(#39)			(#34)			(#34)

WEIGHTING
- Which of our "Want" objectives is the most important? (10)
- What is the relative importance of all other "Want" objectives?
- Does the weight assigned to each objective accurately indicate the contribution that the objective should make to the ultimate decision?

SCORING
- How well do all alternatives under consideration satisfy each specific objective?
- Which alternative provides the greatest satisfaction? (10)
- What is the relative satisfaction provided by all other alternatives?

FORM LMSC 2498 B (FRONT)

LOCKHEED MISSILES & SPACE COMPANY

A-30

Decision Analysis Worksheet

Decision Statement: VIII Parabolic Cylinder

MUST (— Is it absolutely essential? — Is it measurable?)

ALTERNATIVES

OBJECTIVES	A 1 antenna	B 2 antennas	C 4 antennas	D > 4 antennas
	INFO GO/NO	INFO GO/NO	INFO GO/NO	INFO GO/NO

WANT (— All objectives that are not "musts" — "Musts" we wish to minimize or maximize)

WT	Objective	A INFO	SC	WT·SC	B INFO	SC	WT·SC	C INFO	SC	WT·SC	D INFO	SC	WT·SC
10	4 Minimize inadequate gain areas	Problem covering Fla. & New Eng. beams must be in line	3	30	NE & Fla. problem, better feed spacing	5	50	Better than B	6	60	Need to go to 12 to improve spacing (>C) for all beams	6	60
10	5 Maximize beam-to-beam isolation	Could have pol cplg in feeds, better X pol than cir para	7	70	No pol coupling on feeds, good X pol	10	100	like B	10	100	like B	10	100
8	6 Maximize number of users	Restricted by line sources	9	72	like A	9	72	like A	9	72	like A	9	72
7	8 Minimize complexity	3 pillbox feeds support both pol.	6	42	2 refl, 6 feeds alignment good & deep feeds not suitable	4	28	4 refl, 6 feeds worse than B	2	14	Either 12 refl, 12 feeds or 5 refl 8 feeds for NE & Fla	0	0
5	9 Minimize weight	25# ref + 4# supp + 20#/feed = 89#	7	35	2×25# + 6×20# + 72×4# = 178#	6	30	4×25 + 6×20 + 4×4 = 236#	5	25	320#	4	20
3	7 Maximize overall efficiency	about .4 dB worse than cir. para.	6	18	like A	6	18	better than B	6	18	about like C, .3dB	6	18
3	3 Minimize spillover	—	10	30	—	10	30	—	10	30	—	10	30
2	2 Provide coverage of Hawaii	Probably extra pillbox, block + wt	2	4	like A except it blocks only 1 reflector	4	8	like A except blocks 1 refl	5	10	like A except blocks 1 refl	5	10
2	1 Provide coverage of Alaska	like Hawaii	2	4	like Hawaii	4	8	like Hawaii	5	10	like Hawaii	5	10
2	10 Provide growth to more beams	heavier pillboxes, more of them	3	6	worse than A	2	4	worse than B	1	2	worse than C	0	0
	TOTAL WT·SC			**311**			**348**			**341**			**320**
				(#43)			(#27)			(#29)			(#37)

Decision Analysis Worksheet

Decision Statement: IX Offset Parabolic Cylinder

What are we trying to decide?
What is the decision to be made?
What decisions must have already been made?

OBJECTIVES

MUST (— Is it absolutely essential? — Is it measurable?)

ALTERNATIVES

		A 1 antenna		B 2 antennas		C 4 antennas		D > 4 antennas	
		INFO	GO/NO	INFO	GO/NO	INFO	GO/NO	INFO	GO/NO

WANT (— All objectives that are not "musts" — "Musts" we wish to maximize or minimize)

OBJECTIVE	WT	INFO	SC	WT SC	INFO	SC	WT SC	INFO	SC	WT SC	INFO	SC	WT SC
4 Minimize inadequate gain areas	10	like para cyl	3	30	like VIII-B	5	50	like VIII-C	6	60	like VIII-D	6	60
5 Maximize beam-to-beam isolation	10	like para cyl	7	70	like VIII-B	10	100	like VIII-C	10	100	like VIII-D	10	100
6 Maximize number of users	8	like para cyl	9	72	like VIII-B	9	72	like VIII-C	9	72	like VIII-D	9	72
8 Minimize complexity	7	little better than para cyl	7	49	like A	7	49	worse than B	3	21	worse than C	0	0
9 Minimize weight	5	like para cyl 89*	7	35	178*	6	30	236*	5	25	320*	4	20
7 Maximize overall efficiency	3	no block but axial defocusing occurs	7	21	like A	7	21	a little better than B for some beams	7	21	like C unless large number of antennas used	7	21
3 Minimize spillover	3	———	10	30	———	10	30	———	10	30	———	10	30
2 Provide coverage of Hawaii	2	extra wt + more defocusing like VIII-A	2	4	like A	2	4	like A	2	4	like A	2	4
1 Provide coverage of Alaska	2	like Hawaii	2	4	like Hawaii	2	4	like Hawaii	2	4	like Hawaii	2	4
10 Provide growth to more beams	2	like para cyl + defocusing	2	4	worse than A	1	2	worse than B	1	2	worse than C	0	0

TOTAL WT SC	319	TOTAL WT SC	362	TOTAL WT SC	339	TOTAL WT SC	311

(#38)   (#22)   (#30)   (#43)

WEIGHTING
- Which of our "Want" objectives is the most important? (10)
- What is the relative importance of all other "Want" objectives?
- Does the weight assigned to each objective accurately indicate the contribution that the objective should make in the ultimate decision?

SCORING
- How well do all alternatives under consideration satisfy each specific objective?
- Which alternative provides the greatest satisfaction? (10)
- What is the relative satisfaction provided by all other alternatives?

Decision Analysis Worksheet

ecision Statement: X Cylindrical Dielectric Lens

JST (- Is it absolutely essential?)
   (- Is it measurable?)

— OBJECTIVES —

— ALTERNATIVES —

		A 1 antenna		B 2 antennas		C 4 antennas		D >4 antennas	
		INFO	GO/NO	INFO	GO/NO	INFO	GO/NO	INFO	GO/NO

ANT (- All objectives that are not "musts" - "Musts" we wish to minimize or maximize)

# OBJECTIVE	WT	A INFO	SC	WT SC	B INFO	SC	WT SC	C INFO	SC	WT SC	D INFO	SC	WT SC
4 Minimize inadequate gain over	10	about like cyl par.	3	30	like VIII-B	5	50	like VIII-C	6	60	like VIII-D	6	60
5 Maximize beam-to-beam isolation	10	like para cyl.	7	70	like VIII-B	10	100	like VIII-C	10	100	like VIII-D	10	100
6 Maximize number of users	8	like para cyl	9	72	like VIII-B	9	72	like VIII-C	9	72	like VIII-D	9	72
8 Minimize complexity	7	pill boxes, etc, worse than cyl dielbens	6	42	worse than A	4	28	worse than B	2	14	worse than C	0	0
9. Minimize weight	5	1/4π x cir + 3 x pillbox >1500# ans 1300# zenith 360#	4	20	>3000/>600# 726#	1	5	>6000/>1200	0	0	!!!	0	0
7 Maximize overall efficiency	3	Pillbox block, diel loss, lower 25%	7	21	Pillbox block like A	7	21	like A	7	21	like A	7	21
3 Minimize spillover	3	—	10	30	—	10	30	—	10	30	—	10	30
2 Provide coverage of Hawaii	2	wt of ext pillbox	5	10	like A	5	10	like A	5	10	like A	5	10
1 Provide coverage of Alaska	2	wt of ext pillbox	5	10	like A	5	10	like A	5	10	like A	5	10
10 Provide growth to more beams	2	disastrous wt inc	0	0	wt	0	0	wt	0	0	wt	0	0

TOTAL WT SC: **305** ◄   (#46)

TOTAL WT SC: ► **326**   (#33)

TOTAL WT SC: ► **317**   (#40)

TOTAL WT SC: ► **303**   (#47)

Decision Analysis Worksheet

Decision Statement: XI Cylindrical Artificial Dielectric Lens

- What are we trying to decide?
- What is the decision to be made?
- What decisions must have already been made?

OBJECTIVES

MUST (— Is it absolutely essential? — Is it measurable?)

ALTERNATIVES

	A 1 antenna	B 2 antennas	C 4 antennas	D >4 antennas
INFO / GO-NO				

WANT (— All objectives that are not "musts" — "Musts" we wish to minimize or maximize)

WANT	WT	A INFO	A SC	A WT·SC	B INFO	B SC	B WT·SC	C INFO	C SC	C WT·SC	D INFO	D SC	D WT·SC
4 Minimize inadequate gain areas	10	like para cyl	3	30	like VIII-B	5	50	like VIII-C	6	60	like VIII-D	6	60
5 Maximize beam-to-beam isolation	10	like para cyl.	7	70	like VIII-B	10	100	like VIII-C	10	100	like VIII-D	10	100
6 Maximize number of users	8	like para cyl.	9	72	like VIII-B	9	72	like VIII-C	9	72	like VIII-D	9	72
8 Minimize complexity	7	Feeds worse than air par.	6	42	worse than A	4	28	worse than B	2	14	worse than C	0	0
9 Minimize weight	5	75# +3×20# + 4# = 139#	6	30	A+75 +3×20+4 = 278	5	25	B+ 2×75 + 2×4 = 436	3	15	625 #	2	10
7 Maximize overall efficiency	3	like cyl. diel lens	7	21	like X-B	7	21	like X-C	7	21	like X-D	7	21
3 Minimize spillover	3	—	10	30	—	10	30	—	10	30	—	10	30
2 Provide coverage of Hawaii	2	like cyl. diel lens	5	10	like X-B	5	10	like X-C	5	10	like X-D	5	10
1 Provide coverage of Alaska	2	like cyl diel lens	5	10	like X-B	5	10	like X-C	5	10	like X-D	5	10
10 Provide growth to more beams	2	Pillbox wt. better than cyl diel lens	3	6	worse than A	2	4	worse than B	1	2	worse than C	0	0
TOTAL WT·SC				**321**			**350**			**334**			**343**
				(#34)			(#25)			(#31)			(#42)

WEIGHTING
- Which of our "Want" objectives is the most important? (10)
- What is the relative importance of all other "Want" objectives?
- Does the weight assigned to each objective accurately indicate the contribution that the objective should make in the ultimate decision?

SCORING
- How well do all alternatives under consideration satisfy each specific objective?
- Which alternative provides the greatest satisfaction? (10)
- What is the relative satisfaction provided by all other alternatives?

Decision Statement: XII Cylindrical Waveguide Lens

OBJECTIVES

MUST (– Is it absolutely essential? / – Is it measurable?)

ALTERNATIVES

WANT (– All objectives that are not "musts" / – "Musts" we wish to minimize or maximize)	WT	A 1 antenna INFO	SC	WT SC	B 2 antennas INFO	SC	WT SC	C 4 antennas INFO	SC	WT SC	D > 4 antennas INFO	SC	WT SC
4 Minimize inadequate gain areas	10	like para cyl	3	30	like VIII–B	5	50	like VIII–C	6	60	like VIII–D	6	60
5 Maximize beam-to-beam isolation	10	like para cyl	7	70	like VIII–B	10	100	like VIII–C	10	100	like VIII–D	10	100
6 Maximize number of users	8	like para cyl	9	72	like VIII–B	9	72	like VIII–C	9	72	like VIII–D	9	72
8 Minimize complexity	7	like cyl art diel lens	6	42	like XI–B	4	28	like XI–C	2	14	like XI–D	0	0
9 Minimize weight	5	$\frac{133^\# + 4 + 3 \times 20}{197^\#}$	5	25	$\frac{A + 133 + 4 + 3 \times 20}{394^\#}$	4	20	$\frac{B + 2 \times 4 + 2 \times 133}{668^\#}$	2	10	$825^\#$	1	5
7 Maximize overall efficiency	3	slightly better or same for cyl art diel lens.	7	21	like A	7	21	like A	7	21	like A	7	21
3 Minimize spillover	3	———	10	30	———	10	30	———	10	30	———	10	30
2 Provide coverage of Hawaii	2	like cyl diel lens	5	10	like X–B	5	10	like X–C	5	10	like X–D	5	10
1 Provide coverage of Alaska	2	like cyl diel lens	5	10	like X–B	5	10	like X–C	5	10	like X–D	5	10
10 Provide growth to more beams	2	like cyl. A.D lens	3	6	like XI–B	2	4	like XI–C	1	2	like XI–D	0	0
TOTAL WT SC				316			345			329				308
				(#41)			(#28)			(#32)				(#45)

WEIGHTING
– Which of our "Want" objectives is the most important? (10)
– What is the relative importance of all other "Want" objectives?
– Does the weight assigned to each objective accurately indicate the contribution that the objective should make in the ultimate decision?

SCORING
– How well do all alternatives under consideration satisfy each specific objective?
– Which alternative provides the greatest satisfaction? (10)
– What is the relative satisfaction provided by all other alternatives?

A-35

FORM LMSC 2696 D (FRONT)

LOCKHEED MISSILES & SPACE COMPANY

APPENDIX B

EVALUATION OF CANDIDATE ANTENNAS

STEP II ANALYSIS

Evaluation of Candidate Antennas -- Step II

Introductory Remarks

Each of the 15 candidates in the Step II analysis was evaluated against the 7 Wants in the revised Want list. The assessments are discussed in detail in this Appendix. The actual worksheets are also included here.

Want #4: Minimize Inadequate Gain Areas

This Want applies to providing uniform coverage of the service area. Considerations of relative peak gain of different antenna types were ruled as not being pertinent in this Want, since such considerations are covered elsewhere in Want #7. Factors affecting the uniformity of coverage are the achievable cross-over level and relative degradation of beam gain as a function of offset angle. This Want has a weighting of 9.

I Circular Paraboloid

A single circular paraboloid could probably be designed to achieve a -5 dB crossover level. The degradation of peak gain for the beams offset the most from the reflector axis would probably amount to 0.6 dB, based on our studies of paraboloidal reflector off-axis performance with an 0.5 focal length-to-diameter ratio. For the two-antenna case (I-B) a -3 dB crossover was considered possible with the same off-axis degradation. For the four-antenna case (I-C) with the beams divided into east-west sectors, the scan degradation would be a little less.

III Circular Artificial Dielectric Lens

For the single antenna case (III-A) coverage should be about the same as for the circular paraboloid (I-A) except that we can correct the coma to reduce off-axis beam degradation. There might be a problem, however, in obtaining proper illumination if we need to use endfire feeds to get the required feed spacing. With the two-antenna (III-B) and the four-antenna (III-C) cases, the feed problem

B-1

is alleviated due to greater spacing between feeds. Coma correction is possible in the multiple antenna versions also.

IV Circular Waveguide Lens

All versions of the circular Waveguide lens were considered to be comparable to the corresponding versions of the Circular Artificial Dielectric Lens.

V Elliptical Paraboloid

Our studies show that if we maintain a focal length of one half the aperture dimension in the plane of scan, reducing the aperture dimension in the perpendicular plane decreases the gain degradation for off-axis beams and increasing the aperture dimension in the perpendicular plane increases the gain degradation. In the case considered the east-west dimension is smaller than the north-south dimension. While the beam offsets are in all planes, the predominant offset is parallel to the minor axis of the reflector aperture which would tend to increase degradation. This, however, is a matter of only a few tenths dB. Thus the elliptical paraboloid is considered essentially equivalent to the circular paraboloid with respect to the coverage Want.

VI Spherical Reflector

The spherical reflector has no gain degradation for offset beams. Except for that, the spherical reflector versions are essentially the same as the corresponding circular paraboloid versions.

Want #5: Maximize Beam-to-Beam Isolation

Factors which affect satisfaction of this Want are coma lobe and side lobe levels (and locations) and the purity of polarization. A detailed investigation was made of coma lobe and side lobe coupling. All candidates have essentially the same polarization characteristics, except that two-antenna and four-antenna versions of each of the antenna types can be purified in polarization by means of grids.

B-2

I   Circular Paraboloid

For the circular paraboloid the coma lobe for a 0.5 F/D ratio is about -13 to -14 dB below the peak for the offset required. The second side lobe is at the -22 dB level. For the one antenna version (I-A) which has a -5 dB crossover level, the second side lobe will appear within the closest co-polarized beam in the direction toward the reflector axis and is therefore the limiting factor. The coma lobe will appear within the adjacent beam which usually would be cross-polarized. There will be some increase in side lobes over the level mentioned due to blocking effects.

For the two antenna version (I-B) the crossover is assumed to be at the -3 dB level. This places the coma lobe in the nearest co-polarized beam resulting in interference at the -13 to -14 dB level at maximum offset angle. With the two antenna version, cross-polarization coupling may be reduced by using polarization grids. There may be some slight reduction in blocking effects.

For the two antenna version where we have more freedom in setting the cross-over level due to greater feed spacing, it is obvious that we may trade off between achieving a high cross-over level and obtaining better beam-to-beam isolation. Isolation is a matter of which lobe of the off-axis pattern we allow to interfere with the closest co-polarized beam. If we design the two antenna version to have a -5 dB cross-over (like the one-antenna case), then coverage is poorer and the isolation is improved. The two-antenna case is then about the same as the one-antenna case, except for more weight and complexity. The only advantages of designing the two-antenna version to duplicate the coverage of the one-antenna version would be less interaction between feeds (due to greater feed-to-feed spacing) and the capability to use grids to purify the polarization.

B-3

For the four-antenna version (I-C) the beams would be divided into east and west sectors as well as by polarization. This reduces the offset angle required and lowers the interfering coma lobe to -18 dB and the second side lobe to -27 dB. With -3 dB crossover level the interfering lobe is the coma lobe, some 12 or more dB higher than required to provide the needed 30 dB beam-to-beam isolation. As before, we can trade coverage, complexity and weight to improve the isolation slightly.

      III   Circular Artificial Dielectric Lens

      IV   Circular Waveguide Lens

Either of these may be designed for coma correction and their characteristics are essentially the same except that there may be better far-out side lobe performance from the circular artificial dielectric lens. To achieve the required bandwidth, the circular artificial dielectric lens would not be zoned and the circular waveguide lens would be zoned.

Using coma correction designs, the side lobes for the single antenna versions (III-A and IV-A) would be at the -25 dB level (or better) and there would be essentially no degradation for beam offsets of four beamwidths, based on published data. Cross-polarized lobes would probably be at the -20 dB level for the artificial dielectric lens (III-A) and at the -26 dB level for the waveguide lens (IV-A). For the two antenna versions (III-B and IV_B) beam-to-beam isolation can be improved in two ways. First, in the two-antenna versions the polarization can be improved rather simply, either by designing the lenses to support only the appropriate polarizations or by adding grids which can be directly attached to the lens. Second, with larger feed spacing in the two antenna versions, there is a good possibility that a lower side lobe level can be achieved by controlling the feed patterns. Four-antenna versions (III-C and IV-C) offer only a slight improvement in isolation compared to the two antenna versions.

V Elliptical Paraboloid

If we maintain a focal length of one half the aperture dimension in the plane of scan, increasing the aperture dimension in the perpendicular plane decreases the coma lobe level for a given offset and vice versa. In the case considered the east-west dimension is smaller than the north-south dimension. While the offsets occur in all planes, the predominant offset is parallel to the minor axis of the elliptical aperture which would tend to decrease coma lobe problems. For an aspect ratio of 1.5:1 this amounts to only 4 dB for 4 beam widths of offset and is not significant enough to bring the performance of the paraboloidal reflector to an acceptable level. Thus all three versions of the elliptical paraboloid are essentially equivalent to corresponding versions of the circular paraboloid in beam-to-beam isolation.

VI Spherical Reflector

The spherical reflector when optimized for peak gain and adjusted in aperture size to provide the same beamwidth obtained from the circular paraboloid has a first side lobe of -13 dB. This side lobe is rotationally symmetric around the beam axis and therefore interfere with all neighboring lobes (as compared to the circular paraboloid which has a coma lobe only on the side of the beam toward the reflector axis). Thus the spherical reflector has very poor beam-to-beam isolation.

Want #6: Maximize the Number of Users

For the Step II analysis we did not consider different beam arrangements or different numbers of beams for the various candidates. All candidates, since they have the same freedom in location of beams, were considered to have equivalent capability to maximize the number of users.

Want #8: Minimize Complexity

I Circular Paraboloid

The one-antenna version (I-A) is the standard of comparison relative to complexity among the various candidates. A single paraboloid with multiple feeds is involved and the only problem is routing

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15 to 25 waveguides to the backside of the reflector. With the two-antenna version (I-B) there is a less troublesome waveguide routing problem, but there is the additional problem of aligning interlaced beams from two different pieces of hardware. Also packing and stowage for launch and the deployment become more complicated. With the four-antenna version (I-C) the packing and deployment problems are even more complicated.

III   Circular Artificial Dielectric Lens

The single lens (III-A) has simpler waveguide routing since the feeds are behind the objective and direct connections may be made to the individual feeds. For the aperture sizes needed a furlable design is not required, but if the lens is not furled there is a more complicated packing problem for launch (as compared with a furlable paraboloid). Supporting the lens/feed assembly is more complicated than the paraboloidal case because of the long focal length and the relatively high weight of the lens compared to the feed cluster (the feed cluster normally would be the base from which the lens is supported).

For multiple antenna versions (III-B and III-C) we have the alignment problem plus a more complicated packing arrangement and more complicated deployment.

IV   Circular Waveguide Lens

The circular waveguide lens versions (IV-A, IV-B, and IV-C) are similar to the corresponding versions of the circular artificial dielectric lens except that the waveguide lenses are considered to have a more critical tolerance problem.

V   Elliptical Paraboloid

The elliptical paraboloid versions (V-A, V-B, and V-C) are similar to the corresponding versions of the circular paraboloid except that there may be a problem with the feeds in obtaining the required feed pattern shapes.

VI   Spherical Reflector

The spherical reflector versions (VI-A, VI-B, and VI-C) were considered to be essentially the same in complexity as the corresponding versions of the circular paraboloid.

Want #9: Minimize Weight

For the Step II analysis, the weight estimates of the Step I analysis were used. The weight figures were reviewed and, in the absence of a more detailed weight analysis, were considered good enough for the purposes of the Step II analysis. Weight estimates for the reflector candidates were considered to be reliable, as they are based on a large amount of reflector experience. It was recognized that lens weights were less reliable.

The weights for Step II analysis were as follows:

Type	Version		
	A (1)	B (2)	C (4)
I Circular Paraboloid	18.9#	30.5#	53.7#
II Circular Art. Diel. Lens	70	132	256
IV Circular Waveguide Lens	110	212	416
V Elliptical Paraboloid	23	38.5	65.7
VI Spherical Reflector	22	37	67

Want #7: Maximize Overall Efficiency

In this Want we are comparing relative gain of the candidates when the beamwidth is held constant.

I Circular Paraboloid

For the one-antenna version (I-A) there would be a small loss in gain due to blocking by the feeds and about a 0.6 dB maximum gain degradation for offset beams. For the two-antenna version (I-B) there may be some slight improvement in blocking, but gain performance is considered essentially the same as for the one-antenna case. For the four-antenna case, particularly if the beams are divided into east and west sectors, the blocking and offset beam degradation will be reduced.

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III   Circular Artificial Dielectric Lens

For all versions of the circular artificial dielectric lens (III-A, III-B and III-C) there will be no blocking problems. There will be internal losses in the lens plus some losses due to surface mismatch, maybe amounting to as much as 2 to 3 dB. There should be little degradation for offset beams.

IV   Circular Waveguide Lens

For all versions of the circular waveguide lens (IV-A, IV-B, and IV-C) IV-C) there will be no blocking of the secondary aperture and little degradation for offset beams. However, there will be zoning losses, surface mismatch losses and internal losses, all of which may amount fo 2 to 3 dB.

V   Elliptical Paraboloid

We are considering here the reduction (compared to the circular paraboloid) of the east-west aperture dimension to circularize the beam footprints. This reduces aperture area and results in 1 dB less gain for all versions (V-A, V-B, and V-C) compared with the circular paraboloid.

VI   Spherical Reflector

The characteristics of the spherical reflector versions (VI-A, VI-B, and VI-C) are similar to the corrsponding versions of the circular paraboloid except that there is no degradation for offset beams (compared to the central beam) and except that for a fixed beamwidth the spherical reflector produces about 1.7 dB less gain.

Want #8: Provide for Coverage of Alaska and Hawaii

I   Circular Paraboloid

For the single antenna (I-A) and two-antenna (I-B) versions, the additional beams can be provided by additional feeds. For complete coverage of Alaska a synthesized beam from two or more feeds may be required. This coverage can be provided with degraded gain. For the four-antenna version with an east-west division of beams the gain degradation will be somewhat less than obtained for the other versions.

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III Circular Artificial Dielectric Lens

IV Circular Waveguide Lens

Both of these lenses in all versions can be designed to provide the additional coverage with less gain degradation than the circular paraboloid. The four-antenna versions (III-C and IV-C) will probably be better than corresponding two antenna versions if an east-west division of beams is employed.

V Elliptical Paraboloid

The elliptical paraboloid is essentially the same as the circular paraboloid.

VI Spherical Reflector

The spherical reflector provides the additional coverage without further degradation of gain as a function of offset. Of course, the spherical reflector provides lower gain than the circular paraboloid in the first place (for fixed beamwidth determined by coverage of the contiguous 48 states). There is less blockage in the multiple antenna versions.

Decision Statement: *I Circular Paraboloid*

- What are we trying to decide?
- What is the decision to be made?
- What decisions must have already been made?

MUST (– Is it absolutely essential?)
(– Is it measurable?)

─── ALTERNATIVES ───

OBJECTIVES		A 1 Antenna		B 2 Antennas		C 4 Antennas		D

WANT (– All objectives that are not "musts" — "Musts" we wish to minimize or maximize?)

	WT	INFO	SC	WT SC	INFO	SC	WT SC	INFO	SC	WT SC	INFO	SC	WT SC
4 Minimize Inadequate Gain Areas	9	–5 dB x-over degrad. –0.6 dB over scan	9	81	–3 dB x-over poss. degr. –0.6 dB over scan	10	90	less degr than I-B for E-W div of beams	10	90			
5 Maximize Beam-To-Beam Isolation	10	with –5 dB x-over 2nd sidelobe inter. at –22 dB, + blockage effect & X-pol.	2	20	with –3 dB x-over –13→–14 dB coma maybe less block less X-pol coup.	1	10	for EW dir of bms coma –18 dB, 2nd lobe –27 dB, X pol like I-B	1	10			
6 Maximize Number of Users	6	————	10	60	————	10	60	————	10	60			
8 Minimize Complexity	5	simple, no routing problem.	10	50	less routing prob alignment, worse stowage, deploy. more difficult	6	30	even worse pack + deploy, alignment better routing	2	10			
9 Minimize Weight	3	18.9#	10	30	30.5#	9	27	53.7#	8	24			
7 Maximize Overall Efficiency	3	blocking, –0.6 dB scan deg.	9	27	prob. same as I-A or little better –.6 dB scan	9	27	less block than I-A	10	30			
2 Provide Coverage of Alaska, Hawaii	1	degraded gain	6	6	degraded gain	6	6	better than I-B for E-W div.	7	7			

		TOTAL WT SC		TOTAL WT SC		TOTAL WT SC		TOTAL WT SC
	274 ◄		**250**		**231**			

Decision Statement: III Circular Artificial Dielectric Lens

- What are we trying to decide?
- What is the decision to be made?
- What decisions must have already been made?

ALTERNATIVES

OBJECTIVES

MUST (– Is it absolutely essential? – Is it measurable?)

	A 1 Antenna		B 2 Antennas		C 4 Antennas		D	
	INFO	GO/NO	INFO	GO/NO	INFO	GO/NO	INFO	GO/NO

WANT (– All objectives that are not "musts" – "Musts" we wish to minimize or maximize)

OBJECTIVES	WT	INFO (A)	SC	WT SC	INFO (B)	SC	WT SC	INFO (C)	SC	WT SC	INFO (D)	SC	WT SC
4. Minimize Inadequate Gain Areas	9	can coma correct may be worse than I-A due to endfire feed problem	9	81	like I-B except can coma correct	10	90	like I-C except can coma correct	10	90			
5. Maximize Beam-To-Beam Isolation	10	like cir. wg lens(IV-A) -20dB X-pol, maybe better far out side lobes	8	80	like IV-B, maybe better far out side lobes	10	100	like IV-C, maybe better far out side lobes	10	100			
6. Maximize Number of Users	6	————	10	60	————	10	60	————	10	60			
8. Minimize Complexity	5	simple WG Routing support over F/D=1 need not be unfurl, K not, bad pack	8	40	alignment, worse pack, sequential dep, etc.	4	20	worse than III-B	1	5			
9. Minimize Weight	3	70#	8	24	132#	7	21	256#	5	15			
7. Maximize Overall Efficiency	3	no blocking, but internal + surface losses, 2–3 dB	4	12	like III-A	4	12	like III-A	4	12			
2. Provide Coverage of Alaska, Hawaii	1	like IV-A	9	9	like IV-B	9	9	like IV-C	9	9			

TOTAL WT SC ◄ **306** ►   **TOTAL WT SC** ◄ **312** ►   **TOTAL WT SC** ◄ **291** ►   **TOTAL WT SC** ►

WEIGHTING
- Which of our "Want" objectives is the most important? (10)
- What is the relative importance of all other "Want" objectives?
- Does the weight assigned to each objective accurately indicate the contribution that the objective should make in the ultimate decision?

SCORING
- How well do all alternatives under consideration satisfy each specific objective?
- Which alternative provides the greatest satisfaction? (10)
- What is the relative satisfaction provided by all other alternatives?

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Decision Analysis Worksheet

Decision Statement: _IV Circular Waveguide Lens_
- What are we trying to decide?
- What is the decision to be made?
- What decisions must have already been made?

OBJECTIVES

MUST (– Is it absolutely essential?)
(– Is it measurable?)

WANT (– All objectives that are not "musts" / – "Musts" we wish to minimize or maximize)	WT	A 1 Antenna INFO	SC	WT SC	B 2 Antennas INFO	SC	WT SC	C 4 Antennas INFO	SC	WT SC	D INFO	SC	WT SC
4 Minimize Inadequate Gain Areas	9	like A.D lens (III-A)	9	81	like III-B	10	90	like III-C	10	90			
5 Maximize Beam-to-Beam Isolation	10	-25 dB SL, little deg for 4 Beamwidths X-pol -26 dB, better than I-A	8	80	better than IV-A due to more feed room. -30 dB SL, better X-pol, no scan deg	10	100	like IV-B, little more freedom for shaping	10	100			
6 Maximize Number of Users	6	————	10	60		10	60	————	10	60			
8 Minimize Complexity	5	like III-A except more critical tol.	6	30	like III-B except more critical tol.	3	15	like III-C except more crit. Tol.	0	0			
9 Minimize Weight	3	110#	7	21	212#	5	15	416#	2	6			
7 Maximize Overall Efficiency	3	no sec. blocking but zoning loss surface mismatch 2 - 3 dB	4	12	like IV-A	4	12	like IV-A	4	12			
2 Provide Coverage of Alaska, Hawaii	1	extra feeds may affect coma correction	9	9	like IV-A	9	9	prob better than IV-B	9	9			

TOTAL WT SC: **293** ◀ | **301** ▶ | **277** |

WEIGHTING
- Which of our "Want" objectives is the most important? (10)
- What is the relative importance of all other "Want" objectives?
- Does the weight assigned to each objective accurately indicate the contribution that the objective should make in the ultimate decision?

SCORING
- How well do all alternatives under consideration satisfy each specific objective?
- Which alternative provides the greatest satisfaction? (10)
- What is the relative satisfaction provided by all other alternatives?

FORM LMSC 2695 B (FRONT)

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LMSC/D984597

Decision Analysis Worksheet

Decision Statement: _V Elliptical Paraboloid_

- What are we trying to decide?
- What is the decision to be made?
- What decisions must have already been made?

OBJECTIVES / ALTERNATIVES

MUST (−Is it absolutely essential? / −Is it measurable?)

OBJECTIVES	A _1 Antenna_		B _2 Antennas_		C _4 Antennas_		D	
	INFO	GO/NO	INFO	GO/NO	INFO	GO/NO	INFO	GO/NO

WANT (−All objectives that are not "musts" / "Musts" we wish to minimize or maximize)

Objective	WT	INFO (A)	SC	WT SC	INFO (B)	SC	WT SC	INFO (C)	SC	WT SC	INFO (D)	SC	WT SC
4 Minimize Inadequate Gain Areas	9	almost like I-A	9	81	like I-B	10	90	like I-C	10	90			
5 Maximize Beam-to-Beam Isolation	10	like cir par (but different coma, etc.)	2	20	like I-B	1	10	like I-C	1	10			
6 Maximize Number of Users	6	———	10	60	———	10	60	———	10	60			
8 Minimize Complexity	5	like I-A with poss. feed des problem	10	50	like I-B + feed prob.	6	30	like I-C + feed problem	2	10			
9 Minimize Weight	3	23$^{\#}$	10	30	38.5	9	27	65.7	8	24			
7 Maximize Overall Efficiency	3	like I-A except 1 dB less gain for smaller EW dim.	8	24	like I-B except 1 dB less gain	8	24	like I-C but 1 dB less gain	9	27			
2 Provide Coverage of Alaska, Hawaii	1	degraded gain	6	6	degraded gain	6	6	better than V-B for EW dir.	7	7			

TOTAL WT SC: A = 271 ◄ | B = 247 ► | C = 228 ►| D = ►

Decision Analysis Worksheet

Decision Statement: VI Spherical Reflector
- What are we trying to decide?
- What is the decision to be made?
- What decisions must have already been made?

OBJECTIVES

MUST (—Is it absolutely essential?) (—Is it measurable?)

ALTERNATIVES

	A / Antenna		B 2 Antennas		C 4 Antennas		D	
	INFO	GO/NO	INFO	GO/NO	INFO	GO/NO	INFO	GO/NO

WANT (— All objectives that are not "musts" — "Musts" we wish to minimize or maximize)

Objective	WT	INFO (A)	SC	WT SC	INFO (B)	SC	WT SC	INFO (C)	SC	WT SC	INFO (D)	SC	WT SC
4 Minimize Inadequate Gain Areas	9	like VI-A except no scan deg	9	81	like VI-B except no scan deg	10	90	like VI-C except no scan deg	10	90			
5 Maximize Beam-to-Beam Isolation	10	1st lobe -13dB is all around + for all beams, > fill in, cover more area	0	0	like VI-A	0	0	like VI-A	0	0			
6 Maximize Number of Users	6	—	10	60	—	10	60	—	10	60			
8 Minimize Complexity	5	like VI-A	10	50	like VI-B	6	30	like VI-C	2	10			
9 Minimize Weight	3	22#	10	30	37#	9	27	67#	8	24			
2 Maximize Overall Efficiency	3	-1.7 dB gain comp to VI-A, also block	6	18	-1.7 dB gain comp to VI-B, block like VI-A	6	18	-1.7 dB gain com. to VI-C less block than VI-B	7	21			
2 Provide Coverage of Alaska, Hawaii	1	extra feeds extra block no scan deg	10	10	less block than VI-A	10	10	less block than VI-B	10	10			

| TOTAL WT SC | **249** | **235** | **215** | |

WEIGHTING
- Which of our "Want" objectives is the most important? (10)
- What is the relative importance of all other "Want" objectives?
- Does the weight assigned to each objective accurately indicate the contribution that the objective should make to the ultimate decision?

SCORING
- How well do all alternatives under consideration satisfy each specific objective?
- Which alternative provides the greatest satisfaction? (10)
- What is the relative satisfaction provided by all other alternatives?

APPENDIX C

EVALUATION OF CANDIDATE ANTENNAS

STEP III

Evaluation of Candidate Antennas - Step III

Introductory Remarks

Each of the eight candidate antennas in the Step III analysis was evaluated against the 7 Wants in the Want list. The assessments are discussed in detail in this appendix. The actual worksheets are also included.

Want #5: Maximize Beam-to-Beam Isolation

Ability to maintain polarization purity is of prime importance in satisfying this Want. In the area of cross-polarized beam coupling, the dual lens concepts with separate polarizations on each lens (two artificial dielectric lenses of either type, III-B-1 and III-B-2) are considered inherently better than those systems whose lenses must respond to either polarization (one artificial dielectric lens, III-A-1, or two waveguide lenses, IV-B). The waveguide lens with its constraining nature is rated better than the single artificial dielectric lens.

In terms of co-polarized minor lobe performance, experience from our study for NASA Langley [1] shows that a feed when located in a cluster will exhibit broader radiation patterns than its free-space characteristic. This in turn raises the illumination taper on the focussing objective, thereby resulting in higher minor lobes. Because of this effect the two-antenna artificial dielectric lens concepts (III-B-1 and III-B-2) which have fewer feeds per lens are regarded as better than the single lens concepts and the two-antenna waveguide lenses (III-A-1 and IV-B).

On the other hand, the Plano-concave contour of the waveguide lens design provides a larger feed illumination angle than the Plano-Convex designs and thus simplifies the feed design problem for providing low illumination tapers. The Plano-convex artificial

(1) LMSC/D156879, "Multiple Beam Antenna System - Final Report", NASA Contract No. NAS 1-10839 May 1972

dielectric lens will tend to accentuate the illumination taper provided by the feed (as happens with a parabolic reflector, for instance) but this effect is not pronounced for larger focal length-to-diameter ratios. The TEM type of lens (III-B-2) does introduce an asymmetrical amplitude distribution across the aperture which tends to produce higher side lobes than would be obtained with the ordinary type of artificial dielectric lens. The waveguide lens is probably more susceptible to higher far-out side lobes and diffraction lobes due to the zoning necessary to achieve satisfactory bandwidth and due to a requirement for a larger support structure.

In each of these areas of consideration, the 23 beam configuration is generally thought to provide slightly worse performance than the 16 beam configuration.

Want #4: Minimize Inadequate Gain Areas

The prime consideration here is the ability to achieve high pattern crossover levels. There is essentially no difference between the 16 and 23 beam configuration in this respect. Those designs, however, with fewer feeds per lens will permit more latitude in feed placement for higher beam crossover and thus better coverage. Consequently, the two-antenna artificial dielectric lenses (III-B-1 and III-B-2) are considered better than the one antenna artificial dielectric lens (III-A-1) or the two antenna waveguide concept (IV-B).

Want #6: Maximize the Number of Users

More beams increase the number of users in a "worst-case" interference situation. Thus, the 23 beam configurations are given a higher score relative to this Want. There is no essential difference between the different types of antennas.

Want #8: Minimize Complexity

Complexity is evaluated in terms of feed design, lens support, operational considerations and fabrication problems.

With respect to feed complexity, the two-antenna artificial dielectric lenses (III-B-1 and III-B-2) have the advantage of requiring only half the total required feeds for each lens. The waveguide lens configurations have the advantage of requiring its feeds to operate only over a narrow bandwidth.

As for a lens support requirement, the waveguide lens, because of its larger mass, would require a more complex structure for support than would the artificial lens configurations.

Under operational considerations, the problem of alignment of the beams, stowing for launch, the deployment on orbit are considered. The single antenna configuration (III-A-1) appears to be superior to other configurations in all these respects.

As for fabrication ease, it was generally felt that the waveguide lens configurations (IV-B) provided more of a challenge to accurate fabrication than the artificial dielectric lenses. This is because of the large number of waveguide sections which must be fabricated accurately to preserve uniform phase. In the waveguide lens, there are dimensional tolerances to be held in waveguide size and length. In the artificial dielectric lens of the ordinary type, the problem is more one of maintaining appropriate local density of particles instead of being a dimensional problem (except, of course, for the outer contour of the lens). In the TEM parallel plate lens plate spacing is not critical and the outer lens surface is the critical dimensional problem. Thus, on the whole the waveguide lens was deemed to be the most difficult candidate to fabricate.

Want #9: Minimize Weight

The weight of the artificial dielectric lens was taken from the Step I analysis. This is 70 pounds for a single lens and 132 pounds for a two lens system.

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The TEM or parallel plate lens weight estimate was based on the parameters of Figure 31. For a 96 inch lens diameter and a plate spacing of 0.4 inch, the lens is comprised of about 240 plates, each assumed to be 0.030 inch thick. The plate contour is a hyperbola but to simplify its area calculation, we assumed it to be circular. Usingthe bulk density of aluminum, the weight of two lenses was estimated to be about 236 pounds. For magnesium or beryllium, the weight is significantly reduced to 164 pounds. These estimates do not include any lens support structure.

The estimated weight for the waveguide lens uses the parameters shown in Figure 32. The 96 inch diameter lens is subdivided into three equal-width annular rings. Assuming a waveguide cross-section of 0.4 by 0.4 inch, the number of waveguides in each ring is determined. For bandwidth purposes, three equal zones (two steps) are assumed and a mean waveguide length for each annular ring is found. With a wave-guide wall thickness of 0.015 inch and the densities for various metals, weight estimates are derived. For aluminum, the weight of two lenses is 300 pounds. For magnesium or beryllium, the weight of two lenses is reduced to about 200 pounds. As before these estimates do not include any support structure.

Since the feeds are a minor part of the weight of such heavy systems, no distinction is made between the 16 and 23 beam cases.

Want #7: Maximize Overall Efficiency

Of prime importance here is the absolute gain of each of the candidate systems. We are not concerned with aperture efficiency in the usual sense, since the important aspect is to achieve maximum gain for a given beamwidth regardless of the amount of aperture area required. When viewed in this light there was no important distinction between the various candidates when providing a given configuration of beams within the service area. All of the lenses have losses of one type or another, such as internal losses and surface mismatches.

C-4

There is, however, an important distinction between the 16 beam cases and the 23 beam cases of any of the competing antenna types. In comparing the 16 beam case with the 23 beam cases, the beamwidths are different and the latter will require more aperture by the ratio (area) of approximately 23/16. This results in about 1 to 1.5 dB more gain for the 23 beam cases.

Want #2: Provide for Coverage of Hawaii/Alaska

In general, every lens concept should be equally capable of satisfying this Want. Due to this equality among the candidates, and the low weighting of this Want (Weight = 1), it was not considered in the final scoring.

C-5

LMSC/D284597

Decision Statement: One Artificial Dielectric Lens – 16 Beams
- What are we trying to decide?
- What is the decision to be made?
- What decisions must have already been made?

OBJECTIVES

(— Is it absolutely essential?)
(— Is it measurable?)

$\overline{III}-A-1/16$

A		B
INFO		GO/NO

WANT (— All objectives that are not "musts"
— "Musts" we wish to minimize or maximize)

	WT	INFO	SC	WT SC	INFO
4 MINIMIZE INADEQUATE GAIN AREAS	9	SAME AS 1A-23	9	81	
5 MAXIMIZE BEAM-TO-BEAM ISOLATION	10	SAME AS 1A-23 EXCEPT SLIGHTLY BETTER OVERALL	6	60	
6 MAXIMIZE NUMBER OF USERS	6	SAME AS 2B-16	7	42	
8 MINIMIZE COMPLEXITY	5	EASIEST ALIGNMENT, STOWING AND FURLING LEAST COMPLEX OF ALL SINGLE ANTENNA	10	50	
9 MINIMIZE WEIGHT	3	72#	10	30	
7 MAXIMIZE OVERALL EFFICIENCY	3	SAME AS 2B-16	9	27	
				290	

WEIGHTING
- Which of our "Want" objectives is the most important? (10)
- What is the relative importance of all other "Want" objectives?
- Does the weight assigned to each objective accurately indicate the contribution that the objective should make in the ultimate decision?

SCORING
- How well do all alternatives under consideration satisfy each specific objective?
- Which alternative provides the greatest satisfaction? (10)
- What is the relative satisfaction provided by all other alternatives?

FORM LMSC 2695 B (FRONT)

C-6

Decision Statement: One Artificial Dielectric Lens - 23 beams

- What are we trying to decide?
- What is the decision to be made?
- What decisions must have already been made?

OBJECTIVES	A		B
(– Is it absolutely essential? / – Is it measurable?)	INFO	GO/NO	INFO
III-A-1/23			

WANT (– All objectives that are not "musts" / – "Musts" we wish to minimize or maximize)

	WT	INFO	SC	WT SC	INFO
4 MINIMIZE INADEQUATE GAIN AREAS	9	MORE FEEDS PER LENS THAN 2B - LOWER X-OVER THAN 2B	9	81	
5 MAXIMIZE BEAM-TO-BEAM ISOLATION	10	ALL FEEDS PER LENSE BOTH POLARIZATIONS FULL BANDWIDTH - WORST -	5	50	
6 MAXIMIZE NUMBER OF USERS	6	SAME AS 2B-23	10	60	
3 MINIMIZE COMPLEXITY	5	SAME AS 1A-16 EXCEPT MORE FEEDS	9	45	
9 MINIMIZE WEIGHT	3	72#	10	30	
7 MAXIMIZE OVERALL EFFICIENCY	3	SAME AS 2A-23	10	30	
				296	—

WEIGHTING
- Which of our "Want" objectives is the most important? (10)
- What is the relative importance of all other "Want" objectives?
- Does the weight assigned to each objective accurately indicate the contribution that the objective should make in the ultimate decision?

SCORING
- How well do all alternatives under consideration satisfy each specific objective?
- Which alternative provides the greatest satisfaction? (10)
- What is the relative satisfaction provided by all other alternatives?

FORM LMSC 2895 B(FRONT)

Decision Statement: Two Artificial Dielectric Lenses — 16 beams

A What are we trying to decide?
B What is the decision to be made?
C What decisions must have already been made?

———————————————— OBJECTIVES ————————————————

(— Is it absolutely essential?)
(— Is it measurable?)

	A	B
	INFO	GO/NO IN

III - B - 1/16

WANT *(— All objectives that are not "musts"*
— "Musts" we wish to minimize or maximize)

OBJECTIVE	WT	INFO	SC	WT SC	IN
4 MINIMIZE INADEQUATE GAIN AREAS	9	SAME AS 2B-23	10	90	
5 MAXIMIZE BEAM-TO-BEAM ISOLATION	10	SAME AS 2B-16	10	100	
6 MAXIMIZE NUMBER OF USERS	6	SAME AS 2B-16	7	42	
8 MINIMIZE COMPLEXITY	5	REQUIRE ONLY 1/2 THE TOTAL FEEDS PER LENS SAME AS 1A-23	9	45	
9 MINIMIZE WEIGHT	3	132 #	9	27	
7 MAXIMIZE OVERALL EFFICIENCY	3	SAME AS 2B-16	9	27	
				331	

Decision Statement: Two Artificial Dielectric Lenses – 23 beams

- What are we trying to decide?
- What is the decision to be made?
- What decisions must have already been made?

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———— OBJECTIVES ————

	A		B
	INFO	GO/NO	IN

MUST (– Is it absolutely essential? – Is it measurable?)

III – B – 1/23

WANT (– All objectives that are not "musts" – "Musts" we wish to minimize or maximize)

	WT	INFO	SC	WT SC	IN
4 MINIMIZE INADEQUATE GAIN AREAS	9	SAME AS 2B-23	10	90	
5 MAXIMIZE BEAM-TO-BEAM ISOLATION	10	SAME AS 2B-23	9	90	
6 MAXIMIZE NUMBER OF USERS	6	SAME AS 2B-23	10	60	
8 MINIMIZE COMPLEXITY	5	REQUIRES ONLY 1/2 THE TOTAL FEEDS PER LENS – MORE FEEDS THAN 2A-16	8	40	
9 MINIMIZE WEIGHT	3	132 =	9	27	
7 MAXIMIZE OVERALL EFFICIENCY	3	1 TO 1 1/2 dB MORE GAIN THAN 16 BEAM CONFIGURATIONS	13	30	
				337	–

Decision Statement: *Two TEM metal plate lenses – 16 beams*

- What are we trying to decide?
- What is the decision to be made?
- What decisions must have already been made?

—————— OBJECTIVES ——————

MUST (– Is it absolutely essential? / – Is it measurable?)

	A INFO	GO, NO

$III - B - 2 / 16$

WANT (– All objectives that are not "musts" / – "Musts" we wish to minimize or maximize)

WANT	WT	INFO	SC	WT SC
4 MINIMIZE INADEQUATE GAIN AREAS	9	SAME AS 2B-23	10	90
5 MAXIMIZE BEAM-TO-BEAM ISOLATION	10	SAME AS 2B-23 EXCEPT SLIGHTLY BETTER OVERALL	10	100
6 MAXIMIZE NUMBER OF USERS	6	LESS BEAMS THAN 2B-23 – LESS USERS	7	42
8 MINIMIZE COMPLEXITY	5	SAME AS 2A-16	9	45
9 MINIMIZE WEIGHT	3	AL – 236# Mg – 164#	9	27
7 MAXIMIZE OVERALL EFFICIENCY	3	1 TO 1½ dB LESS GAIN THAN 23 BEAM CONFIGURATION	9	27
				331

Decision Statement: Two TEM metal plate lense - 23 beams
- What are we trying to decide?
- What is the decision to be made?
- What decisions must have already been made?

OBJECTIVES

	A		B
	INFO	GO/NO	IN

T (- Is it absolutely essential? / - Is it measurable?)

III - B - 2/23

WANT (- All objectives that are not "musts" / - "Musts" we wish to minimize or maximize)

	WT	INFO	SC	WT SC	INF
4 MINIMIZE INADEQUATE GAIN AREAS	9	LESS FEEDS PER LENS BETTER FEED SPACING HIGHER X-OVER THAN 1A	10	90	
5 MAXIMIZE BEAM-TO-BEAM ISOLATION	10	X POL BEST - SEPARATE FEEDS - S.L BEST - FEWER FEEDS PER LENSE - BEST COUPLING -	9	90	
6 MAXIMIZE NUMBER OF USERS	6	MORE BEAMS THAN 2A-16 - THEREFORE MORE USERS	10	60	
8 MINIMIZE COMPLEXITY	5	SAME AS 2A-23	8	40	
9 MINIMIZE WEIGHT	3	ALUMINUM - 236# MAG - 164#	9	27	
7 MAXIMIZE OVERALL EFFICIENCY	3	SAME AS 2A-23	10	30	
				337	-

WEIGHTING
- Which of our "Want" objectives is the most important? (10)
- What is the relative importance of all other "Want" objectives?
- Does the weight assigned to each objective accurately indicate the contribution that the objective should make in the ultimate decision?

SCORING
- How well do all alternatives under consideration satisfy each specific objective?
- Which alternative provides the greatest satisfaction? (10)
- What is the relative satisfaction provided by all other alternatives?

Decision Statement: Two TE waveguide lenses – 16 beams

- What are we trying to decide?
- What is the decision to be made?
- What decisions must have already been made?

_____ OBJECTIVES _____

	A		B
	INFO		GO/NO

(– Is it absolutely essential?)
(– Is it measurable?)

IV – B/16

WANT (– All objectives that are not "musts"
– "Musts" we wish to minimize or maximize)

WANT	WT	INFO	SC	WT SC	INFO
4 MINIMIZE INADEQUATE GAIN AREAS	9	SAME AS 1A-23	9	81	
5 MAXIMIZE BEAM-TO-BEAM ISOLATION	10	SAME AS 2C-23 EXCEPT SLIGHTLY BETTER OVERALL	8	80	
6 MAXIMIZE NUMBER OF USERS	6	SAME AS 2B-16	7	42	
8 MINIMIZE COMPLEXITY	5	SAME AS 2C-23	5	25	
9 MINIMIZE WEIGHT	3	ALUMINUM – 600# MAG – 400#	6	18	
7 MAXIMIZE OVERALL EFFICIENCY	3	SAME AS 2B-16	9	27	

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WEIGHTING
– Which of our "Want" objectives is the most important? (10)
– What is the relative importance of all other "Want" objectives?
– Does the weight assigned to each objective accurately indicate the contribution that the objective should make in the ultimate decision?

SCORING
– How well do all alternatives under consideration satisfy each specific objective?
– Which alternative provides the greatest satisfaction? (10)
– What is the relative satisfaction provided by all other alternatives?

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Decision Statement: Two TE waveguide lens — 23 beams

- What are we trying to decide?
- What is the decision to be made?
- What decisions must have already been made?

OBJECTIVES

	A		B
(– is it absolutely essential? – is it measurable?)	INFO		GO, NO INFO
●			
$IV - B/23$			

WANT (– All objectives that are not "musts"
 – "Musts" we wish to minimize or maximize)

	WT	INFO	SC	WT SC	INF
4 MINIMIZE INADEQUATE GAIN AREAS	9	SAME AS 1A-23	9	81	
5 MAXIMIZE BEAM-TO-BEAM ISOLATION	10	X-POL BETTER THAN 1A CONSTRAINED - 11JB. HIGHER FNR BUT S.L. GOOD COUPLING - NARROW BAND	7	70	
6 MAXIMIZE NUMBER OF USERS	6	SAME AS 2B-23	10	60	
3 MINIMIZE COMPLEXITY ●	5	NARROWEST BANDWIDTH MORE COMPLEX SUPPORTS DUE TO LARGE MASS - FABRICATION PROBLEMS	5	25	
9 MINIMIZE WEIGHT	3	ALUMINUM - 600 # MAG - 400 #	6	18	
7 MAXIMIZE OVERALL EFFICIENCY	3	SAME AS 2A-23	10	30	
				284	

WEIGHTING
- Which of our "Want" objectives is the most important? (10)
- What is the relative importance of all other "Want" objectives?
- Does the weight assigned to each objective accurately indicate the contribution that the objective should make in the ultimate decision?

SCORING
- How well do all alternatives under consideration satisfy each specific objective?
- Which alternative provides the greatest satisfaction? (10)
- What is the relative satisfaction provided by all other alternatives?

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