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PROCESSOR:

PACIFIC MISSILE RANGE

POINT MUGU, CALIFORNIA

Technical Memorandum No. PMR-TM-64-6

CORRECTION OF NEAR-HORIZONTAL RADAR ELEVATION ANGLES FOR ATMOSPHERIC REFRACTION

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POINT MUGU CALIFORNIA

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SUMMARY

AN/FPS-16 radars at Point Mugu, San Nicolas Island, and Tranquillon Peak, California, observed the variability with time and space of the position parameters (mostly elevation angle) of a fixed transponder beacon on Santa Cruz Island, California. Soundings with an airborne refractometer were taken along the Point Mugu-Santa Cruz Island path, and radiosondes were released at Point Mugu, while radars at Point Mugu collected elevation angle observations. A ray-trace computer program operated on the sounding data to compute predicted elevation angles at the radar. Observed and predicted angles were compared. It was concluded that errors in the observed elevation angles were due mainly to atmospheric refraction. Also, it was concluded that the variability with time and space of propagation conditions make the slowly acquired and inaccurately positioned sounding data inadequate to achieve corrections commensurate with the inherent accuracy of the AN/FPS-16 radar. If accurate low-angle position data are required, methods other than soundings with aircraft-borne refractometers and balloon-borne meteorological sensor packages should be sought and developed.

INTRODUCTION

The tracking of missiles, satellites, and spacecraft is an essential part of range operations. The evaluation of vehicle performance is critically dependent upon the time and position data measured by tracking instrumentation. In present practice, tracking is usually done at elevation angles above 3 degrees. This practice is followed primarily because the uncorrected errors (caused by atmospheric refraction of the microwave energy) at elevation angles less than 3 degrees seriously limit the attainable accuracy of tracking instrumentation. In spite of this limitation, the capability of tracking at low angles with increased accuracy can be useful. For instance, the distances between tracking stations (either shipborne or fixed) over the vast ocean areas can be increased if low-angle tracking accuracy can be improved, thus reducing the requirement for large numbers of ships and shore stations.

To correct low-angle tracking data for atmospheric refraction, certain information is required, namely the index of refraction and its vector gradient along the nearly horizontal atmospheric path at the time and place where the electromagnetic energy is being propagated. It is concluded that this requirement is not being met by current methods of acquiring refractive index data. The reasons are that the balloon-borne radiosonde rises too steeply, and in arbitrary directions as the wind dictates. The aircraft-borne refractometer is too slow because the refractive condition of the atmosphere changes significantly during flights. For example, microwave energy is propagated along a 25-nautical-mile path in about 140 microseconds. An instrumented aircraft would require about 10 minutes (6×10^8 microseconds) to fly the same distance. Atmospheric propagation conditions, as shown in this report, often change significantly* in 1 minute. Thus, whereas the inherent angular accuracy of the radar is well known, the operational accuracy of the radar at small (less than 1 degree) elevation angles is uncertain. This uncertainty is based on a lack of knowledge of the atmospheric dynamics as well as the inadequacies in the methods for obtaining the refractive index. A unique opportunity to investigate this uncertainty was present at the Pacific Missile Range, Point Mugu. At Point Mugu, AN/FPS-16 radars are situated at sea level where they can observe a point source (a transponder beacon) on Santa Cruz Island. The work performed was therefore intended to estimate for these radars the accuracy which can be achieved by correcting near-horizontal elevation angles for atmospheric refraction when the atmospheric condition is measured by radiosonde and airborne refractometer.

CORRECTION OF ELEVATION ANGLE FOR REFRACTIVE GRADIENT

To correct radar data for elevation angle errors due to atmospheric refraction, the condition of the atmosphere along the propagation path during the propagation interval is required; the "condition," in this case, is the gradient of the index of refraction. The above requirement is not met by the radiosonde or the airborne refractometer. Each of these instruments takes a sequential sounding in the changing atmosphere during a period which is long in comparison with the time to obtain a radar "fix." During this period, the radar reports a sequence of elevation angles. At this point, it is necessary to select an angle from the sequence to correspond to the sounding data. The method of selection is based on the assumption that the angle selected should provide the best fit to the predicted angle for the sample of soundings available.

* A significant change is a change which causes the elevation angle to change by an amount which is greater than the attainable accuracy of the radar, that is, greater than 0.1 milliradian.

The situation is clarified by looking at figure 1. This figure shows the observed elevation angle E_o, the predicted angle E_p, and the true angle E_t. E_p is the angle predicted by a computer program using ray tracing equations* operating on the radiosonde or refractometer data. E_t is the true elevation angle of the beacon known from geodetic data. The goal then is, mathematically, to minimize the rms value of $E_o - E_p$ computed from a sample of tests.

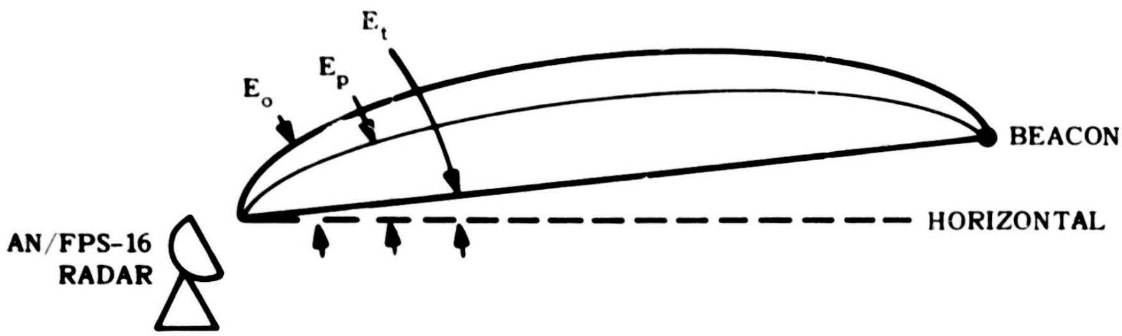

Figure 1. Elevation Angles From Radar to Beacon.

INSTRUMENTATION

The following instrumentation was used to gather the data required for this investigation:

1. PMR's AN/FPS-16 radars at Point Mugu, San Nicolas Island (SNI), and the Naval Missile Facility, Point Arguello, California (NMFPA).
2. A Temco C-band transponder beacon, model CVRT-61A, located at 1,600 feet MSL (mean sea level) at the Naval Compound, Santa Cruz Island (SCI), California, radiating from a vertical dipole antenna.
3. An ASH-14 refractometer (mounted in an R4Y aircraft) recording on a Moseley X-Y Autograf recorder simultaneously with the output of micropotentiometer driven by a barometric altimeter.
4. An AN/GMD-1 radiosonde system.
5. Wet and dry bulb psychrometric thermometers and aneroid barometers used for measuring meteorological variables at radar and beacon, so refractive index could be computed.

The over-all geographical disposition of the major instrumental units is shown in figure 2. Table 1 shows the geodetic position of the beacon relative to each of the radars.

METHODS AND PROCEDURES

The tests were performed in two operating phases. First was the observation phase wherein one or more radars observed the beacon. The other phase was the corrective phase wherein atmospheric soundings were taken while the radar simultaneously "tracked" the beacon. These soundings *estimated* the refractive condition of the atmosphere and were the basis for the predicted elevation angles. The predicted elevation angles were then compared with observed elevation angles to evaluate the accuracy of prediction. The true angles were compared with the observed to evaluate the uncorrected error.

* Equations used in this study are in "Determination of Elevation and Slant Range Errors Due to Atmospheric Refraction," by C. Gardner. This report is Technical Note No. 3280-6 (an internal publication of the Range Operations Department).

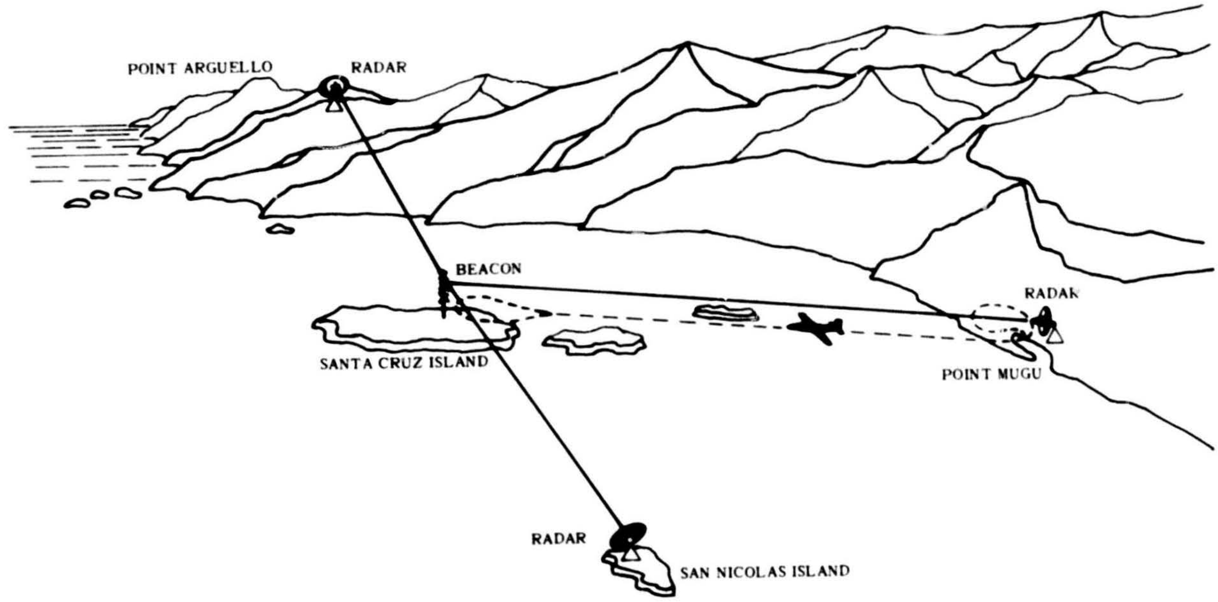

Figure 2. Geographical Setting of Radars Relative to Beacon.

Table 1. True Coordinates of Beacon as Seen by Each of Eight Radars

Location	Radar No.	Height MSL (Ft)	Bearing to Beacon (Deg)	Range to Beacon (Ft)	True Elevation to Beacon (Deg)
Point Mugu	003001	46	252.565	153,084	0.374
Point Mugu	003002	46	252.416	152,664	0.374
Point Mugu	003003	44	252.331	152,427	0.376
Point Mugu	003004	44	252.246	152,190	0.376
San Nicolas Island	013001	900	352.801	274,461	-0.239
San Nicolas Island	013002	900	352.834	275,079	-0.239
San Nicolas Island	013003	900	352.870	273,897	-0.239
Naval Missile Facility, Point Arguello	023001	2,150	127.090	352,905	-0.577

Observation Phase

During August through November 1961, AN/FPS-16 radars "tracked" the beacon on Santa Cruz Island for brief periods (less than 30 minutes) to measure the variability with time and location of observed elevation angle.

Correction Phase

In this phase, the difference between the observed elevation angle and the true (i.e., the uncorrected error) was computed. Next, the corresponding difference between the observed and predicted elevation angles (i.e., the residual error) was found. By comparing the two values (uncorrected error versus residual error), the relative improvement in accuracy of the predictive technique applied to the atmospheric data could be established.

Predicted elevation angles were generated by the ray-trace computer program operating alternately on radiosonde or refractometer data. Calculations of the refractivity at radar and beacon were done by nonmachine methods.

Radar elevation angles read out in raw form each 5 seconds formed a sequence of data points covering the period required to take the atmospheric sounding. Every 15 seconds, 5 of the above points were combined into 5-point smoothing. These smoothed sequences of points were combined into frequency distributions of elevation angle. An exception to the above technique was the two runs of 6 August 1962 where the frequency distributions were formed of raw data points spaced 4 seconds apart.

Some sequences of elevation angles were resolved to 0.005 degree, others to 0.010 degree. The number of data points in the sequences varied. Because of this situation, the frequency distributions had to be normalized for variations in sample size and sampling interval. This normalization was achieved by computing the parameter f/SI, where f is the frequency of occurrence (number of cases) in an interval of width I degrees, for a sample of S data points. This parameter is an estimate of the probability density function $F(E_o)$ centered in the interval I.

The probability density function $F(E_o)$ derived from a sequence of elevation angles satisfies the relation

$$\int_a^b F(E_o)\, dE_o \equiv 1$$

where the elevation angle ranges from a to b for the distribution. In connection with this distribution, a probability parameter x can be defined as follows:

$$(x/100) = \int_a^{E_o(x)} F(E_o)\, dE_o$$

where x is the probability in per cent that an elevation angle selected randomly from the distribution will fall in the interval between a and $E_o(x)$.

The 16 attempts at predicting the elevation angle were taken as a sample for evaluating (1) the method of acquiring the atmospheric sounding data, (2) the theory of refraction and the computer program, and (3) the technique of selecting the elevation angle which gave the best statistical fit. To evaluate the above points, the elevation angle errors were computed before and after correction.

Since elevation angle distributions accumulated during the sounding periods varied from sounding to sounding, the attempt was made to select a single "x" value common to the 16 elevation angle distributions, a value which provided the best fit to predicted values. To find this value of "x," the quantity

$$\mathrm{rms}(x) = \left\{ m^{-1} \sum_{i=1}^{m} \left[E_{oi}(x) - E_{pi}\right]^2 \right\}^{1/2}$$

was computed for x = 10, 20, 30, 40, 50, 60, 70, 80, 90; where $E_{oi}(x)$ is the value of E_o in the *ith* sounding corresponding to the value of x, E_{pi} is the value of E_p for the *ith* sounding, and m is the number of soundings in the sample. The best fit was the value of x which minimized rms(x).

RESULTS AND DISCUSSION

Observation Phase

Figure 3 shows a situation in which an AN/FPS-16 radar at Point Mugu is looking about 3 milliradians above the true elevation angle. These propagation conditions are the most steady observed during these tests. Nevertheless, there is no 10-minute interval (approximate aircraft sounding period) during which the elevation angle changes less than 0.1 milliradian (accuracy of radar).

Figures 4, 5, and 6 show simultaneous observations of the beacon by a Point Mugu radar at 44 feet MSL, a San Nicolas Island radar at 900 feet MSL, and the Tranquillon Peak radar at 2,200 feet MSL. In this case, propagation conditions are more steady for the Point Mugu radar than for the other two. The variation of the elevation angles of the three radars do not appear to be correlated.

Figure 7 shows a steep decrease of elevation angle observed by the Tranquillon Peak radar. In this case, the path length from radar to beacon is 67 miles. The elevation angle rate exceeds 1.2 milliradians per minute. To correct elevation angle observations under these conditions, a sounding of the atmosphere along the propagation path would have to be measured in less than 5 seconds; this could not be done with presently known airborne equipment.

Figure 8 shows the results obtained by simultaneous observation of the beacon by three radars at Point Mugu. The radars are spaced about 380 feet apart along a line bearing N68°E. The separation among the elevation angle ranges from 0.8 to 1.6 milliradians in the 12-minute observation period. Assuming the three radars are stable and performing consistently, these observations prove that a very small displacement in one terminus of a 25-mile horizontal propagation path is an extremely important effect which must be considered in attempts to correct near-horizontal observations. This result implies that the refractivity soundings must be quite close to the propagation path--so close, in fact, that it does not seem possible that aircraft and/or balloon operations could attain accuracy commensurate with the AN/FPS-16 capability.

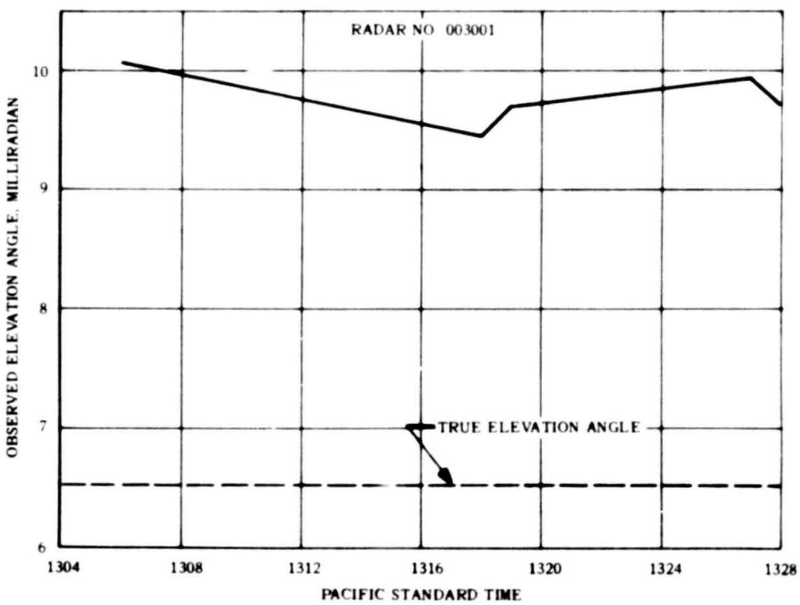

Figure 3. Elevation Angle of Beacon as Seen by Radar at Point Mugu (21 September 1961).

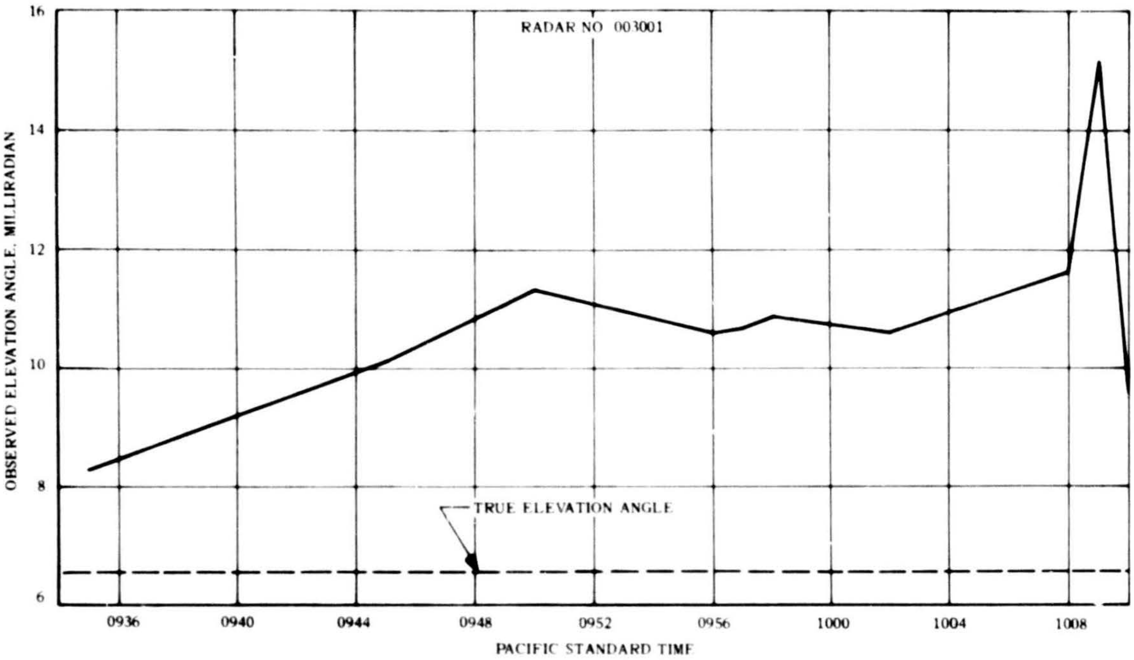

Figure 4. Elevation Angle of Beacon as Seen by Radar at Point Mugu (27 September 1961).

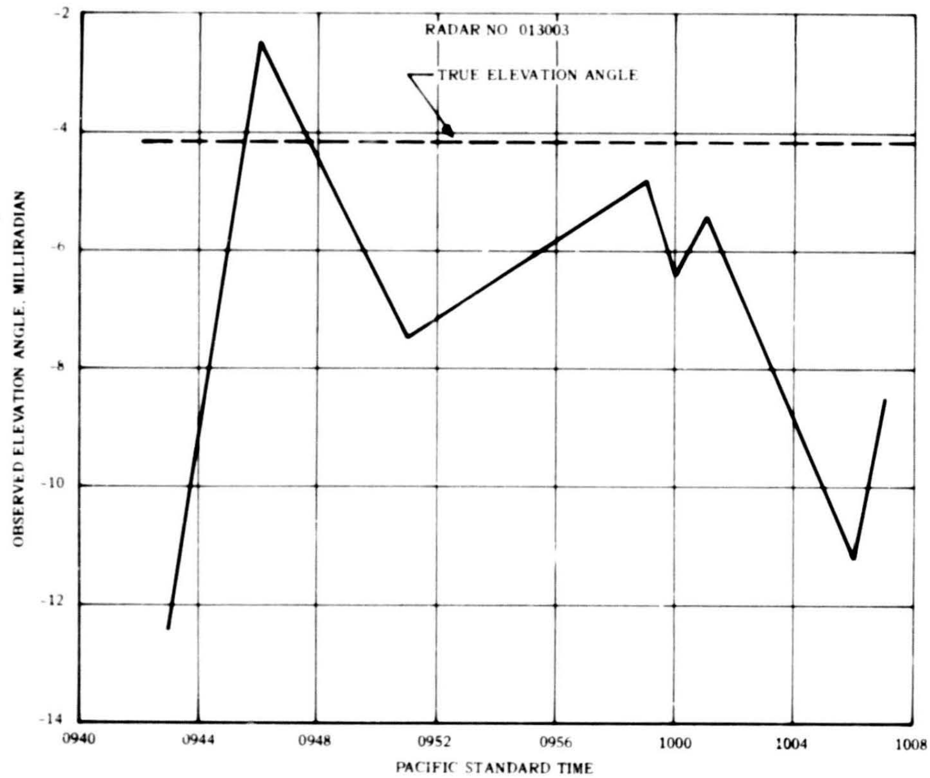

Figure 5. Elevation Angle of Beacon as Seen by Radar at San Nicolas Island.

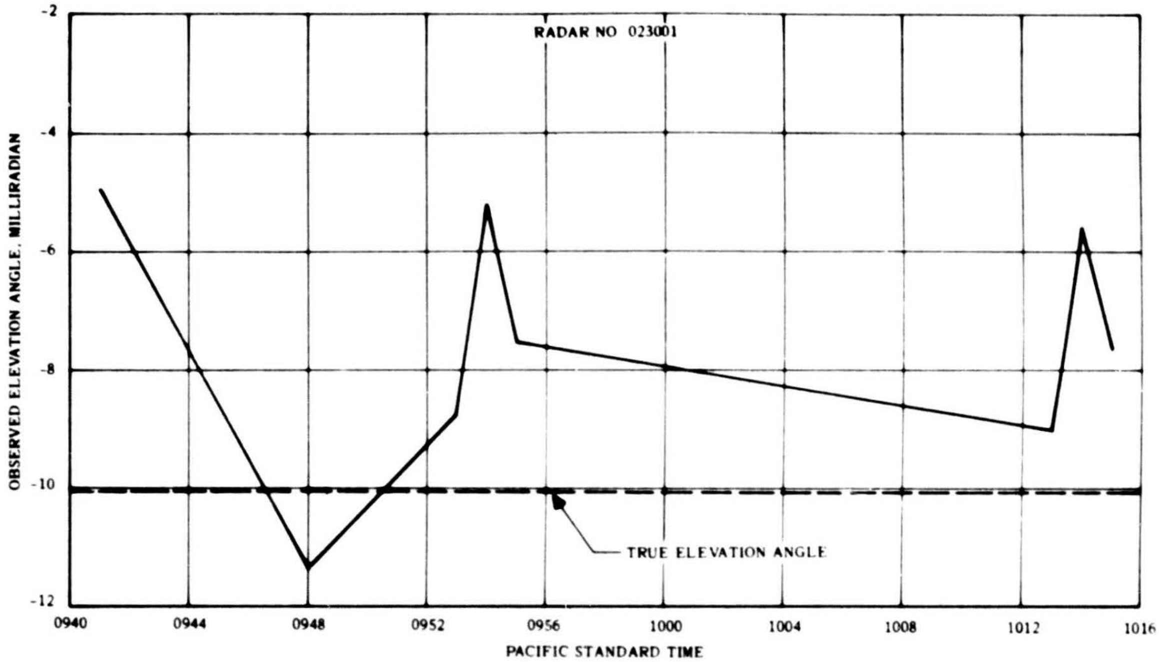

Figure 6. Elevation Angle of Beacon as Seen by Radar at Point Arguello (27 September 1961).

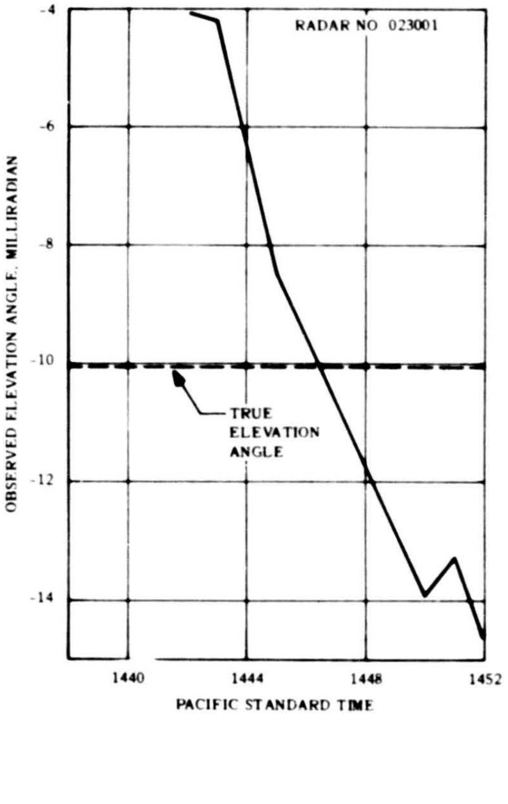

Figure 7. Elevation Angle of Beacon as Seen by Radar at Point Arguello (3 October 1961).

Figure 9 shows the simultaneous observations of two radars at San Nicolas Island. These radars are separated by a distance of 340 feet along a line with bearing N45°E. The observations of these two radars differ by 0 to 1.2 milliradians in 10 minutes. As in the previous case with the three radars, here the curves cross and fail to keep a constant relative position with each other.

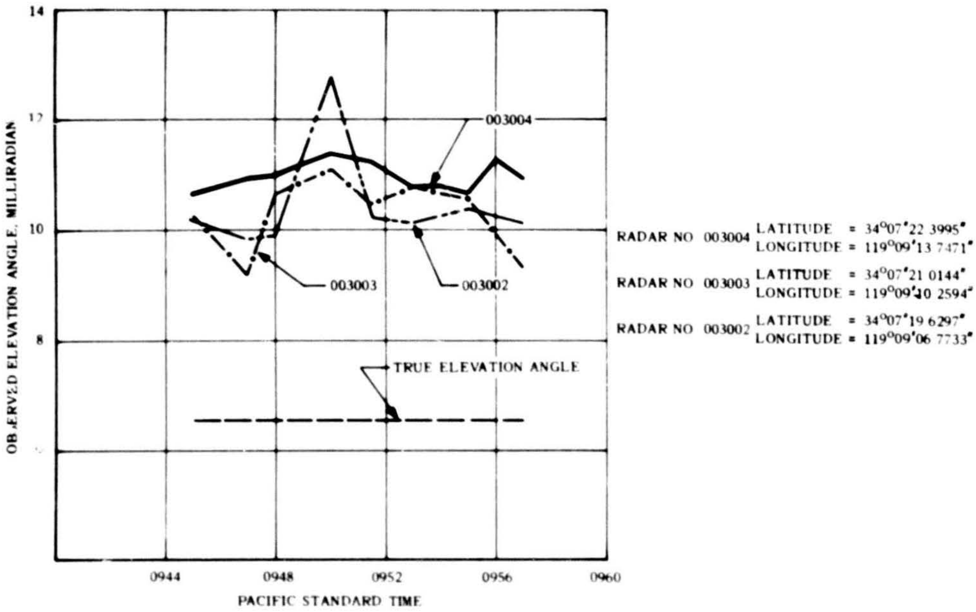

Figure 8. Elevation Angle of Beacon as Seen by Three Radars at Point Mugu.

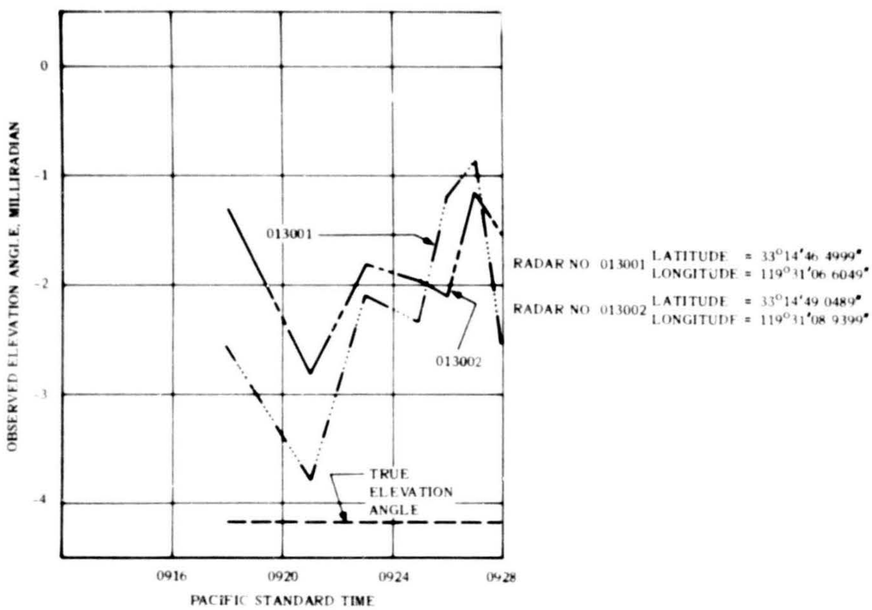

Figure 9. Elevation Angle of Beacon as Seen by Two Radars at San Nicolas Island (14 November 1961).

Figures 8 and 9 offer several pairs of radars for comparison. No pair keeps a constant difference throughout the observation period. It appears that the irregular difference between any pair is due to significantly different propagation conditions along the very close paths.

Correction Phase

During several operations the variability of the data output of three AN/FPS-16 radars was examined. Results of two operations are shown in table 2. These data show that the variability of the elevation angle is at least twice and at most 87 times that of the azimuth. In this report, only elevation angles will be corrected.

On several occasions radar 003001 tracked at negative angles. The transition from negative to positive angles was smooth and at a tracking rate less than the maximum tracking rate of the radar. This is shown in figure 10. During low-angle tracking operations, a quick switch to the sea reflection would invalidate the data. Such data were not used in the corrections reported here.

Table 2. Standard Deviations of Azimuth, Range, and Elevation Angle from a Running Mean

Radar No.	Azimuth (Milliradian)	Elevation (Milliradian)	Range (Ft/1,000 Ft)	Azimuth (Milliradian)	Elevation (Milliradian)	Range (Ft/1,000 Ft)
003001 (Point Mugu)	0.0687	0.254	2.37	0.0119	1.04	0.0588
013003 (San Nicolas Island)	0.172	2.30	0.0478	1.06	3.01	0.0427
023001 (Point Arguello)	0.225	0.466	0.0762	0.418	1.78	0.0273

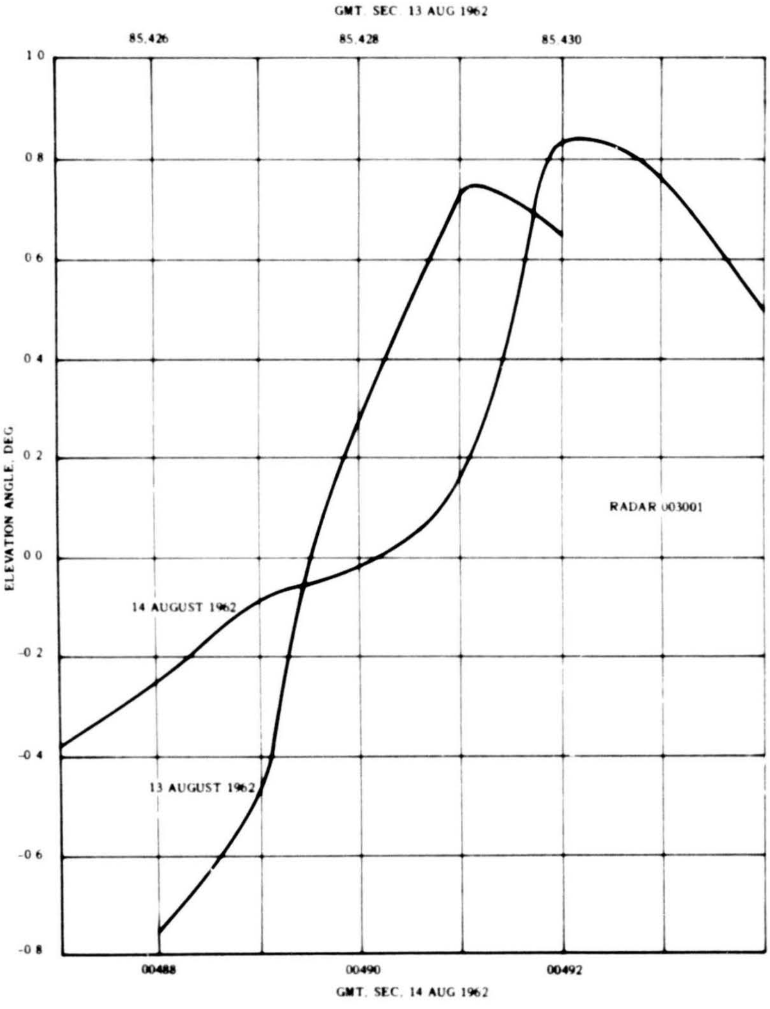

Figure 10. Examples of Observations Wherein Point Mugu Radar Tracked at Negative Elevation Angles.

To correct radar-observed elevation angles for errors due to refraction, the refractivity of the atmosphere must be measured during a period of radar observations. This was accomplished on 16 test runs listed in table 3. Note that the mean gradient, $N_0 - N_{1600}$, given for the radiosonde soundings is from 44 feet MSL to 1,600 feet MSL near the release point at Point Mugu; while, for the refractometer sounding, the mean gradient is along the slant path from radar to beacon.

The variation of $N_0 - N_{1600}$ is shown in figures 11 and 12. The mean gradient is seen to be steady for 40 minutes in one instance, but to change considerably in 10 minutes, in another instance.

The periods required to take refractometer soundings are given in table 3. During these periods, sequences of elevation angles were observed. These sequences were processed by methods described previously into probability density form. These empirical probability density curves are given in the appendix.

Table 3. Test Data

Date (1962)	Observing Period		Elevation Angle (Deg)			Mean Gradient (N_0-N_{1600})
	Sounding	Radar	True E_t*	Predicted E_p**	Observed $E_o(20)$	
	(Pacific Standard Time)					
6 Aug	1145-1147	1139-1146	0.374	0.473	0.600	30
13 Aug	1428-1430	1458-1505	0.376	0.561	0.600	69
13 Aug	1527-1529	1520-1532	0.376	0.699	0.595	112
13 Aug	1630-1632	1615-1620	0.376	0.618	0.620	89
13 Aug	1730-1732	1615-1620	0.376	0.647	0.620	92
17 Oct	0929-0931	0923-0931	0.376	0.434	0.605	24
6 Aug	1137-1146	1139-1146	0.374	0.581	0.600	49
6 Aug	1149-1200	1149-1159	0.374	0.565	0.600	49
13 Aug	1433-1456	1458-1505	0.376	0.618	0.615	98
13 Aug	1512-1518	1512-1518	0.376	0.753	0.595	110
13 Aug	1520-1532	1520-1532	0.376	0.775	0.595	109
13 Aug	1552-1557	1552-1557	0.376	0.709	0.585	109
13 Aug	1613-1620	1615-1620	0.376	0.598	0.620	94
17 Oct	0923-0932	0923-0931	0.376	0.454	0.605	27
17 Oct	0936-0944	0936-0943	0.376	0.550	0.480	38
17 Oct	0948-0954	0947-0953	0.376	0.514	0.655	36

* Angle between local horizontal at radar and straight line from radar to beacon.

** Predicted by ray-trace program operating on sounding data.

Notes: Data shown in the first six rows were from radiosonde soundings; the remaining data were from refractometer soundings.

Radar 003003 observed the beacon on Santa Cruz Island on 6 August 1962.

Radar 003001 observed the beacon on Santa Cruz Island on all other days.

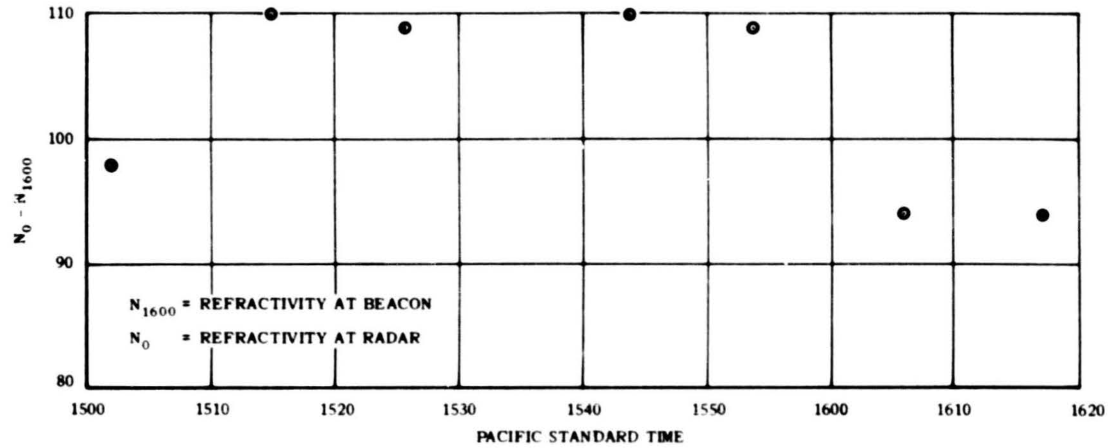

Figure 11. Variation of Refractive Gradient With Time (13 August 1962).

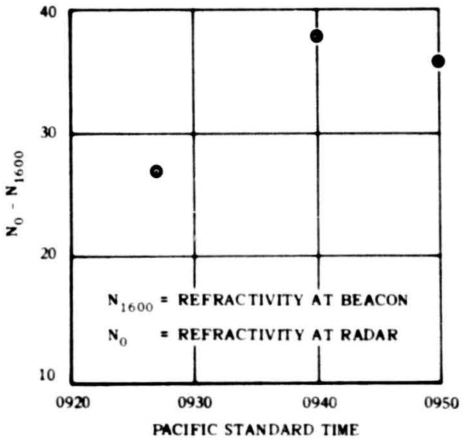

Figure 12. Variation of Refractive Gradient With Time (17 October 1962).

The most probable value of the elevation angle distribution is the angle $E_o(50)$. The question arises: do the $E_o(50)$ values provide the best fit to the predicted values E_p? In answer to this question, figure 13 presents the dependence of rms(x) on x for the sample of 16 soundings. This curve shows that the $E_o(20)$ angle minimizes rms(x) and gives the best fit to the predicted values.

The dependence of $E_o(20)$ and E_p on $N_0 - N_{1600}$ is shown in figure 14. This figure shows that E_p has a greater range than $E_o(20)$; and that E_p does not vary linearly with $N_0 - N_{1600}$.

The dependence of residual errors on $N_0 - N_{1600}$ is shown in figure 15. No difference between refractometer and radiosonde data is seen. The residuals are small when $N_0 - N_{1600}$ is in the vicinity of 77 N-units, which is near the trapping gradient.

The sloppiness of the data acquisition method and the essential correctness of the prediction theory is displayed in figure 16, a bar graph comparing the frequency of occurrence for the 16 soundings of the uncorrected errors with those of the residual errors. The mean of the uncorrected errors is biased about +0.23 degree, while the mean of the residues is biased about +0.01 degree. The residues, however, have a standard deviation near 0.10 degree, which is 17 times the accuracy of the radar system. This result indicates that the elevation angle errors observed for near-horizontal propagation are almost totally due to atmospheric refraction, and

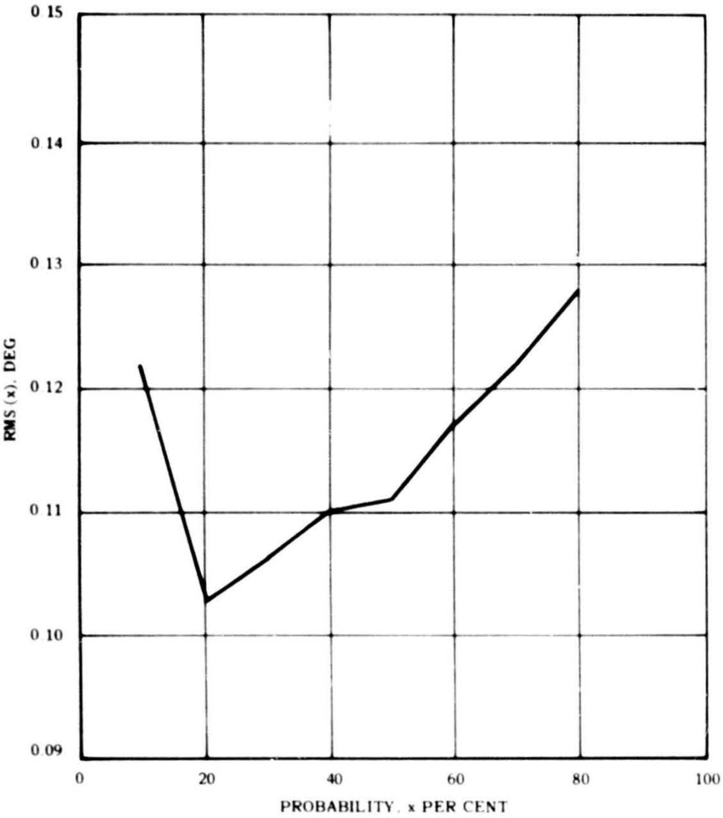

Figure 13. RMS Error Values Versus Probability.

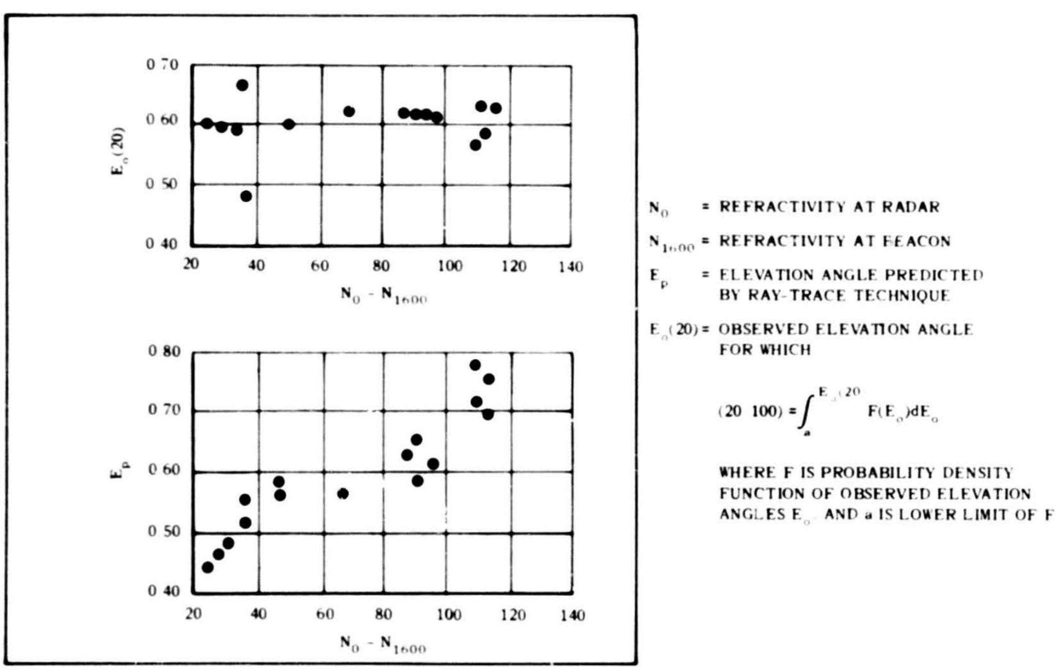

Figure 14. Dependence of Observed and Predicted Elevation Angles on Mean Refractive Gradients.

that the data representing the condition of the atmosphere are not accurate enough to match the requirements for correction of low-angle data observed by an AN/FPS-16 radar. It should be emphasized that this inaccuracy is not to be attributed to the measuring instruments, but rather to the slow acquisition of data in the fast-changing atmosphere.

In view of the residual statistics given above, the effect of the radar system errors on the residual errors is not important to the results of this report.

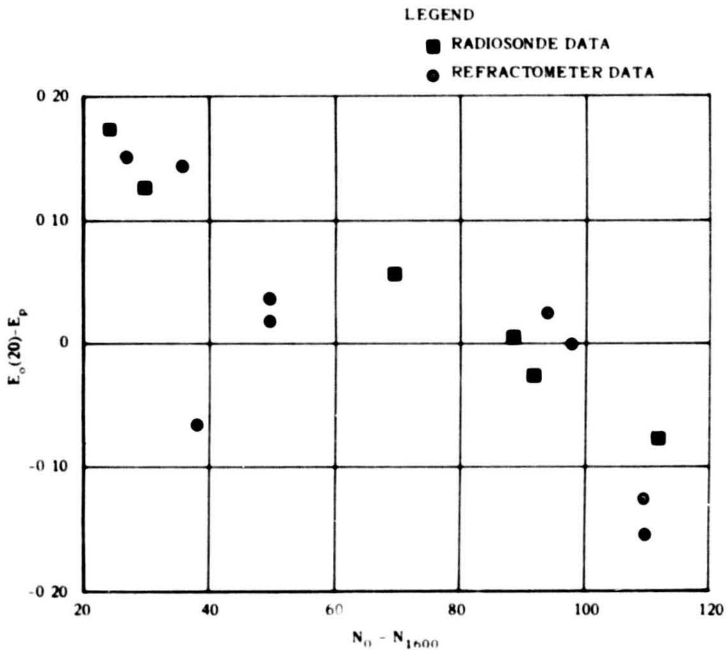

Figure 15. Residual Errors in Observed Elevation Angle After Correction.

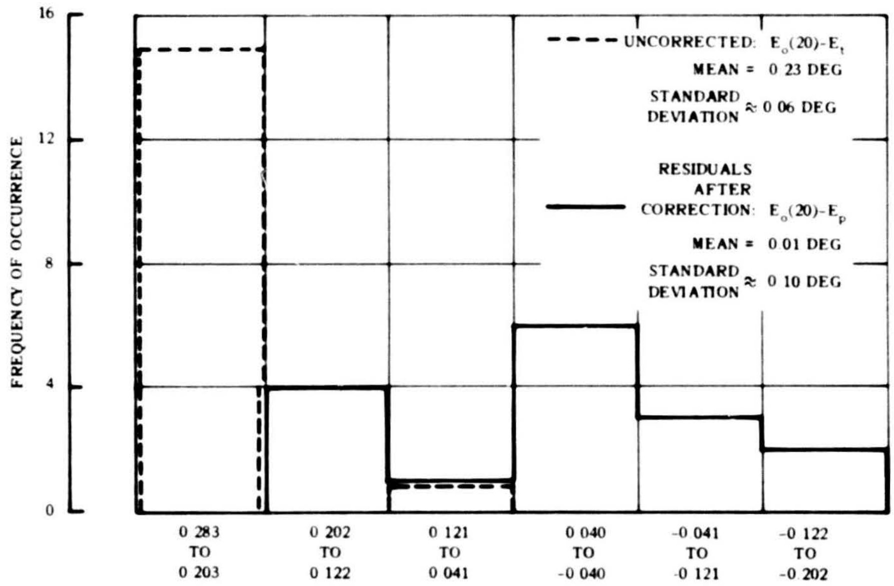

Figure 16. Frequency Distribution of Elevation Angle Errors.

Elevation Angle Distributions

The probability density distribution of elevation angle for the Point Mugu-Santa Cruz Island path varied from hour to hour. However, the distribution for the sampling period 1139 to 1146 PST, 6 August 1962, has major features similar to the distribution of 1149 to 1159 PST on the same day (see figures A-1 and A-2 in the appendix). This result shows that a complicated distribution can be repeated within a 20-minute interval. This situation suggests that the elevation angle distribution observed over a fixed path might be related to the atmospheric condition in some manner, and could probably be used to determine the condition of the atmosphere.

CONCLUSIONS

The radar observations at Point Mugu of near-horizontal elevation angles have indicated the following:

1. The attempt to correct radar elevation angles for atmospheric refraction using the same technique on 16 different soundings failed to produce results useful to the radar tracking art.
2. The failure of the correction technique is attributable to the fact that the radiosonde and refractometer data were not an accurate description of the refractive environment encountered by a pulse traveling from beacon to radar.
3. If an accurate description of the refractive environment encountered by a radar pulse is required to correct angular data, the traditional meteorological and aircraft-borne sensor instrumentation will have to be abandoned and new methods of obtaining refractive soundings will have to be developed.
4. There is some indication that by using statistical techniques on sequences of observed elevation angles, the condition of the atmosphere can be measured with a radar.

APPENDIX A

PLOTS OF PROBABILITY DENSITY FUNCTION

The common feature of these probability density curves (figures A-1 through A-10) is the lobe-like pattern, with several prominent lobes near the middle of the distribution. The two distributions of 6 August 1962 are given in figures A-1 and A-2. Comparison of these two curves shows that the prominent peaks and valleys are nearly identical. These two curves offer evidence that the statistical equilibrium of 8-minute samples can last for 15 minutes.

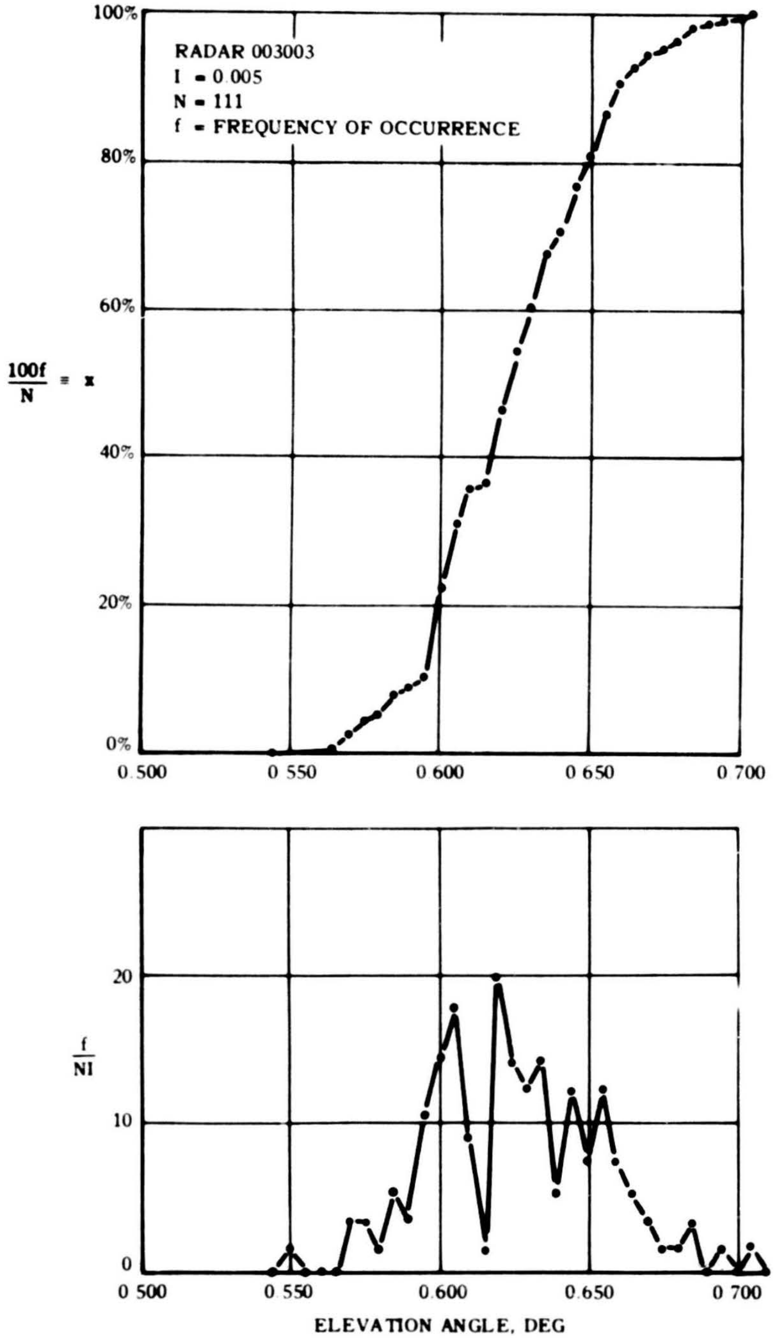

Figure A-1. Distribution of Elevation Angle, 6 August 1962, 1139 to 1146.

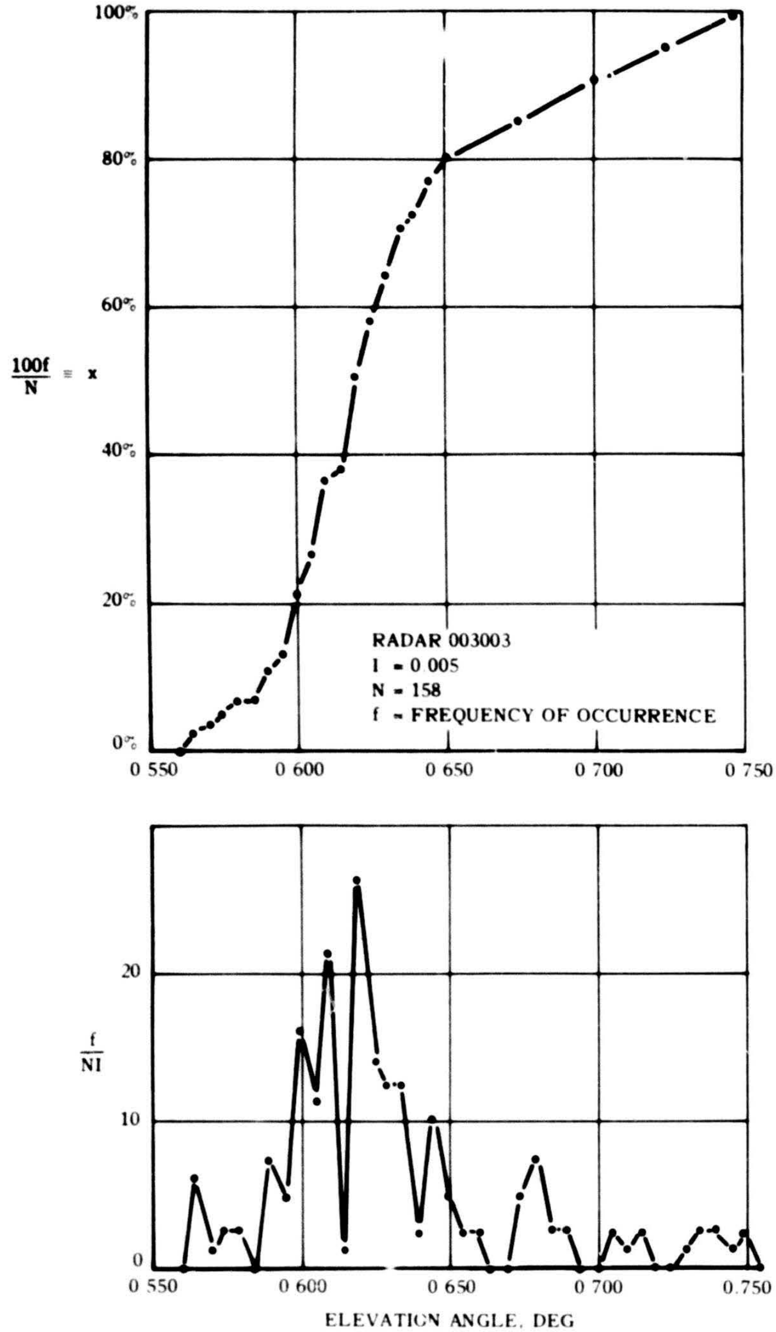

Figure A-2. Distribution of Elevation Angle, 6 August 1962, 1149 to 1159.

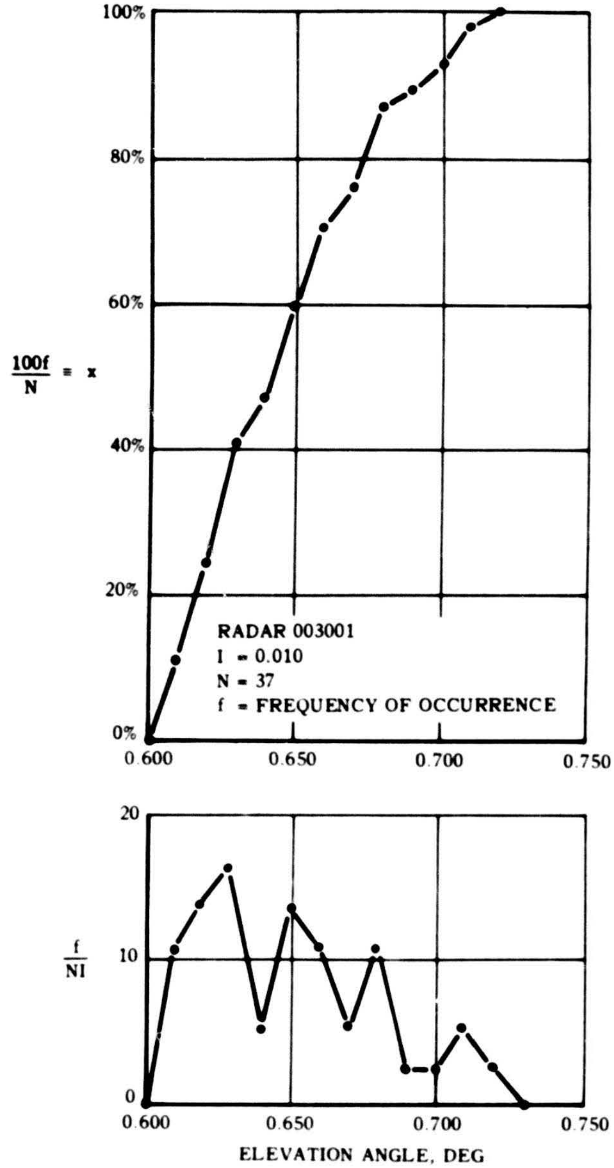

Figure A-3. Distribution of Elevation Angle, 13 August 1962, 1458 to 1505.

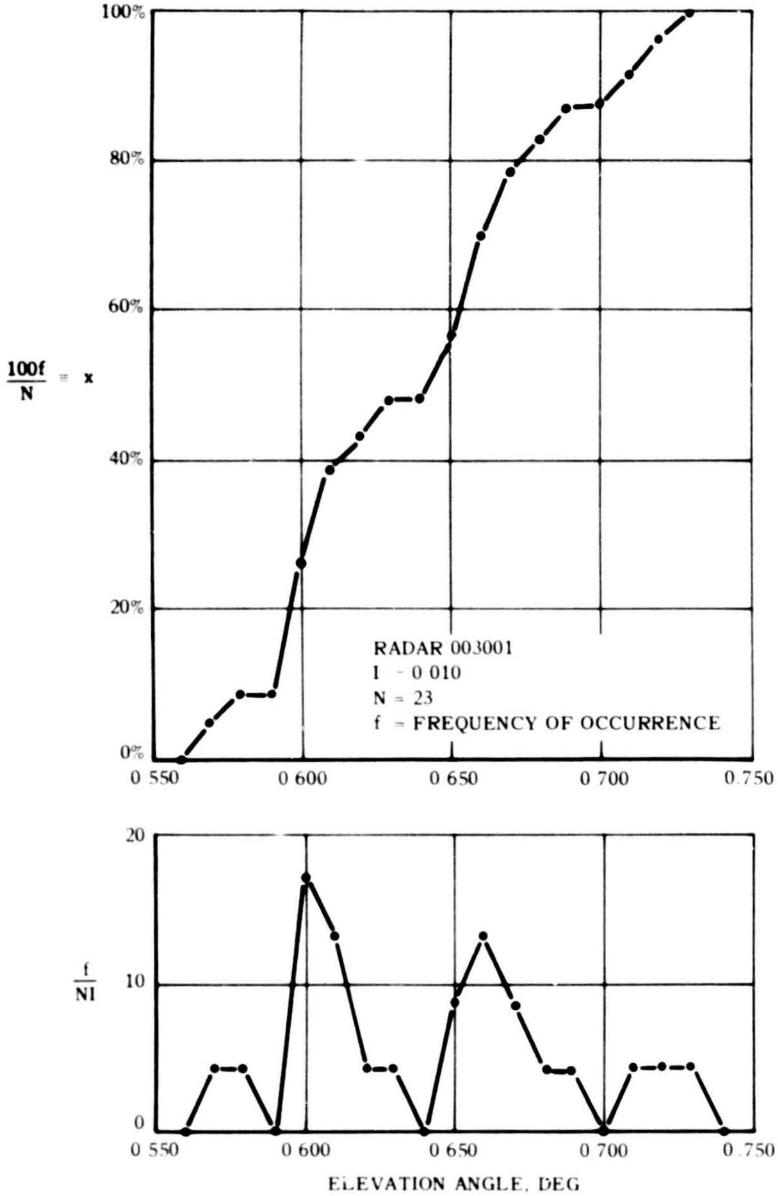

Figure A-4. Distribution of Elevation Angle, 13 August 1962, 1512 to 1518.

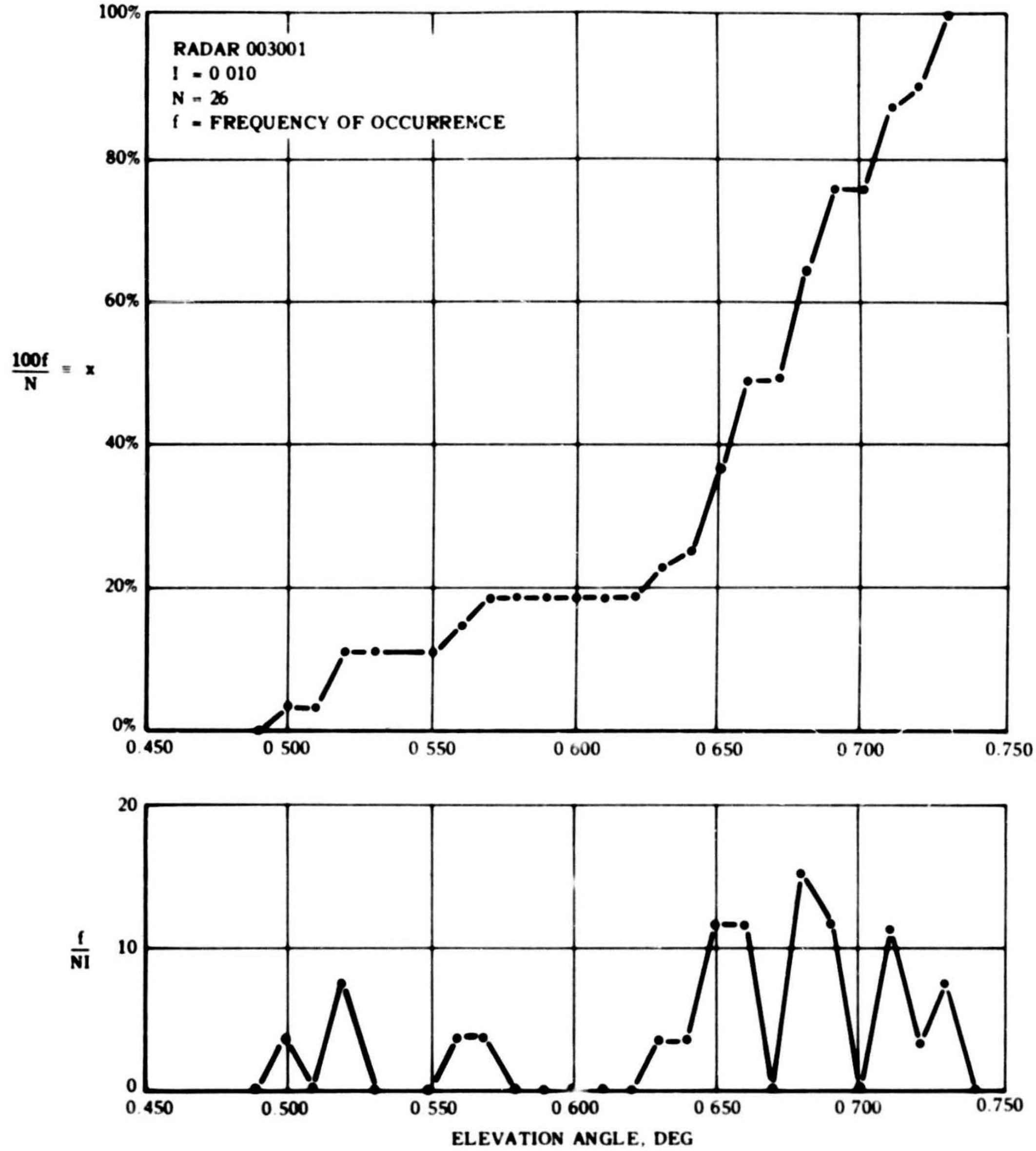

Figure A-5. Distribution of Elevation Angle, 13 August 1962, 1520 to 1532.

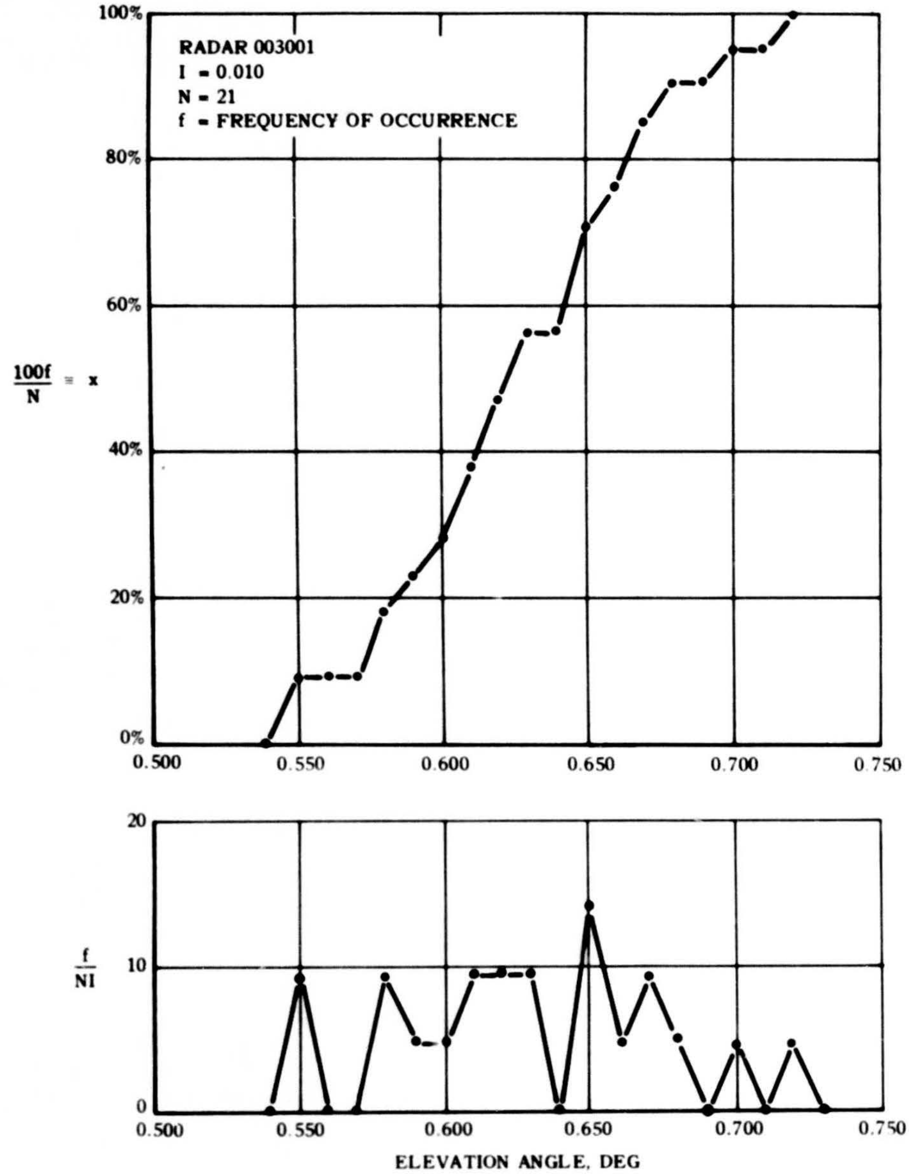

Figure A-6. Distribution of Elevation Angle, 13 August 1962, 1552 to 1557.

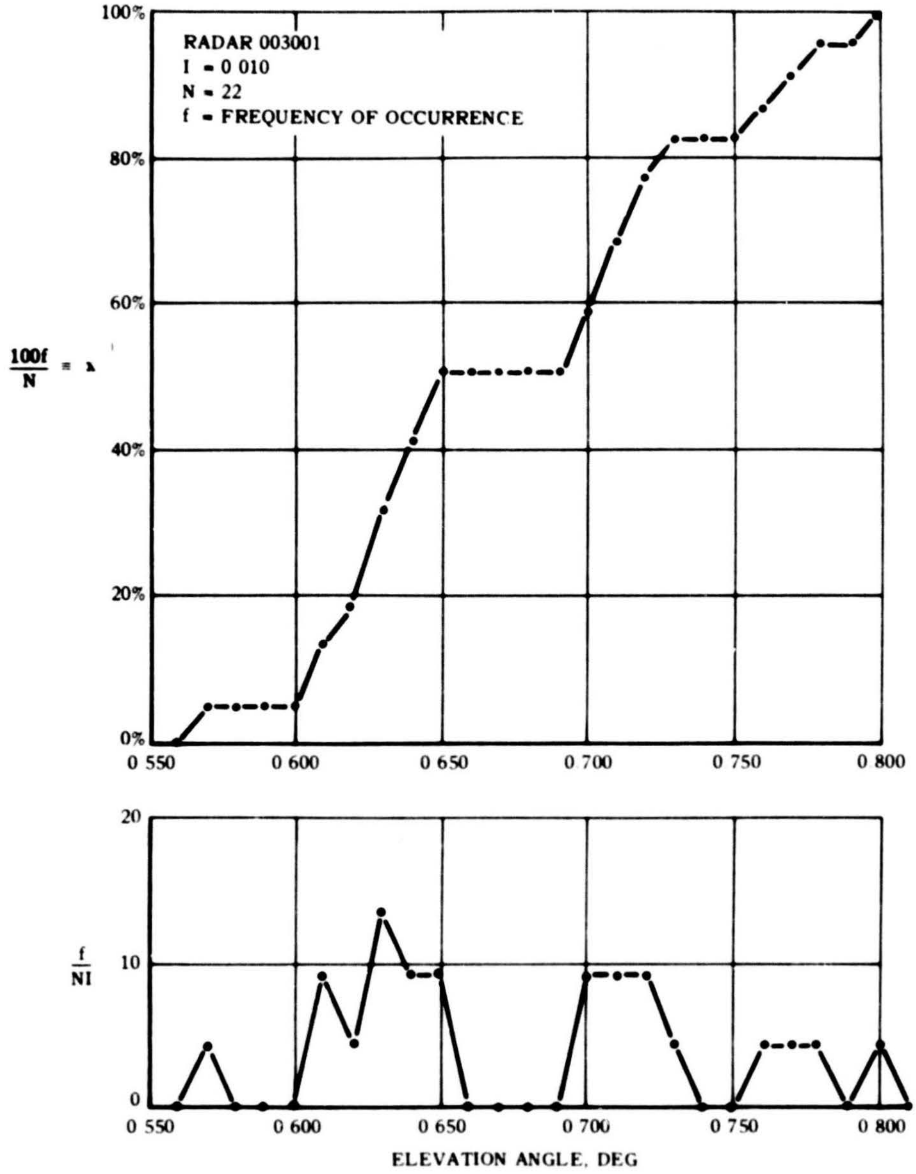

Figure A-7. Distribution of Elevation Angle, 13 August 1962, 1615 to 1620.

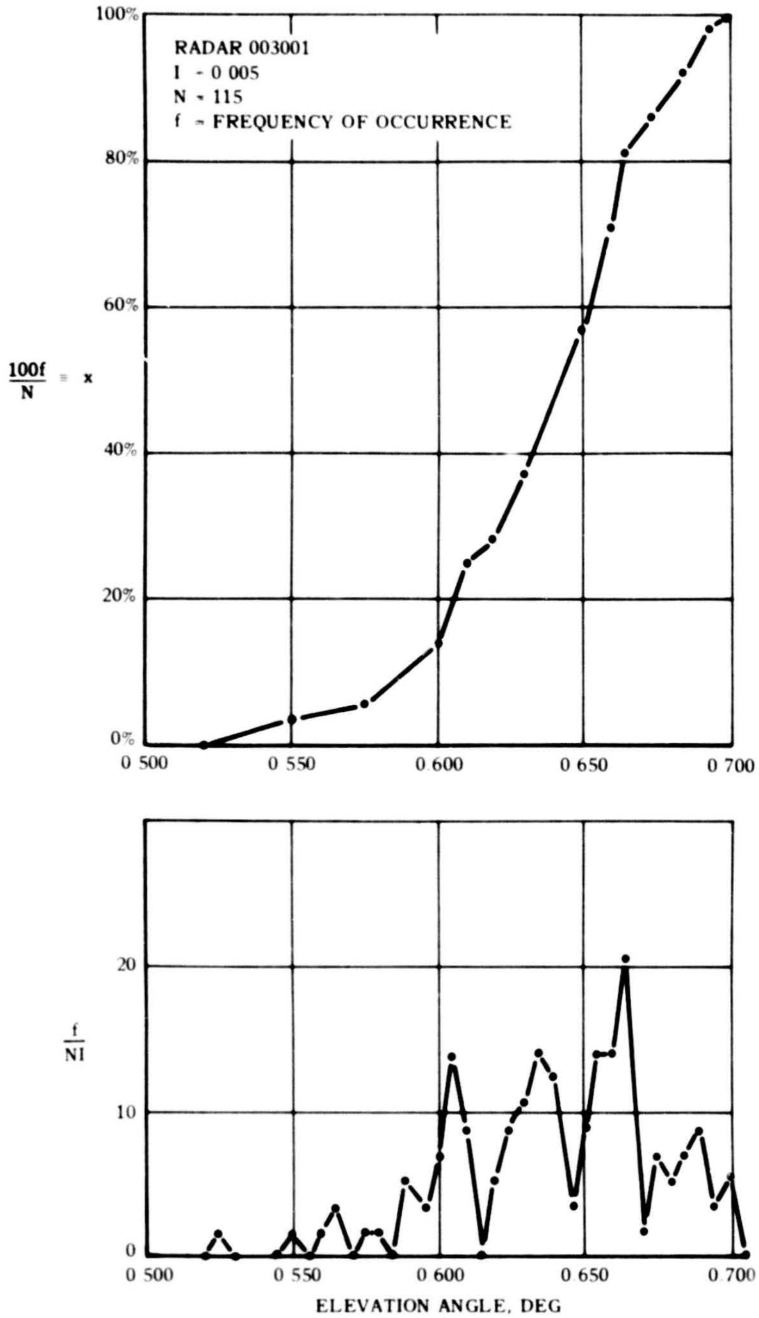

Figure A-8. Distribution of Elevation Angle, 17 October 1962, 0923 to 0931.

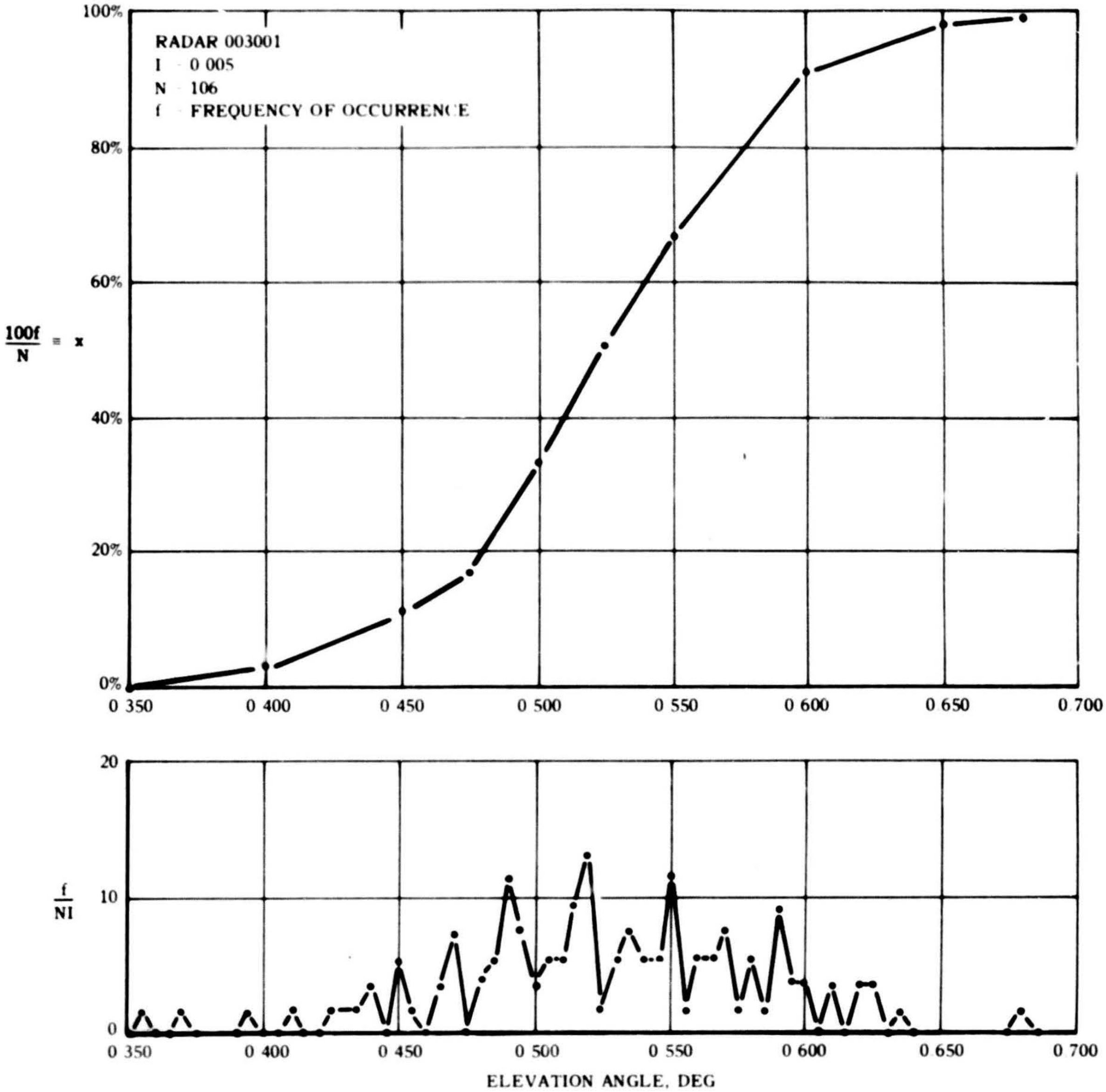

Figure A-9. Distribution of Elevation Angle, 17 October 1962, 0936 to 0943.

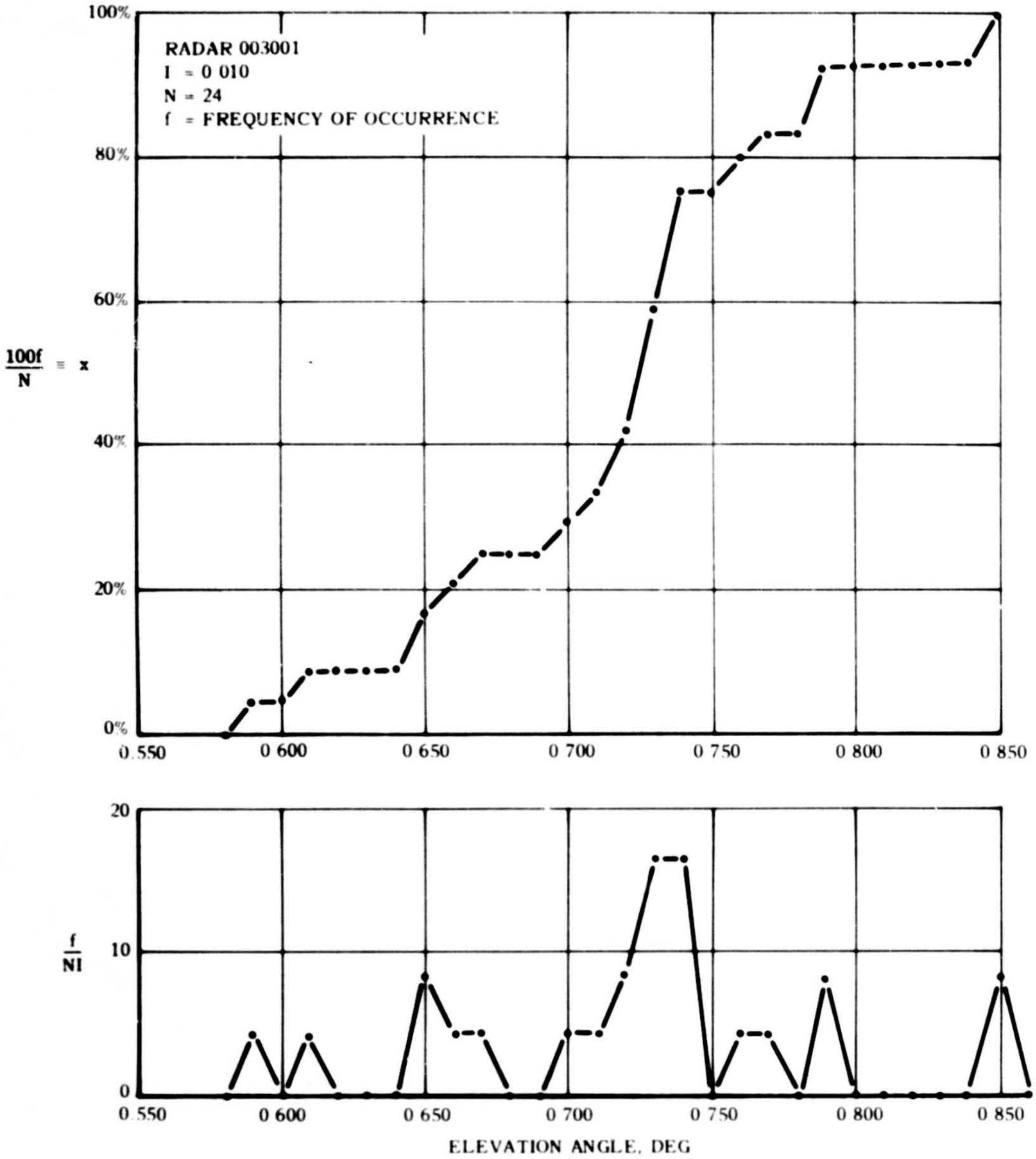

Figure A-10. Distribution of Elevation Angle, 17 October 1962, 0947 to 0953.

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