FEASIBILITY STUDY OF A RADIATOR AND POWER DIVIDER FOR 50 - 60 GHz PHASED ARRAY

by

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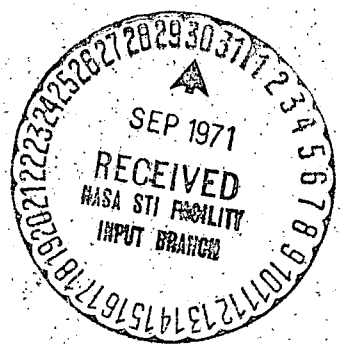
George J. Gill



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1.0 PURPOSE

The primary objective of this study program has been to determine the feasibility of producing broadband antenna components suitable for use in a 50-60 GHz phased array for a radiometric application The two elements considered were

1. an H-plane, line source radiator with low sidelobes that is capable of being "stacked" in an E-plane array, and

2. a power divider capable of division up to 80 ways, or more, with an amplitude distribution suitable for low sidelobes The major parameters considered were

1. sidelobe control
2 bandwidth
3. beamwidth
4 dissipative loss
5 VSWR
6. beam efficiency
7. size and weight

2.0 INTRODUCTION

Radiometric studies in the 50-60 GHz region could use a broadband, electronic scanning antenna which has very low sidelobe power content (high beam efficiency) and low dissipative losses The major component needed is an electronic phase shifter, which is not a part of this study For scanning a pencil beam, in one plane only, the other two antenna components needed are a line source for arraying in the plane of scan and a power divider to feed each radiator's phaser with the desired amplitide distribution Broadband, low loss designs for these two components were conceived, designed, constructed and tested to demonstrate their feasibility for use in a millimeterwave phased array with high beam efficiency

Initial consideration of the array configuration for scanning over wide angles reveals that the only practical type of millimeterwave line source element that can be arrayed in the H plane is the waveguide edge slot array This design is not capable of broadband widths Most types of E plane line sources are eliminated because their width is greater than the required array element spacing An H plane sectoral horn for arraying in the E plane is a practical choice because it has the required physical width and bandwidth and can be fabricated for the millimeter region

RCA studied such an element and reported on its practicality[1] and its performance in a phased array [2]

References 1 and 3 report on a dual mode E plane sectoral horn for use as a power divider with an amplitude distribution suitable for low sidelobes A divider with a 24 wavelength aperture operating in Ku band produced a distribution suitable for -24 dB minor-lobes over a 10% band.

This study considered an improved horn-lens and another type of power divider with greater bandwidth potential. The design criteria employed can be summarized as follows

Frequency	50-60 GHz (20% band)
Beamwidth	1 5° in plane of array, 3 0° in orthogonal plane
Sidelobes	-30dB (to assure high beam efficiency)
Dissipative Loss	Less than 0 5dB in either horn or divider
VSWR	1 30 1 max on each unit

These requirements dictate an aperture of 24X 48 wavelengths in the H and E planes respectively with a well-controlled tapered distribution for -30dB minorlobes

3 0 RADIATING ELEMENT

3 1 Selection

The type of radiator required, for use in the array under study is an H plane line source with a distribution sufficient for -30dB minor-lobes from 50 to 60 GHz The simpliest con-figuration to approach these requirements is an H plane sectoral horn. A wide angle horn reduces the length and therefore the insertion loss, but requires a phase correcting lens in its aperture Performance on a horn of this type, with a plano-convex lens, was reported at lower frequencies by Profero[2] and Jones [4]

An H plane sectoral horn with a phase correcting lens can produce only an approximate cosine amplitude distribution In a line source, this is sufficient only for about -25 dB minorlobes A small horn illuminating a lens can be designed such that the resulting aperture distribution approximates a cosine^2 function This could yield a theoretical sidelobe level of -33dB and a beam factor of 85λ/D This type of radiator was selected for fabrication and testing at 50 to 60 GHz

3 2 Design Details

The radiating lens aperture length must be sufficient to produce a three degree half power beamwidth at the center frequency An aperture distribution was selected to yield -30dB minorlobes

This approximates a $\cos^2\left(\frac{\pi x}{D}\right)$ distribution The aperture distribution at the edges of the lens is reduced 4 dB from the feed pattern energy due to refraction of the lens. The resulting distribution will yield a beamwidth defined by 85 λ/D Therefore, the required aperture length (D) is 27 9 wavelengths (about 6") to produce a three degree beamwidth

Figures 3-1 a and b show the 50-60 GHz horn-lens

"Rexolite 1422" was chosen as the lens material because it has very low loss in the millimeter region (tan δ = 001), well defined dielectric constant (E_r=2 53), and is mechanically acceptable

This consists of the small horn, cover plates and lens The parallel plate separation was selected to be .094 inches This size is the same as the height of WR19 waveguide At 55 GHz, WR19 waveguide has a λ_g/λ_o ratio of 1 22 as compared with a 1 45 ratio for the smaller WR15 waveguide Thus the selected waveguide provides a smaller impedance change with frequency and broader bandwidth It also has lower insertion loss Provisions were made to adjust the lens position relative to the horn for fine focussing

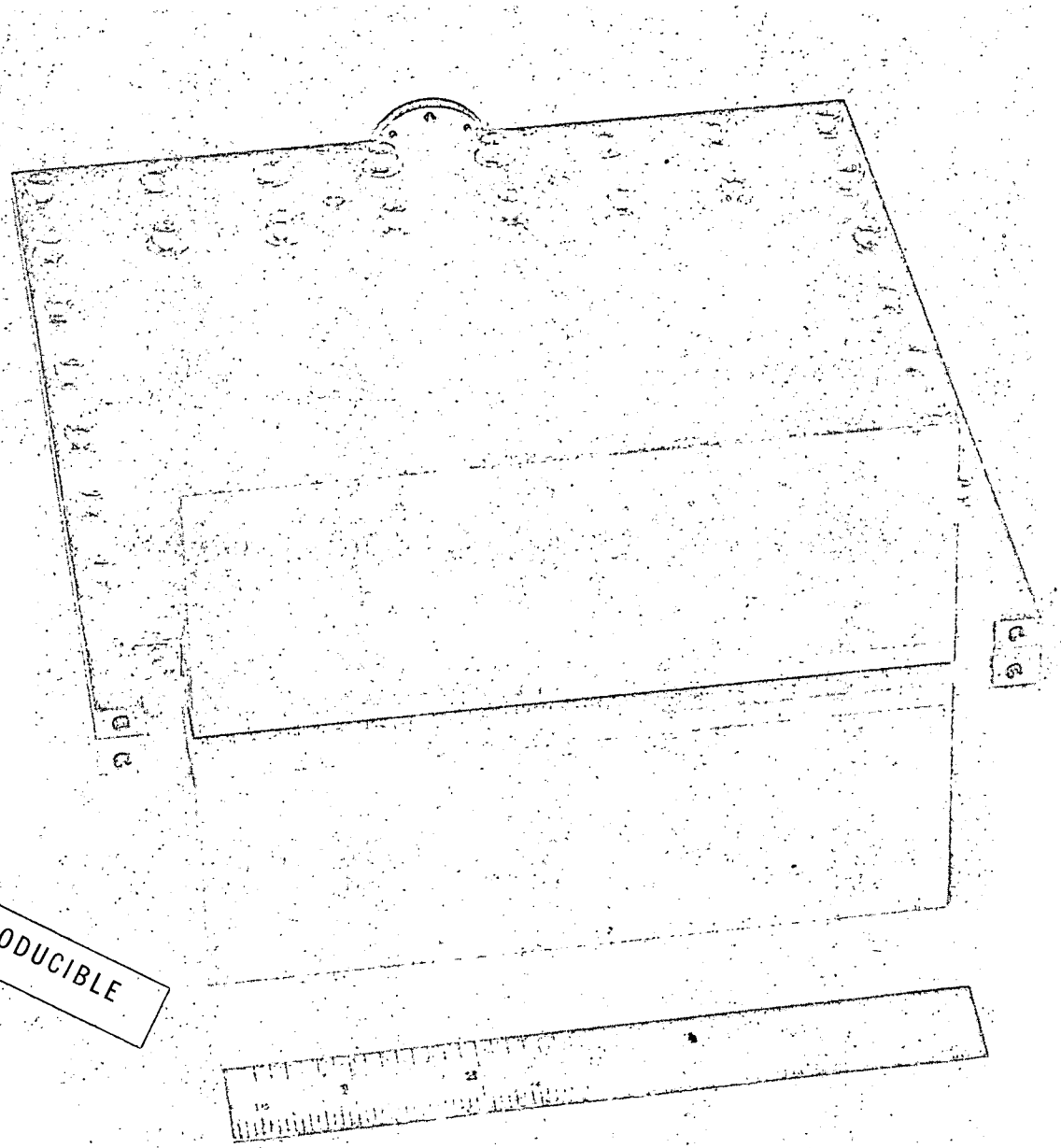

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FIGURE 3-1a H PLANE HORN LENS ASSEMBLY

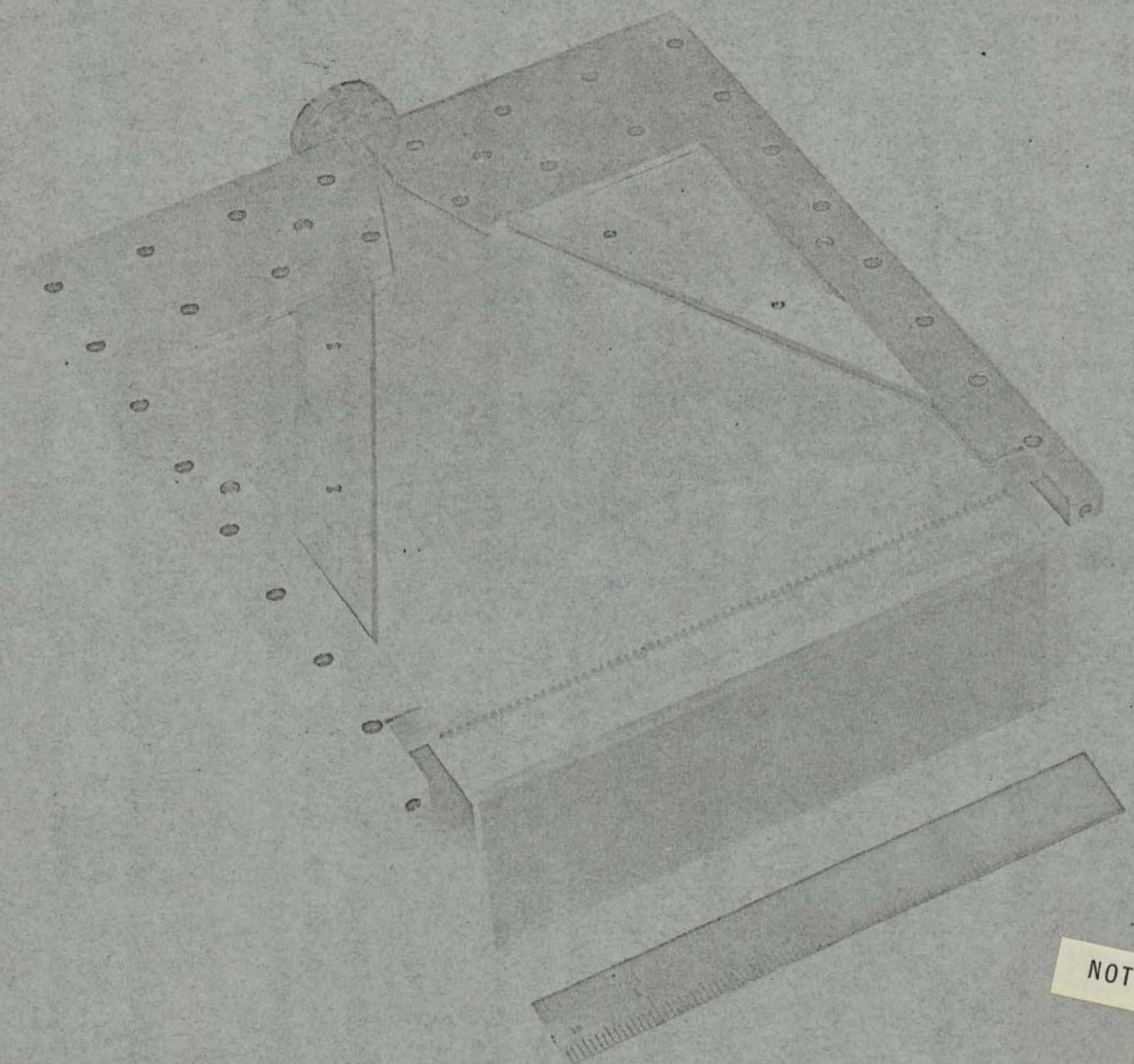

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FIGURE 3-1b H PLANE HORN LENS - INTERNAL VIEW

The feed is a small wide flare horn designed to illuminate the lens with -25dB edge illumination. Such a horn has essentially no sidelobes and very little spillover energy.

The aperture of the lens is flared and fitted with a ground plane to avoid the serious edge diffraction that would occur in a small E plane element with sharp corners. In an array of such elements, this would not be necessary.

In parallel plates supporting this mode, plate flatness is not extremely critical so this design could be built using plates 1/32" thick. Then an array of such elements could be made with .125" spacing, which is sufficient for scanning to $\pm 60^{\circ}$ at 60 GHz without grating lobes.

3.3 Performance

Initially the lens was made and tested without any matching techniques applied to either surface. Also the diagonal plates that run from near the horn aperture to near the lens edge were omitted.

The VSWR across the band was 1.4 to 1.6. This value was expected from a lens with dielectric constant of 2.53. The high VSWR is a result of reflections from the equiphase surface of the lens. These reflections converge, in phase, back at the horn. Reflections from the refractive surface of the lens have the same order of magnitude but they are scattered out of phase and do not contribute significantly to the VSWR. This reflected energy

is rescattered from the side walls to radiate as sidelobes from the antenna. The antenna patterns of the horn with the unmatched lens showed -19dB monorlobes at $\pm 36^{\circ}$ due to reflections between the lens and the flat wall adjacent to the horn

Morita and Cohn[5] have described two techniques for matching microwave lens surfaces with a quarter-wave transformer layer This layer may be a strip of solid dielectric or may be simulated by adding perturbations in the surface of the lens. In either case the depth is a quarter wavelength in a medium whose index is the geometric mean between the lens and the surrounding medium Both techniques are difficult to employ It is difficult to obtain a dielectric with suitable mechanical properties and the appropriate index to match Rexolite. Corrugations in the lens surface require complex machining, especially on the refractive surface of the lens

To demonstrate how much improvement could be obtained by perfect matching of the lens, the inside walls in the parallel plate region were masked with absorbing material so that multiple reflections could not cause sidelobes in the antenna pattern

Patterns for this condition are presented in Appendix A, Numbers A6 to A12 It was found that

the horn lens had several close-in sidelobes from -20 to -27 dB at 50GHz, but the large reflections at $\pm 36^{\circ}$ were eliminated At frequencies from 52 5 to 65 GHz all but the first sidelobe were well below -30dB. The first sidelobe ran from -25 to -31dB The absorber was removed

A simulated quarter wave transformer was added to the plane surface of the lens Note the grooves in Figure 3-1b The VSWR was reduced to 1 15 to 1 35 with little effect on the radiation pattern

A single H Plane groove was machined along the refracting surface of the lens The resulting VSWR across the band was 1 06 to 1 27

These lens matching techniques reduced the reflection caused sidelobes from -19dB to the -25 to -28dB level An attempt was made to place diagonal reflecting strips across the corners of the parallel plate structure to direct the reflected energy into the mainbeam region This was the final configuration of the horn lens as shown in Figure 3-1b Patterns for this case are presented in Appendix A as numbers A1 to A5 The -20dB sidelobe at 50 GHz is still present At other frequencies up to 60 GHz, the first sidelobe is -24 to -27dB The beamwidth varies from 3 0 to 2 8°

4.0 POWER DIVIDER

4 1 Selection

An array with 1 5° beamwidth for scanning up to 60° from broadside requires about 84 elements in an aperture of 48 wavelengths (57 wavelengths/element) Obviously, a broadband, low loss power divider for such a structure must have equal lengths from the input to each output and each path must be low loss A waveguide slot array is too narrowband, and a parallel corporate structure is too lossy. The E plane sectoral horn with its aperture divided into output ports by H plane vanes meets most of the requirements, but the inherent power distribution of the dominate mode is not sufficient for -30dB minorlobes The multimode sectoral horn reported in references 1 and 3 corrects the distribution but thereby introduces frequency sensitivity

Reference 6 describes a method of modifying a Cassegrainian reflector system for aperture amplitude control. This concept of shaped dual reflectors was selected and used to form the power divider

4 2 Design Details

4 2 1 Feed

The type of feed selected to illuminate the dual reflector, parallel plate structure is a corrugated E plane sectoral horn The reasoning for this selection was that very low spillover power and a constant feed pattern over a broadband was required. In an E plane horn, only a corrugated structure has both properties Laurie and Peters[7] and Simmons and Kay[8] have reported on pyramidal and conical corrugated horns, but no design data was found for the sectoral case

To determine the design of such a horn for this application, a scale model was built in Ku band parallel plates. This model was equipped with a coupling slot in the top plate that could be rotated and moved transversely (See Fig 4-1) For each position of the slot, it could be rotated for maximum and minimum coupling This gives the power level at that position, and the orientation of the wave front This information was used to obtain the relative power pattern and to locate the phase center of the horn. Figure 4-2 describes the horn design that was selected to illuminate the shaped reflectors An illumination angle of $\pm 41^{\circ}$ was chosen, at which the feed pattern level was

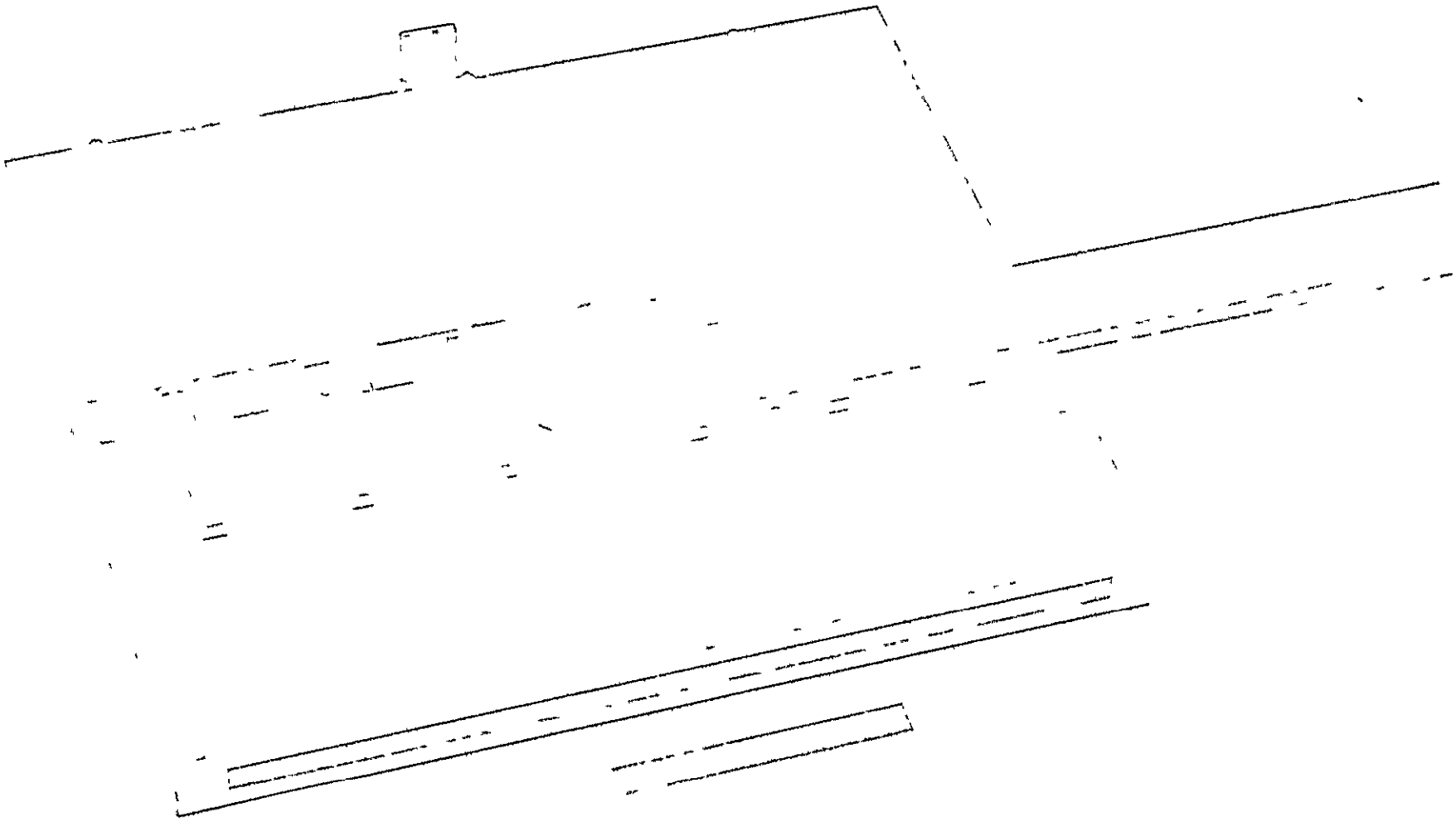

FIGURE 4-1a Ku BAND HORN PROBE ASSEMBLY

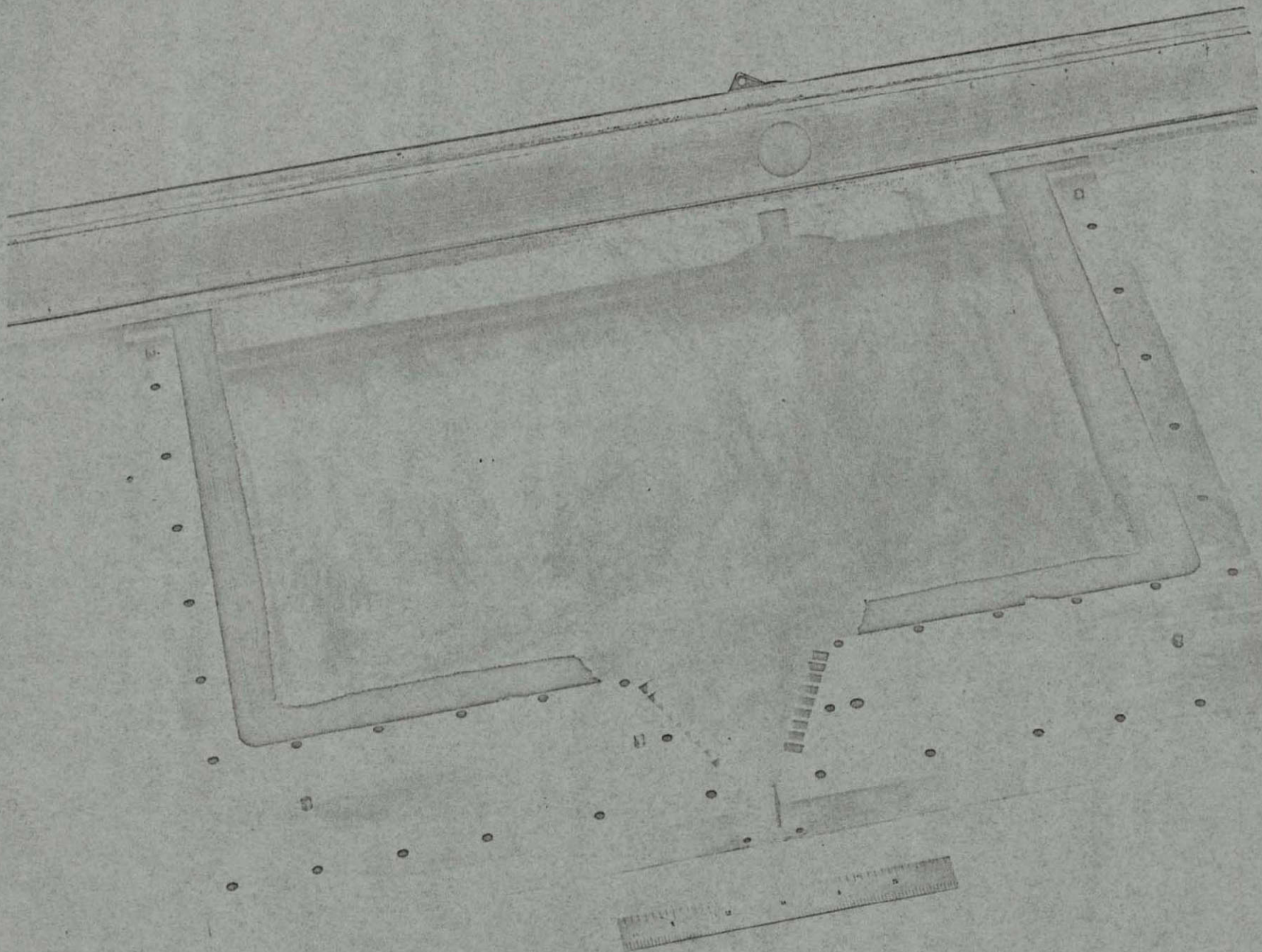

FIGURE 4-1b Ku BAND HORN AND PROBING SLOT

-20 to -26 dB across the band. This level was selected to be as low as possible os that the percent of spillover power past the subreflector could be minimized. The apparent phase center of the feed is also shown in Figure 4-2.

4.2.2 Reflector Contours

The shaped dual reflector concept of Reference 6 has been widely used in Cassegrainian systems to produce nearly uniform illumination for high aperture efficiency. Applications to two dimensional cases, or to produce low sidelobes have not been reported. The expression given by Green[6] is adjusted for the two dimensional case as shown below;

$$\frac{\int_0^{\phi} I(\phi)\, d\phi}{\int_0^{\phi_{MAX}} I(\phi)\, d\phi} = \frac{\int_{\alpha_{MIN}}^{\alpha} P(\alpha)\, d\alpha}{\int_{\alpha_{MIN}}^{\alpha_{MAX}} P(\alpha)\, d\alpha}$$

where $I(\phi)$ is the known feed pattern.

ϕ is the feed angle.

$P(\alpha)$ is the prescribed aperture illumination function referred to the subreflector

α is the aperture angle subtended from the subreflector.

The denominators in the above expression represent the relative integrated power under each curve. These terms may be lumped and expressed as a

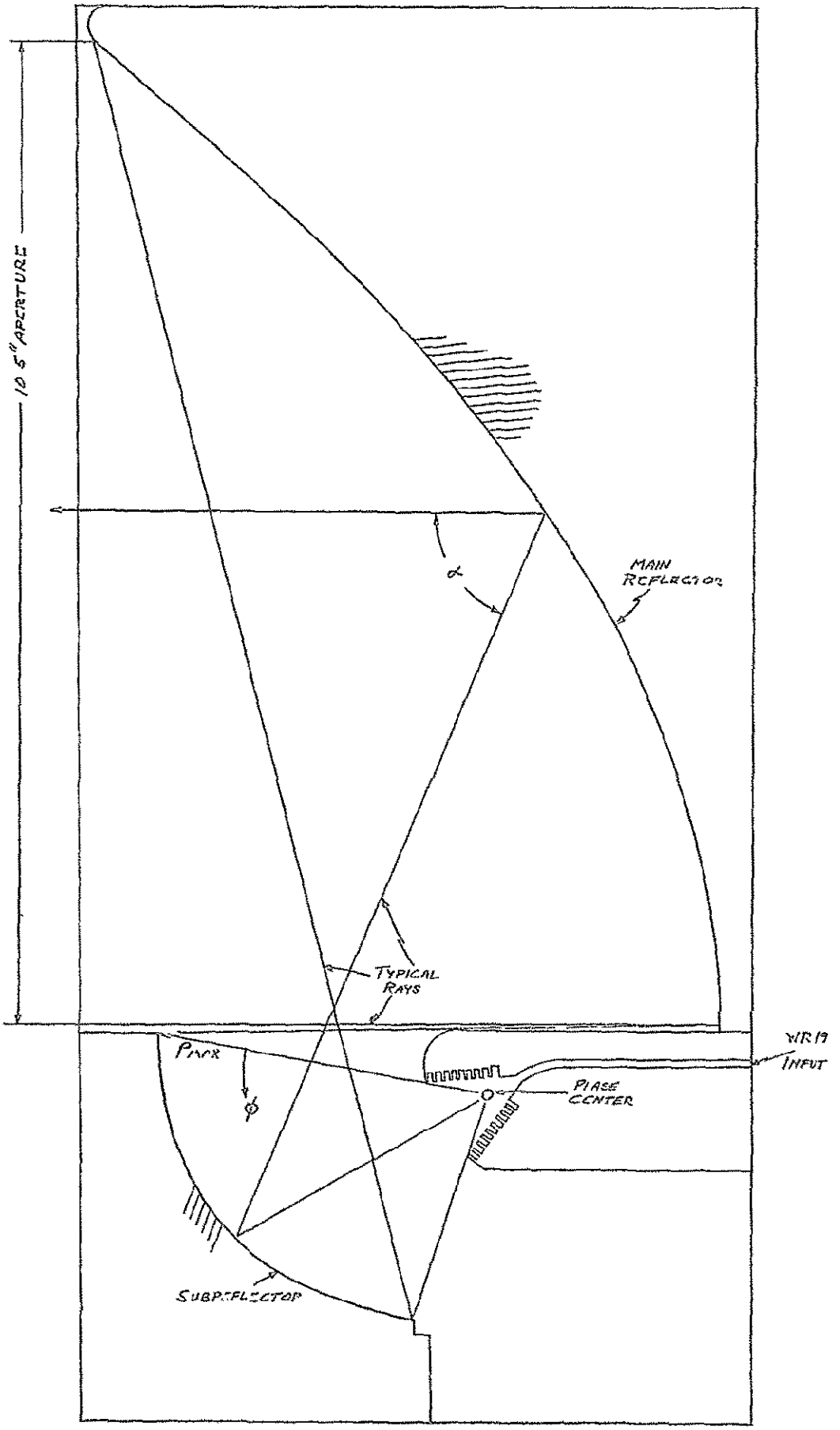

FIGURE 4-2 REFLECTOR GEOMETRY AND COORDINATES

normalizing constant. The expression is restated in summation form.

$$\sum_{c}^{\phi} I(\phi)\,\Delta\phi \;=\; \frac{1}{K}\sum_{\alpha_{MIN}}^{\alpha} P(\alpha)\,\Delta\alpha$$

$$\text{Where}\quad K=\left[\sum_{\alpha_{MIN}}^{\alpha_{MAX}} P(\alpha)\,\Delta\alpha\right]\Bigg/\left[\sum_{0}^{\phi_{MAX}} I(\phi)\,\Delta\phi\right]^{-1}$$

(Normalizing Constant)

Evaluation of the above expression will yield the aperture angles α_1 in relation to the feed angles ϕ_1 The polar coordinates (ρ, ϕ) for the subreflector were then obtained from the following relationship.

(3)

$$\rho / \rho_{max} = \text{EXP}\left(\sum_{0}^{\phi} \tan\left(\frac{\alpha-\phi}{2}\right)\Delta\phi\right)$$

Equations (2) and (3) will yield the shaped subreflector

The shaped subreflector surface deviates from an ideal elliptical curve by the amount necessary to redistribute the feed pattern and obtain the prescribed illumination function A resulting phase error is introduced by this departure from the "Gregorian" geometry. The main reflector must be appropriately modified to maintain the plane phase

front at the aperture Simple ray tracing yields the analytical expressions for the modified main reflector coordinates

A comprehensive computer program was created on a time share computer to generate the complete coordinates of the shaped dual reflector Appendix C describes this program

Using the above program and the measured feed data at midband, reflector contours were calculated to produce a modified $\frac{\sin(\pi u)}{\pi u}$ for a -35dB theoretical sidelobe level [9] The aperture edge illumination desired is -26 8dB The resulting reflector contours are shown in Figure 4-2

4 2 3 Final Design

Figure 4-3a depicts the final power divider assembly and 4-3b shows the internal details of the horn and reflectors The input waveguide is WR19 (188" x 094") which is the largest size guide that can be used up to 60 GHz. Therefore the plate spacing is also 188" This was selected to give the lowest attenuation and the least phase error effect from plate irregularities The parallel plates are ½" aluminum jig plates that were ground to 0001" flatness After assembly, flatness is better than 001" A flared aperture was added to avoid serious edge diffraction and impedance mismatch. This also narrows the H plane beamwidth

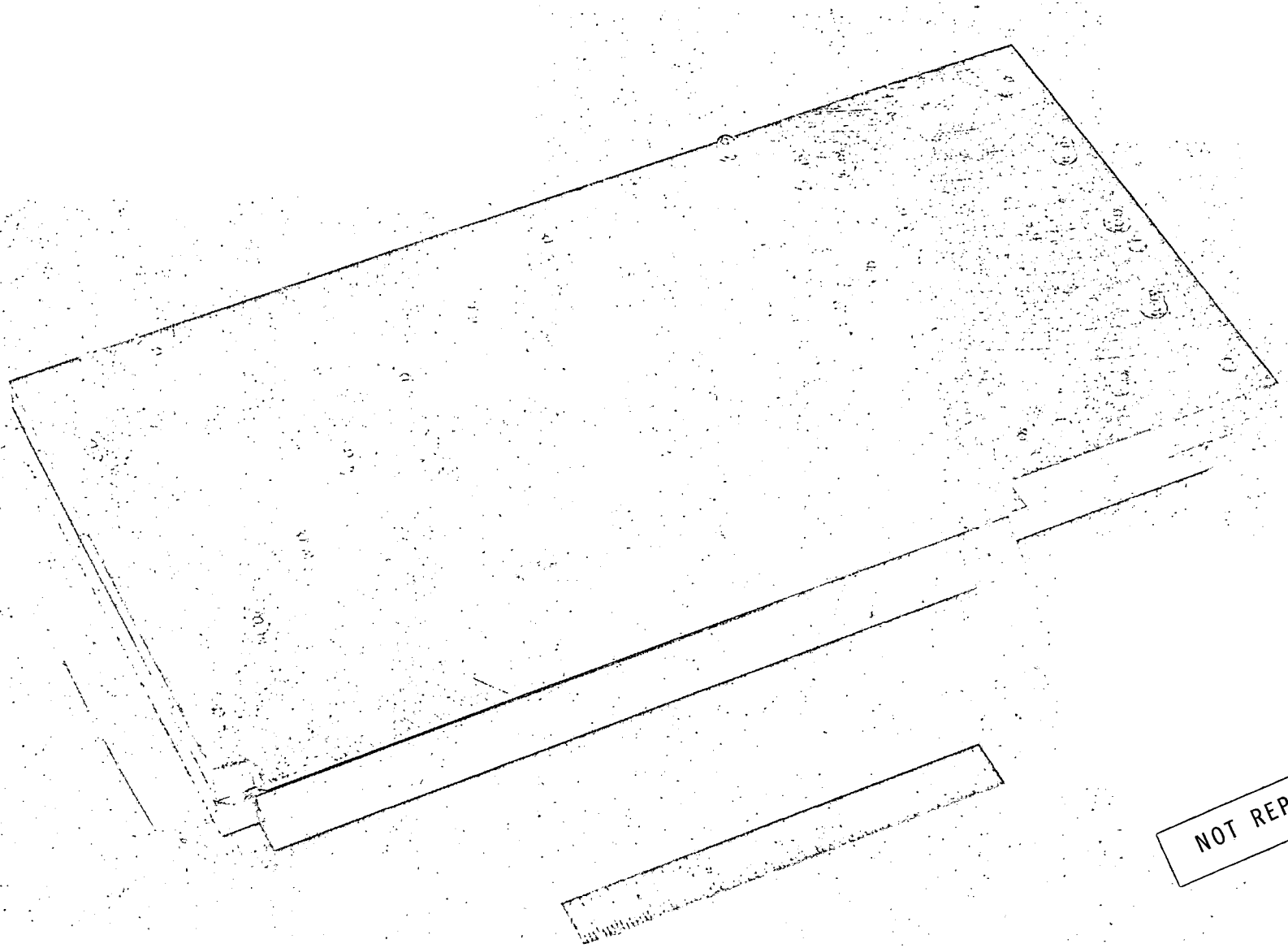

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FIGURE 4-3a E PLANE POWER DIVIDER ASSEMBLY

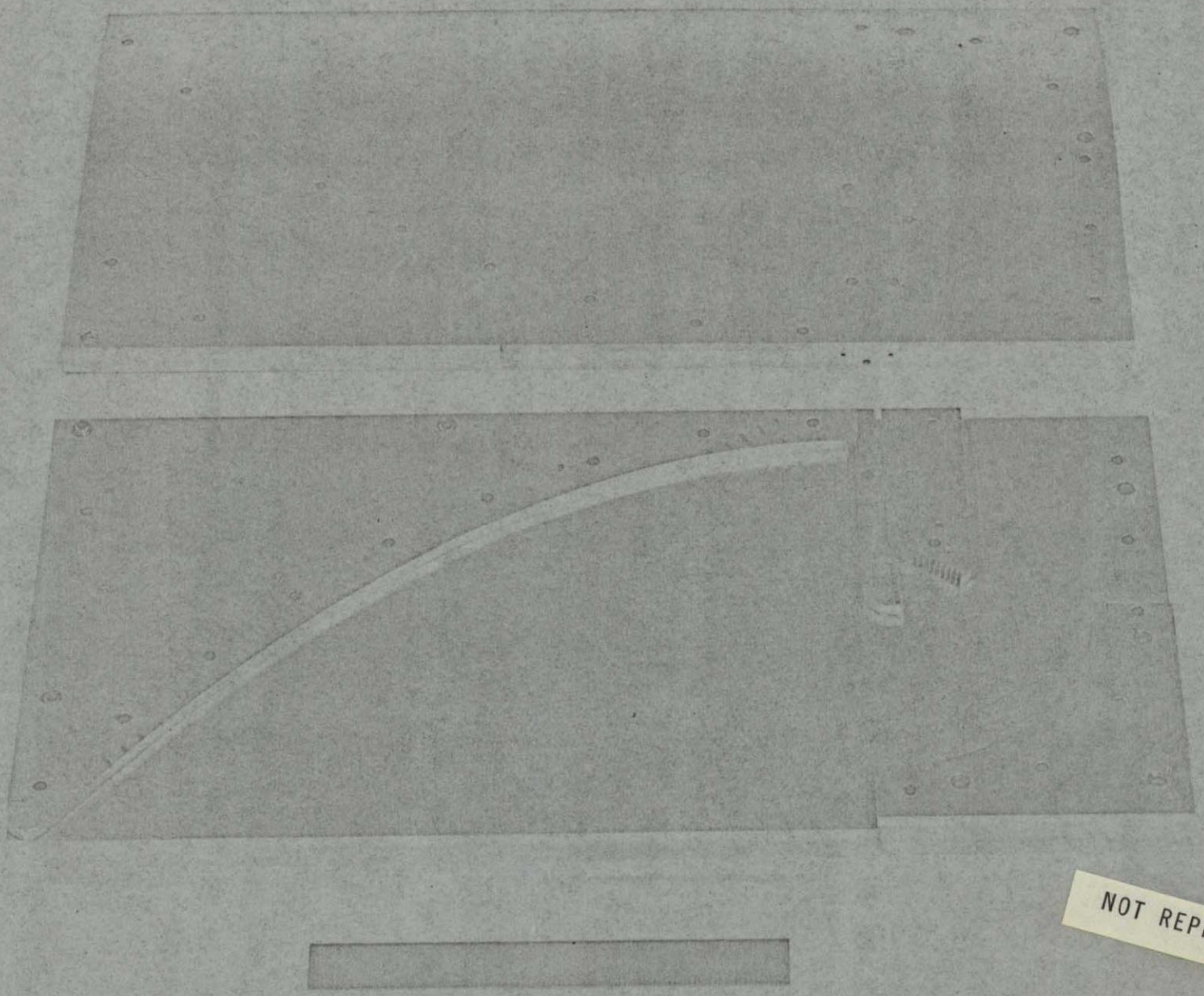

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FIGURE 4-3b POWER DIVIDER HORN AND REFLECTORS

and increases the gain which aid in pattern measurements. This aperture could easily be divided into 80, or more, waveguide parts by adding matched H plane vanes. (See Section 4.4) The reflector contours were ground to within $\pm$.001" of the calculated shapes.

The subreflector was positioned relative to main reflector in its calculated position. The horn's measured phase center was then placed at the focal point of the reflector system. The entire assembly is pinned and bolted together.

The attenuation in standard waveguide with b a was estimated and applied to this parallel plate design. The loss is approximately .17dB/foot, over a path length of 18" average. Loss in the horn and input waveguide is approximately .2dB. Therefore the total loss is estimated at .45dB.

4.3 Performance

Over the band from 50 to 61 GHz, the VSWR of the power divider did not exceed 1.20:1. The half power beamwidth was nearly constant at 1.6°. Appendix B presents the measured patterns. Sidelobes of -30dB were achieved only between 57 and 58 GHz. At 56 and from 59 through 61 GHz the first sidelobe was approximately -27dB. All others were near the theoretical -35dB level. From 50 through 55 GHz the first sidelobe was about -20 dB and other

sidelobes were -27 to -34dB This sidelobe performance is considered very good over 56 to 61 GHz (9%) The -20dB first sidelobe over the lower portion of the band is caused by broadening of the feedhorn pattern. At 50 GHz the deviation of the edge illumination from the design value is at least +3dB This increases spillover past the subreflector, which can be seen in the left side of the pattern. The excellent pattern at 57 GHz indicates there is no difficulty with plate flatness, reflector shapes or feed phase center

The feedhorn pattern is the only frequency sensitive area in the power divider, and with further development its bandwidth could be improved

4 4 Aperture Divider Design

The linear aperture of the power divider can be divided into many waveguide parts by adding thin vanes between the parallel plates The two problem areas are

1) impedance matching from parallel plate guide to rectangular guide,

2) construction of the small, close tolerance parts required

The simplest technique for matching the junction is to put a quarterwave step into the end of each vane This concept was proposed by Yorinks[1] for use in WR15

The design for matching WR19 to the parallel plates is shown in Figure 4-4 It will give a near perfect match at 54 75 GHz and has a theoretical 1 07 VSWR at 50 and 60 GHz

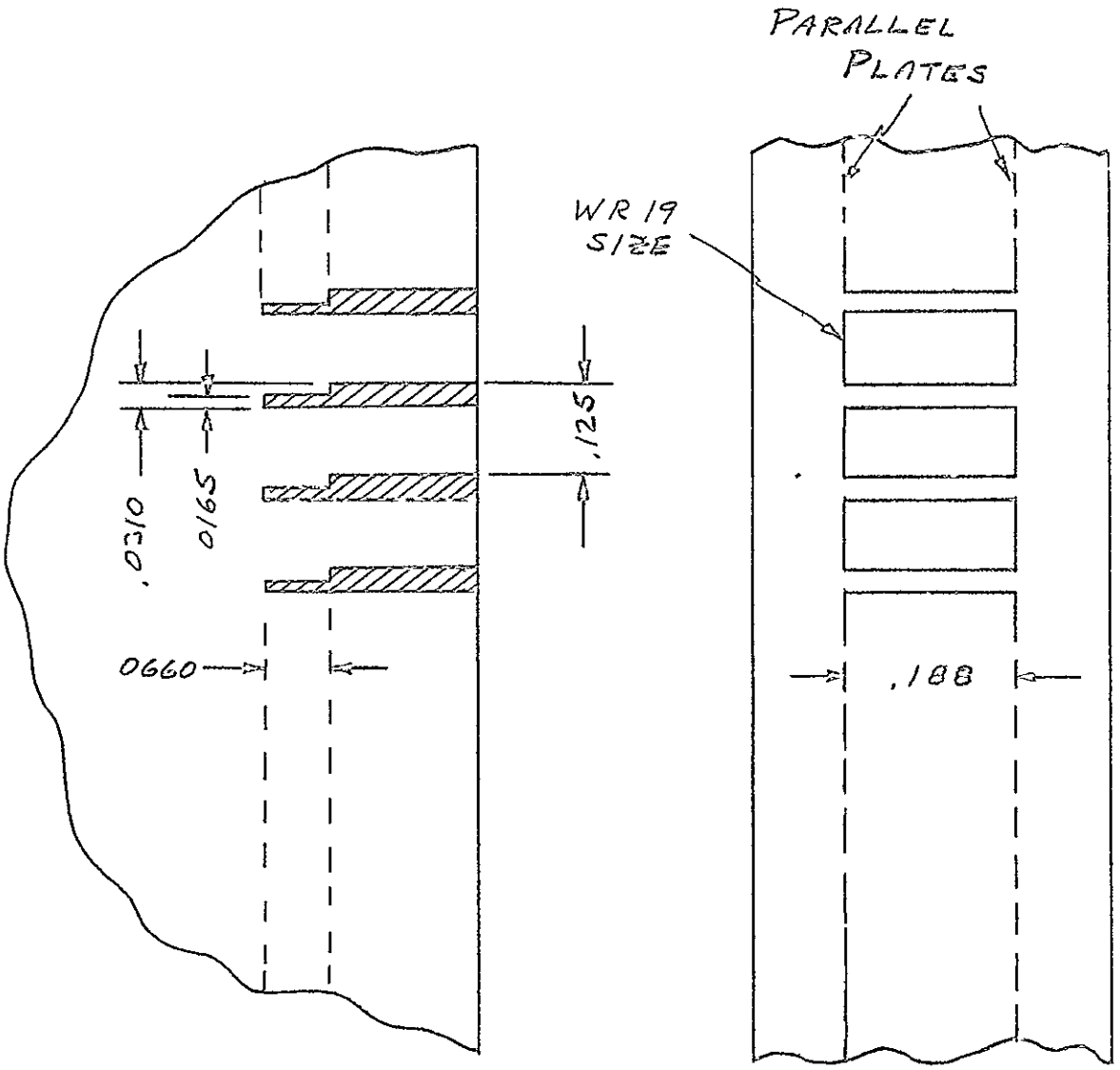

Figure 4-4
Transformer Details

5 0 CONCLUSIONS

The radiation characteristics of an H plane horn lens operating in the 50-60 GHz band have been determined The design tested indicates that a -30 dB minorlobes level can be approached over a 20% band in the millimeter region Performance was limited by the effectiveness of the lens matching technique employed Further work on lens matching should result in some improvement in sidelobes For substantial improvement the lens should be eliminated in favor of the dual reflector concept described herein

The power distribution characteristic of an E plane shaped dual reflector system mounted in parallel plates has been determined A computer program to determine reflector contours for any realistic aperture power distribution was developed. The design tested demonstrated that parallel plates and shaped reflectors adequate for -30 dB minorlobes can be produced for 60 GHz operation To obtain the -30 dB minorlobes over a 20% band an improved feed horn is required A feed horn with considerably improved bandwidth could be developed, but might require another set of shaped reflectors

to maintain the aperture distribution

Dividing the aperture into 84 parts of WR19 size could be done by a relatively easy addition to the parallel plates.

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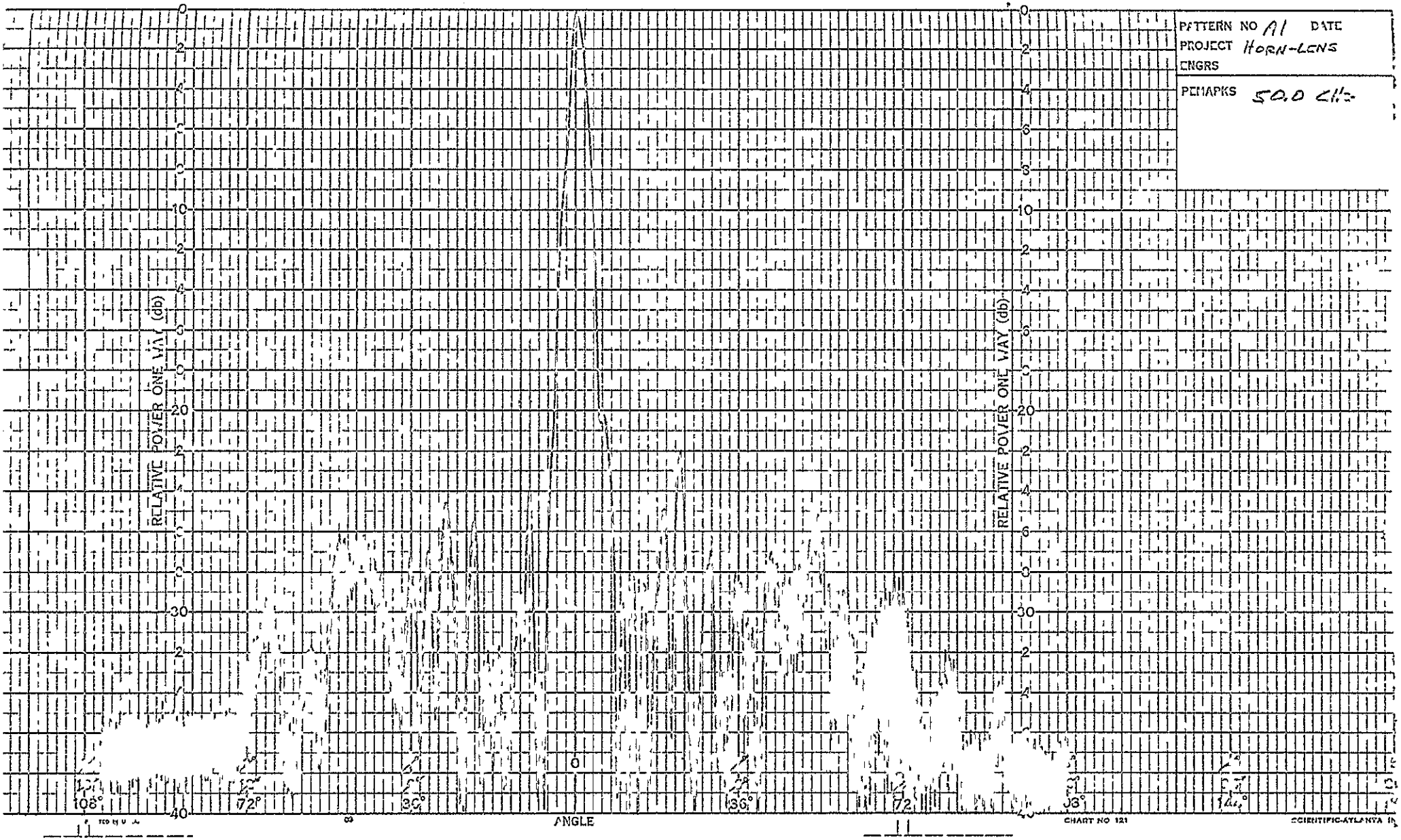
Appendix A

HORN-LENS RADIATION PATTERNS

The appendix presents the measured radiation patterns of the horn-lens Pattern numbers A1 through A5 are of its H plane in the final configuration as discussed in Section 3.2 Pattern numbers A6 through A12 are the results when the internal angled plates are removed and the corner walls are lined with absorber to dissipate lens reflections All of these patterns utilize the lowest scale of the chart paper.

Further discussion of these results is given in Section 3 3 of this report



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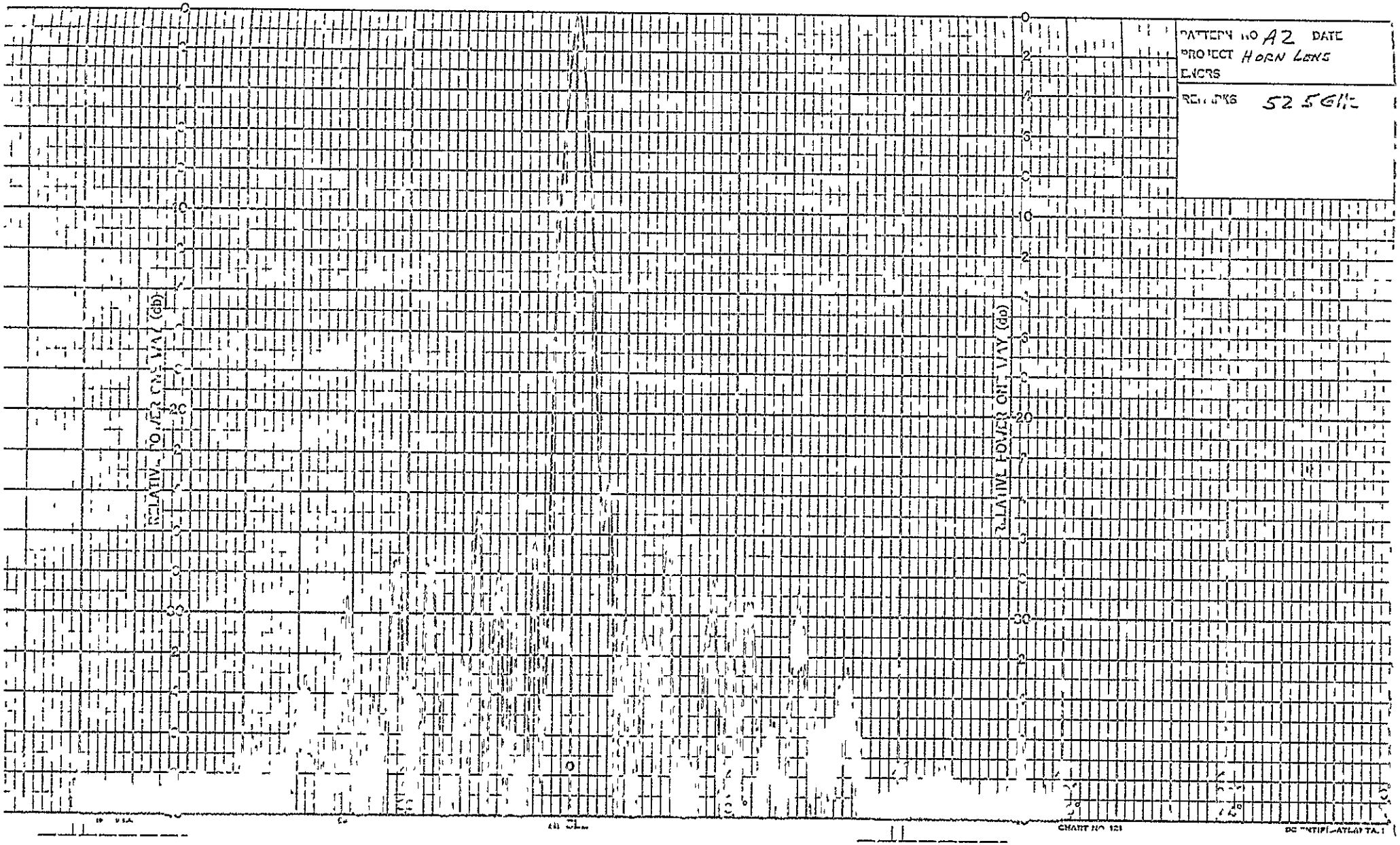
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RELATIVE POWER ON AXIS (db)
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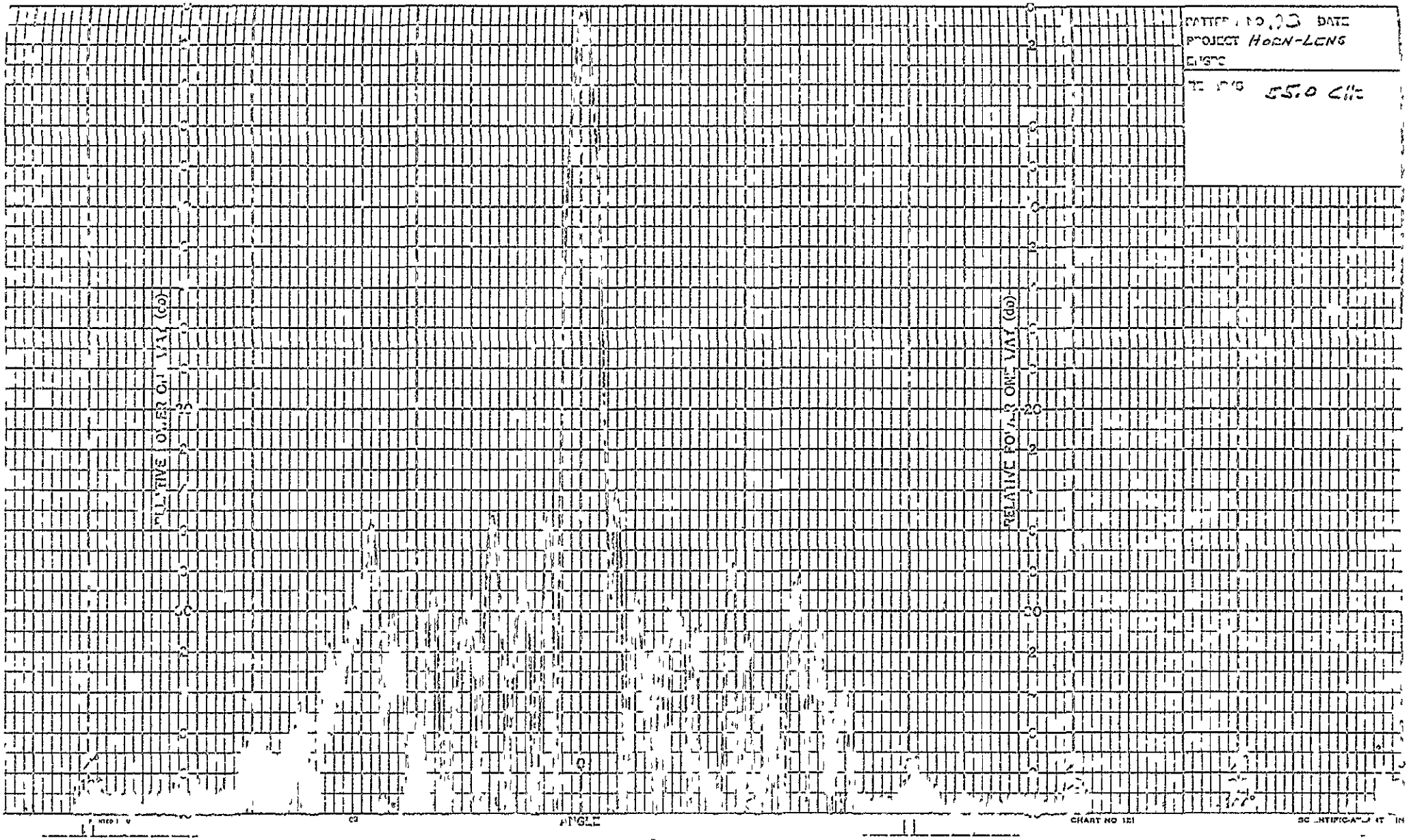
2
4
6
10
20
30
CHART NO 121



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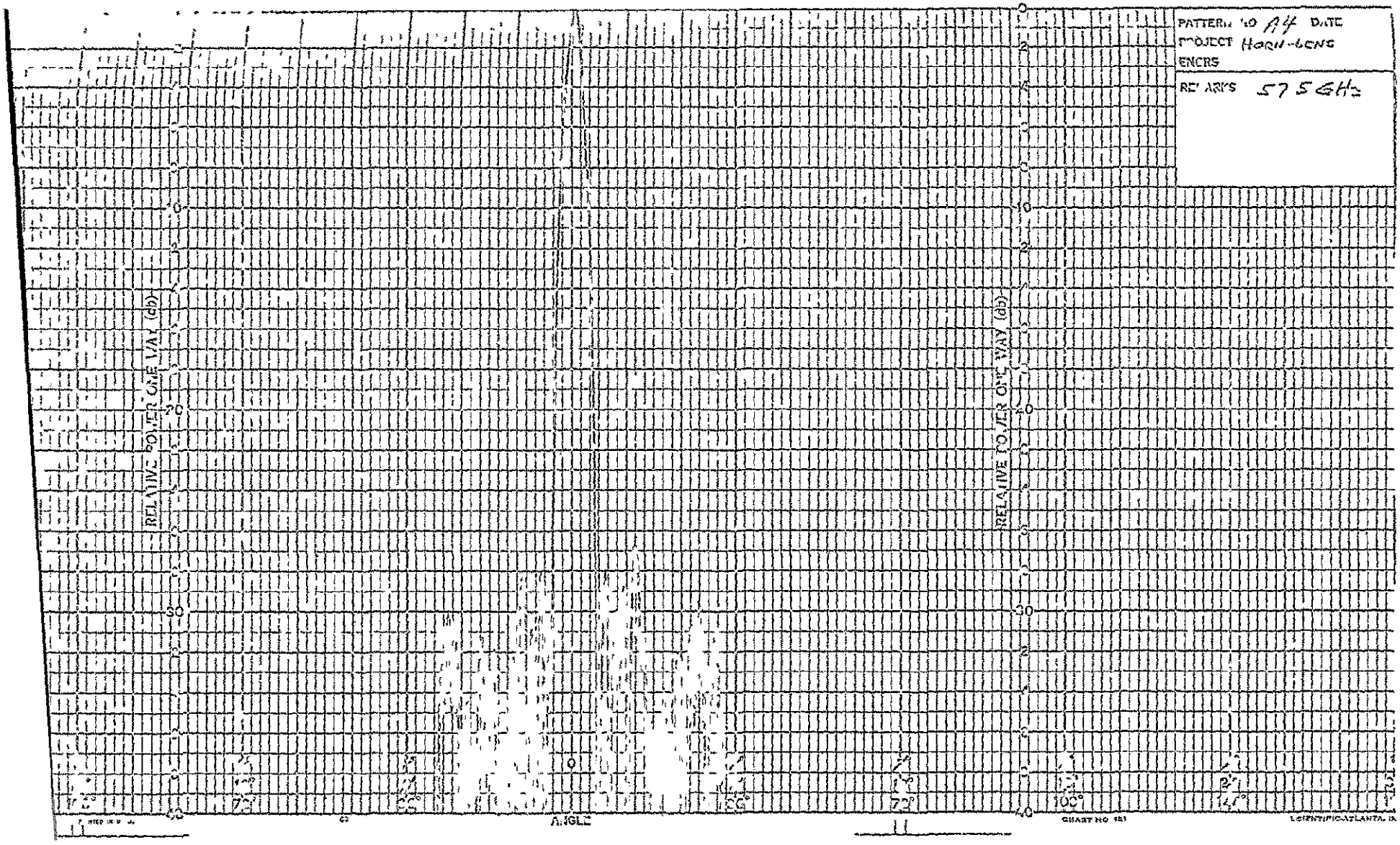
PATTERN NO 84 DATE
PROJECT HORN-LENS
ENGRS
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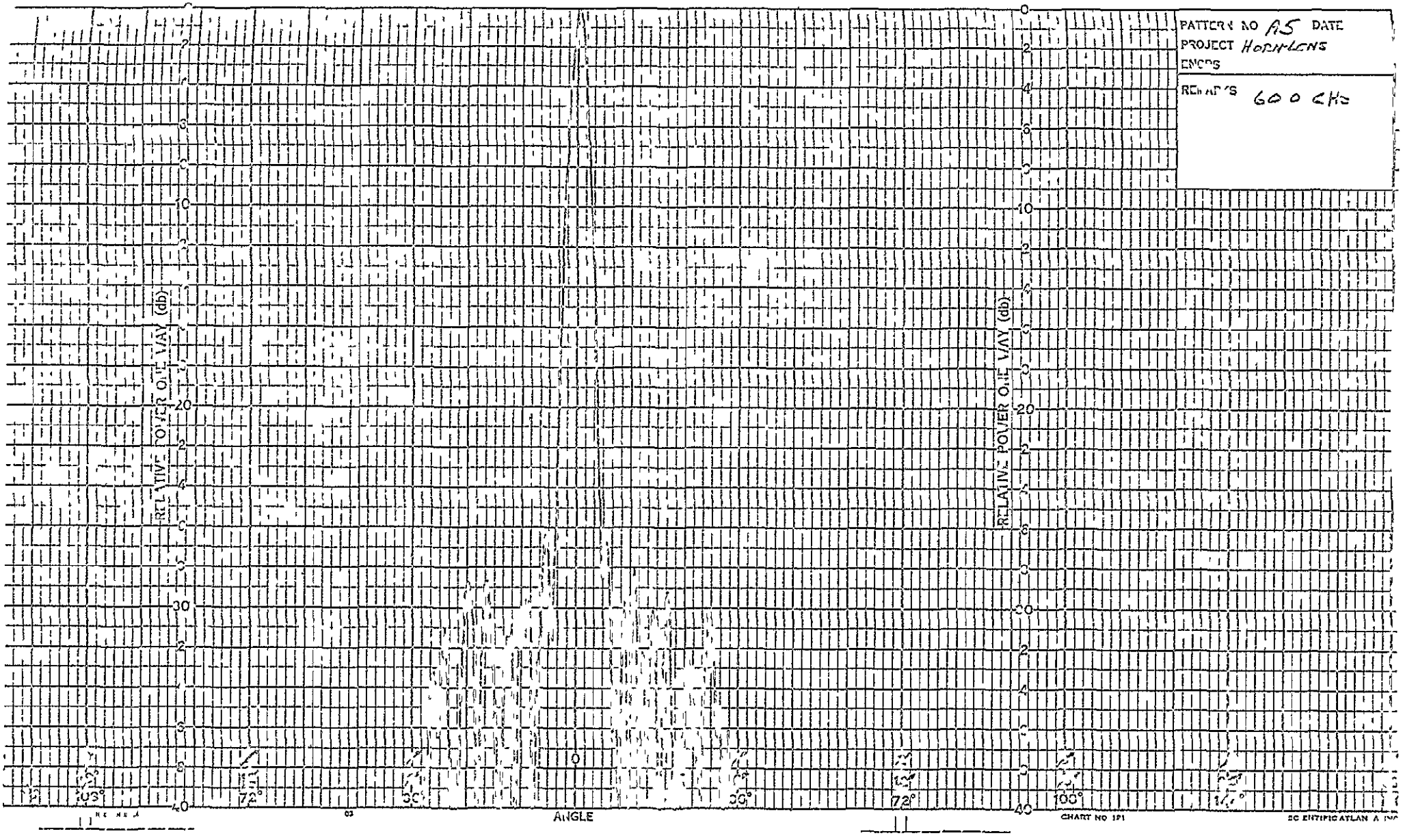
RELATIVE POWER ONE WAY (db)
ANGLE
SCIENTIFIC-ATLANTA, IN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PROJECT HORNLENS
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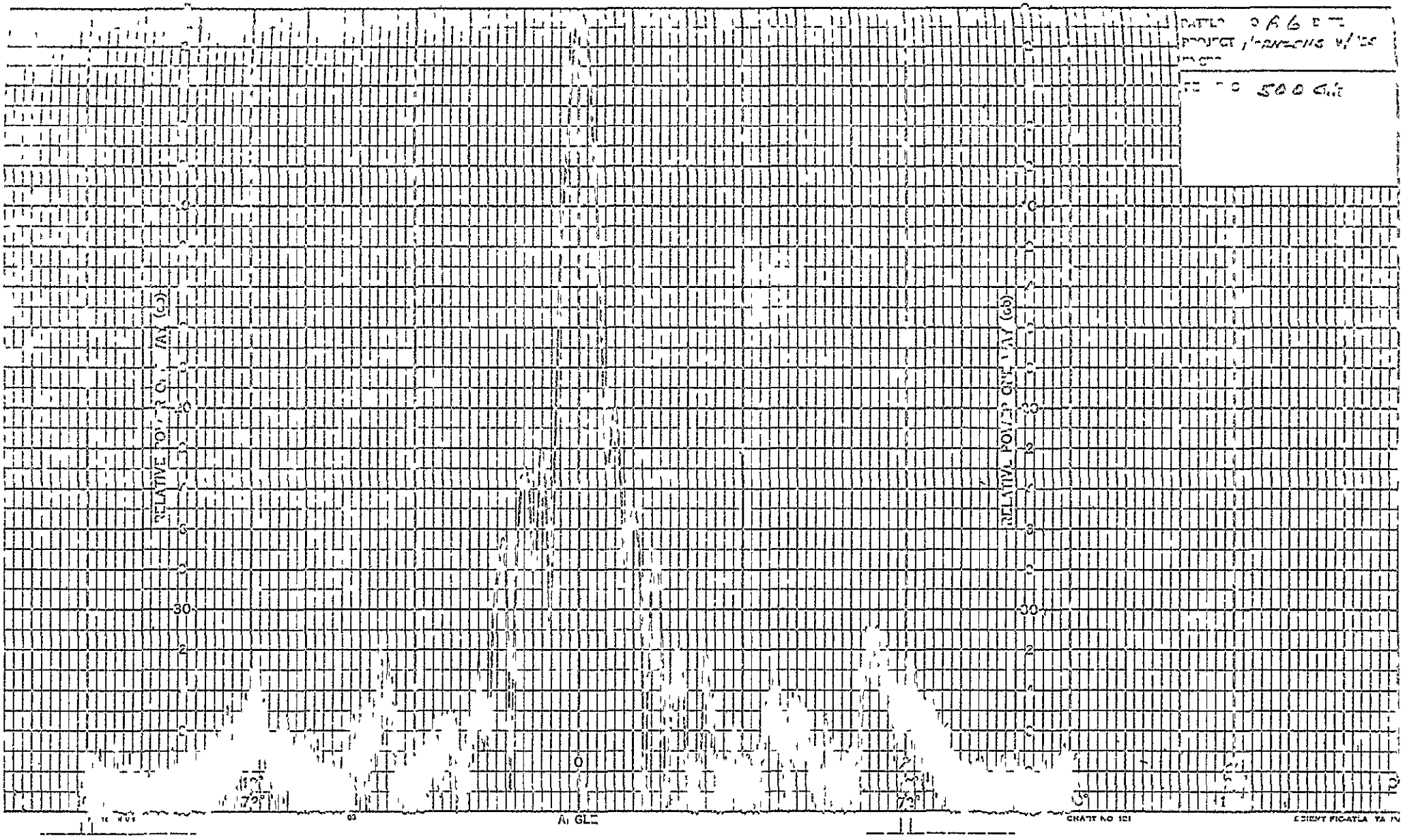
RELATIVE POWER O/E V/AV (db)
ANGLE
CHART NO 1P1



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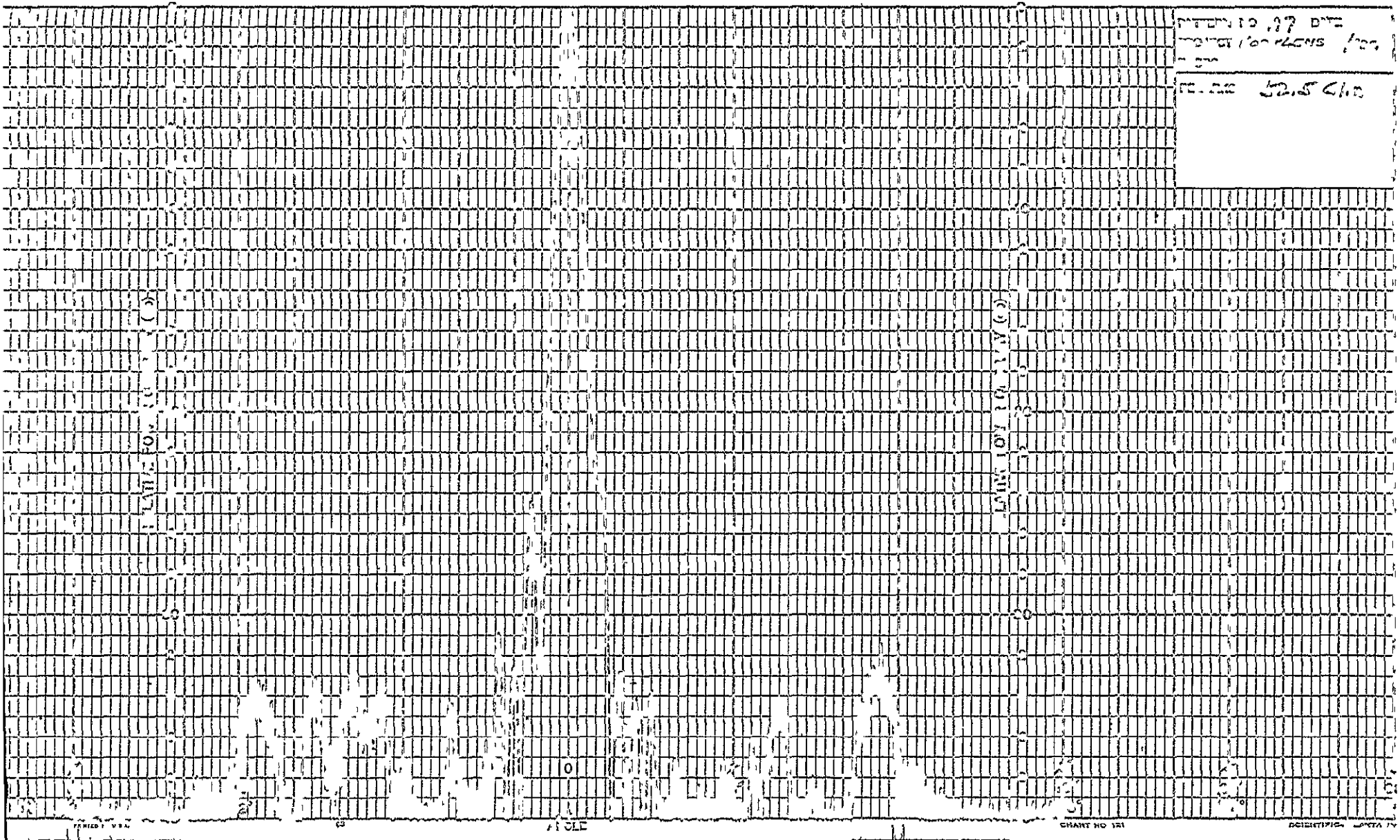
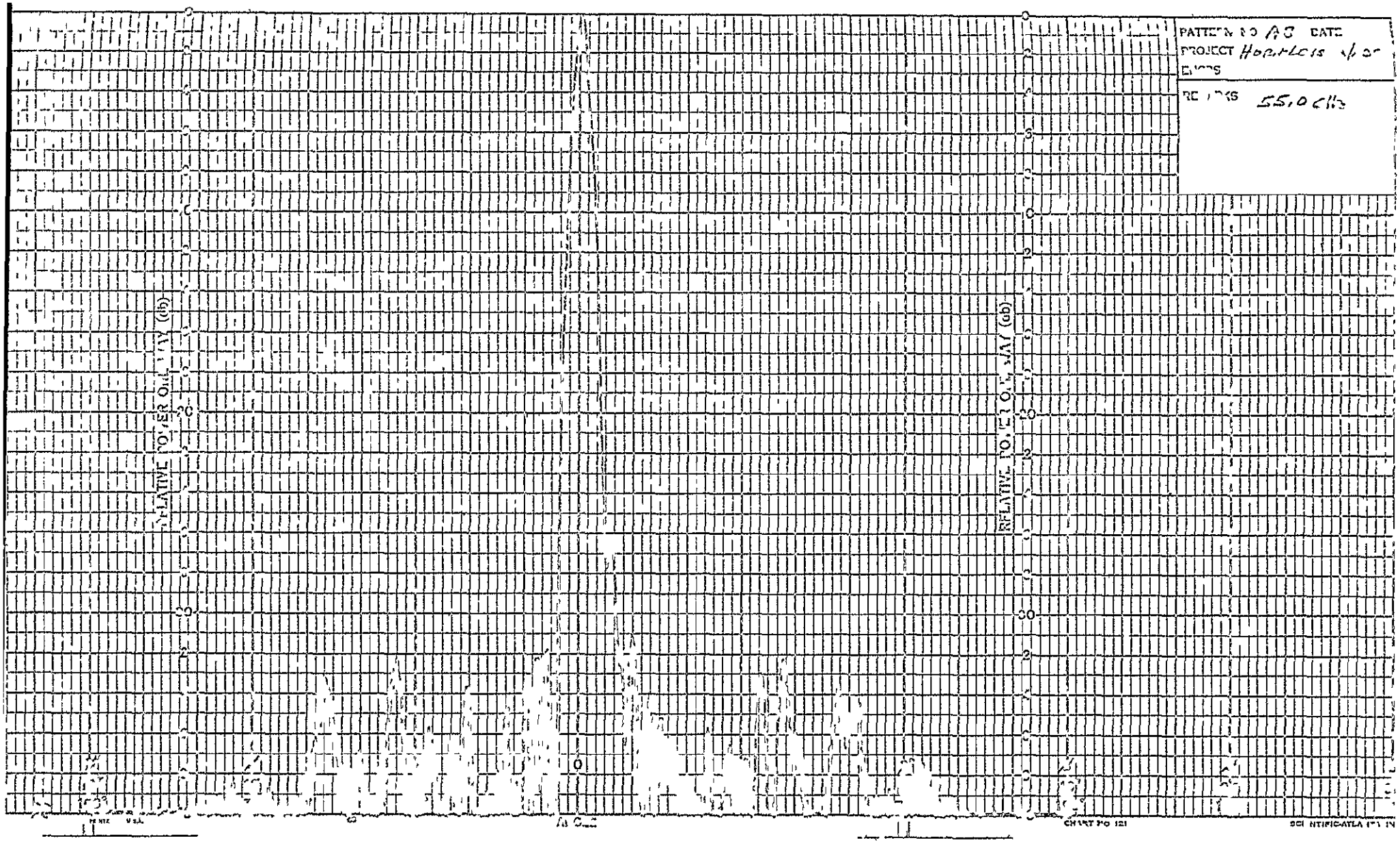
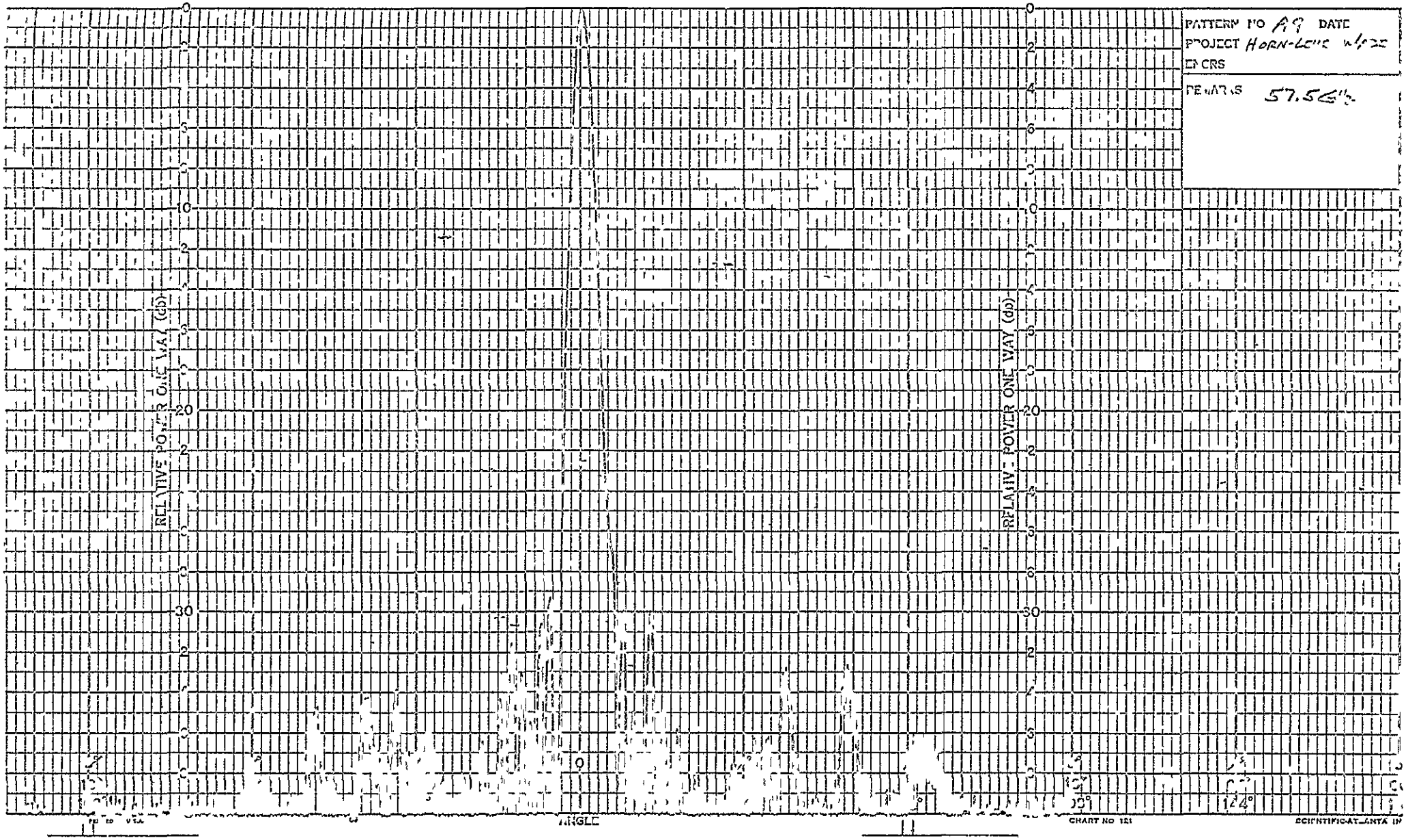



PATTERN NO AC DATE
PROJECT Hopkins 4 of
RECORDS 55,0 CHS
RELATIVE POWER OUTSIDE BAY (db)
RELATIVE POWER OUTSIDE BAY (db)
CHART NO 121



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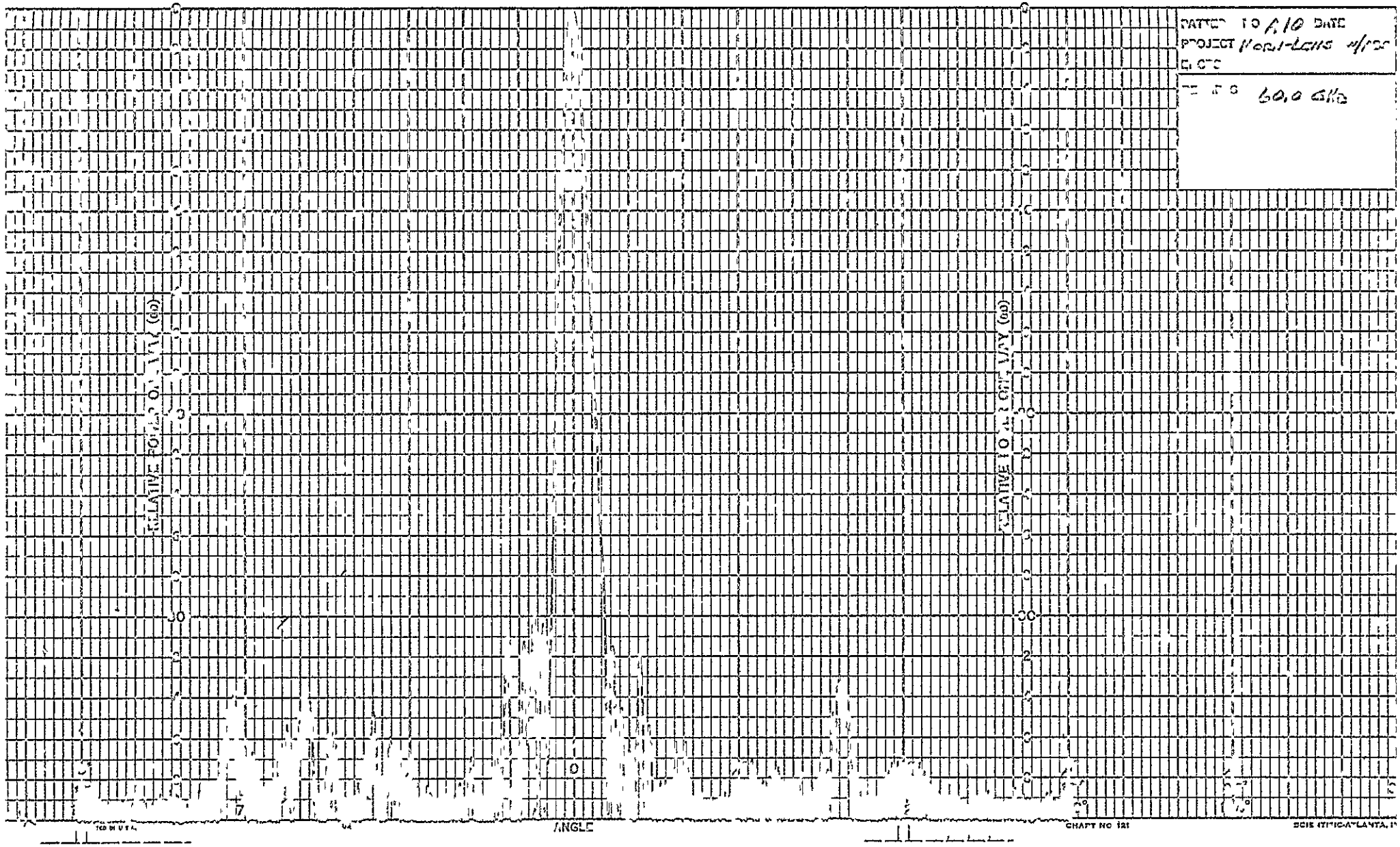
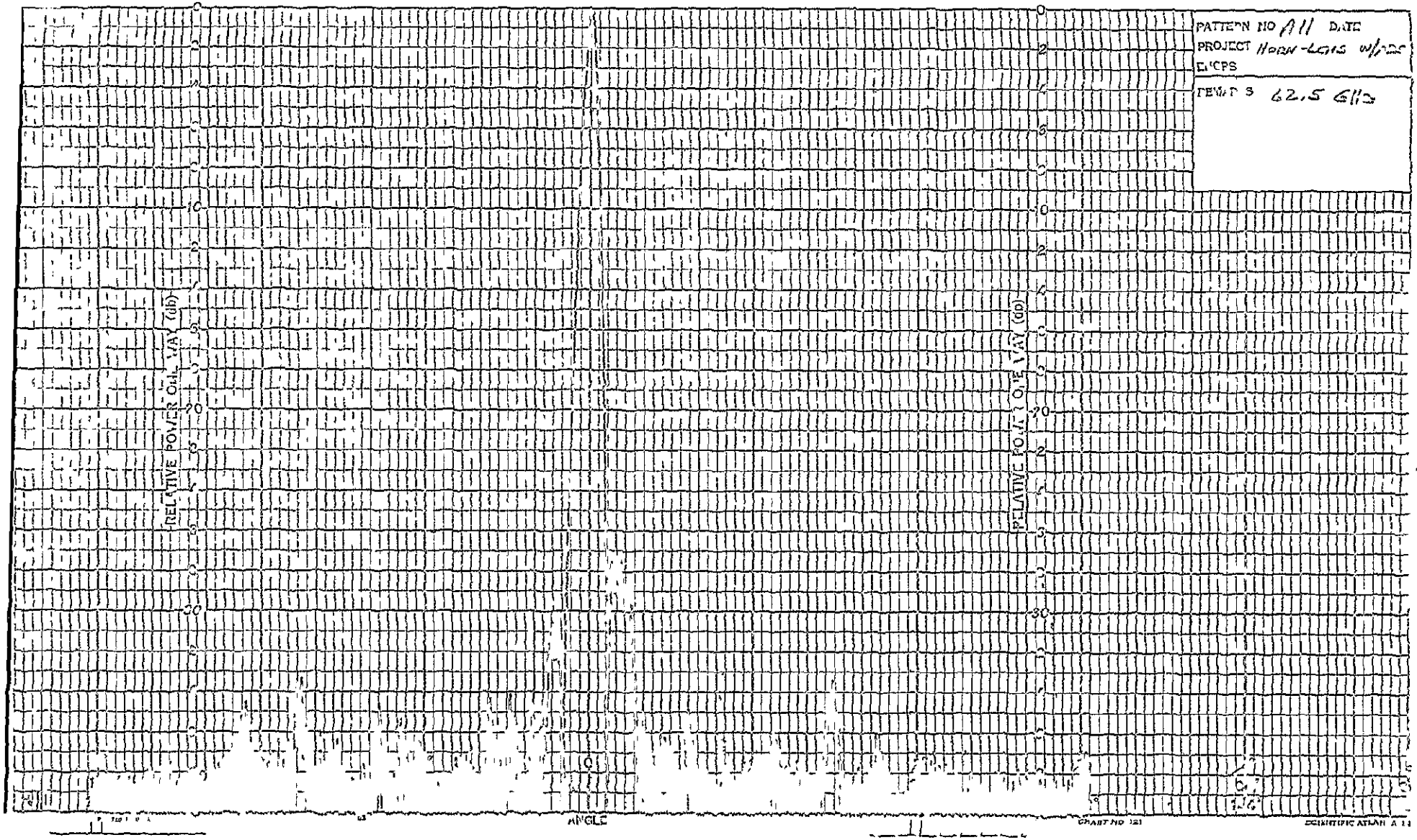
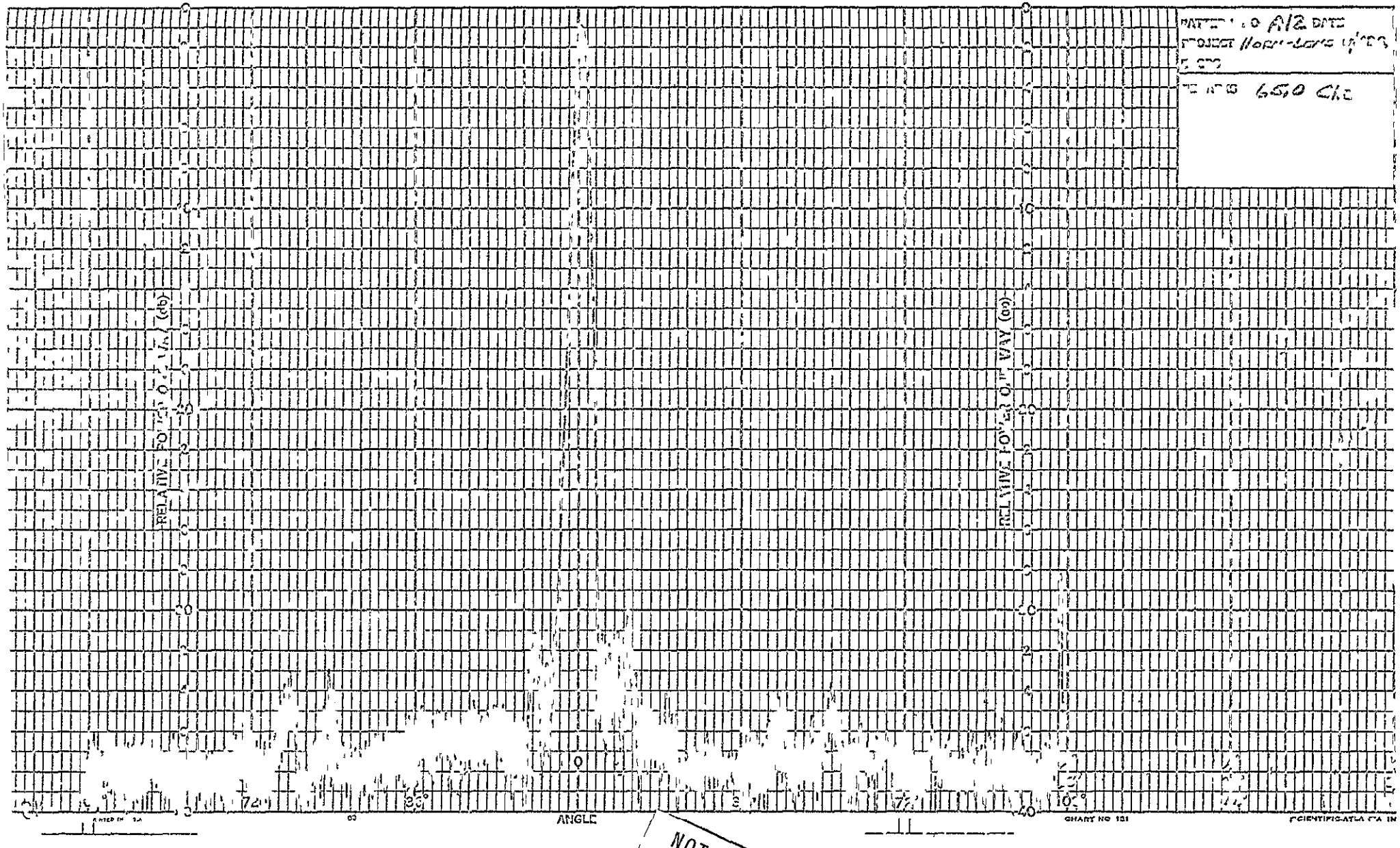

RELATIVE POWER OUTPUT (db)
RELATIVE POWER OUTPUT (db)
ANGLE
CHART NO 121


PATTERN NO A11 DATE
PROJECT Horn-Lens w/Rim
ELEMENTS
REMARKS 62.5 GHz
RELATIVE POWER GAIN (dB)
RELATIVE POWER GAIN (dB)
ANGLE
GRAPH NO 121
SCIENTIFIC ATLANTA



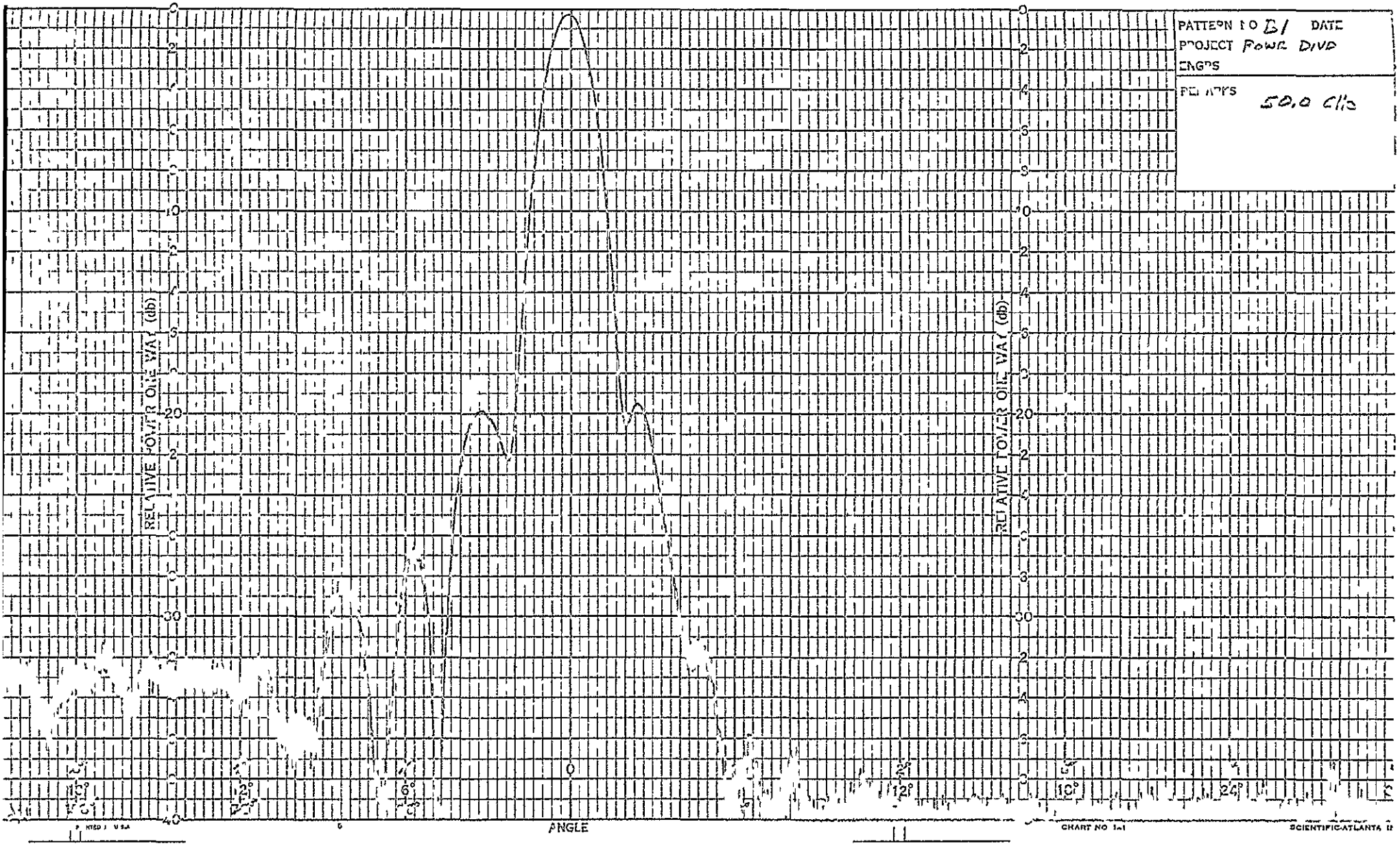
NOT REPRODUCIBLE

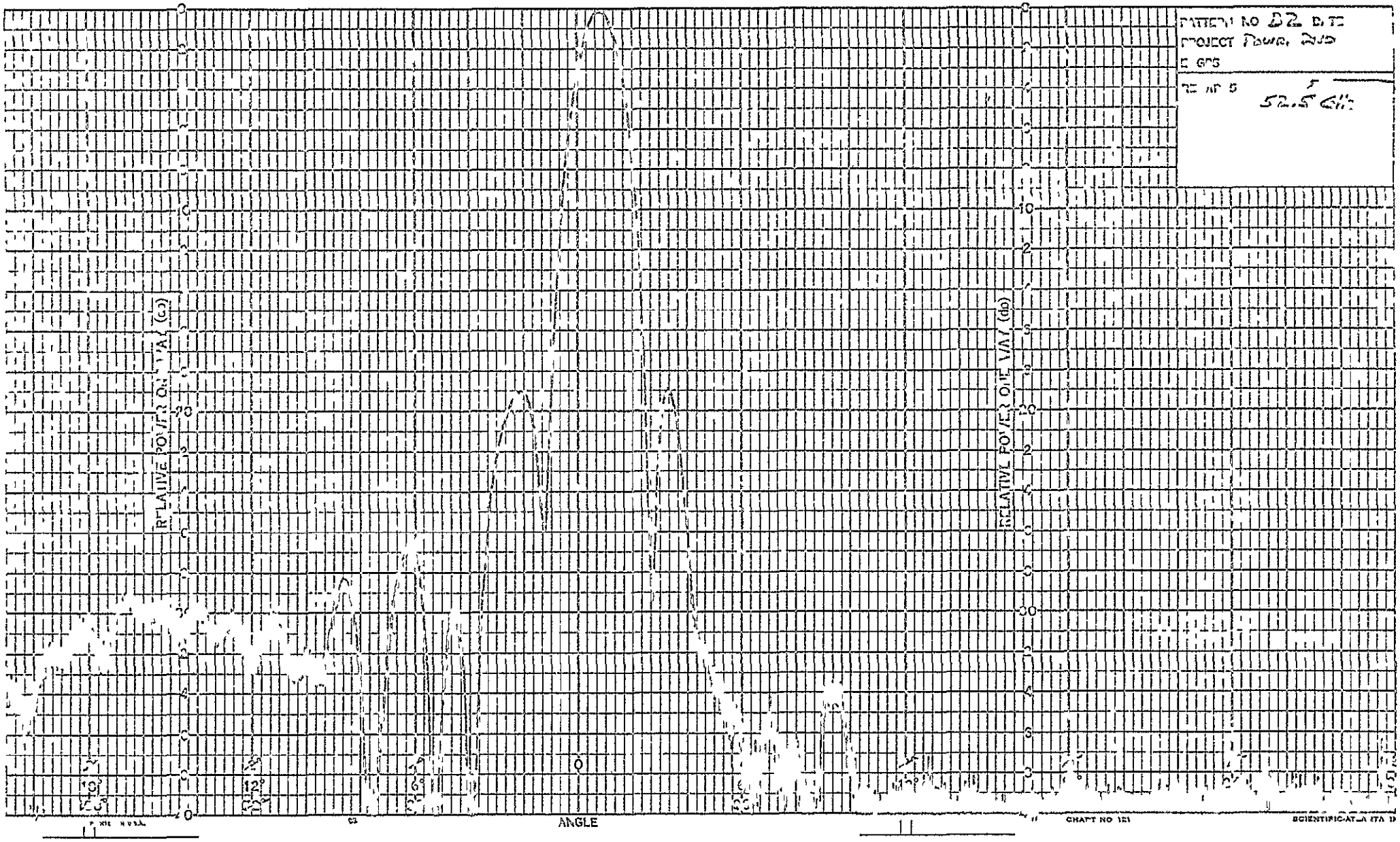
Appendix B

Power Divider Radiation Patterns

This appendix presents the measured radiation patterns of the shaped reflector's E plane aperture Pattern numbers B1 through B9 show the mainlobe and first few sidelobes at 50, 52.5, and 55-61 GHz respectively (These utilize the center scale of the chart paper) Pattern numbers B10-B18 are duplicates except that the bottom scale is utilized to show wide angle characteristics

Further discussion of these results is given in Section 4.3 of this report.


PATTERN NO 21 DATE
PROJECT Power Divid
ENGRS
REMARKS 50.0 c/s
RELATIVE POWER ONE WAY (db)
RELATIVE POWER ONE WAY (db)
ANGLE
CHART NO 1-41
SCIENTIFIC-ATLANTA



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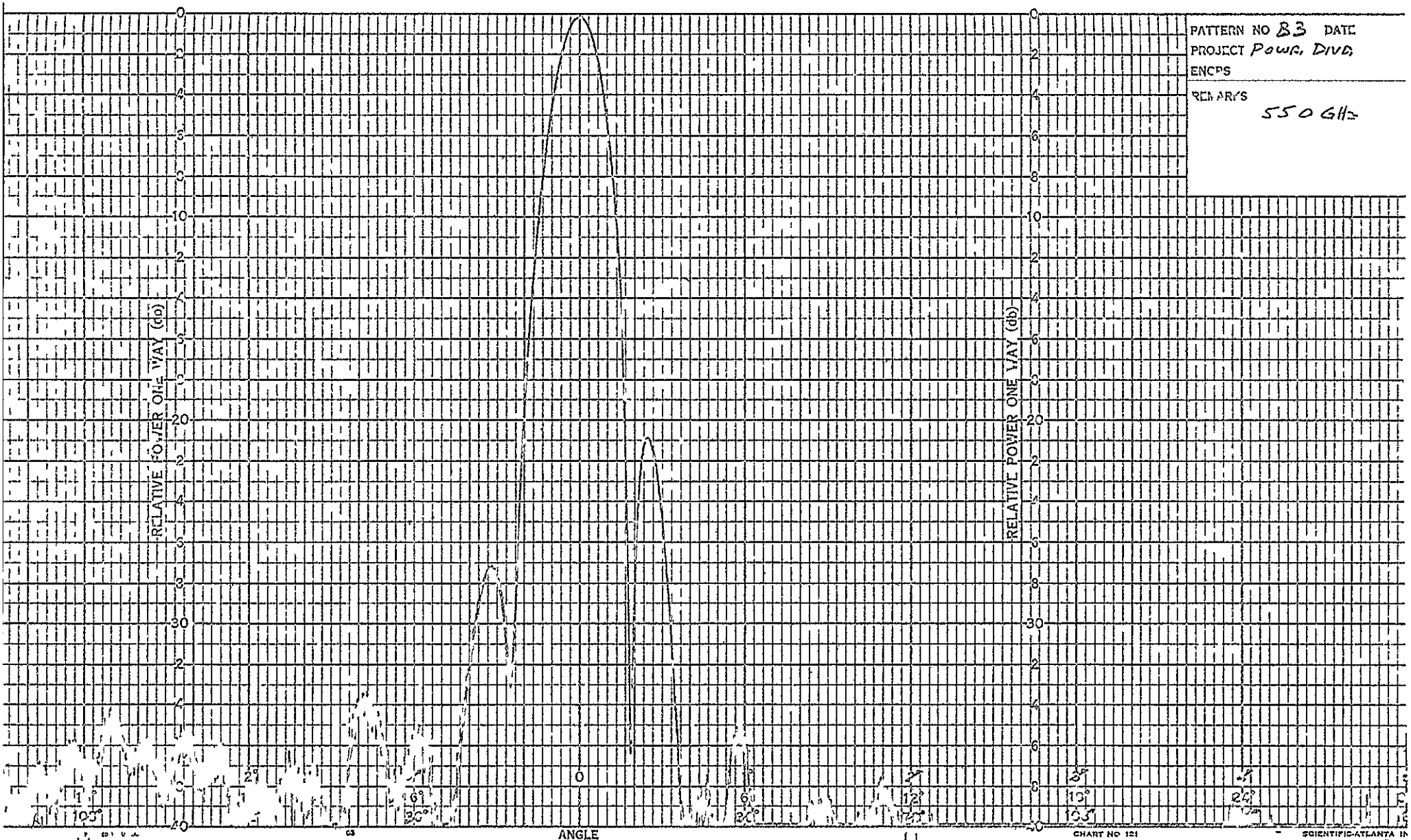
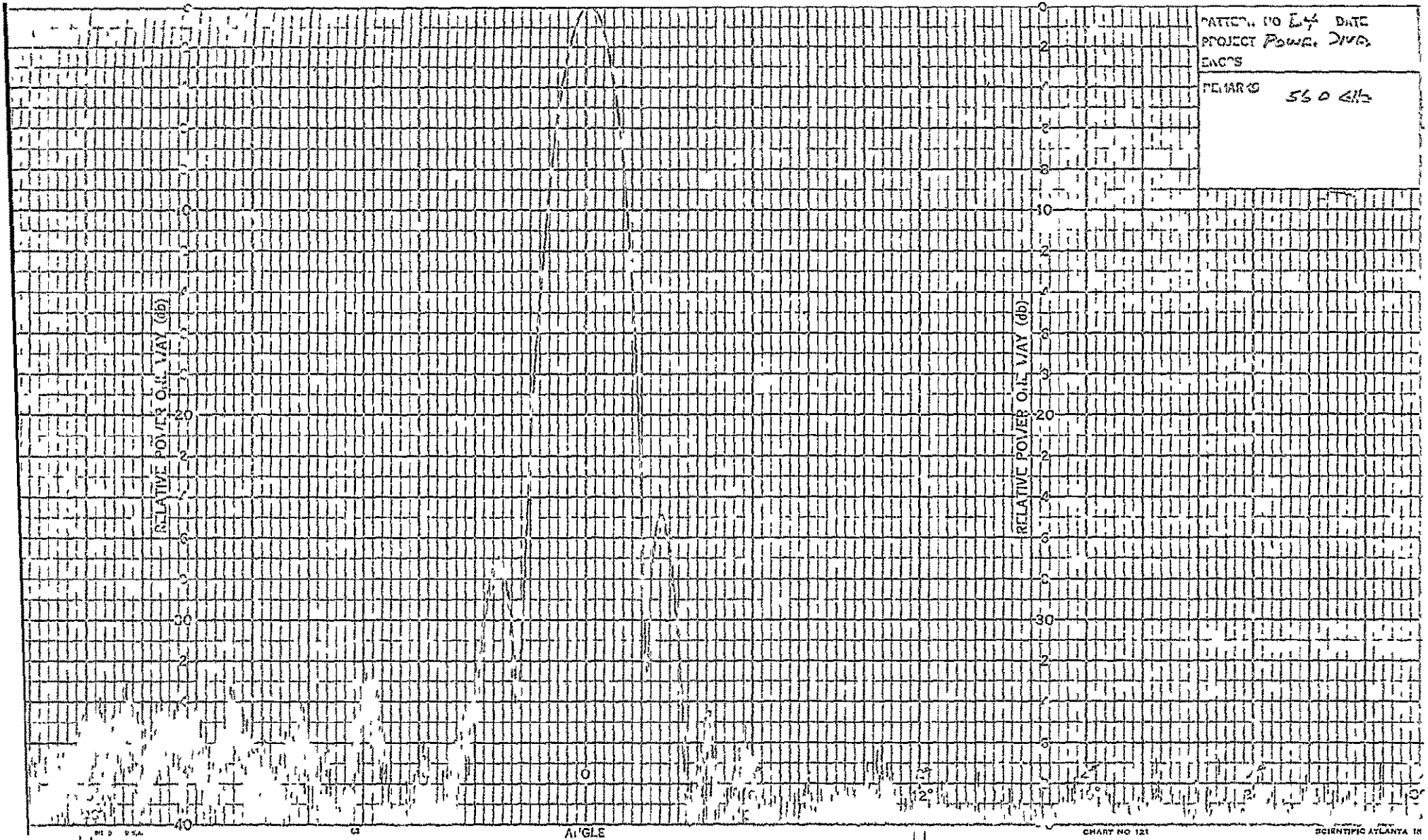

PATTERN NO B3 DATE
PROJECT Powr. Divd.
ENGRS
REMARKS
550 GHz
RELATIVE POWER ONE WAY (db)
RELATIVE POWER ONE WAY (db)
ANGLE
CHART NO 121
SCIENTIFIC-ATLANTA



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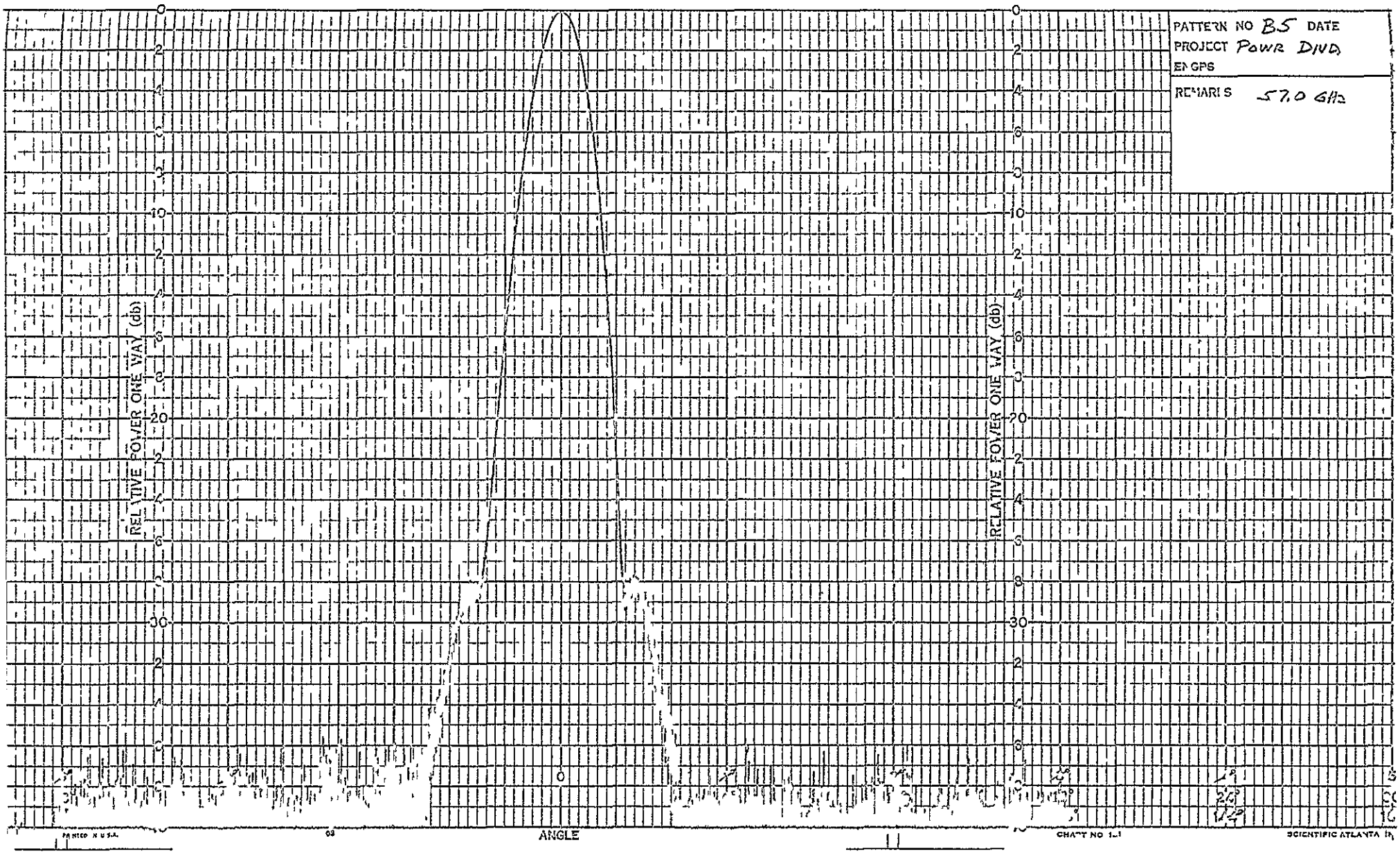

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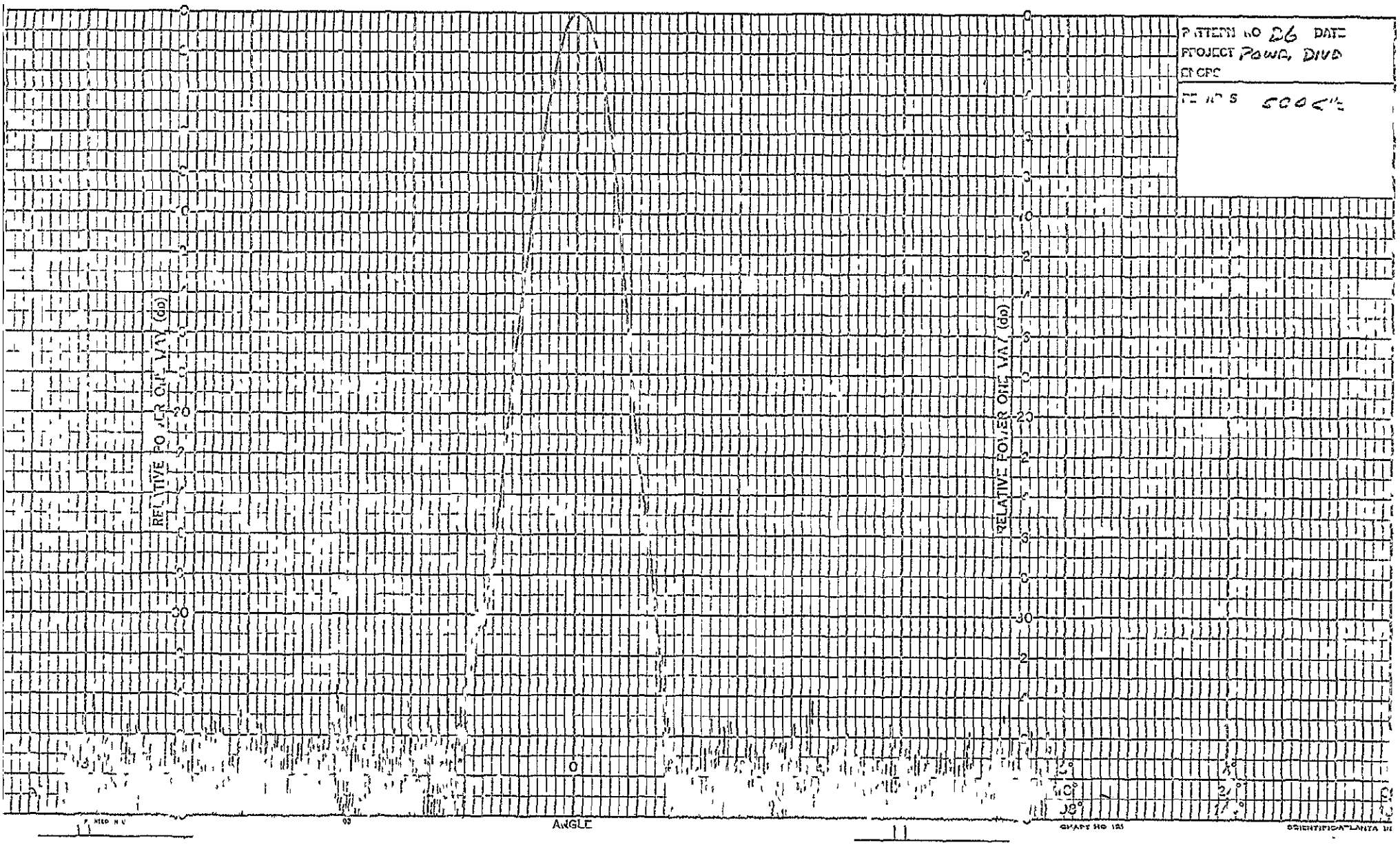

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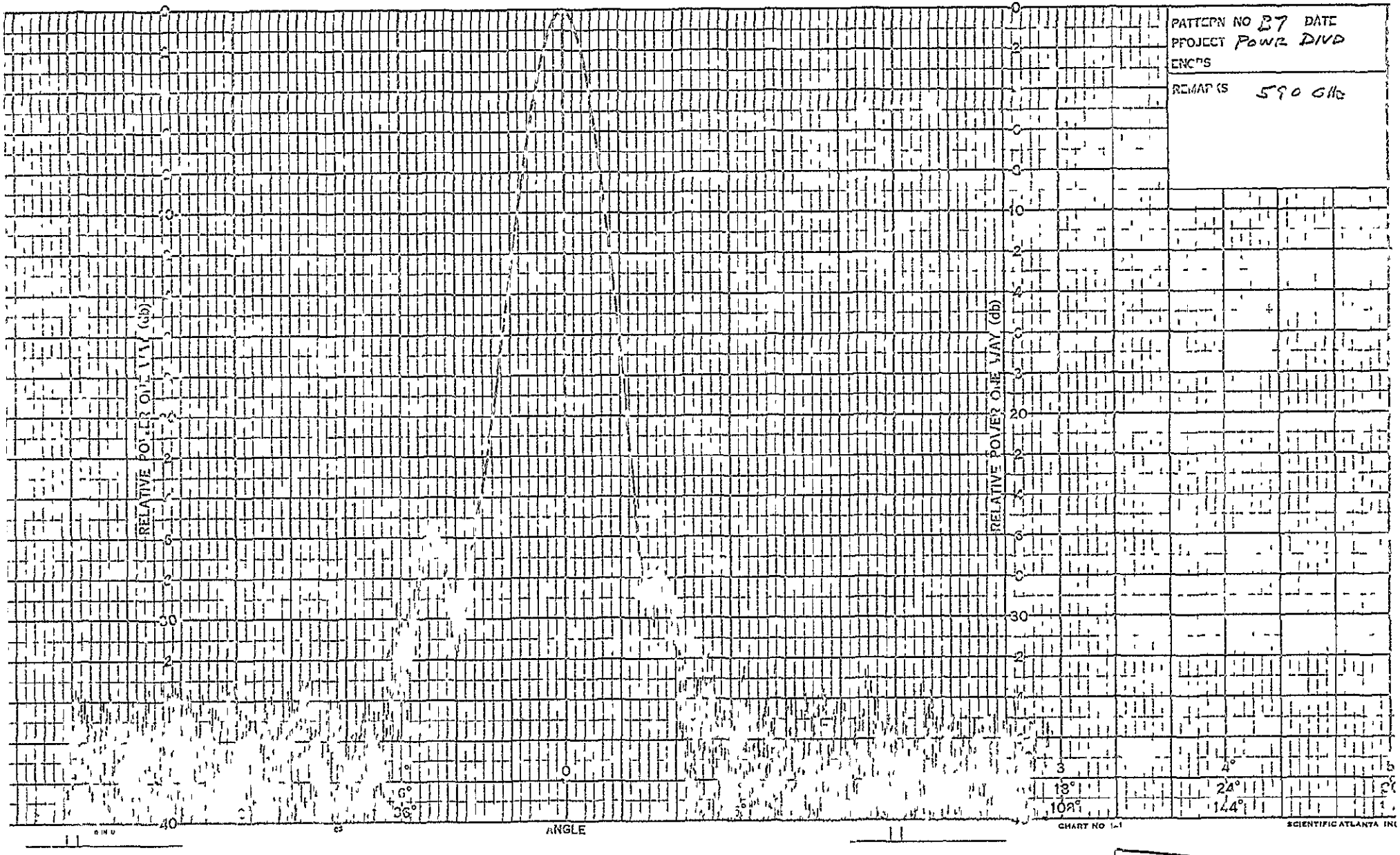

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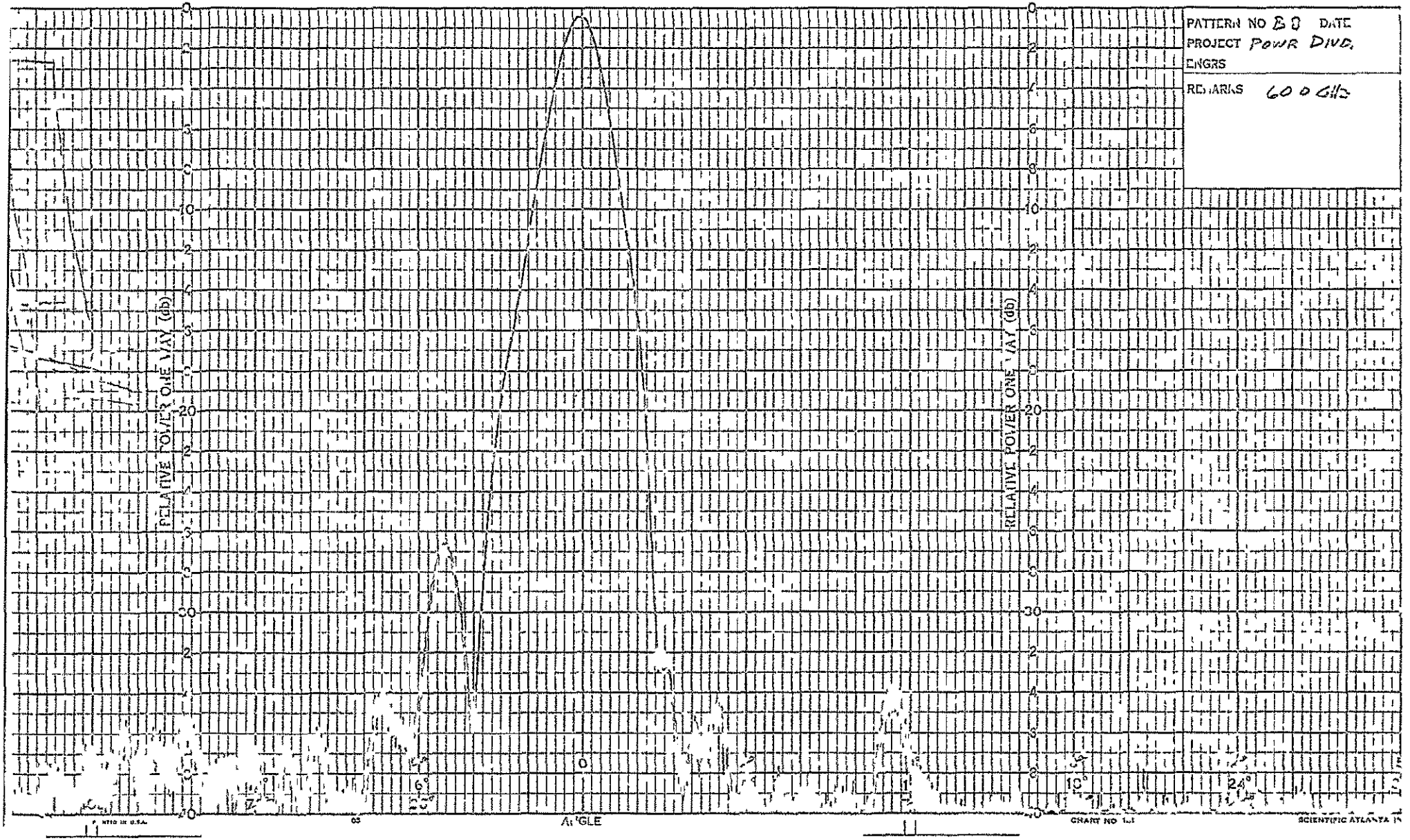

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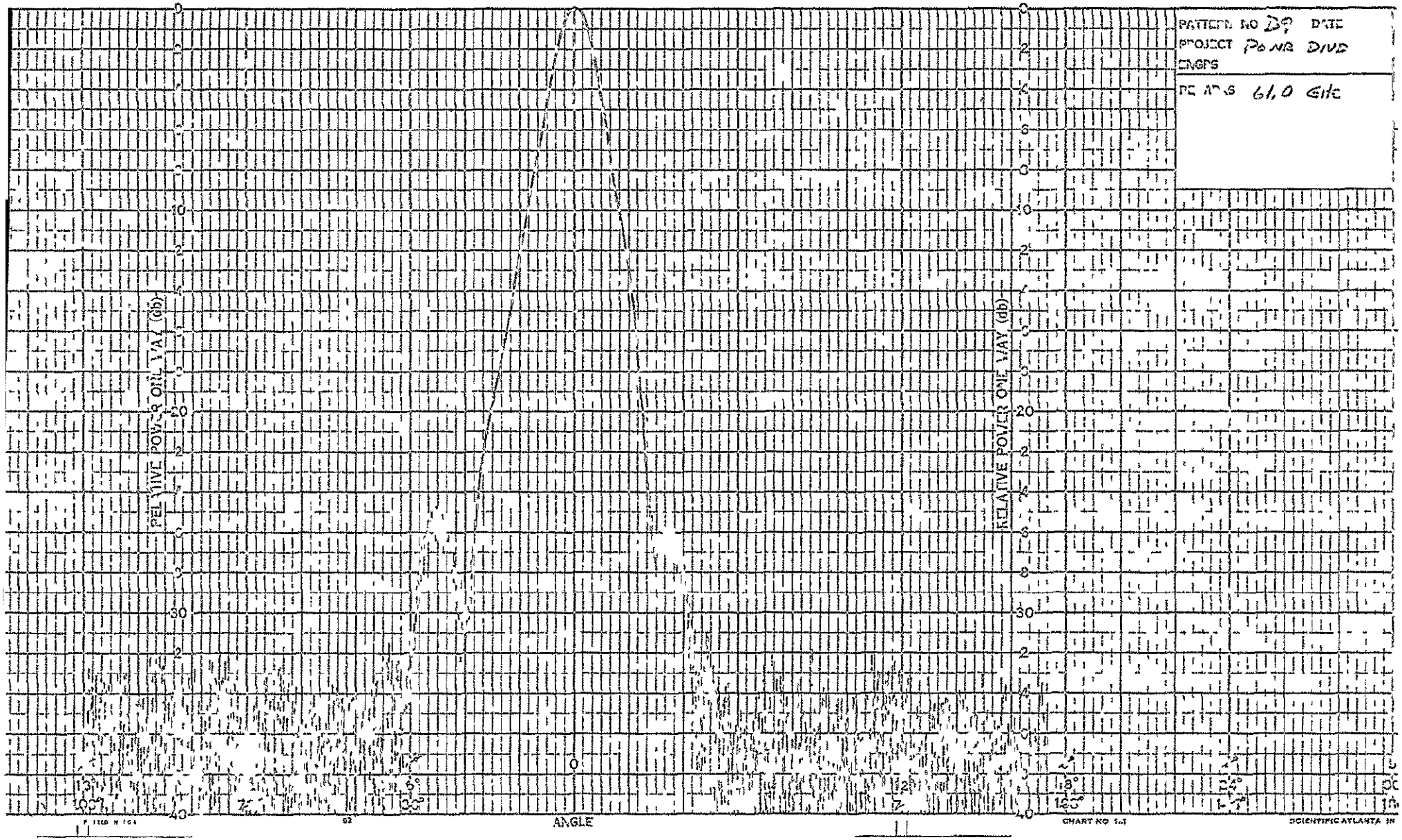

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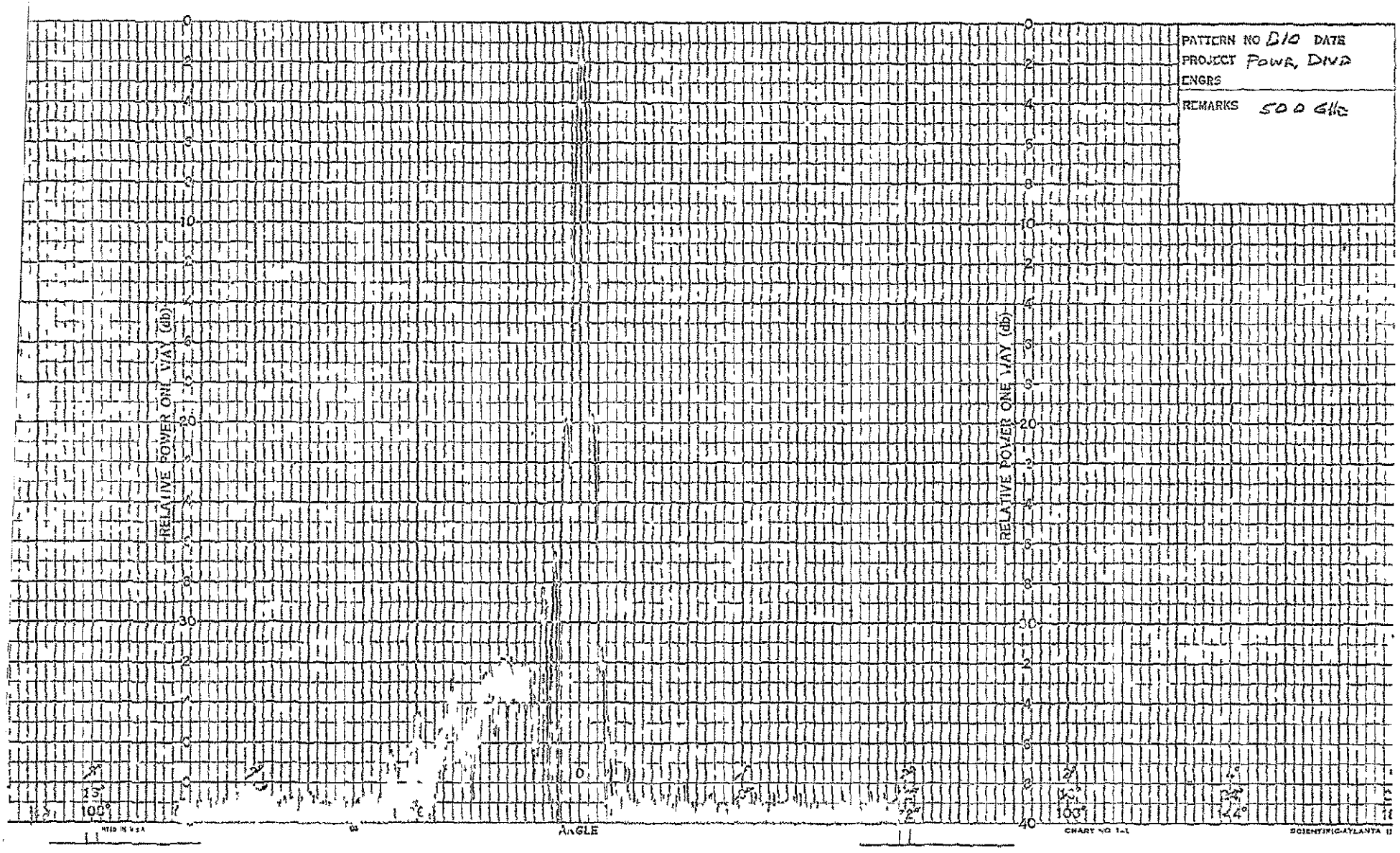
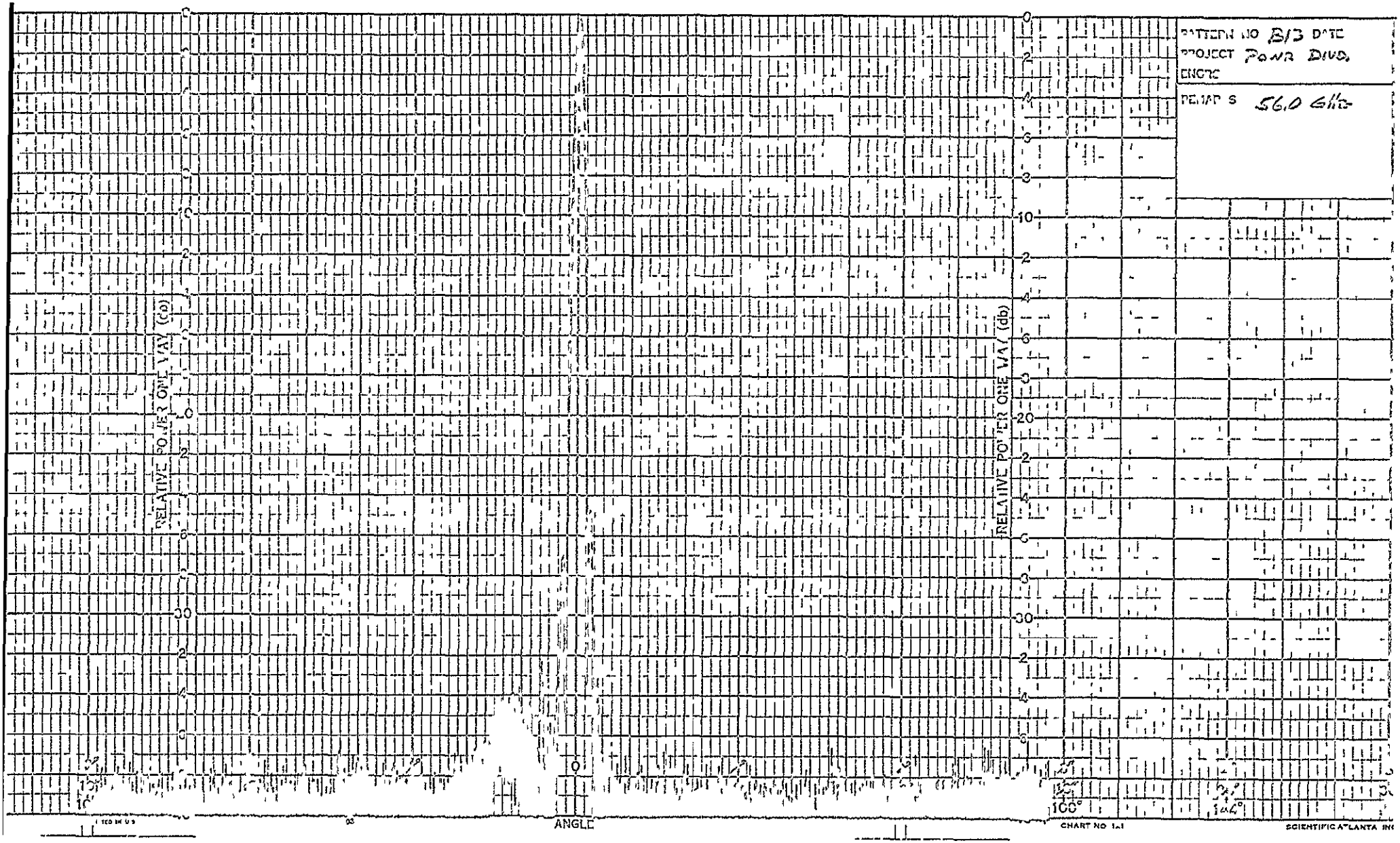

PATTERN NO D10 DATE
PROJECT POWR, DIVD
ENGRS
REMARKS 500 GHz
RELATIVE POWER ONE WAY (db)
0
2
4
6
8
10
20
30
40
ANGLE
100°
124°
SCIENTIFIC-ATLANTA

PATTERN NO D11 DATE
PROJECT Powr Divd
ENGRS
REMARKS 525 Gl/2
RELATIVE POWER ONE WAY (db)
0
2
4
6
8
10
20
30
40
108°
72°
100°
144°
0
ANGLE
CHART NO 1-1
SCIENTIFIC-ATLANTA II

PATTERN NO 012 DATE
PROJECT Powr. Divd.
FREQ 3GHz
POLARIZATION 55.0 CW
RELATIVE POWER OVER ONE WAY (db)
RELATIVE POWER OVER ONE WAY (db)
0
10
20
30
ANGLE
CHART NO 1-1
SCIENTIFIC-ATLANTA



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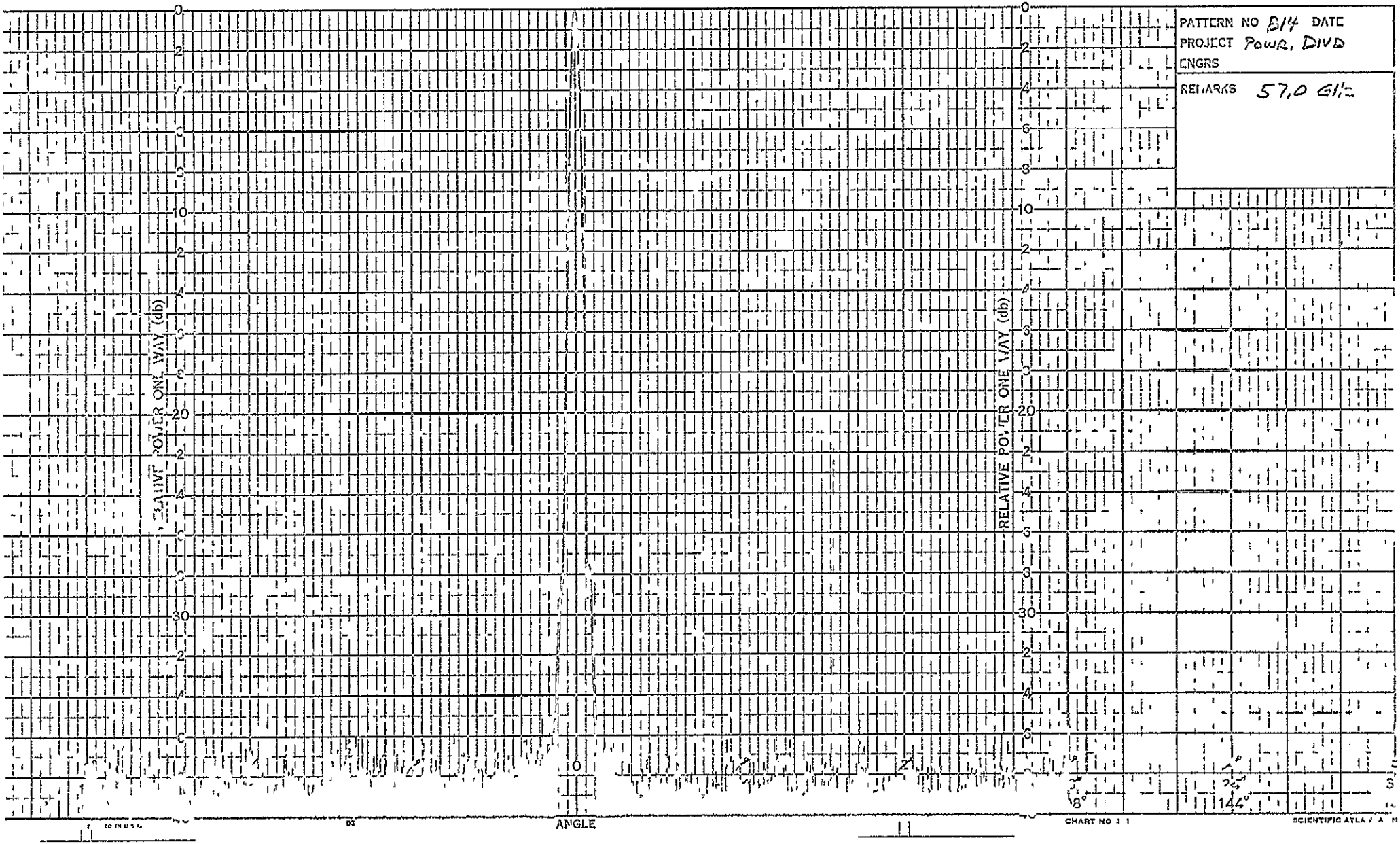
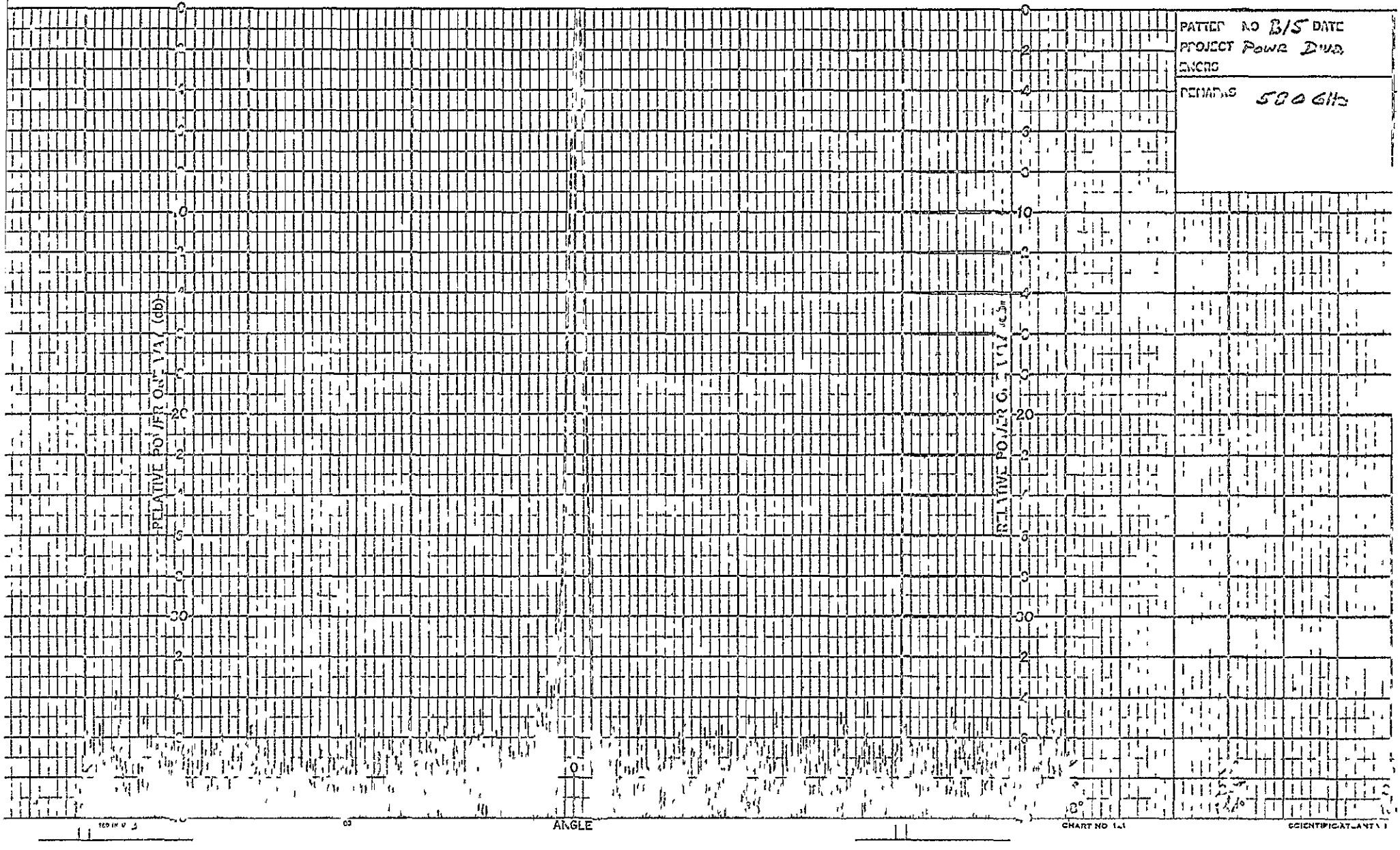
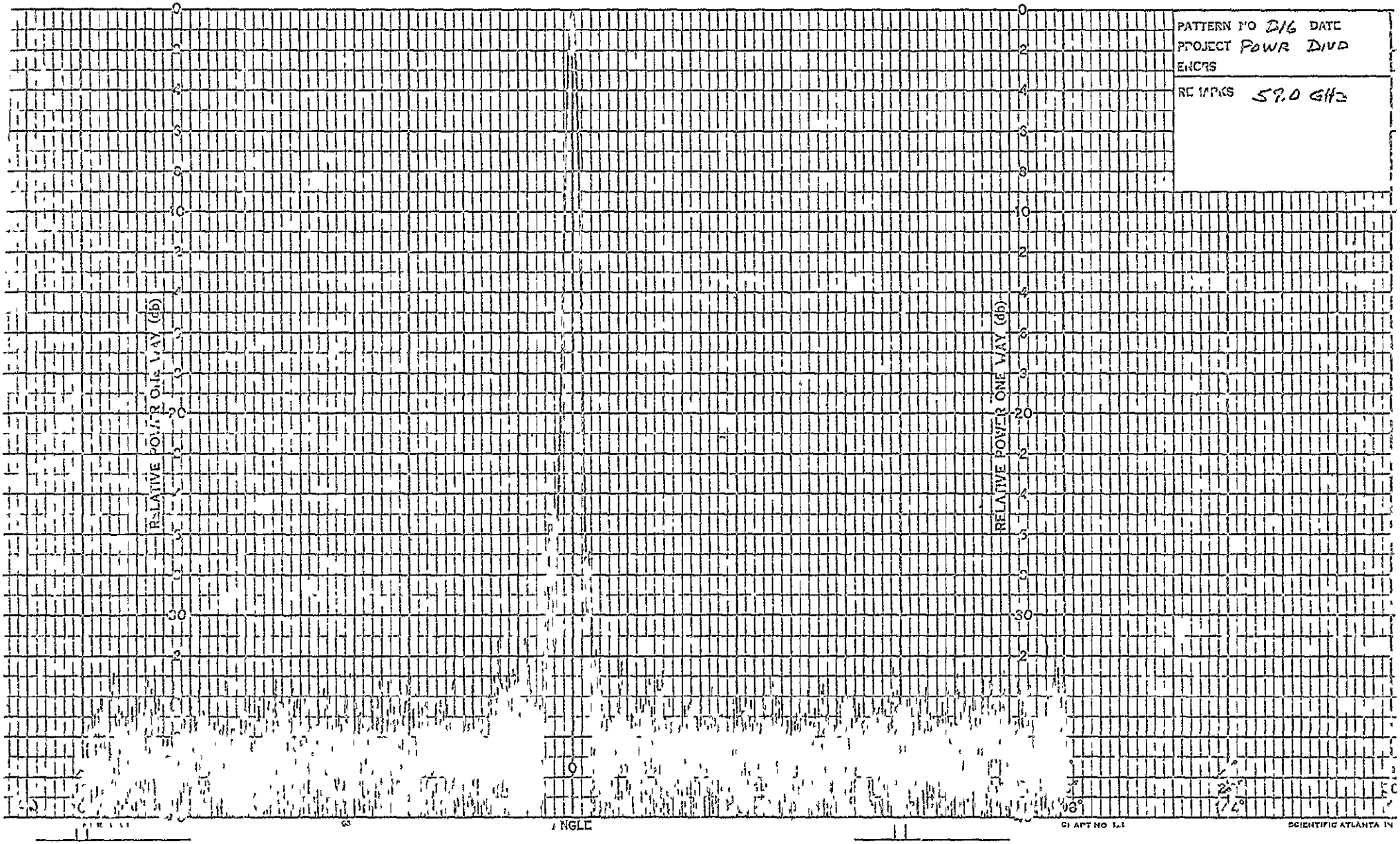


NOT REPRODUCIBLE


PATTERN NO B/S DATE
PROJECT Power Dish
ENGRS
REMARKS 500 MHz
RELATIVE POWER OUTPUT (db)
RELATIVE POWER OUTPUT (db)
ANGLE
CHART NO 1-A
SCIENTIFIC ATLANTA



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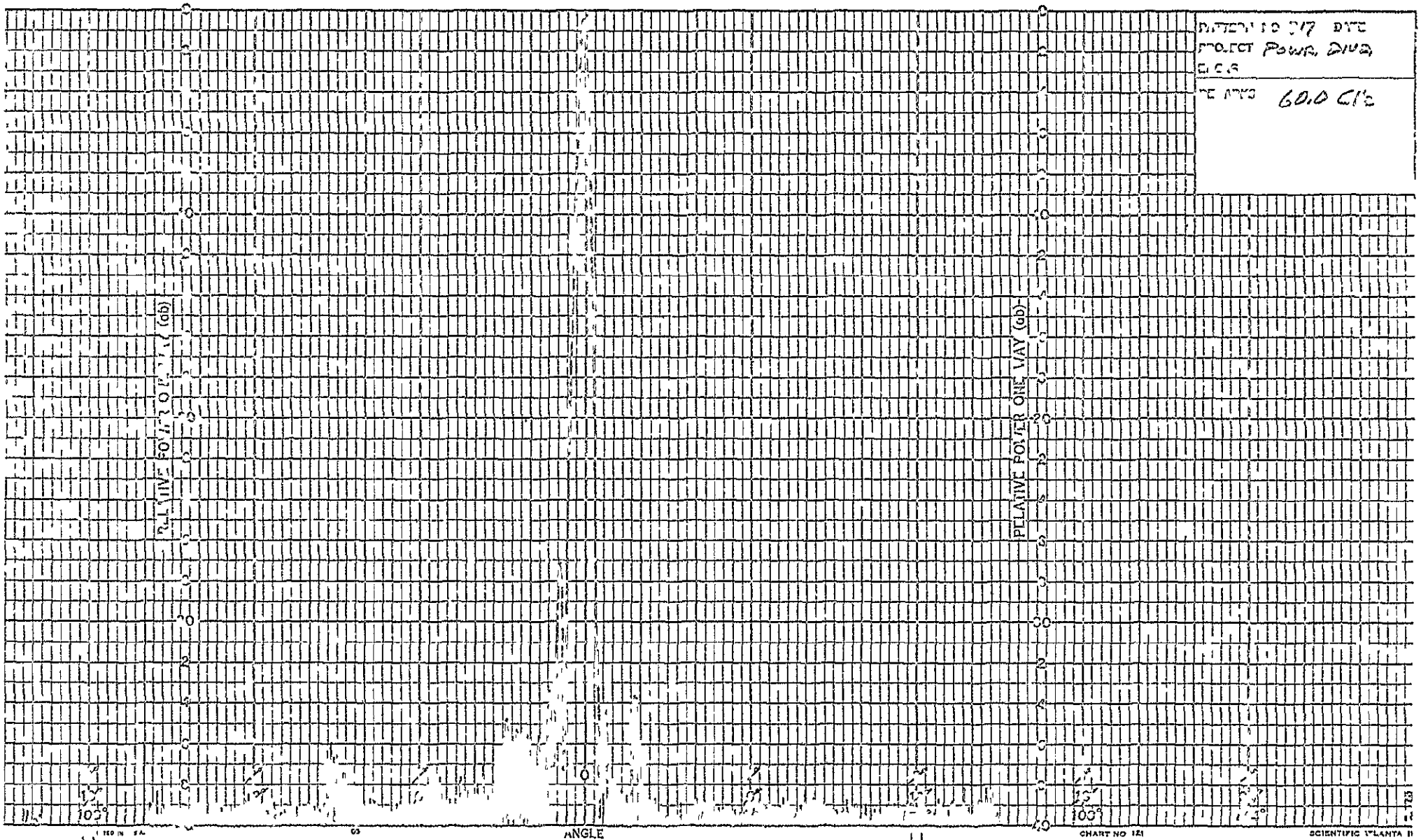

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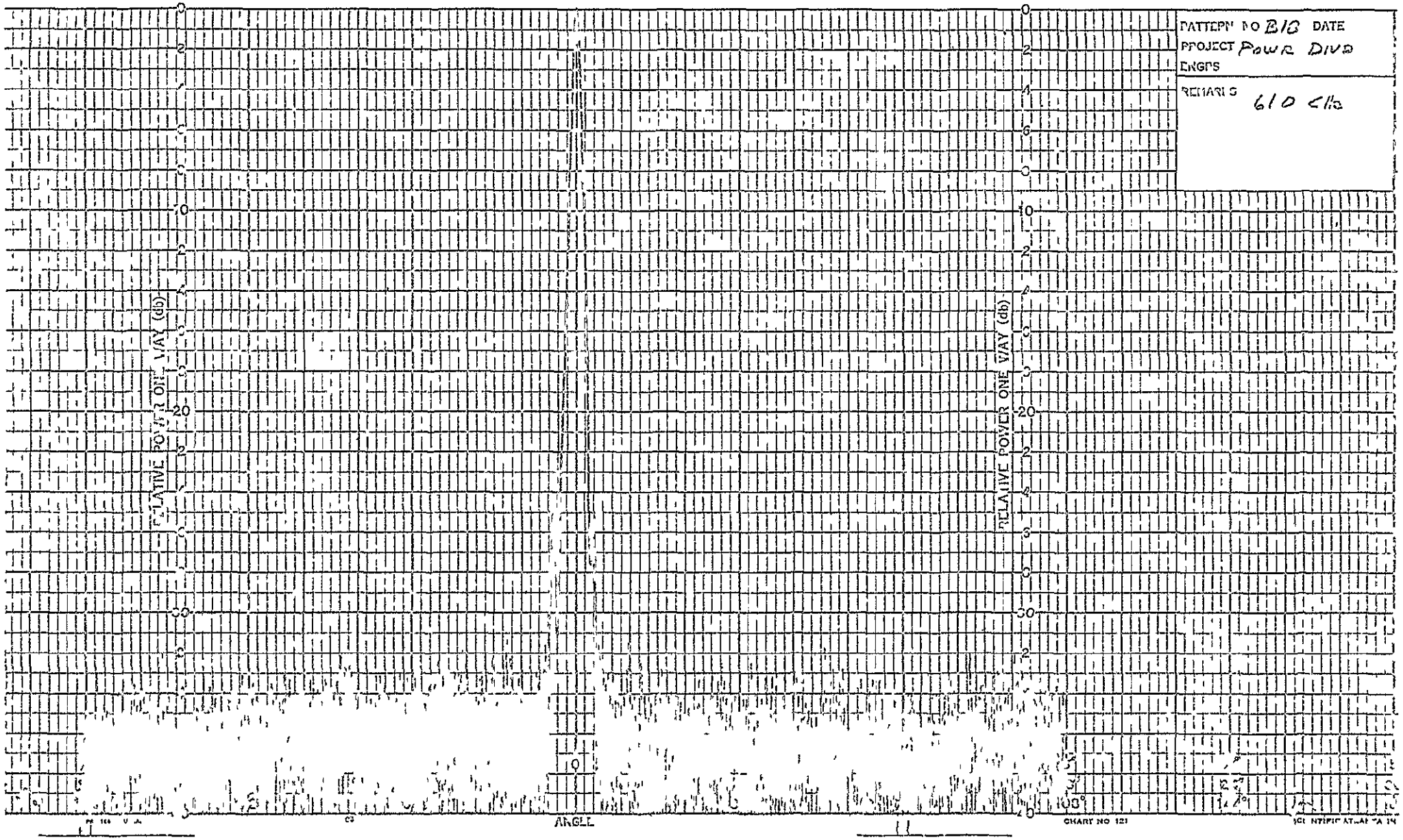

NOT REPRODUCIBLE

Appendix C

SHAPED DUAL-REFLECTOR COMPUTER PROGRAM

The expressions for the derivation of the shaped dual-reflector were based on papers by Green(1) and Dunbar(2) The terms representing the feed and subreflector patterns were modified for the two dimensional case according to a derivation given in Silver(3) The following equations were then obtained in summation form

$$\sum_{o}^{\varphi} I(\varphi)\,\Delta\varphi = \frac{1}{K} \sum_{\alpha_{min}}^{\alpha} P(\alpha)\,\Delta\alpha \qquad (1)$$

$$\ln(\rho/\rho_{max}) = \sum_{\varphi}^{\varphi_{max}} \tan\left(\frac{\alpha-\varphi}{2}\right)\,\Delta\varphi \qquad (2)$$

where

φ = subreflector angle subtended from the feed phase center

$I(\varphi)$ = feed radiation pattern

α = aperture angle subtended from the subreflector

$P(\alpha)$ = prescribed aperture illumination function referred to the subreflector

K = integration normalizing constant

$$= \frac{\sum_{}^{\alpha_{max}} \left(P(\alpha)\,\Delta\alpha\right)}{\sum_{o}^{\varphi} \left(I(\varphi)\,\Delta\varphi\right)}$$

ρ/ρ_{max} = normalized radial coordinate of subreflector

$$P(\omega) = \left| \sum_{n} E_n(\omega) \, e^{-i\omega(\Delta)} \right|^2$$

where z is the radiating aperture coordinate

P(z) is the radiating aperture power illumination function

Jo is the bessel function describing the aperture distribution

L is the aperture length

This represents the desired power distribution whose peak is at the end of the aperture By translating the coordinates, the peak of the power distribution may be positioned in the center of the aperture yielding

$$P(z) = \frac{Jo^2 \left[i\pi B/L \sqrt{4z(L-z)}\right]}{4\pi^2}$$

This expression may now be related to the main reflector geometry by substituting from the equation of a parabola, $z = 2F \tan(\alpha/2)$ The resulting expression then becomes a function of the angle α

$$P^1(\alpha) = \frac{Jo^2 \left[i\left(\frac{1.5136\pi}{L}\right) \sqrt{\left[8F\tan(\alpha/2)\right]\left[L-2F\tan(\alpha/2)\right]}\right]}{4\pi^2}$$

On referring this expression to the feed and subreflector, the space attenuation factor (SAF) must be considered For the two dimensional case, this

is given as SAF=$\sec^2(\alpha/2)$. The above expression then becomes

$$P(\alpha) = \frac{Jo^2 \left[i\left(\frac{4.76}{L}\right)\sqrt{[8F\tan(\alpha/2)]}\,[L-2F\tan(\alpha/2)]\right]}{21\ 8\cos^2(\alpha/2)} \qquad (4)$$

Equations (1), (2), and (4) are in final form for derivation of the shaped reflectors

The computer program is given in Figure C1 with its flow charts given in Figures C2 and C3. Referring to Figure C2, the program logic is explained as follows First, the feed pattern storage array is dimensioned, the heading is printed and a feed conversion function is defined. Then several reference constants, required by the program to define the system geometry and dimensions, are calculated and defined. Next the pattern and radius summations of equations (1) and (2) are initialized

The integration normalizing factor (K) is then calculated This is the ratio of the total summations of the feed and subreflector patterns This factor insures that the patterns are weighed proportionally The first loop accumulates the subreflector pattern integration and stores the result in K_1 The second loop, similiarly, stores the accumulated feed

pattern integration in K_2 The integration constant is then given by $K = K_1/K_2$

The summations of the patterns must be initialized again and the shaped reflector coordinates computed The reflector computings begin by computing the power in a differential sector of the feed radiation Similiarly the power integrations of differential sectors of the subreflector pattern are accumulated until the summation is equal to that of the feed pattern summation. That is, the conditional statement $S < 0$ causes the program to branch, indicating a partial solution A reiterative conditional loop at this point will cause further looping until the final summations are within a specified limit ($S < 10^{-4}$) This limit is prescribed by the required tolerances of the coordinates. When this condition is satisfied a partial solution will be realized, relating the feed angle (φ) to the subreflector angle (α) The coordinates of the main reflector and subreflector will then be computed and printed The program control will then select another differential sector of the feed pattern and the iterative process continues until the reflectors are completely defined

The subroutine, given in Figure C3, is for the calculation of the aperture illumination function The main program calls upon the subroutine, as required during execution of the program, to compute the values of the subreflector pattern according to Equation 4

---

1 K A Green, "Modified Cassegrain Antenna for Arbitrary Aperture Illumination", IEEE Trans on Ant and Prop., pp 589-590, Sept 1963

2 A Dunbar, "Calculation of Doubly Curved Reflectors for Shaped Beams", Proc IRE, vol 36, pp 1289-1296, Oct 1948

3 S Silver, "Microwave Antenna Theory and Design", M I T Rad Lab Series, McGraw-Hill Book Co , Inc , New York, N Y , vol 12, Chapter 13, 1949

```
10 REM I9=SUM(FEED) ; P9=SUM(AMP) ;F9=RHO/RHOMAX=EXP(SUM(TAN))
12 REM
14 REM J=PHI        ; A=ALPHA
16 REM
20 REM MAIN REFLECTOR
22 REM F=FOCAL LENGTH; L=APERTURE LENGTH
24 REM
26 REM SUBREFLECTOR
28 REM F1=FOCAL LENGTH; E=ECCENTRICITY
30 REM
32 REM L1=TOTAL PATH LENGTH; K=DISTANCE FROM FEED ORIGIN TO APER
50 FILE FEED
60 DIM I(670)
70 PRINT  PHI   ALPHA , RHO , X1   Y1
80 DEF FNA(Y)=EXP(-Y/4 3429)
85 Q=1/8
90 P9=0\ I9=0\ R9=0
95 SET ALL=4 4
100 P1=3 14159265
110 F=4 2\L=10 5
113 J0=19 85*P1/180
117 L1=16 5 \ K=4 43
118 F1=1 8 \ E=1/3
119 R0= 5*P1/E*(E+1)
120 P9=1305 6
125 FOR J=10 TO 50
130 READ FILE 1 I7
135 J8=8*J-70
140 I(J8)=I(668-J8)=FNA(I7)
145 IF J=10 THEN 165
150 I(J8-4)=I(664-J8)= 5*(I(J8-8)+I(J8))
152 I(J8-6)=I(666-J8)= 5*(I(J8-4)+I(J8-8))
155 I(J8-2)=I(662-J8)=,5*(I(J8-4)+I(J8))
157 I(J8-7)=I(667-J8)= 5*(I(J8-8)+I(J8-6))
160 I(J8-5)=I(665-J8)= 5*(I(J8-4)+I(J8-6))
162 I(J8-3)=I(663-J8)= 5*(I(J8-4)+I(J8-2))
164 I(J8-1)=I(661-J6)= 5*(I(J8)+I(J8-2))
165 NEXT J
170 FOR J=10 TO 90 STEP Q
175 J8=8*J-70
180 I9=I9+I(J8)*Q
190 NEXT J
200 K1=I9 \K2=P9
202 PRINT  K1= K1, K2= K2
203 PRINT
205 I9=0\ P9=0
208 A=0
210 FOR J=10 TO 90 STEP Q
215 J1=J*P1/180
217 J8=8*J-70
220 I9=I9+I(J8)/K1*Q
225 X=1
230 A=A+X
235 A1=A*P1/180
240 GOSUB 600
250 P9=P9+P0/K2*X
251 S=I9-P9
260 IF S<0 THEN 280
270 GO TO 230
280 IF ABS(S)<= 00001 THEN 290
282 P9=P9-P0/K2*X
284 A=A-X
286 X=X/10
288 GO TO 230
290 R9=R9+TAN((J1-J0-A1)/2)*P1/180*Q
300 R1=R0*EXP(R9)
310 C1=COS(A1)
312 X1=(R1*(C1+COS(J1-J0)))+(F-L1)*C1)/(1+C1)
315 Y1=R1*(SIN(J1-J0)-COS(J1-J0)*TAN(A1))+X1*TAN(A1)
316 Y2=-Y1+ 616
317 X2=X1+2 492
318 Y1= 70711*(Y2+Y2)
319 X1= 70711*(Y2-X2)
325 Y6=R1*SIN(J1-J0)+ 616
326 X6=3 5458-R1*COS(J1-J0)
327 Y5= 70711*(Y6+X6)
328 X5= 70711*(Y6-X6)
330 PRINT J8;X5;Y5;X1;Y1
335 NEXT J
340 STOP
390 REM BESSEL FCN OF IMAG ARG===JP(IZ)=====T9
400 A7=A1/2
410 Z=1 5136*P1/L*SQR(8*F*TAN(A7)*(L-2*F*TAN(A7)))
420 P=0
430 IF Z>20 THEN 630
440 LET X9=Z/2
450 LET Y9=X9↑2
460 LET J9=1
470 LET F9 = 50
520 LET T9 = J9
530 FOR K9 = 1 TO F9
540 LET J9 = J9*Y9/K9/(P+K9)
550 LET S9 = T9 + J9
560 IF S9 = T9 THEN 650
570 LET T9 = S9
580 NEXT K9
590 PRINT
600 PRINT   THE MAXIMUM NUMBER OF ITERATIONS HAS BEEN EXCEEDED
610 PRINT
620 GO TO 670
630 PRINT  THE VALUE OF EITHER P OR Z IS GREATER THAN 20
640 GO TO 670
650 P0=(T9/COS(A7))↑2/21 8
670 RETURN
```

Figure C1

Dual Reflector
Computer Program

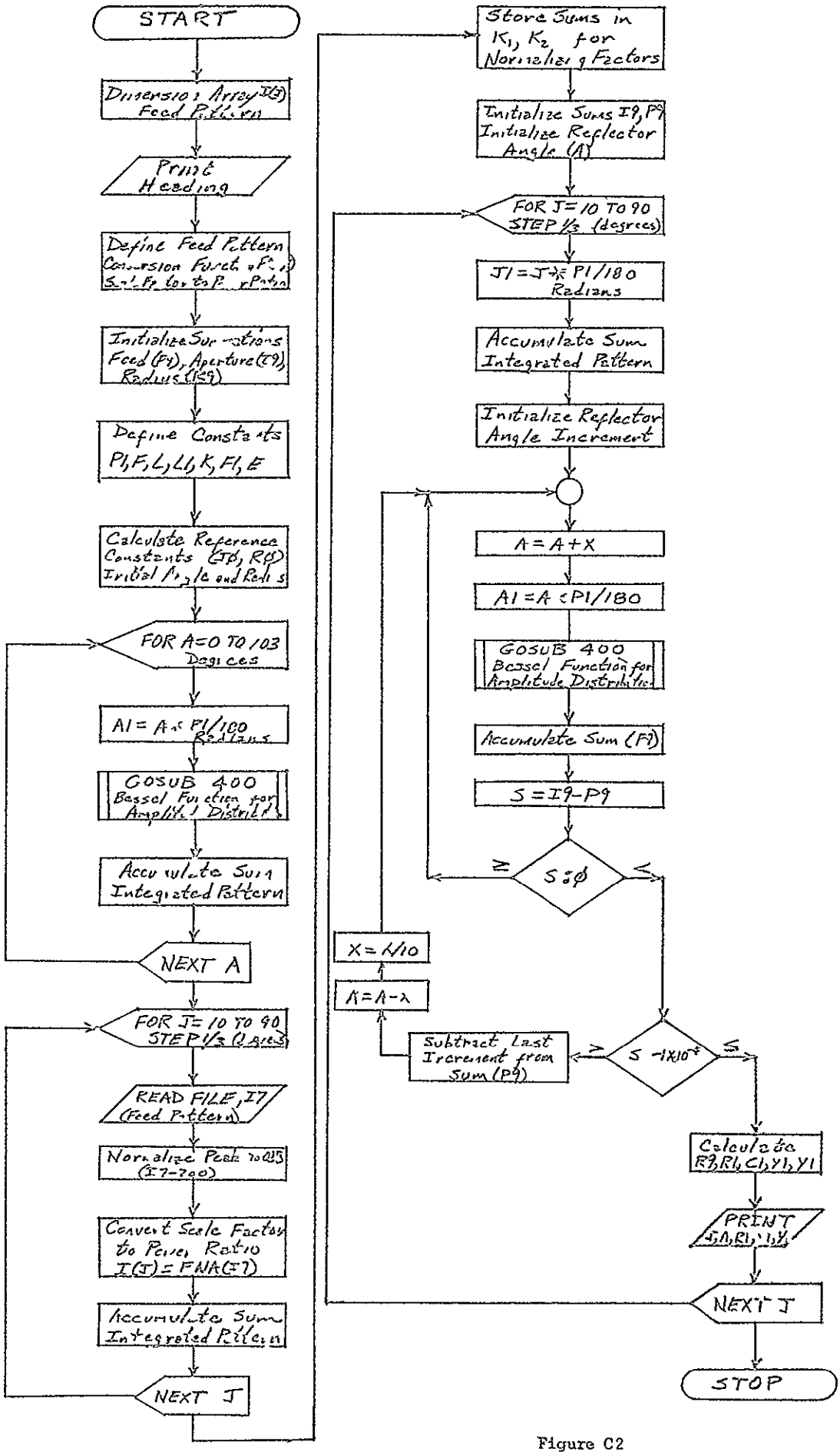

Figure C2
Flow Diagram

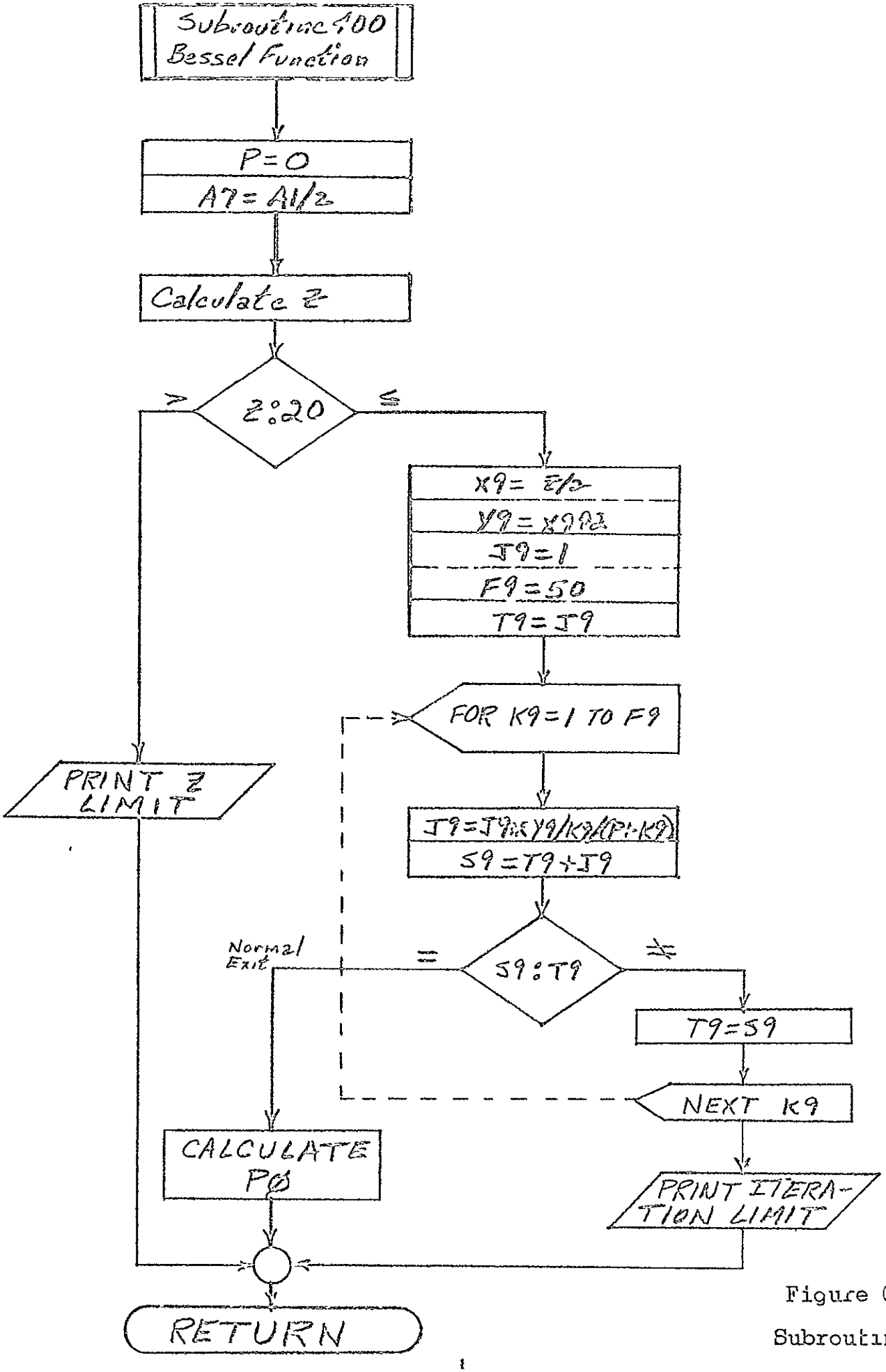

Figure C3

Subroutine