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RADAR EVALUATION REPORT. A TECHNICAL AND COST ANALYSIS OF THE G--ETC(U)
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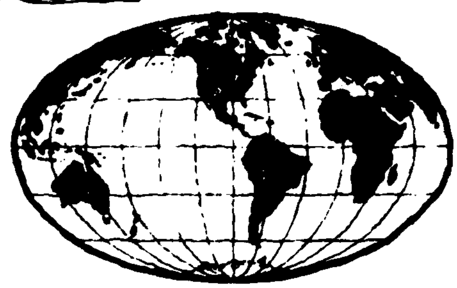

RADAR EVALUATION REPORT (U)

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RADAR EVALUATION SQUADRON

HILL AIR FORCE BASE, UTAH

24 March 1981

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Prepared by:

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Evaluation R

A Technical and Cost Analysis of the German Air Force MPR Radar Antenna Boresighting Requirement

Approved:

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Commander

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Department of Mechanical and Industrial Engineering, University of Utah (1)

A TECHNICAL AND COST ANALYSIS OF THE GERMAN AIR FORCE MPR RADAR ANTENNA BORESIGHTING REQUIREMENT

A comprehensive Engineering Report

Presented to the Faculty of the Department of Mechanical and

Industrial Engineering of the

University of Utah

In Partial Fulfillment of the Requirements for the

Degree of Master of Engineering Administration

By

Lee R. Bishop

24 March 1981

Chapter 1

INTRODUCTION

Background

Antenna boresighting is required to define the pointing direction of a radar beam . The boresighting references are mechanical indicators of azimuth and elevation. The need to boresight exists because antenna focusing and alignment tolerances can offset a radiated beam, particularly in elevation, by as much as 2.5 degrees from the expected pointing direction. A typical nodding-beam height finder boresight error will vary as much as 0.04 degrees in elevation over the range of focusing tolerances.

Before boresighting radar antennae, the antenna indicators of azimuth and elevation must be set to their reference or mechanical zero positions. The mechanical zero position is usually specified by the manufacturer of the antenna. A typical elevation specification would read: "Drop a plumb line from the red hook atop the antenna. Adjust the antenna in elevation until there is a distance of 54.8 centimeters between the plumb line and the red tab at the bottom of the reflector. Set the pointer on the elevation indicator to read exactly zero degrees."

When the antenna is at a position such that the mechanical indicator of elevation reads zero degrees, it is said to be set at elevation <u>mechanical zero</u>. The mechanical zero calibration for an azimuth indicator is similar.

The determination of mechanical zero is a first step in antenna calibration. The desired determination is azimuth or elevation electrical zero.

The difference between antenna mechanical and electrical pointing angles is called boresight error and defined as

Boresight Error = Mechanical Angle - Electrical Angle

The foregoing definition is in accordance with the scientific convention that error equals the indicated minus the true quantity.

When boresighting on an antenna range, a signal source is placed in a known angular position relative to the antenna. The antenna is then rotated in azimuth and elevation until the energy received from the signal source is maximized. The mechanical indicators for azimuth and elevation are then read. The difference between the mechanical (indicated) pointer angle and the true angle (electrical) to the signal source is the boresight error.

Most radar antennae are individually boresighted on an antenna test range prior to disassembly and shipping. Antennae for critical applications such as height-finding or satellite tracking must be reboresighted in the field before use. Subsequent field boresighting requirements can also develop because of shaft slippages, windloading, and antenna modifications.

Because it is a radio frequency signal source with a position that can be calculated, the sun is frequently used for the field boresighting of radar antennae. Sun position in azimuth and elevation can easily be computed using U.S. Naval Observatory tables and a pocket calculator. Unfortunately, the radar antenna does not "see" the sun at the calculated elevation angle because of vertical beam bending due to non-uniform atmosphere. The azimuth angle at which the sun appears to the radar antenna is little affected by the atmosphere. This is because the atmosphere is laterally homogeneous within the boundaries of the radar beam.

When a radio ray is propagated in a vacuum, the path followed by the ray is a straight line. A ray that is propagated in a vertical direction through the earth's atmosphere (the case with solar radiation) encounters variations in the refractive index that impart a downward bending.

Figure 1-1 illustrates the geometry associated with solar boresighting. Because the law of reciprocity holds for both transmission and reception, Figure 1-1 is, for conceptual simplicity, discussed as though the ray path had started at the antenna rather than the sun.

To receive maximum solar energy, a ray must leave the antenna location at an angle θ_0. This ray is bent downward in the earth's atmosphere on its way to the sun. Because of beam bending, the ray will pass through a point in space represented by the sun position and exit at an angle θ. The angle θ depends on the angular bending that the beam has undergone in passing though the earth's atmosphere to the sun. The net effect of the bending is that the antenna must point to a higher elevation angle than the true elevation angle of the sun by an amount approximately equal to the angle, τ. Unless τ, the atmospheric bending, can be quantified and corrected for, it is not practical to use the sun for antenna boresighting.

Solar radiation has been used for boresighting military radar antennae since the late 1950's. The most critical air defense solar boresighting application to date has been that of the nodding-beam height finder. Nodding-beam height finder antenna boresighting is normally required to meet angular accuracy requirements of $\pm$ 0.01 degrees or less. The equivalent angular tolerance for a search radar has been until recently, approximately $\pm$ 0.1 degree.

Nodding-beam height finder antennae can be boresighted at vertical angles between 20 and 30 degrees. Published bending tables based on the Central Radio Propagation Laboratory, (CRPL) Exponential Reference

Atmosphere (EXPRAM) statistical model (5:12-67) are sufficiently accurate at these angles in almost every instance. For this reason, CRPL bending tables and surface refractivity readings have been used for more than 20 years to estimate τ for solar boresighting purposes.

In the past, most radar stations have been equipped with two radars: a search radar provided range and azimuth data; a vertically-nodding-height-beam radar provided height data. Economy considerations have dictated 3-D radar systems combining the search and height function into one radar as replacements for the older two-radar systems.

The 3-D radar uses a series of vertically stacked beams. Targets will appear in more than one beam at a time. If the pointing angles and shapes of the individual stacked beams are known, target angles can be determined by a received signal strength comparison between beams. Knowing aircraft angle and range, aircraft height can be determined.

Problem

By assuming the evaluation mission for the German Air Force (GAF) in 1975, the 1954th Radar Evaluation Squadron became liable for the radar evaluation of six 3-D French-manufactured Medium Power Radars (MPR). The MPR is used for both search and height finding.

One of the essential portions of a radar evaluation is boresighting of all radar antennae. This boresighting is normally done in the field using the sun as a radio-frequency signal source of known position.

During initial customer discussions, it became clear that the GAF considered the matter of MPR boresighting accuracy to be particularly important for three reasons: (a) it is desired to maintain the height accuracy of the MPR to at least the manufacturer's specification of plus or minus 3000 feet at 150 NATO (6000 feet) miles; (b) a shift in beam position from the antenna-range-measured value is an indication of damage and the need for repair; and (c) the effect of upcoming radome installations on boresight error must be quantified if height accuracy is to be maintained.

In the first three MPR evaluations performed for the GAF by the 1954th Radar Evaluation Squadron, the CRPL EXPRAM was used for refraction correction. Unlike a nodding-beam height finder, the axis of beam 1 on the MPR can only be raised to approximately 1.2 degrees.

The CRPL EXPRAM had never been used for height finder boresighting at this angle. There was considerable concern over how well the model would estimate bending at such a low angle as well as the appropriateness of the US model in a German atmosphere. Nevertheless, for lack of other means, the CRPL EXPRAM was used for first three MPR evaluations.

The beam 1 boresighting results for these first three evaluations are shown in TABLE 1.1. Two out of three measured boresight errors met the 0.5 plus or minus 0.15 degree manufacturer's specification. One appeared not to meet requirements.

Table 1.1 MPR Beam 1 boresighting results achieved by the 1954th Radar Evaluation Squadron using CRPL EXPRAM refraction correction.

STATION	YEAR	BORESIGHT ERROR (DEG)	0.35 - 0.65 (DEG)
Visselhoevede	1975	-0.4916	YES
Lauda	1977	-0.4040	YES
Breckendorf	1977	-0.3162	NO

The late Frau Doctor Charlotte Wierczeyko, Regierunsdirectorin of the Amt fur Wehrgeophysik, believed that the Breckendorf antenna was not necessarily out of specification. She opined that the CRPL EXPRAM Statistical model used by the 1954th RADES for refraction correction was not representative of the German atmosphere. She offered to augment the weather support team during the solar phase of the radar evaluation so that numerical ray tracing (Appendix A) through the atmosphere defined by actual radiosonde data could be used, rather than just surface weather data as required by the CRPL EXPRAM.

In-field ray tracing was started in 1978 with the Freising radar evaluation. The results of the Freising and two subsequent radar evaluation boresighting efforts are depicted in TABLE 1.2.

Table 1.2 MPR Beam 1 boresighting results achieved by the 1954th Radar Evaluation Squadron using ray tracing through the atmosphere to determine refraction correction.

STATION	YEAR	BORESIGHT ERROR (DEG)	0.35 - 0.65 (DEG)
Freising	1978	-0.4988	YES
Auenhausen	1979	-0.3166	NO
Visselhoevede	1979	-0.4405	YES

TABLE 1.2, also shows one out of three boresightings to be out of specification, but in this case a radome had been added to the Auenhausen radar, and the out-of-specification condition in the zero direction was not unexpected. The impending installation of other radomes makes boresighting of the MPR critical and emphasizes the need to produce accurate low angle boresightings. It is the purpose of the paper to show that:

a. Solar boresighting produces a monetary benefit that exceeds the cost of the effort, even when numerical ray tracing from radiosonde data is used.

b. The use of the CRPL EXPRAM statistical model is questionable for boresighting height finder antennae below 2 degrees.

c. For nodding beam height finder boresighting at angles above 15 degrees, where atmospheric bending is approximately one third of the 1.2 degree value, the CRPL EXPRAM can still be used.

This paper will recommend that numerical ray tracing from radiosonde date be continued because:

a. When actual rather than modeled data are used, the results are free of controversy.

b. Numerical ray tracing from radiosonde data produces a greater-than-unity cost-benefit ratio.

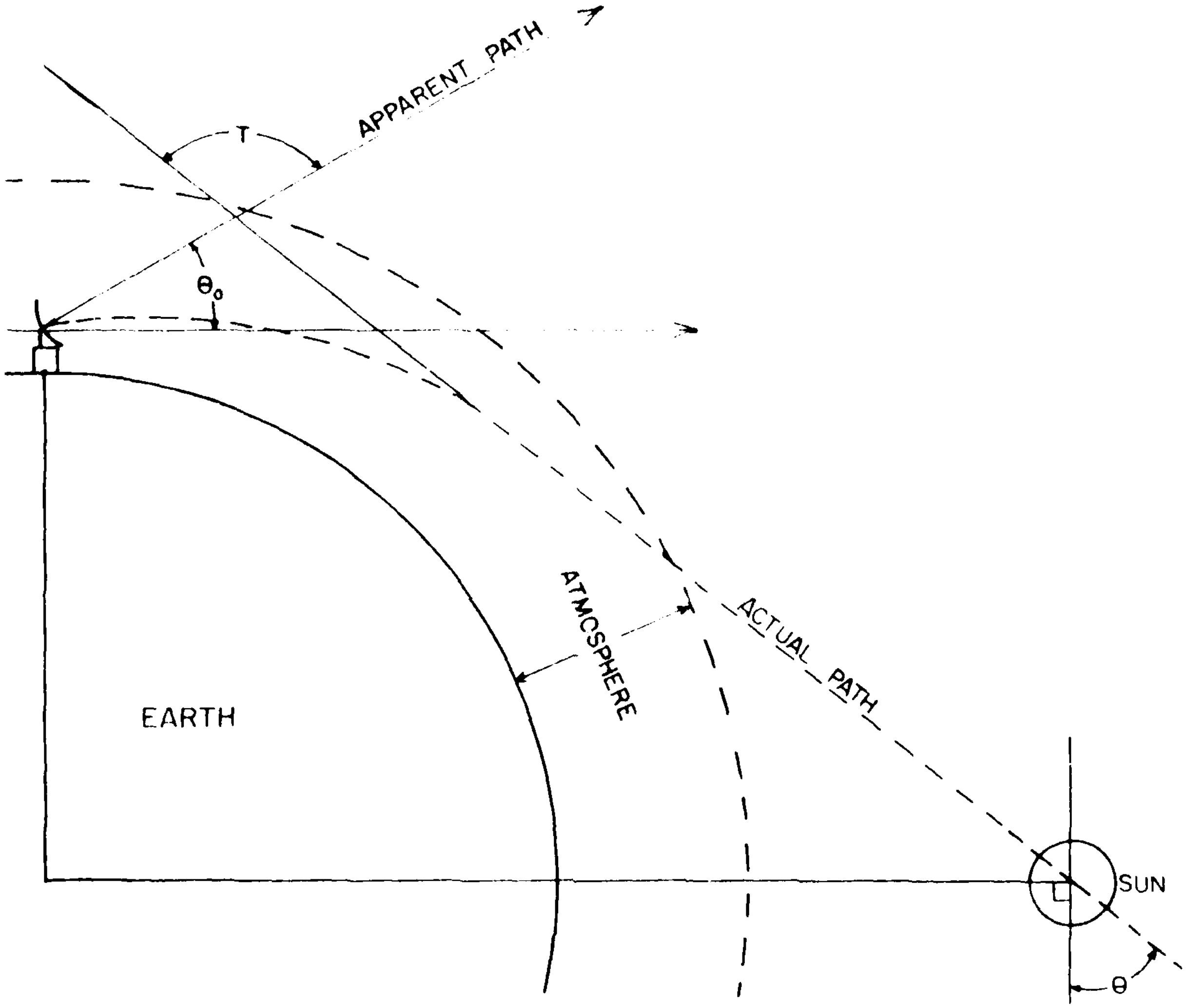


FIGURE 1-1. Solar Refraction Geometry

Chapter 2

THE CRPL EXPRAM APPEARS TO BE UNUSABLE IN GERMANY FOR REFRACTION CORRECTION AT LOW BORESIGHTING ANGLES, BUT USABLE FOR BORESIGHTING AT ANGLES OF 15 DEGREES OR GREATER

Test Philosophy

Although raytracings from radiosonde data provide the best estimate of atmospheric refraction, the procedure is expensive. Thus it seems necessary to ask (a) is the CRPL EXPRAM significantly different from the German atmosphere, and (b) if different, what are the practical effects on boresighting accuracy of using the CRPL EXPRAM in Germany.

To answer the foregoing questions, the investigation pursued in this chapter proceeds along two lines. First, the ΔN values[1] predicted by the CRPL EXPRAM, ΔN_{CRPL}, are paired with the actual ΔN, ΔN_{TRUE}, values measured during the Visselhoevede and Auenhausen evaluations and the differences taken. The paired differences are submitted to a non-parametric statistical test for the significance of a difference between the means. Next, using the same regression technique used in developing the CRPL EXPRAM, an EXPRAM from the Auenhausen and Visselhoevede weather data is developed. Using the CRPL and Auenhausen/Visselhoevede EXPRAMs, the differences in boresighting refraction correction at initial angles of 1.2 and 15 degrees are compared. These differences are converted to a height error to guage the operational effects of using the two different atmospheres.

[1]The quantity ΔN is the difference between the index of refractivity (Appendix A) at the earth's surface (N_S) and the index of refractivity 1 km above the earth's surface.

The author's experience, verified by conversations with numerous German meteorologists, is that the German atmosphere is extremely volatile. It is not uncommon to go through snow, rain, and sunshine in the course of one hour; thus a 1-hour sampling interval gives good assurance of a different atmosphere at each sampling. The Auenhausen and Visselhoevede weather soundings were all separated by at least an hour, covered a range of several days and two seasons, and can be considered as constituting a presenting sample (4:49). There were 31 weather soundings from Auenhausen and 12 from Visselhoevede. Tables based on these soundings showing the date, Zulu Time[1], N_s, ΔN_{CRPL}, ΔN_{True}, and the ΔN differences for Auenhausen and Visselhoevede are included as Figures 2-1 and 2-2 respectively.

<u>CRPL Model Predictions Differ Significantly From Actual Auenhausen/ Visselhoevede Data</u>

The Wilcoxon Signed Ranks test was applied to the paired differences between the ΔN_{CRPL} and the ΔN_{TRUE} values for both the Auenhausen and the Visselhoevede data. The test data are presented in Figure 2-3 and 2-4 respectively. A non-parametric test was used, since nothing is known of the distribution of a ΔN - difference statistic. Test results show a significant difference between the ΔN values predicted by the CRPL model and the measured ΔN values at both Auenhausen and Visselhoevede. Although the test was designed for the 10 percent level, [2] both samples showed significant differences at the 5 percent level.

[1] Zulu time is military terminology for time at the Greenwich meridian.

[2] The 1954th Radar Evaluation Squadron, as a matter of long-standing policy, normally uses customer and producer risks of 10 percent, i.e., a 90 percent confidence interval will be used for all antenna boresighting work.

Ray Tracing and CRPL Model Refraction Corrections Produce Different Boresighting Results

Given that there is a difference between the CRPL and actual German atmosphere, the question arises: "Is there any operationally significant difference in average boresighting results when using the CRPL EXPRAM in a German atmosphere." Any error greater than 375 feet (the least significant bit for the MPR digital height circuitry) is deemed operationally significant.

The Difference Between CRPL and Auenhausen/Visselhoevede EXPRAM Refraction Predictions is Approximately 0.03 Degrees at 1.2 Degrees.

This analysis was designed to estimate the difference in average boresight error from using the CRPL EXPRAM rather than ray tracing data.

A simple exponential atmosphere was developed by combining the Visselhoevede and Auenhausen radiosonde data. As in the case of the CRPL model atmosphere development, a least squares fit of $\ln|\Delta N|$ to N_s was performed. In this case actual, rather than mean N_s and ΔN values were used. The least squares analysis is plotted in Figure 2-5. The a and b constants of the $y=a\,[\exp(bx)]$ equation for the Auenhausen/Visselhoevede EXPRAM are 4.16 and 0.006866 respectively. Values of 7.32 and 0.005577 are used in the CRPL EXPRAM (5:2). Other investigators have found constants of 9.30 and 0.004565 for a German (location(s) unspecified) atmosphere (1:16).

The next step in the analysis was to take separate averages of all N_s values for Auenhausen and Visselhoevede. Each station's average N_s was used to compute an average refraction value for that station using the CRPL EXPRAM. An initial angle of 1.2 degrees was chosen as a representative angle. Next, the constants in the HP-97 program used for numerical ray tracing through the CRPL EXPRAM were replaced with the constants from the regression analysis of

Auenhausen and Visselhoevede data. Again, a 1.2 degree angle was assumed and a raytrace initiated through the revised EXPRAM. The results are shown in TABLE 2.1.

Table 2.1 Refraction Differences Exist Between the Auenhausen/ Visselhoevede and CRPL EXPRAMS using a 1.2 Degree Initial Angle.

STATION	N_S AVERAGE	REFRACTION CORRECTION(DEG) Auenhausen/Visselhoevede	CRPL	DIFFERENCE (DEG)
Auenhausen	302.8	0.41287	0.44167	0.02880
Visselhoevede	331.7	0.47423	0.50036	0.02613

The angular differences shown in TABLE 2.1 indicate height errors at 150 DM of approximately 450 feet for Auenhausen and 410 feet for Visselhoevede. Since these errors exceed 375 feet, they are considered to be operationally significant.

The CRPL EXPRAM is Adequate for Boresighting Nodding-Beam Height Finders.

Using the preceeding procedure, the beam bending at an initial angle of 15 degrees was computed. The Table 2.1 average N_s values from Auenhausen and Visselhoevede were again used. These refraction values were compared with the results from the CRPL EXPRAM.

The difference between the amount of refraction correction calculated between the Auehausen/Visselhoevede and CRPL EXPRAMs for Auenhausen data was 0.00023 degrees. This would amount to approximately 4 feet of height error at 150 DM. The difference between the amount of refraction correction calculated between the same two EXPRAMs for Visselhoevede data was 0.00018 degrees, and this would result in approximately 3 feet of height error at 150 DM. Thus it seems reasonably safe to conclude that the CRPL EXPRAM, while technically inappropriate, is adequate for nodding-beam height finder boresighting in Germany: only the lower boresight angles associated with the MPR radar require actual weather data and raytracing.

STATION: Auenhausen   STATION HEIGHT: 310 meters   YEAR: 1979

DATE	TIME (Z)	N_s	ΔN (CRPL)	ΔN (TRUE)	DIFFERENCE
26 March	1725	298.1	38.59	34.06	4.53
26 March	0527	299.0	38.79	42.03	-3.24
27 March	1706	299.0	38.79	33.65	5.14
28 March	0552	299.4	38.88	32.18	6.70
28 March	1700	291.4	37.18	31.56	5.62
29 March	0530	299.0	38.79	40.01	-1.22
29 March	1702	302.1	39.47	32.58	6.89
30 March	0530	303.0	39.66	31.96	7.70
30 March	1704	304.2	39.93	36.51	3.42
2 April	1700	300.8	39.18	32.68	6.50
3 April	0534	304.0	39.89	37.82	2.07
3 April	1703	301.9	39.42	37.74	1.68
4 April	0542	299.8	38.96	38.25	0.71
11 April	0815	289.4	36.77	17.73	19.04
11 April	1006	296.6	38.27	50.87	-12.60
11 April	1200	294.1	37.74	39.66	- 1.92
11 April	1357	294.5	37.83	32.28	5.55
12 April	0820	308.1	40.81	29.41	11.40
12 April	0930	309.9	41.22	29.54	11.68
12 April	1200	319.9	43.58	44.74	- 1.16
12 April	1335	313.8	42.126	37.23	4.896
12 April	1435	309.8	41.20	32.21	8.99
12 April	1600	315.7	42.58	46.11	- 3.53
17 April	0821	310.5	41.36	36.46	4.90
17 April	1016	311.2	41.52	36.97	4.55
18 April	0815	301.9	39.42	32.51	6.91
18 April	1000	300.9	39.20	29.35	9.85
18 April	1215	299.3	38.85	25.57	13.28
18 April	1415	295.7	38.08	24.50	13.58
19 April	0820	311.4	41.57	39.92	1.65
19 April	1005	301.7	39.38	28.22	11.16

Figure 2-1. Weather Sounding Results.

STATION: Visselhoevede STATION HEIGHT: 82 meters YEAR: 1979

DATE	TIME (Z)	N_S	ΔN (CRPL)	ΔN (TRUE)	DIFFERENCE
8 June	2000	325.6	44.99	42.57	2.42
20 June	0700	341.1	49.05	53.38	-4.33
20 June	1032	337.3	48.03	43.68	4.35
20 June	1300	334.9	47.39	31.77	15.62
21 June	0700	342.3	49.38	44.61	4.77
21 June	1000	326.1	45.12	22.24	22.88
21 June	1300	327.6	45.50	28.58	16.92
21 June	1600	327.6	45.50	36.71	8.79
22 June	0700	340.7	48.94	58.21	-9.27
22 June	1000	346.3	50.50	46.28	4.22
25 June	0700	317.3	42.96	37.54	5.42
25 June	1000	313.4	42.03	30.04	11.99

Figure 2-2. Weather Sounding Results.

DIFFERENCE VALUES	TALLY	RANK VALUES	+ RANKS	- RANKS
0.71	+	1	1	
1.16	-	2		2
1.22	-	3		3
1.65	+	4	4	
1.68	+	5	5	
1.92	-	6		6
2.07	+	7	7	
3.24	-	8		8
3.42	+	9	9	
3.53	-	10		10
4.53	+	11	11	
4.55	+	12	12	
4.896	+	13	13	
4.90	+	14	14	
5.14	+	15	15	
5.55	+	16	16	
5.62	+	17	17	
6.50	+	18	18	
6.70	+	19	19	
6.89	+	20	20	
6.91	+	21	21	
7.70	+	22	22	
8.99	+	23	23	
9.85	+	24	24	
11.16	+	25	25	
11.40	+	26	26	
11.68	+	27	27	
12.60	-	28		28
13.28	+	29	29	
13.58	+	30	30	
19.04	+	31	31	
				57

$z_{0.10} = 1.64$ Test $z = 3.85$ $z_{0.05} = 1.96$

Figure 2-3. Wilcoxon's Signed-Ranks Test for Auenhausen ΔN_{CRPL} and ΔN_{TRUE} Difference.

DIFFERENCE VALUES	TALLY	RANK VALUES	+ RANKS	– RANKS
2.42	+	1	1	
4.22	+	2	2	
4.33	–	3		3
4.35	+	4	4	
4.77	+	5	5	
5.42	+	6	6	
8.79	+	7	7	
9.27	–	8		8
11.99	+	9		
15.62	+	10		
16.92	+	11		
22.88	+	12		
				11

$z_{0.10} = 17.5$ Test $z = 11$ $z_{0.05} = 13.5$

Figure 2-4. Wilcoxon's Signed-Ranks Test for Visselhoevede ΔN_{CRPL} and ΔN_{TRUE} Differences.

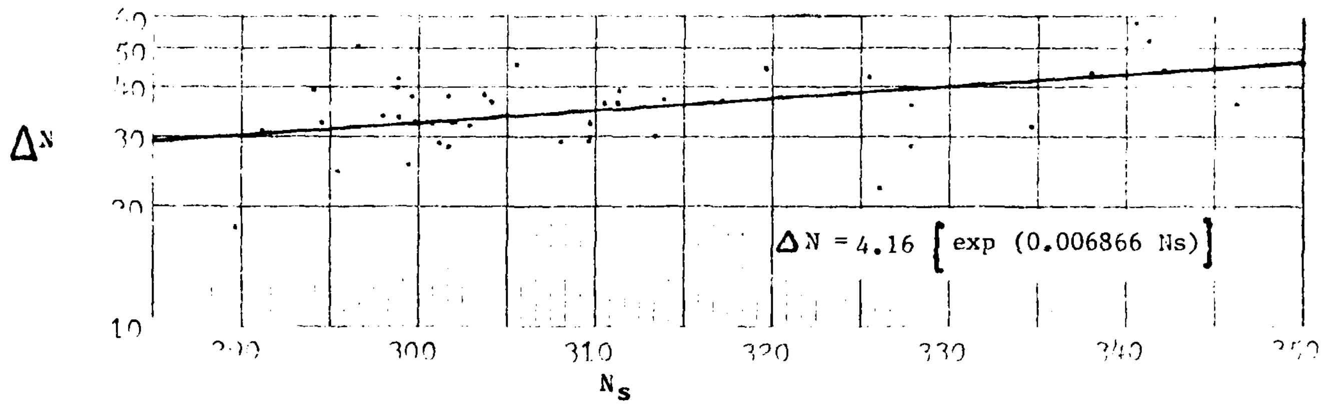


Figure 2-5. A Least Squares Analysis of ΔN and N_s
for Auenhausen and Visselhoevede.

Chapter 3

ANTENNA BORESIGHTING HAS A QUANTIFIABLE MONETARY BENEFIT

Cost Factor Development

The boresighting of an MPR antenna produces a monetary benefit that exceeds the actual cost of the boresighting effort. The monetary benefit from a typical MPR antenna boresighting is $6,200[1], approximately twice the cost of the manhours and material used for the boresighting.

The foregoing $6,200 figure is based on the amount presently being paid by the German Air Force into the USAF Foreign Military Sales Case, $83,200, for the MPR portion of a station evaluation. It is derived from the currently paid $83,200 MPR evaluation price with a radar evaluation benefit-value scheme based on normalized weights.

The first step taken in assigning values was to prepare a list of radar evaluation benefits. This list was submitted to two authorities in the radar evaluation field for revision and concurrence. The next step was to secure the assistance of the same individuals in ranking the selected benefits using the binary decision technique (3:96-103), and then weighting the ranked benefits.

The binary decision technique lends objectivity and ease to ranking multiple alternatives by comparing _n_ alternatives 2 at a time. As an example, alternative 1 is first compared to alternative 2. If alternative 1 is considered to be more important than alternative 2, a 1 is placed in column 1, row 1; and a 0 is placed in column 1, row 2. If alternative 2 is more important than 1, the placing of the 1 and 0 would be reversed. If a clear cut decision can-

[1] Rounded to the nearest $100.

not be made, the 1 and 0 are replaced with 0.5. This process is continued until all comparisons have been made. The numbers in the rows can then be summed. The row (alternative) with the highest sum has the highest ranking.

For the binary decision matrix used in this report, there were 9 benefits (rows). As 9 things taken two at a time = 36, there are 36 columns. The evaluation benefits[1] that were used in the binary decision process, their rankings, and the ranking matrix are presented in Figure 3-1.

With the benefits ranked, the weighting task was considerably facilitated. The binary decision technique produced 3 sets of tied rankings. The ties were easily resolved when the ordered benefits were subjected to weighting on a 1 to 10 scale.

The normalized weights used in the benefit value determination were computed by totalling all the weights and dividing each individual weight by the total of all the weights. TABLE 3.1 is the finalized list of radar evaluation benefits, reordered on the basis of benefit weight, along with raw and normalized weights.

Table 3.1 Normalized Radar Evaluation Weighted Benefits

	BENEFIT	Weight	NORMALIZED WEIGHT
A.	Optimize Configuration	10.0	0.18
B.	Define Operational Performance	9.5	0.17
C.	Verify Equipment Performance	8.5	0.15
D.	Discern Effects of Age and Changes	7.0	0.13
E.	Continuous Evaluation Baseline	6.5	0.12
F.	Environmental Sensitivity Analysis	5.0	0.09
G.	Guidance for Reoptimization	4.0	0.07
H.	Training of Site Personnel	3.0	0.05
I.	Peaking Service	2.5	0.04
	TOTAL	56.0	

[1]The original list of radar evaluation benefits to be used in this paper was prepared by the author. TABLE 3.1 contains a list revised by Mr Bud M. Compton and Lt Col James R. Reid of the 1954 Radar Evaluation Squadron, Hill AFB UT. The weighting of the listed benefits was accomplished by the author and Dr George F. Parker, of the 1954 Radar Evaluation Squadron Technology Branch.

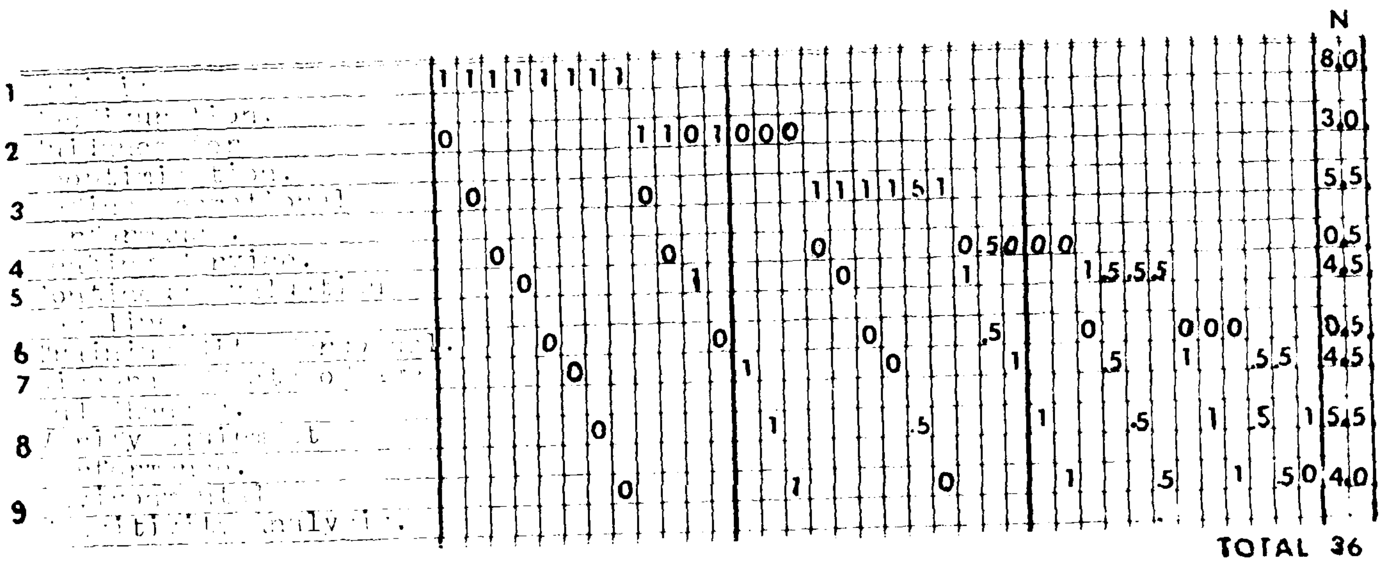
Antenna boresighting is the major element of Benefit C in TABLE 3.1. The value of antenna boresighting, if it were the sole component of Benefit C would be calculated as Cost Benefit C = $83,200 X 0.15 = $12,480.

There are many components of a radar system whose performance is verified on a daily or hourly basis, but the antenna, waveguide, and critical cabling wait for a radar evaluation before their performance is verified. Waveguide and critical cabling could possibly be checked by site personnel before the radar evaluation, but antenna boresighting requires special training. It is for this reason that 50 percent of the monetary benefit of item C, $6,200, is assigned to antenna boresighting.

Sampling Considerations

In the preceeding chapters, it has been shown that at the low elevation angles used for MPR boresighting, the CRPL EXPRAM is inadequate. Little was mentioned regarding the additional costs associated with the ray-tracing-from-radiosonde method.

The actual cost associated with the ray-tracing method of refraction correction is a function of the number of boresightings that must be done. The number of boresightings required is a function of (a) required confidence interval, (b) Type I and II, errors and (c) the variability associated with the boresight measurement method.



N = ROW SUM

Figure 3-1. Binary Decision Matrix for Ranking Radar Evaluation Benefits.

One Half the Boresight Confidence Interval Should be 0.09 Degrees.

The 1954th Radar Evaluation Squadron has successfully used 7.5 percent of the antenna vertical beamwidth as one-half the boresighting confidence interval for a height finder radar. The vertical beamwidth of beam 1 of the MPR radar is 1.2 degrees. The required confidence interval for MPR boresighting thus becomes 1.2 times 0.075 or plus or minus 0.09 degrees.

Current Boresighting Procedures Yield a Standard Deviation of Approximately 0.07 Degrees.

Knowing the required confidence interval and having an estimate of the variability associated with the averages of boresighting measurements enables the use of O-C curves to estimate the sample size required to hold Type I and II errors to less than 10 percent. The variability associated with the boresighting measurement was estimated by combining the standard deviations of MPR boresightings where the ray tracing method of refraction correction had been used. The data from three such evaluations is shown in TABLE 3.2.

Table 3.2 Boresighting Averages and Standard Deviations for Evaluations Employing Ray Trace Refraction.

STATION	YEAR	BORESIGHT ERROR	STANDARD DEVIATION	SAMPLE SIZE
Freising	1978	0.4997	0.1041	5
Auenhausen	1979	0.3166	0.0277	5
Visselhoevede	1979	0.4405	0.0264	4

The pooled standard deviation (2:68) from these evaluations is, rounded to 4 decimal places, 0.0664 degrees.

Table 3.3. Number of Observations Required for a Symmetrical t-Test of the Mean With Type I and II Errors of 10 Percent.[1]

D	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.0	0.95
Sample Size	5	6	6	7	7	8	9	11	11

[1]Extracted from G.P. Sillitto, Research Supplement, J. Royal Statistical Society, 11:520(1948)

A Minimum of 7 Boresighting Samples are Required.

TABLE 3.2 relates sample size to units of the estimated standard deviation of the measurements. Dividing one half the desired confidence interval by the standard deviation yields D, which is related to the minimum number of measurements necessary to limit the probabilities of the Type I and II errors to less than 10 percent. Dividing 0.09 degrees by .0664 degrees yields a D of 1.36 or, rounded to one place, 1.4. This equates to a sample size of 7. Since solar boresighting measurements can only be made one to a sunrise or sunset, three and one half days of boresighting will be required to produce the desired results.

The German Costs Per Day for a Weather Sounding Team are 984 DM per Day (Approximately $492

A German Bundeswehr 4-man weather team using slow-rise free flight balloons can provide the needed radiosonde data. The costs for such a team residing on the economy (most expensive case) and their materials is 984 DM per day, or 492 DM per solar boresight sampling[1]. Thus, the German Air Force expense for 7 boresighting measurements (3.5 days) becomes 3,444 DM or approximately $1,722.00.

[1]Based on a 13 November 1979 letter from Hauptmann Wolfdieterich Mueller, GAF C and F Command.

The American Costs per Day for the Boresighting Effort are $617.50 per Day.[1]

The boresighting effort for a day requires the full-time services of one MSgt and one TSgt. Additionally, the services of another TSgt is required for one half day, and the services of a Major are required for one fourth day. TABLE 3.4 lists the accelerated FMS pay rates for these grades. Based on the pay rates of TABLE 3.4, the daily rate for American labor becomes $291.50. The $45.00 per day *per diem* rates for Americans are not included in the daily pay rates, but must be included to assess total costs. Since the presence of all personnel is required for the day of the solar boresighting, the total *per diem* cost is $45.00 times 4 individuals, or $180.00 per day. The approximately $800 round-trip air fare for each of the 4 participants in the boresighting work can be pro-rated over an average trip duration of 22 days and this, for the four involved individuals, comes to approximately $146.00 per day. Thus, the American labor cost for 7 boresighting measurements becomes 3.5 times the total daily cost of $617.50, or $2,161.25.

Table 3.4. Accelerated FMS Daily Pay Rates

GRADE	DAILY PAY RATE ($)
Major	172
MSgt	109
TSgt	93

The Cost Benefit Ratio for the Boresighting Effort is 1.6.

The boresighting effort produces a monetary benefit of $6,200. The German weather team cost for 3.5 days is $1,722. The corresponding American labor cost is $2,161.25. Thus the total cost for the boresighting effort is $3,883.25. Dividing $6,200 by $3,883.25 and rounding to one place yields a Cost-Benefit ratio of 1.6 for the ray-trace-from-radiosonde boresighting effort.

[1] Based on Accelerated AF Military Pay Rates for FMS, AFAFC/XSMI Msg 1914307, Jan 79

Chapter 4

CONCLUSIONS AND RECOMMENDATIONS

Recapitulation

While this report has not shown conclusively that the CRPL EXPRAM is inadequate for low-angle boresighting in a German atmosphere, there is evidence against the correctness of its use, both in the literature and in this report. This evidence, coupled with the importance of accurate boresighting, dictates a method capable of producing certain results. The ray-trace-from-radiosonde is such a method.

Although the total cost of a single boresighting measurement is $554.75, the American labor portion of this cost ($308.75) exists regardless of the method of refraction correction used. Thus the only real cost increase over the CRPL EXPRAM method of refraction correction is that of the Bundeswehr weather team, a cost increase that is fully justified by both operational needs and a Cost-Benefit Ratio of greater than unity.

Conclusions

1. The US-developed CRPL EXPRAM produces uncertain results in Germany at low boresighting angles. It can create operationally significant errors of approximately 0.03 degrees if used for computing refraction corrections for MPR boresightings.

2. The total cost of a single boresighting measurement is $554.75.

3. Based on commercial value, boresighting to a plus or minus 0.09 degree confidence interval has a cost benefit ratio of 1.6.

4. Numerical ray tracing through an atmosphere defined by weather soundings will insure a best estimate of the refraction correction to be used for boresighting the MPR radar.

5. Ray tracing from radiosonde data is not required for use with nodding-beam height finder radars; the CRPL EXPRAM is adequate.

Recommendations

1. Continue to use weather teams when boresighting MPR radars.

2. Do not use weather teams when boresighting nodding-beam height finders.

3. Seek an improved method of solar boresighting that will reduce the variability inherent in the measurement, thereby reducing the sample size requirements and cost associated with the measurement.

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APPENDIX A

TECHNIQUES FOR COMPUTING REFRACTION OF RADIO WAVES IN THE TROPOSPHERE

1. INTRODUCTION:

If a radio ray is propagated in free space, where there is no atmosphere, the path followed by the ray is a straight line. A ray that is propagated through the earth's atmosphere encounters variations in atmospheric refractive index along its trajectory that cause the ray-path to become curved. The geometry of this situation is shown in figure A-1, which shows the variables of interest.

The angle θ_0 represents the pointing angle of the antenna, the angle of entry into the first layer of the troposphere. The angle θ is the exit angle from the first layer of the troposphere, entry angle into the next layer. R_0 is the geometric distance between layer entry and exit points. R represents the curved path taken by a radio wave in passing from layer entry to exit. Ray tracing schemes attempt to piecewise linearly approximate R by dividing the atmosphere into small layers. Refractivity values at the layer boundries are indicated by n. The total angular refraction of the ray-path between two points is designated by the Greek letter τ, and is commonly called the "bending" of the ray. The atmospheric radio refractive index, n, always has values slightly greater than unity near the earth's surface (e.g., 1.0003), and approaches unity with increasing height. Thus ray paths usually have a curvature that is concave downward, as shown in figure A-1; for this reason downward bending is usually defined as being positive.

If it is assumed that the refractive index is a function only of height above the surface of a smooth, spherical earth (i.e., it is assumed that the refractive index structure is horizontally homogeneous), then the path of a radio ray will obey Snell's law for polar coordinates:

$$n_2 r_2 \cos\theta_2 = n_1 r_1 \cos\theta_1; \qquad (1)$$

the geometry and variables used with this equation are shown in figure A-2. With this assumption the   for a height increment may be obtained from the following integral:

$$\tau_{1,2} = -\int_{n_1}^{n_2} \frac{\cot\theta}{n}\, dn \qquad (2)$$

Unfortunately, the integral for (2) cannot be evaluated directly without a knowledge of the behavior of n as a function of height. Consequently, the approach of the many workers in this field has been along two distinct lines: (a) the use of numerical integration techniques and piecewise linear approximation methods to evaluate τ from radiosonde data which yield n at discrete values of height, and (b) the construction of model n atmospheres to evaluate average atmospheric refraction. The 1954th RADES has mainly used the latter method for economic reasons: only a knowledge of surface refractivity is required.

2. CRPL EXPRAM:

The model selected by the 1954th RADES to use in estimating beam bending is the Central Radio Propagation Laboratory Exponential Reference Atmosphere Model (CRPL EXPRAM).

The CRPL EXPRAM (1:1-3) is the product of a six year study made a 45 U.S. weather stations. The study encompassed many climatically and geographically diverse locations. It was found that ΔN (the difference between N_s, the surface refractivity, and the value of refractivity at a height of 1 kilometer) and N_s were related exponentially; more specifically:

$$\overline{\Delta N} = -7.32 \exp [0.005577 \overline{N}_s] \tag{3}$$

Where $\Delta\overline{N}$ and $\overline{N}_s$ represent monthly mean values from the weather stations.

The exponential reference atmosphere was defined as that family of N profiles having a simple exponential decay with height and passing through the values N_s at the surface and $N_s + \Delta N$ at a height 1 kilometer above the surface. So N(h), N at height h, is given by:

$$N(h) = N_s \exp [-c_e(h-h_s)] \tag{4}$$

Where h_s is the surface elevation, h is the altitude above mean sea level, and c_e is the decay constant given by:

$$c_e = \ln \left[\frac{N_s}{N_s + \Delta N} \right] \tag{5}$$

Equation (4) is the basis of the CRPL EXPRAM.

It should be noted that this model is not suitable for use in Southern California in the summer (2:63). It is not unreasonable to expect that it would be inappropriate for other times and locations.

3. RAYTRACING WITH NUMERICAL INTEGRATION:

Equations (1) and (2) form the basis for numerical integration schemes to derive τ. Using equation 1 and knowing θ_1, it is always possible to solve for θ_2. To do this it is only necessary to divide the atmosphere into concentric layers and either measure the n at each layer (the case with radiosonde data) or compute n using some model.

Equation (2) presents a problem because it assumes n and θ to be continuous. Schulkin has presented a relatively simple, numerical integration method of calculating bending for N-profiles obtained from radiosonde data. The N-profile obtained from the radiosonde data consists of a series of values of N for different heights: one then assigns to N(h) a linear variation with height between the tabulated profile points, so that the resulting N versus height profile is that of a series of interconnected linear segments. Under this assumption, (2) is integrable over each separate linear N-segment of the profile (after dropping the n term in the denominator, which can result in an error of no more than 0.04 percent in the result (3:6-7)), yielding the following result:

$$\tau_{1,2}(\text{rad}) \doteq -\int_{n_1,\,\theta_1}^{n_2,\,\theta_2} \cot\theta \, dn \doteq \frac{2(n_1 - n_2)}{\tan\theta_1 + \tan\theta_2} ,$$

or

$$\tau_{1,2}(\text{rad}) \doteq \frac{2(N_1 - N_2) \times 10^{-6}}{\tan\theta_1 + \tan\theta_2} \qquad (6)$$

where $N = (n-1) \times 10^{-6}$.

For the conditions stated above, this result is accurate to within 0.04 percent or better of the true value of $\tau_{1,2}$, an accuracy that is usually better than necessary.

Figure A-2 shows the geometry associated with the solutions to equations (1) and (6). Given θ_0 and the $\underline{n}$ values associated with each height, successively new values of θ are solved for. With two values of θ and the height gradient, the bending for each layer τ, is computed. Total bending is the summation of all the τs from trace beginning to trace ending.

The 1954th RADES has developed HP-97 software based on equations (1) and (6) to estimate bending in the atmosphere, from either radiosonde data or the CRPL EXPRAM model.

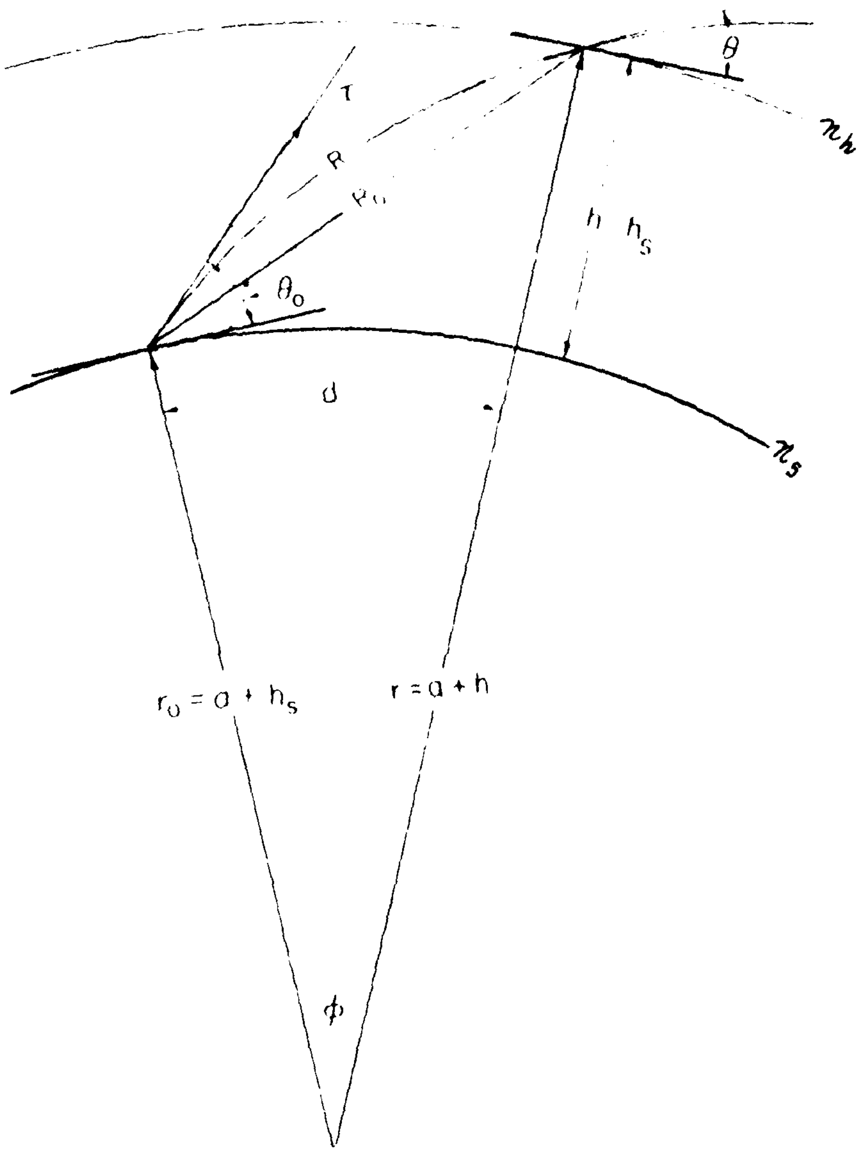

FIGURE A-1. Geometry of the Refraction of Radio Waves

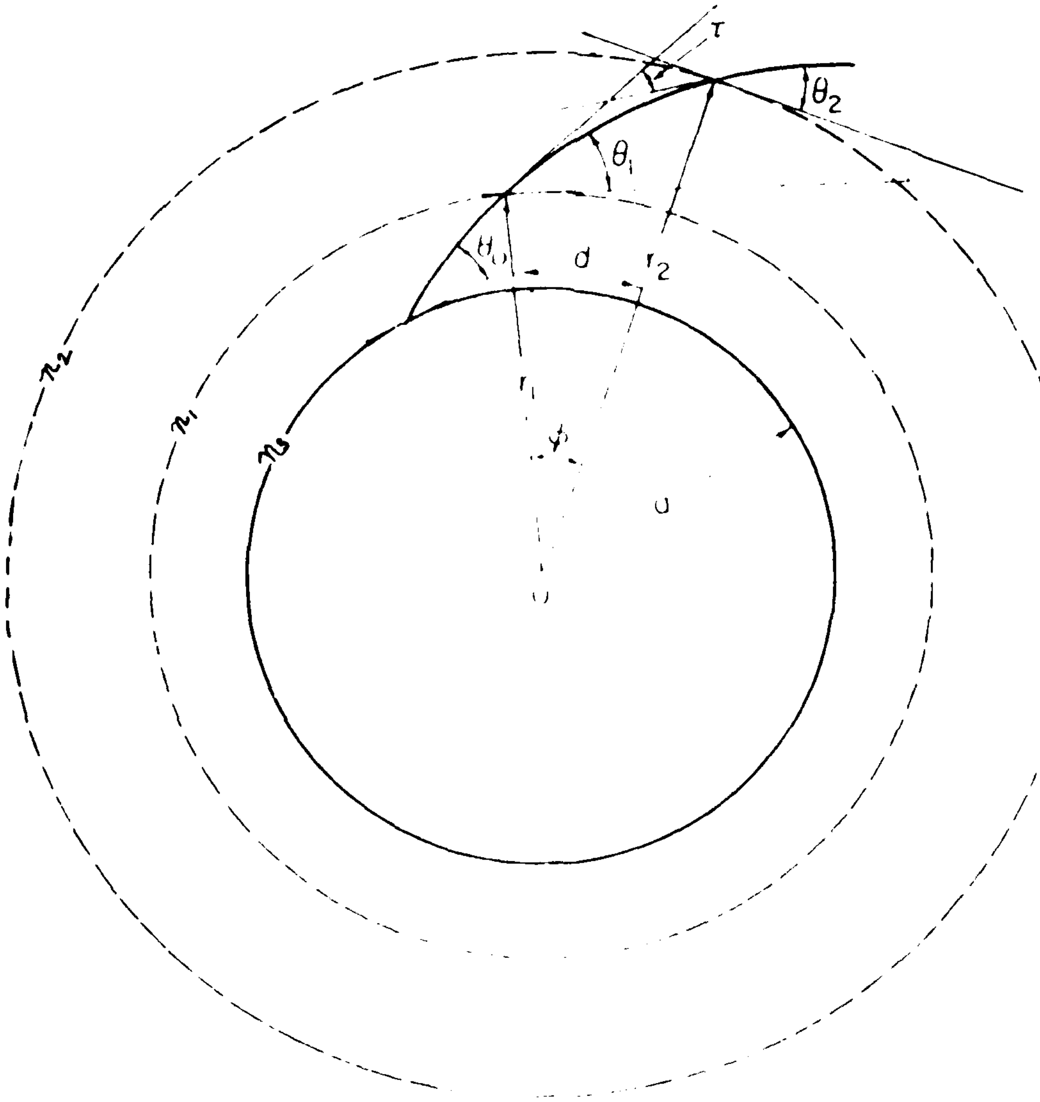

FIGURE A-2. Bending Geometry on a Spherical Earth with Concentric Layers

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