RCA

FINAL REPORT

AN INVESTIGATION OF ANTENNA TRACKING METHODS SUITABLE FOR USE WITH THE REMOTE GROUND TERMINALS ASSOCIATED WITH CTS COMMUNICATIONS EXPERIMENTS

prepared for

DEPARTMENT OF COMMUNICATIONS

Communications Research Center
Shirley Bay, Ontario

by

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Government & Commercial Systems Division
Ste Anne de Bellevue, Quebec

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A COMPUTOR PLOTS OF CTS MOTIONS AS SEEN BY AN OBSERVER AT OTTAWA

(Generated at the Communications Research Center at Shirley Bay, Ontario)

B STEP-TRACK CONSIDERATIONS

C CONE-SCAN TRACKING SYSTEM

D N. Tom

AUTO-TRACKING OF COMMUNICATIONS SATELLITES BY THE STEP-TRACK TECHNIQUE

SECTION 1

INTRODUCTION

1.1 Reference

This report summarizes the antenna tracking portion of a study entitled "Consulting Services for CTS SHF Communications Experiments" and performed by RCA Limited for the Communication Research Center at Shirley Bay, Ontario under contract PL 36001-1-3296. The remaining portion of the study dealing with computer programs COMM and COMM1 is completed under a separate cover.

SECTION 2

GENERAL

2.1 Scope

The trend of communications satellite systems development includes the simplication of ground terminal facilities and the increase in satellite EIRP. CTS is an example of an experimental system which has the above as its objective and does so by

a) operating in the 12 GHz and 14 GHz bands
b) using a high power TWT transmitter
c) using high gain, steerable antennas
d) operating from a near-stationary orbit

in order that relative low cost, simplified ground terminals may operate with it.

In this report, we are concerned not with the aspect of transmitted or received powers, but with the aspect of antenna tracking related to the CTS capabilities. For the purpose of this report, we categorize tracking as follows:

(1) Manual - in which the operator causes the antenna to move

(2) Programmed - in which the antenna moves in a prescribed manner according to the characteristics of a reference source such as a mechanical cam, potentiometer output, etc.

(3) Auto Track - in which the antenna moves in such a direction as to tend to reduce an error signal that is generated by the difference between the antenna to electrical boresight and the line-of-sight between satellite and ground terminal

Ideally, of course, for lowest costs we maintain that the best tracking is no tracking, implying that the station-keeping capabilities of CTS should be adequate to maintain its observed pointing position within the effective beamwidth of an operating ground station.

Unfortunately, such is not the case since CTS, being experimental, sacrifices some potential station-keeping capabilities in the interest of overall spacecraft weight. Therefore, for all antenna sizes except the very smallest, the observed satellite motion will exceed the ground antenna's beamwidth.

The fact that CTS is not truly representative of the next generation of communications satellites raises some fundamental questions :

1. How much effort in time and money should be invested in the CTS experimental program to develop antenna auto tracking systems, if there is little likelihood that such systems would be used in an operational system?

2. Even though technically not needed, are there other advantages to tracking systems in future operational systems that may merit further consideration?

3. Is programmed tracking a reasonable alternative for CTS during the experimental program?

To these, of course, we could add a more basic question - why have tracking at all?

Traditionally, antenna auto tracking systems have been rather costly, both in development and installation. The main reason for this has been the need for very precise performance coupled with the need for a large angular travel range. One need only to observe the operation of existing systems, such as NASA Rosman's 85 foot tracking antenna, to appreciate this.

Traditional systems are, of course, over designed for the needs of the CTS ground terminal. Further traditional systems are mostly "one of a kind" - optimized for a particular specialized need. If these were the only available concepts, the answers to the first two questions posed above would be forthcoming immediately. However, recently there has been considerable interest - both experimentally and now operationally - in simpler limited performance, auto tracking systems. Step track is currently the most prominent in this class.

A typical step track* is defined by the following general characteristics:

a) tracking coverage is limited
b) antenna motion is not continuous but in incremental steps
c) the interval between steps is controllable
d) the loop is not closed except for brief time intervals straddling the step.

* See Appendix D

Rough cost projections based on this technique suggest that relatively low cost systems, particularly in quantity seem feasible. For that reason we have examined some implications of step track quite closely in this report.

More recently, a different auto-track concept has been developed using electronic beam deflection. Because of the basic similarity of this technique to the earlier "conical scanning" systems used in radars, we have retained the term "cone scan"* for this system as well. In addition to potential low cost, this technique also may provide better rejection to fading effects, and a more sensitive measurement of error than step track.

Both step track and cone scan systems are potentially suitable for the CTS experimental program and must be considered. While some significant development costs are still involved, these will be considerably lower than those encountered if a more conventional monopulse system were to be adapted.

Both systems also have advantages in operational systems where an auto-track capability would provide

a) simpler antenna installation (relaxed levelling requirements)
b) automatic satellite acquisition
c) self-alignment to the earth-satellite line-of-sight
d) some degree of improved overall pointing in the presence of winds or where thermal distortions may be significant

to partly compensate for the cost of the tracking facility.

Thus, the answer to the first two questions posed earlier becomes clearer. To the first, we say that most certainly, reasonable effort in developing antenna track capability is warranted. To the second, we say Yes.

This leaves the last numbered question, relating to programmed track. At first, we thought that programmed tracking was a reasonable procedure, but as the study progressed, we came to the conclusion that the performance, while adequate, was not sufficiently good to compensate for the rather fussy and time consuming procedures necessary to install, align and operate the system. It may be of interest to test, say, one mechanism during the program, but we would place this activity at a very low priority level. We make further comments in the text.

* See Appendix C

We now arrive at the question raised almost as an after thought - why have tracking at all? For technically minded personnel, manual tracking can in fact be practical and at least as accurate as programmed track and so is an acceptable solution. However, for experiments involving the Mobile terminal, the operator's time may be at a premium. It may therefore be more profitable to remove from his list of field duties the repetative task of satellite chasing. And for TV receiver terminals, the concept of a "technically unattended" terminal requires continuous operation without operator intervention.

2.2 Recommendations

We make the following recommendations regarding the ground terminal antenna tracking capabilities for the CTS experimental program:

1. Small terminals, say up to 2 feet - diameter (nominally) may be fixed. Elliptical reflectors should be used if necessary to "shape" the beam so that it may be better superimposed over the observed range of CTS motions.

2. Installations with antennas of modest size (say, 2' to 6' nominal diameter) having relatively short operating intervals (such as field 2-way voice units) may be equipped with manual tracking capability only. However, to simplify operation, 3rd axis adjustment should be provided so that repeated manual acquisitions can be made using one axis adjustments.

3. Most larger receive only terminals representative of "domestic user" categories (5' to 10' nominal antenna diameter) should be equipped with simplified auto-track capability over a limited range. *

4. Some large receive only terminals may be supplied with no tracking capabilities in specific instances (See the last paragraph of this section).

5. Larger terminals capable of both receive and transmit functions (say, 6' to 15' nominal antenna diameter) should be equipped with both manual and auto-track facilities. *

We have not considered the tracking needs for the main communications control center at Ottawa. We assume that the existing, high performance, conventional monopulse system already part of that installation will be used.

In recommendation No. 4 above we have noted that some large receive-only terminals can be useful even without tracking. This statement is made under the assumption that some experiments will need only a limited observational interval, and this interval can fit within the time that is required for the satellite line-of-sight to pass through the ground terminal's antenna beam. (For an estimate of this time interval, and other notes, see section 4).

* Either step-track or cone-scanning systems.

In these cases, antenna alignment can be made to coincide with the expected line-of-sight angle during some specific time interval and taking into consideration

(a) The "nodding" motion occurs in sidereal time which has a time cycle about 4 minutes less than universal time
(b) The fact that the useful time interval is longest when the satellite is at the extreme limits of its nodding range *
(c) Satellite motion predictions are available by transmitted data or observation

Further analysis of this mode will not be undertaken as it is dependent upon the experimental requirements, the experimental time cycle, and the actual achieved satellite orbit.

2.3 Tracking Loss Estimate Summary

One side result of this study is a revised estimate of antenna tracking and deformation losses in the 12 GHz and 14 GHz bands for ground terminals operating in the CTS experimented program. Representative loss values, exceeded 0.01% of the time, are given in Table 2-1. These are extracted from Tables 8-2 and 8-3 of Section 8.

We recommend that, until these values are superceeded by an improved estimate or measured values, they be used as the "Tracking Loss" allowance entered into appropriate system thermal noise calculations using Program COMMIA or equivalent (ref. 15).

* See Section 4

SUMMARY OF ESTIMATED TRACKING LOSSES FOR CTS GROUND TERMINALS

TERMINAL	ANTENNA DIAMETER (Ft.)	TYPE OF TRACKING	TRACKING LOSS (dB) 12 GHz	TRACKING LOSS (dB) 14 GHz
Radio Reception (F^r)	2	Fixed	1.4	N/A
Voice (2-Way)	4	Manual	1.5	1.8
TV Receive	8	Step-Track	1.2	1.6
Mobile	10	Step-Track	1.6	2.0

NOTES

(1) Loss Exceeded 0.01% of the time

(2) See Table 3.1 for definition of Terminals

(3) See Table 8-2 for angular errors corresponding to losses at 12 GHz

(4) See Table 8-3 for angular errors corresponding to losses at 14 GHz

TABLE 2.1

SECTION 3

GROUND TERMINAL CONSIDERATIONS

3.1 General

Only a few basic parameters directly influence the tracking characteristics. These include antenna beamwidth (related to diameter), terminal location, and intended use. In addition to these, the category of personnel operating or maintaining the terminal is also of consequence. We therefore begin this section by selecting an appropriate representative sampling of terminal configurations.

3.2 Types of Terminals

The possible range of terminal types that might be used in a system utilizing the CTS Spacecraft is rather enormous. For our purposes, therefore, we have chosen to examine the representative selection which was earlier developed (ref. 1) which still serves as a reasonable cross-section. They are categorized by function and identified by nominal antenna diameter as summarized in Table 3-1.

Receive-only terminals are representative of those which might be used by non-technical, or "consumer" type users. The 2' diameter version would be a fixed (non-tracking) type used primarily for radio reception while the 8' diameter version would require tracking (in one dimension) type used primarily for television reception. The intent for both of these terminals is to examine the requirements for a simple, potentially inexpensive, minimum technical configuration for a consumer market. A low cost step track (or cone-scan) type of tracking should be used rather than programmed tracking for the larger diameter version.

Two-way voice service is thought to be of more use from portable, light-weight configurations. The 4' diameter version is intended to satisfy this requirement. The basic terminal does not have a tracking capability as it is felt that two-way voice communications would be intermittent in use, and normal readjustment of pointing, once initial acquisition has been made, should be quite simple.

The larger diameter terminals - the 10' and 30' versions - are representative of those used by technical personnel. Their rather narrow bandwidths and accurate pointing requirements tend to remove them from the "consumer user" category. The 10' version intended for mobile terminal service may be equipped with an auto-track capability as well as manual track.

ASSUMED TYPES OF GROUND TERMINALS FOR THE CTS EXPERIMENTAL PROGRAM

SERVICE	TYPICAL DIAMETER (FT)	TRANSMIT CAPABILITY	PERSONNEL CATEGORY*	OPERATING DUTY CYCLE**
RADIO RECEPTION (FM)	2	NO	UNTRAINED	CONTINUOUS
VOICE (2-WAY)	4	YES	VARIABLE	INTERMITTENT
TV RECEIVE	8	OPTIONAL	UNTRAINED	CONTINUOUS
TV TRANSMIT (MOBILE)	10	YES	TRAINED	AS REQ'D.
CONTROL	30	YES	TRAINED	AS REQ'D.

* NOTES ON PERSONNEL CATEGORY

(a) UNTRAINED - persons such as householders, general public, etc.

(b) VARIABLE - skilled or unskilled in operation of 2-way radio equipment.

(c) TRAINED - skilled electronics personnel with tracking system experience.

** NOTES ON DUTY CYCLE

(a) CONTINUOUS - equipment to be installed and left unattended for long periods of time.

(b) INTERMITTENT- operation usually for 1/2 to 1 Hour at a time. Selectable re-aqusition normally required for each operational interval.

(c) AS REQ'D. - stations normally manned and operational time will be pre-arranged or pre-scheduled.

TABLE 3-1

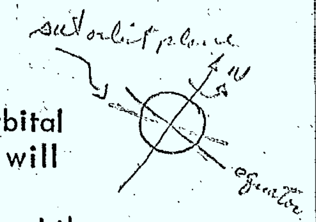
Some form of program track could be provided on an optional basis as an experiment. The 30' version represents the control terminal and is included for completeness only and no further discussion will be made.

3.3 Terminal Locations

The representative terminal may be located anywhere on the earth's surface within the 5^o coverage circle * appropriate to the CTS satellite located at its intended nominal parking spot at 114^oW longitude. The study aspects for tracking requirements have stressed adaptability of alignment and tracking throughout this range so that an actual specification of location is not necessary for most purposes.

However, for specific evaluations we have selected a geographical site. Notably, some of the analysis of the observed motion of the satellite has been performed with the observer at Ottawa (see Appendix A). The observed satellite motions would in general vary from one point to another but the general or "gross" behaviour should not change significantly and such changes as might occur can be easily compensated for.

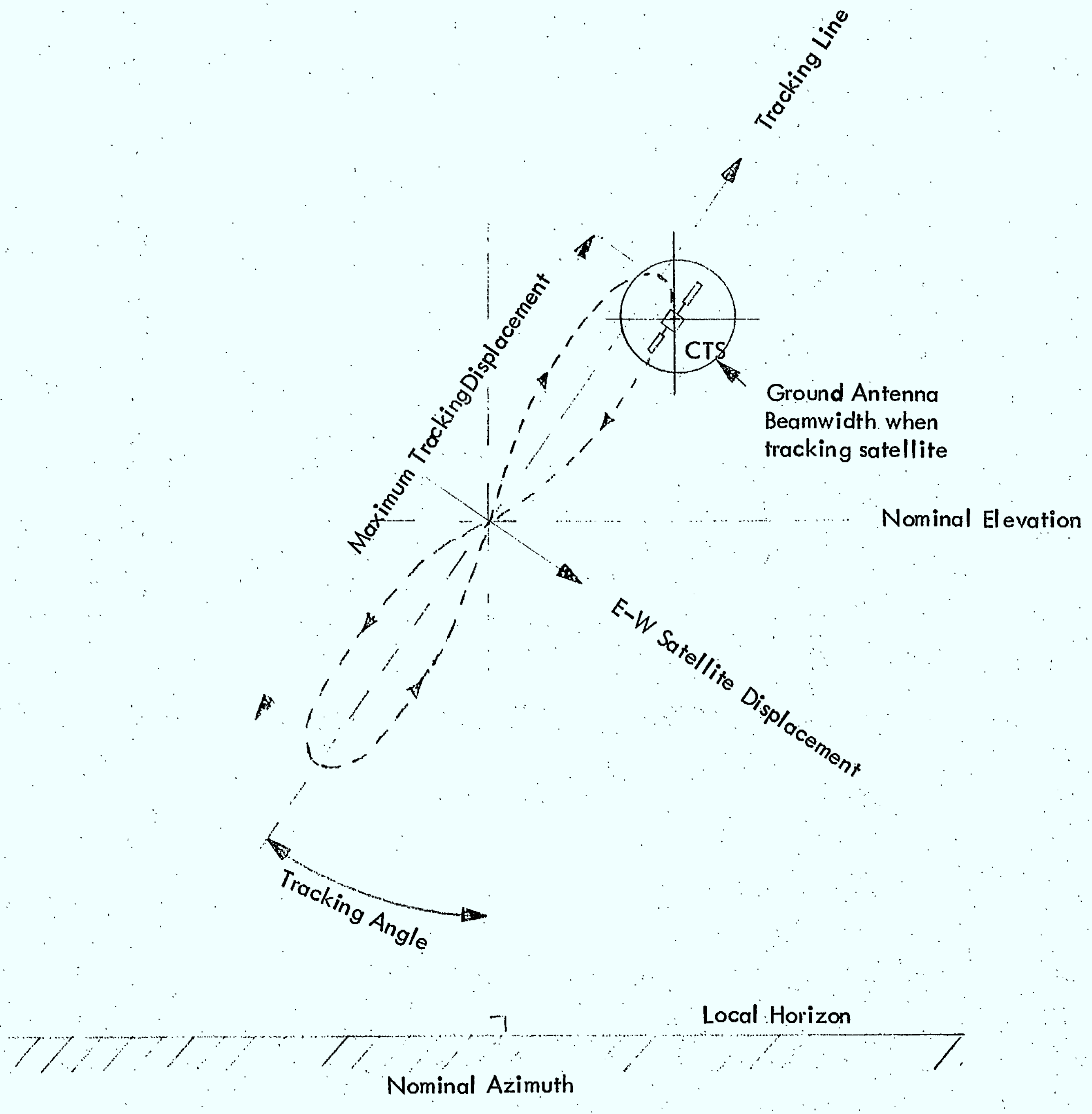
3.4 Tracking Line and Tracking Angle



Some definitions might be made at this point. Because of an assumed CTS orbital "tilt" relative to the earth's equatorial plane, a spacecraft in circular orbit will be observed to move along a very narrow "figure 8".
If, however, the observer is in Canada, his point-of-view will be different and the observed motion will be slightly modified. Further, if he is not on the same longitude as the satellite, the path alignment will have an east-west component. The alignment of the "figure 8" will be defined as the tracking line, and the angle of the tracking line measured from the vertical will be defined as the "tracking angle" ** as shown in Figure 3-1. This permits an antenna that is equipped with rotatable "tracking" axis to be oriented such that the tracking axis is perpendicular to the tracking line in which case only one tracking mechanism is needed, providing that other incidental E-W motions do not exceed the antenna beamwidth.

* The 5^o coverage circle is an imaginary circle on the earth's surface enclosing all points where a ground antenna can "see" the satellite at an elevation angle of 5^o or more above its local horizon.

** The observed satellite motion when other perturbing influences (such as eccentricity due to solar pressure) are added will in general be along a different path than the tracking line. We will consider this later.



GEOMETRY OF OBSERVED CTS MOTIONS

FIGURE 3-1

3.5 Ground Station Antenna Beamwidths

The beamwidth of an antenna is a function of both its frequency and its diameter. One further characteristic must be specified to provide a more complete understanding. This is the definition of the loss in maximum gain at the beam edge. It is common practice to specify beamwidths at the 3 dB down points; however, in more accurate systems it is advantageous to specify beamwidth at something less than the 3 dB points, such as the 2 dB, 1 dB, or .5 dB down points. Figure 3-2 shows the beamwidth characteristic for a typical parabolic reflector antenna of 10' diameter at a frequency of 14 GHz.

Figure 3-3 is a graph prepared to illustrate the relationship between the antenna diameter and various beamwidths as specified above at a frequency of 12 GHz. The curves are appropriate for an assumed parabolic antenna with a 55% efficiency value. The effect of applying different gain loss values to the beamwidth is clearly evident on this figure. For example, for a 10 foot diameter antenna the beamwidth at the 3 dB down points is 0.56 degrees, whereas it decreases to .23 degrees at the 0.5 dB down points. In this figure no allowance has been made for tracking or other errors. Two horizontal reference lines have also been included. One is at a beamwidth of 0.4 degrees which represents the maximum limit of east-west motion of the satellite. Thus if the antenna is not to be moved east or west then the appropriate beamwidth must be larger than 0.4 degrees in order to provide continuous coverage. A second horizontal reference line has been shown at 0.2 degrees which was the original east-west objective.

Figure 3-4 is a similar graph prepared for 14 GHz frequencies corresponding to the transmitter bands for CTS. The reduction in Beamwidth because of frequency for antennas of a given diameter is clearly evident. Table 3-2 lists selected beamwidth values for a representative selection.

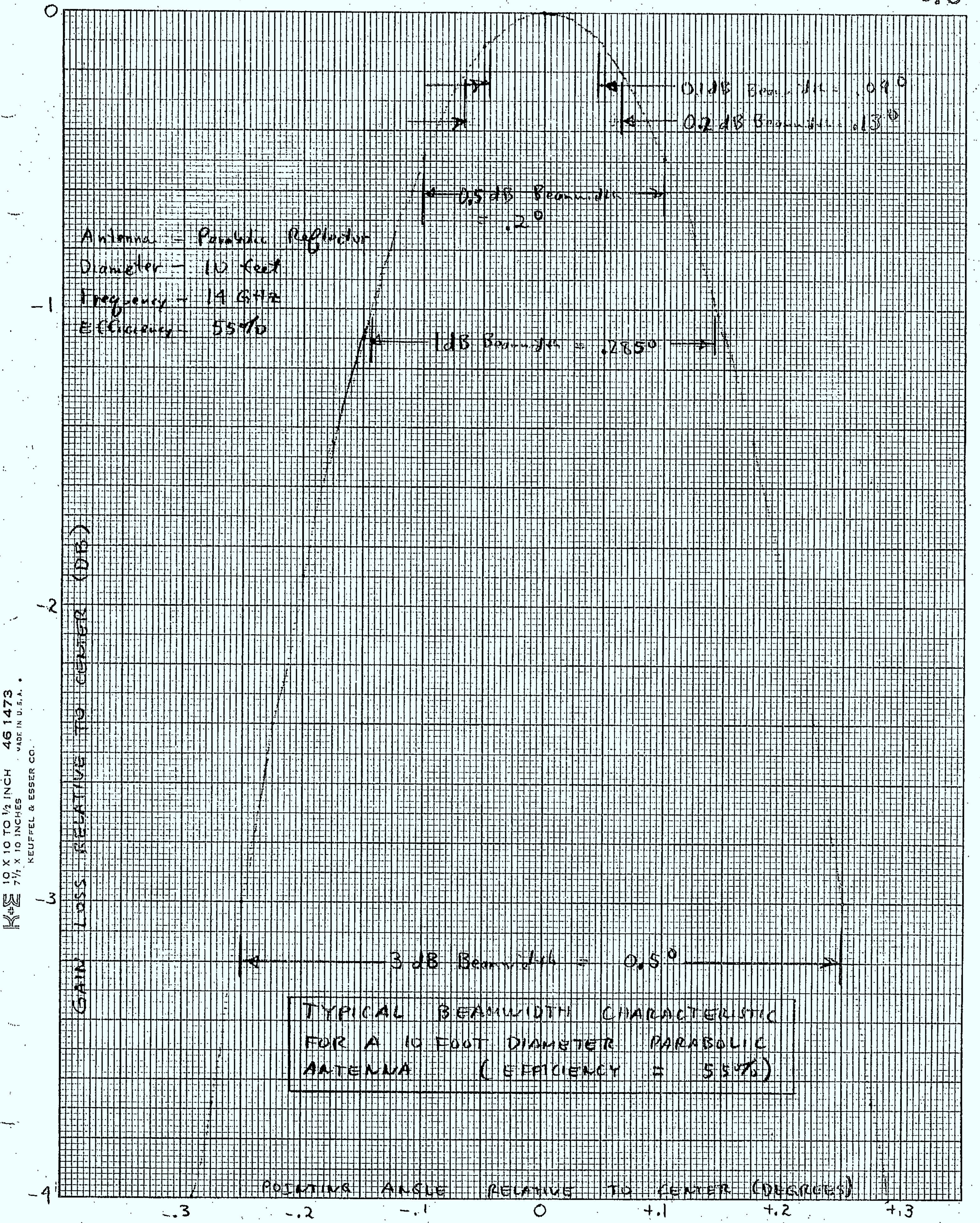
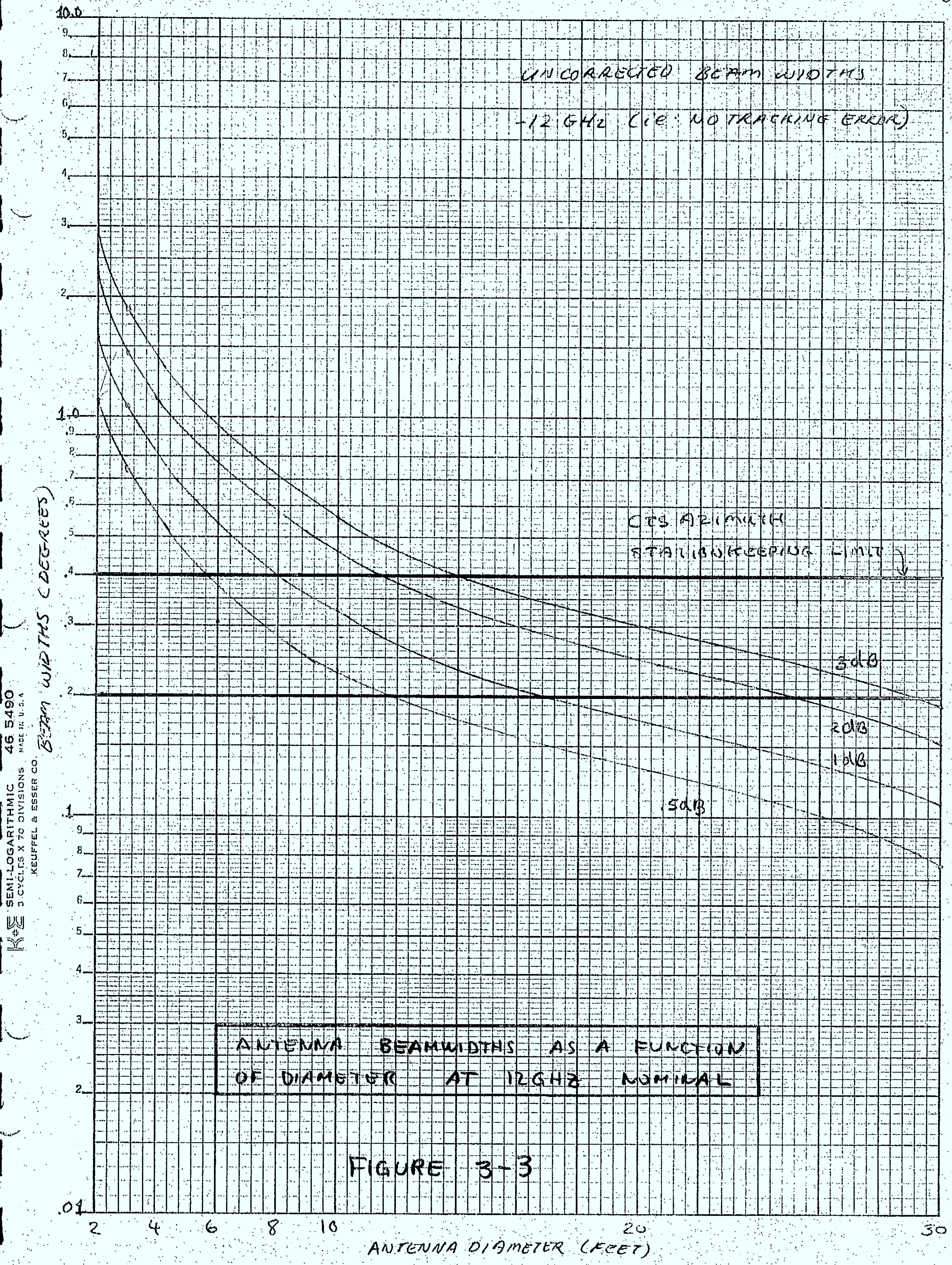
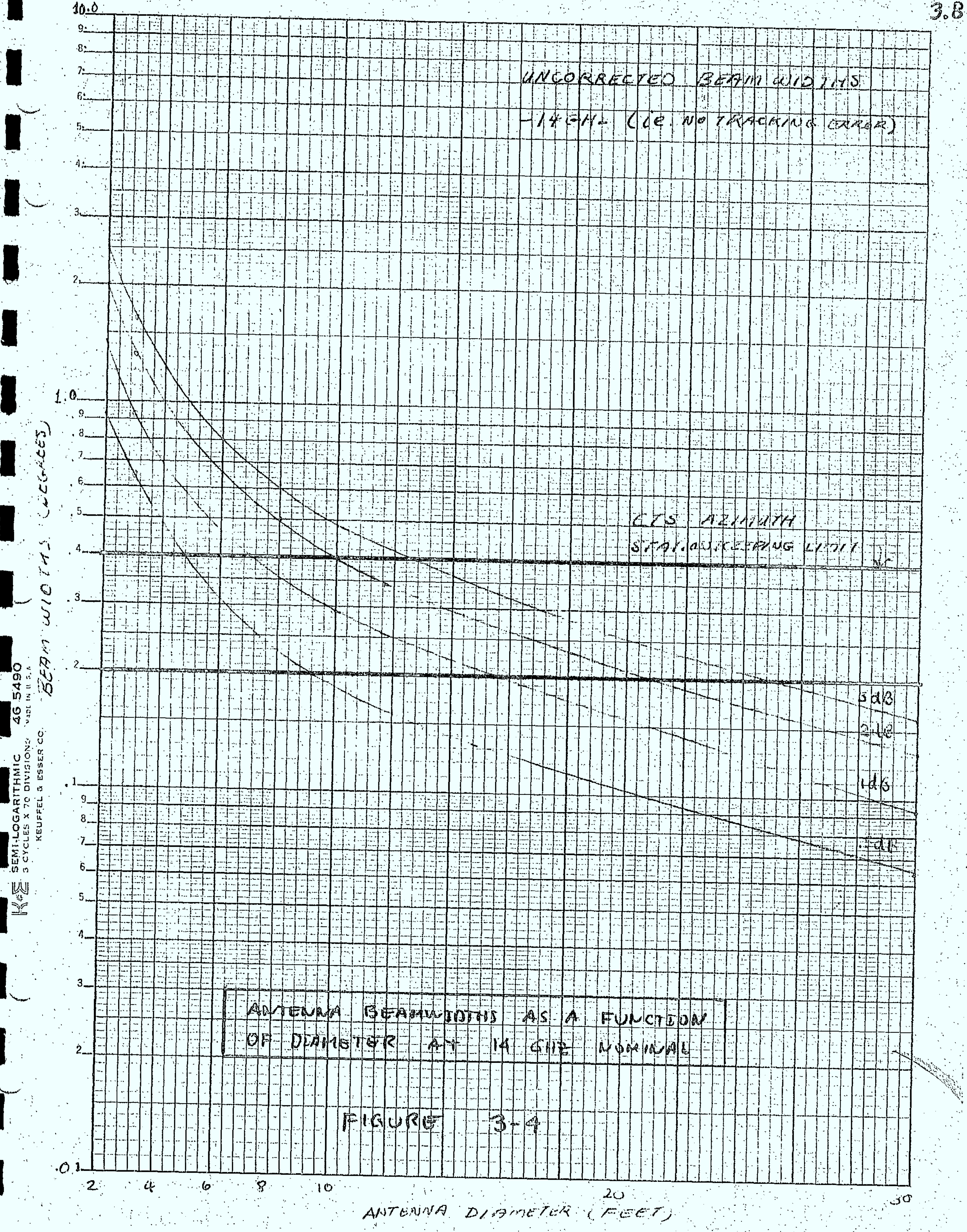

0.5 dB Beamwidth = .2°
Antenna = Parabolic Reflector
Diameter = 10 feet
Frequency = 14 GHz
Efficiency = 55%
1 dB Beamwidth = .285°
3 dB Beamwidth = 0.5°
TYPICAL BEAMWIDTH CHARACTERISTIC FOR A 10 FOOT DIAMETER PARABOLIC ANTENNA (EFFICIENCY = 55%)
GAIN LOSS RELATIVE TO CENTER (DB)
POINTING ANGLE RELATIVE TO CENTER (DEGREES)
0
-1
-2
-3
-4
-.3
-.2
-.1
0
+.1
+.2
+.3
10 X 10 TO 1/2 INCH 46 1473
7 1/2 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

FIGURE 3-2



ANTENNA BEAMWIDTHS AS A FUNCTION OF DIAMETER AT 12GHZ NOMINAL

FIGURE 3-3



ANTENNA BEAMWIDTHS AS A FUNCTION OF DIAMETER AT 14 GHZ NOMINAL

FIGURE 3-4

TYPICAL ANTENNA BEAMWIDTHS

NOMINAL ANTENNA DIAMETER (Feet)	BASIC BEAMWIDTHS 0.5 dB DOWN (Degrees)		1.0 dB DOWN (Degrees)		3 dB DOWN (Degrees)	
	12 GHz	14 GHz	12 GHz	14 GHz	12 GHz	14 GHz
2	1.1°	0.93°	1.6°	1.4°	2.8°	2.50°
4	0.56°	0.46°	0.81°	0.68°	1.4°	1.20°
8	0.28°	0.23°	0.40°	0.35°	0.72°	0.60°
10	0.23°	0.19°	0.35°	0.29°	0.56°	0.48°

NOTE: Antennas assumed to be Standard Parabolic types with 55% efficiency.

TABLE 3-2

SECTION 4

SPACECRAFT ORBITAL CONSIDERATIONS

4.1 General

In this section, we briefly consider the presently understood orbital behaviour of the satellite, including the effects of the major deviations. We examine first the station-keeping tolerance, and then assess the observed satellite motions resulting from these tolerances.

4.2 Satellite Station Keeping Limits

The following characteristics for the station keeping ability of the CTS satellite have been assumed:

a) No north-south station keeping is provided. Therefore the maximum limits of the orbital tilt of the CTS spacecraft has been assumed to lie within the $\pm$ 2 degrees maximum limits.

b) A total east-west movement of the satellite of $\pm$ 0.2 degrees relative to its nominal longitude is permitted. This latter figure has been suggested by the Spacecraft Systems Group in order to reduce some of the spacecraft fuel requirements.

The resulting angular motion of the spacecraft relative to its nominal synchronous position may therefore be considered to lie within a "box" of 0.4 degrees by 4.0 degrees.

4.3 East-West Deadband Components

The east-west deadband of $\pm$ 0.2 degrees is considered to be made up of 3 major components:

a) Displacement due to orbit inclination
b) Displacement due to the earth triaxiality
c) Displacement due to eccentricity resulting from solar pressure

Values for these displacements are given in Table 4-1. The total displacement, added on a peak basis, is $\pm$ 0.189 degrees, leaving an unassigned value of $\pm$0.011 degrees for other minor contributions, not specified.

MAIN EAST-WEST DISPLACEMENTS FOR CTS

SOURCE	BUDGET	PEAKING FREQUENCY	OCCURENCE
Orbital Inclination	± 0.0175°	4 times daily (sidereal time)	At 2° orbital tilt limit
Triaxiality	± 0.025°	2 times in 11 days (Nom) (solar time)	Continuous throughout life
Solar Pressure	± 0.146°	Twice daily (solar time)	Maximum Once/Year
SUB-TOTAL	± 0.1885°		
Specified Limit	± 0.2000°		
Unassigned	± .0115°		

NOTES: Peaking frequency refers to the number of times that the maximum displacement occurs per noted interval.

Occurrence refers to the conditions under which maximum peaking occurs.

TABLE 4-1

The time characteristics of these displacements is of some interest. Ignoring orbital precession due to the sun and the moon, each "figure 8" traverse due to orbital tilt requires one sidereal day. Therefore, the resultant east-west motion due will occur twice per sidereal day. The east-west drift due to the triaxiality will require correction about every eleven days. Finally the east-west motion due to solar pressure will have a period of one solar day while its amplitude will "peak" once a year. Figure 4-1 illustrates the time behaviour of these displacements.

Because of the different cycle time frames for the 3 major displacements, the time intervals during which they will add up on a purely peak basis are relatively few. (In making this comment, we assume that satellite control procedures will not include relaxing the tolerance applied to, say, correction of triaxiality displacement when eccentricity due to solar pressure is at its lowest).

The major source of drift is due to the effect of solar pressure. For a continuous interval of about 36% of the year it will have a value of less than 0.095° resulting in a total peak east-west displacement of about 0.15°, 25% less than maximum. For about 17% of the year this contribution will be less than $\pm 0.046^{\circ}$ resulting in a peak EW displacement of $\pm 0.10^{\circ}$, or half the maximum value. Special experiments relating to minimum tracking can thus be scheduled during this interval. At other times, there will always be periods of the day where total displacement errors are small, or where the apparent motion of the satellite slows down (for example, at the extreme limits of the motion about the tracking line) where appropriate experiment scheduling can be done to make use of these factors.

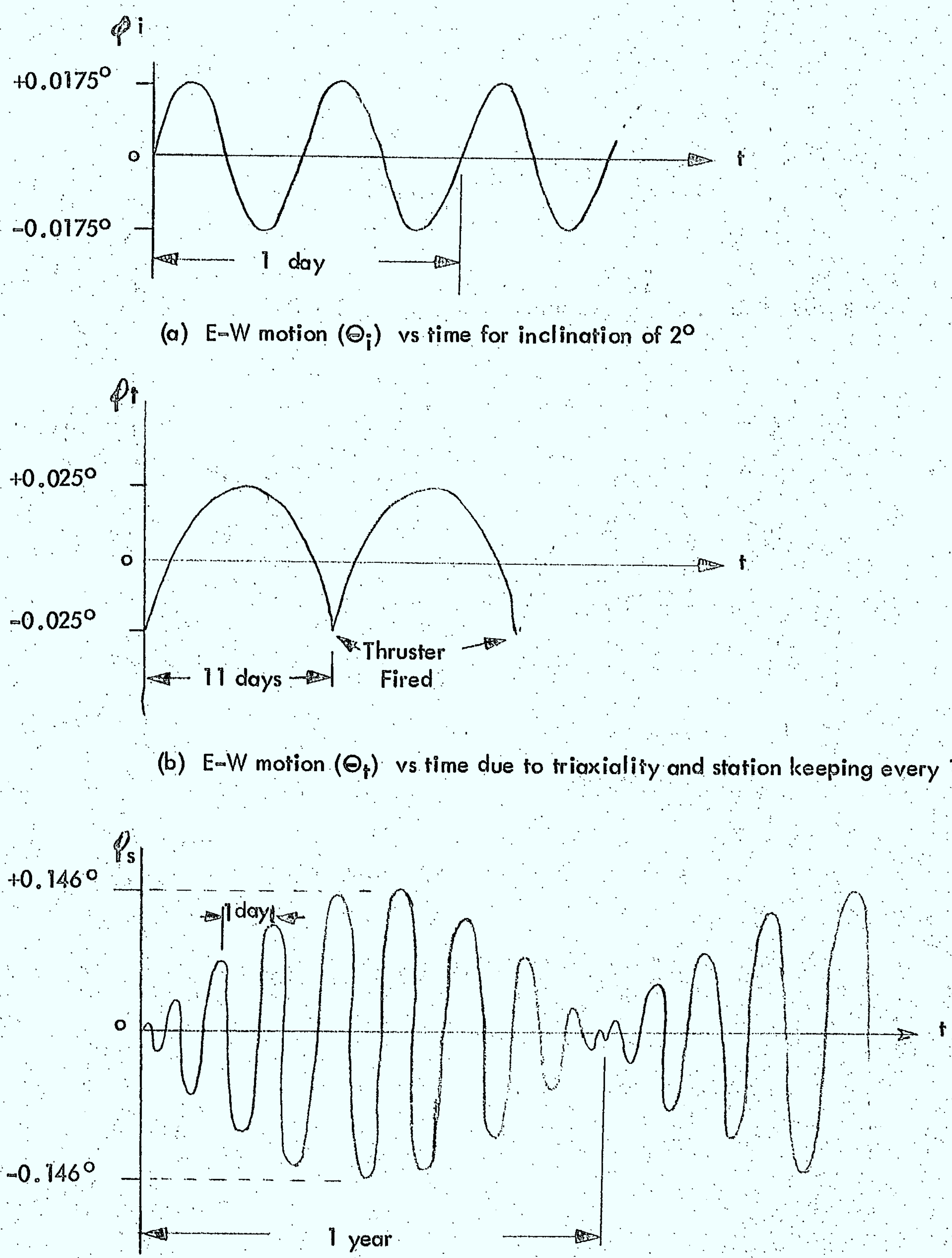
4.4 Displacement due to Eccentricity

Considering the error due to solar pressure, the following approximate equation * relates the eccentricity ϵ to the east-west motion φ_s (in radians)

$$\epsilon = \varphi_s / 2$$

For CTS, the east-west motion of $\pm$ 0.146 degrees corresponds to an orbital eccentricity of 0.00128.

* This equation is derived in ref 7. φ_s is in fact the true anamoly.



(a) E-W motion (Θ_i) vs time for inclination of 2°

(b) E-W motion (Θ_t) vs time due to triaxiality and station keeping every 11 days

(c) E-W motion (Θ_s) vs time due to solar pressure

TIME BEHAVIOR OF CTS EAST-WEST DISPLACEMENTS

FIGURE 4-1

4.5 Observed Satellite Motions

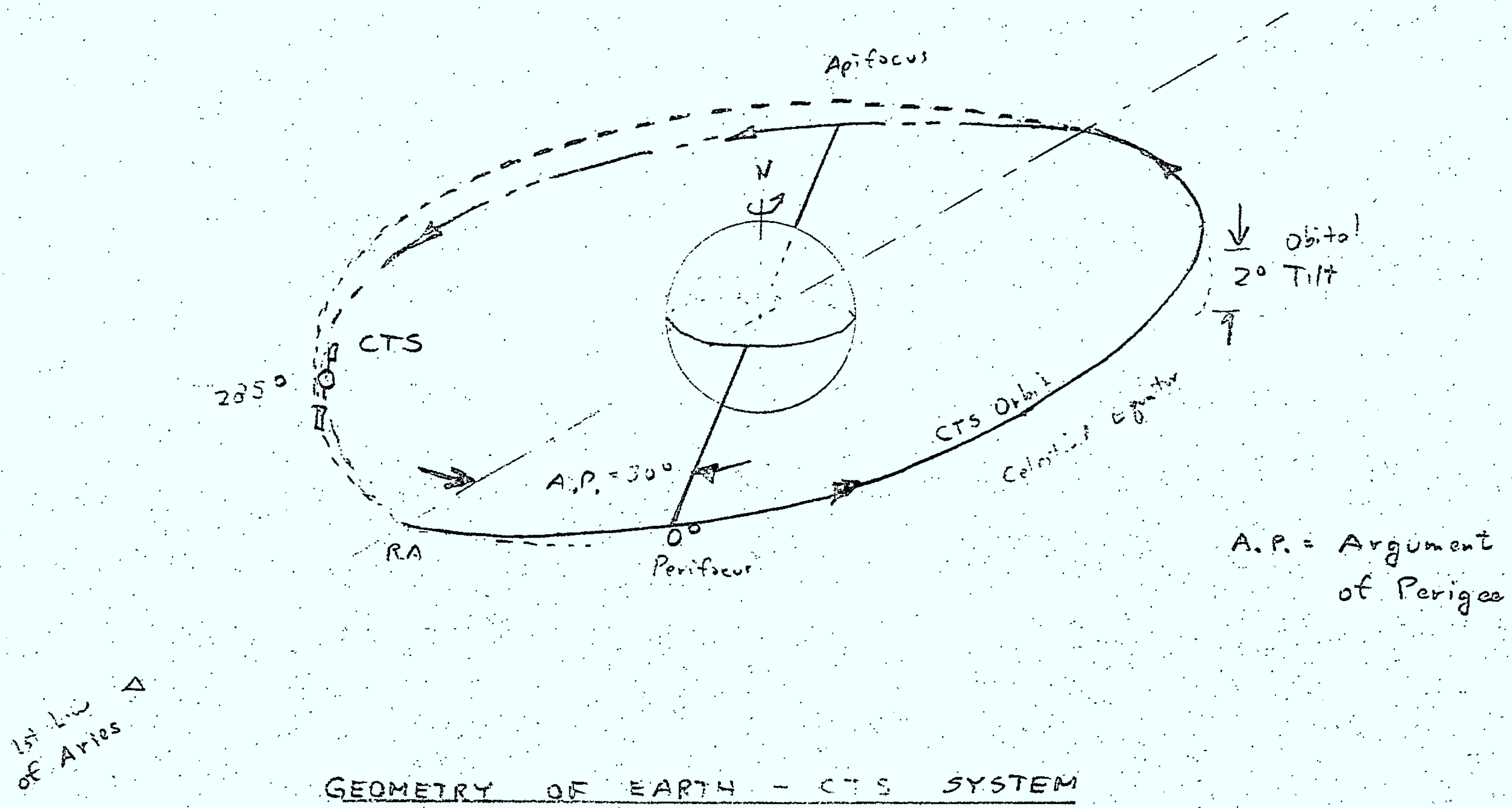
A CRC computer program enables the path of a satellite in an inclined orbit and having a given eccentricity, and as seen by an observer at any observation point, to be plotted on a graph. Appendix A are individual plots for the case of an observer located at Ottawa. The satellite is assumed to have a 2^{o} orbital tilt (consistant with the CTS limits) and a right ascention of 0^{o}. Figure 4-2 shows the geometry of the earth-satellite system.

An examination of these plots reveals that the observed motions can vary from a straight line to an open circle at varying angles depending upon the argument of perigee and the eccentricity. Since solar pressure contributions, and therefore eccentricity, cause the greatest east-west motions, these curves are most important in determining what type of antenna tracking characteristics are required for earth terminals.

It is rather difficult to examine the overall behaviour of the satellite from these plots. Therefore, the observed satellite motions for a range of eccentricities for specific arguments of perigee (A.P.) have been superimposed. Figures 4-3 to 4-8 show their superimposed plots for A.P.'s of 0^{o}, 30^{o}, 90^{o}, 150^{o}, 180^{o}, and 240^{o} respectively with eccentricity as a running parameter. The general observation is that the actual tracking lines rotate as a function of ϵ for A.P.'s close to 0^{o} or 180^{o}, while the tracks themselves "open out" with ϵ for A.P.'s close to 90^{o} or 270^{o}. These two effects are exclusive, that is, one is minimum while the other is maximum.

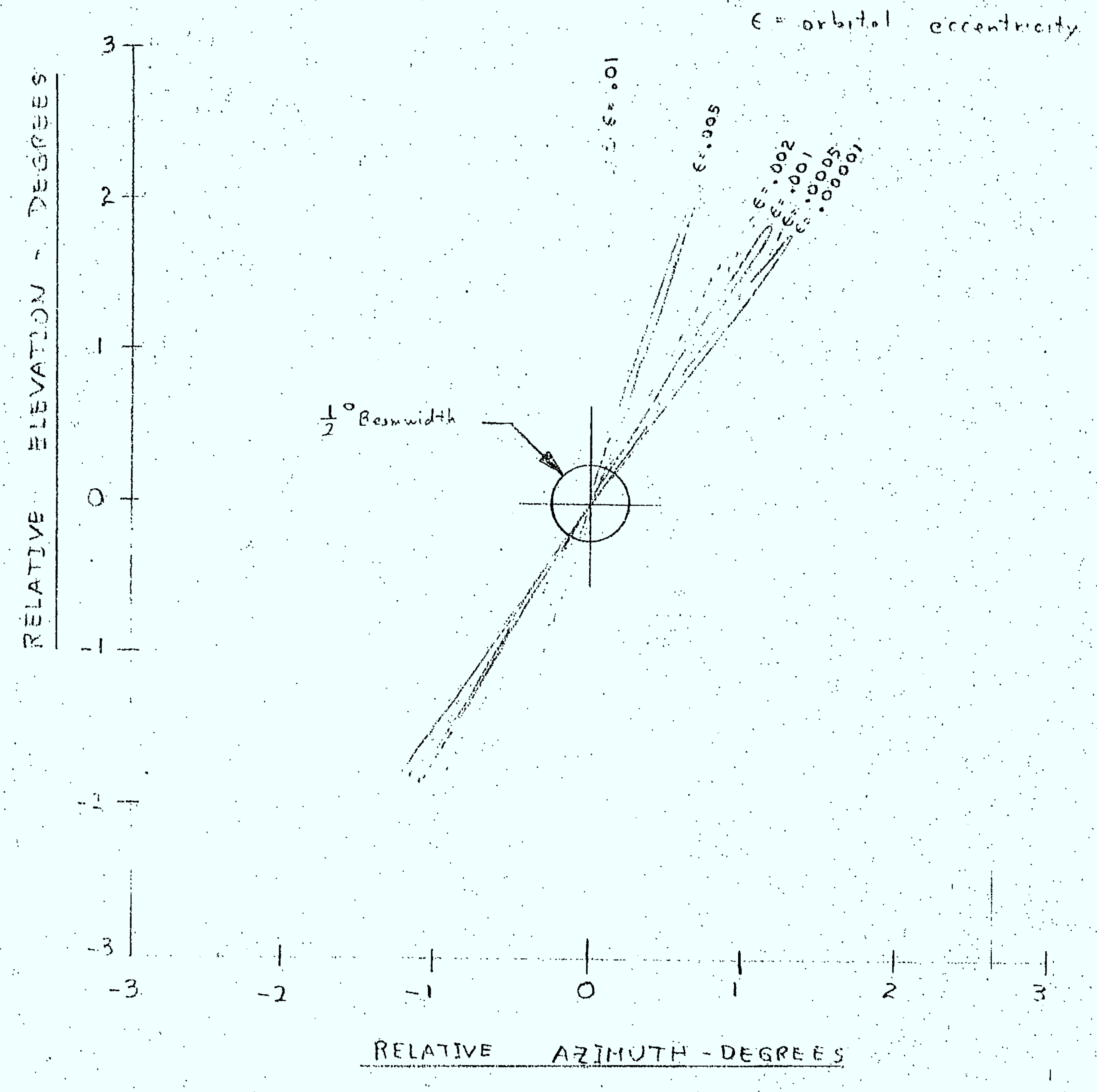
One can conclude that the observed behaviour is variable with the argument of perigee and that if the beamwidth is small compared to the aggregate area traced out by the satellite, then simple one dimensional tracking is clearly impossible.

Now, a set of superimposed curves were prepared for different eccentricity values. These are shown in Figures 4-9 and 4-10 for ϵ's of 0.001 and 0.01 with A.P. as a running parameter. Observe that the envelope which encloses all possible tracks is roughly a rectangle. Assuming that it is a rectangle, then Figure 4-11 shows the maximum size of these rectangles centered along the tracking line. Clearly, the effect of ϵ is primarily on the width of the rectangle rather than on its length. Further, the length of the rectangle is somewhat larger than the north-south dimension of the station-keeping "box" (See 4.2).



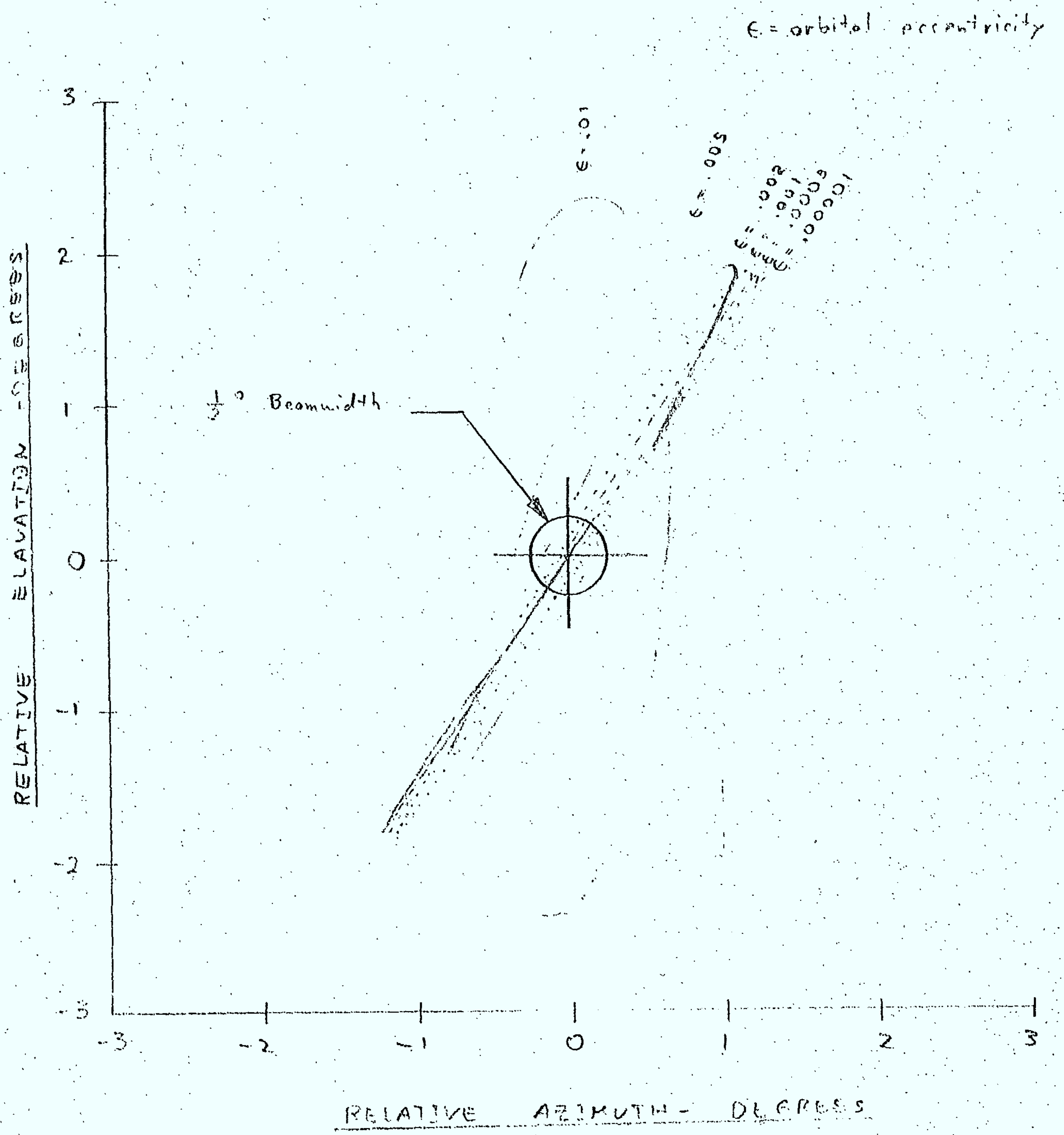
GEOMETRY OF EARTH - CTS SYSTEM

FIGURE 4-2



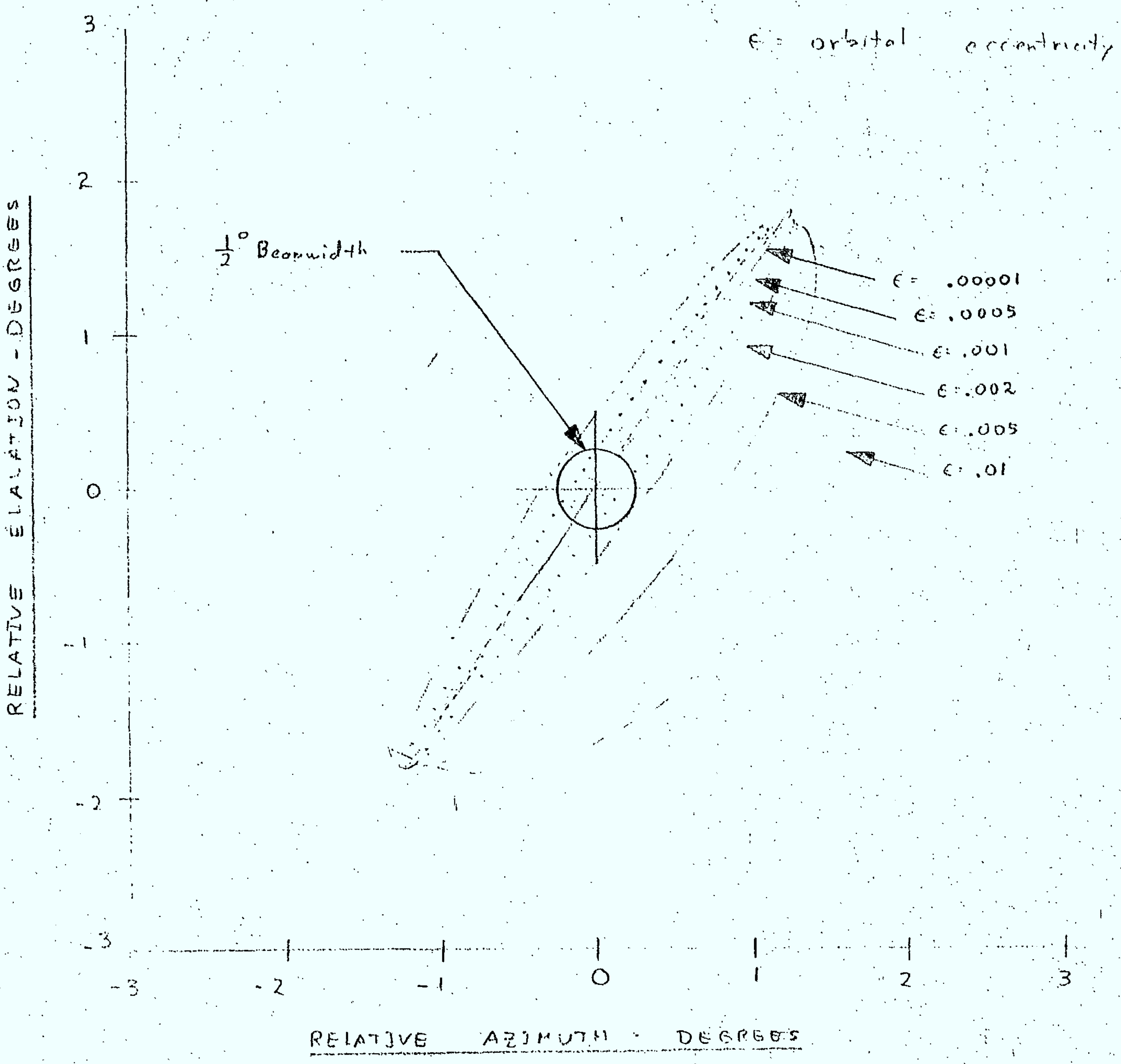
OBSERVED SATELLITE MOTIONS
(ARGUMENT OF PERIGEE = 0°)

FIGURE 4-3



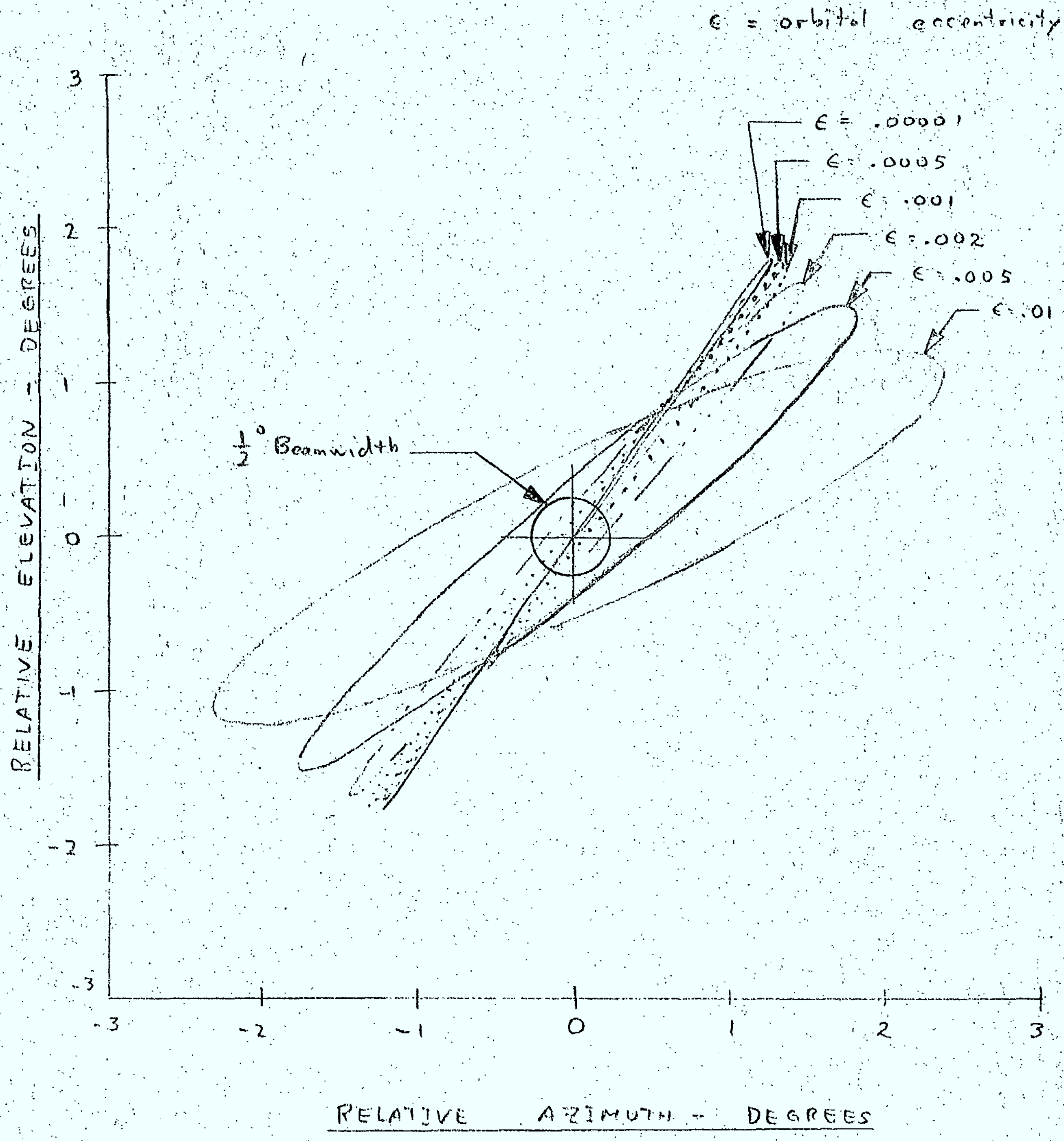
OBSERVED SATELLITE MOTIONS
(ARGUMENT OF PERIGEE = 30°)

FIGURE 4-4



OBSERVED SATELLITE MOTIONS
(ARGUMENT OF PERIGEE = 90°)

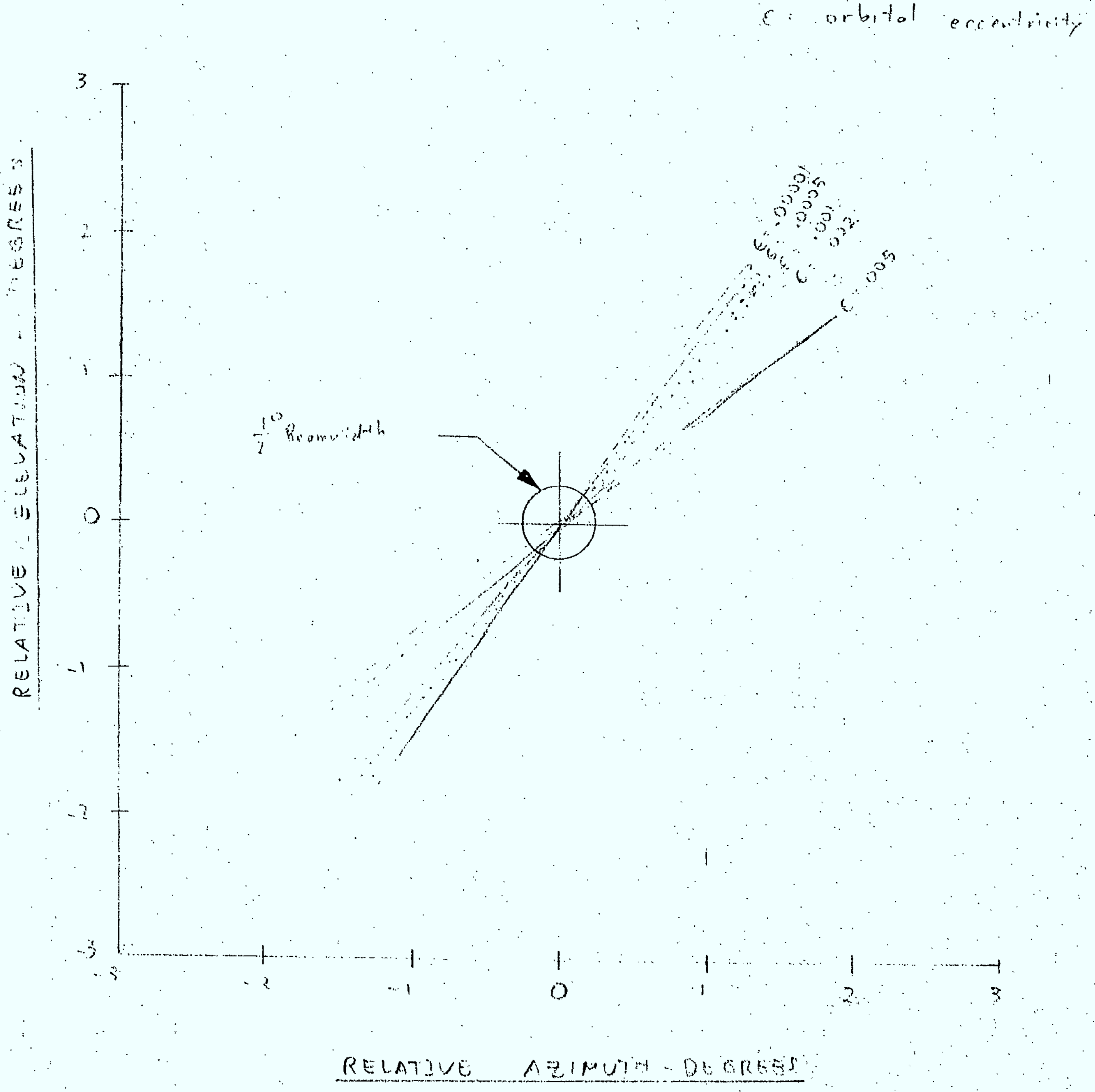
FIGURE 4-5



OBSERVED SATELLITE MOTIONS

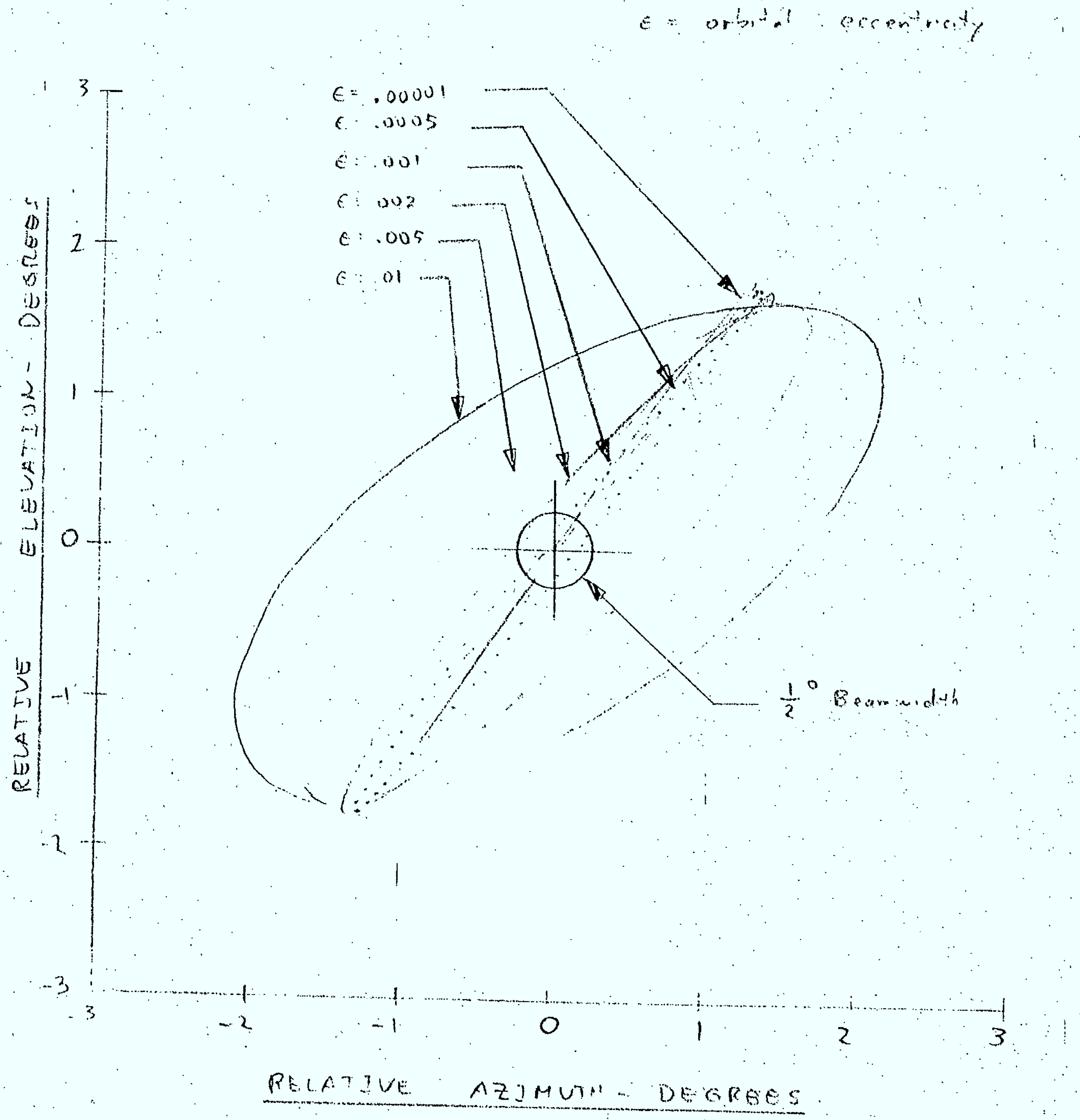
(ARGUMENT OF PERIGEE = 150°

FIGURE 4-6



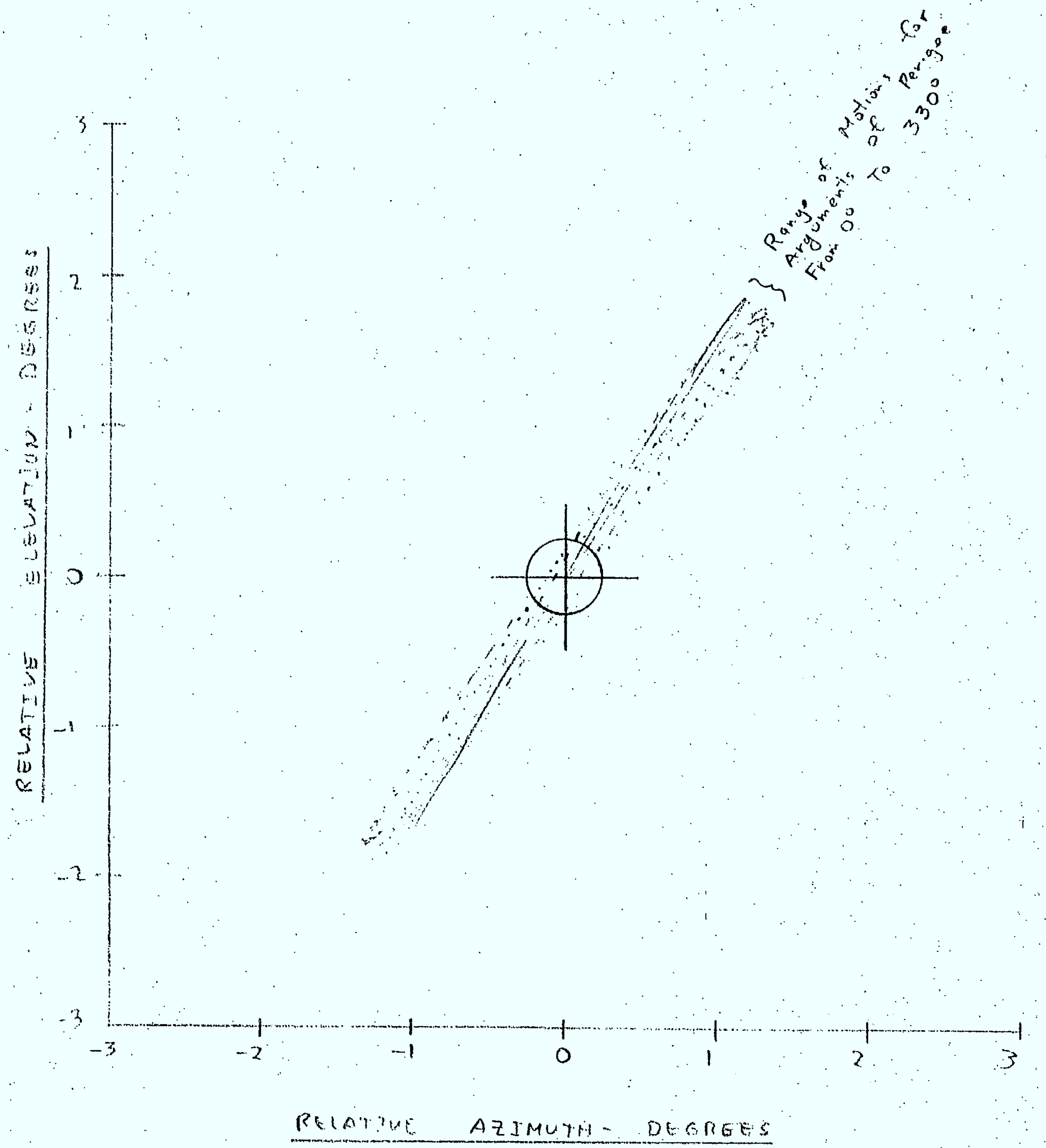
OBSERVED SATELLITE MOTIONS
(ARGUMENT OF PERIGEE = 180°)

FIGURE 4-7



OBSERVED SATELLITE MOTIONS
(ARGUMENT OF PERIGEE = 240°)

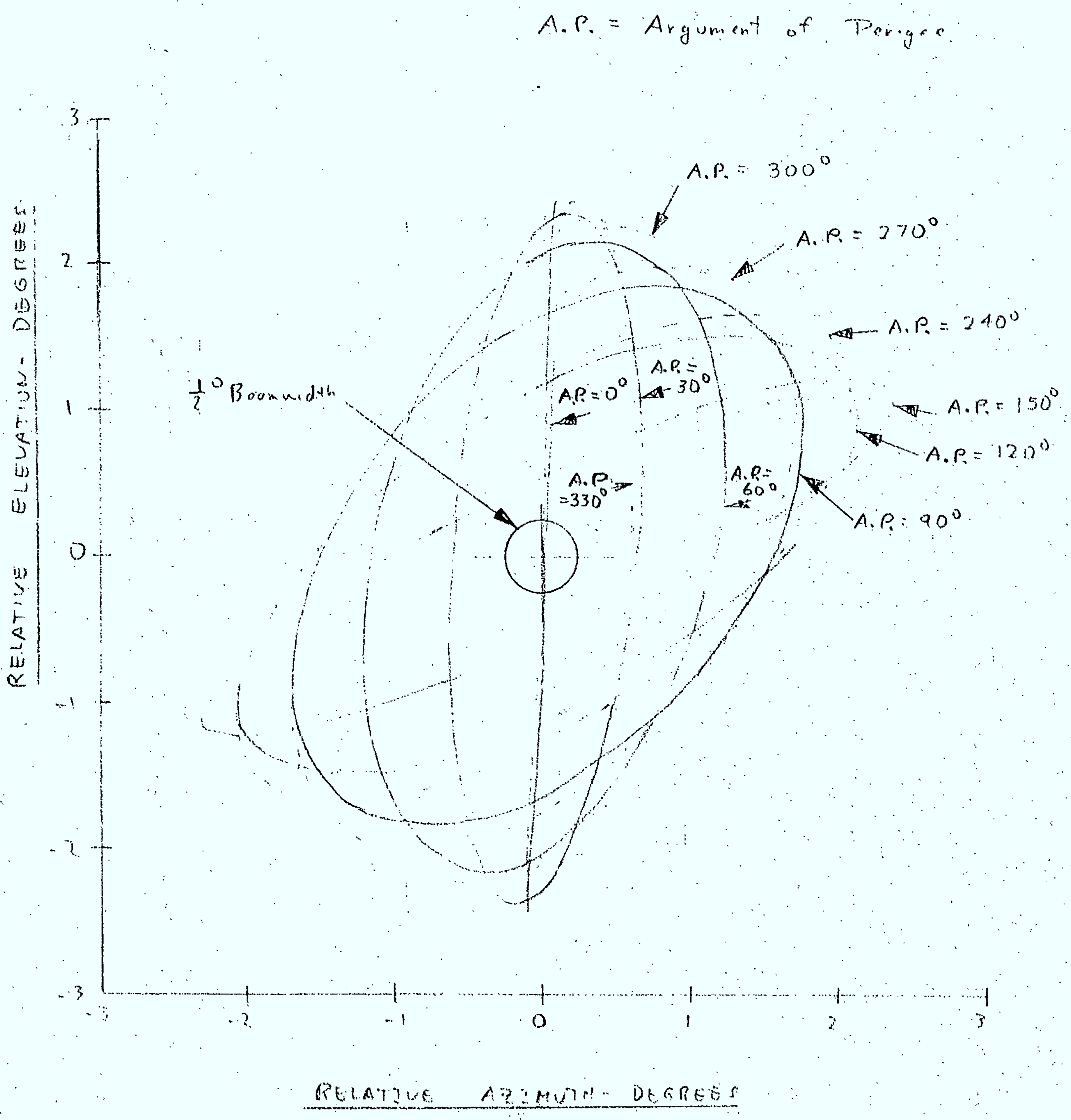
FIGURE 4.8



OBSERVED SATELLITE MOTIONS

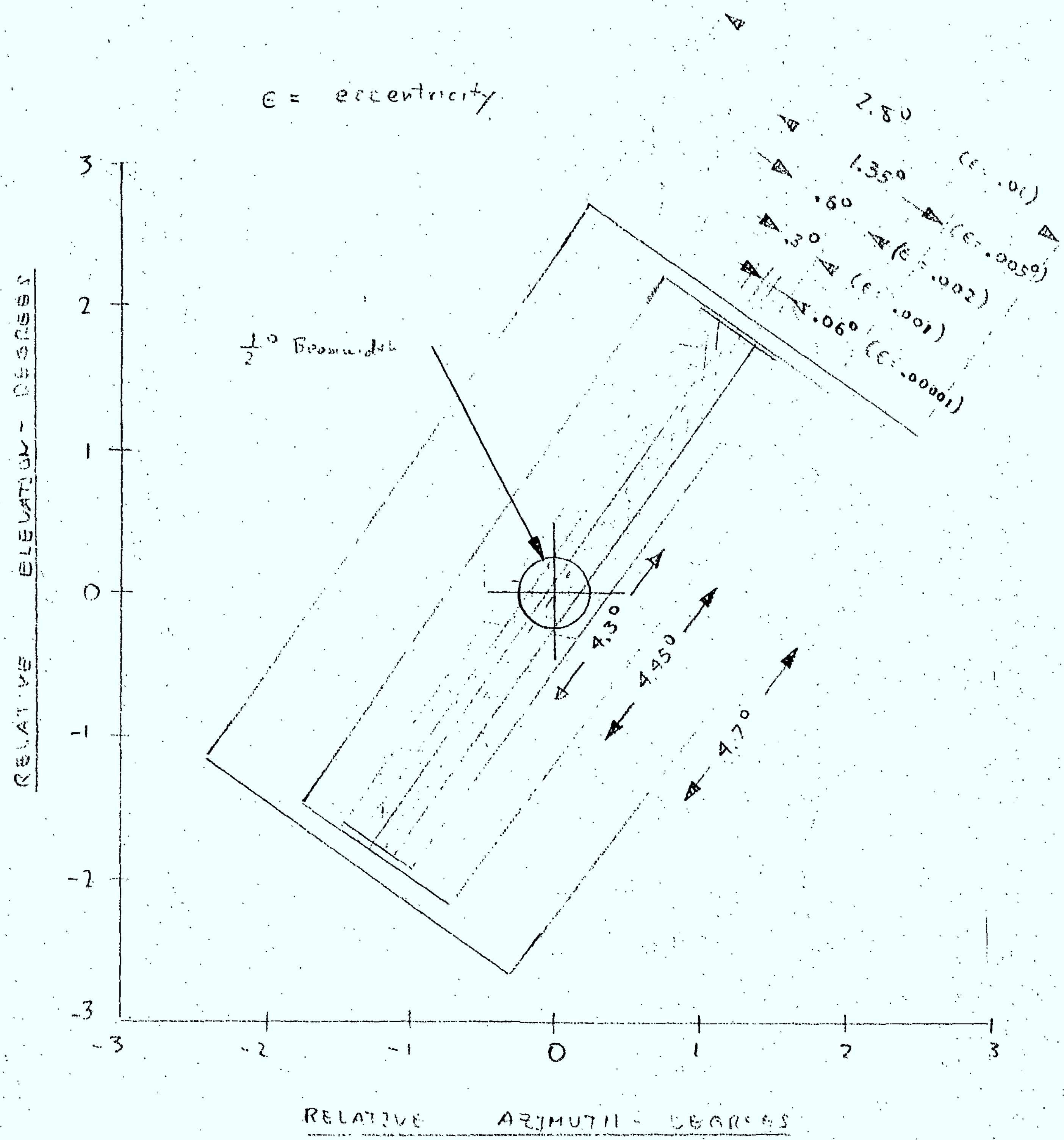
(ORBITAL ECCENTRICITY = 0.001)

FIGURE 4-9



OBSERVED SATELLITE MOTIONS
(ORBITAL ECCENTRICITY = 0.01)

FIGURE 4-10



OBSERVED LIMITS OF SATELLITE MOTION
(RECTANGULAR APPROXIMATION)

FIGURE 4-11

The graph of figure 4-12 relates the E-W motion limits to eccentricity for both the actual satellite motion and the observed motion perpendicular to the tracking line. The observed motion limits are larger than the actual motion limits. The same relationship is likely to prevail for the drift due to orbital tilt so that, including triaxiality, the motion "box" seen by an observer at Ottawa will be perhaps up to 15% wider and 10% longer than that specified, * so that we can take the required "box" limits over which an earth terminal must track to be $0.46^{o} \times 4.4^{o}$ centered on, and aligned with, the tracking line.

Now recalling that the north-south motion due to inclination is based on a cycle of one sidereal day, and that the east-west motion due to eccentricity is based on a cycle of one solar day, we conclude that the major axis of an elliptical orbit will rotate 360^{o} through the plane of the orbit once every year. That is to say, the satellite behaviour will describe all those motions of the preceding figures that are appropriate to the range of eccentricities to be encountered. And eccentricities will vary through the year.

Clearly, to avoid complex set-ups we should

a) use an antenna beamwidth wide enough to cover the narrow width of the overall rectangle.

b) use antenna tracking

c) limit experimental measurement to a reasonable length of time

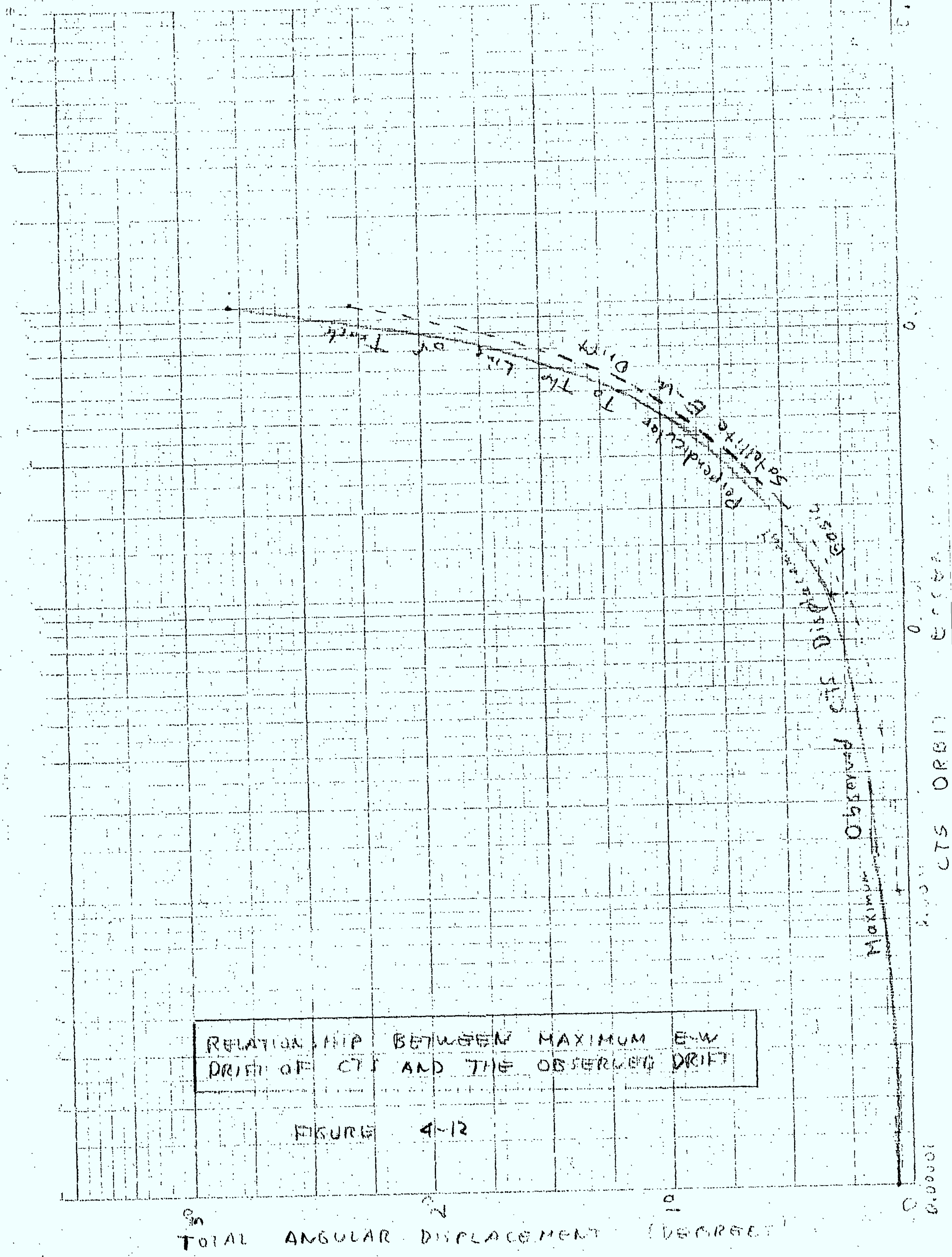
These three considerations form part of the basic "rules" that we can apply to the tracking needs.

4.6 Observation Time Estimated for a 0.2^{o} Beamwidth

Because the observed motion of the satellite within the box is quite complex, the ideal solution is to have the antenna beamwidth completely cover the area defined by the box so that tracking is not required. Except for the case of the 2' nominal diameter ** antenna, this is an impossible requirement. Therefore, for all other antennas either the antenna must track, or the time duration that useful reception is possible must be limited. Let us examine the latter alternative.

* Further north the dimensions of this box tend to decrease.

** Actually, an elliptical reflector would be used to "shape" the beam to optimize this coverage.



RELATIONSHIP BETWEEN MAXIMUM E-W DRIFT OF CTS AND THE OBSERVED DRIFT

FIGURE 4-12

Suppose that the component of satellite motion along the tracking line is sinusoidal with maximum amplitude A. Then the displacement "a" from the nominal line-of-sight may be given by

$$a = A \sin (wt + \beta)$$

The rate-of-change is obtained by differentiating the above equation,

$$\frac{da}{dt} = Aw \cos (wt + \beta)$$

which is maximum when

$$wt| + \beta = 0, 2\pi, 4\pi, \text{etc.}$$

so that

$$\left(\frac{da}{dt}\right)_{max} = A\,w$$

Now, β is simply a phase constant determining when t is zero. For simplicity we choose β equal to zero, so that the maximum value of da/dt occurs when

$$t = T$$

and T is the period of the sinusoid. Therefore

$$w = 2\pi/T$$

Over a short period of time, the maximum total displacement Δa of the satellite during a time Δt is given by

$$\Delta a = \Delta t \left(\frac{da}{dt}\right)_{max}$$

$$= A \frac{2\pi}{T} \Delta t$$

providing Δt is very small compared to T. If we assume that an acceptable value of Δa is $\pm 0.1^\circ$ and that A is $\pm 2.2^\circ$ (maximum observed satellite displacement from nominal along the tracking line) then

$$\Delta t = \frac{24 \times 60}{2\pi \times \pm(2.2)} \times (\pm 0.1)$$

$$= 10.4 \text{ minutes}$$

which is the shortest time interval for the satellite to move through an observed arc of 0.2° (12') along the tracking line and occurs when the satellite is crossing the equatorial plane. For other positions the time interval will be longer. At the limits of travel,

$$\Delta t = 288 \text{ minutes} \quad *$$

ignoring basic alignment errors.

* this assumes that the satellite moves $\pm 0.2^{\circ}$ e.g. from $|2.0^{\circ}|$ to $|2.2^{\circ}|$, thence back to $|2.0^{\circ}|$.

SECTION 5

TRACKING METHODS

5.1 General

Before we examine the sources and magnitudes of errors in a working system* we will briefly review the current applicable concepts for tracking. Not all possible concepts are discussed - only those considered applicable to the CTS experimental program objectives.

The fact that the total observed satellite motion is confined to a "box" $0.45^\circ \times 4.4^\circ$ greatly simplifies the requirements. However, within the box, tracking accuracy may be required to be very high.

We consider manual, programmed and auto-track concepts as listed in Table 5-1.

5.2 Manual Tracking

This method of tracking is suitable for smaller antennas where their greater beamwidth accomodates a larger percentage of the daily apparent satellite motion, with only occasional peaking up of the signal required, or for medium size antennas (say, up to 10 feet in diameter) in systems operated by skilled personnel with adequate satellite motion predictions.

Figure 5-1 is a block diagram for a typical method of manual tracking. This method permits remote adjustment of the antenna position using switches and electrical actuator motors, with position synchros for reference.

For small antennas which require only very infrequent adjustment, a simple hand wheel method of adjustment would suffice, with no electric actuators or controls required.

5.3 One-Axis Programmed Tracking

The apparent satellite motions have been discussed in some detail and the feasibility of program tracking for CTS earth stations can be analyzed together with the use of an adjustable third axis (tracking axis).

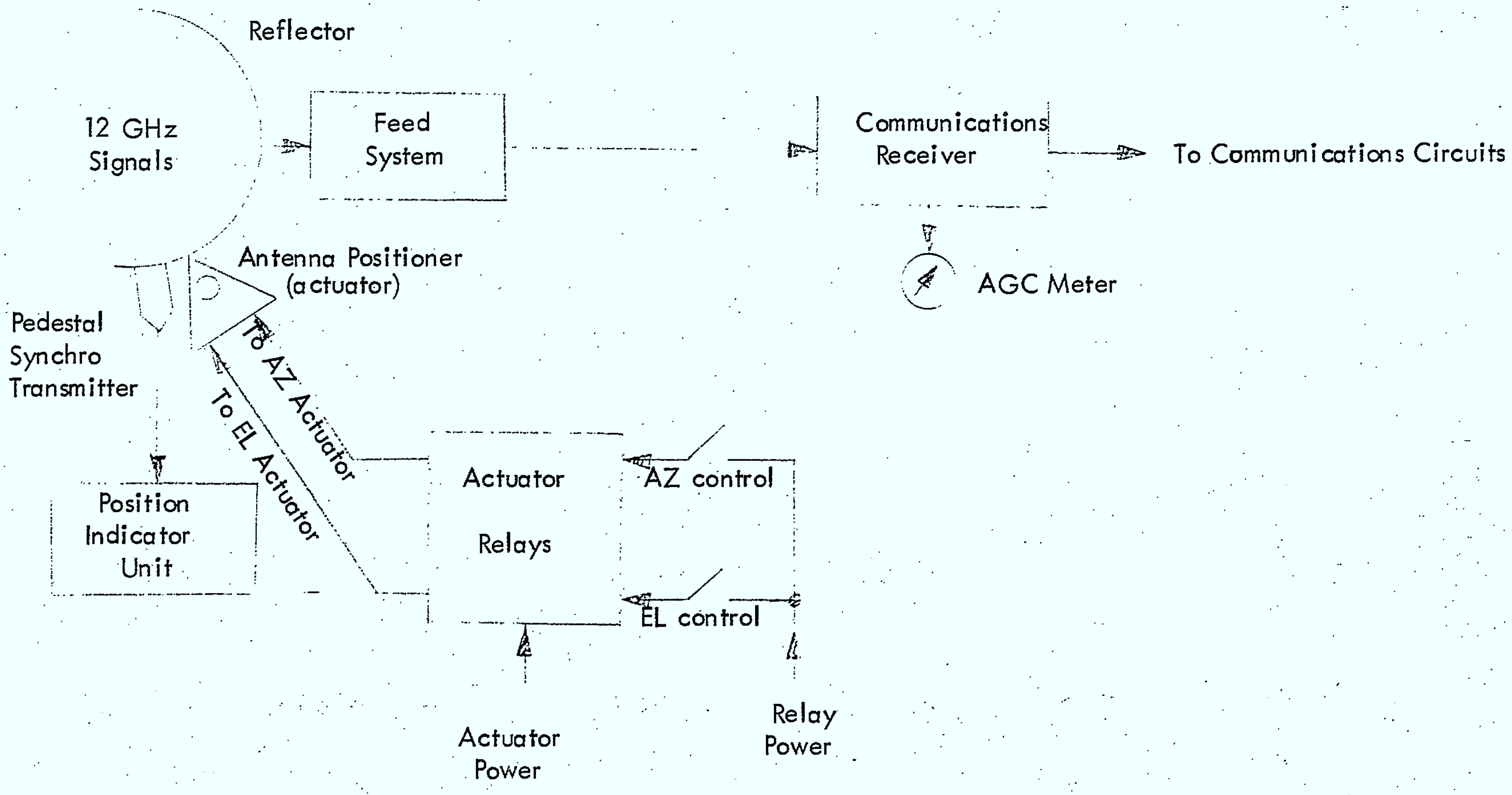
---

* Error source estimates are derived in section 7 while total errors are developed in section 8.

ANTENNA TRACKING CONCEPTS FOR LOW COST GROUND TERMINALS

TRACKING CATEGORY	VARIATION	MOTION ORIENTATION 1ST AXIS	MOTION ORIENTATION 2ND AXIS	COMMENTS
Manual	Two Axes	Elevation	Azimuth	Manually controlled motor driven systems are included in this category.
Programmed				
(a) Simple	One Axis	Tracking	———	Manually controlled offsets in the azimuth direction to improve tracking accuracy are included in this category.
(b) Compound	Two Axes	Tracking	Azimuth	Timing of motion along the tracking line is related to the sidereal clock. Timing along the azimuth plane is related to both solar and sidereal clocks.
(c) Conventional	Two Axes	Elevation	Azimuth	Timing of motion in both planes is related to both solar and sidereal clocks.
Auto-track				
(a) Monopulse	Two Axes	Elevation	Azimuth	Three receive channels are required.
(b) Step	Two Axes	Elevation	Azimuth	Intermittent Antenna motion is used to derive error signal from single receive channel AGC.
(c) Conical	Two Axes	Elevation	Azimuth	Continuous Electronic Deflection of Antenna Beam is used to develop error signal from single receive channel AGC. Antenna moves only where error exceeds specified magnitude.

TABLE 5-1



MANUAL TRACKING SYSTEM BLOCK DIAGRAM (USING LINEAR ACTUATORS)

FIGURE 5-1

Where the observed satellite motions lie within a rectangle whose width is less than the specified beamwidth, single axis tracking would be sufficient provided that the tracking axis can be adjusted to coincide with the satellite tracking line. Figures 5-2 and 5-3 are block diagrams for single axis tracking. Both methods employ a sidereal clock to drive a sinusoidal potentiometer. In Figure 5-2, a linear potentiometer is driven by the antenna positioner and its voltage output is compared to that from a sine potentiometer and at a predetermined error voltage level, the actuator is operated, driving the antenna until the error voltage is reduced to a lower limit set by the comparator. In Figure 5-3 a position synchro is used to supply the position indication for the comparator and the linear potentiometer is eliminated. This would permit better resolution of position over the small range of angular movement through which control is required.

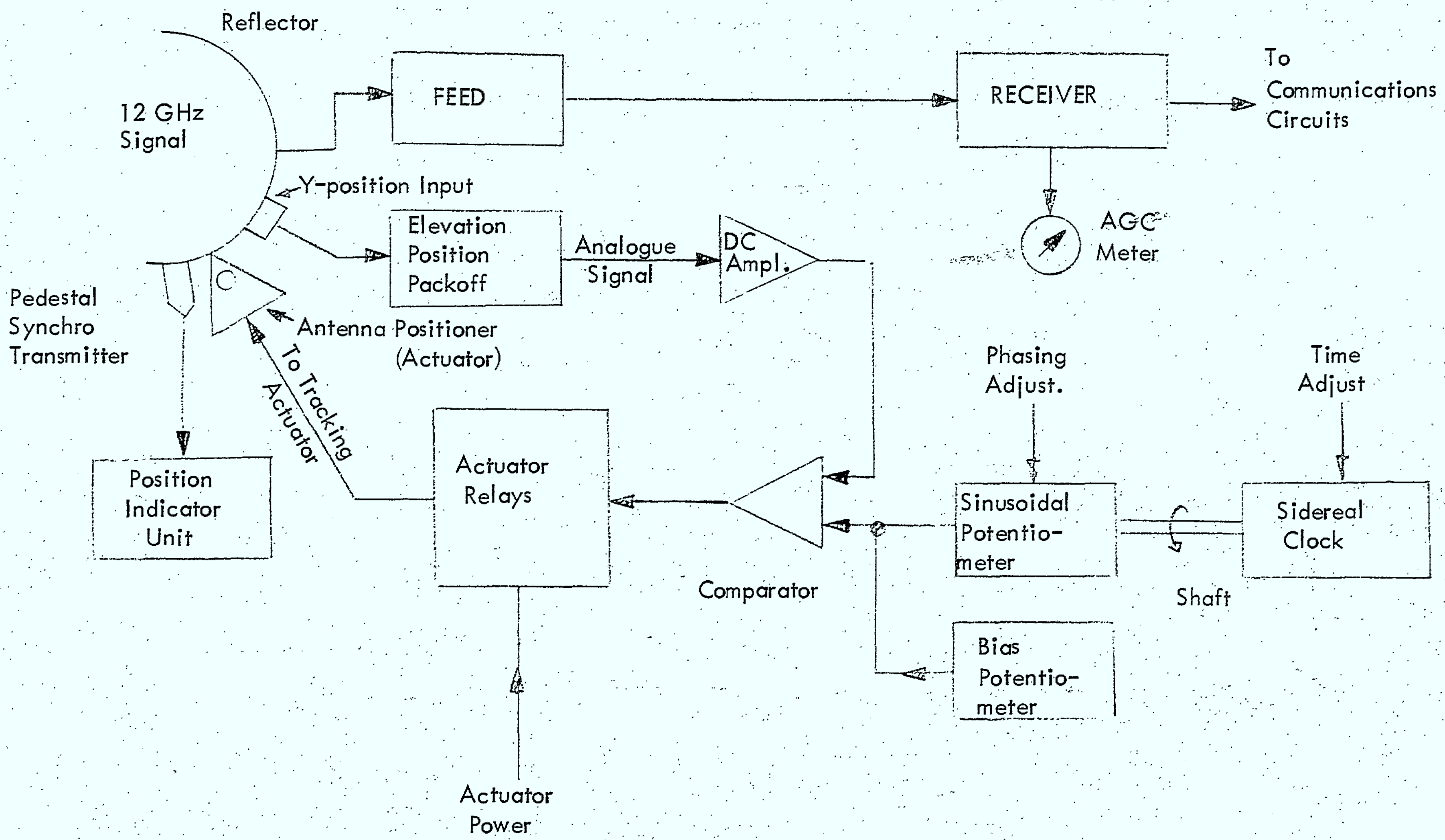
5.4 Two-Axis Programmed Tracking

If the observed satellite motion lies within a box whose width exceeds the specified antenna beamwidth then two-axis tracking is required. It is convenient to implement programmed tracking with one axis governing motion along the tracking line while the other is governing motion along the azimuth. A block diagram of a system incorporating this method is shown in Figure 5-4.

Under the assumption that north-south satellite motions occur in sidereal time and east-west satellite motions occur in solar time, the tracking mechanism must have clock references in both standards. Since motion along the tracking line corresponds to north-south satellite motion, its programming mechanism need only be controlled by a sidereal clock. However, for motion along the azimuth, the programming mechanism must be controlled by both the sidereal and the solar clock. This complication and its consequences are discussed further in Section 7.

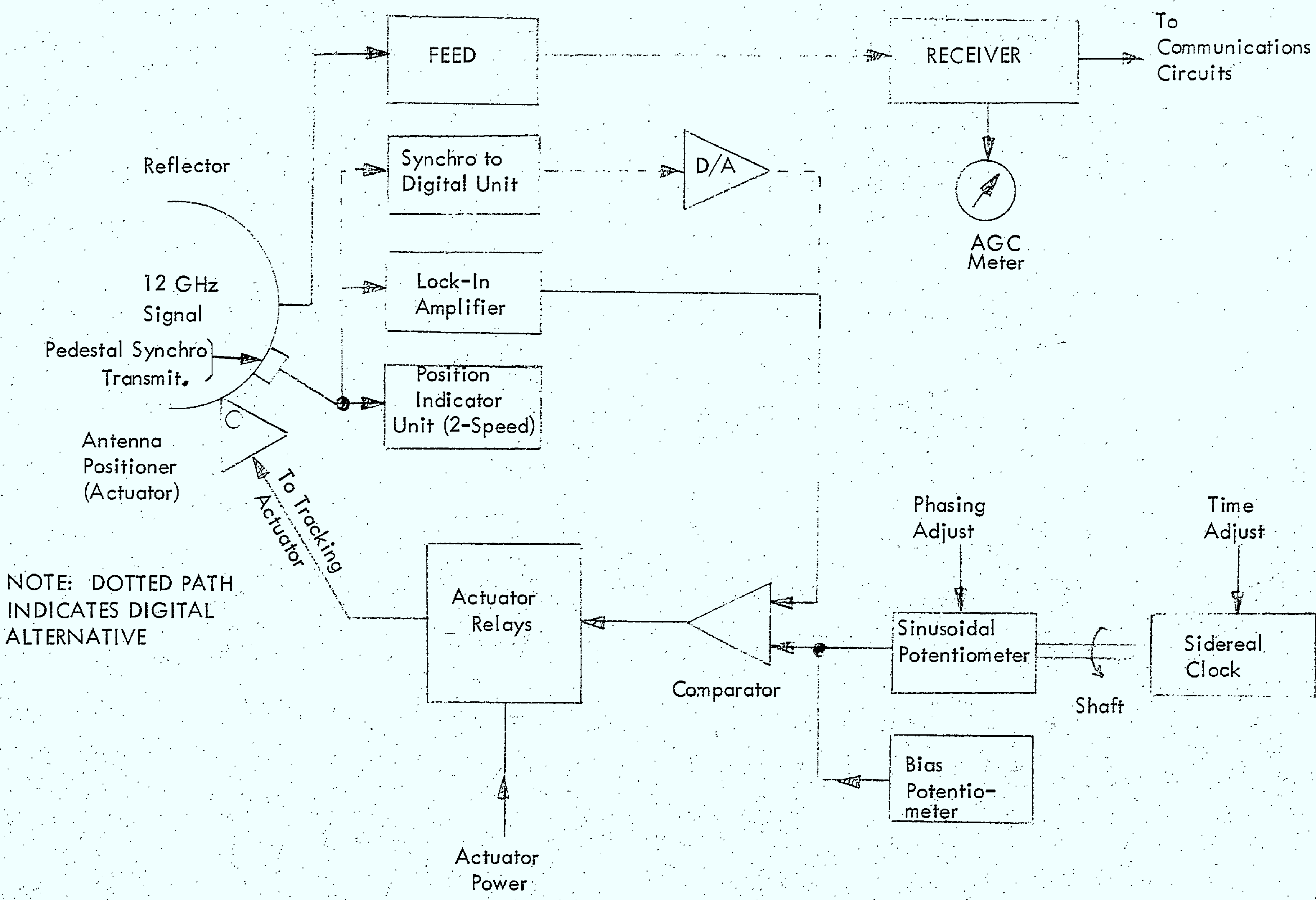
Tracking can also be accomplished with the more conventional azimuth and elevation axis. In this case both axes must be controlled by a combination of both clocks.

Finally, we can contemplate tracking along the tracking line and perpendicular to the tracking line. In this case, the former motion is controlled by a sidereal clock; the latter by a solar clock. This is perhaps the simplest mechanism requiring only that the two clocks be phased insofar as the time aspects are concerned, but requires a third axis for proper set-up, since azimuth angle settings are still required.



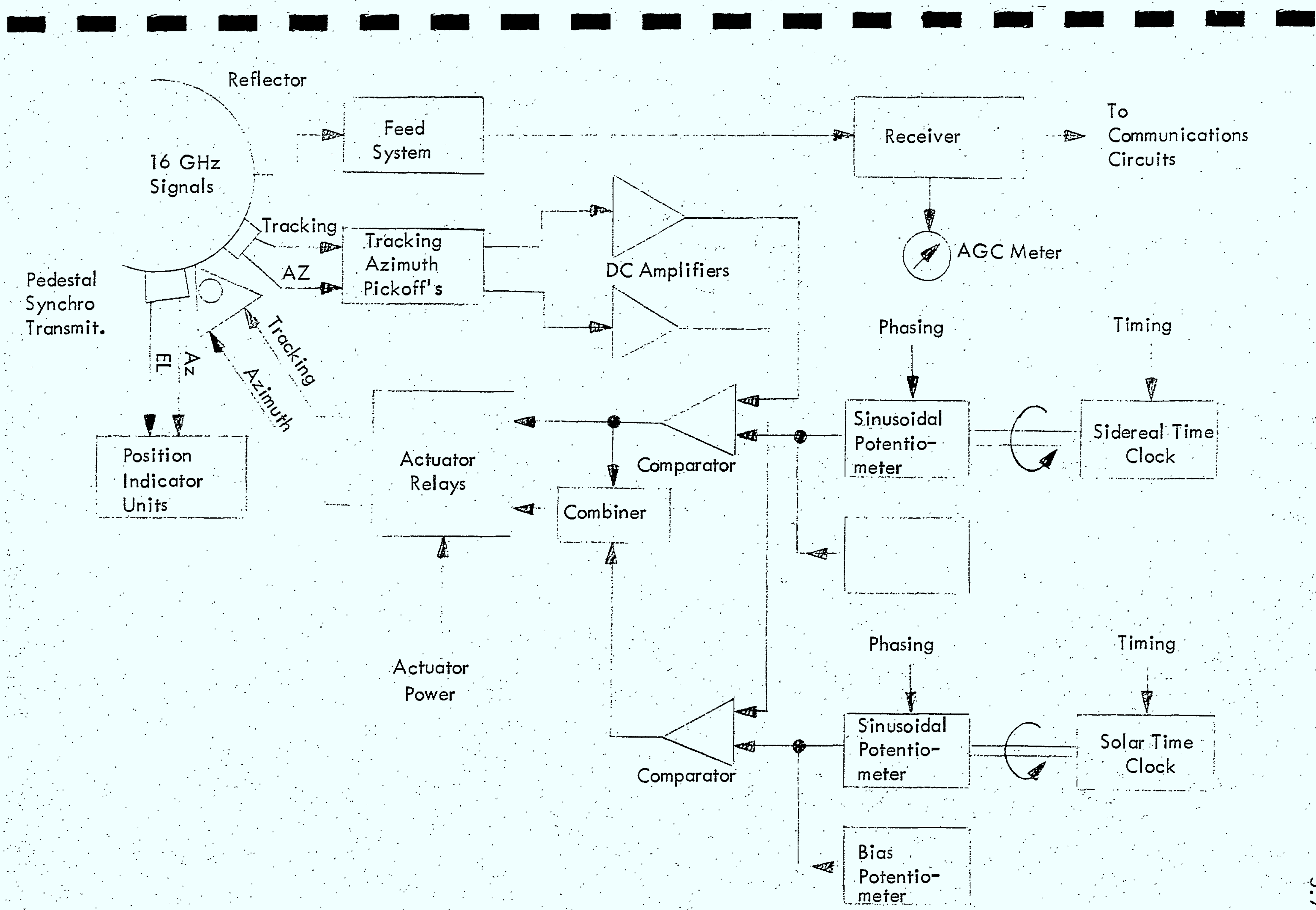
ONE-AXIS PROGRAMMED TRACKING SYSTEM BLOCK DIAGRAM - BASIC SYSTEM

FIGURE 5 - 2



ONE- AXIS PROGRAMMED TRACKING SYSTEM BLOCK DIAGRAM - IMPROVED TRACKING RESOLUTION

FIGURE 5 - 3



TWO AXIS PROGRAMMED TRACKING SYSTEM BLOCK DIAGRAM

FIGURE 5 - 4

5.5 Conventional Monopulse Auto-Track

Figure 5-5 shows the block diagram of a typical 3 channel conventional monopulse auto-track system. This is the type of system required for higher performance systems and narrow beamwidth antennas, such as on the 30' control station at Ottawa. Because they are typically very expensive, we shall not consider them further.

5.6 Step-Track

For satellites which have limited apparent motion to earth stations a method of tracking using discrete steps in elevation and azimuth to peak up AGC voltage, has been found to be potentially simple and inexpensive.*

Systems using this principle are currently being developed by RCA Limited for the large Telesat Earth Station for operation at 4 and 6 GHz frequencies. For the relatively smaller CTS ground terminal antennas, the step track approach should be equally suitable. Figure 5-6 is a block diagram of a typical step track system along one axis only, for simplicity.

The basic operating principles of a step track system are as follows: Assume that the antenna is pointed towards the satellite and that a signal is being received so that an AGC voltage is being developed in the receiver. If the antenna boresight is slightly off from the antenna-to-satellite line-of-sight, then the received signal will not be as great as it would be for perfect alignment. Now, we give the antenna an arbitrarily small initial angular "step" in a random direction. If this initial step were in a direction to increase the misalignment, then the AGC level of the receiver would drop slightly. However, if the initial step were in the opposite direction, the AGC level would increase. Thus, observation and comparison of the AGC level immediately before and after the step would reveal whether or not the initial random step were in the right direction.

In practice, this observation and comparison would be done with logic circuitry. If it decided that the initial step was in the wrong direction, the second step would be made in the opposite, or right direction. The AGC levels of the second step would also be monitored to confirm whether the second step were made in the right direction. This action of stopping and confirming is continued throughout the tracking operating interval.

It is easy to see that, for a series of steps, the antenna motion would be such as to reduce the misalignment between the boresight and the line-of-sight. In effect, the characteristic is for the gain to "climb the antenna pattern" towards maximum.

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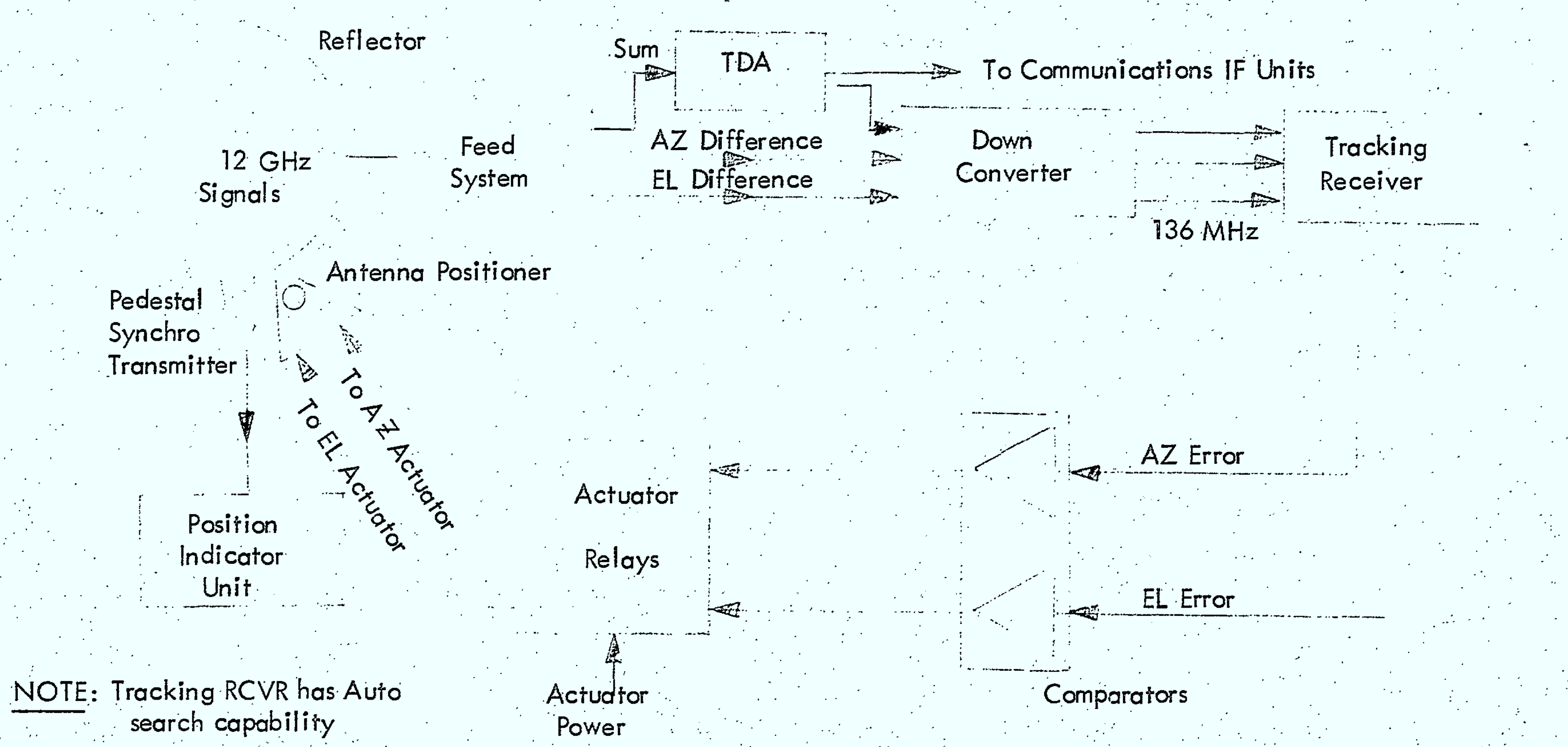
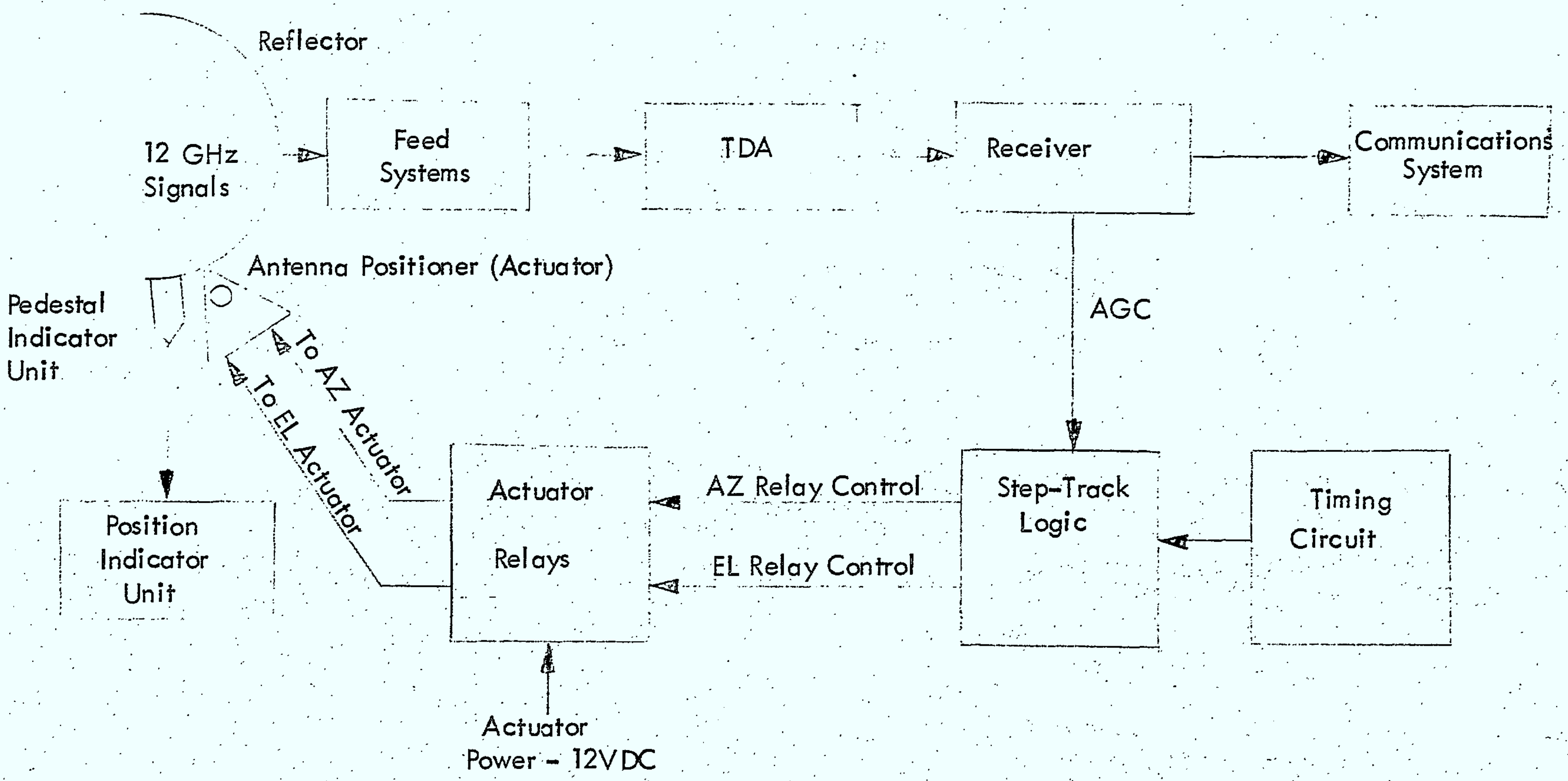
* See Appendix B and Ref. 3 for a more detailed discussion.



TRACKING MONOPULSE SYSTEM (AZ-EL AXES)

FIGURE 5-5



STEP-TRACK SYSTEM BLOCK DIAGRAM (AZ -EL AXES)

FIGURE 5-6

When the steps cause the antenna pointing to move past the maximum, the AGC level will again drop causing the logic circuit to reverse the direction of the steps. The net effect, then, is that the antenna track motion will oscillate about the maximum. On the average, therefore, a slight effective loss of gain must be tolerated.

Some of the problems associated with step track lie in determining

a) optimum step size

b) step frequency

c) logic decision criteria

since the effects of noise in the received signal, fading, and antenna distortions due to wind all tend to upset the accuracy of the step-direction decisions upon which the system is based. An estimate of the errors due to these effects is given in Section 7. Further evaluations have been performed (ref. 9) and field tests of actual systems are currently contemplated.

Some methods of implementing step track are given in Table 5-2.

5.7 Cone-Scan

This is a modification of the classical type of "conical scanning" used by certain types of tracking radar system. Figure 5-7 is a block diagram of such a scheme.

In this system, the antenna beam is electronically "bent" through a small angle and the effect in the AGC output of the receiver is noted. The beam is then moved through the same angle magnitude but in the opposite direction, and again the AGC output of the receiver is noted. If the antenna boresight were aligned with the satellite to ground line-of-signt, then the AGC output levels would not change. However, if there were a misalignment, then the AGC levels would be different.

In practice, the antenna beam "bending" would be rapidly switched back and forth between the two offsets, and the output of the AGC would be synchronously switched into a balanced detector. The output from the detector would be an error signal proportional to the misalignment between boresight and line-of-sight.

---

* Comsat has conducted tests using a 95 foot antenna. More recently Telesat has purchased terminals using step track systems from RCA Limited.

POSSIBLE STEP CONTROL METHODS FOR STEP-TRACK SYSTEMS

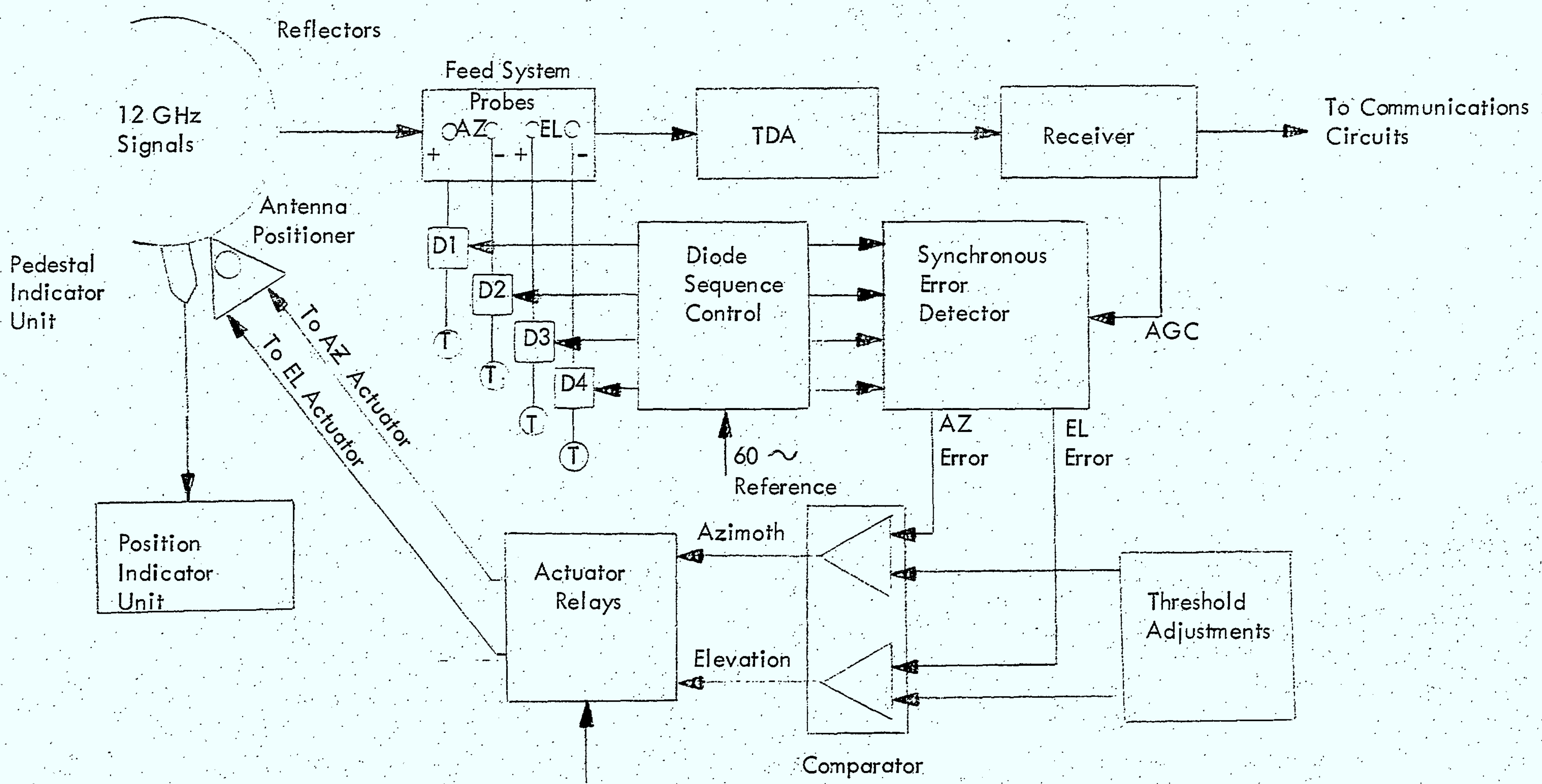
	Timer	Gear Driven Cam on Actuator	Magnetic Pipper and Counter	Digital Output from position Indicator	Follower Mechanism on positioner	Stepper Motor
Method of Actuator step size control	Accurate adjustable electronic timer	Actuator motor drives Cam. Microswitch controls motor relay	Counter switches after preset No. of pulses	Digital pulses counted & used to switch motor off	Amplifier cyclic motion & limit switch	Motor Pulsed req'd no. of times
Ease of altering step size	No problem	May require different gears or cams	No problem except variable in step increments only	No problem	May be difficult	No problem except variable in step increments only
Modification req'd to standard actuator	None	Probable Major re-design	Addition of perm magnet to shaft and associated sensing coil	None	None	Major re-design probable
Effect of friction & wind gusts on step size	Can result in large errors	Small effect on overtravel	Small effect on overtravel	Small effect on overtravel	Small effect on overtravel	None
Estimated Normal accuracy	± 20%	± 5%	± 2%	± 1%	± 5%	No significant error
Estimated accuracy (worst environment)	+ 100% - 50%	± 7%	± 3%	± 2%	± 7%	"
Relative development cost	Lowest	Medium	High	Low-neglecting positioner cost	Medium	Probably highest

TABLE 5-2 (Continued on Page 5.13)

POSSIBLE STEP CONTROL METHODS FOR STEP TRACK SYSTEMS (Continued)

	Timer	Gear Driven Cam on actuator	Magnetic Pipper & counter	Digital Output from position indicator	Follower Mechanism on positioner	Stepper Motor
Estimated reliability	Excellent	Poor for 1 million cycles	Good	Good	Poor for 1 million cycles	Good
Maintainability	Excellent	Good	Excellent	Excellent	May be a problem	Excellent
Recommended methods, small quantity production	Not recommended	Alternative to follower mech.	Not recommended	Recommended ✓	Recommended ✓	Not recommended
Factors to consider for quantity production	Testing could show this to be an acceptable method particularly for small antennas	Redesigned actuator might not be very expensive	Could be installed at low cost	Recommended if digital position indicator selected. Probably not the case for smaller terminals	Not recommended	Probably still highest cost but most accurate positioning provided

TABLE 5-2



NOTE: T - Termination
Dn = Switching Diode N

CONE-SCAN SYSTEM BLOCK DIAGRAM

FIGURE 5-7

Adding provisions to move the antenna beam along a path 90^{o} to the above completes the facility necessary for two direction tracking. The synchronous switch can also be used to separate the error signals into azimuth and elevation components.

Switching may be reasonably rapid - a 15 to 20 Hz rate is probably quite satisfactory. This rate is fast enough that normal signal fading should not affect the error signal since the rate of fading is typically much slower.

A method of bending the beam is to insert probes of specified characteristics into a standard horn at specified locations. These probes are then connected to termination, using switching diodes. These probes slightly distort the fields inside the horn resulting in beam bending when only one termination is removed by opening a switch.

If the probes are connected to the diode switches via narrow and pass filters, then the beam bending can be restricted to a specified range of frequencies (say, around the beacon). Thus the beam pointing at other frequencies, and particularly for the signal, would not be affected, therefore maximum antenna gain would be available. However, the cost would be the addition of a separate beacon IF and AGC receiving system.

A system making use of the above techniques has not yet been built. However, cone-scan appears to be very attractive and could be quite economical after development. We strongly suggest further investigation into this system.

SECTION 6

OPERATING PROCEDURES

6.1 General

For any of the terminals* we assume that a table listing nominal azimuth, elevation and tracking angles as a function of latitude and longitude would be available. The site coordinates should also be known but the reference direction of true north may not be known with much accuracy.

For the 2 foot and 8 foot terminals, which are receive only, the operators may have no special training and in many cases would not know the phasing or amplitude of apparent satellite motion. The 2 foot terminal would not have any tracking facility. The 8 foot terminal might have either program track along the tracking line or 2 axis step track.

The 4 foot terminal which would in general only be operated for short periods of time would only be fitted with a manual tracking capability but would probably have a means to adjust its tracking axis.

The 10 foot mobile TV terminal would most likely be fitted with 2 axis step track (or cone-scan) but could also include either single axis or dual axis programmed tracking. A manual tracking capability would also be provided.

6.2 Antenna Mounting

The 4' antenna for the portable two-way voice terminal is assumed to be mounted on a tripod pedestal with a gear driven head. The 2 foot radio receive only terminal would probably be fitted with adjustable sliding brackets such as the standard mounts for microwave tower installations. The TV receive terminal would probably have hand cranks to traverse its 8 foot dish.

* See "Types of Terminal" Table 3-1.

6.3 Acquisition Methods

The first requirement when setting up any of the terminals is to determine true north as accurately as possible. Then the antenna is positioned to point at the nominal azimuth and elevation angles as determined from the table provided for the site coordinates. The antenna positioner is accurately levelled and, if this feature is provided, its tracking axis is adjusted to the tracking angle specified in the table. Then with the receiver operational, the antenna is moved either manually or automatically according to a prescribed search pattern in order to acquire the satellite.

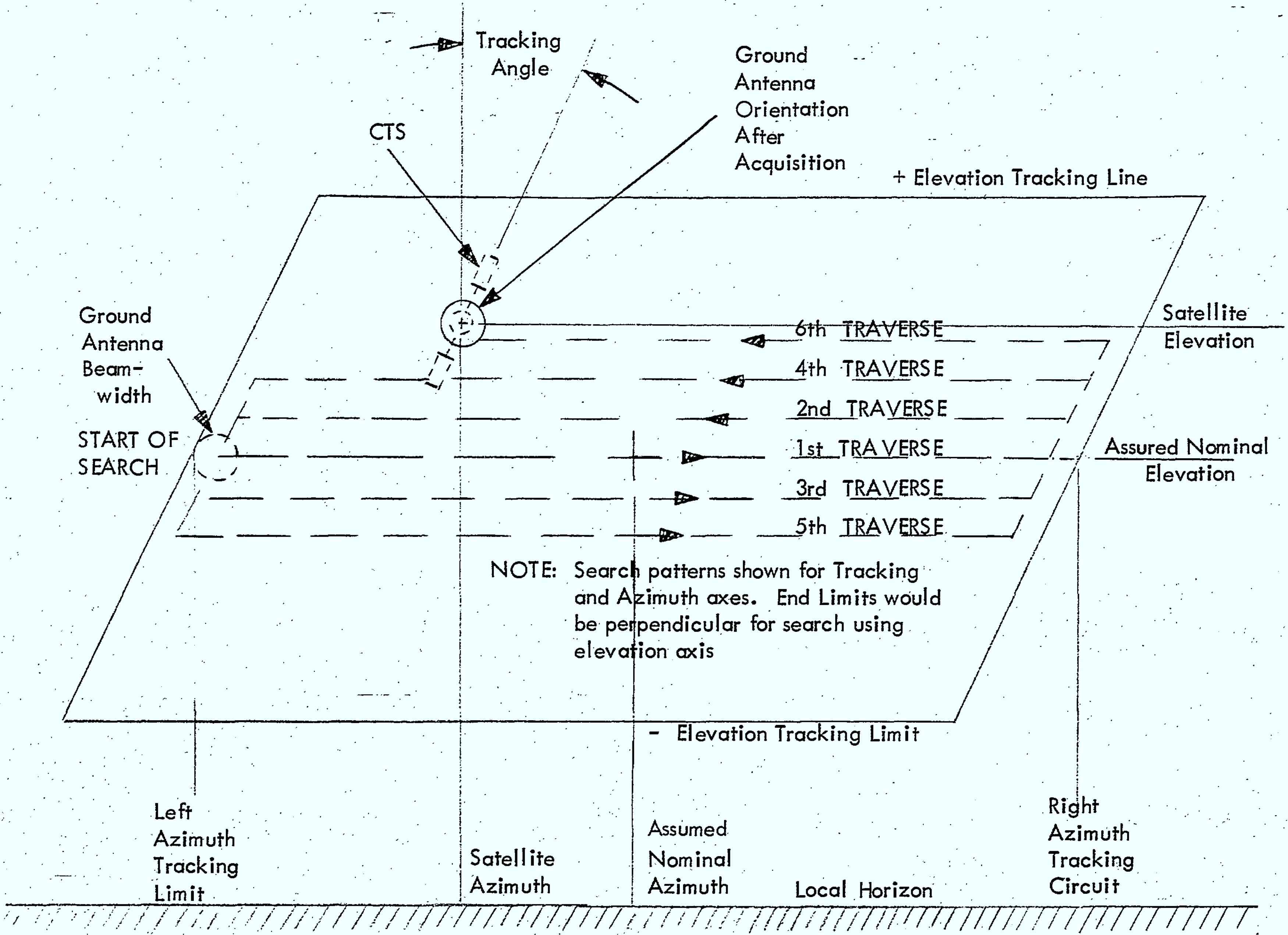
With manual search, a searching rectangle would be selected and the antenna moved in azimuth sweeps with discrete elevation step changes at the end of each sweep such that the full rectangle can be covered as shown in Figure 6-1. The step changes would be selected to be less than the 3 dB bandwidth of the antenna and the sweep rate would be slow enough so that a concurrent frequency sweep of a band of frequencies in the receiver would result in lock-on when the required carrier to noise level is exceeded. (Ref. 11).

Control of sweep may be via switch control and a remote position indicator or simply by hand crank. Adjustment by hand is satisfactory for the smallest antennas. The antennas which are provided for step track should automatically enter into a search mode when first energized. Their coverage can also be that shown in Figure 6-1. Program track systems could also be provided with a search program but this would probably not be necessary or justifiable.

The 2-foot antenna requires special attention in its alignment because it has no tracking capability and must be pointed so that for the entire diurnal satellite path the required gain is provided. The antenna would be adjusted to provide peak response separately 12 hours apart and the sliding bracket which adjusts elevation marked at these points. The location of the elevation zero crossing point would be located approximately half way between the two points. When the satellite next goes through this point the antenna would be adjusted to peak response again. For a "Figure 8" pattern of motion, this is now the correct pointing. For an elliptical satellite motion, the same procedure would be followed except that the sliding brackets for both elevation and azimuth adjustment would be marked and the correct setting would be half way between each of these marks in order that the antenna will point to the center of the ellipse.

6.4 Manual Track Operating Procedures

This would require periodic peaking up of the signal. The period between corrections may be increased by overcorrecting each time, i.e. driving past the peak signal position in the direction of motion.



TYPICAL SEARCH PATTERN FOR CTS GROUND TERMINALS

FIGURE 6-1

With a position indicator and a table showing position as a function of time this would be easily accomplished, and even at periods of fastest apparent motion corrections for 1 dB variation would only be required approximately every 15 minutes for a 10 foot antenna.

At the other extreme six hours later, the time to travel one beam width of 1 dB would be approximately 2 hours with a further 2 hours to come back to the same elevation. For other sizes the required intervals would vary inversely with the antenna diameters.

If we consider that steps should be made twice as often to allow for errors due to wind, etc., this would still not be a significant burden on the operator.

6.5 Program Track Operating Procedures

Manual acquisition of the satellite must be performed first, in accordance with the preceding procedures. Following this, the tracking motions must be phased with the observed satellite motions. To do this we note the angular positions of the satellite when manually acquired at intervals exactly 12 sidereal hours apart. The position half way between these limits should be the zero crossing point. A slight correction may be necessary when the satellite crosses the zero point, and phasing is complete.

The amplitude of tracking may be made next by manual acquisition at the expected time of maximum displacement. It is assumed that the angle about which tracking is required would be known for the site and this would be preset. Some slight adjustments of angle might be subsequently required.

Several possible methods of program tracking have been discussed. For each method, when the satellite has been acquired there is a requirement to align or phase the programming to the actual satellite motion. Alignment can be accomplished using the reference point at which the satellite crosses through the zero reference point, as was noted in the previous description of a method for alignment of the 2 foot antenna following satellite acquisition

Where program tracking employs a simple electro-mechanical drive this would simply have to be adjusted to the starting position and the motor started up. For the more complex systems shown in Figures 5.3 and 5.4 it would also be required to phase the outputs of the position indicators to the reference sine-cosine potentiometers which must be phased to the zero crossing point.

In practise the sine-cosine potentiometers would be phased directly to the clock drivers and providing the clocks are on time they will provide the correct output. To phase the tracking would require adjustment of the position indicator potentiometers such that their voltage is the same as the sine-cosine potentiometer outputs.*

During the first few tracking cycles AGC voltage should be recorded at regular intervals to provide an indication of how well the satellite is being tracked and certain corrections to the program might be advantageous and subsequently at periodic intervals spot checks should be made to determine whether or not the tracking is still within limits. Limit switches to prevent the antenna from being driven outside the re-acquisition range would also be a good feature.

6.6 Auto-Track Operating Procedures

We describe auto-track operations from the point of view of step-track systems. Most of these procedures are, however, applicable to the other systems.

The basic advantage of an automatic tracking system is that once enabled, there should be little additional effort required further from the operator. A search mode may be included in the capabilities to relieve the operator from the task of initial acquisition beyond that of ensuring that the antenna points approximately in the right direction. The search pattern is essentially the same as the described in Figure 6-1. Transition from the search mode to the tracking mode occurs when the AGC level exceeds a preset threshold level. Details must, of course, be left for the designers.

Loss of signal while tracking should ordinarily cause the system to revert to the search mode. Manual override, however, is recommended to prevent search for specified events such as cessation of spacecraft emissions.

During extremely bad weather conditions it should be possible to drive the antenna to a stow position. This would be controlled by another switch. We recommend that level lock switches be used for control (and for the override switch) to prevent inadvertent operation.

Basic design of a step track system would include adjustable step size and adjustable intervals between steps. Part of the experimental program should be concerned with optimization of these parameters for different signal conditions due to wind, fading, or other factors.

* Adjustment of mechanical cam followers also follows this principle.

SECTION 7

ERROR SOURCES

7.1 General

Any effect which causes the electrical boresight of the antenna to deviate from the line-of-sight between the antenna and CTS resulting in a loss of antenna gain is an error source for our purpose (we do not, in this analysis, consider loss in maximum gain due to antenna surface contour deformation, tropospheric bending of the signal wave, Faraday rotation, or fading effects.) Not all of the effects apply in each tracking category.

Broadly speaking, we can divide the errors in three classes:

a) Positional errors which result from differences between the assumed satellite position and the actual satellite position.

b) Pointing errors which result from deviations in the ground beam pointing angle due to equipment or operational limitations.

c) Operational errors which result from "deadband" allowances introduced to simplify certain operational procedures.

Table 7-1 lists the error under the above classification and identifies the major regions of applicability.

7.2 Positional Errors

The meaning of "positional errors" may be taken to mean the difference between an assumed simplified satellite motion and the actual motion, and primarily applies to programmed tracking systems.

We recall from Section 4 that north-south satellite motions result primarily from orbital tilt ($\pm 2.0^\circ$ nominal) while east-west motions result from three sources:

a) orbital tilt ($\pm 0.018^\circ$)

CLASSIFICATION OF ERRORS IN ANTENNA TRACKING SYSTEMS

CLASS	DESCRIPTION	APPLICABILITY	NOTE
Positional	Deviation in satellite position from that predicted	Programmed Track	
Pointing	Antenna Distortion Due to Wind	Manual Track Programmed Track Auto Track	This contribution can be reduced if auto-tracking is continuous.
	Measurement Errors	Manual Track	
	Programming Errors	Programmed Track	
	Wind, Noise and Fading (Step Track)	Auto Track	Step Track only.
Operational	Deadband	Manual Track Auto Track	Depends on correction interval, Hysteresis effect.

TABLE 7 - 1

b) triaxiality ($\pm$ 0.025°)

c) solar pressure ($\pm$ 0.146°)

d) others ($\pm$ 0.011°)

each with its own time frame of reference.

North-south CTS motion is mainly sinusoidal. We shall, however, assume that a small contribution due to "other" motions is also present. * An allowance of $\pm$ 0.010° will be introduced to account for the variations from a sinusoid.

Programmed tracking along the line of track (following north-south satellite motions) is implemented by generating a sinusoidal reference with a period of 1 sidereal day and then causing the antenna motion to follow the reference. Ignoring errors in the reference signal (which will be considered under pointing errors,) the positional errors along the line of track are solely due to "others" and are therefore taken to be about $\pm$ 0.010°. These are increased by 10% to yield the observed limit (See Figure 4-11).

Any attempt to develop an equation precisely describing motion perpendicular to the tracking line (following east-west motions), or to shape a "cam" so that a mechanical follower can reproduce the motion, would be extremely difficult, if not impossible. A more reasonable procedure would be to follow the motion of the greatest contribution (solar pressure) and to accept the motions of the others as "errors". Assuming that the motion due to solar pressure is sinusoidal, then a tracking reference signal can be developed to follow its contribution. The remaining deviations after removal of the solar pressure contribution constitute positional error limits. We increase these by 15% to determine the observed error limits (See Figure 4-11). Table 7-2 lists these errors both along and perpendicular in the line of track.

If we track along the tracking line only, the positional error perpendicular to this line is equal to the total observed E-W motion of the satellite. The consequences of doing this are seen later when we add together all errors.

* Due to gravitational effects and also the fact that satellite motions are in fact described on the surface of a sphere, rather than on a plane. Changes in observational angles are also included here.

POSITIONAL ERROR DERIVATIONS

CONTRIBUTION AT LIMITS	DEVIATION (DEGREES) ALONG LINE OF TRACK	PERPENDICULAR TO LINE OF TRACK	NOTE
Solar Pressure	0	± 0.146	
Triaxiality	0	± 0.025	
Orbital Tilt	± 2.000	± 0.018	
Others	± 0.010	± 0.010	1
	± 2.010	± 0.199	
Ideal Tracking Range	± 2.000	± 0.146	2
Position Error (Actual)	± 0.010	± 0.053	
Position Error (Observed)	± 0.012	± 0.061	3

NOTES: (1) "Others" are estimated to be ± 0.010° in both directions.

(2) Assuming ideal tracking mechanisms.

(3) As observed from Ottawa. This is about 15% higher than the actual error.

TABLE 7 - 2

7.3 Pointing Errors

Such errors arise from

a) basic antenna distortion due to wind

b) measurement errors in manual tracking

c) programming errors in programmed tracking

d) step track errors due to wind and noise and fading

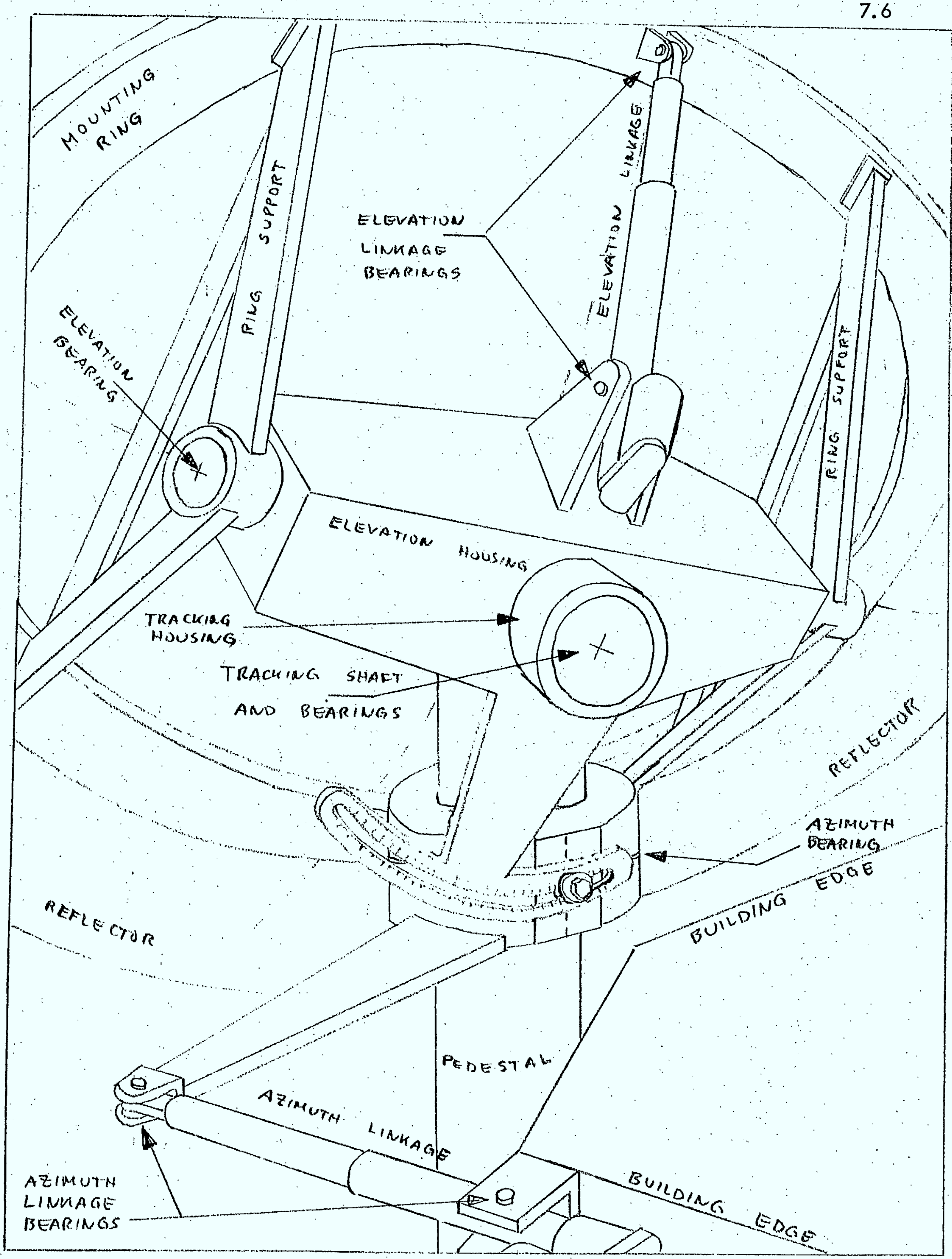
The effective magnitude of the contribution from these sources depends upon the tracking system under consideration. For example, if a program tracking system is in use, wind errors are quite prominent, but noise errors are not introduced. For cone-scan systems, wind errors may be relatively small (compared to programmed track) if sampling and corrections are continuous , but noise errors (in the error signal) may be quite significant. For our purpose, we are examining the use of a step-track auto-track scheme so that, since sampling and corrections are intermittent, wind effects are significant.

7.4 Basic Antenna Distortions Due to Wind

The effect of wind is to generate forces which tend to deform the antenna and mount structure or, because of unequal wind forces arising from the peculiar antenna constructions and wind angles, to develop torques about the axis of rotation. A rough assessment of these deformations has been made for a 10' diameter antenna installed on a mount having the general concept shown in Figure 7-1. The values resulting from this assessment are given in the appropriate column of Table 7-3. In compiling this table, we have not analyzed a design. Rather, we have examined a concept only so that we may derive a reasonably justifiable expectation for the performance of an antenna which might be designed along the lines suggested by the format.

Values for the other antenna diameters in Table 7-3 are scaled from the 10' baseline under the assumption that;

a) the rigidity of smaller antennas is less so that the deformities may be considered equal.



TRACKING MOUNT CONCEPT

FIGURE 7-1

PRELIMINARY ANTENNA DEFORMATION BUDGET (SHEET 1)

	Displacement (In)	Lever Arm (In)	Angular Deformation (Degrees) 2 Foot Ant. Az	2 Foot Ant. El	4 Foot Ant. Az	4 Foot Ant. El	8 Foot Ant. Az	8 Foot Ant. El	10 Foot Ant. Az	10 Foot Ant. El	Notes
REFLECTOR											
Bending Due to Wind and Gravity	–	–	0.010	0.010	0.025	0.025	0.020	0.020	0.025	0.025	6
Sub-Total			0.010	0.010	0.025	0.025	0.020	0.020	0.025	0.025	
ELEVATION											
Effect of Ring Twist	–	–	–	–	0.015	0.015	0.010	0.010	0.010	0.010	
Ring Support Differential Error	–	–	–	–	–	–	0.005	0.005	0.005	0.005	
Main Bearing	0.001	20	–	–	0.006	0.006	0.003	0.003	0.003	0.003	3
(2) Linkage Bearing	0.001	20	–	–	–	0.012	–	0.006	–	0.006	3
Linkage Expansion -Temperature(ΔT=10F)	–	–	–	–	–	–	–	0.004	–	0.004	5
Linkage Expansion - Pressure (Δ P=1000#)	0.001	20	–	–	–	–	–	0.004	–	0.004	5
Sub-Total			–	–	0.021	0.033	0.018	0.032	0.018	0.032	
TRACKING											
Elevation Housing Bending	0.002	40	–	–	0.024	–	0.006	–	0.006	–	
Main Bearing	0.001	20	–	–	0.006	0.006	0.003	0.003	0.003	0.003	3
Tracking Housing Bending	0.001	10	–	–	0.012	0.012	0.012	0.012	0.012	0.012	
Shaft Bending	0.002	30	–	–	0.004	0.004	0.004	0.004	0.004	0.004	
Sub-Total			–	–	0.046	0.022	0.025	0.019	0.025	0.019	
AZIMUTH											
Main Bearing	0.001	20	–	–	0.006	0.006	0.003	0.003	0.003	0.003	3
(2) Linkage Bearing	0.001	20	–	–	0.012	–	0.006	–	0.006	–	
Linkage Expansion-Temperature ($\Delta T=10^{o}F$)	–	–	–	–	–	–	0.004	–	0.004	–	5
Linkage Expansion-Pressure (Δ P=1000#)	–	–	–	–	–	–	0.004	–	0.004	–	5
Sub-Total			–	–	0.018	0.006	0.017	0.003	0.017	0.003	

TABLE 7-3 (Continued on Page 7-8)

REFLECTOR ANTENNA DEFORMATION BUDGET (SHEET 2) (Continued)

	Displacement (In)	Lever Arm (In)	Angular Deformation (Degrees) 2 Foot Ant. A_Z	2 Foot Ant. El	4 Foot Ant. A_Z	4 Foot Ant. El	8 Foot Ant. A_Z	8 Foot Ant. El	10 Foot Ant. A_Z	10 Foot Ant. El	Notes
SUPPORTING STRUCTURE											
Corner Twisting	-	-	-	-	-	-	0.010	0.010	0.010	0.010	
Wall Deformation	0.10	20	0.100	0.100	-	-	0.017	0.017	0.017	0.017	
Sub-Total			0.100	0.100	-	-	0.027	0.027	0.027	0.027	
TOTAL DEFORMATION			0.110	0.110	0.110	0.088	0.107	0.101	0.112	0.106	

NOTES:

1. Tracking Axis Assumed Horizontal
2. See Figure 7-1 for Concept of Mount
3. Lever Arm 10" for 4 Foot Antenna
4. Coefficient of Thermal Expansion: 6.22×10^{-6} (Steel) 12.78×10^{-6} (Aluminum)
5. Young's Modulus : 30×10^{6} (Steel) , 10×10^{6} (Aluminum) $= Pl/Ae$
6. 4 Foot Antenna assumed relatively light construction for portability.

TABLE 7-3

b) the 2' diameter antenna has no tracking axis

c) the lever arms for actuators are scaled with diameters.

7.5 Measurement Errors in Manual Tracking

In manual tracking, the operator adjusts the antenna pointing to maximize a received signal as indicated by a meter reading of AGC. Assuming a square law detector is the receiver, the AGC meter reading is proportional to power. Therefore, at full scale, a change in received power of 1 dB corresponds roughly to a 10% change in the reading. Assuming that we can read (on a relative basis) a 1.0% change in meter reading, then the uncertainty in power reading is 0.1 dB. The uncertainty in antenna beamwidth resulting from this is a function of antenna diameter. Table 7-4 lists the appropriate alignment errors.

7.6 Programming Errors in Programmed Tracking

We consider tracking equations for an observed elliptical satellite path (see Figure 7-2). Assume first, that the tracking axes are horizontal and vertical to the local horizon. If the tracking angle is θ^o from the vertical, the equations for azimuth angle displacement $\triangle H$ and elevation angle displacement $\triangle E$ are

$$\triangle H = A \sin\theta \cos\phi - B \cos\theta \sin\phi$$

$$\triangle E = A \cos\theta \cos\phi + B \sin\theta \sin\phi$$

Where,

A = amplitude of observed major axis travel

B = amplitude of observed minor axis travel

θ = orientation angle of elipse

ϕ = regular angle postion of satellite from starting point (See Figure 7-2)

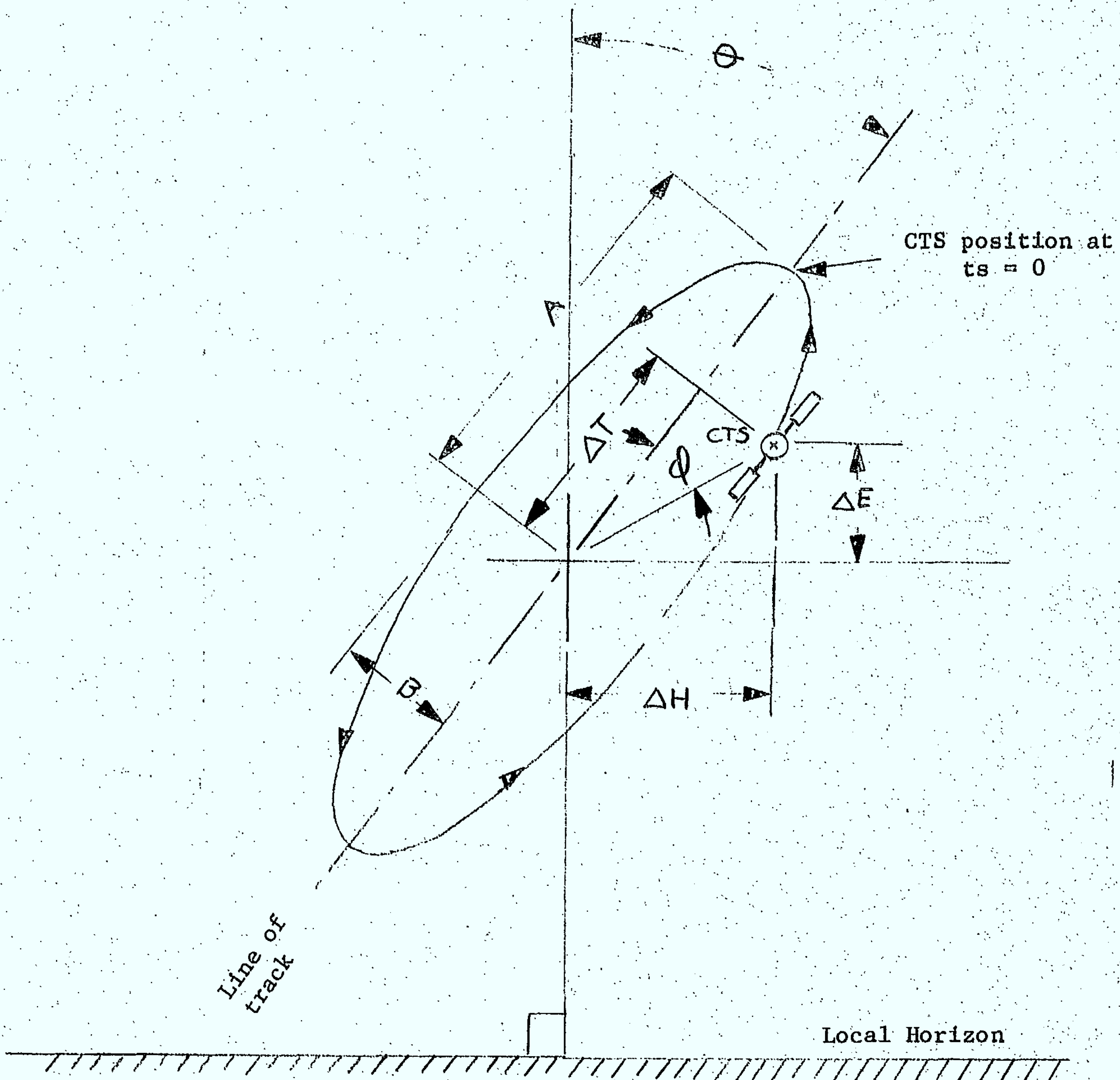
The values of $\triangle H$ and $\triangle E$ can be calculated easily when the values of A, B and θ are known (from a computer program) for the location. For any location the values of A Cos θ, A Sin θ, B Cos θ and B Sin θ would not change significantly except over a long period of time. Thus if values of Cos E and Sin E are generated in sidereal time and the values added or subtracted from each other control of X and Y motion could be achieved using a similar method to that of Figure 5-4.

MANUAL ALIGNMENT ERRORS

(MANUAL TRACKING)

NOMINAL DIAMETER (FEET)	1% MEASUREMENT UNCERTAINTY (DEGREES)
2	± 0.270
4	± 0.133
8	± 0.068
10	± 0.054

TABLE 7 - 4



GEOMETRY OF OBSERVED ELLIPTICAL SATELLITE PATH

FIGURE 7-2

If we choose to provide two axis tracking whereby the antenna moves along the tracking line and in azimuth, then the equations are:

$$\triangle H = \frac{B}{\cos \theta} \sin \phi$$

$$\triangle T = A \cos \phi - B \tan \theta \sin \phi$$

Where:

$\triangle T$ = angle measured along the tracking line.

The pointing accuracy achievable by programmed tracking is dependent upon the accuracy with which the azimuth and elevation angles can be determined, or the accuracy with which the analogues of these angles can be generated, the accuracy and resolution capability of the position transmitter and receiver, and the accuracy of its comparator. Through conservative design techniques it is possible to design a low compliance positioner and structure so that the error due to wind is a small portion of the total error. Table 7-5 summarizes the estimated errors from an analysis of the source.

7-7 Step Track Error Sources

The most significant sources of errors with step track are disturbance torques due to wind gusts, variations in signal to noise and signal fading. All of these result in transient changes to AGC levels which must be discriminated against by the step track control electronics. Operation in 30 mph winds is required.

Step track has already been tested on large antennas. * By comparing the 1 dB beam angles for smaller antennas with that tested, and scaling for frequency, we see that the tracking accuracy does not have to be as good, larger deflections due to wind are permissible and step sizes can be made relatively larger.

With respect to step size, a recent paper ** suggests that the beamwidth between the 3 dB down points be divided into 10 steps to establish step size. This will be the procedure followed for our study. Since

$$\theta_3 = 0.56^\circ$$

the step size may be taken to be

$$\theta_s = 0.056^\circ$$

* See Section 5.6

** See Appendix D

ERRORS IN PROGRAMMED TRACKING MECHANISMS

ERROR TABLE	TOLERANCE	EST. EFFECT
Servo Potentiometer	± 0.1%	± .03°
Sine-Cosine Potentiometer	± 0.5%	± .013
Regulated Voltage Source	± 0.1%	± .002
Voltage Comparator	± 0.1%	± .002
Comparator Switch Hysteresis	Equiv. to steps of	.03°
Actuator Overtravel *	± .02°	± .01
Error in A (ellipse major axis)	± 0.5%	± .013
Error in B (ellipse minor axis)	± 0.5%	± .013
Error in θ	± 0.5°	± .02
Error in ϕ	Negligible	Negligible
		± .143°

* not additive to Hysteresis error.

TABLE 7 - 5

7-8 Effect of Wind

Wind torque deflections depend on the wind direction and velocity. We are primarily concerned with the difference between average wind velocity and peak velocity because this determines the change in antenna pointing in a short time interval. AGC voltage is sampled immediately before the step and then with a short delay after the step. The voltage is averaged or integrated over a short time period to filter out short term signal-to-noise changes. If the wind deflection angle is small relative to the stepping angle then the probability of an error due to the wind is small. This demonstrates the importance of ensuring that the antenna positioner and pedestal have low compliance (high rigidity).

For a 30 m.p.h. change in wind velocity the change in wind torques for a typical 10 foot antenna dish is 230 lbs. ft.* We will assume that the maximum permitted deflection due to wind is less than a step increment (1/10 of the 3 dB beamwidths) that a wind deflection can be no greater than 0.056°. On this basis the compliance of the antenna pedestal must be

$$\text{Compliance} > \frac{0.56 \times 0.5 \text{ degrees}}{230 \text{ lb. feet}}$$

$$> 1.22 \times 10^{-4} \text{ degrees/lb ft.}$$

The wind deflection θ_w is therefore

$$\theta_w = \theta_s = \pm 0.056^\circ$$

7-9 Effect of Signal to Noise

With respect to noise, an analysis of the tracking accuracy due to noise alone ** indicates that in an environment of 3 dB CNR, and where there are 10 steps between the 3 dB points, the 0.01% probability of error due to noise is 0.35 X 3 dB beamwidth, or $\pm$ 0.1° for a 10 foot antenna. For a CNR of 10 dB, we have estimated that the pointing error θ_n is

$$\theta_n = \pm 0.05^\circ$$

and we use this value in our analysis.

* Data obtained from Scientific Atlanta

** See Appendix D

7-10 Effect of Fading

Now, the effect of fading is interpreted by the step track decision circuitry as a pointing error. This arises because of the time difference between the "before the step" reading and the "after the step" reading so that in the presence of a fade, a difference in signal level will be erroneously interpreted as resulting from the step itself.

To obtain a rough indication of magnitude, we have examined a chart recording of a typical received level over a 15 minute interval * at 7.3 GHz. Maximum fading rates are of the order of 1 dB/4 seconds and occurred for an estimated total of about 10 or 12 seconds during this interval (about 1% of the time). This is extrapolated to a fading rate of about 2 dB per 4 seconds exceeded only 0.01% of the time at 12 GHz, or about 0.4 dB, in a measuring interval of about 1 second. (This level is constant with typical integrating times).

Figure 7-3 relates antenna loss as a function of the relative 3 dB beamwidth. For a 10 foot antenna, from Figure 3-3

$$\theta_3 = 0.56^\circ$$

therefore, from Figure 7-3, a 0.4 dB reduction in signal level results in a equivalent fading angle of

$$\theta_F = (0.38 \times 0.56)^\circ$$

$$= 0.22^\circ$$

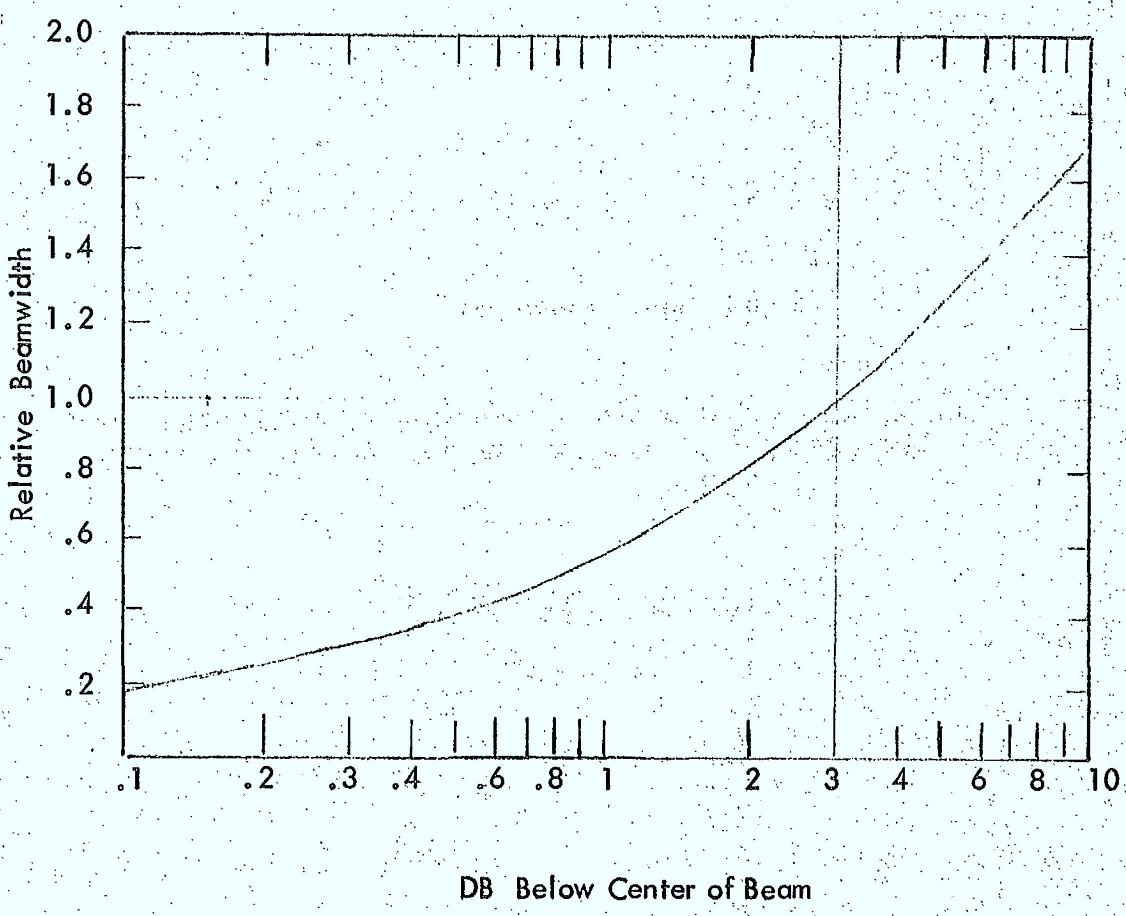
$$= \pm 0.11^\circ$$

exceeded less than 0.01% of the time.

7-11 Addition of Pointing Errors

We assume that the errors are gaussian random variables and independent. They all conspire to contribute errors by the logic decision circuits therefore we can add them on an RSS basis.

* See Reference 4. The necessary statistics for fading rates do not appear to be too available in the form necessary for our purposes. We have therefore chosen this admittedly crude procedure to obtain an indication of the effect.



Note: Curve shown for a tapered circular aperture with 25 dB sidelobes. (Ref - Microwave Engineers Handbook 1966, Page 174)

BEAMWIDTH CONVERSION

FIGURE 7 - 3

The total pointing error is therefore

$$|\theta_P|^2 = |\theta_W|^2 + |\theta_N|^2 + |\theta_F|^2$$

$$= |0.05^\circ|^2 + |0.05^\circ|^2 + |0.11^\circ|^2$$

from which

$$\theta_P = \pm 0.13^\circ$$

exceeded less than 0.01% of the time.

Since fading is the greatest source, steps should be taken to reduce its effect. Thus the logic circuits should contain a feature to inhibit the decision making process during a fade (identifiable by gain AGC changes in the absence of wind gusts or antenna motions) so that the $\pm 0.11^\circ$ contribution can be reduced. We feel that this component can be decreased by at least 50% so that typically an achievable value is

$$|\theta_P|^2 = |0.05^\circ|^2 + |0.05^\circ|^2 + |0.055^\circ|^2$$

$$\theta_P = \pm 0.089^\circ \text{ total}$$

exceeded less than 0.01% of the time. These values are scaled for other antenna diameters and are listed in Table 7-6.

7-12 Deadband Errors

In manual tracking, we must periodically re-establish antenna pointing to compensate for continuous satellite motion. Since correction is periodic, errors will accrue during the time interval between adjustments. These errors will be functions of satellite angular velocity, antenna diameter, and frequency of adjustment.

In Section 4, we have determined that the maximum angular velocity of the satellite is 0.2° along the tracking axis in 10.4 minutes, occurring when the satellite crosses the equatorial plane. Thus, if the minimum readjustment interval is 10.4 minutes, then the loss of antenna gain would correspond to that value related to $\pm 0.1^\circ$ offset for a given antenna diameter.

TRACKING ERRORS

NOMINAL DIAMETER (Feet)	TOTAL TRACKING ERROR (± Degrees)
2	0.444
4	0.222
8	0.111
10	0.089

NOTE: Tracking errors estimated for a 10' diameter parabolic antenna (see text) and are scaled for other diameters.

TABLE 7-6

Earlier, we have noted that a basic uncertainty in measurement exists. For practical purposes, we can assume that a deadband allowance of at least equal this value must be permitted. Table 7-7 relates the deadband allowance to antenna size and gives the minimum interval between readjustments to correct for it.

In auto-track systems, deadband may be considered as a hysteresis type of action in which the corrective motion of the antenna begins when the measured error exceeds some value, say ϵ_1, and continues until this error reduces to a smaller value, say ϵ_2. (basic tracking error). Deadband θ_D is thus

$$\theta_D = \epsilon_1 - \epsilon_2$$

Typically, deadband in auto-track systems is smaller than that in manual system.

A deadband error of about $\frac{1}{2}$ the value of tracking error is a reasonable starting point. Assuming that the estimated tracking errors of Table 7.6 apply, then deadband errors for tracking systems may be determined. These allowances are also given in Table 7-7.

Auto-track deadband is normally applied to monopulse or conical scan systems. However, in step-track systems, it is included in the basic tracking error resulting from the decision errors and therefore does not appear as a separate entry.

DEADBAND ERRORS

NOMINAL DIAMETER (FEET)	DEADBAND ALLOWANCE MANUAL TRACKING (DEGREES)	DEADBAND ALLOWANCE AUTO- TRACKING (DEGREES)
2	± 0.540	± 0.222
4	± 0.266	± 0.111
8	± 0.136	± 0.056
10	± 0.108	± 0.045

TABLE 7-7

SECTION 8

TOTAL SYSTEM LOSSES

8.1 General

Total system angular errors are tabulated in Table 8-1 for the various tracking schemes. We include only the case of step track under the Auto-track Category. We may make these basic comments.

8.2 Combining Error Contributions Along Orthogonal Axes

The following rules are used to combine error contributions along orthogonal axes:

a) Pointing errors are assumed to be random and uncorrelated. They are assumed to be related by

$$\left(\frac{\theta_{px}}{a}\right)^2 + \left(\frac{\theta_{py}}{b}\right)^2 = 1$$

where

θ_{px} = error along x axis

a = maximum error along x axis

θ_{py} = error along y axis

b = maximum error along y axis

The maximum error is then obtained by;

$$\theta_p^{\,2} = \theta_{px}^{\,2} + \theta_{py}^{\,2}$$

b) Measurement errors are assumed to be established separately for each axis, and once established, are fixed (for a given measurement). Their maximum magnitudes are considered to be obtained by adding the errors on an RSS basis.

c) Deadband errors are assumed to be established separately for each axis and are therefore combined on an RSS basis.

ESTIMATE OF ANGULAR ERRORS

SYSTEM MOTION RELATIVE TO TRACKING LINE	ANGULAR ERRORS (± DEGREES) 2 ft. Antenna Along	 Across	 Maxi-mum	4 ft. Antenna Along	 Across	 Maxi-mum	8 ft. Antenna Along	 Across	 Maxi-Mum	10 ft. Antenna Along	 Across	 Maxi-mum	REF. TABLE
MANUAL													
- Pointing Errors	0.110	0.110	0.110	0.110	0.088	0.098	0.107	0.101	0.104	0.112	0.106	0.109	7-3
- Measurement Error	0.270	0.270	0.382	0.133	0.133	0.188	0.068	0.068	0.096	0.054	0.054	0.077	7-4
- Deadband Errors	0.270	0.270	0.382	0.133	0.133	0.188	0.068	0.068	0.096	0.054	0.054	0.077	7-7
TOTAL	0.650	0.650	0.874	0.376	0.354	0.474	0.243	0.237	0.296	0.220	0.216	0.263	
PROGRAMMED (ONE-AXIS)													
- Positional Errors	0.012	0.229	0.230	0.012	0.229	0.230	0.012	0.229	0.230	0.012	0.229	0.230	7-2
- Pointing Errors	0.110	0.110	0.110	0.110	0.088	0.098	0.107	0.101	0.104	0.112	0.106	0.109	7-3
- Programming Error	0.143	-	0.143	0.143	-	0.143	0.143	-	0.143	0.143	-	0.143	7-5
TOTAL	0.265	0.339	0.483	0.265	0.317	0.471	0.262	0.330	0.477	0.267	0.335	0.382	
(TWO-AXIS)													
- Positional Errors	0.012	0.061	0.062	0.012	0.061	0.062	0.012	0.061	0.062	0.012	0.061	0.062	7-2
- Pointing Errors	0.110	0.110	0.110	0.110	0.088	0.098	0.107	0.101	0.104	0.112	0.106	0.109	7-3
- Programming Error	0.143	0.143	0.202	0.143	0.143	0.202	0.143	0.143	0.202	0.143	0.143	0.202	7-5
TOTAL	0.265	0.314	0.374	0.265	0.292	0.312	0.262	0.305	0.368	0.267	0.310	0.373	
STEP-TRACK													
- Pointing Errors	0.110	0.110	0.110	0.110	0.088	0.098	0.107	0.101	0.104	0.112	0.106	0.109	7-3
- Tracking Errors	0.444	0.444	0.444	0.222	0.222	0.222	0.111	0.111	0.111	0.089	0.089	0.089	7-6
TOTAL	0.554	0.554	0.554	0.332	0.310	0.320	0.218	0.212	0.215	0.201	0.195	0.198	

NOTES

(1) See Table 3.1 for antenna usage

(2) Estimates based on antenna concepts similar to that of Figure 7.1.

(3) Angular errors exceeded 0.01% of the time.

TABLE 8-1

d) Programming errors are assumed to be established separately for each axis and are therefore combined on a RSS basis.

e) Tracking errors (Auto-track) are assumed to be random uncorrelated and equi-valued between axes. Their magnitudes are therefore considered constant along any radial vector.

The column headed "maximum" in Table 8-1 is obtained by adding the orthogonal error contributions (under column headings "along" and "across" in accordance with these rules).

8.3 Manual Tracking Total Angular Errors

Manual tracking angular errors include these primary sources:

a) Pointing errors from the fact that, once the boresight has been manually established with the limits of (b) below, wind forces can distort the structure. (See Table 7-3)

b) Measurement errors resulting from the inability of the operator to accurately read peak AGC response in the presence of noise, fading, and meter resolution (see Table 7-4).

c) Allowance for deadband gain loss between antenna pointing adjustments (see Table 7-6).

We assume these contributions are added on a peak basis noting that only the positional errors are random variable with time. Deadband allowances being deliberate, is fixed while positional errors are random with setting-up procedures.

Note that the positional errors are identical for both along and across the tracking line, on the assumption that the antenna beam is circular.

8.4 Programmed Track Total Angular Errors

In programmed tracking, errors result from;

a) satellite positional errors (see Table 7-2)

b) Pointing errors (see Table 7-3)

c) programming errors (Table 7-5)

Maximum error contributions are added on a peak basis.

If a one-axis tracking scheme is used, then satellite positional errors across the line-of-track are greatly increased (see Sec. 7.2) but the errors could be reduced by manual offset adjustments. For a two-axis tracking system, errors across the line-of-track are reduced but basic tracking errors are increased. It may be seen that one effect partly compensates for the other.

For antennas with diameters of the order of 8 to 10 feet tracking errors are excessive and so there appears to be little benefit in programmed tracking for these categories, unless error estimates are unduly pessimistic.

8.5 Step-Track Total Angular Errors

Values in the tables are appropriate for a step-track system. In any auto-track, satellite positional errors are not significant, and for step-track no deadband need be provided. We have contributions from;

a) Antenna deformation (see Table 7-3)

b) Tracking error (see Sec. 7-7)

We include, for step track, the total wind effect since corrections only take place at specific step intervals.*

Again, contributions are added on a peak basis.

8.6 Antenna Gain Losses due to Angular Errors

The relationship between the antenna beamwidth and the antenna diameter has been given earlier in Figures 3-3 and 3-4 respectively. The effect of angular errors is to reduce the basic beamwidth to the effective beamwidth where effective beamwidth is defined as the angular separation between points on the antenna response curve corresponding to a defined gain reduction when the antenna's pointing error is included.

---

* In a cone-scan, or monopulse system, corrections can take place at any time. Thus better average performance may be expected.

8.6 (Cont'd)

Therefore,

$$\theta_E = \theta_B - 2\left|\sum \theta_i\right|$$

where;

θ_E = effective beamwidth

θ_B = basic beamwidth

$\sum \theta_i$ = sum of all the angular errors appropriate to the system under consideration.

Figures 8-1 to 8-3 relate effective beamwidths to antenna diameter for maximum gain reductions of 0.5 dB, 1 dB, 2 dB and 3 dB respectively for a frequency of 12 GHz. Figures 8-4 to 8-6 perform the same duties for a frequency of 14 GHz. The sets of curves are separately plotted for maximum tracking errors of $\pm 0.05^\circ$, $\pm 0.10^\circ$ and $\pm 0.15^\circ$ respectively. They are prepared from Figures 3-3 and 3-4 by subtracting tracking errors from basic beamwidths.

Using these figures, Figures 3-3 and 3-4, and Table 8-1*, we can determine the effective tracking loss in dB for the models. These are given in Tables 8-2 and 8-3 for 12 GHz and 14 GHz respectively. The tabulated losses are those which should be used in system's calculations to allow for losses due to tracking that are not exceeded 99.99% of the time.

---

* We interpolate between the curves where necessary.

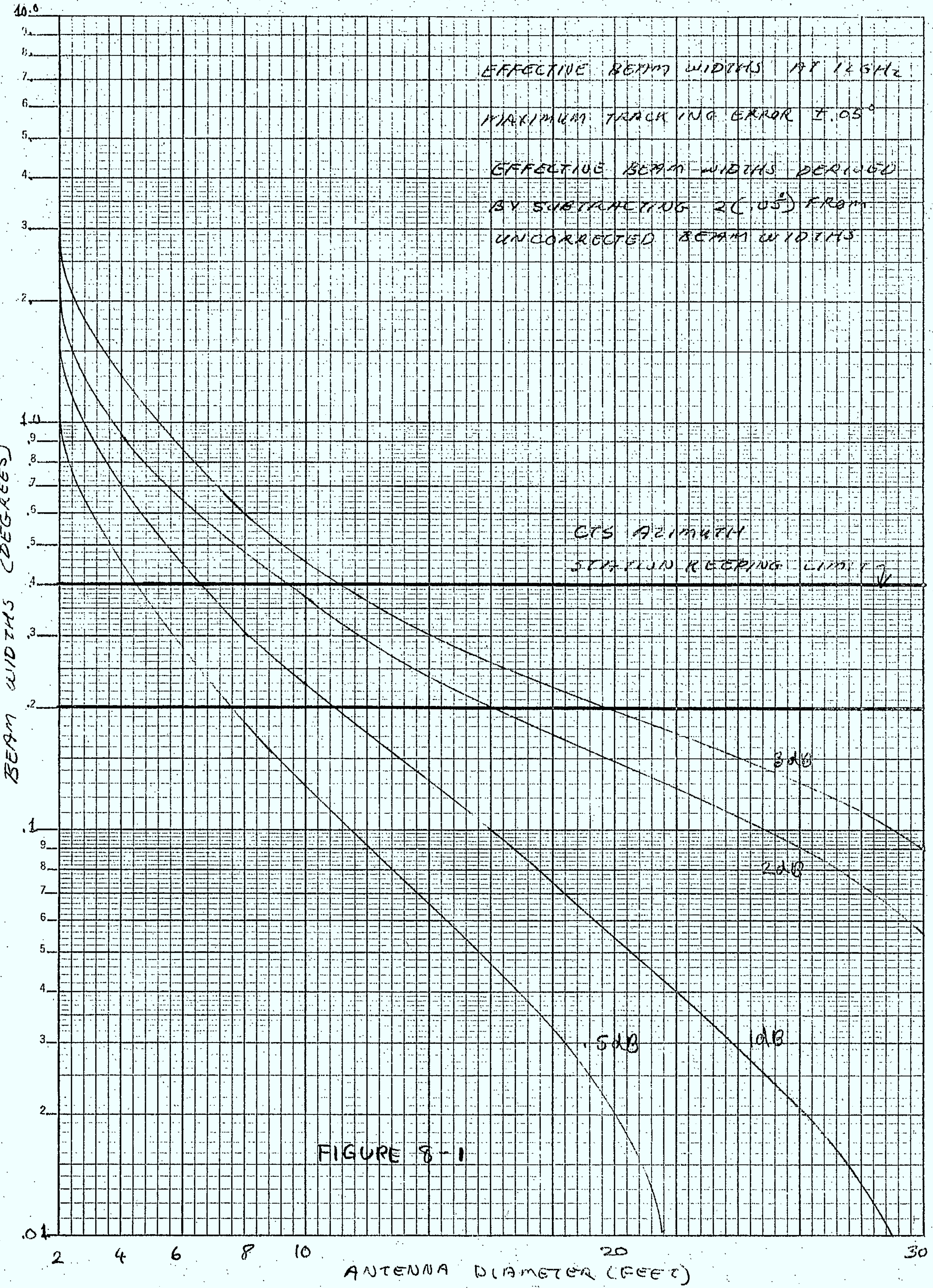

EFFECTIVE BEAM WIDTHS AT 12 GHz
MAXIMUM TRACKING ERROR ±.05°
EFFECTIVE BEAM WIDTHS DERIVED
BY SUBTRACTING 2(.05°) FROM
UNCORRECTED BEAM WIDTHS
CTS AZIMUTH
STATION KEEPING LIMIT
3dB
2dB
1dB
.5dB
BEAM WIDTHS (DEGREES)
ANTENNA DIAMETER (FEET)
10.0
1.0
.1
.01
2
4
6
8
10
20
30

FIGURE 8-1

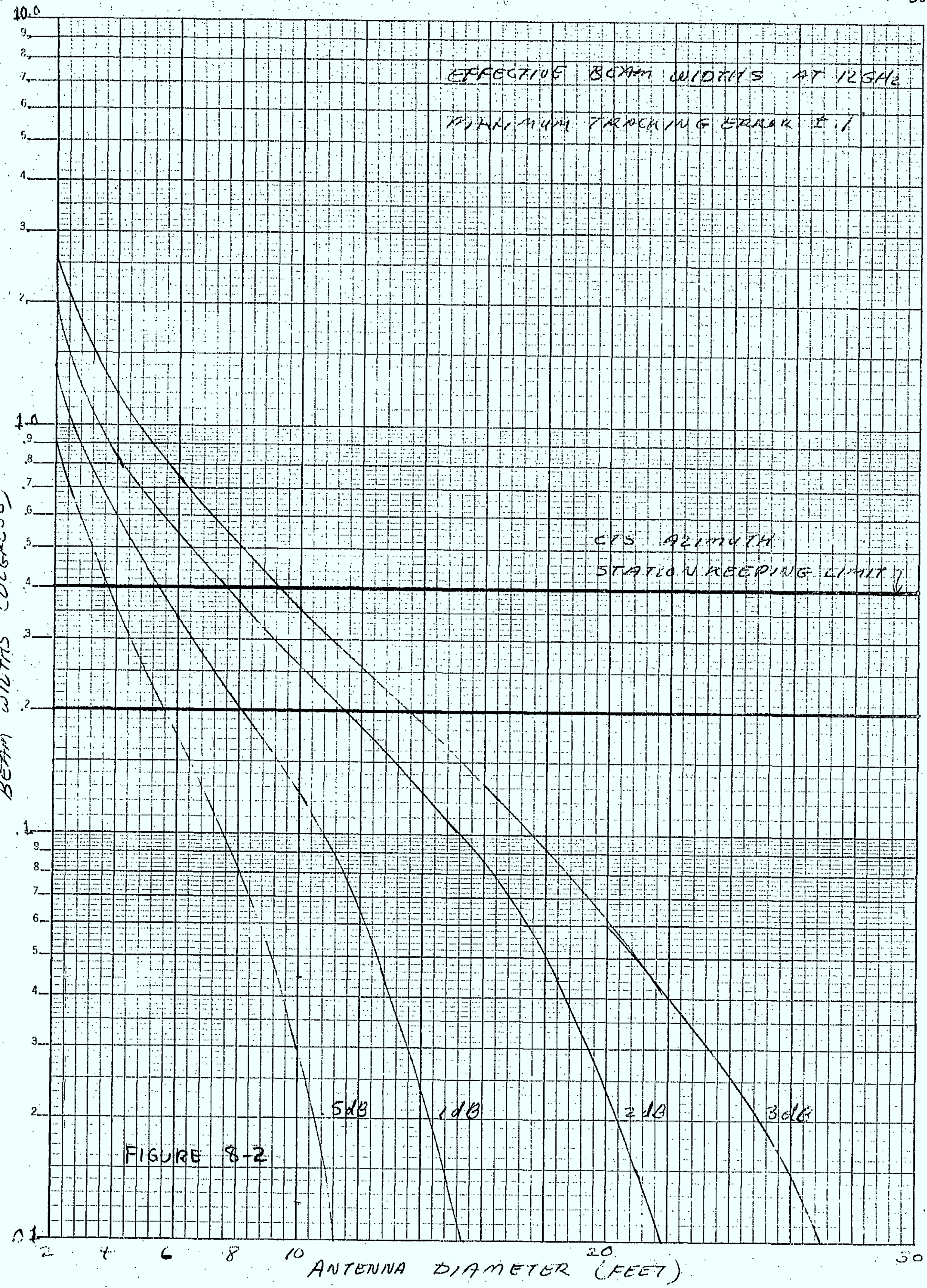

EFFECTIVE BEAM WIDTHS AT 12GHz
MINIMUM TRACKING ERROR ± /
CTS AZIMUTH
STATION KEEPING LIMIT
.5dB
1dB
2dB
3dB
BEAM WIDTHS (DEGREES)
ANTENNA DIAMETER (FEET)
10.0
1.0
.1
.01
2
4
6
8
10
20
30

FIGURE 8-2

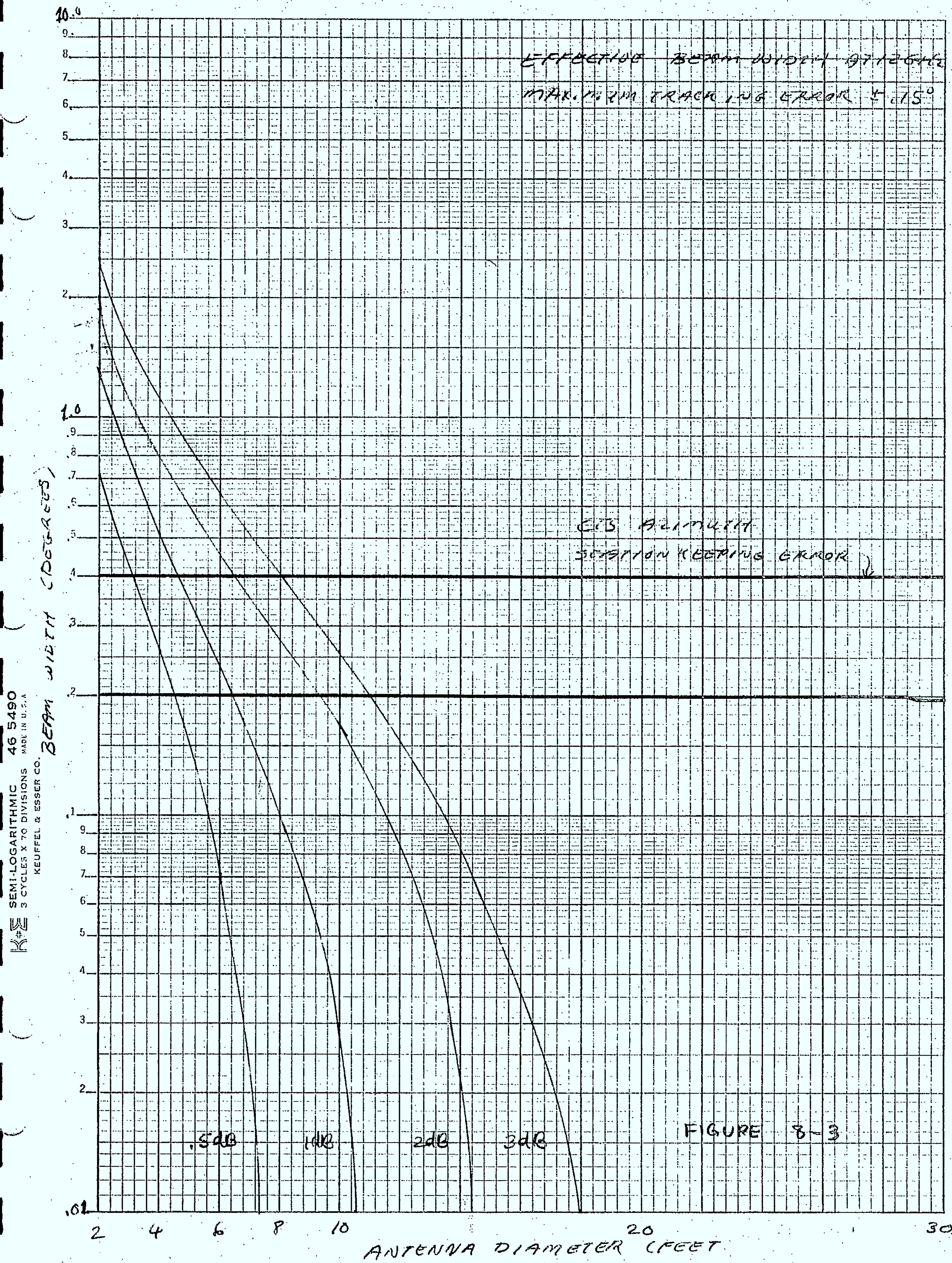

EFFECTIVE BEAM WIDTH
TRACKING ERROR ±.15°
AZIMUTH
STATION KEEPING ERROR
.5dB
1dB
2dB
3dB
BEAM WIDTH (DEGREES)
ANTENNA DIAMETER (FEET)
SEMI-LOGARITHMIC 46 5490
3 CYCLES X 70 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.

FIGURE 8-3

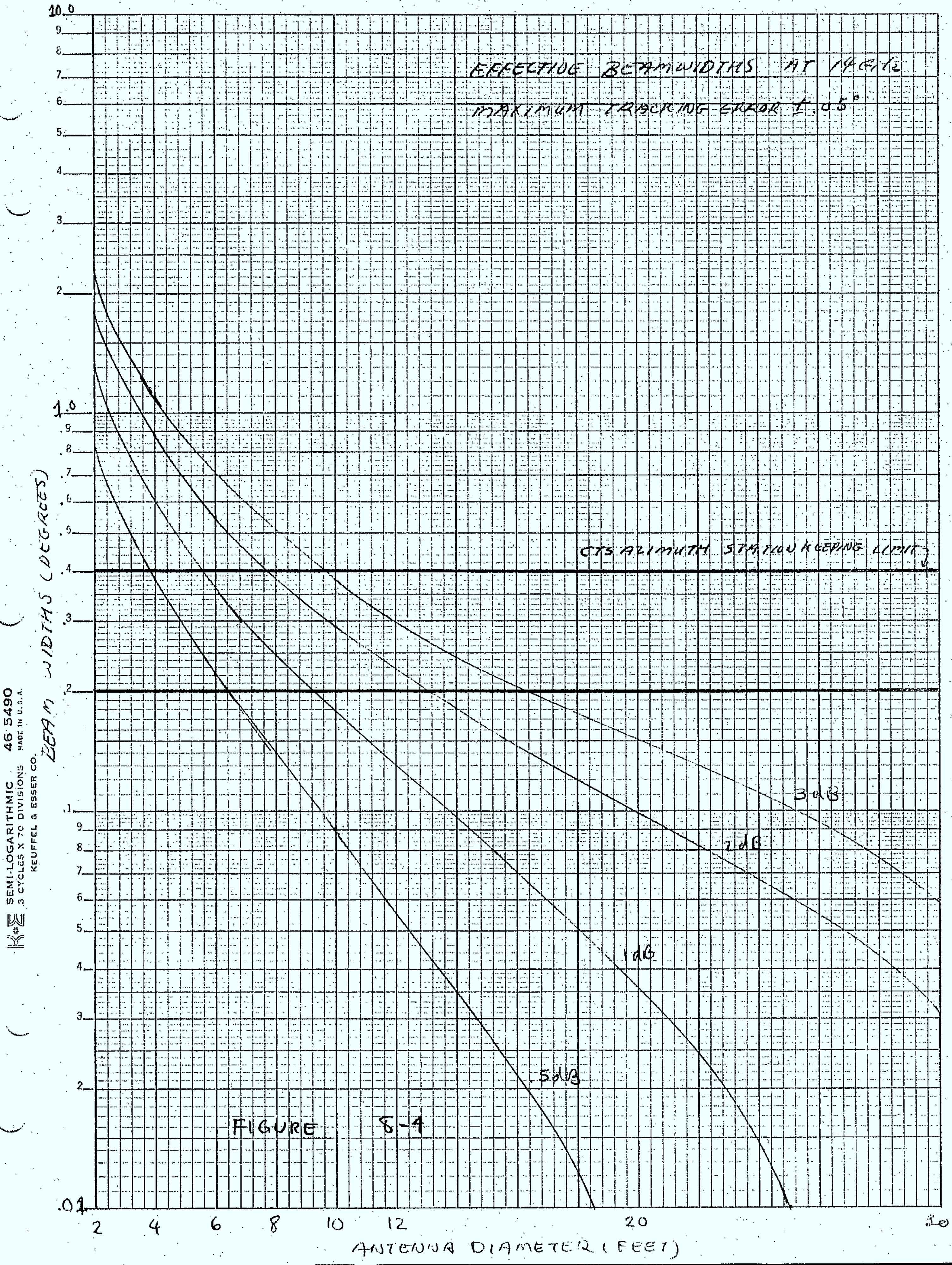

EFFECTIVE BEAMWIDTHS AT 14GHz
MAXIMUM TRACKING ERROR ±.05°
CTS AZIMUTH STATION KEEPING LIMIT
3dB
2dB
1dB
.5dB
BEAM WIDTHS (DEGREES)
ANTENNA DIAMETER (FEET)
SEMI-LOGARITHMIC 46 5490
3 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO.

FIGURE 8-4

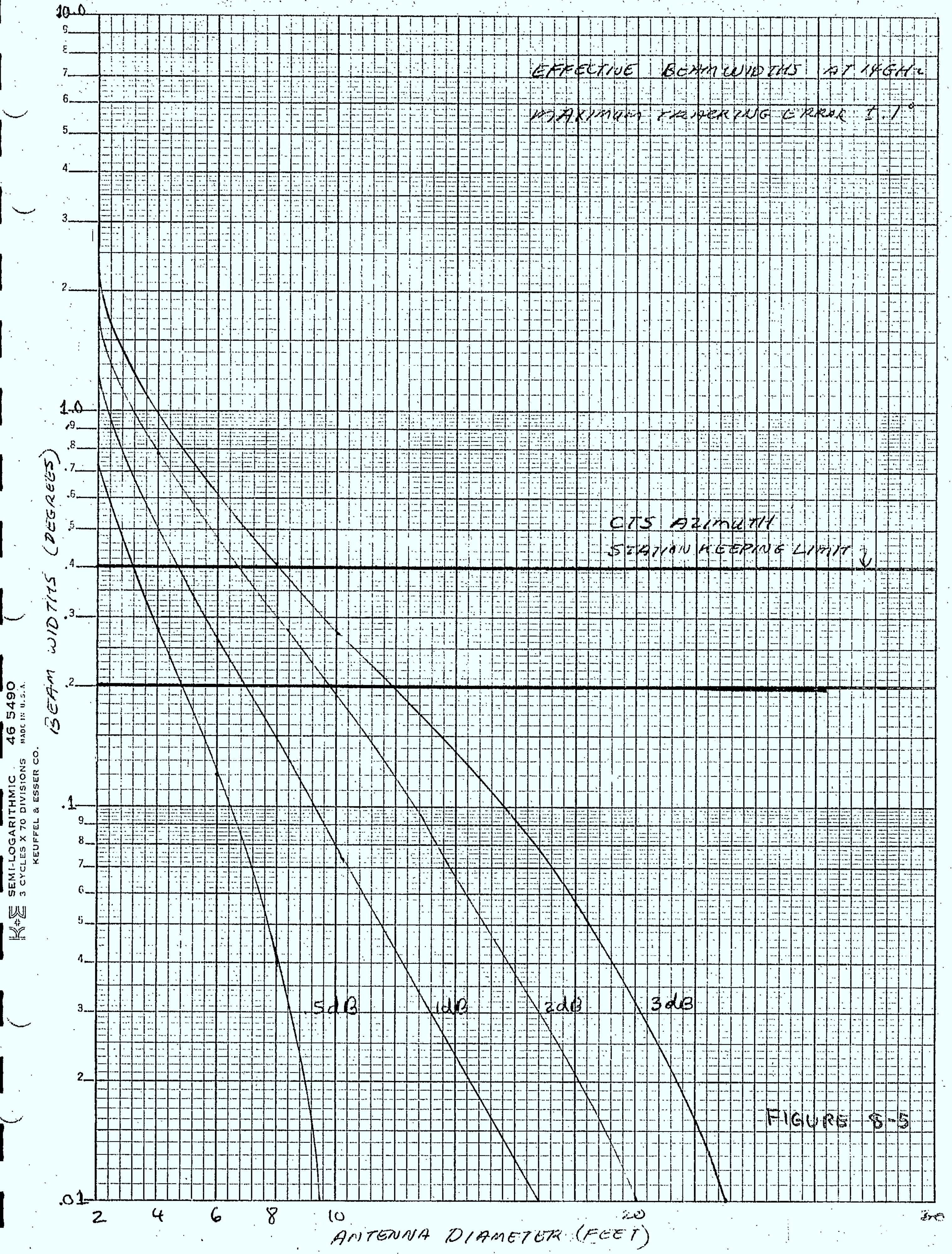

EFFECTIVE BEAMWIDTHS AT 14GHz
MAXIMUM TRACKING ERROR ± .1°
CTS AZIMUTH
STATION KEEPING LIMIT
.5dB
1dB
2dB
3dB
BEAM WIDTHS (DEGREES)
ANTENNA DIAMETER (FEET)
10.0
1.0
.1
.01
2
4
6
8
10
20
K+E SEMI-LOGARITHMIC 46 5490
3 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO.
MADE IN U.S.A.

FIGURE 8-5

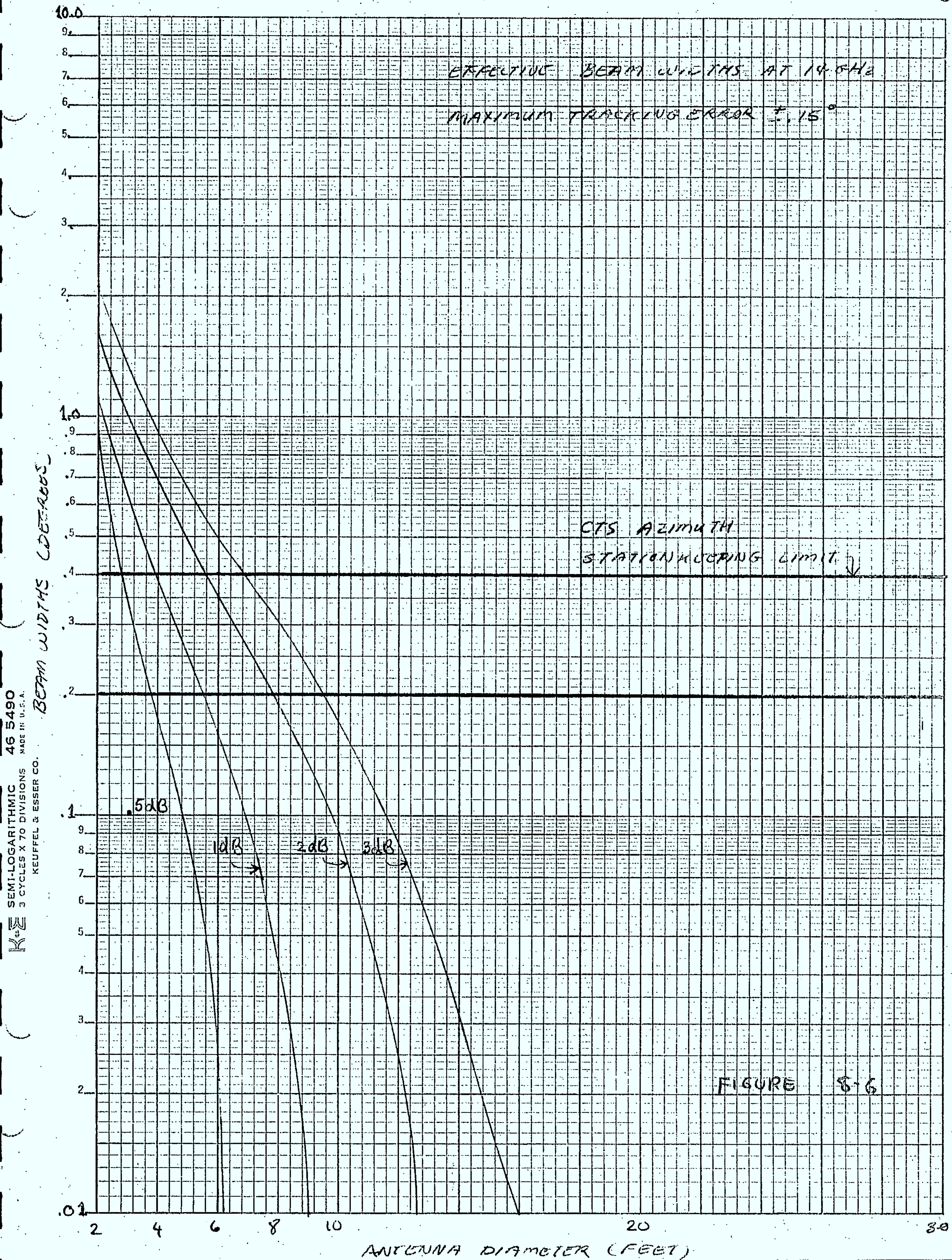

EFFECTIVE BEAM WIDTHS AT 14 GHz
MAXIMUM TRACKING ERROR ±.15°
CTS AZIMUTH
STATIONKEEPING LIMIT
.5dB
1dB
2dB
3dB
BEAM WIDTHS (DEGREES)
ANTENNA DIAMETER (FEET)
10.0
1.0
.1
.01
2
4
6
8
10
20
30
SEMI-LOGARITHMIC
3 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO.
46 5490
MADE IN U.S.A.

FIGURE 8-6

ESTIMATED TRACKING LOSS AT 12 GHZ

Tracking System	EFFECTIVE TRACKING LOSS AT 12 GHz							
	2 Ft. Antenna		4 Ft. Antenna		8 Ft. Antenna		10 Ft. Antenna	
	Maximum Error (Degrees)	Tracking Loss (dB)	Maximum Error (Degrees)	Tracking Loss (dB)	Maximum Error (Degrees)	Tracking Loss (dB)	Maximum Error (Degrees)	Tracking Loss (dB)
Manual	±0.874	1.4	±0.474	1.5	±0.296	2.1	±0.263	2.7
Programmed One-Axis	±0.483	< 0.5	±0.471	1.5	±0.477	> 3.0	±0.382	> 3.0
Two-Axis	±0.374	< 0.5	±0.312	0.6	±0.368	≈ 3.0	±0.373	> 3.0
Step-Track	±0.554	0.5	±0.320	0.7	±0.215	1.2	±0.198	1.6

NOTE: Tracking Loss exceeded 0.01% of the time.

TABLE 8-2

ESTIMATED TRACKING LOSS AT 14 GHZ

Tracking System	EFFECTIVE TRACKING LOSS AT 14 GHz							
	2 Ft. Antenna		4 Ft. Antenna		8 Ft. Antenna		10 Ft. Antenna	
	Maximum Error (Degrees)	Tracking Loss (dB)	Maximum Error (Degrees)	Tracking Loss (dB)	Maximum Error (Degrees)	Tracking Loss (dB)	Maximum Error (Degrees)	Tracking Loss (dB)
Manual	± 0.874	1.7	± 0.474	1.8	± 0.296	2.9	± 0.263	>3.0
Programmed One-Axis	± 0.483	0.6	± 0.471	1.8	± 0.477	>3.0	± 0.382	>3.0
Two-Axis	± 0.374	<0.5	± 0.312	0.8	± 0.368	>3.0	± 0.372	>3.0
Step-Track	± 0.554	1.4	± 0.320	0.9	± 0.215	1.6	± 0.198	2.0

NOTE: Tracking Loss exceeded 0.01% of the time

TABLE 8-3

SECTION 9

DEVELOPMENT COST ESTIMATES

9-1 General

A breakdown of the equipment and engineering costs required for the various CTS terminals, with the exception of the Ottawa Control Station, is shown in Table 9-1. The breakdown is purely arbitrary, but does serve to compare the complexity and costs of the different approaches. The cost estimates are based on our judgement of complexity, possible "off-the-shelf" availability and an attempt to estimate development effort. A more accurate estimate would require preparation of detailed specifications and detailed planning of design, manufacturing and procurement tasks and is beyond the scope of this study. The following general comments apply to the table entries and provide some understanding of our selection of antenna and tracking options.

9-2 Radio Receive and 2-Way Voice Terminal Antenna Development Costs

Both terminals are simple, * the first has fixed pointing and the second requires manual tracking. The cost of production units would be considerably lower. A value engineering study would show how design of simpler reflectors, feeds and positioners could be achieved and this effort is recommended because of potential large quantity requirements.

9-3 TV Receive Only Antenna Development Costs

These terminals are also likely to be required in quantity and this is a significant factor in selecting the preferred tracking methods. Single Axis Program Tracking by a constant speed motor driven mechanically programmed antenna is feasible provided that a constant frequency a.c. power source is available. The cost of the pedestal base and positioner head should be easily reducable on a production basis.

* We refer to the antenna, tracking and mount requirements only.
The electronics for 2-way voice terminals is rather complex.

ESTIMATED ANTENNA AND TRACKING SYSTEM DEVELOPMENT COSTS (DOLLARS)

Item	Radio Receive	2-way Voice	TV Receive			Mobile Terminal				Source of Estimate	Comments
	Fixed Track	Manual Track	One-Axis Programmed	Two-Axis Programmed	Step Track	Manual Track	Two-Axis Programmed	Step Track	Cone Scan		
1 Pedestal Base	100	500	1,000	1,000	1,000	500	500	500	500	RCA Eng.	
2 Positioner Head	50	500	2,000	2,000	2,000	5,000	5,000	5,000	5,000	RCA Eng.	
3 Pos. Synchros				*	1,000		1,000	1,000	1,000	Scientific Atlanta	* Req'd if Item 13 fitted
4 Pos. Linear Pot.				200		200			--	RCA Eng.	Not req'd if Items 3 & 13 fitted
5 Comparators & Drivers				500			500			RCA Eng.	
6 Pos. Ind. Unit				500	1,000	500		1,000	1,000	RCA & Scientific Atlanta	Lower cost unit is now synchro
7 Error Detector 8 Logic Electronics					{10,000}			{10,000}	{7,000}	*RCA Earth Station Eng.	*Based on costs for Telesat Earth Station.
9 Sidereal Clock				300			300			RCA Eng.	
10 Sine-Cos Pots				500			500			RCA Eng.	
11 Reg. Pur Supply				300	300		300	300	300	RCA Eng.	
12 Bias Pots				50			50			RCA Eng.	
13 Digital Pos. Ind.				*	*	*	5,300	*	*	Scientific Atlanta	*Optional instead of Item 6
14 Motor Relays			60	60	60	60	60	60	60	RCA Eng.	
15 Linear Actuators				200	200	200	200	200	200	Saginaw Steering Gear	
16 Drive Motor			200							RCA Eng.	
17 Gear Box			250		500			500	500	RCA Eng.	
18 Cam			75							RCA Eng.	
19 Feed	750	750	1,500	1,500	1,500	1,500	1,500	1,500	2,000	Scientific Atlants	
20 Reflector	300	750	1,000	1,000	1,000	1,500	1,500	1,500	1,500	Various	
21 Manual cont. panel							1,000		1,000	RCA & Scientific Atlanta	
22 Tracking cont. unit							1,000	1,500	1,500	RCA & Scientific Atlanta	
Total recurring cost	1,200	2,500	6,085	8,110	18,560	10,460	18,710	23,060	20,560		Basic Antenna, mount & drive
Non-rec. Engineering dev.	5,500	6,500	15,500	24,000	24,000	24,000	35,000	35,000	39,000		
Non-rec. systems & Interface activity	500	1,000	1,500	3,000	3,000	1,000	5,000	5,000	5,000		
Antenna development						14,000	14,000	14,000	14,000	Plastal Budgetary Estimate	For Mobile Unit Only
Approx total *	7,200	10,000	23,085	35,110	45,560	49,460	72,710	77,060	78,560		1st Unit

* Costs Data at Engineering Level Only. G & A, taxes (as applicable), and profits extra.

TABLE 9-1

Two-axis Tracking is not recommended because of the rather complex installation and alignment problems. The estimated costs do not include such installation on alignment entries.

Step-Track eliminates many of the problems of program tracking. It would be comparatively expensive for small quantity production but with mass produced electronic black boxes and design of actuators with cam driven limit switches the cost should be comparable to programmed tracking. We strongly recommend that a design aimed for low cost step-track systems * be developed as part of the CTS experimental program.

Manual Track is not considered acceptable for the TV receive only station except that on a purely experimental basis a remote control manual tracking system could be considered. (See, in particular Sec 2.2). Costs are not given in the table but are estimated to be about $17,000 recurring and $7,500 non-recurring.

9 - 4 Mobile Terminal Antenna Development Costs

This terminal has many practical tracking concepts for consideration. A significant factor is the cost of development of a segmented fibreglass antenna (ref 2). It is possible that an already developed dismountable 10 foot reflector could be found or a refined system analysis might indicate that an 8 foot integral antenna reflector might be suitable. The smaller antenna would also ease the tracking problem because of its wider beamwidth.

The mobile terminal's engine generator set would not provide a good frequency reference for a synchronous motor drive. However, for short operating periods it might permit use of the simple mechanically programmed drive, with occasional phasing correction.

If a very low cost scheme is desired Manual Track only can be provided. This would be remotely controlled manual tracking, with remote indication of relative antenna position, so that maintenance of the antenna on track should not be too difficult.

* As noted in the preceding section, a cone-scan system using electronic beam switching also offers great potential. We therefore extend our recommendations to include cone-scan development.

Cone-scan is potentially a low cost tracking system, when built in production quantities. Conventional Auto Track would come down in price somewhat in production quantities too but does not seem to be a justifiable approach for any of the ground terminals. Production of large numbers of mobile terminals is unlikely, but either Step-Track or Conical-Scan could be attractive if used on some of the other terminals too.

Table 9-2 has been prepared to show the costs for development of the tracking facility for antenna and positioner which are additional to those estimated in ref. 2 where a manual tracking concept was assured.

ESTIMATED COST OF ADDING TRACKING TO MOBILE UNIT

(DOLLARS)

ENTRY	TRACKING OPTION COSTS			NOTES
	Programmed Track	Step Track	Cone Scan	
Basic Estimate	72,710	77,060	78,560	From Table 9-1
Less:				
Antenna Estimate	32,500	32,500	32,500	From Ref. 2, Table M-3
Mount Estimate	13,600	13,600	13,600	From Ref. 2, Table M-4
Cost of Adding Tracking	26,610	31,960	32,460	Assuming Mount and Antenna available
Plus:				
Additional Interfacing	5,000	5,000	5,000	
Additional Costs	31,610	36,960	37,460	To be added to Basic Mobile Unit Antenna and Mount Costs

NOTES: Cost Data at Engineers level only
G & A, taxes (as applicable) and profits extra.

TABLE 9 - 2

SECTION 10

REFERENCES

Ref.	Description

1. J. A. Stovman

   "Basic Communications System Model for SHF Experiments, Revision 2" September 1971, report prepared for Communications Research Center.

2. J. A. Stovman and D. McClintock

   Final Report on "An Investigation of TV Mobile Terminals Requirements for the CTS Communications Experimental Program" prepared under Contract PL 36001-1-2208, Serial No. OPLI-01481, July 1972.

3. N. N. Tom

   "Autotracking of Communication Satellites by the Step-Track Technique" Paper given at the Conference on Earth Station Technology, 14-16 October, 1970, by the Institute of Electrical Engineers, Savoy Place, London, England.

4. K. S. McCormick and L. A. Maynard

   "Low Angle Tropospheric Fading in Relation to Satellite Communications and Broadcasting". Paper #12E International Conference on Communications, June 14-16, 1971, Montreal, Canada sponsored by the IEEE.

5. R. R. Newton

   "Astronomy for the Non-Astronomer", IRE Transactions on Space Electronics and Telemetry, March 1960.

Ref.	Description

6. W. C. Nelson and E. E. Loft
"Space Mechanics" Prentice Hall, 1962.

7. R. H. Greene
"Test Plan for Maintaining ATS-3 within an Antenna Beamwidth", IBM Report No. TM-68-51 prepared for NASA under contract NAS 5-10022, December 1968.

8. M. B. Tamburro, A. S. Abbott and G. E. Townsend
"Guidance, Flight Mechanics and Trajectory Optimization" NASA Contractor Report, NASA CR-1000, February, 1968 prepared by North American Aviation Inc., under contract NAS 8-11495.

9. "Auto-Track Simulation Results", Report submitted to Telesat Canada by RCA Limited. The results of a computor simulation program on wind effects on an antenna structure using step-track as summarised.

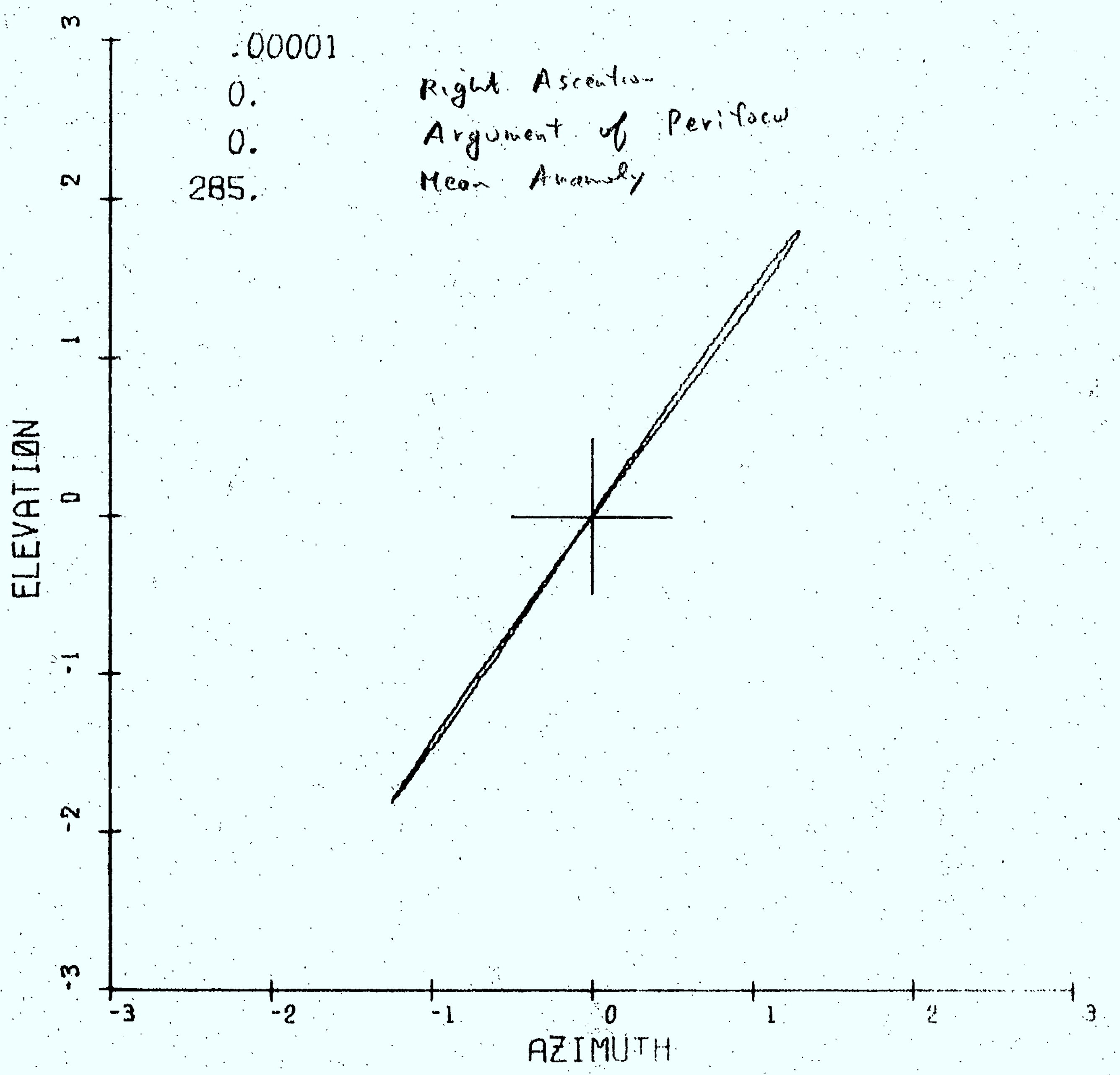
10 Microwave Engineer's Handbook - 1966.

11 J. Stovman to K. Farrell, RCA Limited, Internal Memorandum, September 17, 1971, revised February 24, 1972.
"A Note on Frequency Stability - CTS Communications Experimental Program".

Ref.	Description
12	CRC Document SY 01-04, 30 May, 1972. Configuration Control Baseline Document - Spacecraft.
13	W. M. Evans to V. E. Lapins CTS Mission Outline - Revision 2 CRC Internal Memorandum, 7 July, 1971, File CRC 6666-6-3 (NSTL) Program.
14	CRC Document SY 01-02, 13 December, 1971 Requirements, Spacecraft.
15	Program COMMIA developed by RCA Limited for CRC. This program computes Communications Experiment performance with respect to thermal noise for the CTS program.

APPENDIX A

Computer plots of CTS motions as seen by an observer at Ottawa (Generated at the Communications Research Center at Shirley Bay, Ontario).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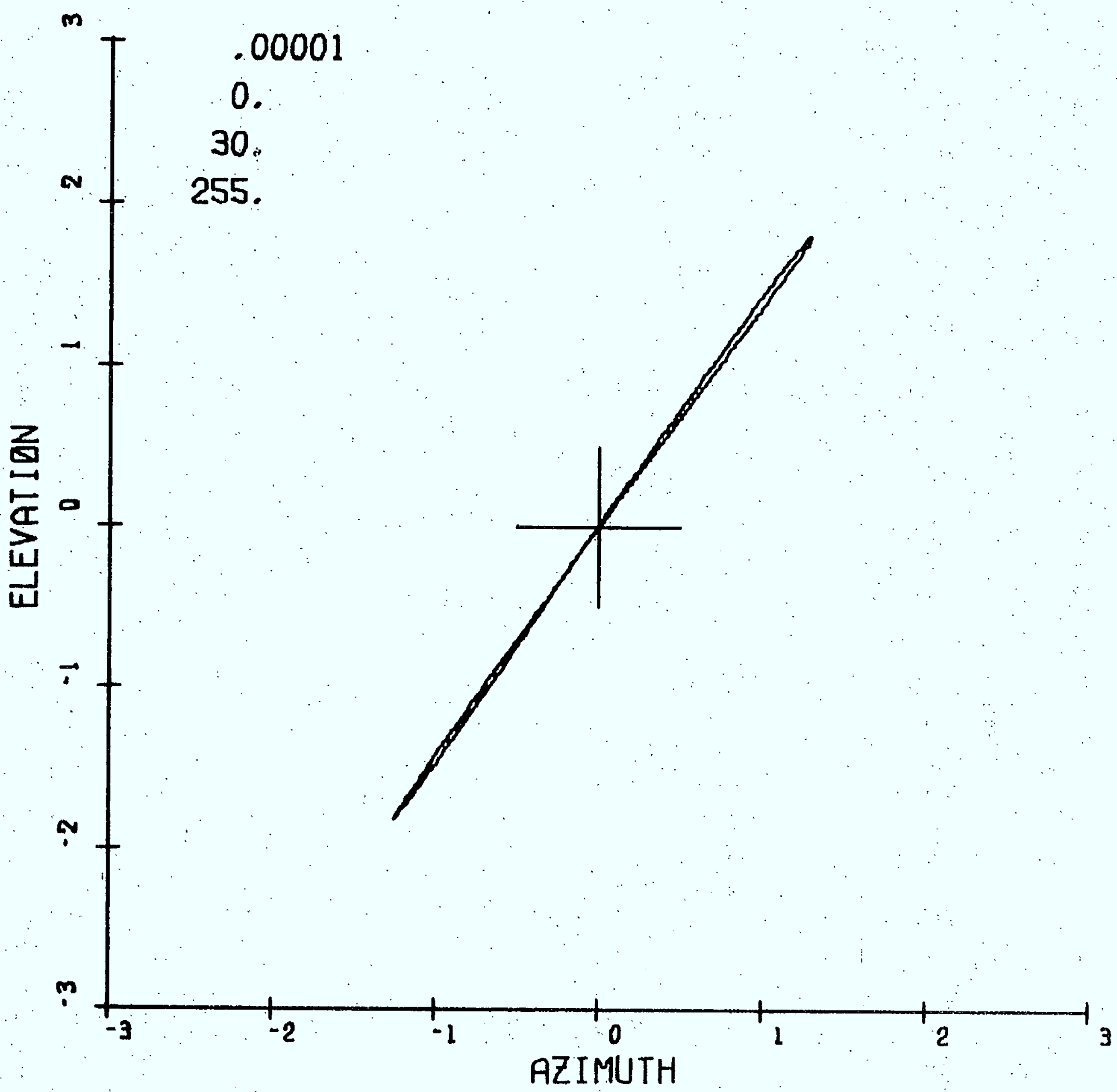
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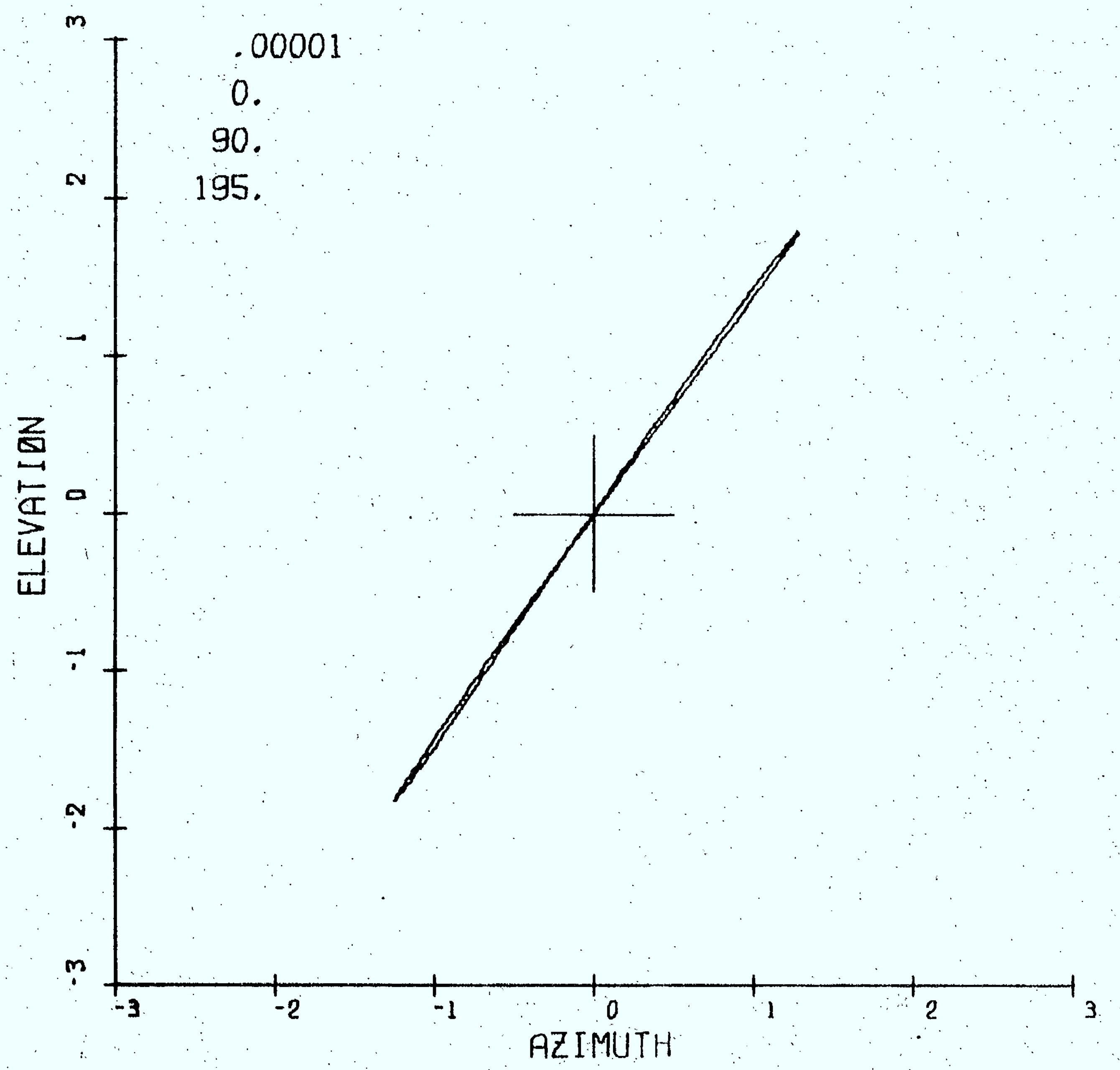
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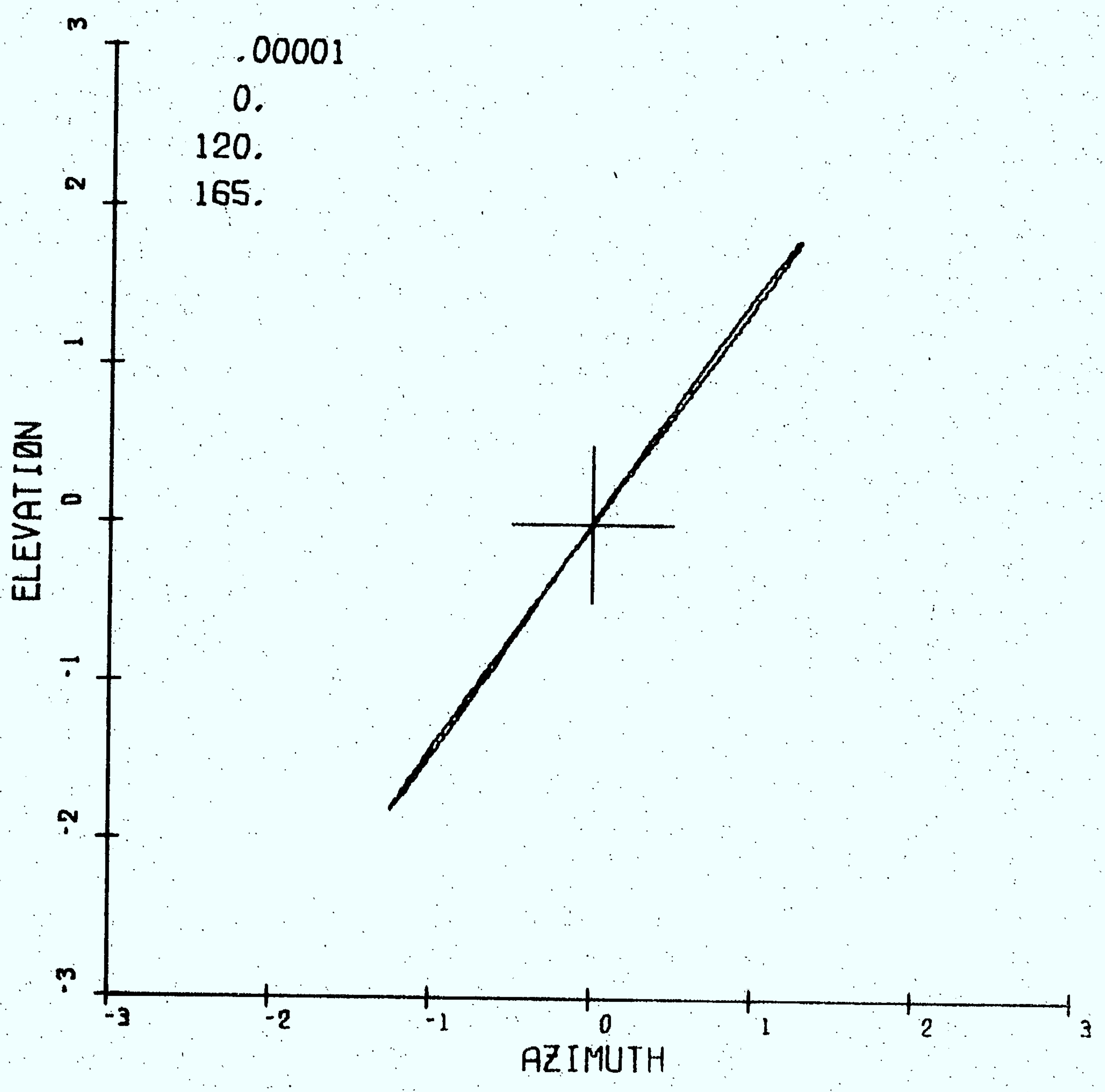
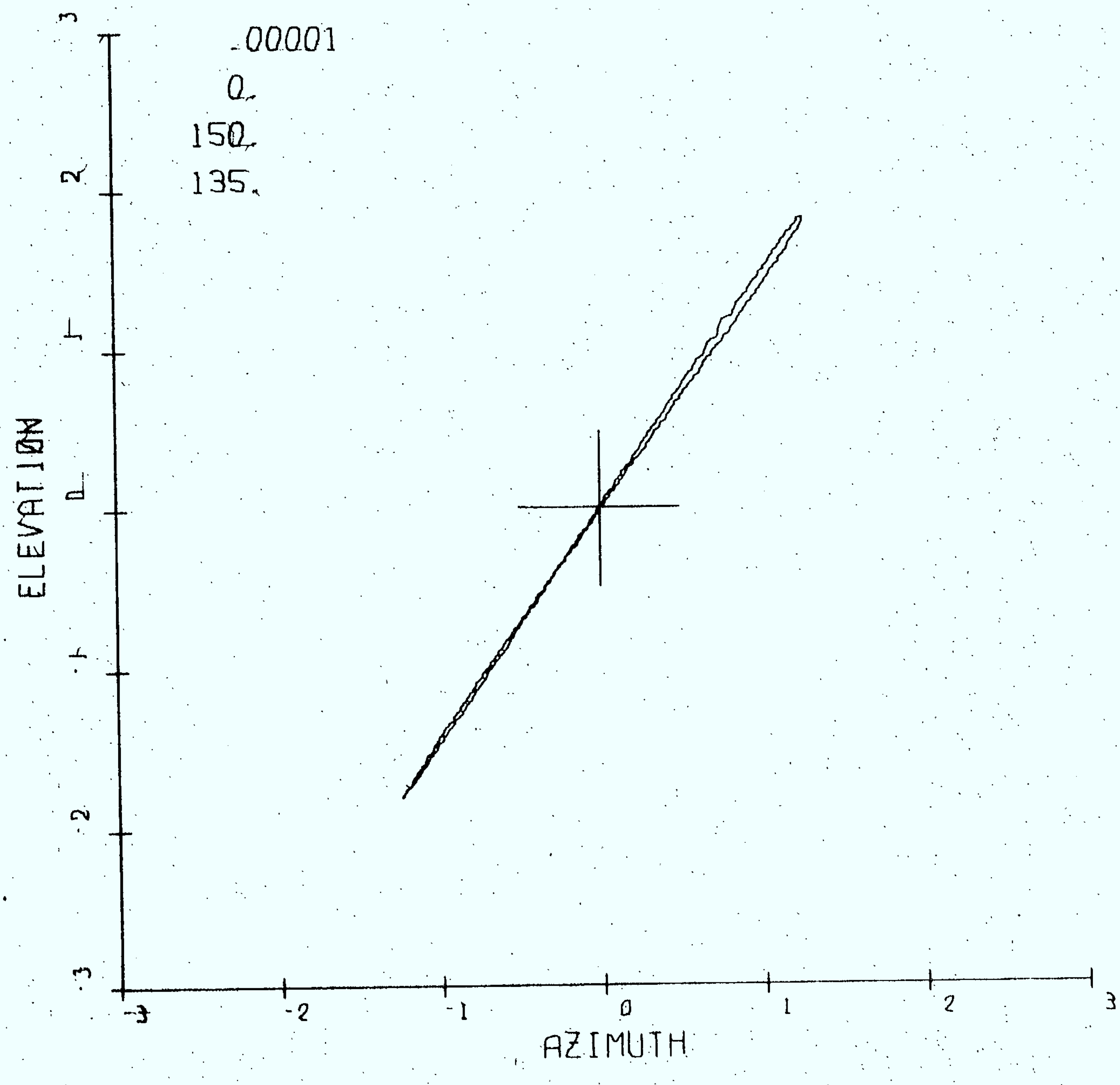
2
3



.00001
0.
120.
165.
ELEVATIØN
3
2
1
0
-1
-2
-3
AZIMUTH
-3
-2
-1
0
1
2
3



.00001
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150.
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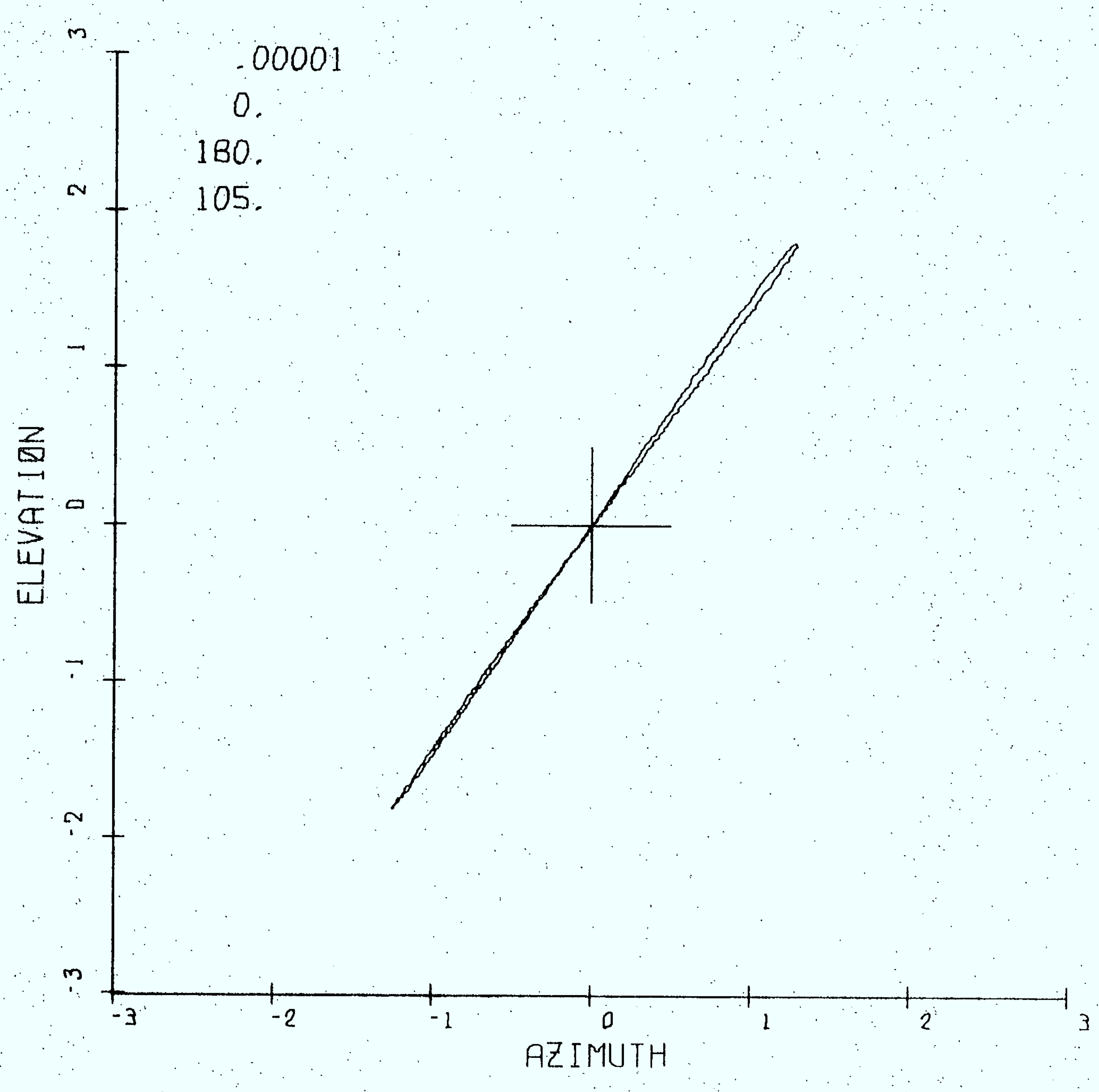
ELEVATION
AZIMUTH
-3
-2
-1
0
1
2
3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0.
180.
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ELEVATIØN
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2
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0
-1
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-3
-3
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-1
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1
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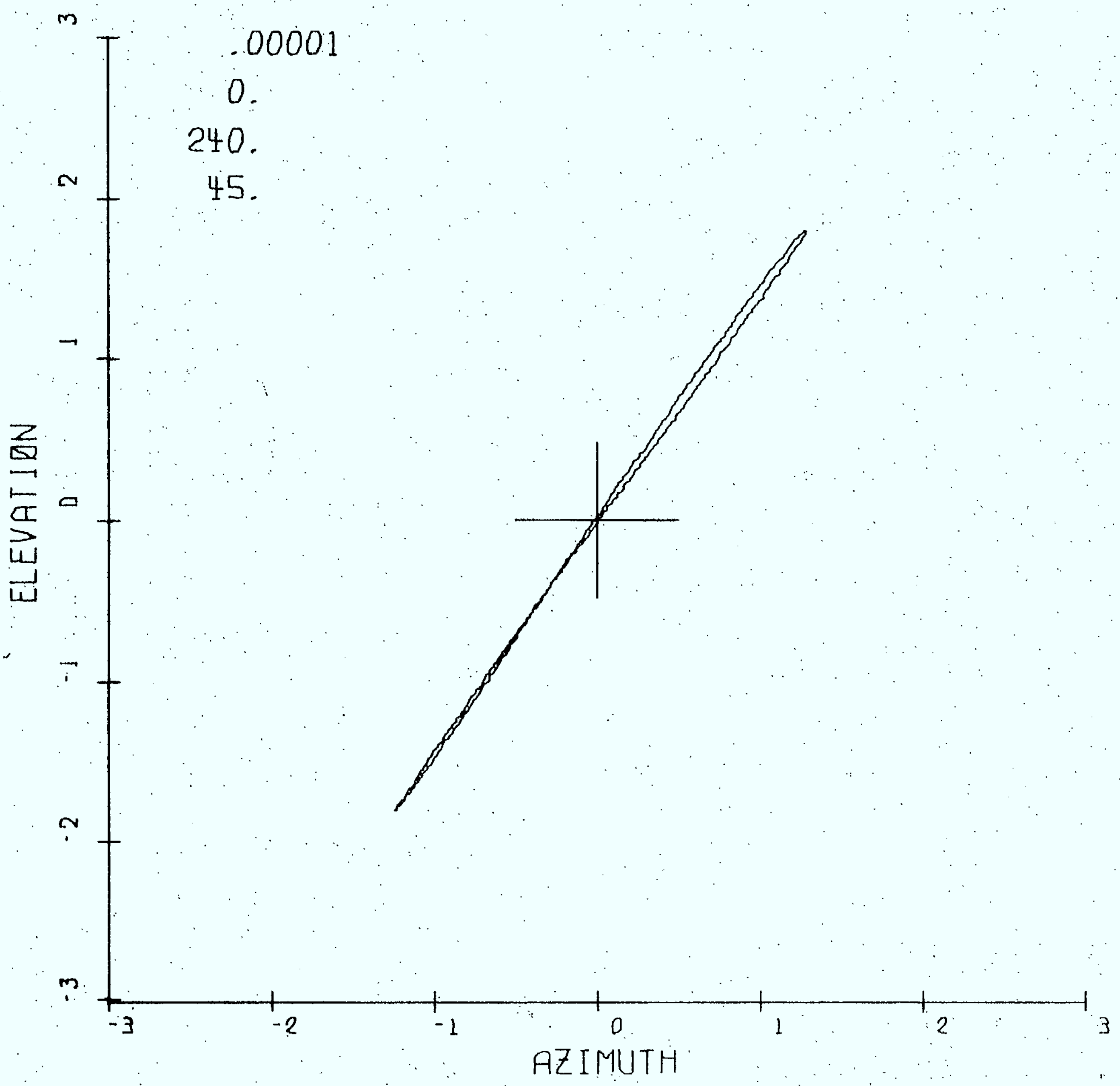
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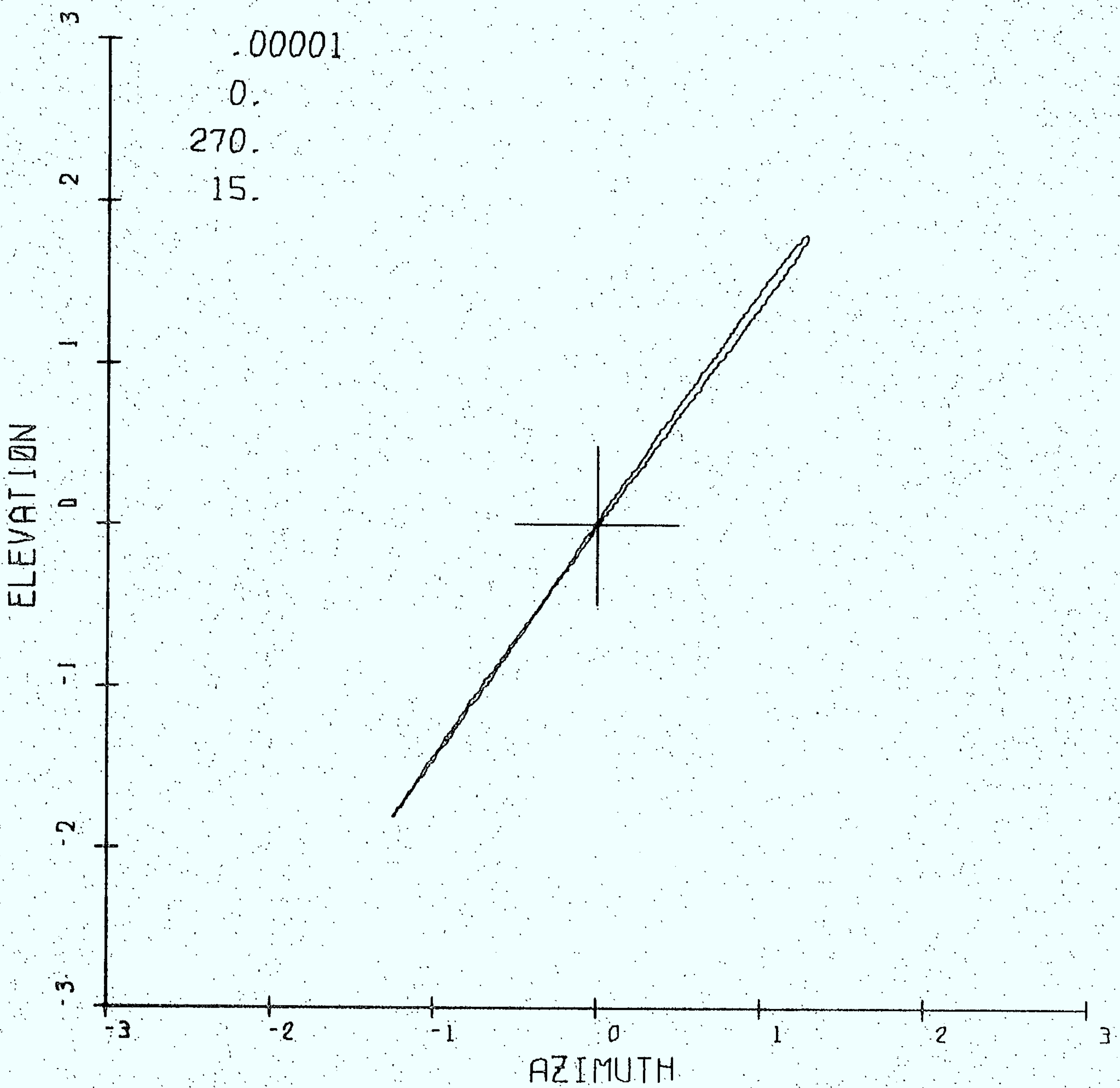

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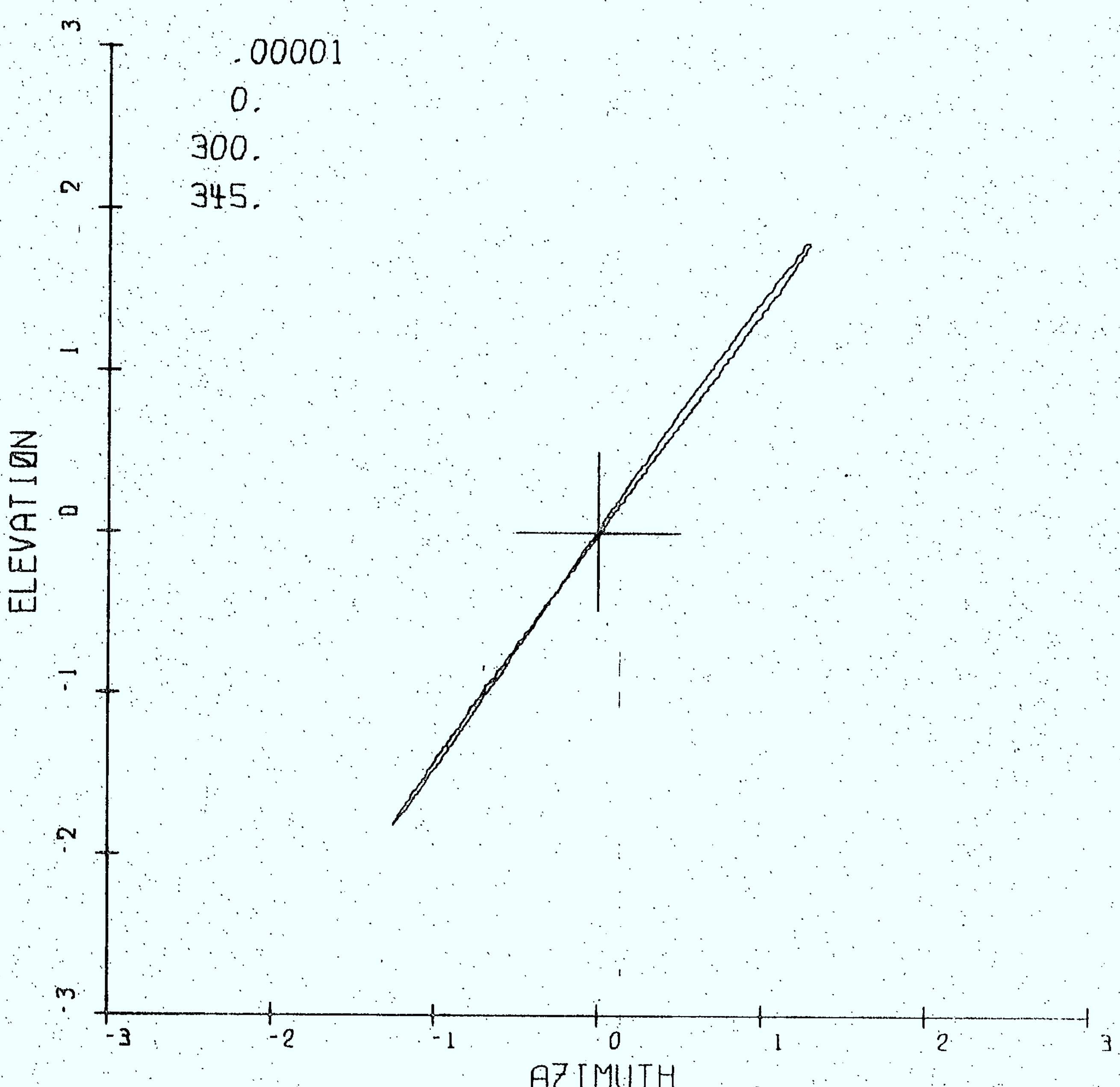
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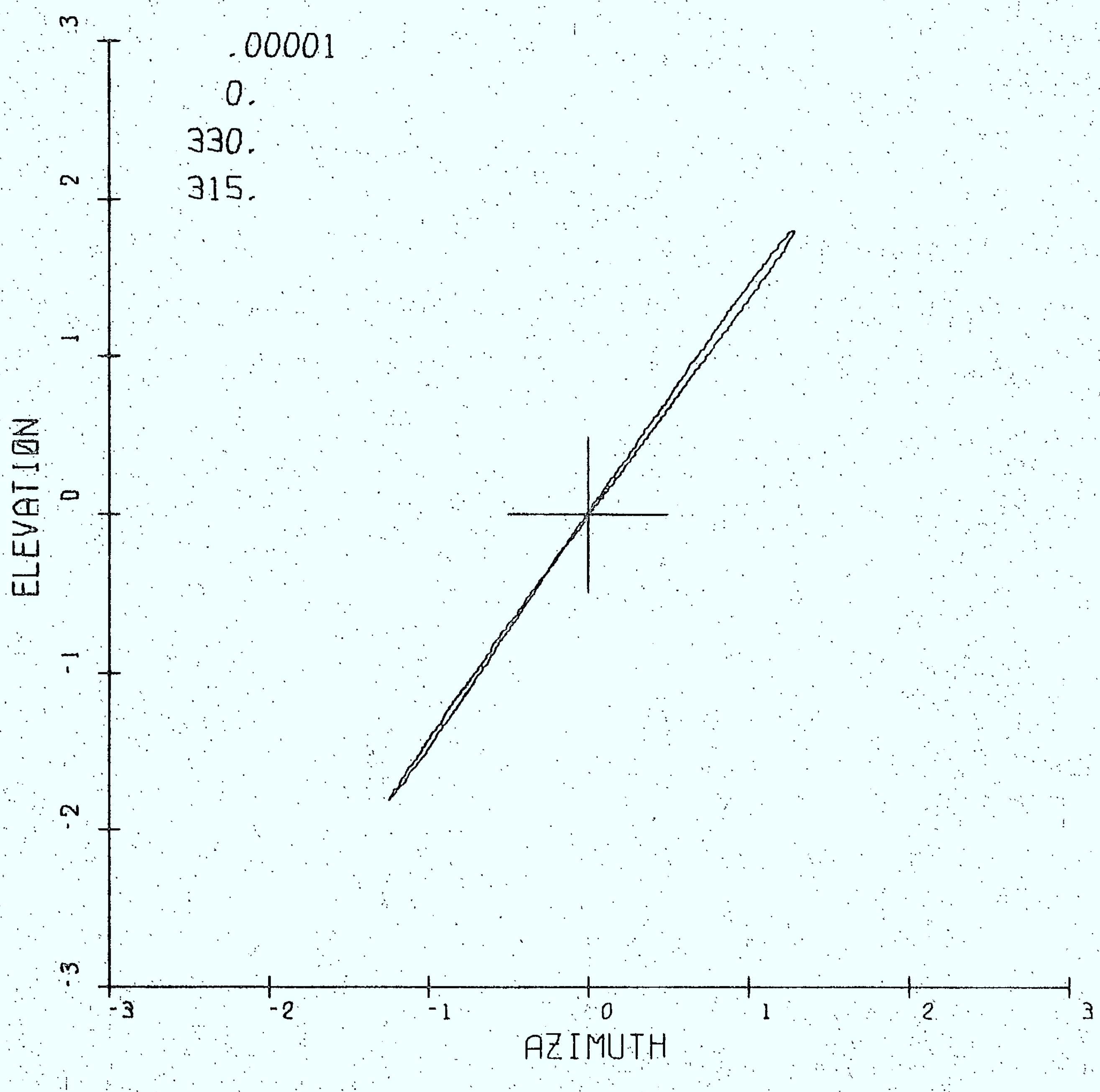
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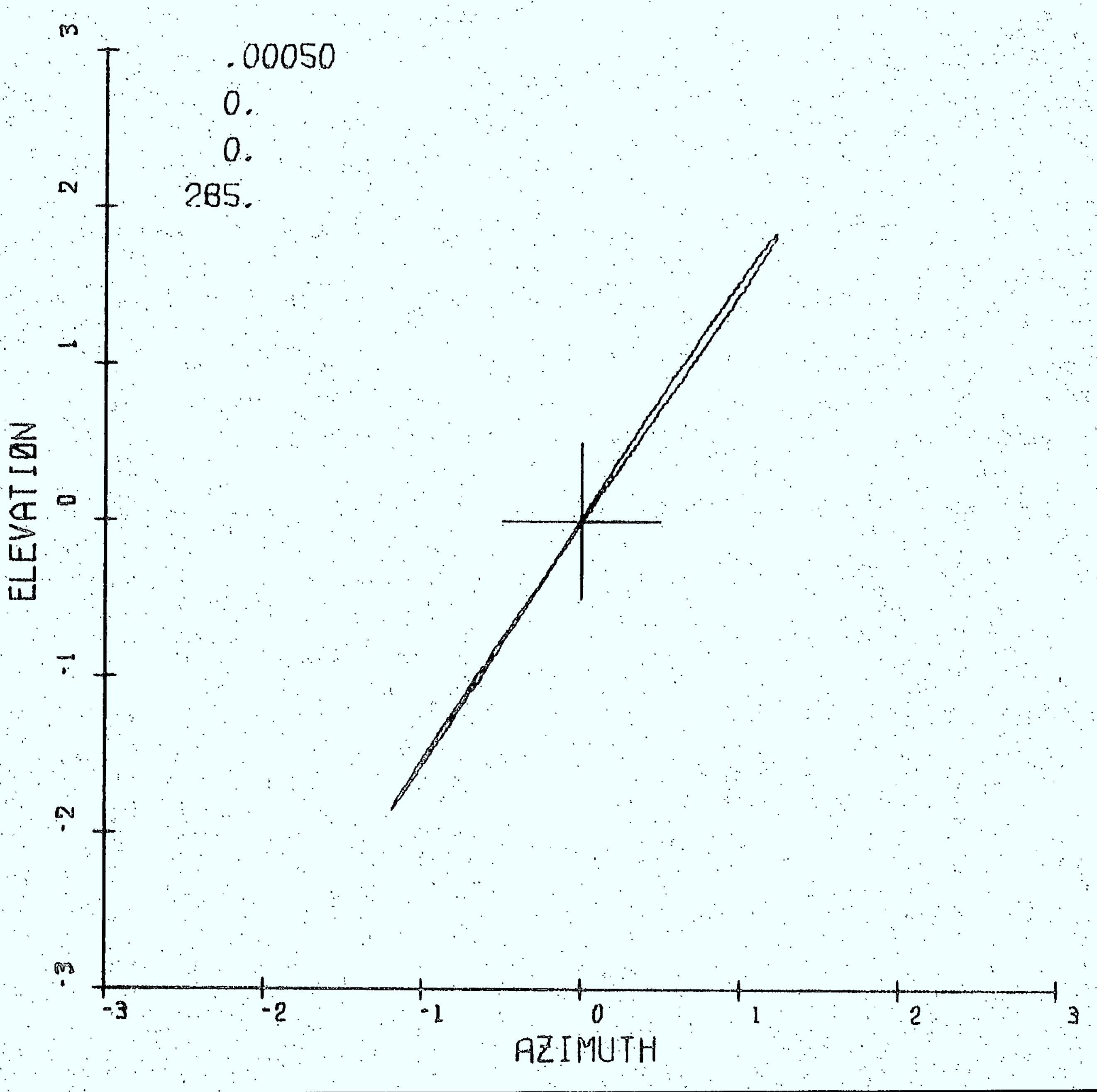
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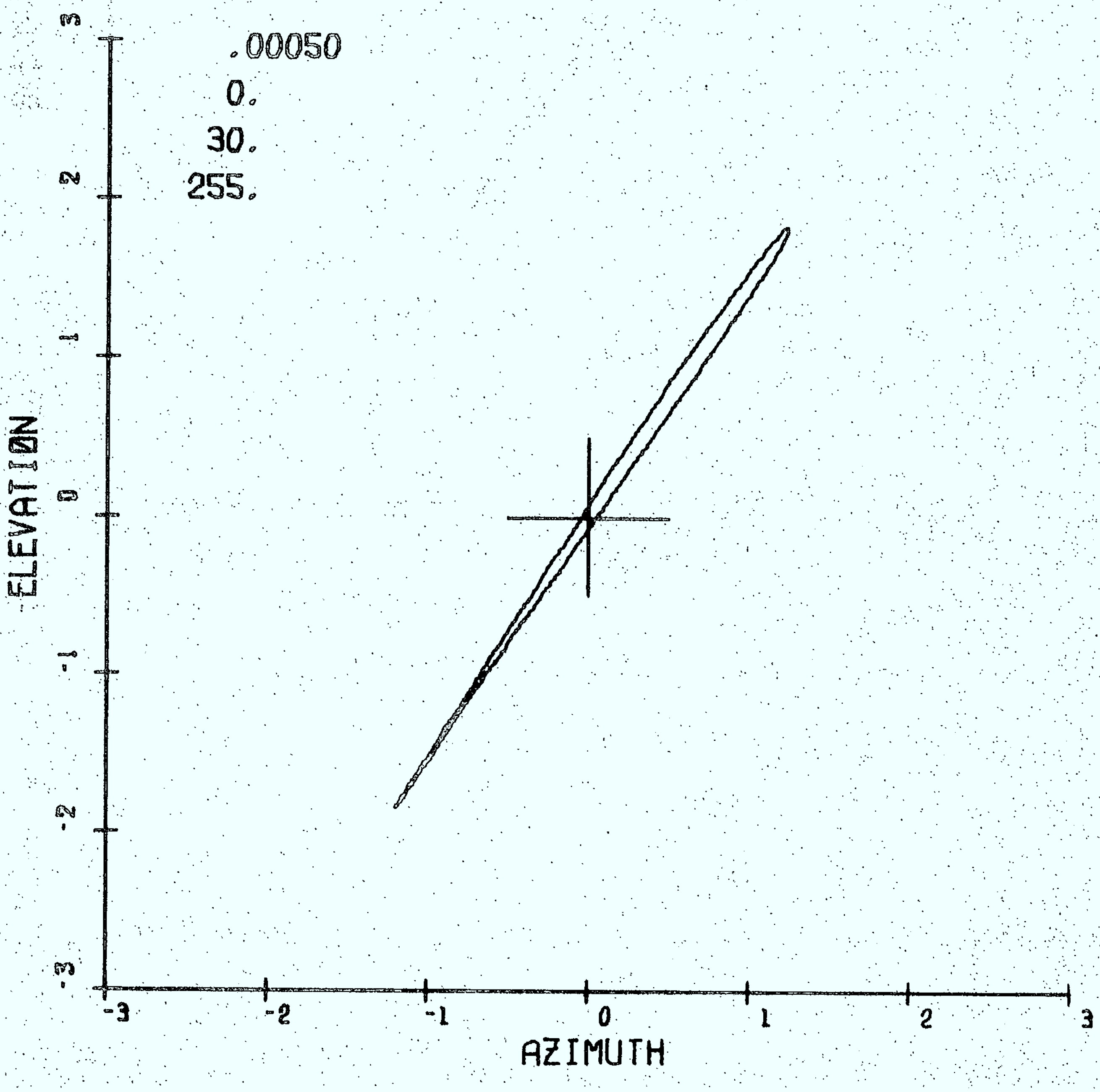

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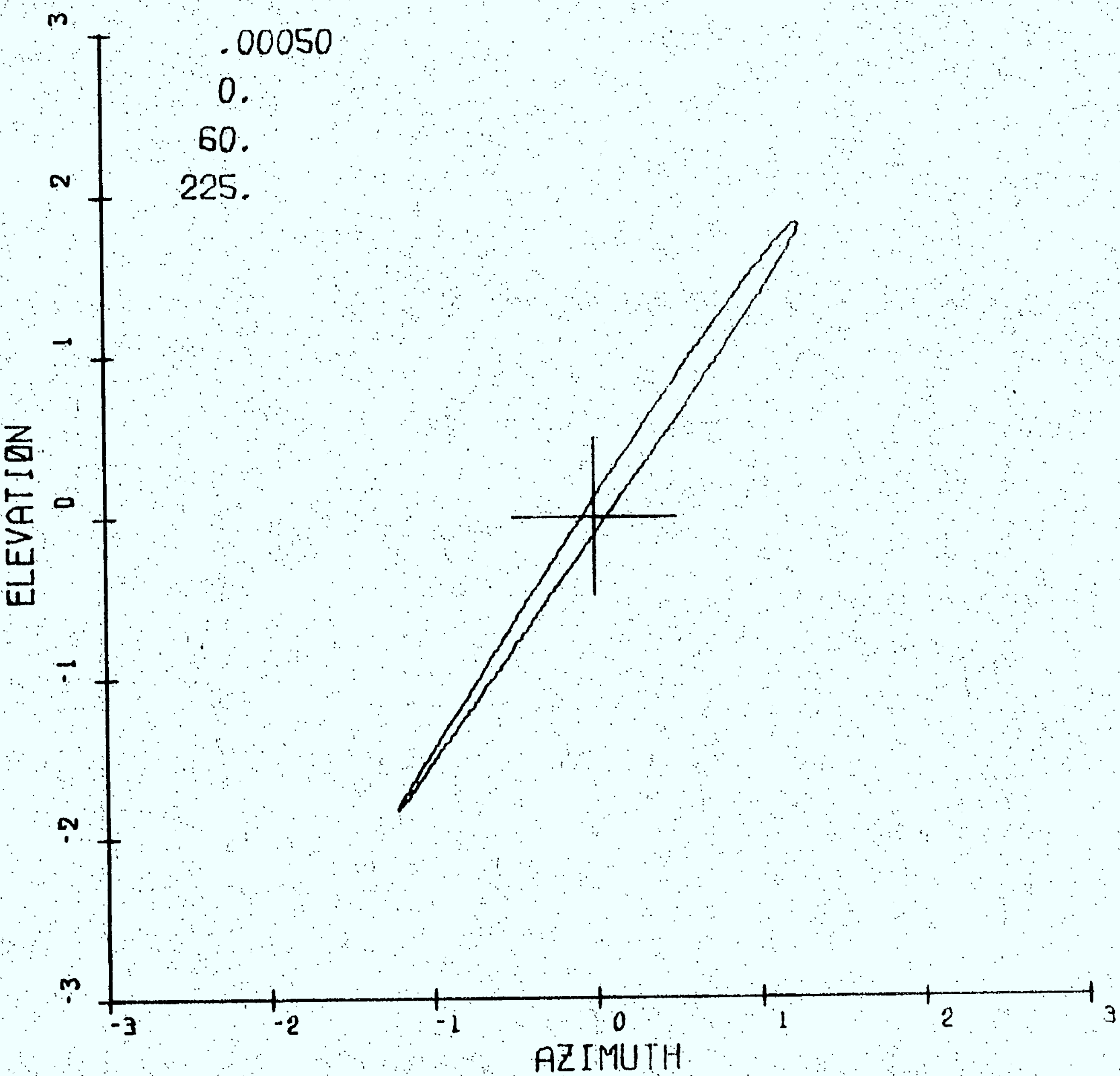
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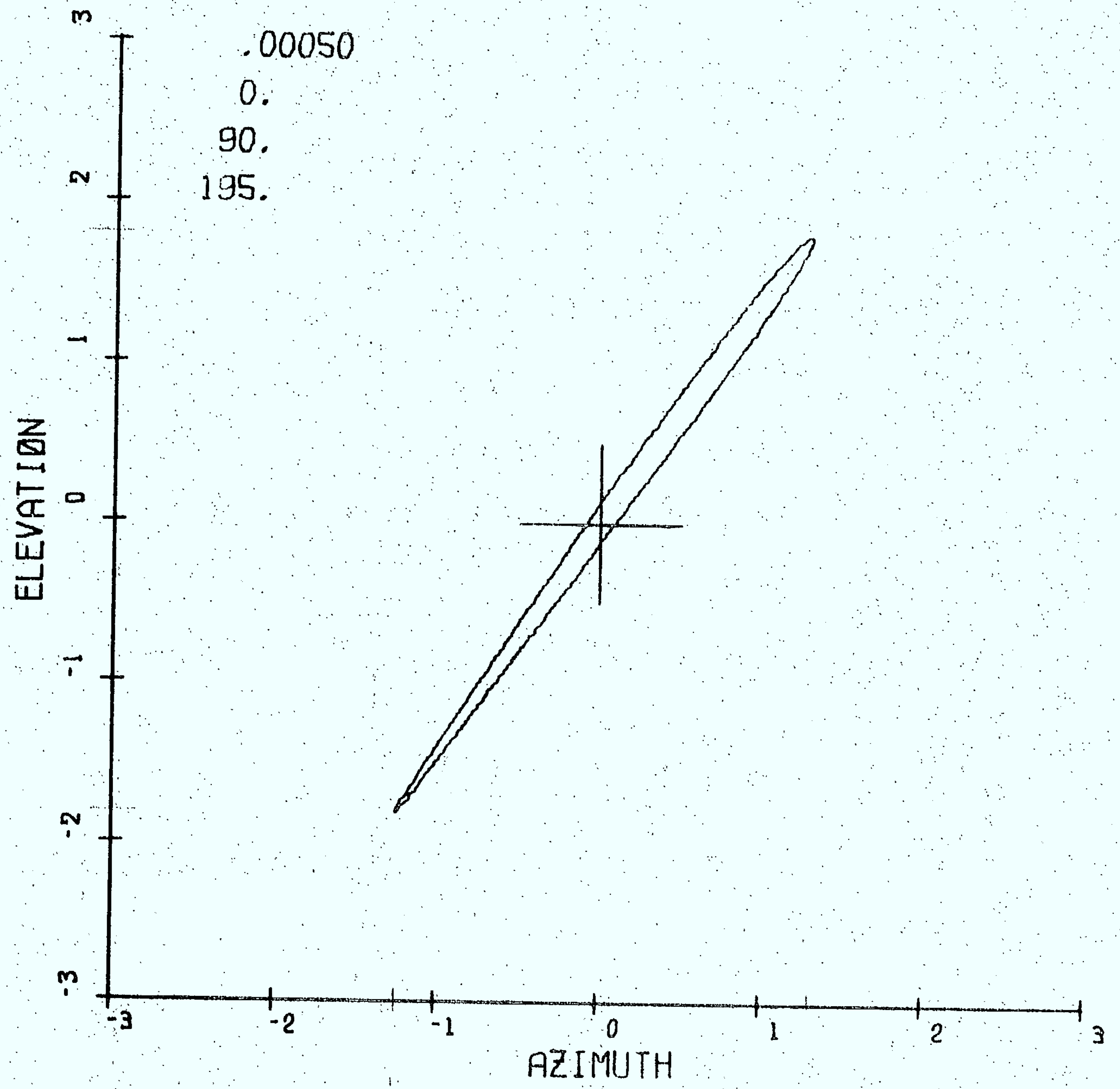
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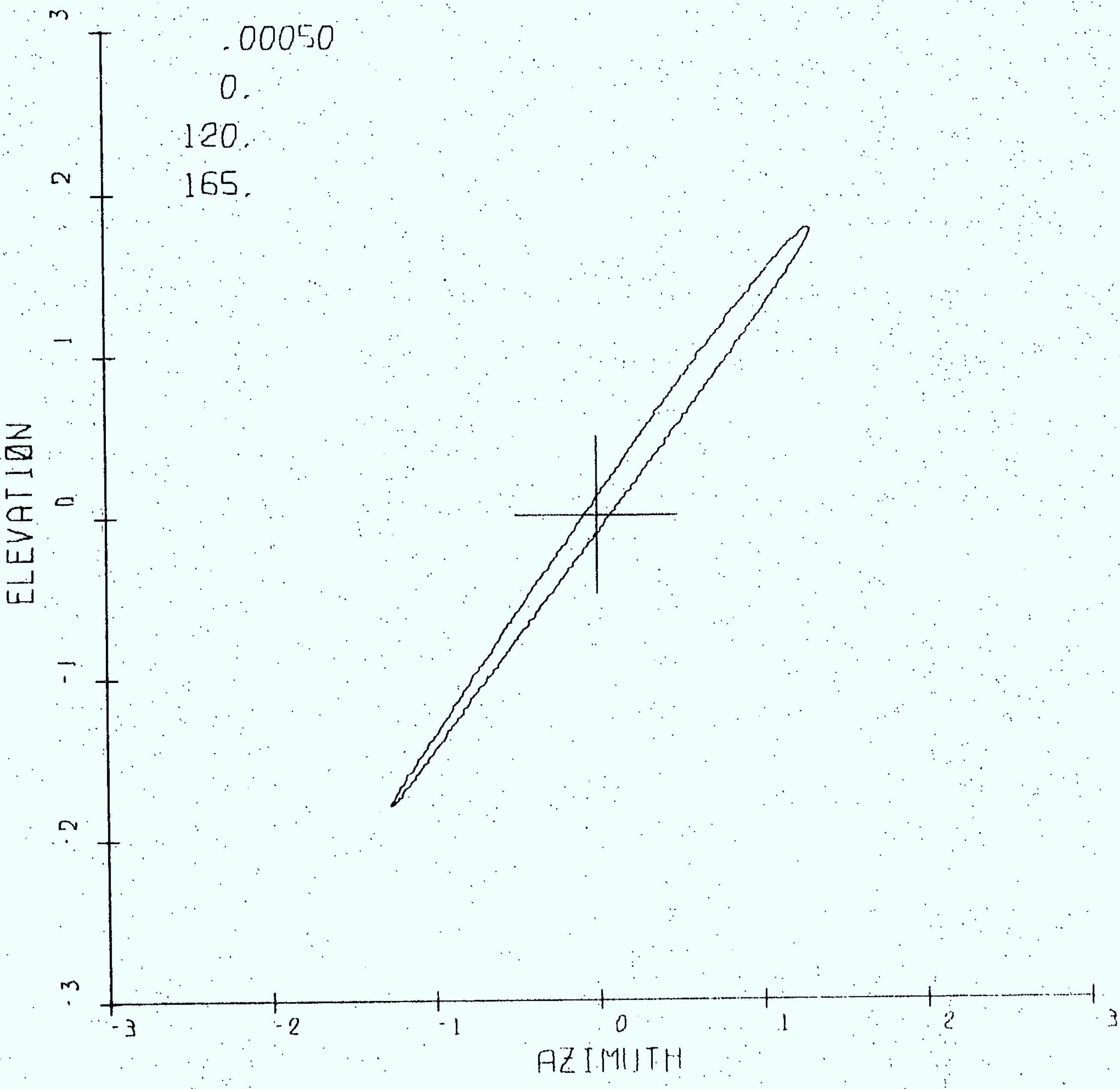
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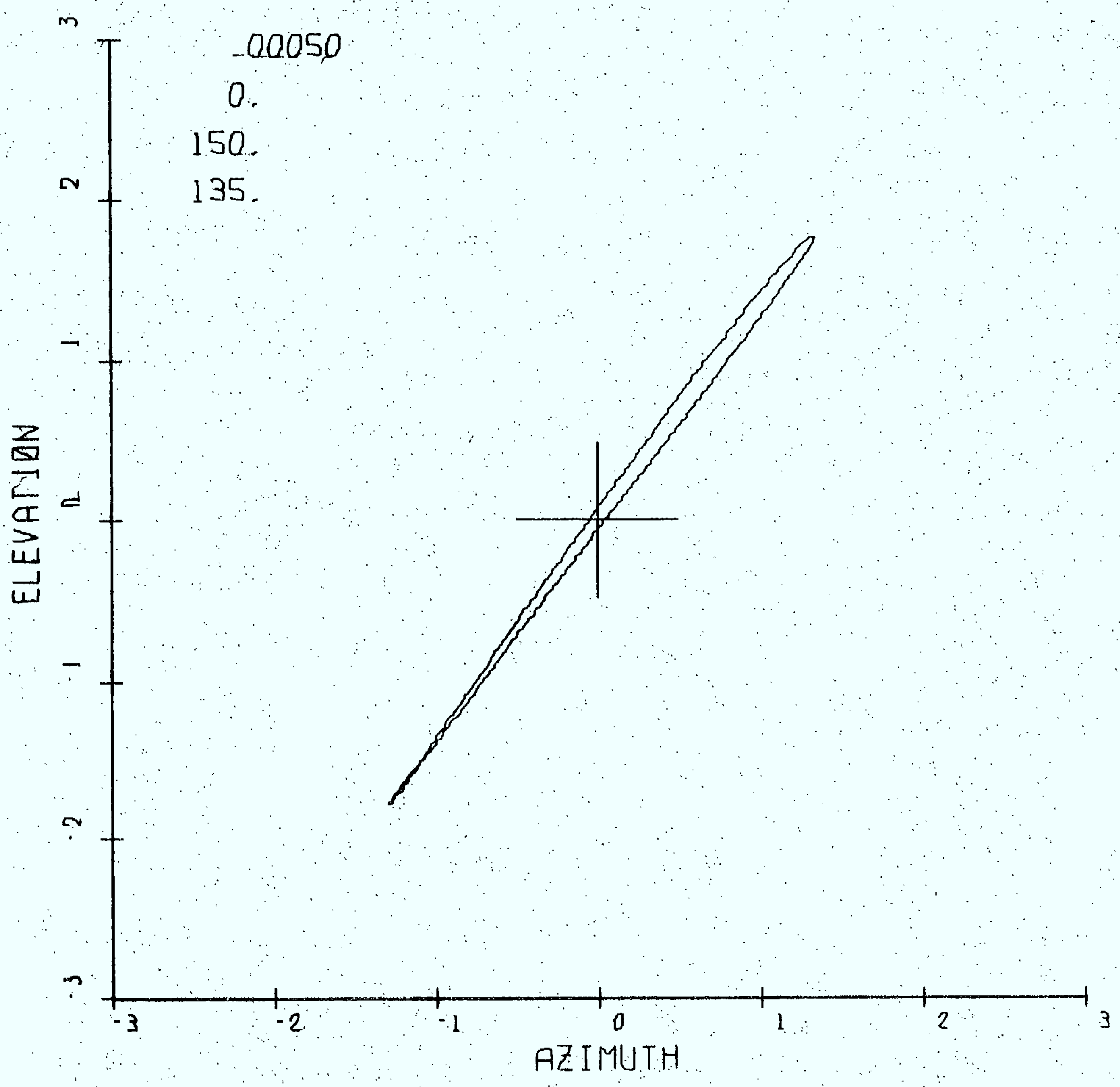
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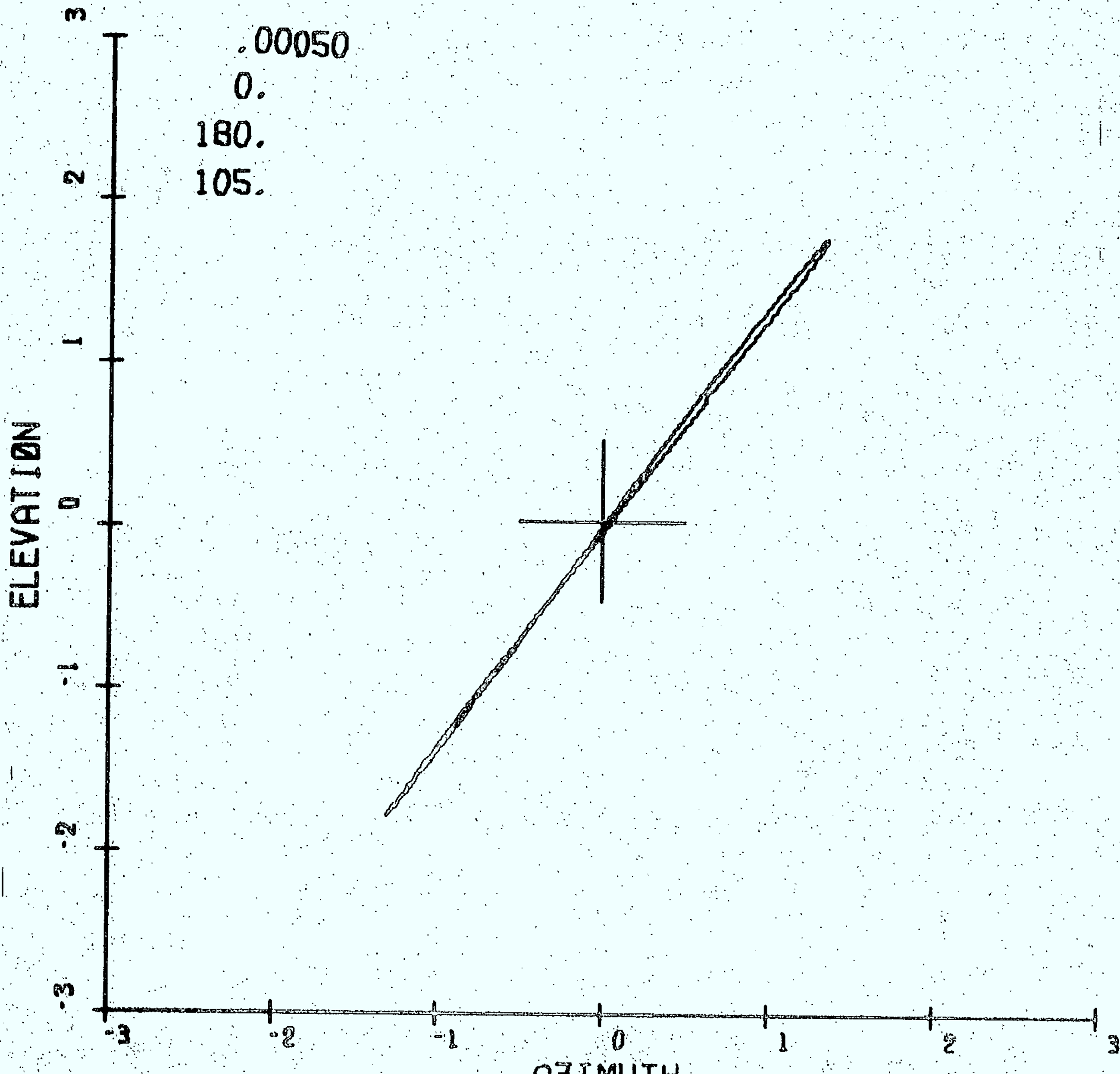
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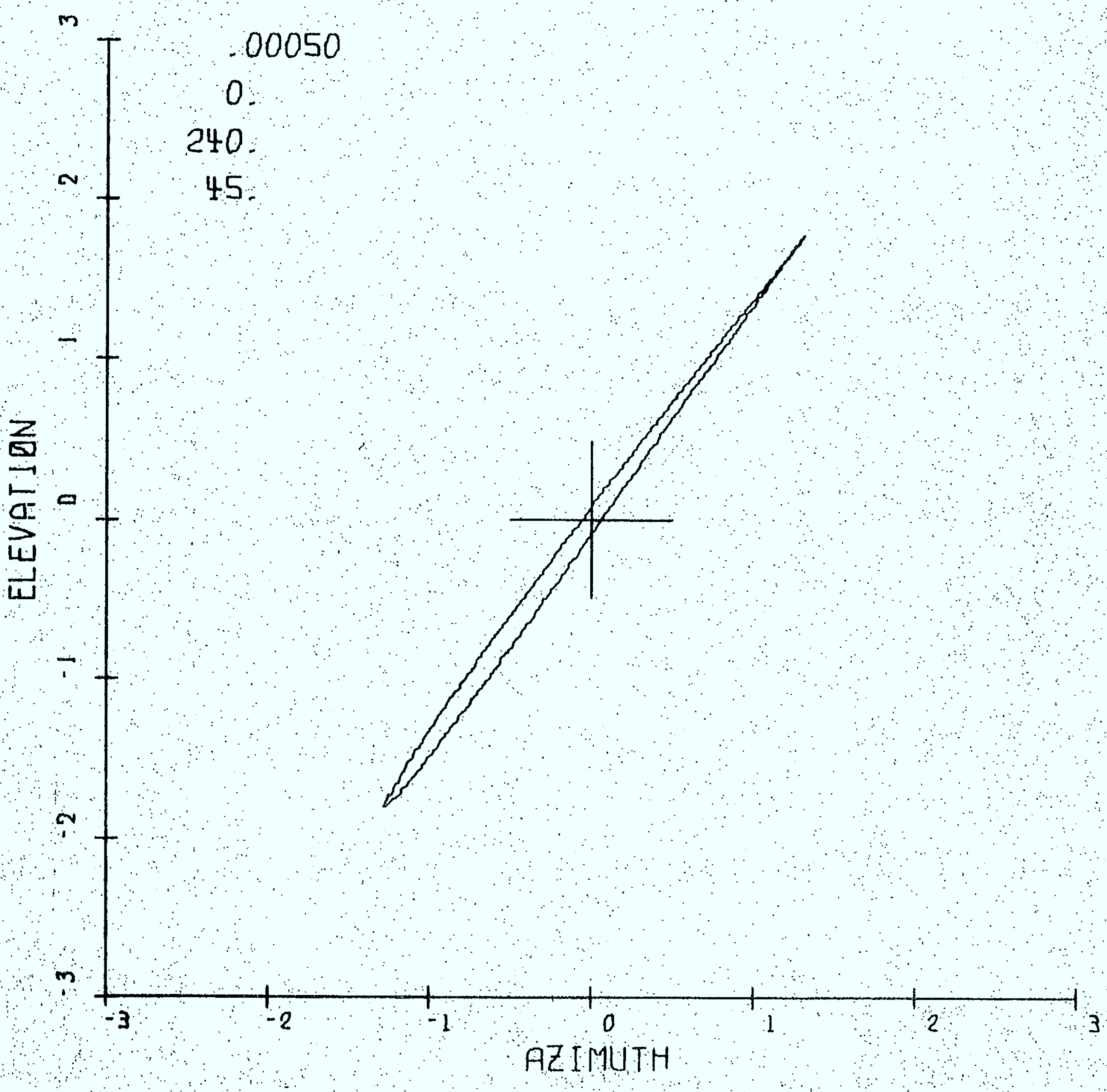
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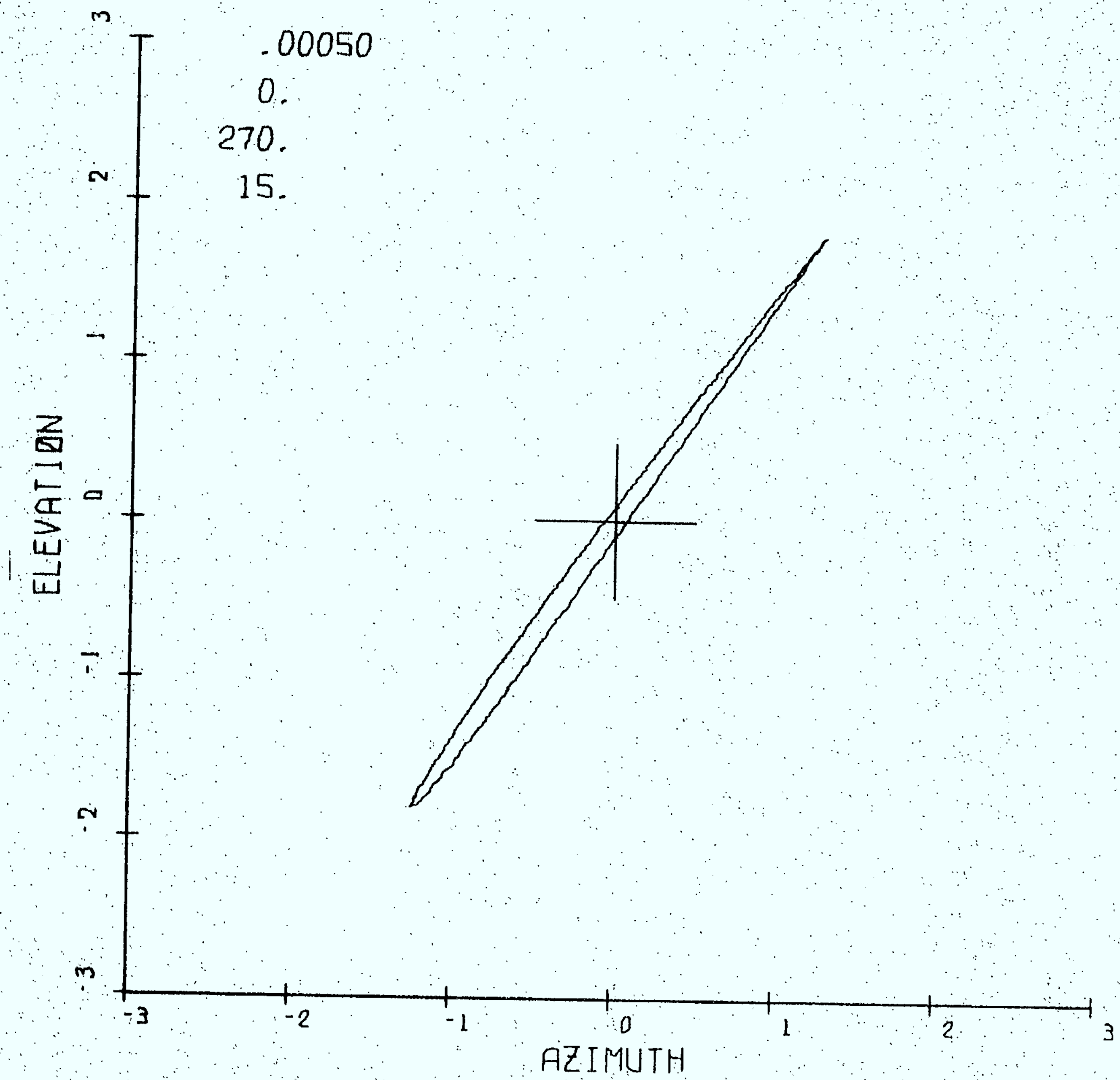
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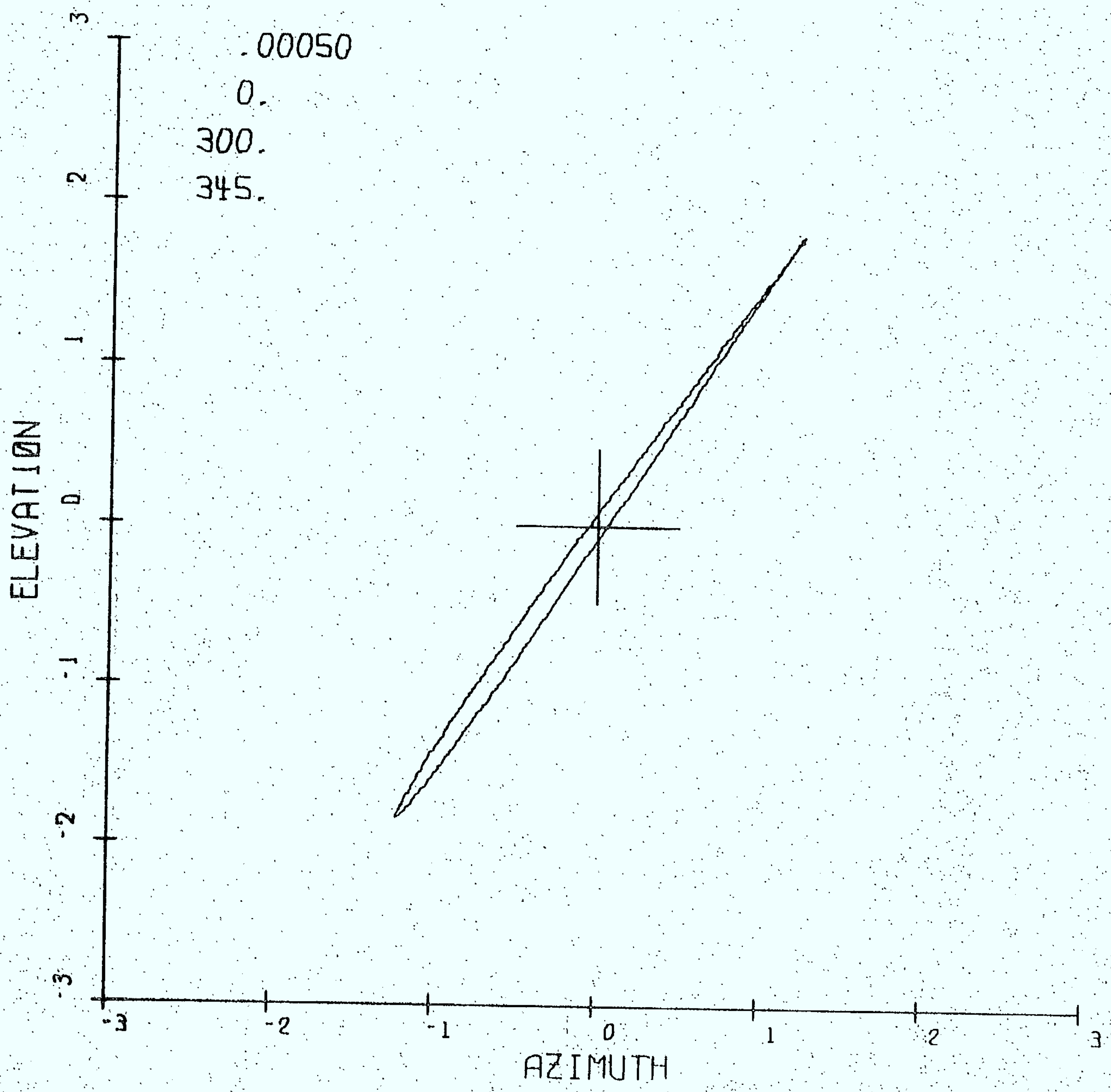

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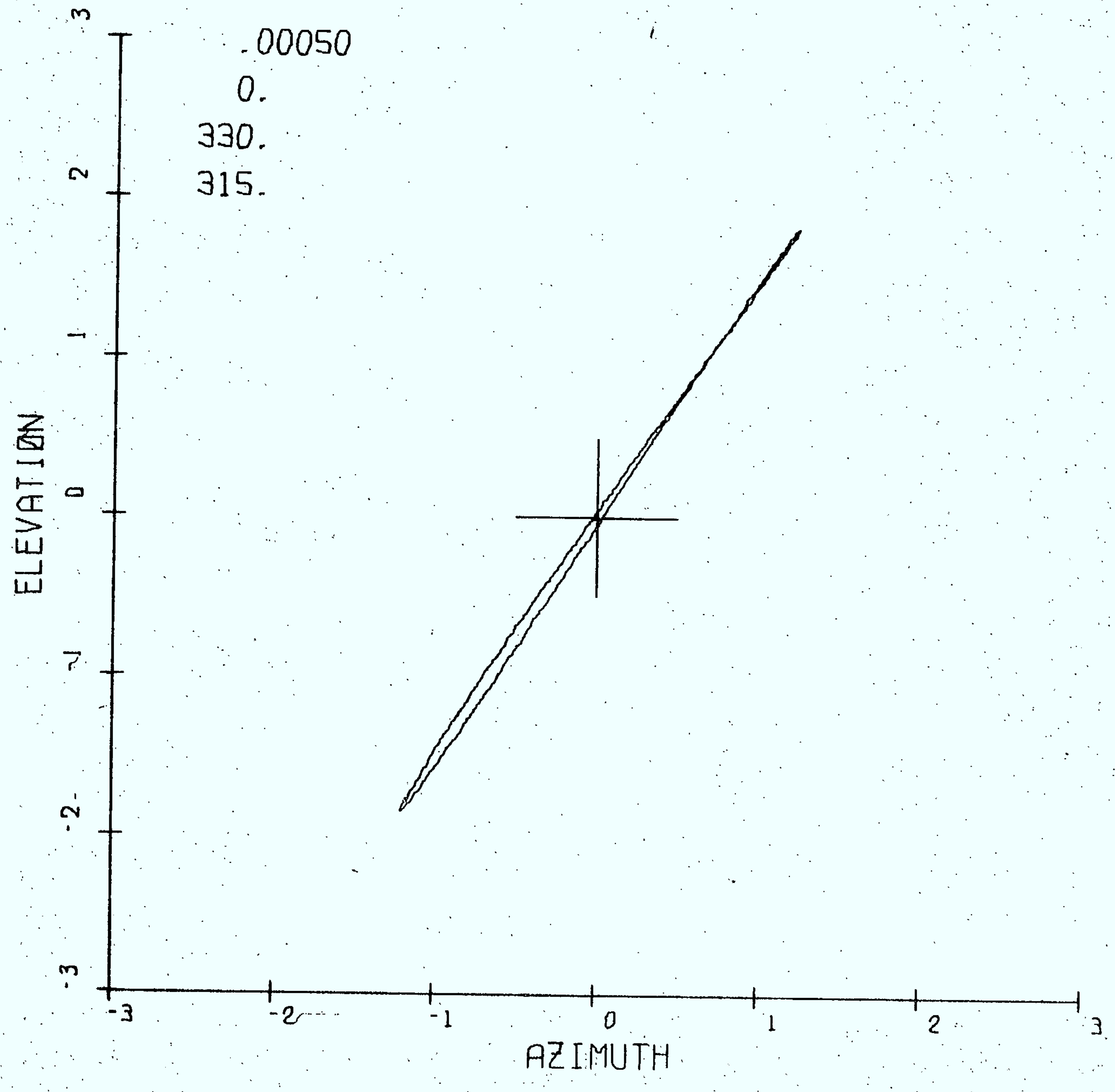

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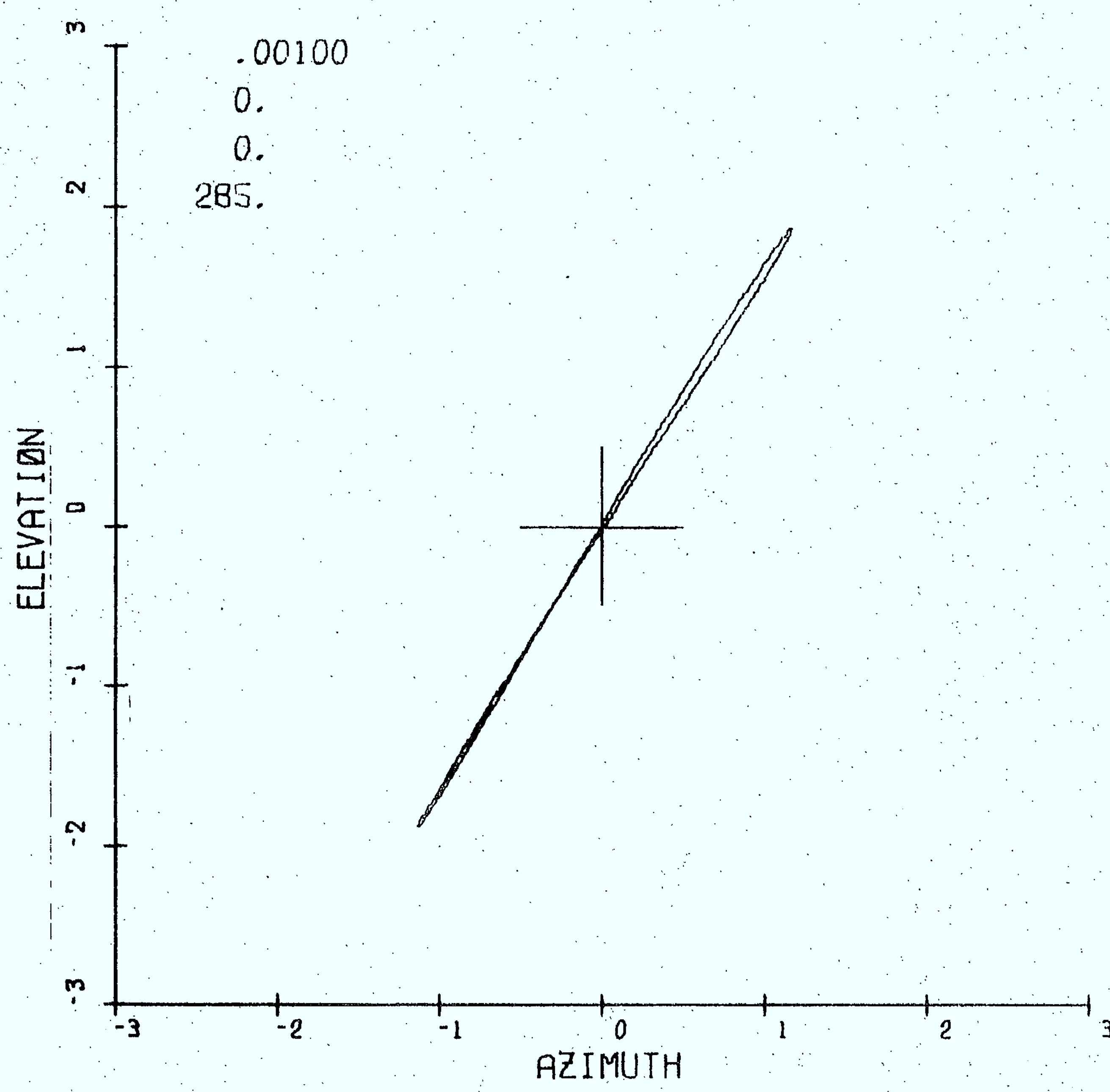
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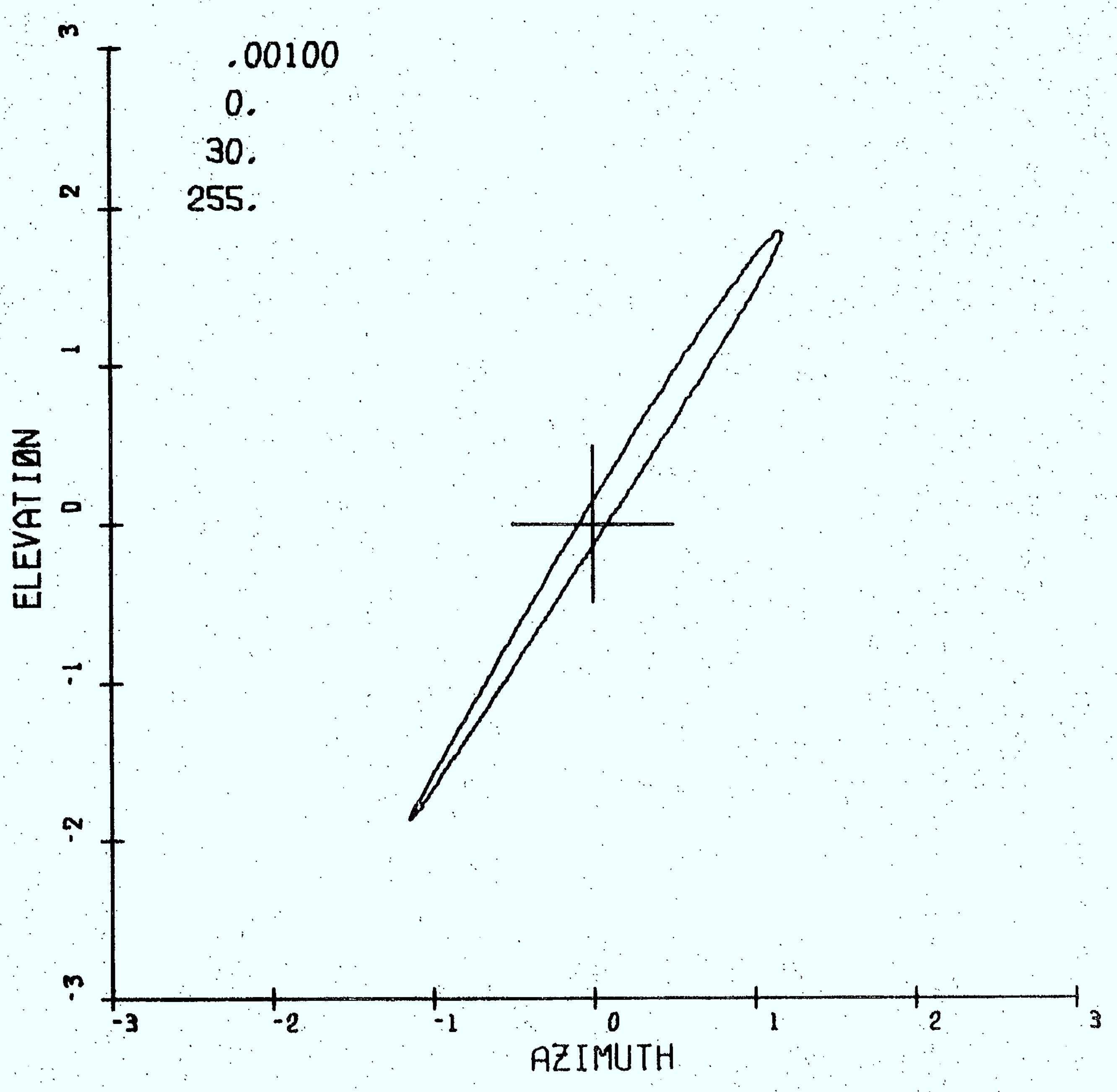
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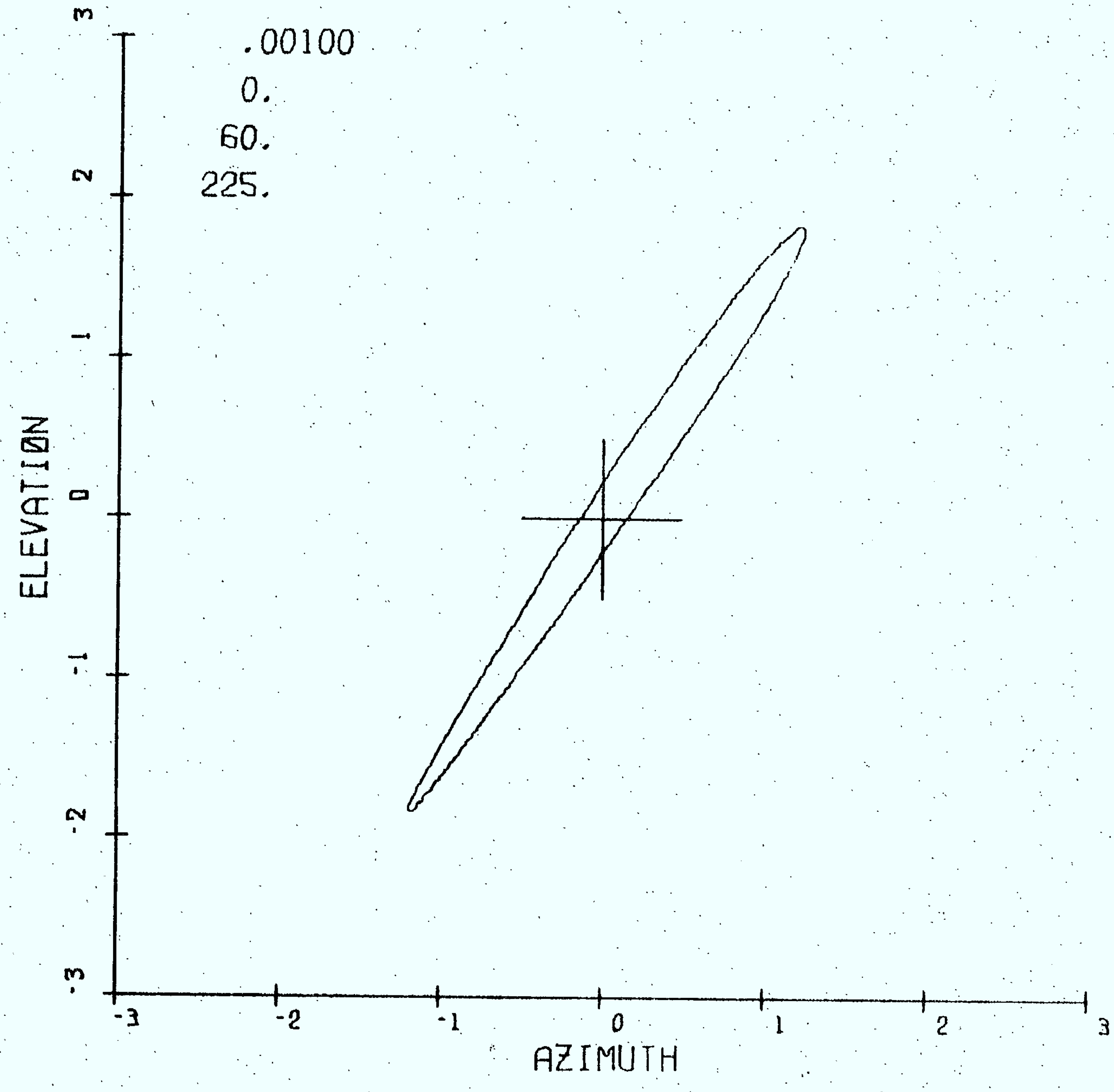

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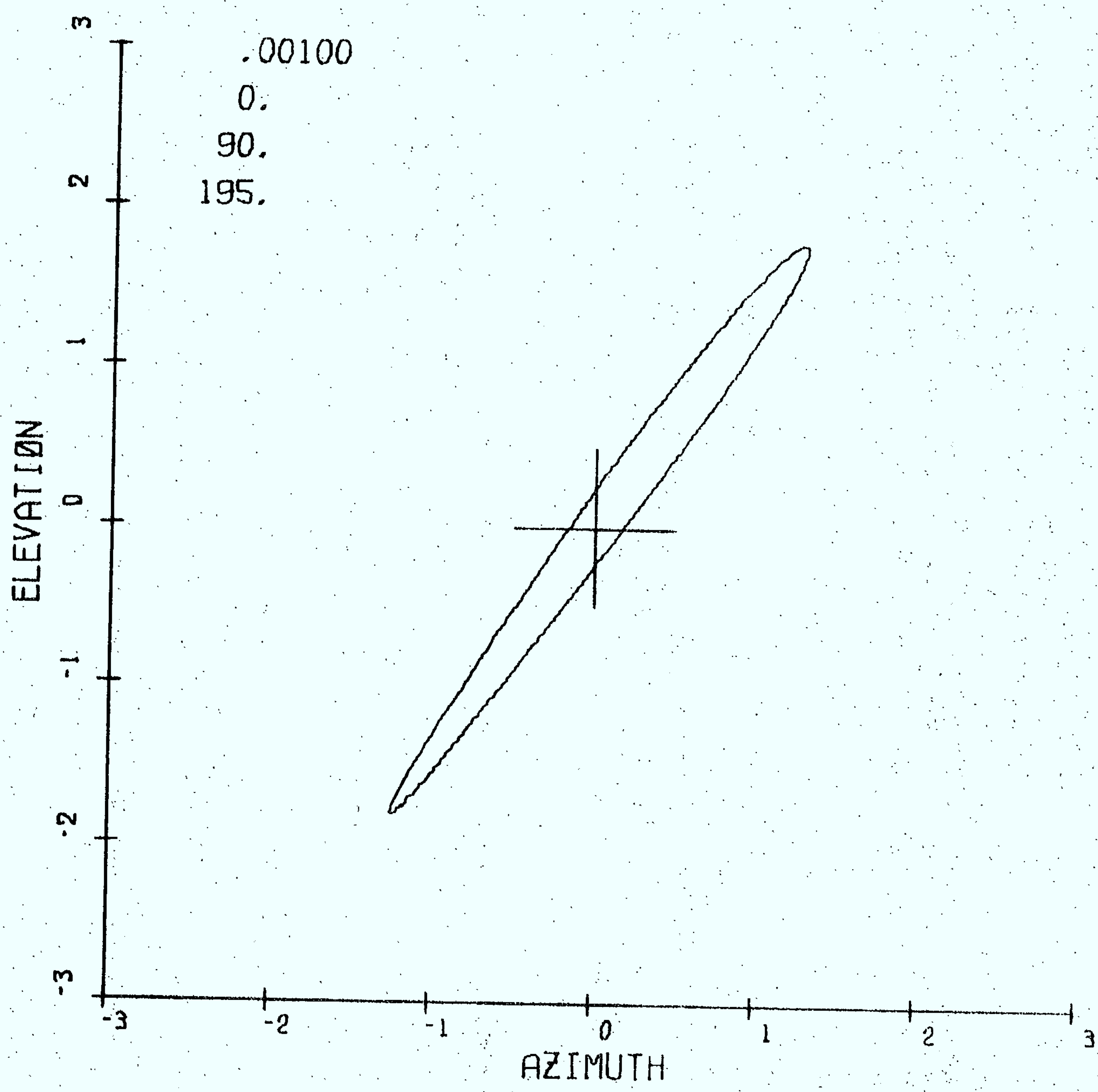
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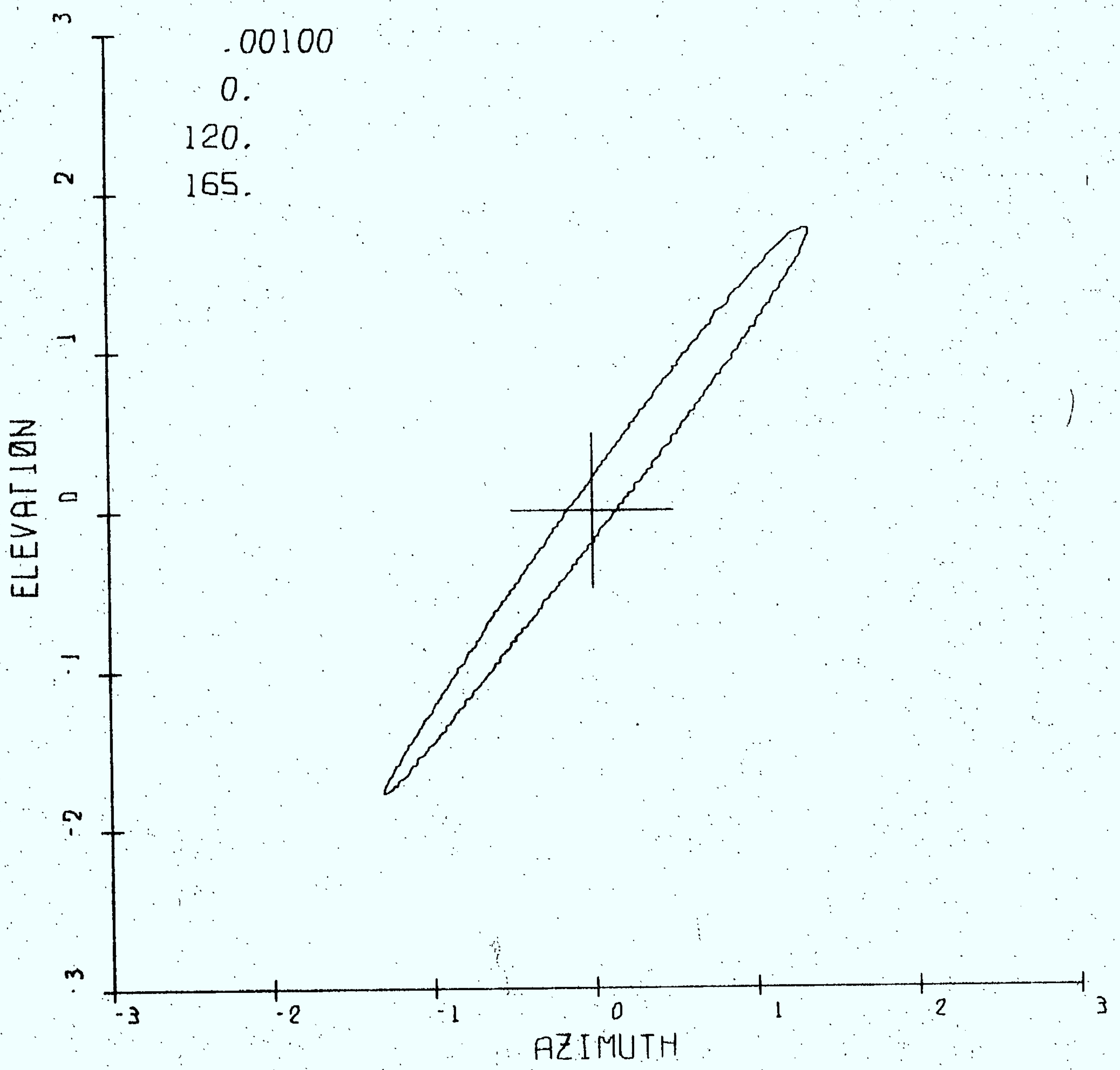
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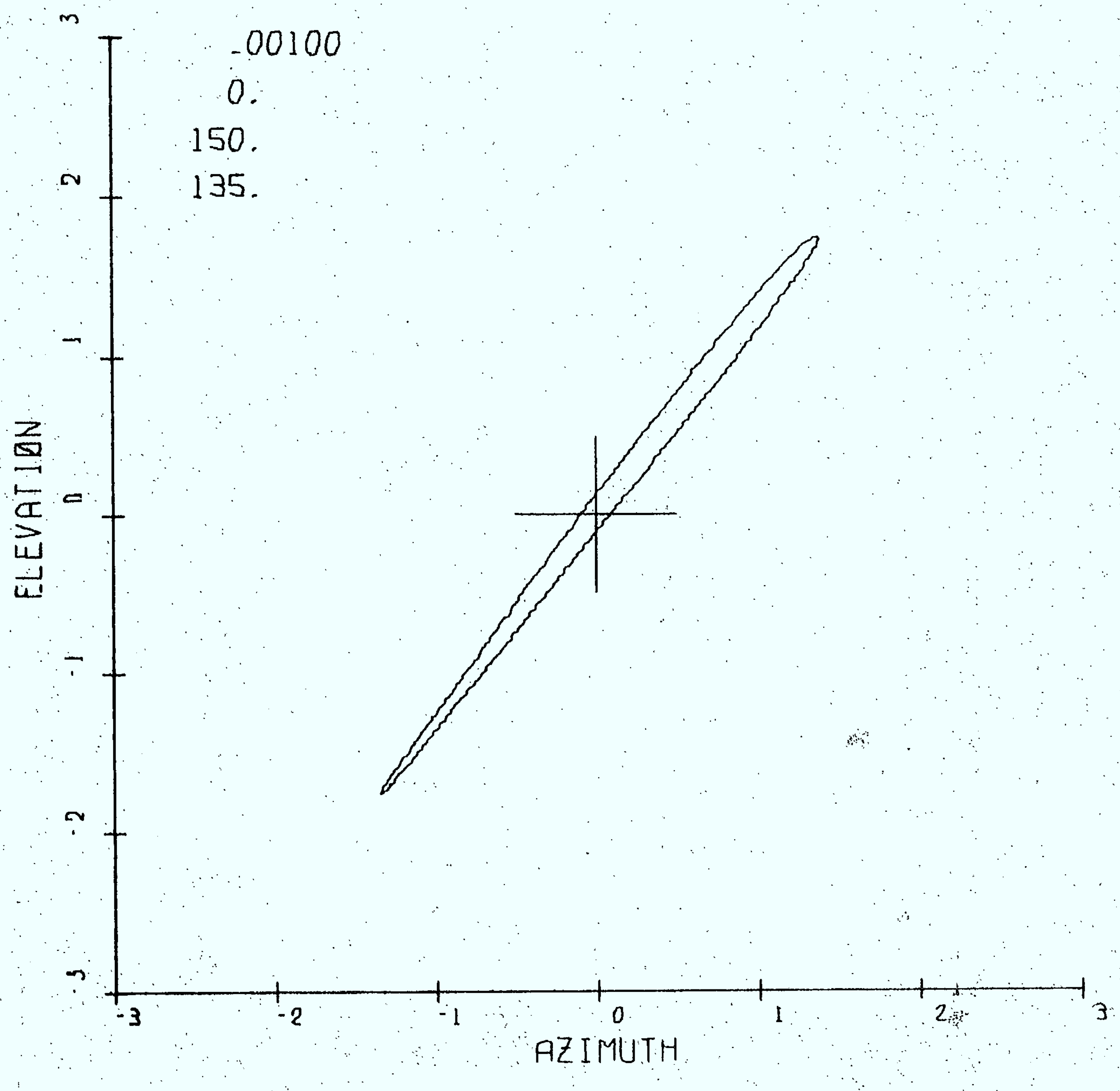

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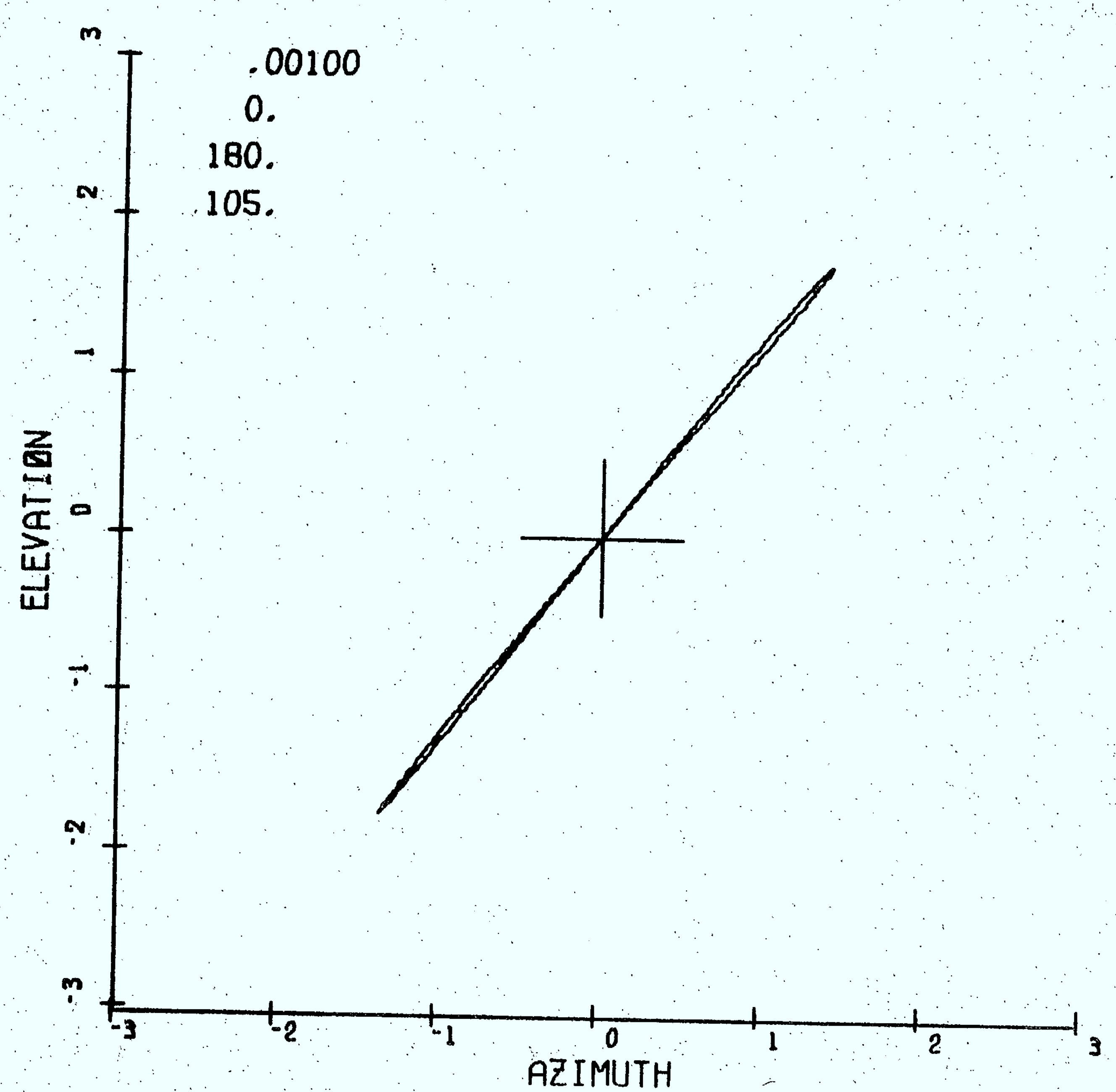
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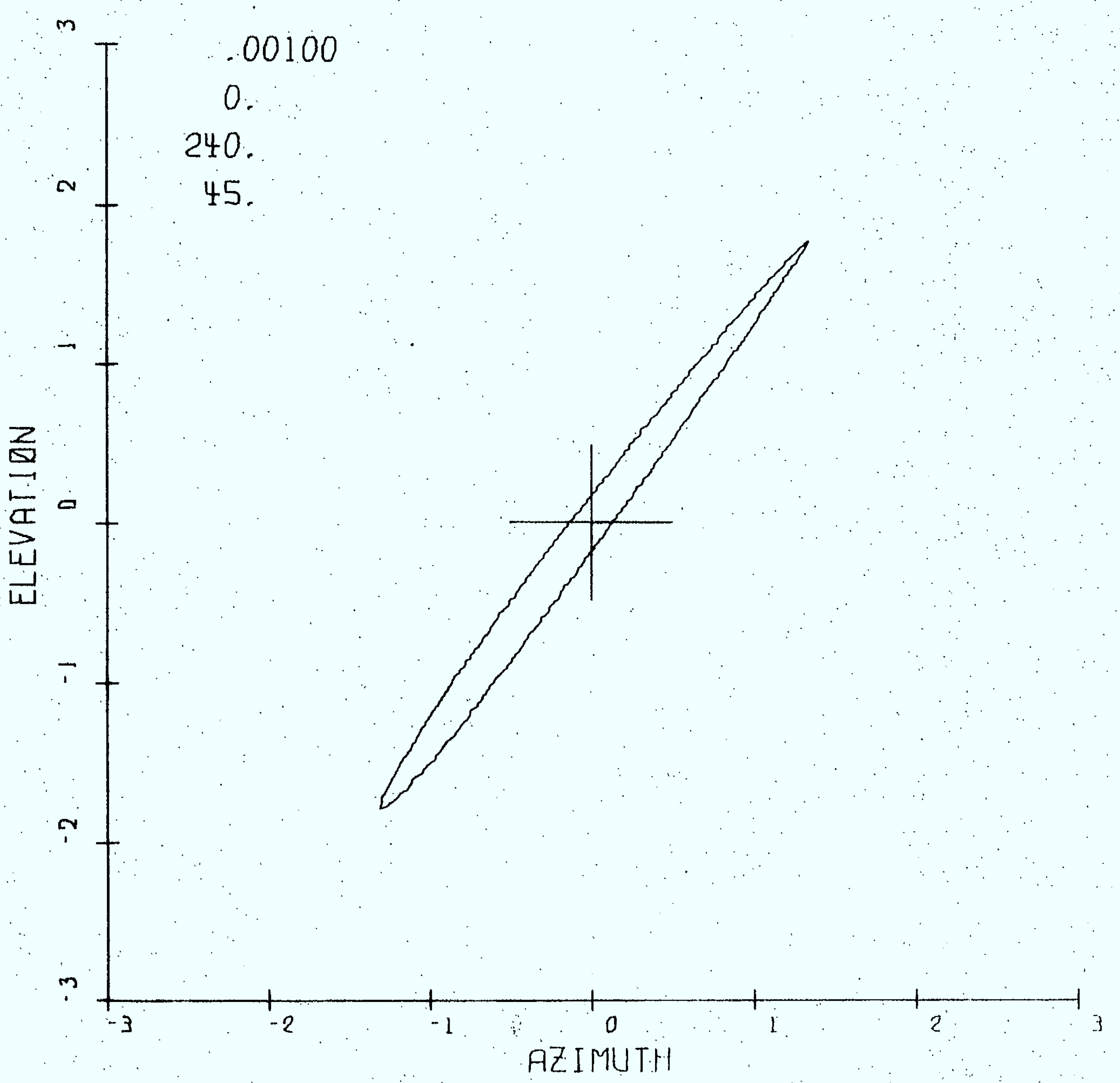
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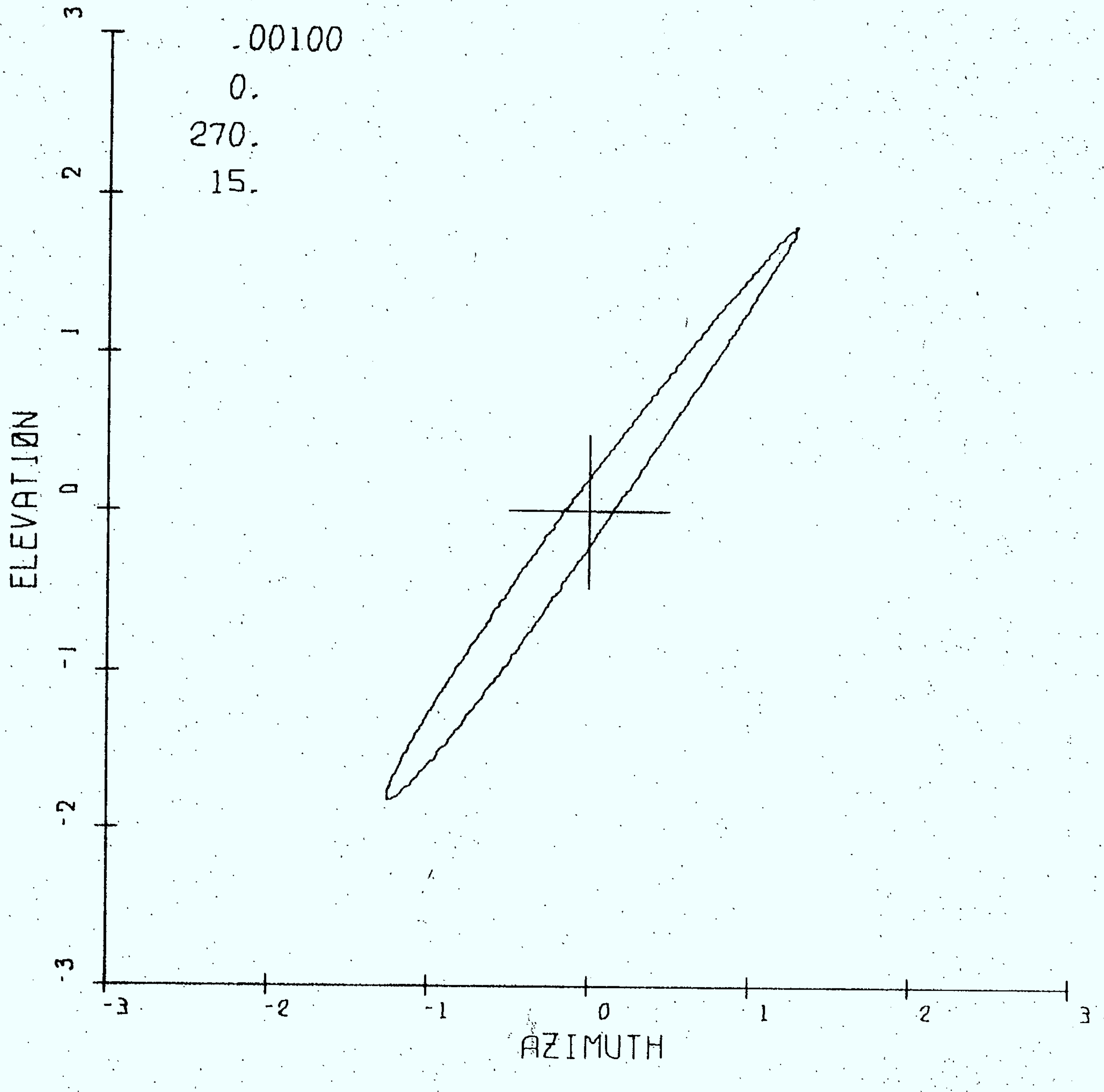
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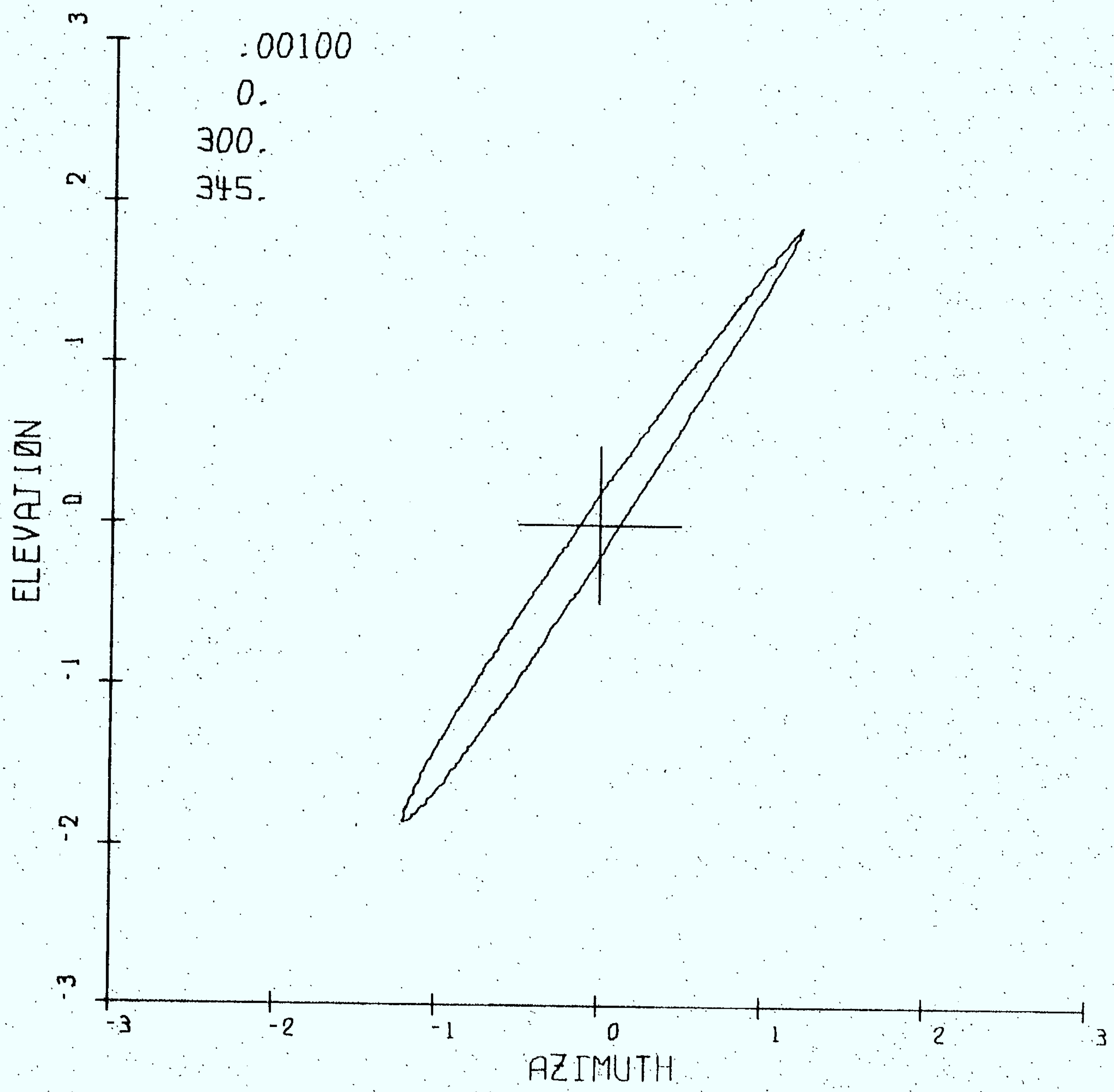

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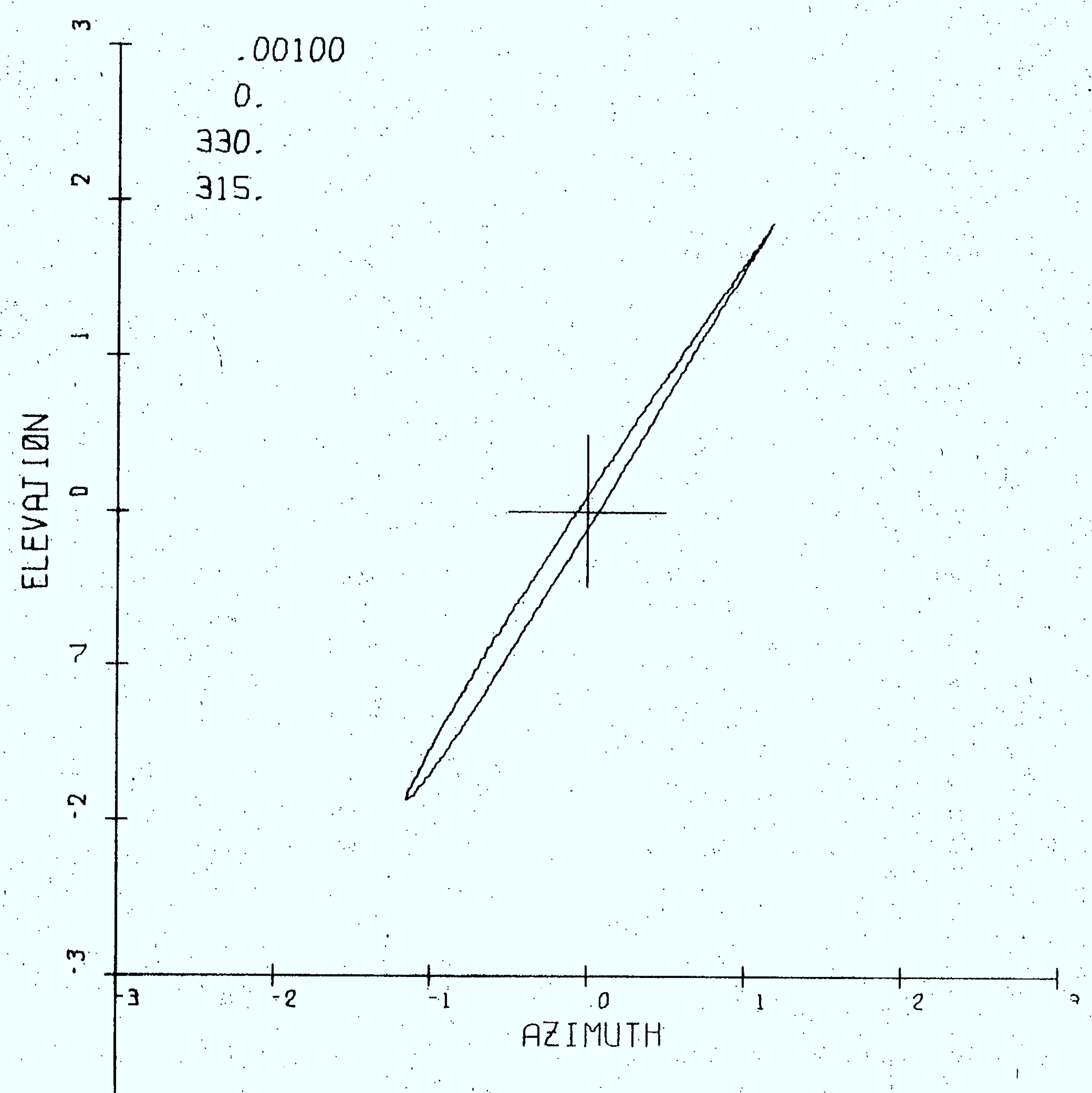
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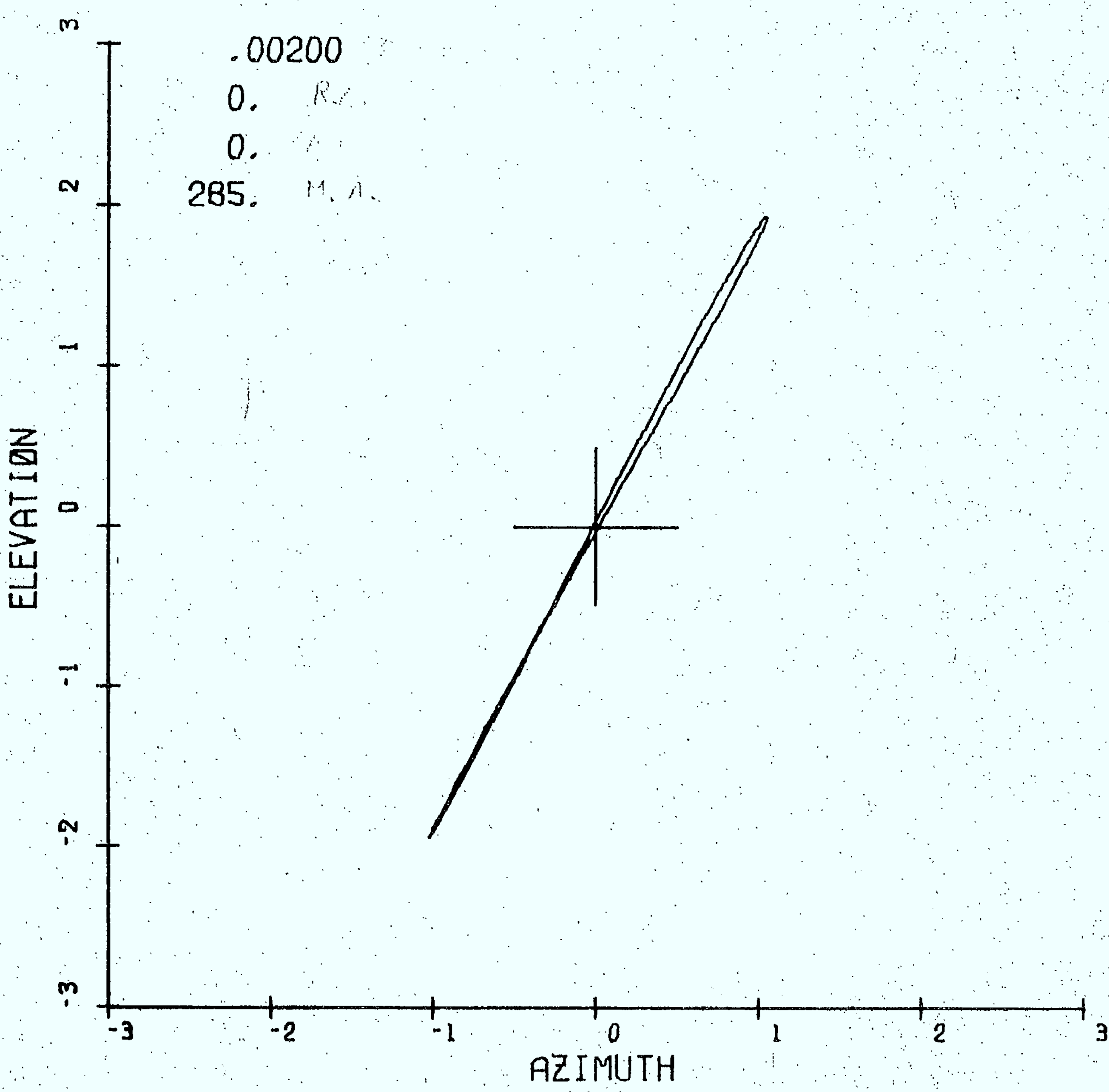
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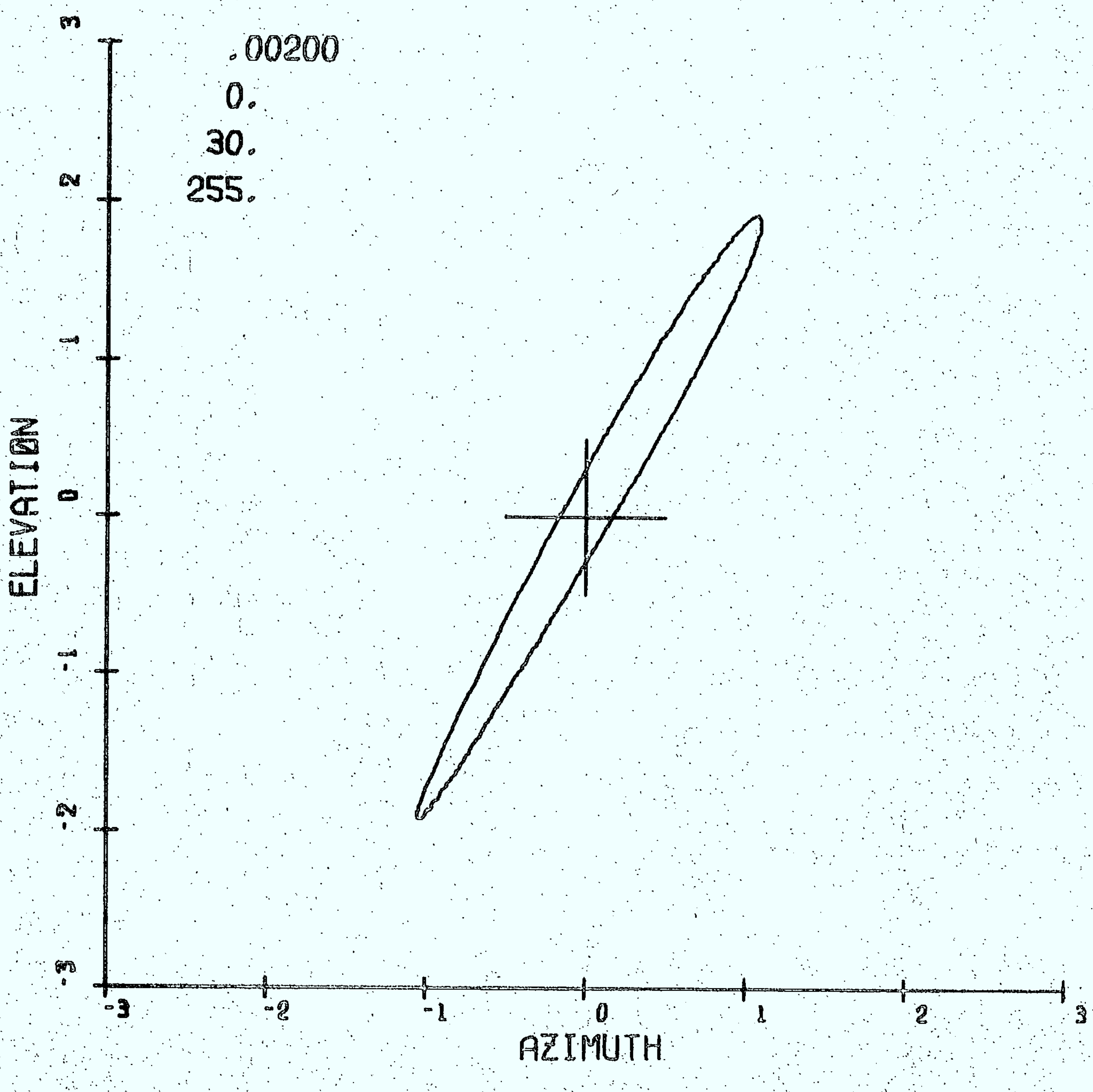
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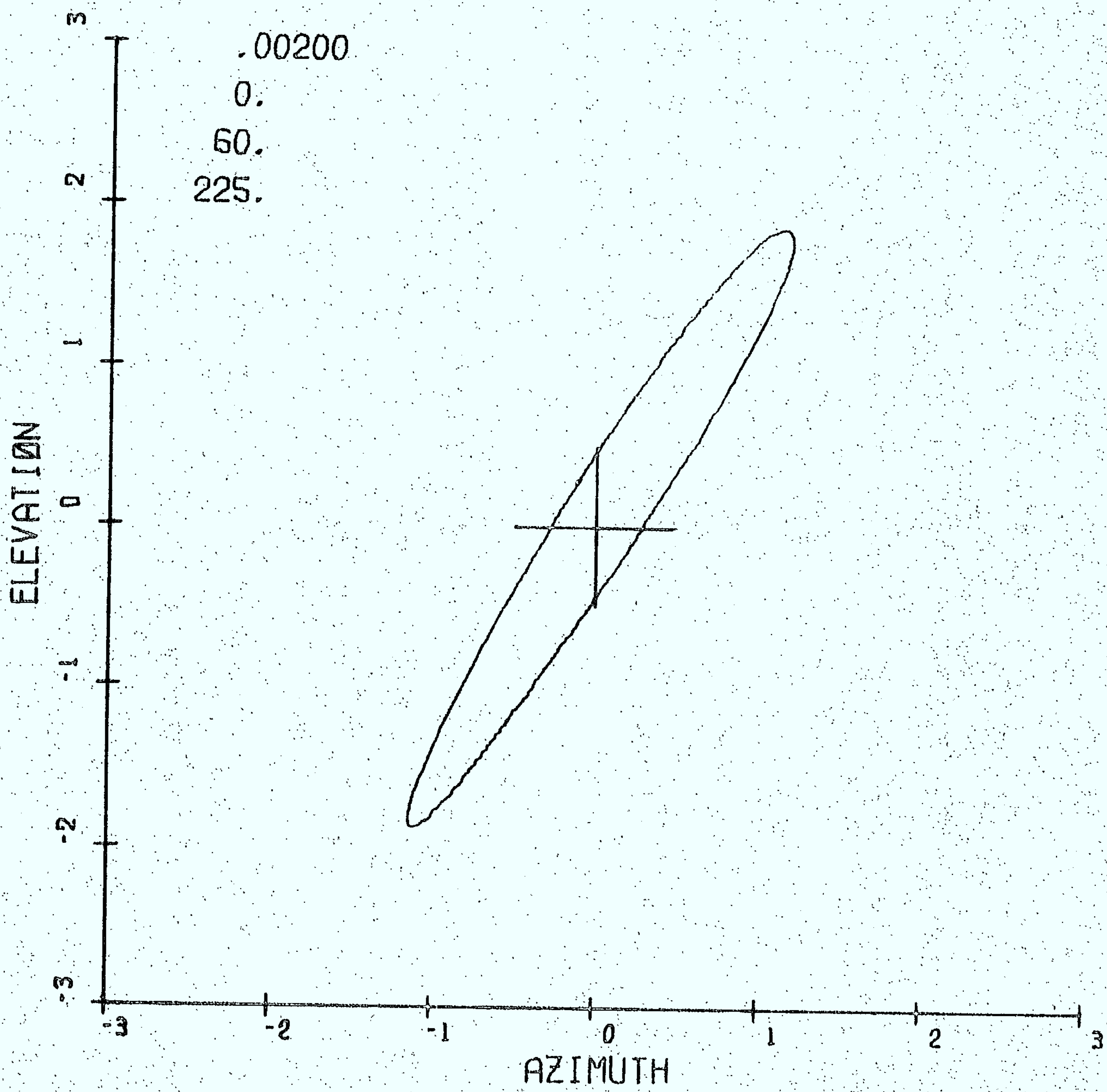
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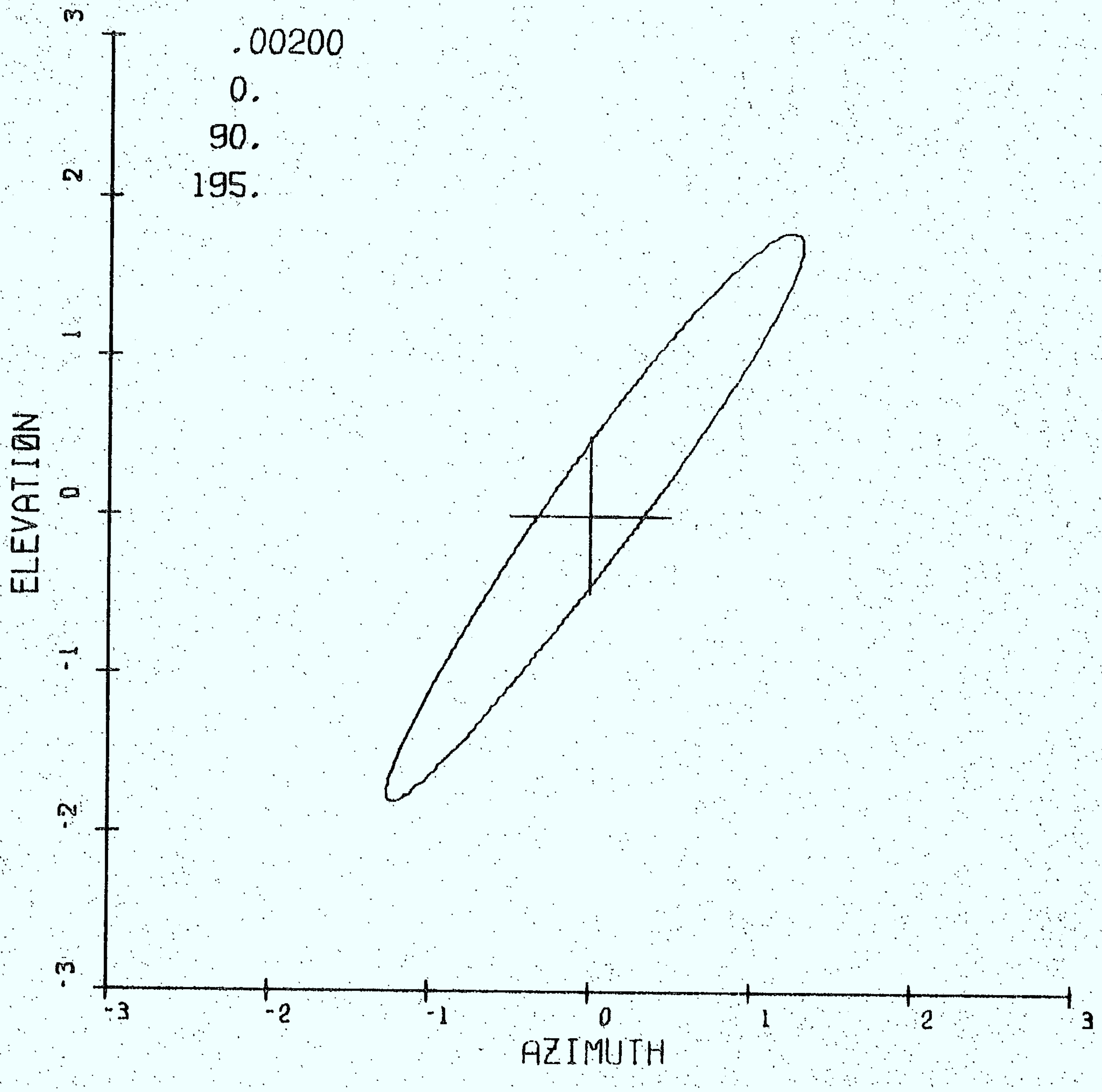
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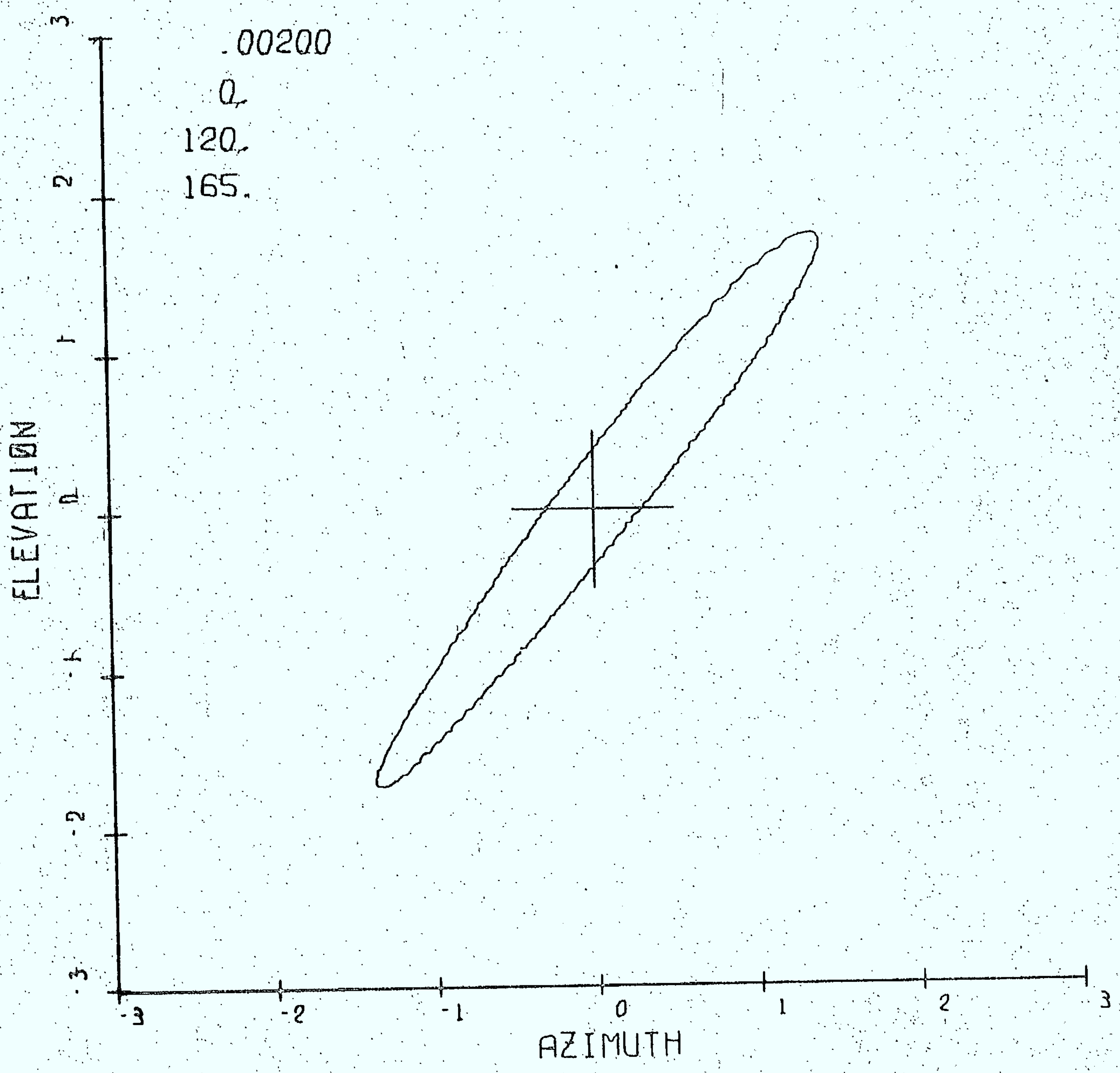
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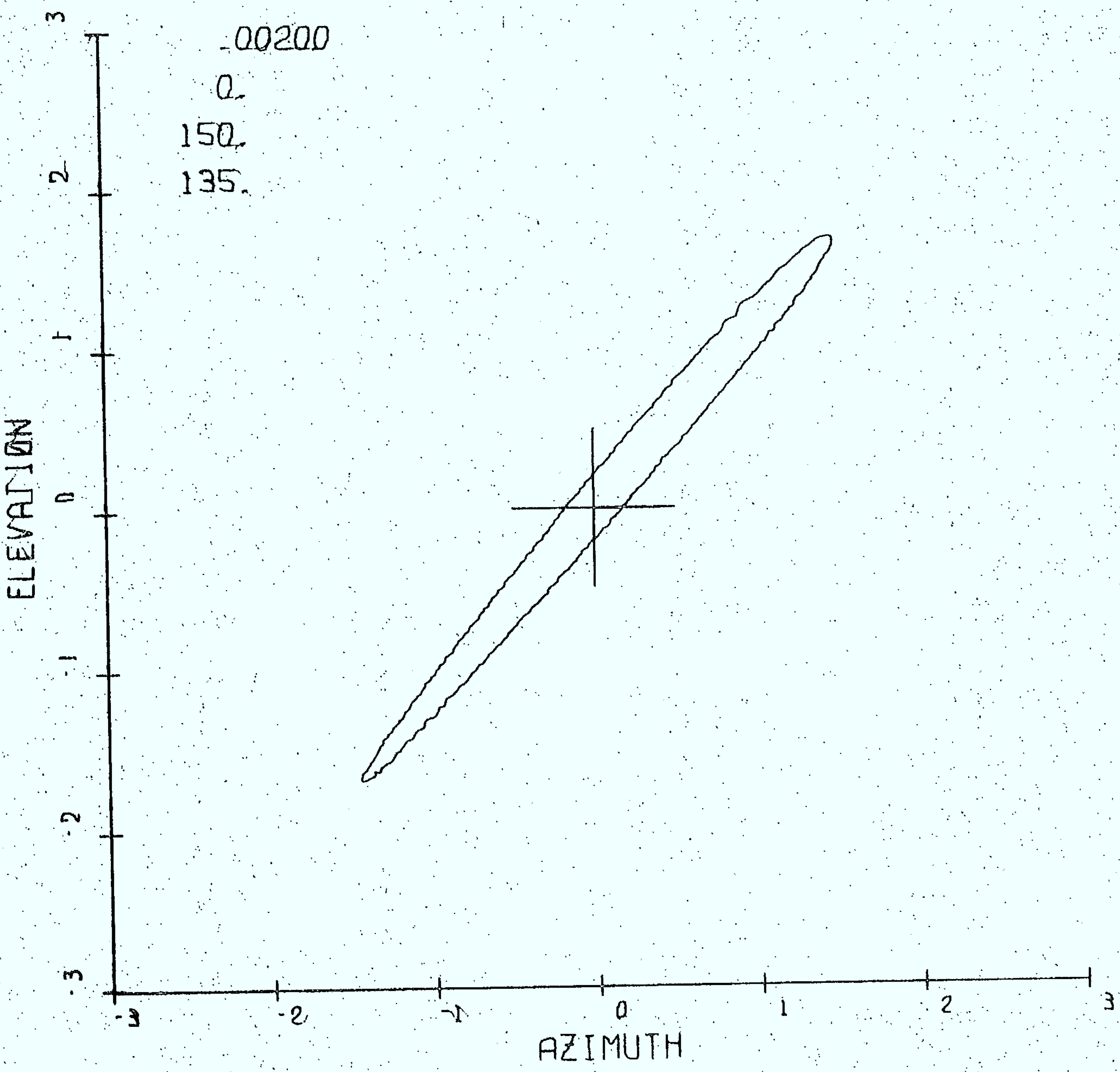
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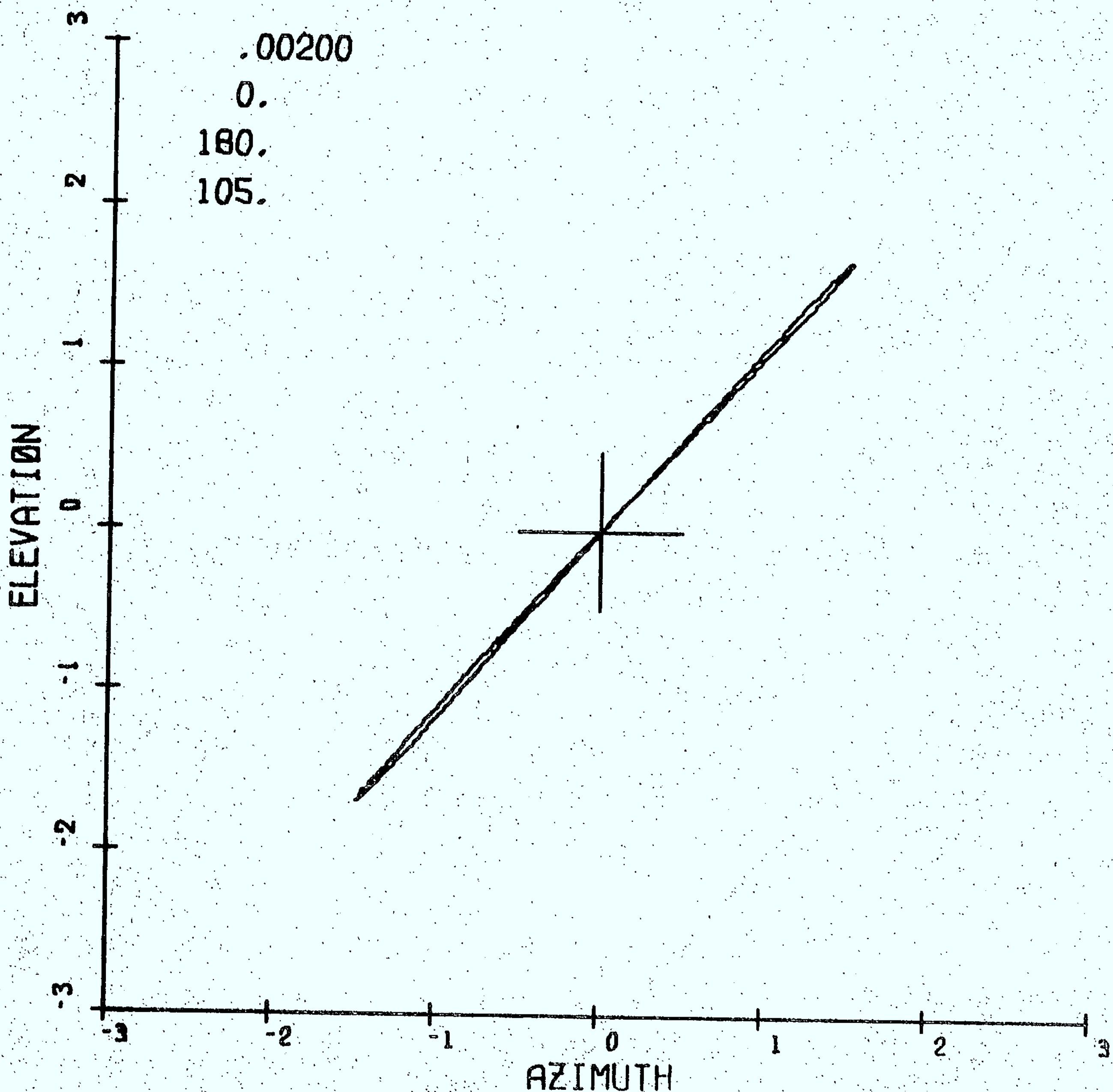
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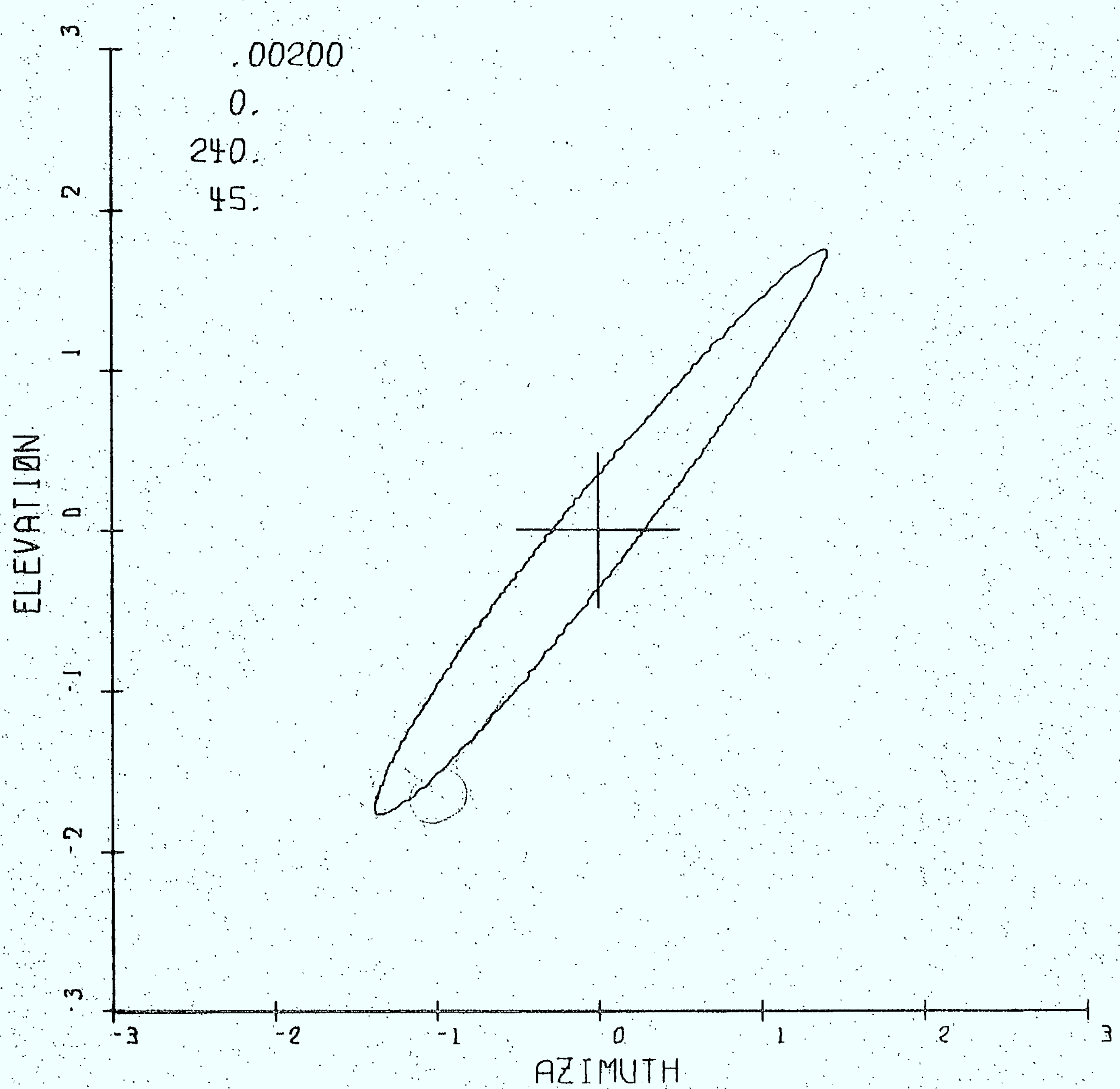
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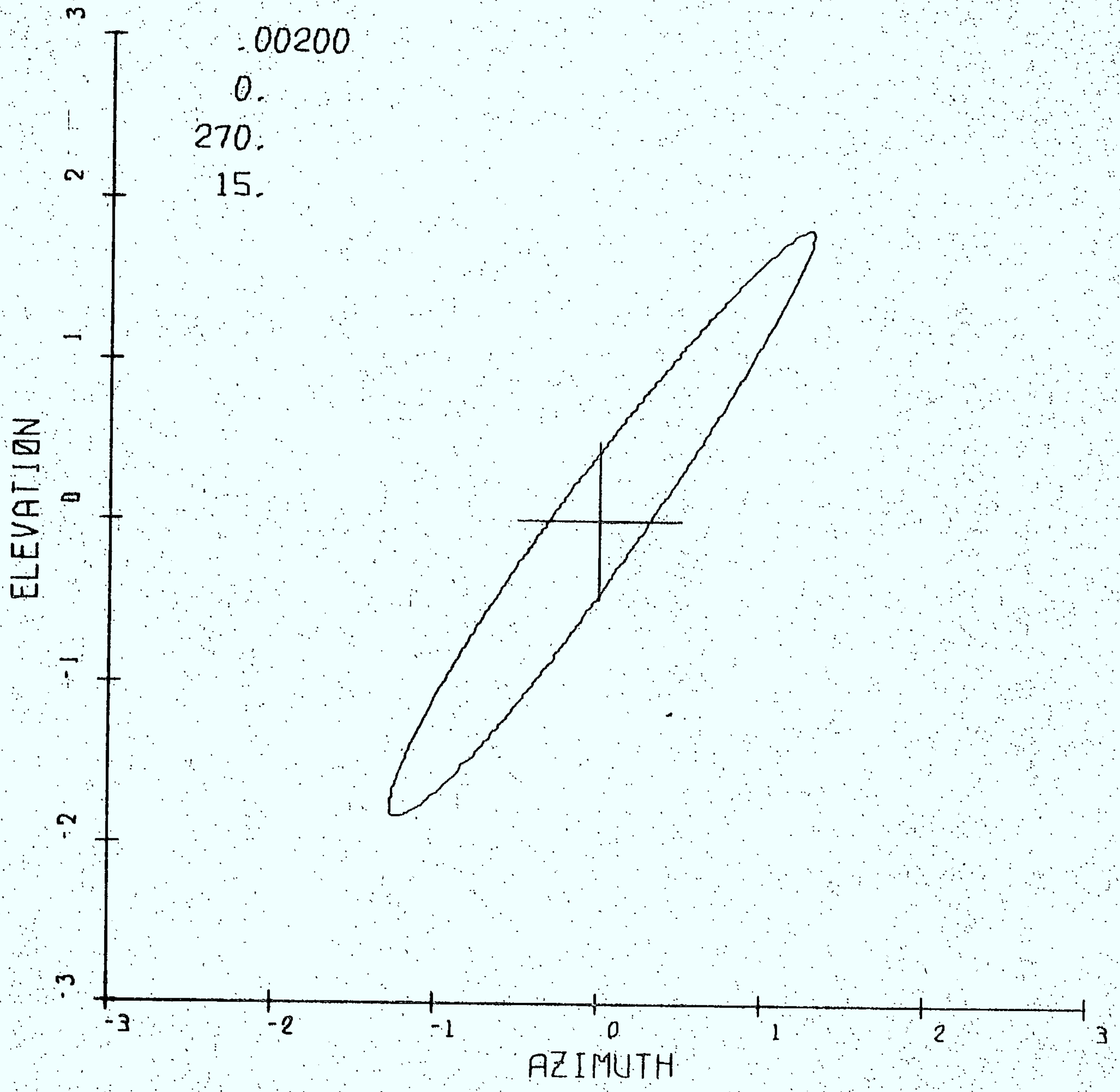
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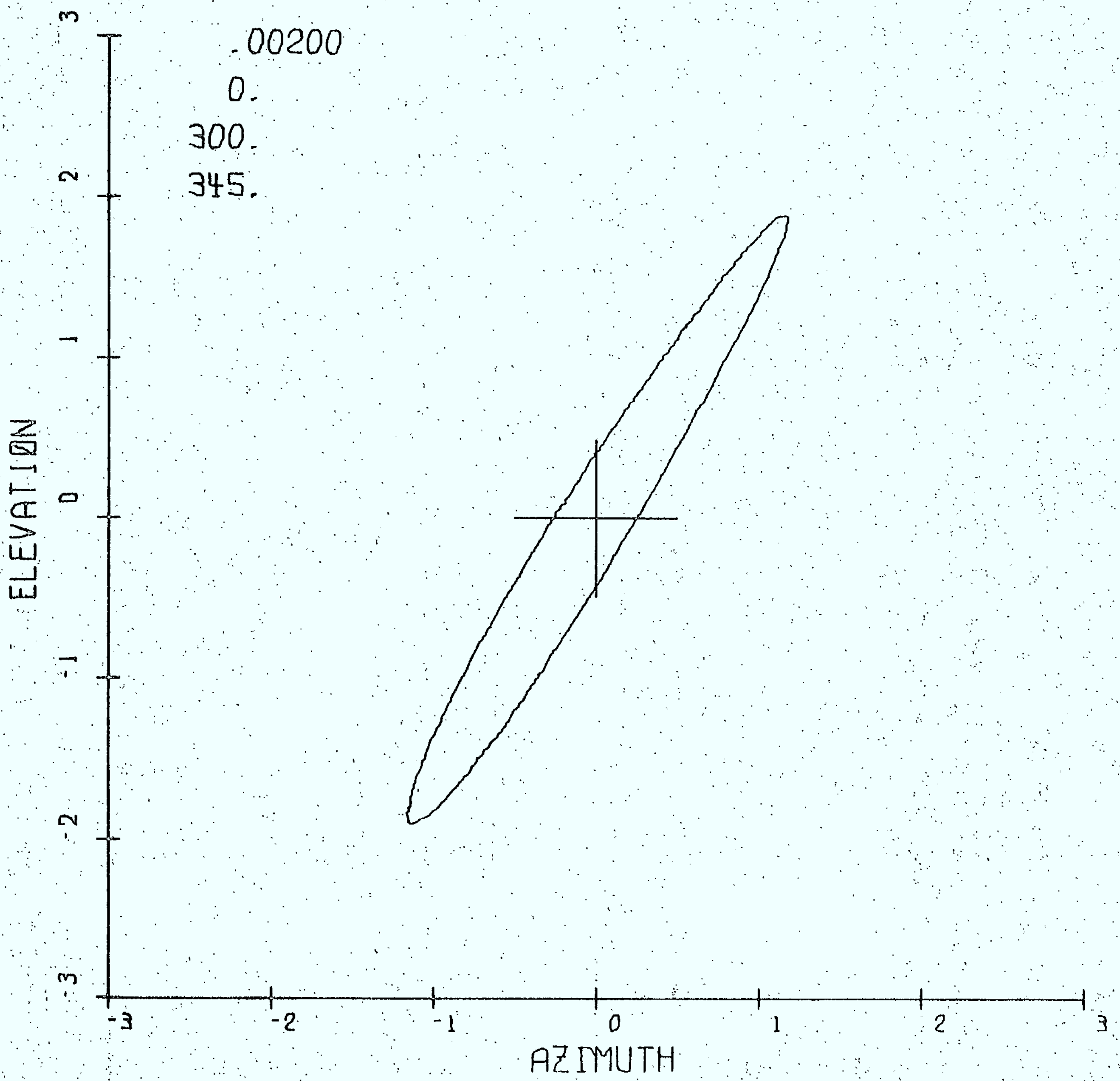
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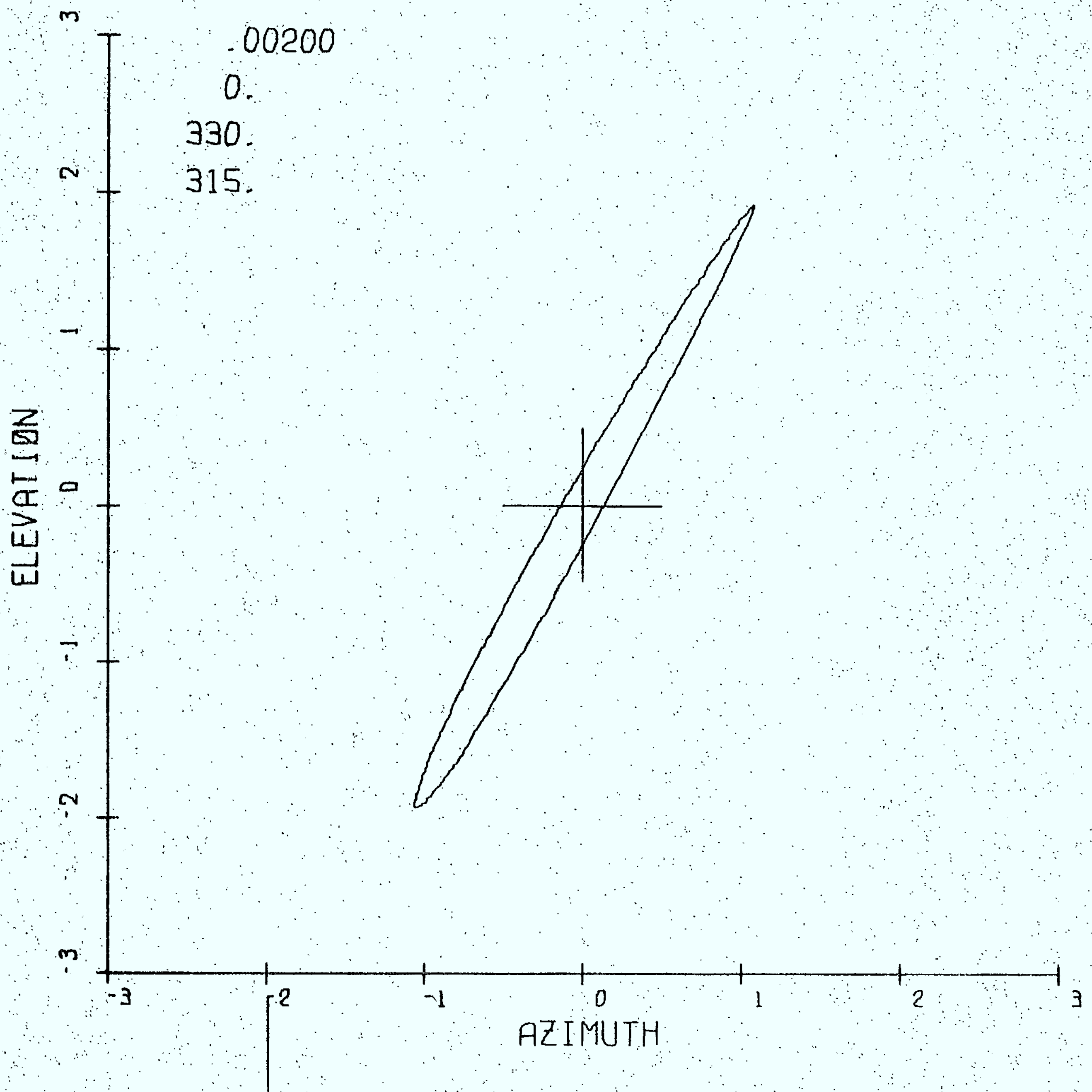
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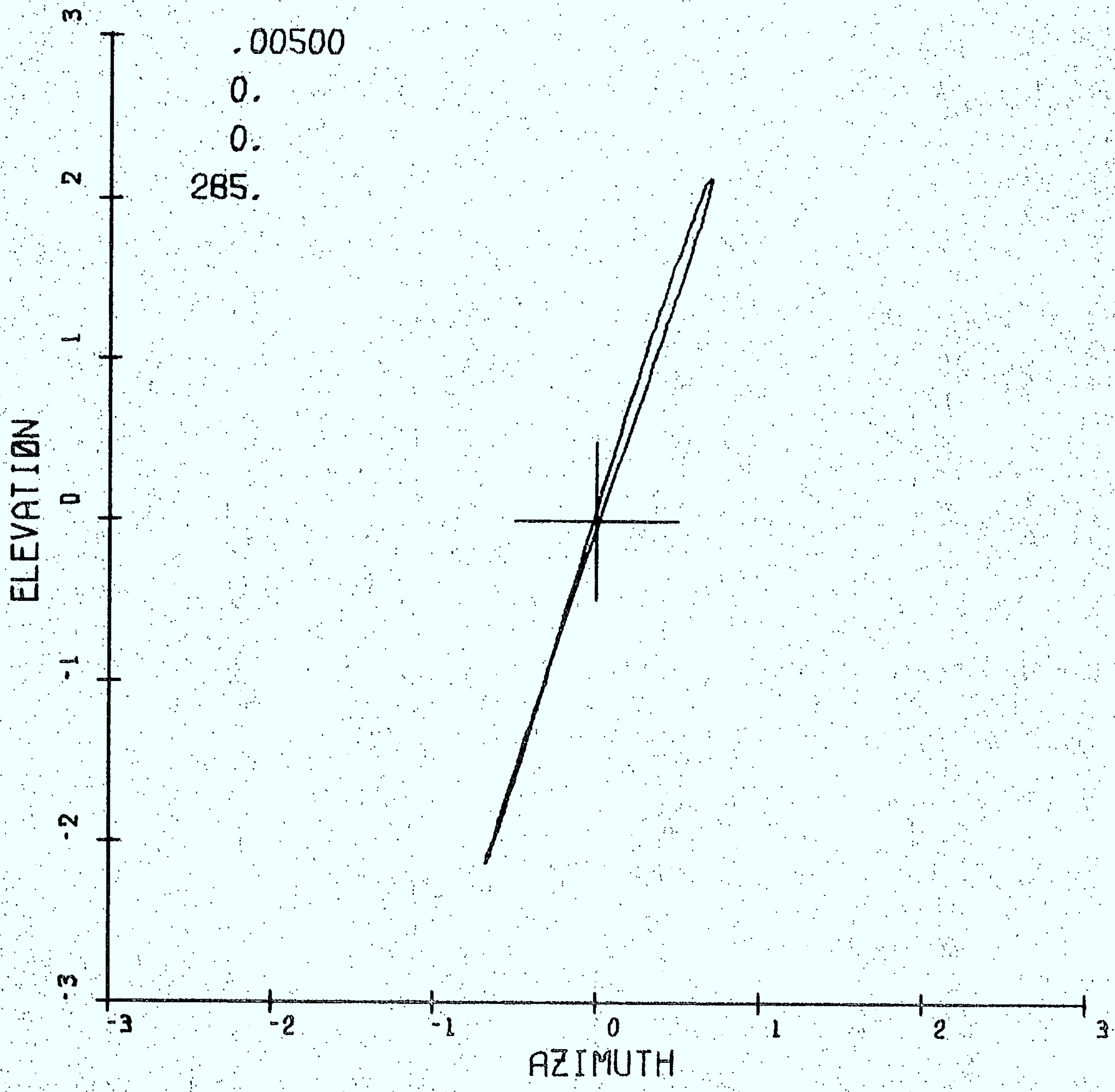

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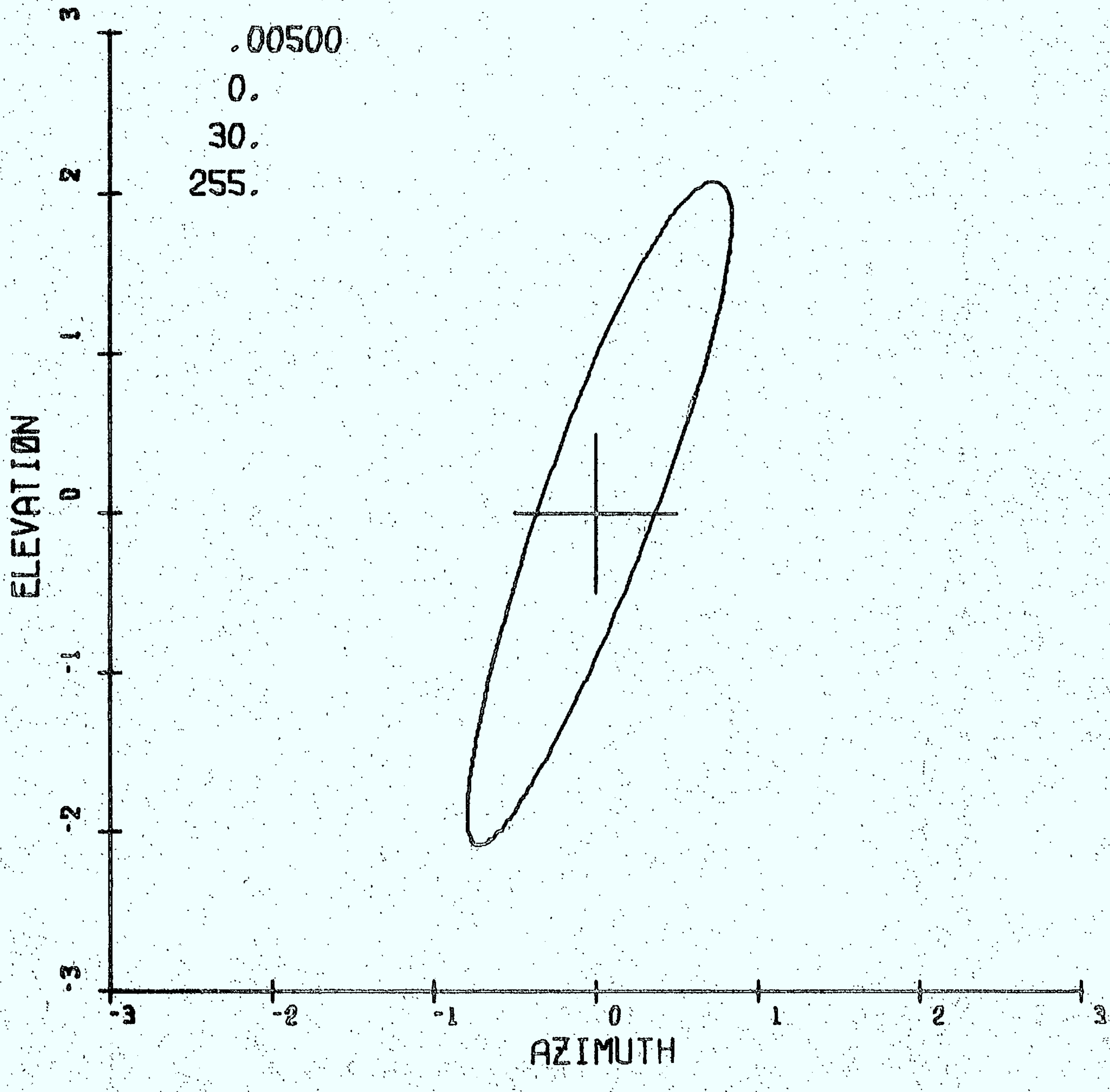
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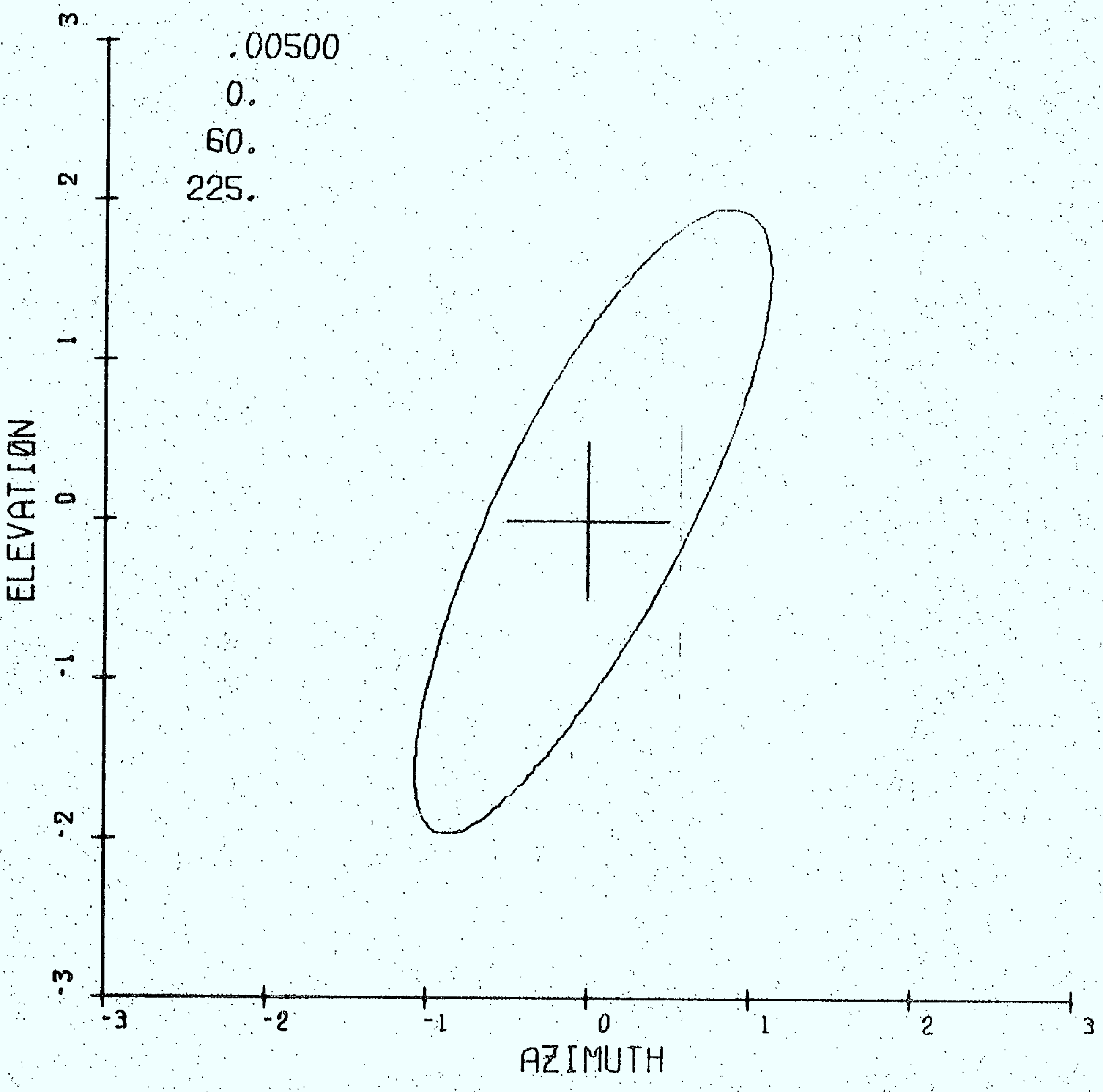
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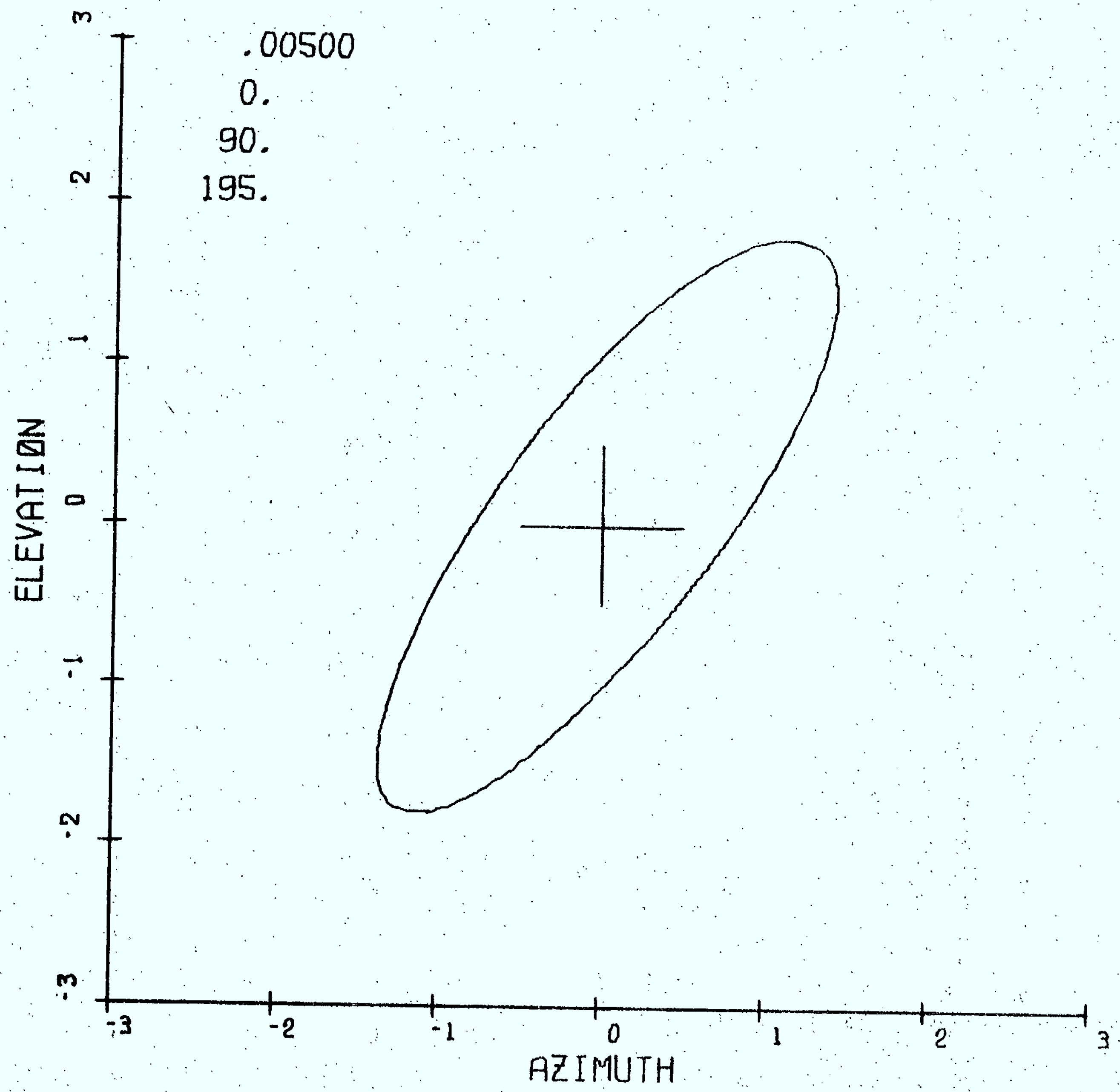

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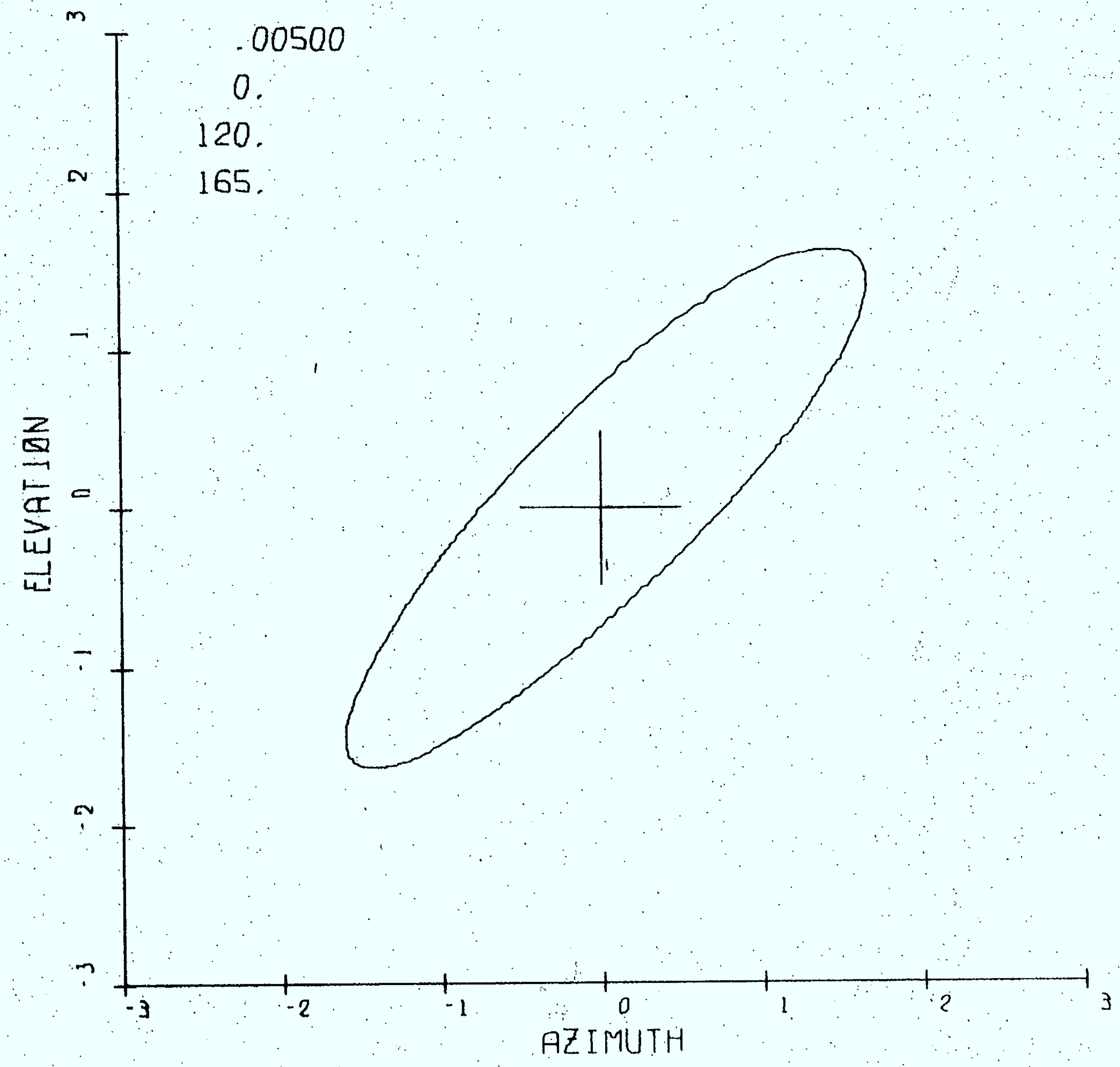
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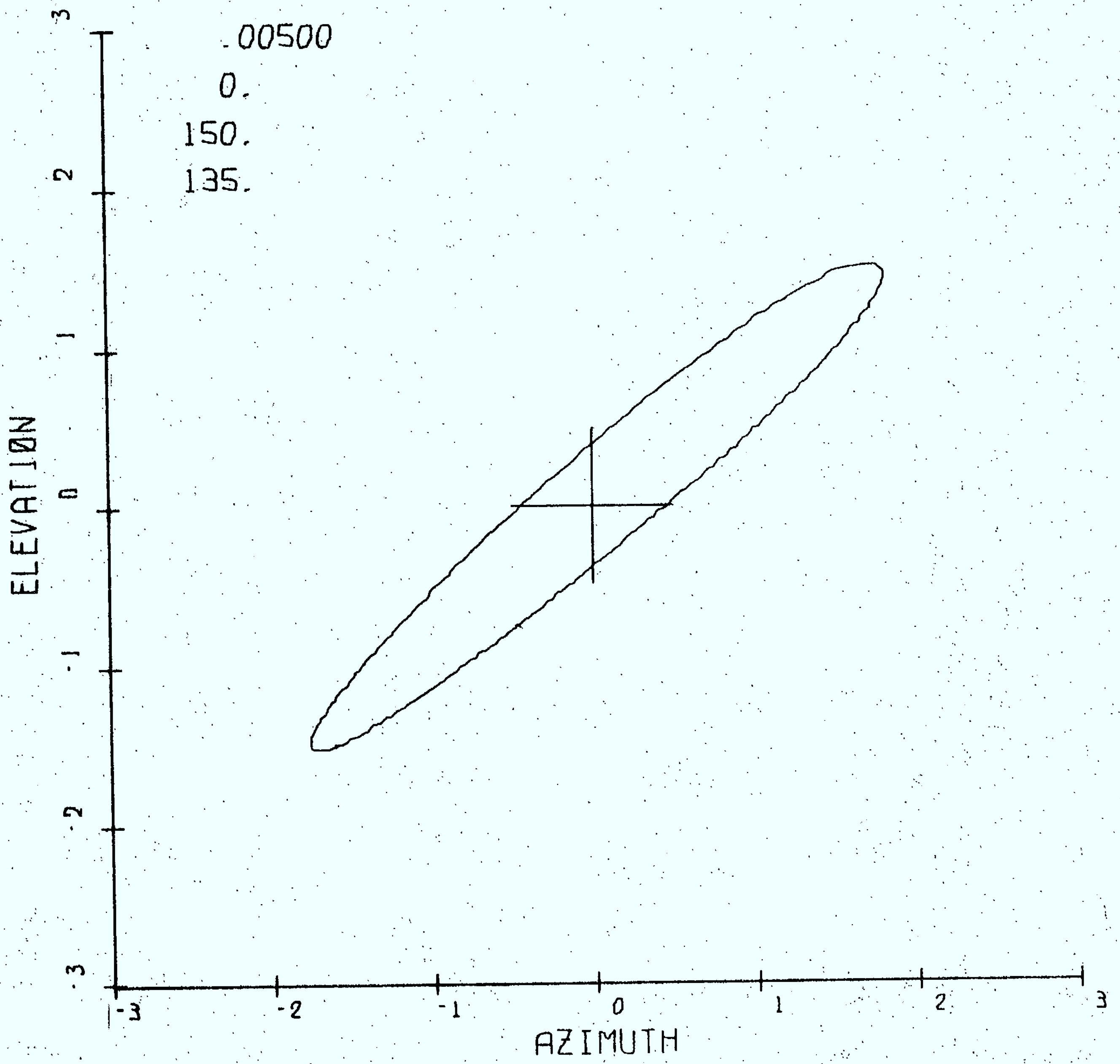
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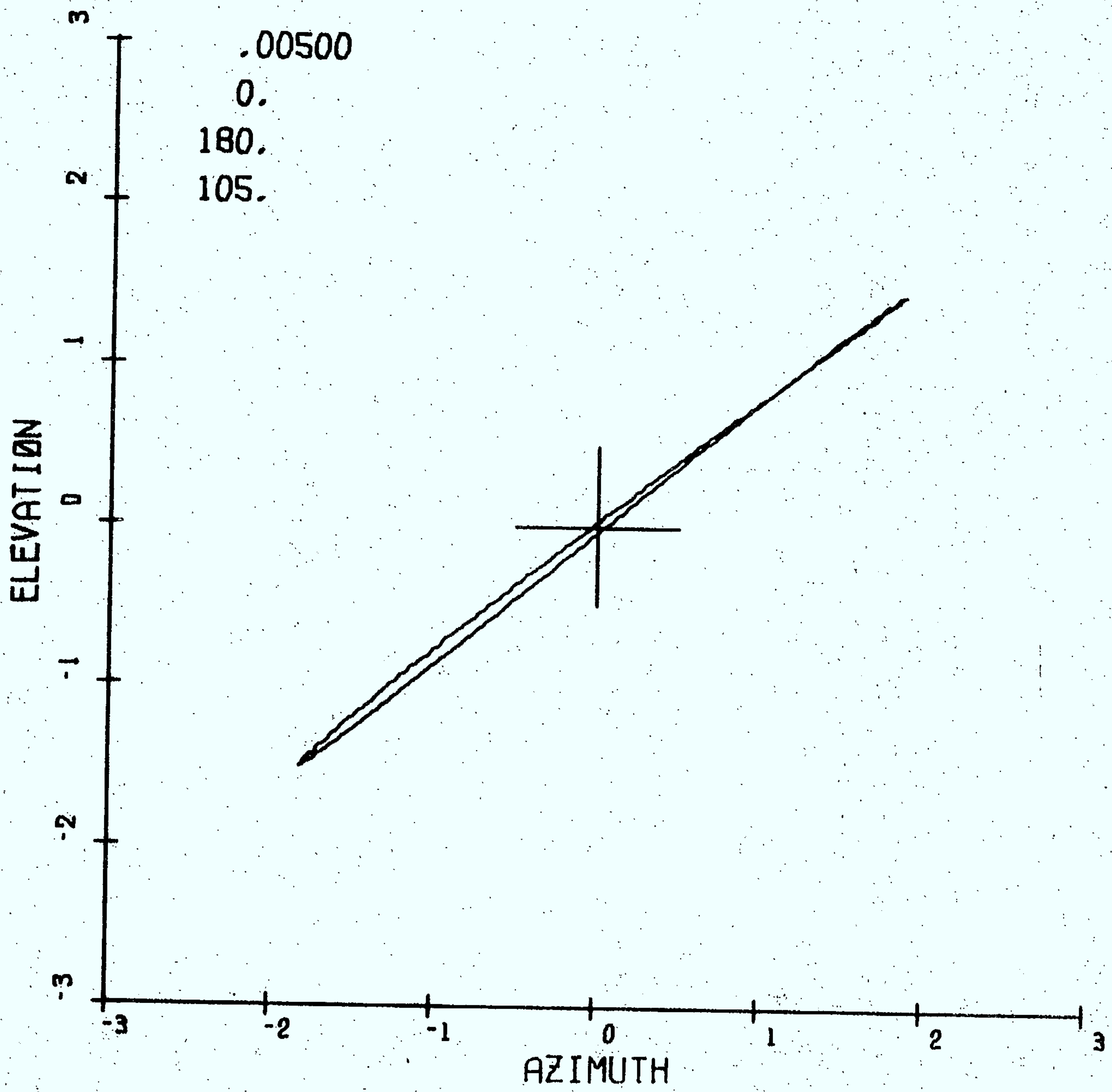
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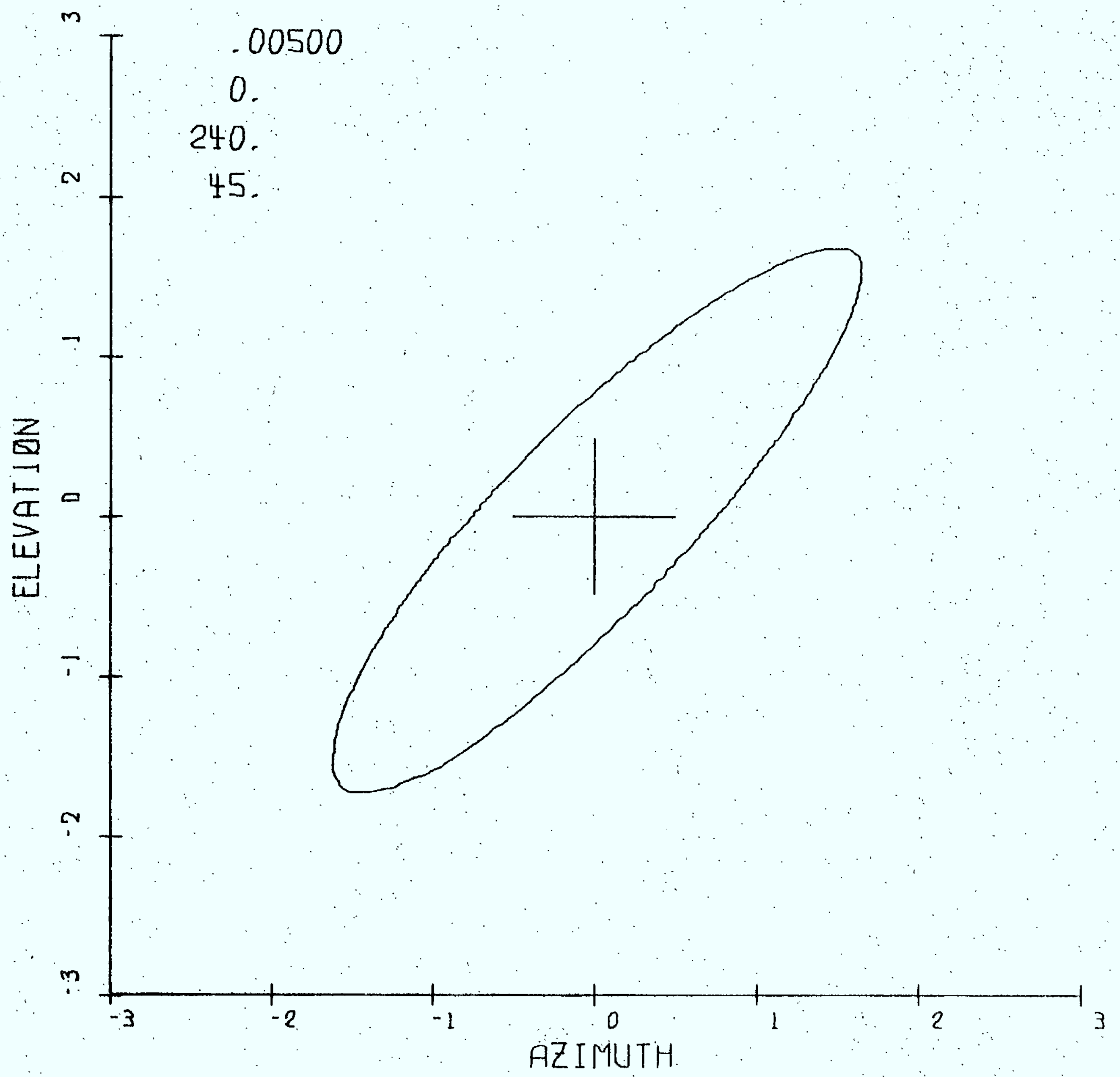
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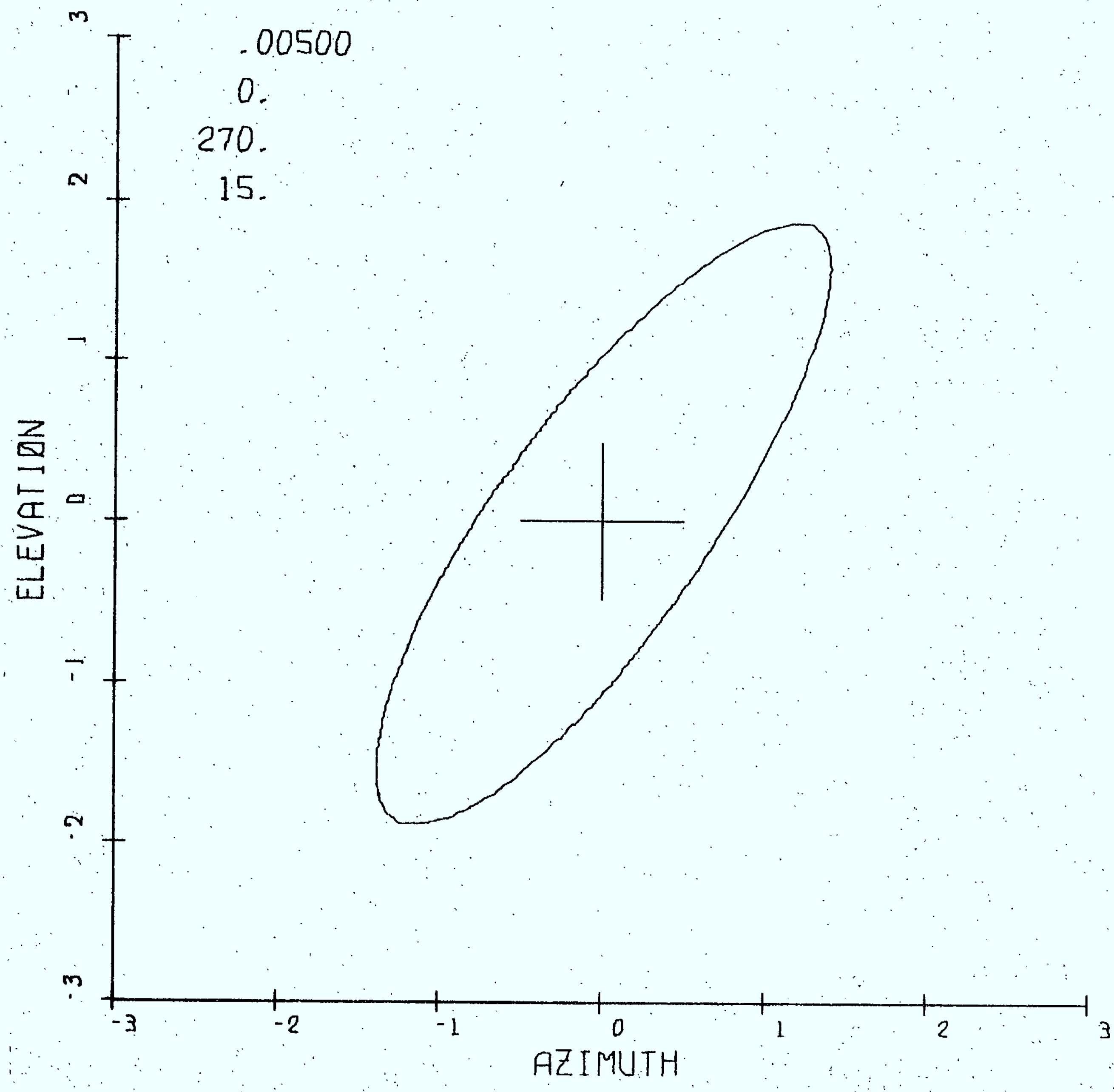
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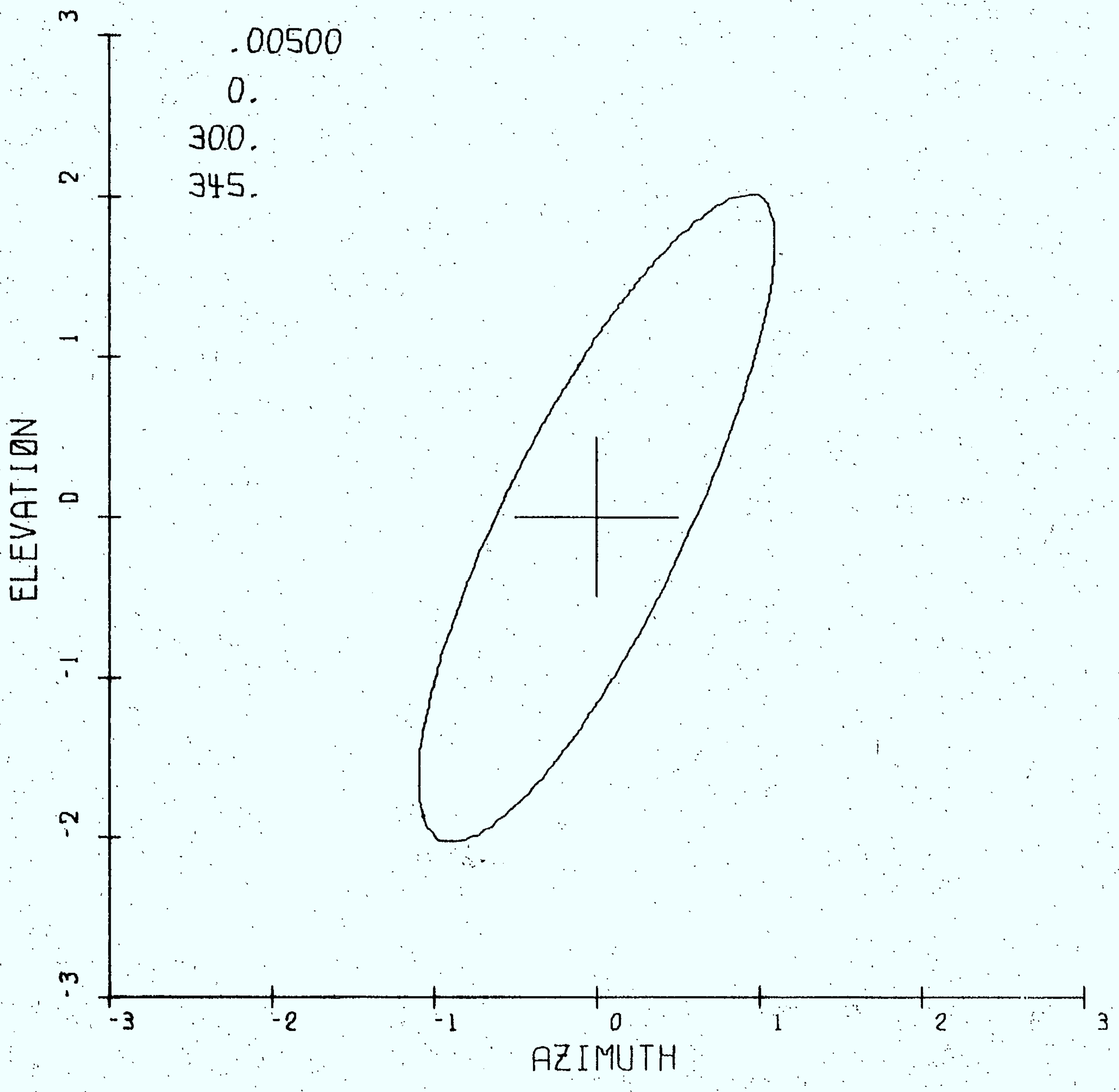
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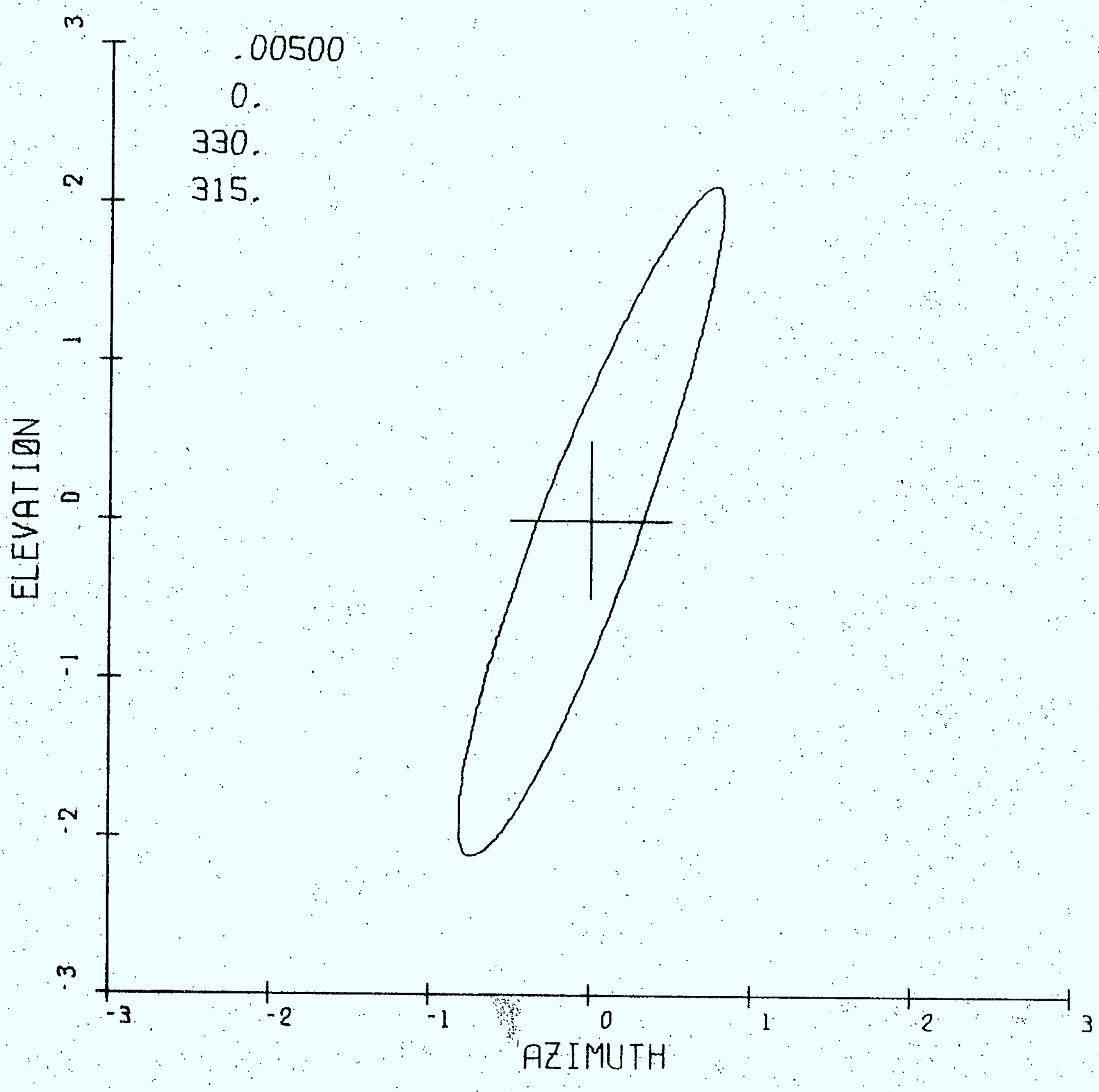

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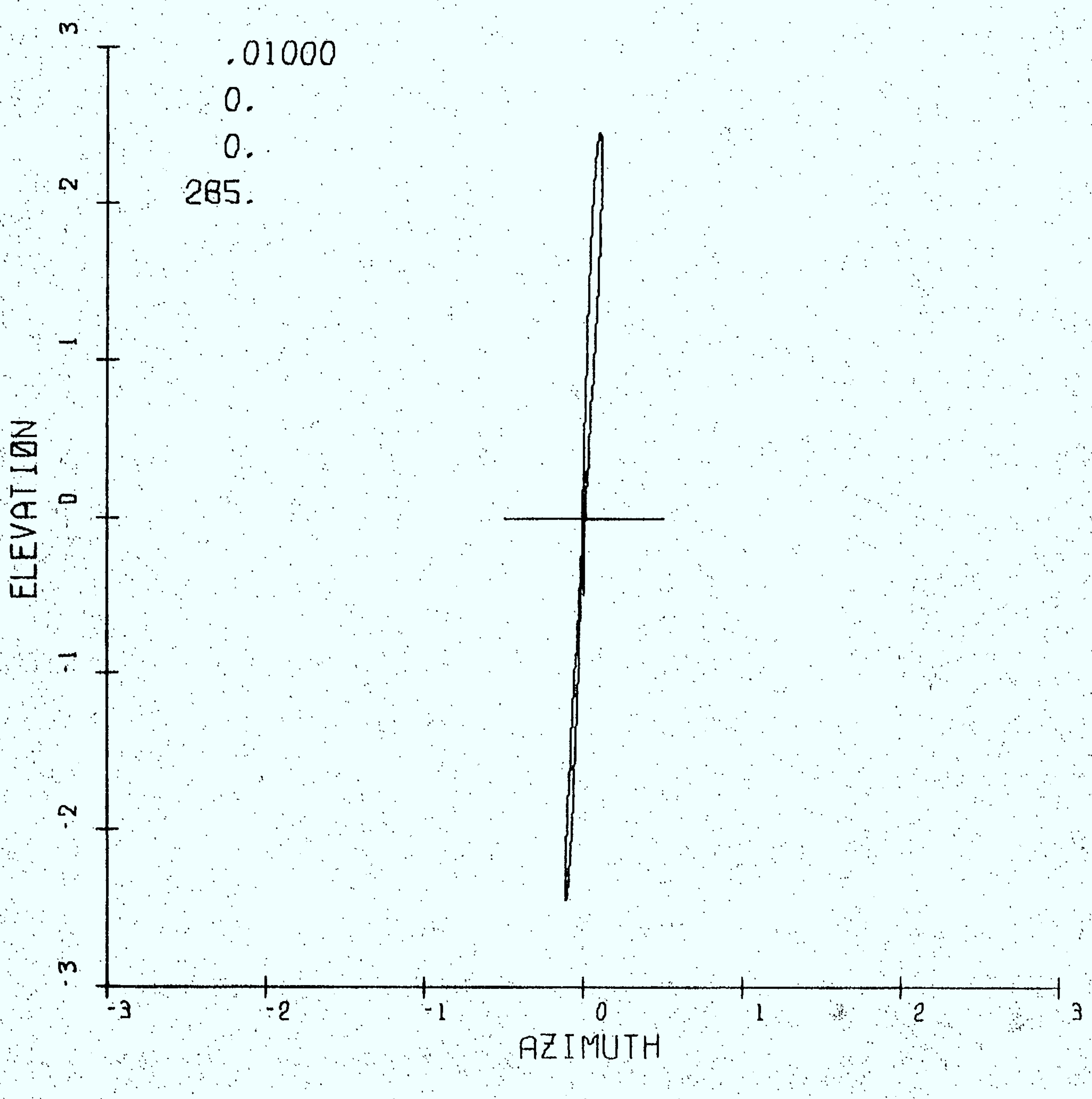

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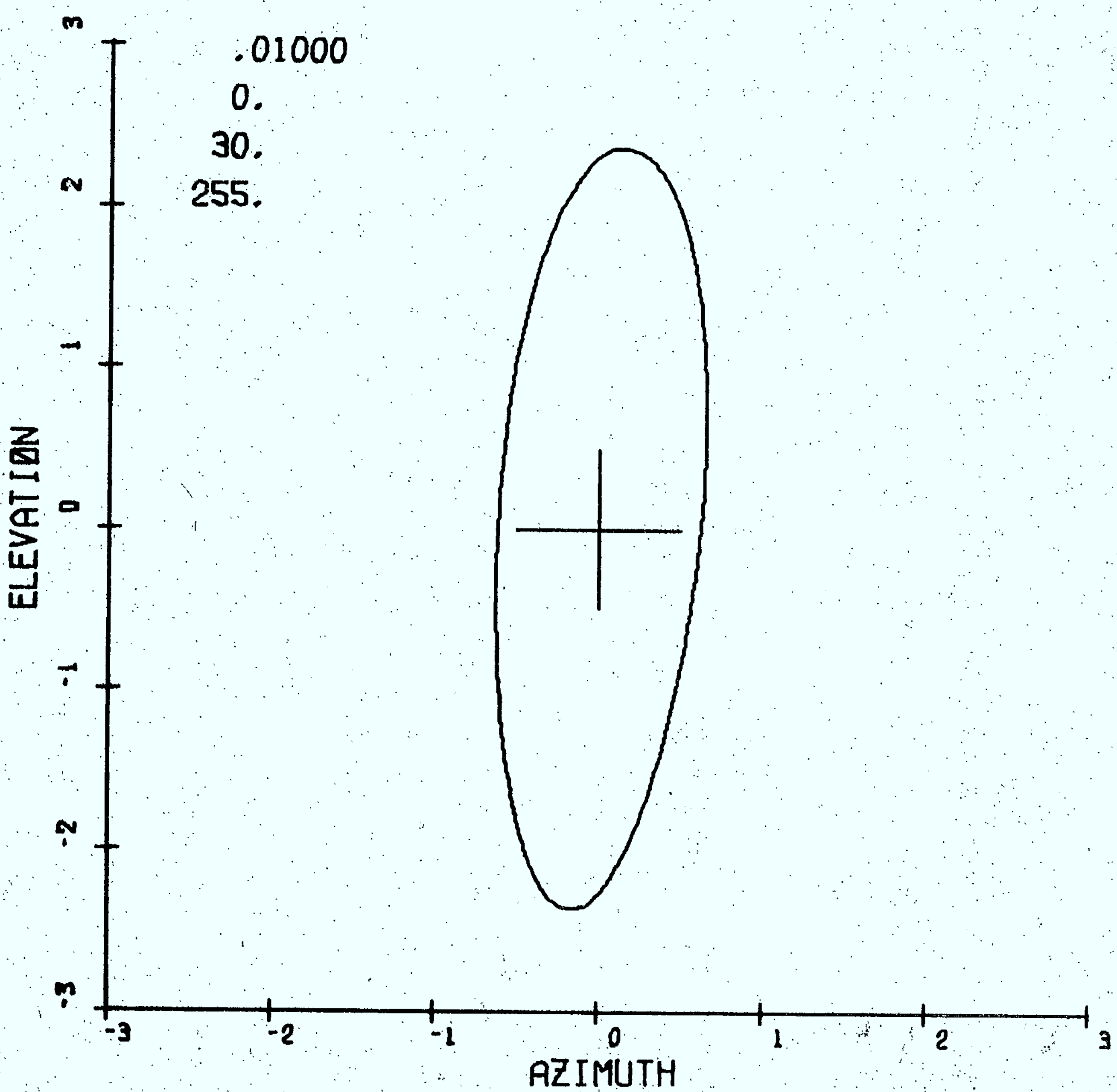

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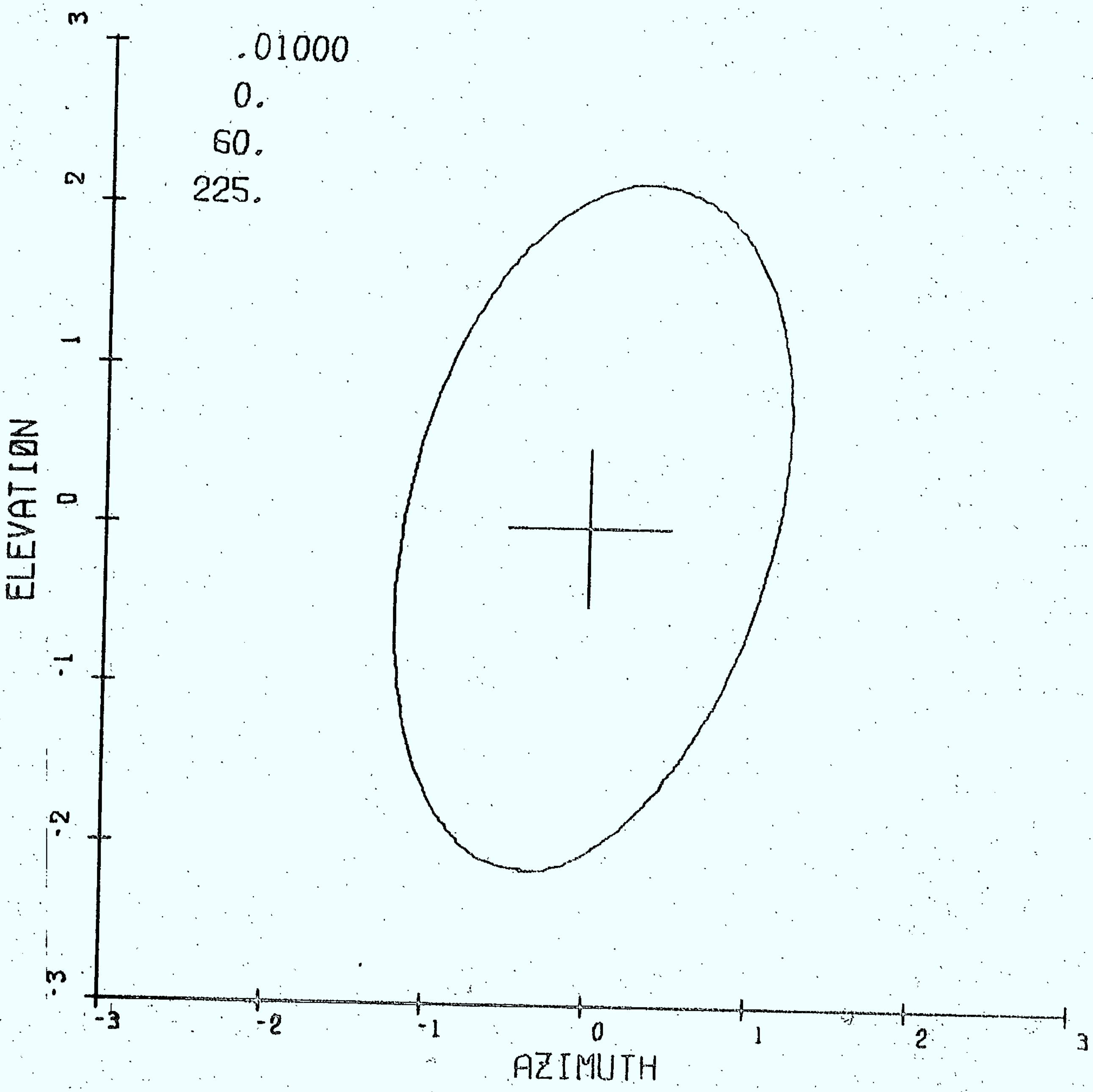
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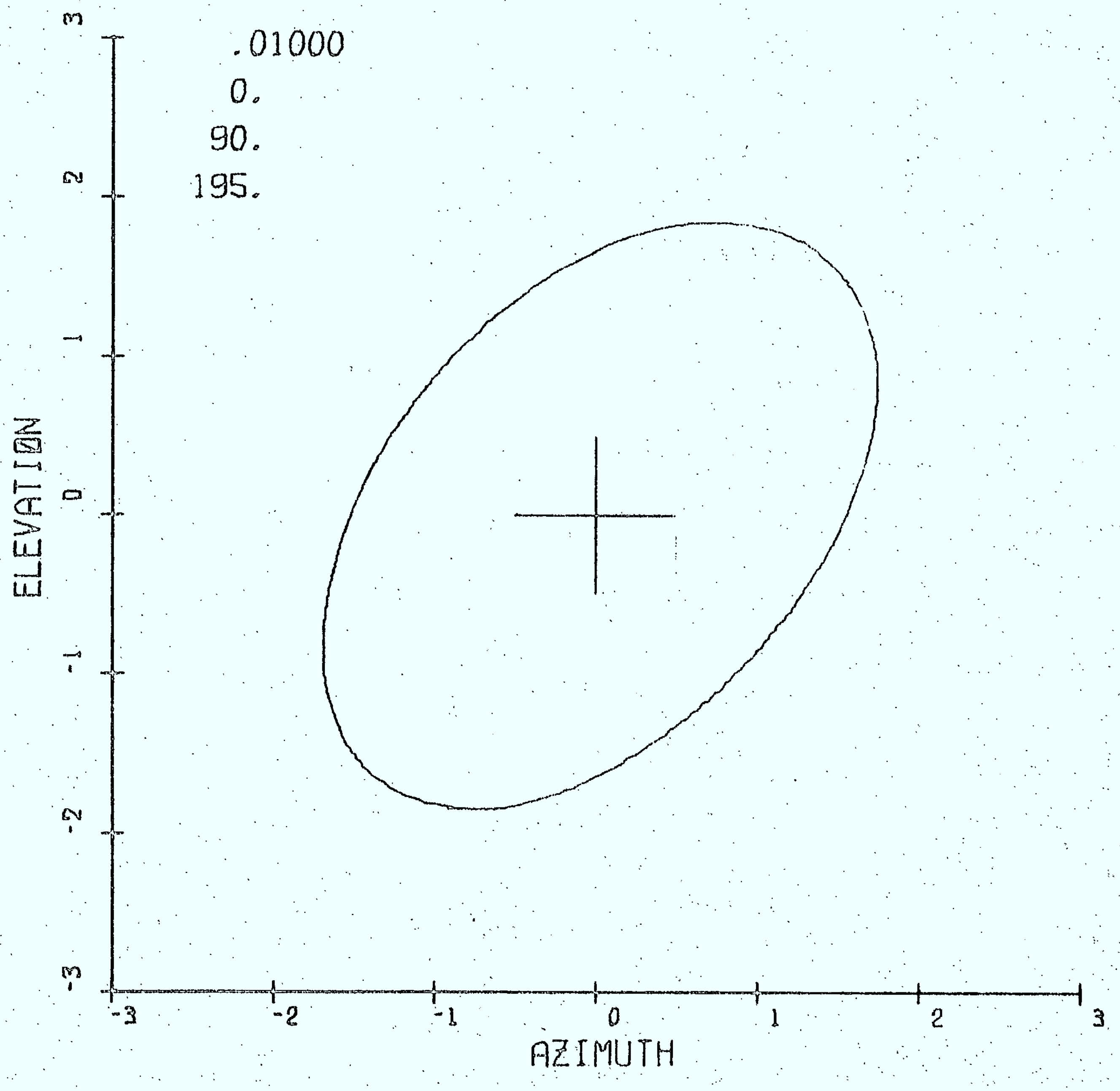

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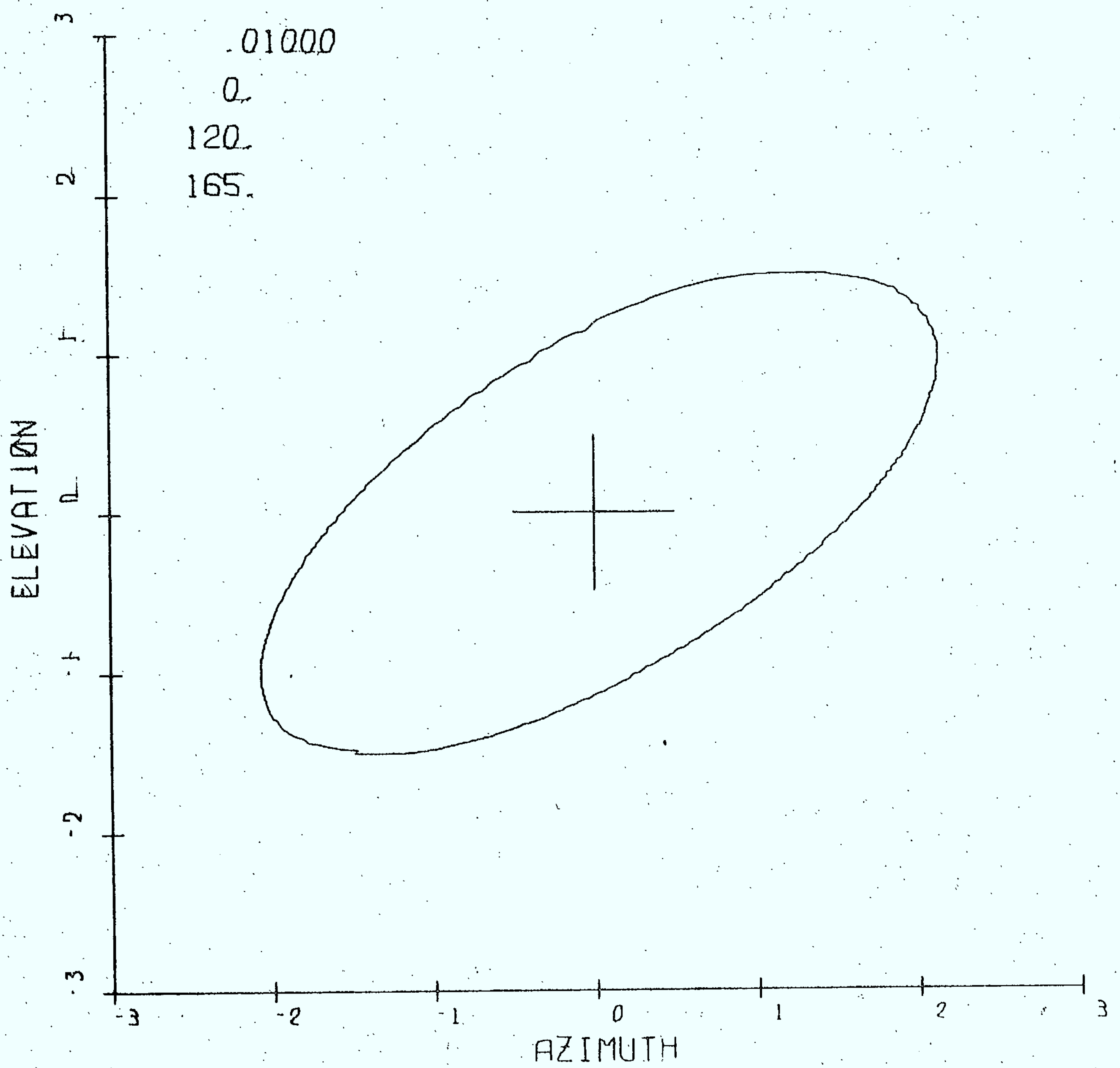

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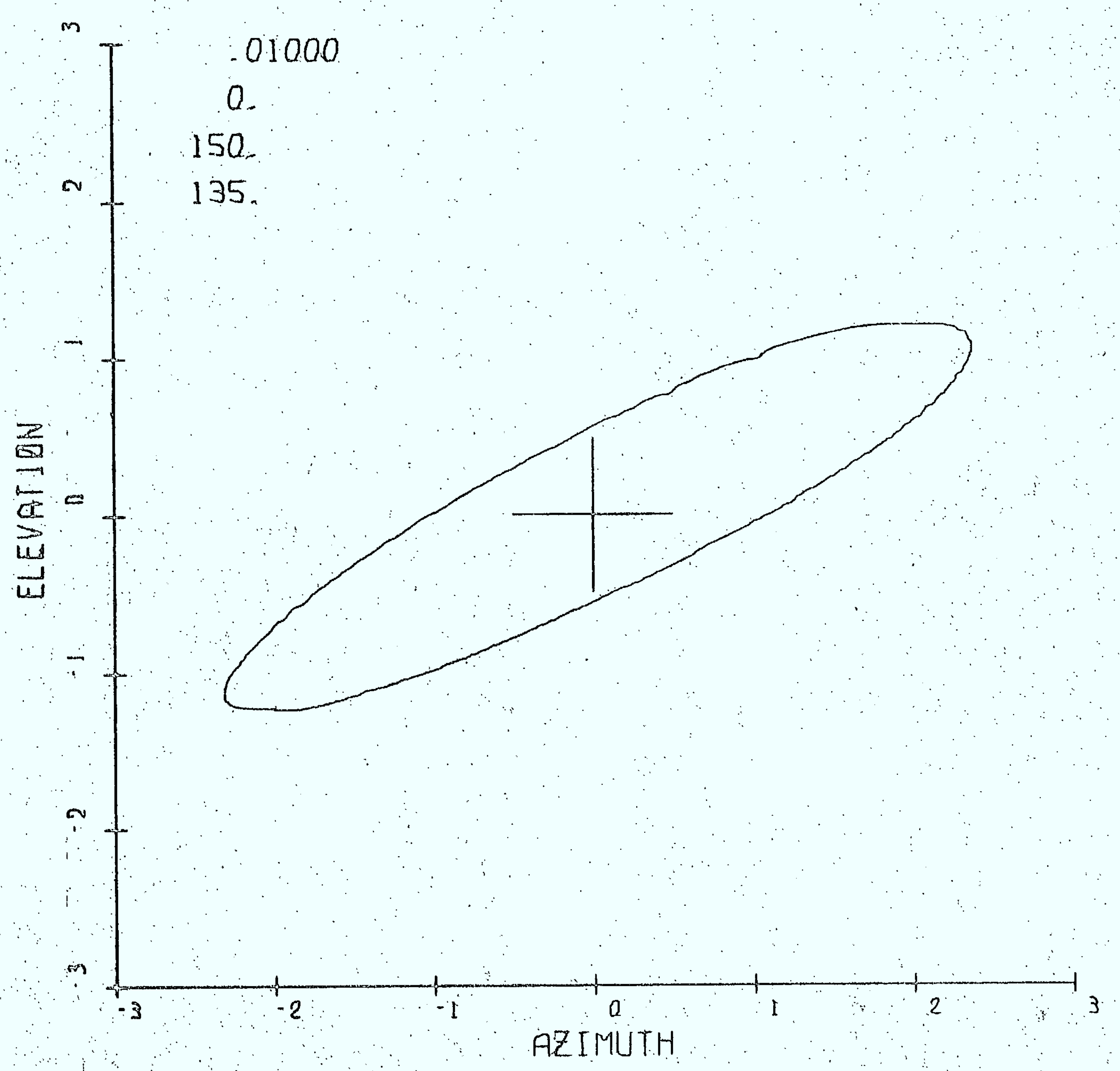
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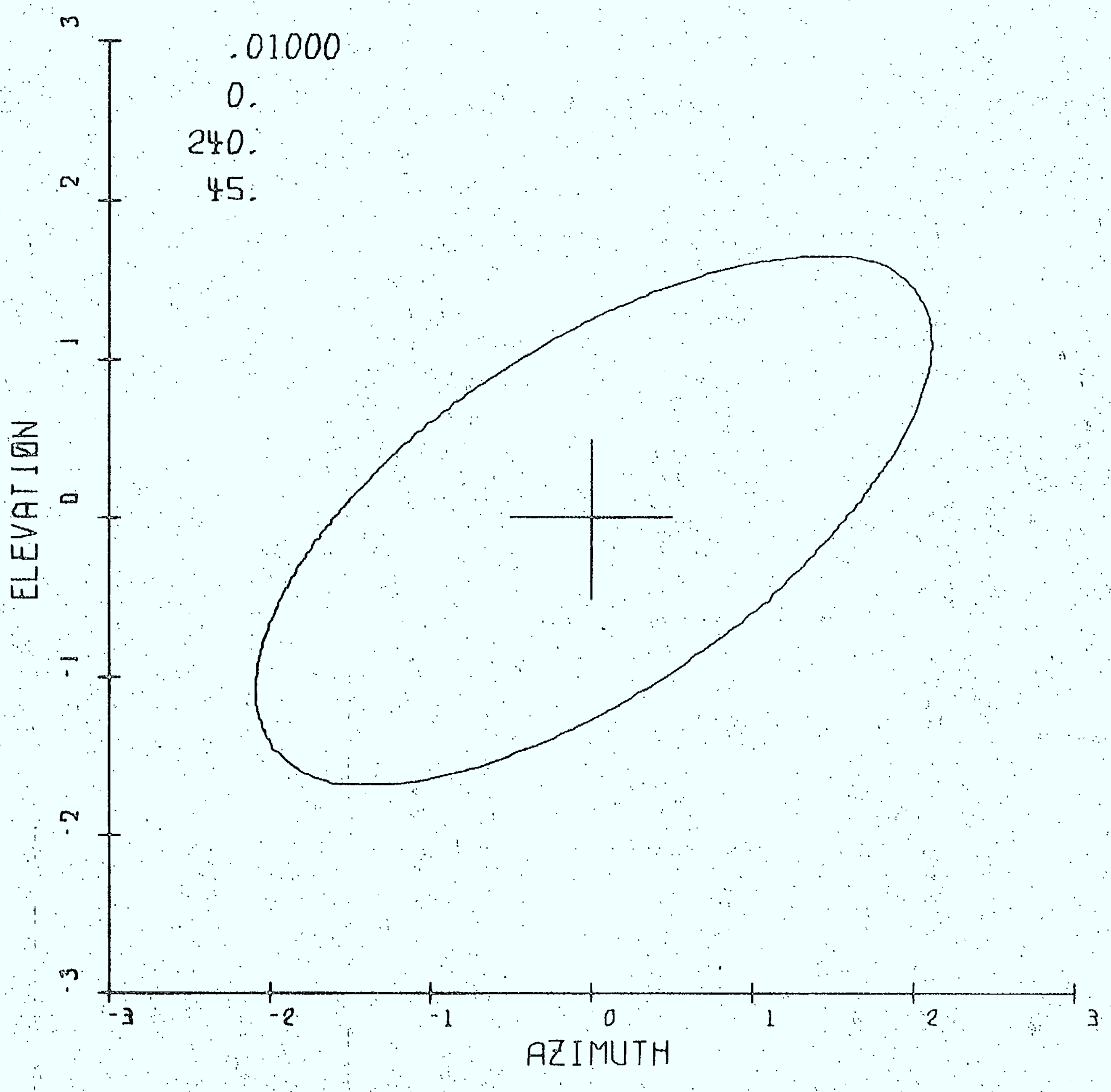

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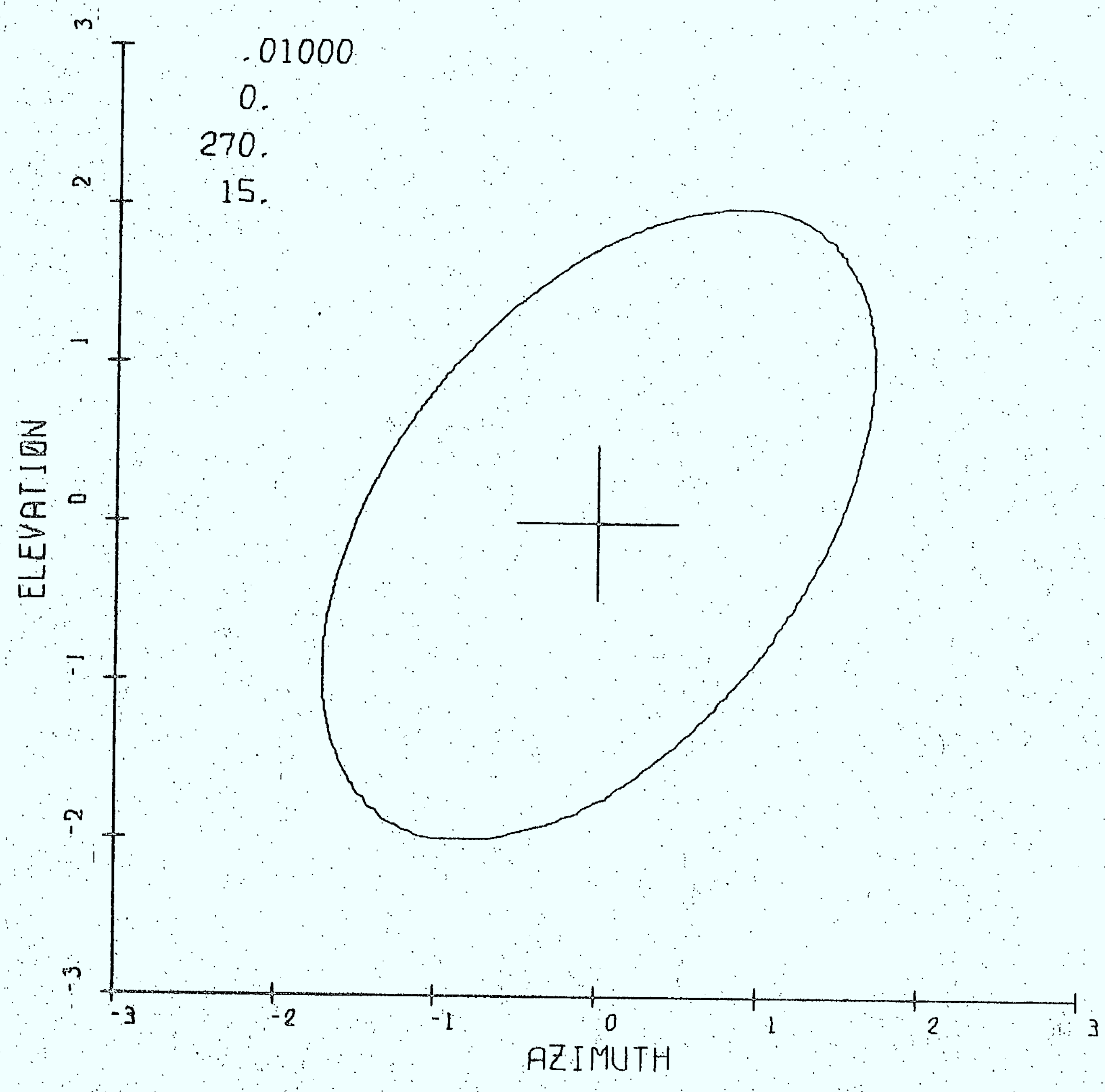

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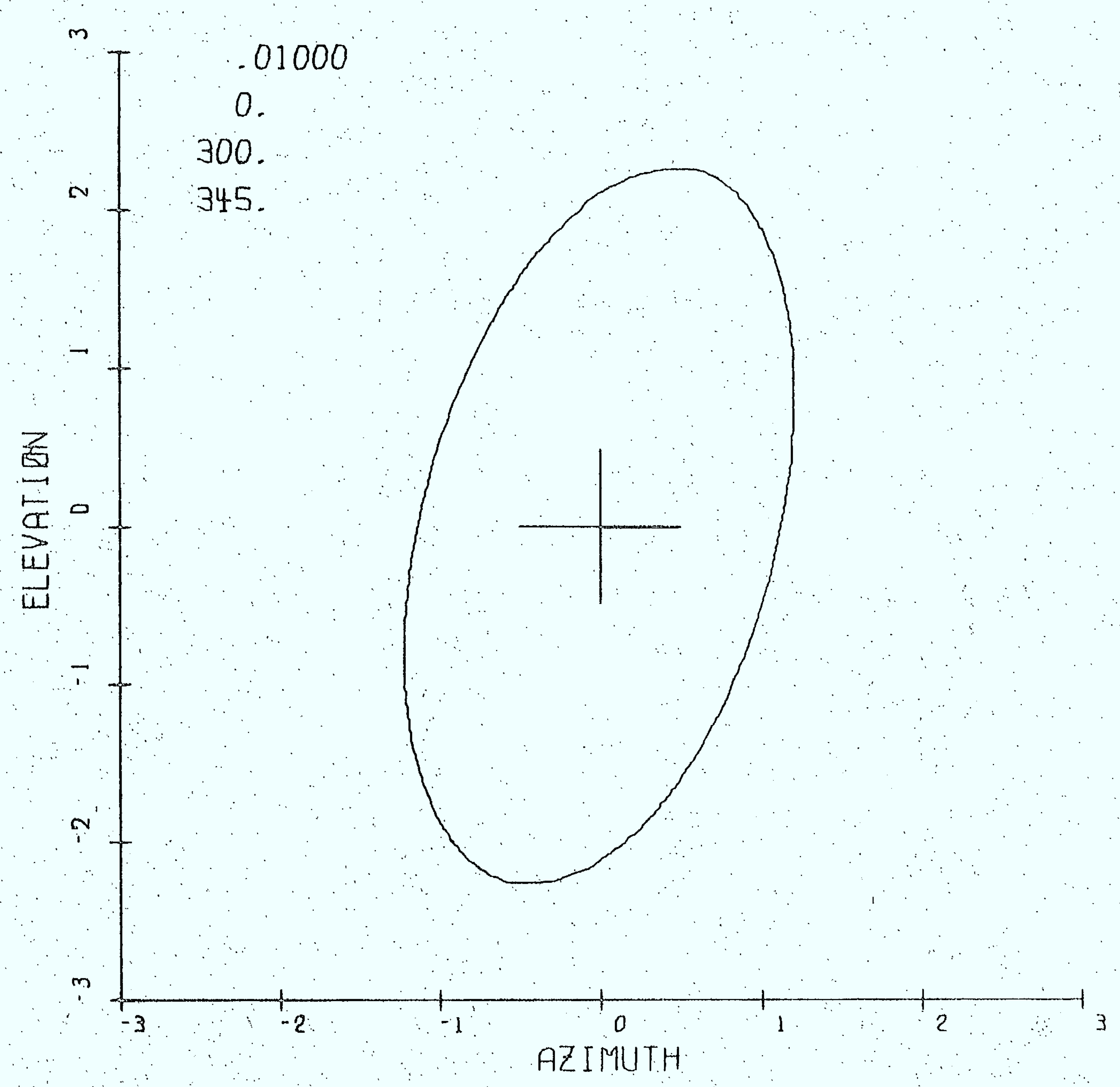
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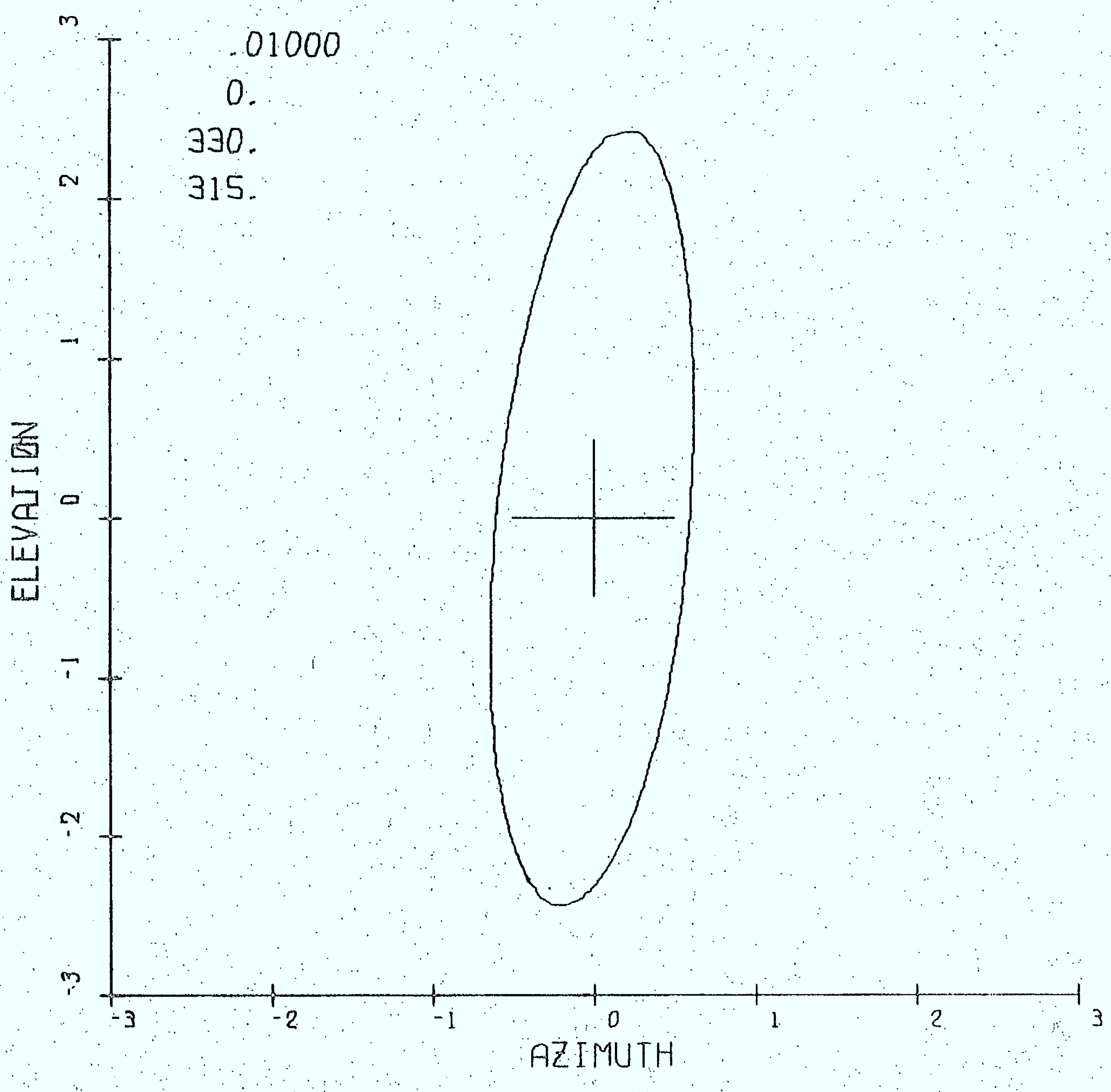
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APPENDIX B

STEP-TRACK CONSIDERATIONS

STEP TRACK CONSIDERATIONS

1. Allowable Maximum Gain Degradation

We assume that a maximum gain degradation of 1.0 dB is allowable for the step track system.

2. Step Size

In keeping with the 1.0 dB maximum allowable gain degradation, it is desirable to approach the maxima of the beam as closely as possible when optimizing the pointing direction. A study of Figure B1 indicates that a $\pm$ 0.04 step could potentially locate the beam within 0.1 dB of the maximum level. Furthermore, at the 0.5 dB point of the beam where the slope is becoming much steeper (12 dB/degree) the 0.04° step provides an easily detectable change of up to 0.5 dB/step.

3. Criterion for Pointing Correction

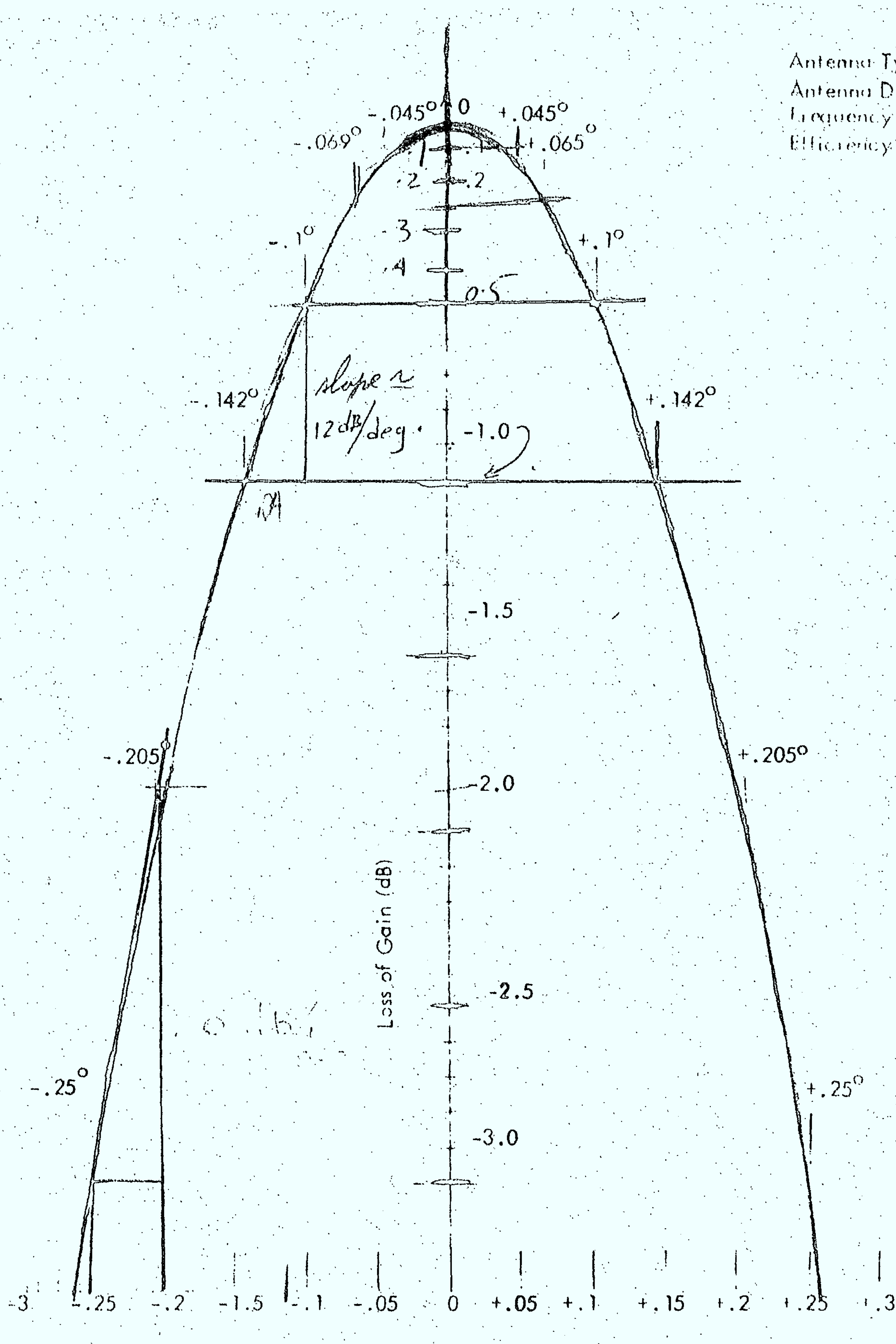
A gain degradation of 1.0 dB occurs at $\pm$ 0.14° on the beam. From vectorial addition, it follows that the maximum pointing error for each axis due to the operation of the step track system should be limited to 0.1°. Therefore, if the beam's pointing direction is corrected within + 0.1 dB, then a further degradation of 0.4 dB is available prior to the next pointing correction. This 0.4 dB would be used directly as a criterion for the optimum hold system. (See Figure B1, 0.1 dB and 0.4 dB = 0.5 dB which occurs at the 0.1° level). A step in the wrong direction (which will occur since the tracking system will not always know the correct direction to step) will result in a pointing error of no greater than $+0.1 + 0.04 = +0.14^{\circ}$ (1.0 dB level).

The continuous stepping system, however, has the advantage of not requiring the 0.4 dB criterion and this would tend to hold the worst case closer to 0.5 dB.

4. Effect of Signal Fading

Signal fading, if significant (say more than one or two tenths of a dB) would result in a wrong decision following the integration of the AGC voltage. We will first consider the beginning of a fade. For a step in the correct sense, the net result due to the erroneous indication, by the algorithm, would be a step back to the original pattern. For a step in the incorrect sense, the fade would show an even worse result but would not effect a wrong decision. At worst then, the fade while in the transient state, could prevent a signal improvement for the case when the fade begins. Now, during the steady state portion of the fade period, the system would simply track in the usual manner. During the fade recovery transient period, however, a sudden increase in signal level could obscure a decrease in level due to a step in the wrong

Antenna Type = Cassegrain
Antenna Diameter = 10 ft.
Frequency = 14 GHz
Efficiency = 55%



ANGLE OFF BORESIGHT (DEGREES)

FIGURE B1

LOSS OF ANTENNA GAIN WHEN POINTING OFF BORESIGHT

4. Effect of Signal Fading (Continued)

direction. The result would be an incorrect decision and a change of pointing direction away from the axis of the beam. This may not be serious, however, since the beam should originally have been in the near optimum orientation.

A method of minimizing fade problems might be to automatically disable the system during fades.

5. Wind Effects

The effect of wind shouldn't be a serious problem since the structure is designed to limit motions to within approximately $\pm 0.03^o$. For the continuous stepping system it may result in momentary wrong decisions which would subsequently be corrected. The gain degradation would not, however, exceed 1.0 dB. For the optimum hold system, wind effects would prematurely initiate an optimization sequence but this would not be a serious problem.

STEP TRACK SYSTEM CONTROL

ALGORITHM POSSIBILITIES

Two system control algorithms are considered here. The first is the continuous stepping system. The second is the optimum hold approach which involves stepping only when a pointing correction is required. The control algorithm for each system is given below:

Method 1 (Continuous Stepping)

With this method, a cycle would occur in the elevation plane followed by a cycle in the azimuth plane. The cycles would repeat themselves continuously.

1. Step in one direction (either plane).

2. If an increase in level occurs switch to other plane. Otherwise step back once and switch to the other plane.

3. Repeat steps 1 and 2. (Step 1 starts with a step in the same direction as the previous step for the particular plane).

NOTE: This system could be designed such that it operates for only a specific duration following a specific time interval.

Method 2 (Optimum Hold)

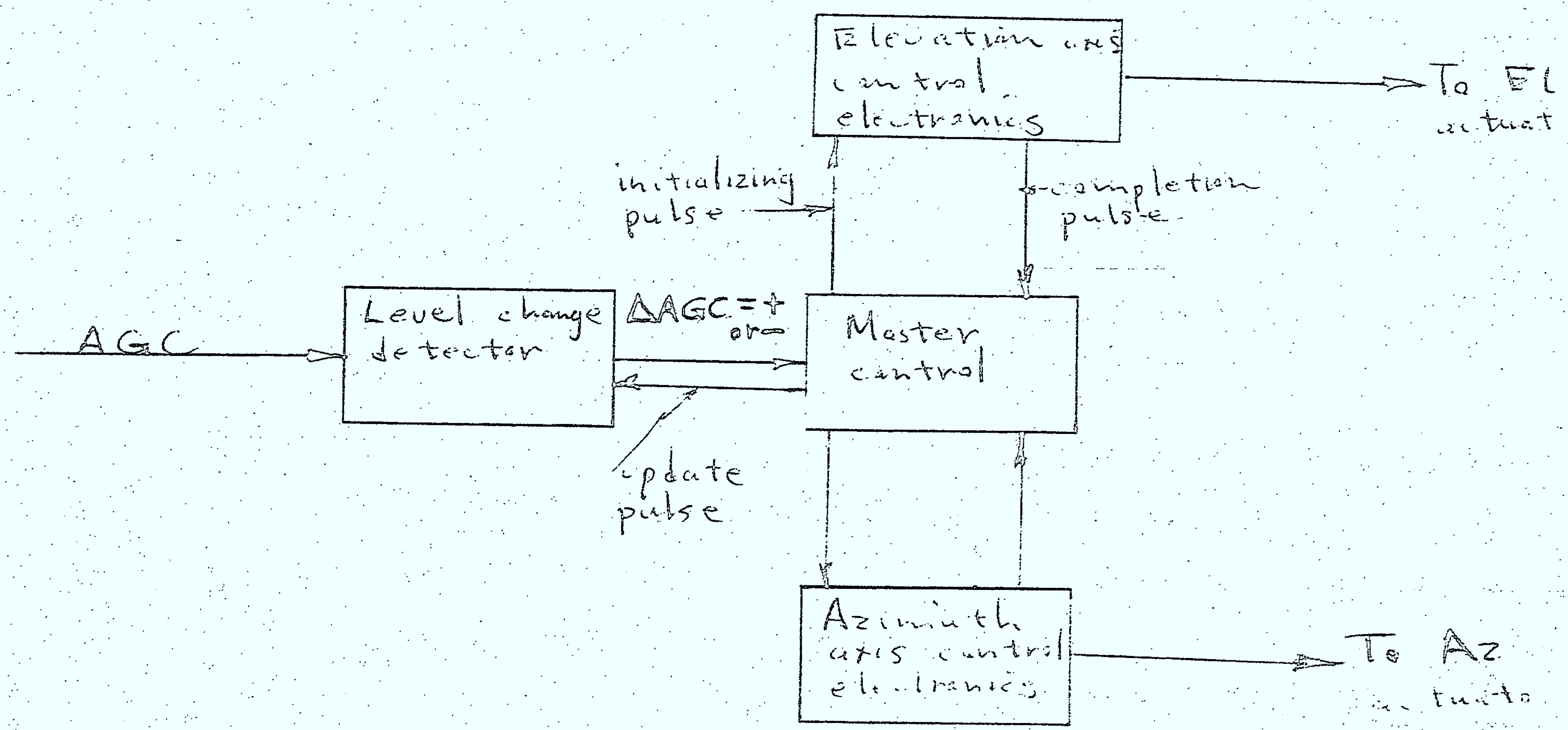
With this approach an optimization occurs in both planes following the observance of a degradation of signal level of more than 0.4 dB relative to the signal level immediately following the previous optimization. During the period between optimizations, the memory of the previous signal level is updated if and only if a signal increase occurs. This is to avoid fade problems.

1. Perform steps 2 to 4 twice.

2. Step in one direction (either plane)

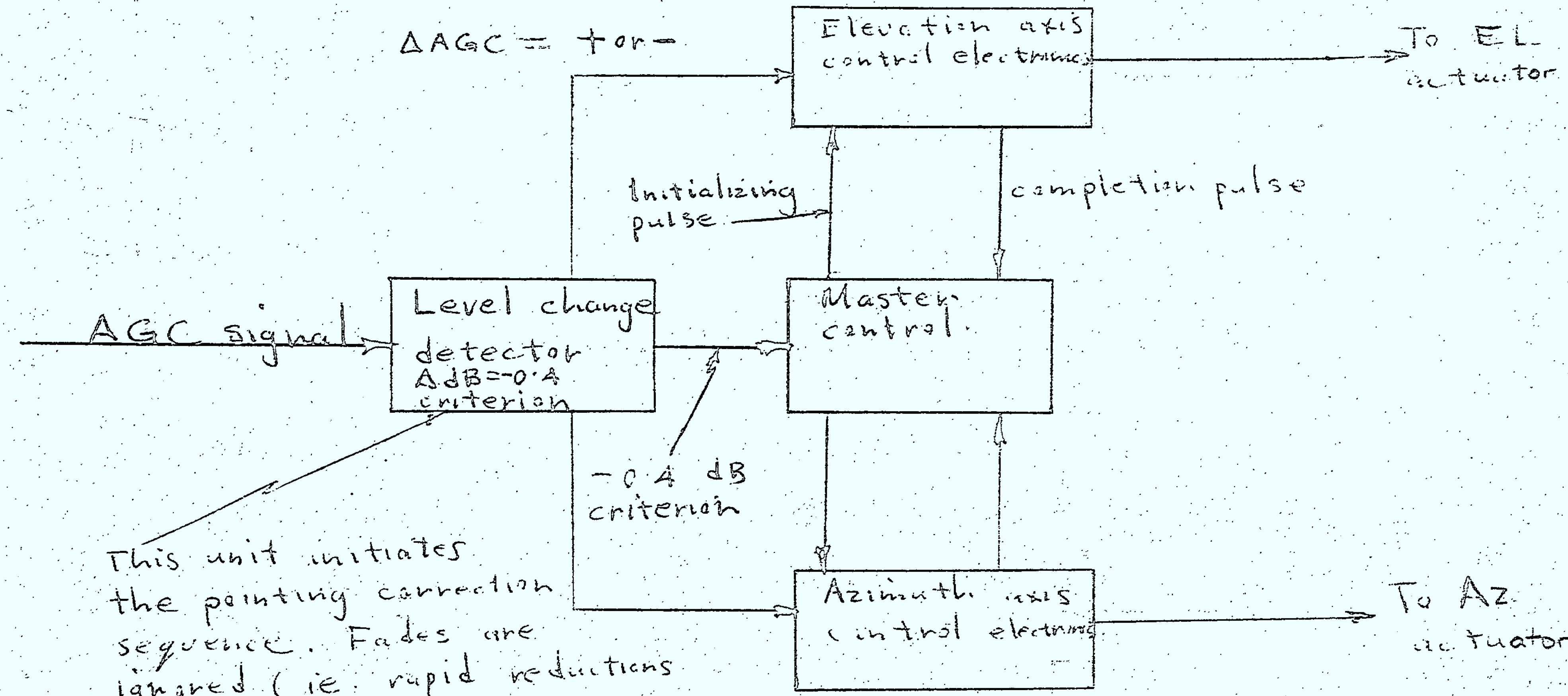
3. If an increase in level occurs switch to the other plane. Otherwise step back once and switch to the other plane.

4. Repeat steps 2 and 3.



CONTINUOUS STEPPING SYSTEM

FIGURE B.2



This unit initiates the pointing correction sequence. Fades are ignored (ie. rapid reductions in signal level of greater than say 0·3 dB.) The AGC signal is integrated over say 15 second intervals.

OPTIMUM HOLD SYSTEM

FIGURE B.3

APPENDIX C

CONE-SCAN TRACKING SYSTEM

CONE-SCAN TRACKING SYSTEM

1. Introduction

The proposed cone-scan represents a simplification relative to the conventional cone-scan system. The conventional cone-scan system obtains its error signal by sweeping the beam continuously in a circle about the axis of the antenna. The beam thus sweeps out a cone (see Figure C1) which if the antenna is not pointed correctly will result in a varying signal level from which the error signal is derived. The simplified system, however, simply scans the beam sequentially in two orthogonal planes. The scanning is not continuous but operates in discrete steps which switch among four different beam directions, two in each orthogonal plane. (See Figure C2). The error signal in each plane of the simplified system is derived from the difference in level observed between the two opposing beam directions.

2. Proposed System

The block diagram of the proposed system is shown in Figure C3. The system centers around a mode controlled feed shown of a Cassegrain antenna. Mode control is effected by exciting higher order modes in the throat region of the horn by means of four normally short circuited coupling loops. The loops store basic mode energy and re-radiate the energy in the form of higher order modes.

The short circuits of the coupling loops can be isolated from the loops by bandpass filters to restrict operation of the tracking system to the tracking frequency only if a separate tracking receiver is utilized although use of the communications band and thus the communications receiver results in a more economical system. Thus with filters the beam is not scanned at the communications frequencies.

Now, if all four loops are short circuited, a symmetrical higher order mode results (i.e. the TM01 mode) and a small change in the shape (or taper) of the beam results but neither the symmetry nor the direction of pointing changes. If, however, one of the loops is terminated into a dissipative load instead of a short circuit, asymmetric modes will result giving a shift in the axis and the phase center of the feed horn's beam. It is thus evident that the beam can be scanned by sequentially switching the loops into dissipative terminations by opening shunt connected short circuits (i.e. switching diodes).

With reference to Figure C3, the system is seen to operate sequentially by means of switching diodes) opening the shunt path to ground and allowing the RF energy to pass into the termination of each loop in turn. The switching diode control unit sends a synchronization signal

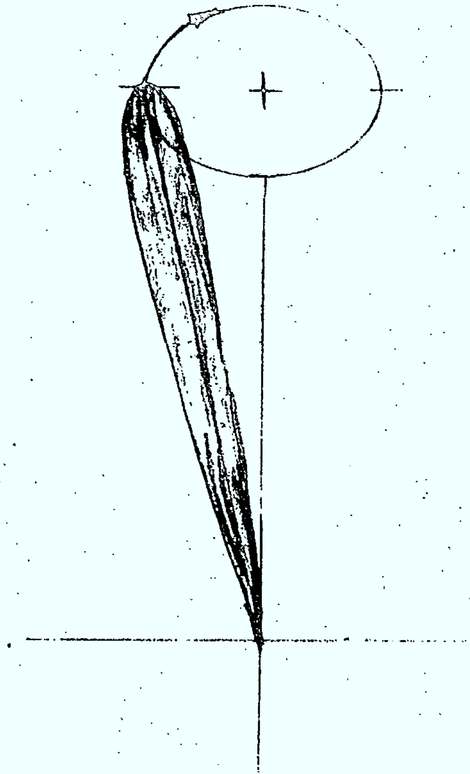


FIGURE C.1 [illegible]

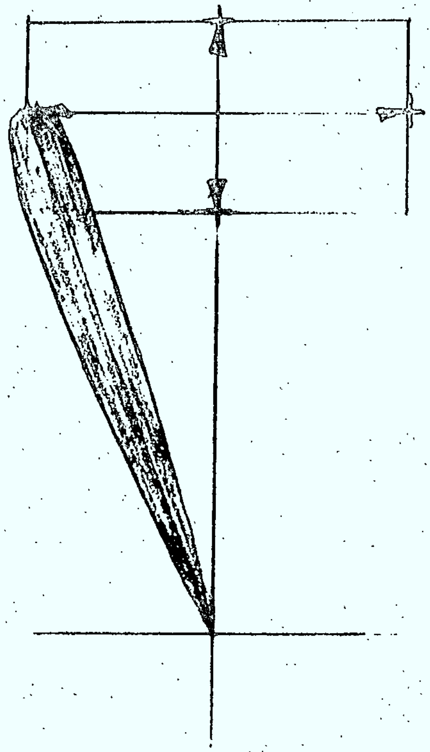


FIGURE C.2 [illegible]
[illegible]

2. Proposed System (Continued)

to the resolver. The resolver will deliver one of the three following signals to each axis following each scan.

+ 1 north correction (or west

- 1 south correction (or east)

0 no correction

3. Scan Rate

A scan rate of 60 Hz is chosen in order to take advantage of the available AC mains reference.

4. Scanning Amplitude

The scan amplitude (in degrees) should be minimized in order to keep the coupling loops small enough so as not to disturb the performance of the horn at the communications frequencies if a separate tracking receiver is used, or, to minimize loss if the communications beam is scanned. A value can be chosen on the basis of choosing a point on the pattern where the slope is becoming reasonably linear. On this basis, a value of $\pm$ 0.08^o is chosen. This angle occurs approximately at the -0.4 dB level. (See Figure C4).

5. Pointing Correction Decision Criteria and Step Size

If the antenna is pointing 0.04 degrees off axis, then a differential level of 0.4 dB will be observed by the tracking system. (See Figure C4). It is assumed, at this time, that a differential level of this magnitude will be easily recognizable. If the correction criteria of 0.4 dB is chosen, it then follows that the step size should be 0.04^o.

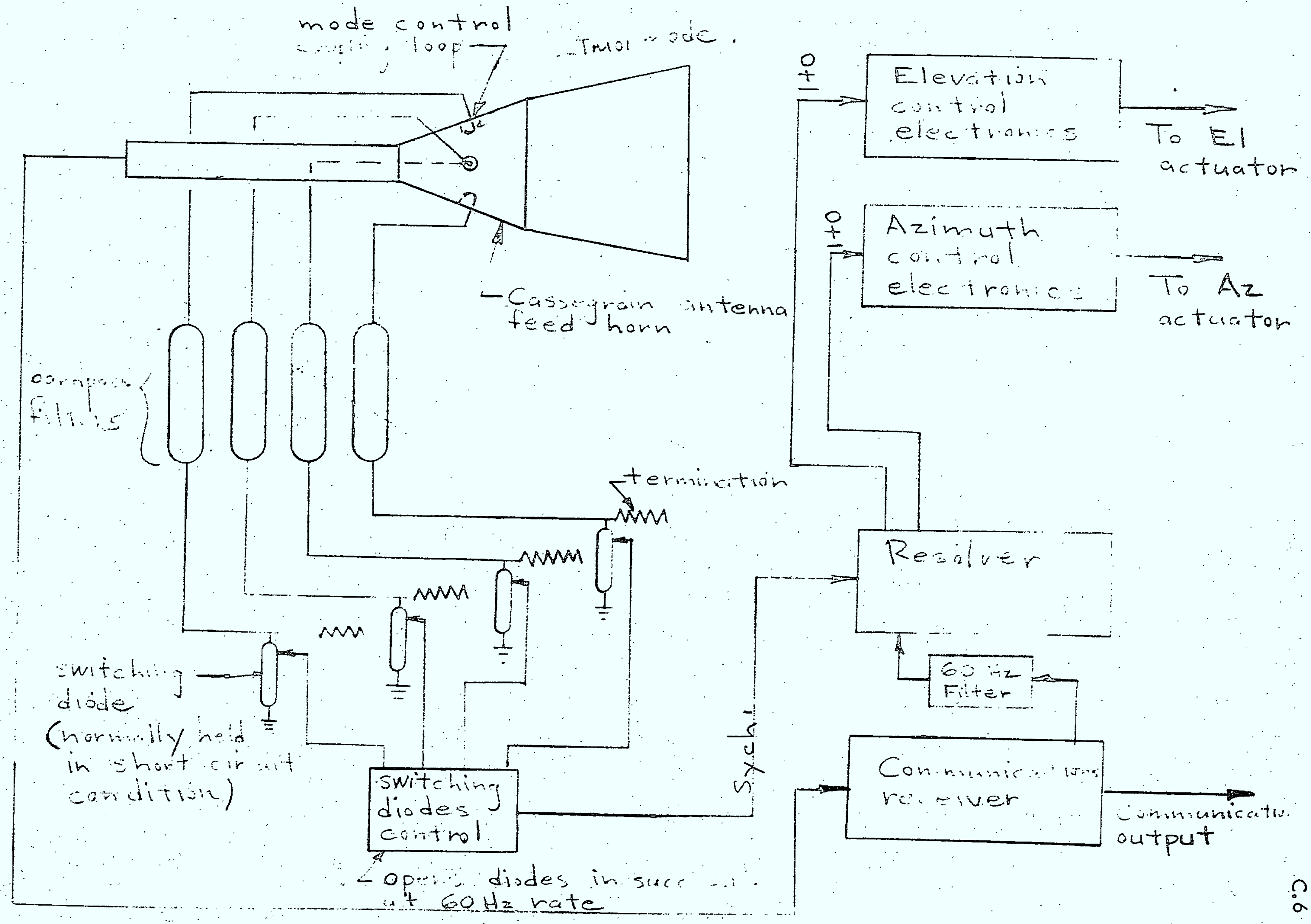


FIGURE C.3 CONE-SCAN SYSTEM

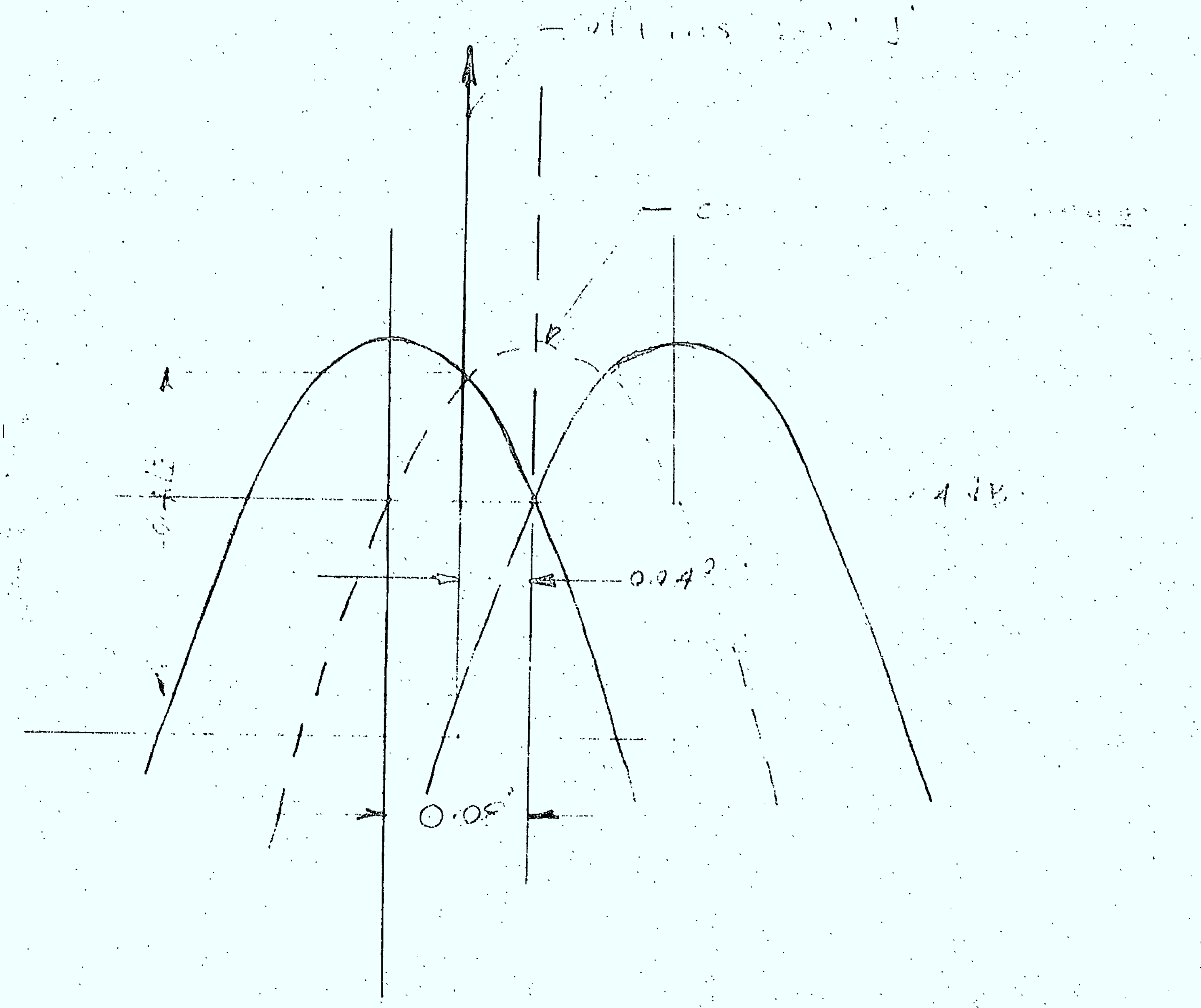


FIGURE C4 SCAN AMPLITUDE

APPENDIX D

N. Tom

Autotracking of Communications Satellites by the step-track technique

(Paper given at the Conference on Earth Station Technology, 14 - 16 October, 1970, by the Institute of Electrical Engineers, Savoy Place, London, England.)

AUTOTRACKING OF COMMUNICATION SATELLITES BY THE STEP-TRACK TECHNIQUE

N. N. Tom

1. Introduction. The lack of high angular dynamics in modern communication satellites offers the potential for a significant decrease in complexity of the earth station autotracking system. A scheme is presented herein which permits the exclusion of tracking feeds and multiple receiver channels in satellite earth stations, at the expense of a typically small increase in pointing error.

Conventional autotracking systems basically consist of closed feedback loops which null out the error channel signals. While these systems have many desirable features, they can be unnecessarily complex with unwarranted high-performance capability, especially for some satellite communication receiving stations where the only purpose of the tracking system is to maintain the operational gain of the antenna.

The desire for a simpler tracking system led to the development of Computrack.[1] The operation of Computrack is similar to the operation of manual tracking in which the peak of the antenna beam is sought instead of the null of the error pattern except that a small computer is used to perform the functions of the operator. The experimental results of Computrack demonstrated conceptual credibility of the peak seeking technique.

Step-Track is a further simplification of the Computrack scheme. The scheme presented is especially applicable for low-cost satellite communication receive-only stations, such as for future domestic TV distribution systems.

This paper discusses the general operating philosophy and the implementation of the Step-Track scheme. The performance of the Step-Track technique is also analyzed.

2. Step-Track Concept. The operation of the Step-Track system is quite simple. After signal acquisition, the antenna is commanded to make an initial angular move. By comparing the received signal level before and after the move, the direction of the next move can be decided. That is, if the signal level has increased, the antenna continues to be moved in the same direction. If the signal level has decreased, the direction of movement is reversed. This process would be continuous and alternating between the two orthogonal antenna axes. Because the antenna is made to Step-toward-energy-peak, the name Step-Track was derived.

Step-Track has a number of limitations. It is almost axiomatic that locating a beam maximum can never be as accurate as finding a sharp null. Further, tracking can be degraded by amplitude fluctuations in the received signal levels owing to atmospheric perturbation or satellite antenna stabilization. Because of the constantly stepping of the antenna, the communication signals would be amplitude modulated at the stepping rate. Although the small amplitude modulation may

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not degrade the receive signal, the same modulation may not be allowed on the uplink, especially when the satellite power is shared by more than one communication link. Thus, this scheme is more applicable to receive-only stations. While the Step-Track has these limitations, it constitutes what might be considered the ultimate in simplicity.

3. Implementation. The simplicity of the Step-Track system can be seen by the general block diagram shown in Figure 1. This system only requires a signal strength detector, a decision circuit with associated timing generator, and stepper-motors.

The dc voltage into the decision circuit, representing the received signal level, could come from any demodulator equipped with AGC or S-meter monitors or from a separate self-contained IF energy detector.

The decision circuit (Figure 2) can be easily implemented with two sample/hold and integrator modules, a voltage comparator, and a few logic gates. The two sample/hold and integrator modules are used to sample the input voltage levels before and after the antenna has been moved. Then, these two samples are compared. The logic modules take the output of the comparator, together with the knowledge of the previous move, and generate new commands for the stepper-motors for the next move.

The timing generator can simply be an oscillator with a count down network which provides four output lines. The timing pulses appear sequentially from line 1 to line 4. With this timing arrangement, the sequence of operation is as follows:

1. Sample with Sample/Hold Module #1
2. Move X-axis
3. Sample with Sample/Hold Module #2
4. Move Y-axis

Because the antenna's boresight axis is continuously being stepped, some average pointing error would obviously exist even if the system is operating under perfect conditions. Of course, with noise perturbations, erroneous decisions could be made which would increase the pointing error. The Step-Track performance is analyzed in the following sections.

4. Step-Track Performance. For communication earth stations, the effective antenna gain is actually the only critical parameter that is affected by tracking accuracy. Thus, the average effective antenna gain loss is a meaningful angle tracking performance criterion and is used here as the figure of merit in evaluating the performance of the Step-Track technique.

To simplify the analyses, it can be assumed that each antenna axis is independent of the other. The analysis is performed in three steps:

1. Determination of the probability of error when comparing the two sequenced output voltage samples in a noisy environment,
2. Derivation of the transitional probabilities between steps and the stationary probabilities of given antenna offsets, and

3. Calculation of the corresponding antenna gain loss.

As an algebraic convenience, the analysis is separated into two situations: (1) a stationary satellite and (2) a moving satellite.

4.1 Stationary Satellite Tracking. The simplest case, which can be considered, is when relative motion between the satellite and earth station is negligible. However, because of the step-track mechanization, the antenna would still be moving in incremental angular steps of size $\Delta\theta$ after the satellite has been acquired. Since the antenna is moving in fixed increments, the possible locations of the satellite are discrete points on the antenna beam pattern, with each point being $\Delta\theta$ away from its adjacent points. Assuming that one of the points is at the peak of the antenna beam, the discrete points can be marked off on the antenna beam pattern and the specific angle may be denoted ..., θ_{-1}, θ_0, θ_1, θ_2, ... etc., where θ_i is an angle which is $i\Delta\theta$ angular distance from the peak. With the discrete angles so designated, the tracking model is analogous to a random walk problem in which the antenna is stationary and the satellite moves from one discrete point to another. The interpretation of the random walk is such that if the decision circuit detects the satellite walking up the slope of the beam pattern (received signal level increasing), the walk continues to be in the same direction. Otherwise, the direction is reversed. According to this rule, if the detection is always a correct one, the satellite would quickly reach the peak of the beam, and thereafter, walks back and forth between θ_i and θ_{-1}. When the received signal is perturbed by noise, there is a finite probability that an erroneous detection would be made. In this case, the satellite would be walking further down the slope.

The probability of an erroneous detection can be solved in the same manner as in determining the error rate for demodulating an amplitude modulated digital signal. Assuming that the normalized antenna voltage gain pattern is guassian in shape and assuming square law detection, it can be shown that the probability of an erroneous detection is given by:

$$P_e\,(\theta_i \rightarrow \theta_{i+1}) = \frac{1}{\sqrt{\pi}} \int_{\rho_i}^{\infty} e^{-x^2}\, dx \qquad (1)$$

where $p_e\,(\theta_i \rightarrow \theta_{i+1})$ = probability of erroneous detection after the satellite has moved from θ_i to θ_{i+1}

$$\rho_i = \frac{(S/N)\left[G(\theta_i) - G(\theta_{i+1})\right]}{2\sqrt{2}\left\{b/B_{IF}\left[1 + S/N\left(G(\theta_i) + G(\theta_{i+1})\right)\right]\right\}^{1/2}} \qquad (2)$$

where S/N = input signal-to-noise ratio in the IF bandwidth when the satellite is at the peak of the beam.

$G(\theta_i)$ = normalized power gain of the antenna at θ_i

$= \exp\left[-2.77\,(\theta_i/\theta_{hp})^2\right]$

b = post-detection low-pass filter bandwidth

B_{IF} = IF bandwidth

θ_{hp} = half-power antenna beamwidth

Similar expressions can be derived when the satellite is moving from θ_i to θ_{i-1}. Therefore, the probability of a detection error is a function of the input S/N, the size of the incremental angular step $\Delta\theta$, and the bandwidth ratio B_{IF}/b.

The transistion probability, $P(\theta_i \rightarrow \theta i{+}1)$, is defined as the probability that the satellite would, after arriving at θ_i, move from θ_i to θ_{i+1}. The stationary probability, $P(\theta_i)$, is the long-term average of the time that the satellite is at θ_i.

Based on the symmetry of the antenna beam, the following formulas can be derived.

$$P(\theta_i) = \frac{P(\theta_o)}{2} \left[1 + \frac{P_e(\theta_{i-1} \rightarrow \theta_i)}{1-P_e(\theta_{i+1} \rightarrow \theta_i)} \right] \prod_{j=1}^{i-1} \left[\frac{P_e(\theta_{j-1} \rightarrow \theta_j)}{1-P_e(\theta_{j+1} \rightarrow \theta_j)} \right] \text{for } i > 0 \qquad (3)$$

Now, because the satellite must be at one of the discrete angles, it is clear that

$$\sum_{i=-\infty}^{\infty} P(\theta_i) = 1 \qquad (4)$$

Using equations (3) and (4), and knowing the probabilities of detection errors, the stationary probability of a given pointing offset can be calculated for specific system parameters.

The preceding analysis is valid only if the sum of the stationary probabilities for angles outside the first nulls is small. This sum of stationary probabilities represents the probability of loss of track.

Finally, the average loss, $\overline{L}$, in antenna effective gain can be easily obtained by:

$$\overline{L} = -10 \text{ Log} \sum_{i=-\infty}^{\infty} P(\theta_i)\, G(\theta_i) \quad \text{dB} \qquad (5)$$

The stationary probability distribution for an input S/N of 10 and a step size of $\theta_{hp}/10$ is shown in Figure 3. Figure 4 shows the average antenna gain loss as a function of the step size.

4.2 Moving Satellite Tracking. The above analysis for stationary satellite tracking indicated that the average loss is a monotonically increasing function of the postdetection filter bandwidth, b, and the step size $\Delta\theta$. Thus the system can be optimized by keeping b and $\Delta\theta$ as small as possible. However, if the satellite is moving, additional constraints need to be considered. Since, before sampling the voltage, the decision circuit must wait for the output of the postdetection filter to reach the steady state condition, and since rise-time is inversely proportional to b, a small b means a relatively large time interval between samples, which in turn, implies a large time interval between successive stepping of the antenna. If the time interval between successive stepping is too large, the satellite angular drift will itself constitute an appreciable error. In fact, if the amount of angular drift during this time interval is larger than $\Delta\theta$, the antenna can never catch up with the satellite and it will result in permanent loss of track. Thus, optimum parameters exist which are functions of the satellite drift rate.

The analysis for the moving satellite is analogous to the stationary satellite, except that the rule of the random walk would be modified. Defining the time interval between stepping and sampling to be T , then, the time between successive stepping of the antenna in the same axis is 4T. During this period, the satellite would have drifted through an angle of $4T\dot{\delta}$ where $\dot{\delta}$ is the satellite drift rate. Thus, equation 2 must be modified as follows:

$$\rho_i = \frac{\left(\frac{S}{N}\right)\left[G(\theta_i \mp \dot{\delta}T) - G(\theta_i + \Delta\theta \pm \dot{\delta}T)\right]}{2\sqrt{2}\left\{\frac{b}{B_{1F}}\left[1 + \left(\frac{S}{N}\right)\left(G(\theta_i \mp \dot{\delta}T)\right) + G(\theta_i + \Delta\theta \pm \dot{\delta}T)\right]\right\}^{1/2}} \quad (6)$$

The plus or minus signs in front of T depends on whether the stepping is in the same or opposite direction of the satellite drift. The effective stepping size is also changed to $\Delta\theta \pm 4T\dot{\delta}$.

Because of the asymmetrical characteristics of the effective step-size, a closed-form formula for the transition probability is not obtainable. The transition probability must then be obtained by successive approximations. Assuming a small IF bandwidth of 2kHz, an input S/N of 3 dB, a satellite drift rate of 0.00042 deg/sec (corresponding to 5° Figure 8 motion), a step size of $\theta_{hp}/10$, and selecting T to be 5/b, the stationary probabilities for various postdetection bandwidths were calculated and are shown in Figure 5. This figure clearly indicates the dynamic lag of the antenna beam. The average losses for three different types of stations are shown in Figure 6 as functions of the postdetection bandwidth which showed that an optimum choice of b exists for each.

5. <u>Conclusion.</u> The Step-Track scheme has two fundamental disadvantages. It is susceptible to AM interference, of which there are many sources and it is less accurate than conventional means. However, even in the lowest practical input signal-to-noise ratio examples (S/N = 3 dB), the gain loss from tracking can be moderately small if the satellite drift rate is not excessively large. Thus, it is concluded that Step-Track represents the most cost-effective approach for tracking synchronous or near synchronous altitude satellites.

Reference

1. R. J. Larkin. Philco-Ford Invention Disclosure Memo, October 16, 1967.

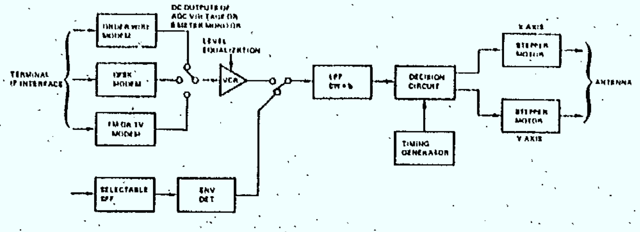


Figure 1. A Possible Step-Track Subsystem Configuration

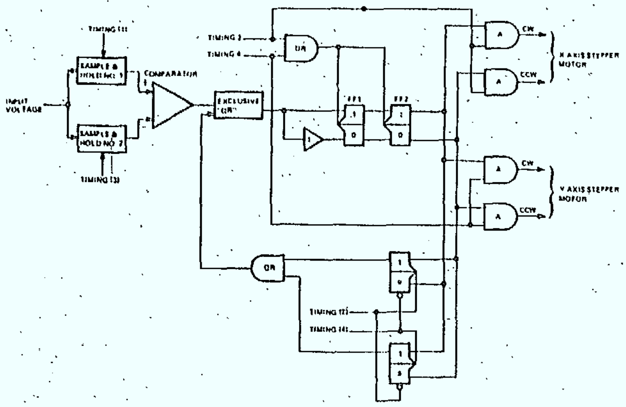
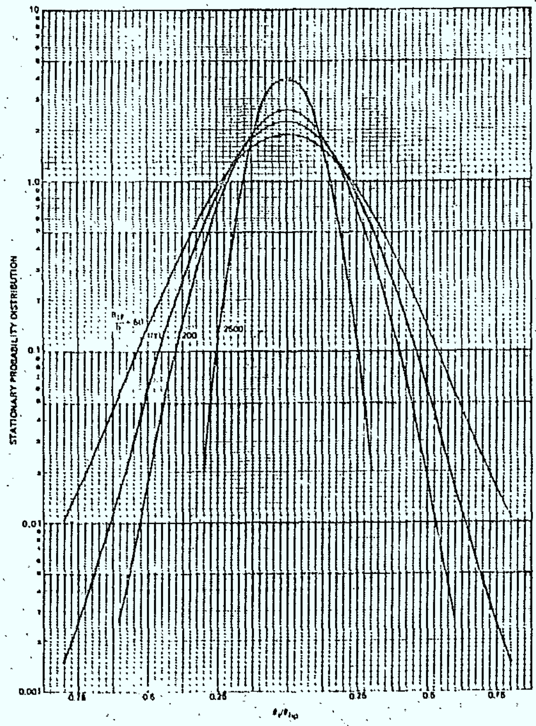


Figure 2. Step-Track Decision Circuit

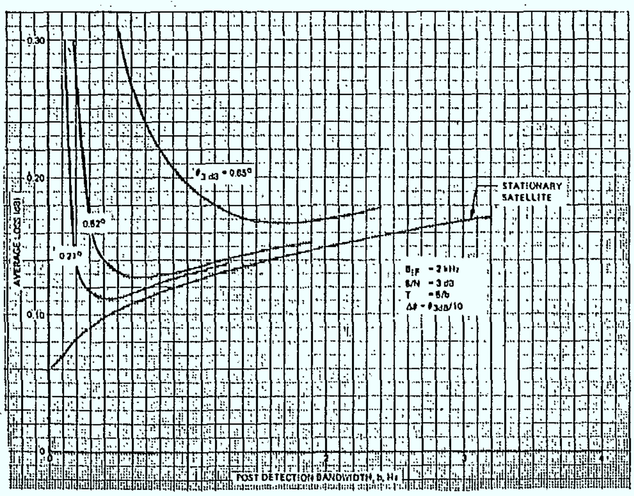


Stationary Probability Distribution, S/N = 3 dB, θ hp/Δθ 10

Figure 3.

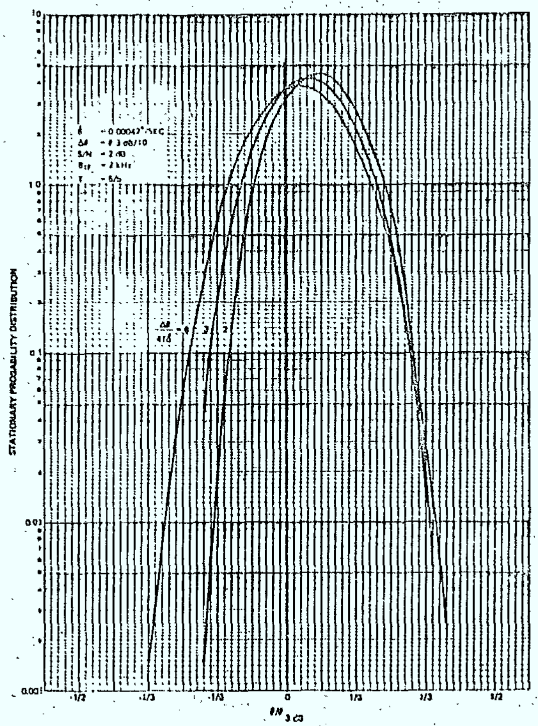
Average Effective Antenna Gain Loss as Function of Step-Size Δθ

Figure 4.



Average Antenna Gain Loss Vs. Step-Track Post-Detection Filter Bandwidth

Figure 6.



Stationary Probability Distribution $\theta_{hp} = 0.52^0$

Figure 5.