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IONOSPHERIC LIMITATIONS IN THE ULTIMATE ACCURACY OF DIRECTION F--ETC(U)
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IONOSPHERIC LIMITATIONS IN THE ULTIMATE ACCURACY OF DIRECTION FINDING

Raymond F. Gleason
James H. Trexler

RADIO DIVISION II

September 1952

NAVAL RESEARCH LABORATORY, WASHINGTON, D.C.

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(6) IONOSPHERIC LIMITATIONS IN THE ULTIMATE ACCURACY OF DIRECTION FINDING.

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by

(10) Raymond F. Gleason
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ABSTRACT

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PROBLEM STATUS

This is an interim report; work on the problem is continuing.

AUTHORIZATION

NRL Problem 39R06-03
NRL Problem 39R06-07
NRL Problem 39R06-35

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INTRODUCTION

Experimental investigations with a wide aperture high frequency direction finder at the Naval Research Laboratory have shown that the ionospheric limitations in the ultimate accuracy of direction finders may be less than has commonly been supposed. For example in a recent series of tests using short signals transmitted over distances near 1200 nautical miles, the standard deviation of bearing taken under normal ionospheric conditions was less than 0.5 degree. The purpose of this memorandum report is to draw conclusions from recent experimental work that should be helpful in the design of wide aperture direction finders and in estimating operational results to be derived from the use of such direction finders for countermeasures purposes. A brief statement of the background of direction finding limitations precedes the description of the new Naval Research Laboratory experimental results.

BACKGROUND

In high frequency sky wave direction finding three types of bearing errors result from the passage of the radio frequency wave through the ionosphere. The three degradements are polarization error, Heiligtag effect and lateral deviation. Polarization errors result from a lack in consistency of antenna patterns for various polarizations of the arriving signal. Past direction finders have attempted to suppress the undesired polarizations effect by careful antenna design and balancing. A newer technique has been to attempt to equalize the antenna patterns for all polarizations. Heiligtag effect is interference phenomena resulting from several simultaneously arriving rays having variable phase relationships causing an irregular wave interference pattern in the vicinity of the direction finder. Lateral deviation is a result of a systematic tilting of the ionosphere over a large area in the region of the reflection point between transmitter and receiver. There are other phenomena such as scatter from abnormal isolated regions of the ionosphere and distortions near the earth's poles but these will not be considered here. In military direction finding equipment polarization error has usually overridden the other effects so completely that, in the past, work on the latter has been purely academic. Elaborate permanent U. S. military direction finder installations have been shown to have standard deviations ranging from 3 to 5 degrees. It seems probable that a greater part of these large deviations is caused by polarization error, providing that difficulties such as site errors, instrument errors, and uncertainties in the knowledge of the location of targets, have not been predominant. Comparative observations on military direction finders using crossed loops and Adcocks have lead many investigators to the conclusion that polarization error was not the limiting factor since the supposedly polarization-free Adcocks gave very little

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improvement over the loop. The more elusive difficulties of Heiligtag and lateral deviation were quickly blamed and Adcocks were generally condemmed. The best Adcock and spaced-loop systems which are specially designed to overcome polarization error, have shown standard deviations as low as 2 and 1.5 degrees respectively on normal traffic. Special spaced-loop systems operated by the National Physical Laboratories of England have shown standard deviations as low as 1 degree when time averaging of observations by the most experienced operators has been applied.

From a countermeasures viewpoint it is desirable to know what the limitations in accuracy are for direction finders working against short "burst" type transmissions. For short duration signals the effects of all three ionospheric errors are increased, since a time averaging of bearing swing is restricted. A search for systems having the greatest possible immunity to these effects has been under way for several years. To date the most successful has been the group-Adcock system which uses three or more high class Adcock direction finders in a small geographical area obtaining a statistical "best" bearing from the group as one cut. The statistical improvement factor for an ideal group system should be the square root of the number of individual direction finders used but this improvement has never been fully obtained in practice. The best operating group has shown a standard deviation of 1.5 degrees on operational traffic at ranges of 1200 nautical miles. More elaborate instrumentation which will centrally operate, and automatically correlate the outputs of such a system will undoubtedly improve the group results.

The development of wide aperture systems such as the German Komet and Wullenweber and the Bell Telephone Laboratories' Musa have offered the possibility of reducing polarization and Heiligtag effects along with improvements in sensitivity and reduction of site errors. None of these systems have shown great promise operationally but the difficulties in the case of the Wullenweber may possibly be overcome by better design. Operational checks of the small German built Wullenweber showed a standard deviation of 2.4 degrees at 1200 nautical miles. Other wide aperture direction finders such as the phase-modulated, or Dopler, direction finders are not in the same general class as the above systems. They have diversity properties without directivity and may have special advantages for improvement in probability of intercept but may lose in bearing accuracy because of their inability to resolve the desired signal from scatter, interference and noise.

With polarization error seemingly reducible to a second order effect with symmetrical wide aperture systems such as Wullenweber, the residual errors are Heiligtag and lateral. These two errors are related since a small amount of lateral deviation must exist to give the scattered rays necessary for Heiligtag's wave interference effects to produce deviations. The appearance of the two types of errors at the output of the direction finder may be so similar that special techniques other than simple direction finding may be needed to separate or identify them.

The most important difference between Heiligtag effect and lateral deviation is that a wide aperture direction finder may possibly be able to show some ability to reduce the Heiligtag wave interference thru a space averaging effect, while there is little hope of overcoming lateral deviation without continuously conture-mapping the whole ionosphere and making corrections for its momentary shape.

MODEL EXPERIMENTS

In an attempt to obtain an experimental background on which to base more elaborate work, the Naval Research Laboratory conducted a model study comparing the bearing accuracy of a normal crossed Adcock with a large parabolic reflector used as a direction finder. The tests were made at 100 megacycles using a simulated irregular "ionosphere" between target and direction finders. The Adcock was approximately one-fifth of a wavelength in aperture while the parabola was two-and-a-half wave lengths in diameter or about two wave lengths in aperture. The results were quite dramatic; while the Adcock's bearings swung through complete circles, the instantaneous simultaneous lobing indicator on the parabola followed small movements of the target as reflected in the "ionosphere". The results of this work encouraged the Naval Research Laboratory to publish a report on Circularly Disposed Antenna Arrays (NRL Confidential report No. R-3213 dated December 1947). This report recommends a direction finder having an antenna of approximately 1800-foot aperture for use in the high frequency band.

FULL SCALE WIDE APERTURE EQUIPMENT

More recently a full scale high frequency band wide aperture antenna has been built by the Naval Research Laboratory at its Fox Ferry direction finding site (Figure 1) and tested as a direction finder on pulses and short signals to obtain quantitative results on the possible limitations of countermeasures direction finders having apertures near 1000 feet. In building this system every practical precaution was taken to eliminate instrumental and site errors. No attempt was made to build a service direction finder but rather a laboratory instrument having high bearing observation resolution and the ability to check its own errors continuously. Because of the necessity for simplicity the Fox Ferry direction finder was built as a single frequency device which allowed the use of techniques much less complex than would have been necessary in a broad band system.

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The choice of frequency was 6420 kilocycles, since ionospherically produced errors at this low end of the high frequency band are normally greater. The direction finding system chosen was the well-proved simultaneous lobing technique using two slightly displaced, but parallel, antenna beams. The outputs of the two antennas are compared in a Sum-Difference circuit and displayed on a cathode ray tube as a phase difference between the signals in the two antennas. The relationship between the phases at the outputs of the two antennas can be expressed in terms of the azimuth and elevation angles of arrival of the signal. In the normal range of elevation angles of arrival a ten-degree change will produce approximately a ten-percent change in the observed azimuth. By keeping all observations within 3.0 degrees of the center line, or azimuth zero, changes in elevation angle of arrival should cause less than 0.3 degree of uncertainty. This 0.3 degree variation in azimuth will statistically increase the errors observed with the direction finder. This type of error could be eliminated by providing a complete separate orthogonal system whose observations would be combined with the original system to provide true azimuth and elevation angles. The complication of doubling the system complexity did not seem justified. In arranging tests for the system most of the target angles were kept within 2.5 degrees of the center-line with only five percent being as far out as 2.83 degrees.

In choosing the Fox Ferry site on the Potomac River considerable thought was given to the surroundings of the array. The antenna is in the center of a cultivated river-bottom area of several hundred acres. Flooding takes place frequently keeping the ground highly conductive since the river is tidal at this point. A thousand feet in front of the array the river begins, extending over a mile in the direction of the antenna beam. No power lines or fences are in the immediate area. The direction finder is powered by its own engine generator equipment. Probably the greatest site errors result from structures on the horizon. Church spires and the Washington Memorial, two miles away in Alexandria, Virginia, seem now to have been responsible for some of the large errors that have been observed in detailed calibrations.

Figure 1 shows an artist's perspective view of the antenna array and receiving house. There are forty single-turn shielded loops arranged coaxially and divided into two interleaved arrays of twenty loops each. The over-all antenna is 1128 feet wide, or slightly more than seven wave lengths in aperture. Each array is two simple end-fed broadside systems using coaxial cable to inter-connect the loops. The loops in each array are separated by a half-wave length of cable, and alternate loops in an array are reversed in their connections so that all the loops feed inphase to the central point of their array. The artist displaced the two arrays in order to better show the cabling, but actually all loops of both arrays are carefully aligned along a common axis. Since the loops are only four feet high and are twenty-five feet apart the coupling between arrays for such a coaxial system

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is very low. This precaution of low coupling was taken to assure independent voltages in the two arrays. The coaxial cable used to interconnect the loops has an attenuation which gives a three-decibel tapering off of effectiveness for the outermost loops. This tapering reduces the effective aperture to about 1000 feet but greatly reduces the side lobe characteristics of the pattern. A clean pattern is desirable to provide a smooth phase shift with azimuth, and to reduce off-axis interference. A serious limitation of the antenna is the reciprocal beam. High ground within a half-mile along the back lobe may be the cause of some difficulties due to reflections but this was tolerated for the sake of simplicity. It was felt that exact symmetry and low coupling in the arrays were more important than possible errors from back-scatter. Due to the large and tenuous nature of the antenna it is quite difficult to obtain an over-all photograph. Figure 5 is a picture taken from near the center of the antenna looking along the line of loops.

Figure 2 is a system cable diagram showing schematically how the over-all system is interconnected. Cables from the centers of the two arrays feed the two inputs of a coaxial form of hybrid transformer known as a "Rat-Race". Adjustable attenuators in these input cables (not shown in the schematic for simplicity's sake) provide balanced and impedance matched inputs to the hybrid. The two outputs from the hybrid provide the Sum and Difference of the antennas' two outputs, whose relative amplitudes can be used to provide a vector solution of the phase difference between the voltages coming from the two arrays. A fixed length of cable in one of the hybrid's outputs is used to provide a 90-degree phase shift to bring the two outputs into phase for vector addition. These two outputs are put thru coaxial unbalance to balance impedance-raising transformers and then are applied to the inputs of the two receiving channels of the British FHB instantaneous high frequency direction finder. The cathode ray tube indicator of this direction finder provides a simple means of directly measuring the phase relationships of the antenna. The spacing of the two array centers of the antenna determines the ratio of azimuth angle to phase angle. The wider the array spacing is the greater the resolving power of the indicator. However, wide spacings place the two antenna arrays in different radio field environments resulting in unequal input voltages being fed to the hybrid. This unequality of array voltages will result in an ellipsing of the pattern on the indicator which causes only second order errors, but reduces the ability of the operator to read the bearing. The spacing used, which is 72 feet, provides a good compromise. Ellipsing has never limited the ability to read the indicator and the multiplication factor, which is approximately three for ground waves, is enough to obtain reasonable resolution.

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The alignment and checking procedure for this system is so speciallized that it would be unwise to include it in the discussion of this report. The FHB is, in itself, a nicely designed self-checking instrument capable of high stability. The over-all testing procedure should be mentioned. By providing a switch to disconnect one antenna from the hybrid, yet keeping the hybrid matched in impedance the output on the indicator changes from a line vector to a circle. Any mismatch in receiver gain or phase will produce an ellipsing. The orientation of the ellipse and its eccentricity immediately tell the operator which adjustments to make to bring the system into perfect alignment. This check and alignment are easy to make and not critical since a large amount of ellipsing can be tolerated before a readable bearing error develops. This test is carried out every one or two minutes to assure the operator that observed fluctuation in bearings is real and not instrument failures. The test is particularly good since it includes all circuits except the antenna. Since every effort was made to keep the environment of the antenna clean, no test radiator was placed in the field. However, the antenna was tested three times a week against signals arriving via the E layer. These tests will be described later. Further, balloon calibration and ground wave checks were run during the period of operations to keep a constant check on the operation of the antenna. By careful attention to details the estimated reliable repeatable resolution on a long-term basis seems to be close to 0.25 degree of azimuth. To speed the taking and handling of data all observations were recorded to the closest 0.25 degree. Final results indicated that higher resolution might have provided smoother data but probably would not have altered the statistical results.

E LAYER TESTS

The azimuthal orientation of the Fox Ferry direction finder was arranged to be along the great circle path to the transmitter at the Engineering School of the University of Ohio. This transmitter, which is operated primarily for a direction finding project at the University of Illinois, provides a special complex pulse signal. The frequency is 6420 kilocycles and its operating times are daytime only. The distance from Fox Ferry to the University of Ohio is 286 nautical miles which places it at a good E layer range. The signals from this transmitter were observed at Fox Ferry for many months during which time the stability of bearings was studied for short and long transmitted pulses. These tests will not be reported in detail here since the results are of interest more to fundamental research than to countermeasures. A random sample of some 400 observations in April of 1952 showed a standard deviation of 0.33 degree. The Bureau of Standards was asked to determine the ionospheric conditions during the tests and reported that by far the predominant mode of transmission for the period of the test was normal E. No large errors have ever been noted on the signals from the University of Ohio transmitter. The signal has produced such stable bearings that it is now used to check the condition of the antenna.

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Since it has been found impossible to make an accurate local calibration of the direction finder, the mean bearing on the University of Ohio transmitter has been assumed to be correct and the antenna phase balanced on it. All later tests were run with this adjustment.

In August 1952 a Naval Research Laboratory mobile transmitter, NKF 16, operating at 6420 kilocycles with a power of 500 watts feeding an omnidirectional antenna, was sent to Ohio, Indiana and Illinois to study the E layer and short distance F layer bearings. This transmitter emitted 0.25-second dots every half-second and a 5-second dash at the beginning of each minute. Bearings were taken on both the dots and dashes. The 5-second dash was meant to simulate, in length, a practical "burst" transmission and the dots a futuristic "burst". Although the data from the August test has not been analyzed in detail, the bearing stability remained about the same as that of the University of Ohio test, with a slight tendency to become less stable on night time F layer transmissions from Richmond, Indiana and Urbana, Illinois.

F LAYER TESTS

In September 1952 the mobile transmitter NKF 16, still on 6420 kilocycles but emitting only 200 watts, went to Colorado and Wyoming to make a short test for single-hop nighttime F layer propagation. The transmitter travelled in a north-south shuttling fashion along U.S. highway 85 making transmissions between 0520 and 0610 Universal Time each day from 1 September through 11 September. It is the examination of this data that is the primary purpose of this memorandum report.

On the first five days of the test the transmitter moved across the useful azimuth angle of the direction finder's center line, i.e. from -3.0 degrees to +3.0 degrees. The purpose of this run was to check the system for local site errors. For analysis purposes it would be desirable to have a region in which the bearings were varying linearly with azimuth. It was found that the northern half of the path was more linear than the southern, probably due to interference from the Washington Memorial in Alexandria. For the remaining days the transmitter moved in the region between the center line and +3.0 degrees. The exact position of the transmitter was not available to the operators at Fox Ferry during the test to eliminate the possibility of biasing the observations. The table below gives the locations of the various transmitting sites and the bearings relative to the center line of the Fox Ferry direction finder. The location of the Fox Ferry direction finder is 77°01'17'' West Longitude 38°48'16" North Latitude, just south of the southeastern boundry of the District of Columbia.

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TABLE OF TRANSMITTER LOCATIONS

Site Number	Date in Sept.	Longitude W	Latitude N	Relative Bearing
1	1	105° 1.'	40° 36.'	-3.08°
2	2	104 43.5	41 17.	-1.19
3	3	104 13.7	41 41.	-0.11
4	4	104 8.7	42 4.3	1.02
5	5	104 23.	42 43.	2.83
6	6	104 22.	42 25.	1.94
4	7	104 8.7	42 4.3	1.02
7	8	104 10.	42 12.3	1.38
8	9	104 35	42 33	2.35
5	10	104 23	42 43	2.83
6	11	104 22	42 25	1.94

For the reader to be able to judge the military countermeasure usefullness of the results of this test he should understand precisely how the bearings were read.

First, the five-second dash at the beginning of each minute was read as a separate and isolated bearing. Usually the few seconds before the dash were used for checking the alignment so the operator was not influenced by immediately previous conditions.

Second, a short series of dots was read as a bearing at approximately 30 seconds after the dash if alignment and checking duties would permit.

Third, bearings were taken on schedule at a precise time and not at a time of minimum fade or least swing.

Fourth, no bearings were ignored or thrown out because they looked "wild".

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Fifth, bearings were read thru interference, both man-made and natural, if the desired signal could be seen at all.

Sixth, bearings were not normally read at the beginning, end and fifteen minute calls since at these times information on the schedule was transmitted requiring the operator's attention in copying the message.

Seventh, the operator's best judgement of the bearing and his guess as to the bearing swing were recorded for each observation. Since the maximum swings usually take place during the trough of a fade it is hard to get a precise figure but the approximate values may be useful. Also it was noted that the swings were not always symmetrical about the bearing of the maximum in the fading cycle. This unsymmetrical type of swing is a characteristic of simple Heiligtag effect. No attempt was made to record the lack of symmetry in the swings due to the difficulty of making the observations.

Figure 3 is a plot of all the observed bearings on signals from NKF 16 received between 3 September and 11 September inclusive. The data is plotted against Universal Time and the estimated swing is shown as a vertical line at each point having a length equalizing the total swing. Those points not having such a line represent bearings which were perfectly still as far as the observer could tell. Pronounced fades are noted by the letter F on the plots and complete fade outs by the letters F.O. Field strength measurements indicated that a signal level of at least 1 microvolt per meter was required to provide a 1:1 signal to noise ratio on the indicator of the direction finder. Signals having ratios as low as 1:1 were often used for bearings, but signals of lower level were too indistinct to read. The Bureau of Standards ionospheric condition symbol for the period of the data is shown under the date. N represents normal conditions, U, unstable and W is a storm warning. Three periods were N, one was U and five were W. On the last day, 11 September, which was a W day no signals were heard and transmitters of five times the power of NKF 16 were just detectable over parallel paths.

Due to the mathematically small amount of data obtained on individual days no statistical treatment will be given for the daily tests. The observations for N and U days were combined to find the mean azimuth of the center line of the array and to determine the azimuth multiplication factor which is a function of the elevation angle of the arriving signals. Both these figures were close to expected values and checked azimuthally with meager observations made in Ohio. After reducing all observations to the closest 0.25 degree of azimuth the data was analyzed.

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Figure 4 shows three histograms summarizing the whole test. Each graph shows the distribution of bearings about the "true" azimuth as determined from the straight line calibration derived from the observations made on N and U days. The first histogram is for the four normal days. The symmetry of this graph is remarkably good and there is little evidence of the leptokurtic condition found in the Wullenweber tests. The graphs for individual days were not so smooth due to an obvious tendency of the individual operator to favor particular numbers over others. However, with the transmitter moving in a random way, this type of systematic error was smoothed out. It is felt that the moving target technique of gathering data is the only sure way of eliminating many forms of errors that have compromised such studies in the past.

The second histogram of Figure 4 is the distribution for W days. In this case each of the individual sets of data seemed to have its own distribution, and they combined into a broad flattopped, or platykurtic, family. The idiosyncracies of the individual operators showed up in the skirts of this graph because of the lack of overlapping data. Possibly a significant feature of the graph is its tendency towards moving south. It was observed that on W days the bearings seemed to swing farther south than north around the "best" bearings. It is difficult to decide whether this southern trend is the result of a true layer tilt or is an accidental Heiligtag effect.

The final graph of Figure 4 is a combination of all the days of the test from 3 thru 10 September. The shape of this curve is far from simple due to the southern trend of the W days but the over-all shape is much better than might have been expected for such a stormy period.

The following table summarizes the calculated data for the September test.

Statistical Results of September Test

Ionospheric Condition	Number of Observations	Variance σ^2	Standard Deviation σ	Total Range
N and U	249	0.20°	0.45°	3.0°
W	203	0.85°	0.92°	5.25°
All	452	0.49°	0.70°	5.25°

Notice that the number of observations is not evenly divided between good and bad days even though there were four each of such days from which data was used. This condition is a result of more fades and lower level signal level on the W or bad days. This inequality of

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observations should not compromise the statistics since the data was taken as a "true" sample of the existing conditions. It is believed that further mathematical manipulation of the data is not justified in this case since the number of variables present takes the data out of the class of phenomena easily handled by statistics.

CONCLUSIONS

It is difficult to draw comprehensive conclusions from such a specialized set of observations. The 1200 nautical mile path is an ideal compromise for reducing errors due to elevation angles and for maintaining the simpler single-hop mode. Most direction finder tests have shown their best results near this range. This ideal range was used to obtain, as close as possible, a measure of the best accuracy the wide aperture system can achieve. The purpose has not been to see how bad errors in direction finding can be, but rather to determine how good the direction finder must be, to be utilized to its fullest under average or better than average conditions. It is stressed that all observations were made when the frequency used should have been below the MUF (Maximum Usable Frequency). This is a compromise since, in practice, the frequency is not at the control of the countermeasure direction finder. By making observations above the MUF a greater percentage of large deviations would have been expected due to possible scattering from dense ionospheric clouds existing off the great circle paths. This type of difficulty takes place more often at high frequencies and in cases where the transmitter is using a beam antenna not directed towards the direction finder. Since beamed antennas are normally used with permanent installations, which are of little interest to the countermeasures direction finder, it would seem that too much importance has been given this type of error. The omission of tests at times when a sunrise or sunset zone was in the path was done purposely since this problem has been considered by others with more appropriate facilities. Realizing the above considerations and the fact that the data relates to a direction finder having an aperture of 1000 feet, the following very general conclusions are drawn:

1. That under all types of ionospheric conditions, single-hop E or F layer high frequency signals at frequencies below the MUF will provide bearings with a standard deviation of less than 1 degree.

2. That under stable ionospheric conditions, which exist most of the time, single-hop E or F layer high frequency signals at frequencies below the MUF, will provide bearings with a standard deviation of less than 0.5 degree.

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3. That even with an aperture of 1000 feet, Heiligtag effect is still a major cause of momentary errors.

4. That the above conclusions hold for short "burst" type transmissions of less than 5 seconds duration and longer transmissions will materially reduce the error.

RECOMMENDATIONS

In view of the high accuracy of wide aperture direction finding systems indicated by the Naval Research Laboratory observations it would be wise to consider certain recommendations before an attempt is made to construct an operational wide aperture system. Some of these recommendations stem directly from observations made during the recent Naval Research Laboratory test and others resulted from improved instrumentation necessary for precision direction finding.

1. The utmost care must be used in the selection of a site. It is difficult to state specifications for the site but it has been obvious in the testing of the Naval Research Laboratory direction finder that a site such as Fox Ferry leaves much to be desired.

2. The antenna array and all its component parts should be constructed with an accuracy such that bearings can be taken with a precision of at least 0.25 degree without introducing masking variables associated with time, temperature or frequency.

3. The project should provide for an extensive long term evaluation program with opportunities for operational type tests.

4. The antenna design should be flexible enough to provide for eventual instantaneous bearing indication.

5. The contractor should not plan to use ground wave signals for calibrations or polarization error measurements.

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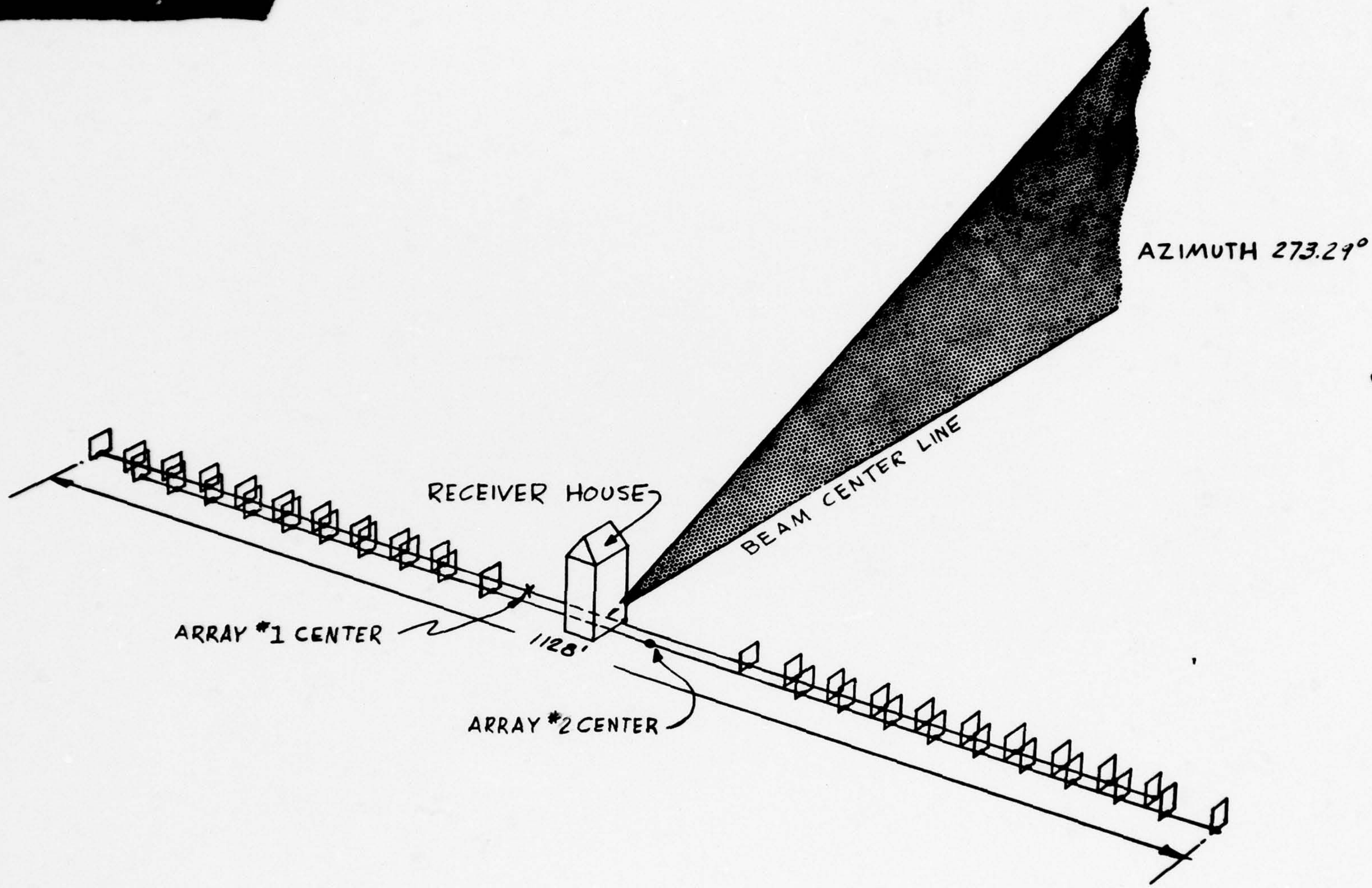

Figure 1 PERSPECTIVE VIEW OF FOX FERRY ANTENNA

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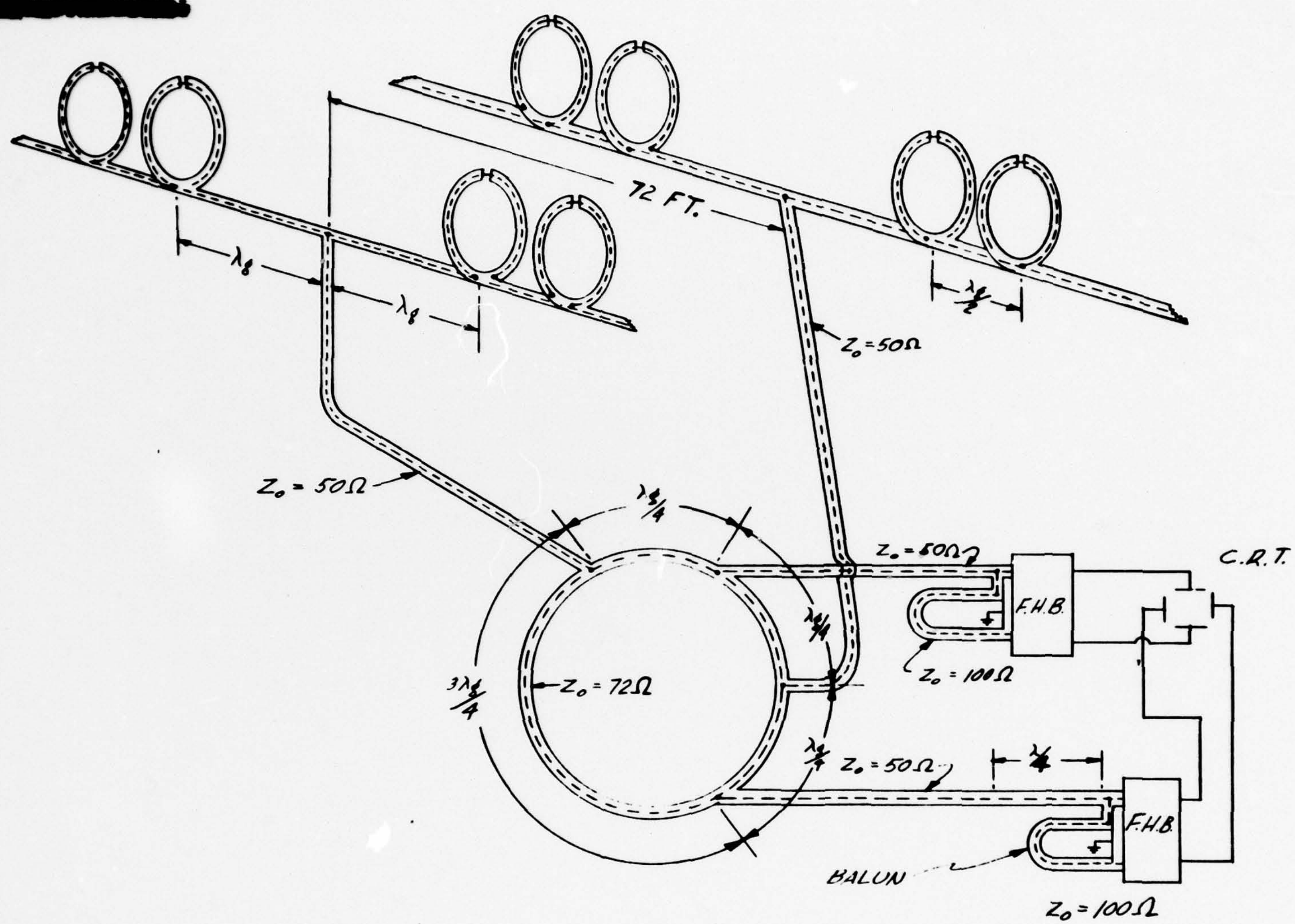

Figure 2 SCHEMATIC OF ANTENNA CABLING SYSTEM

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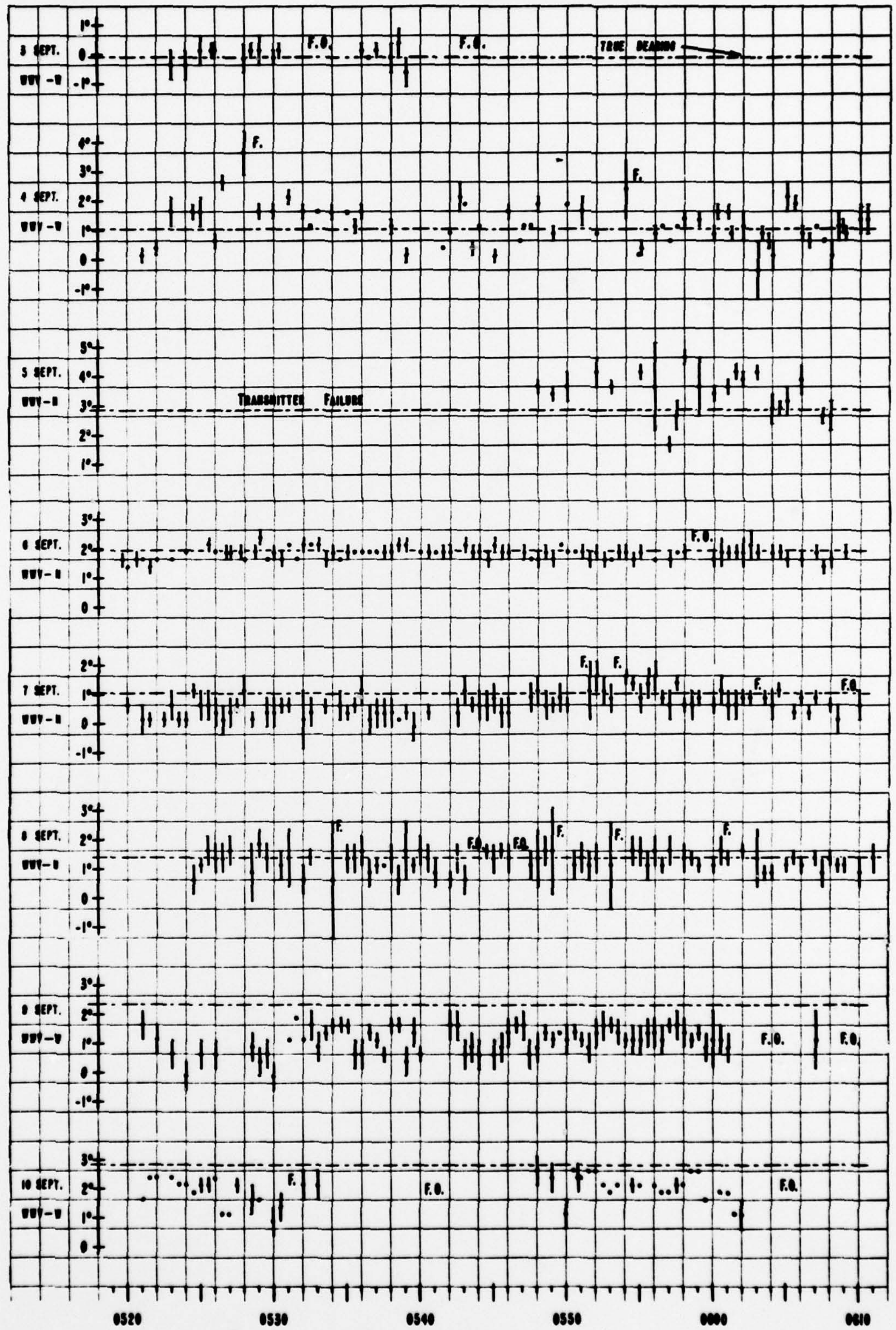

[redacted] Figure 3 DAILY OBSERVED BEARING PLOT

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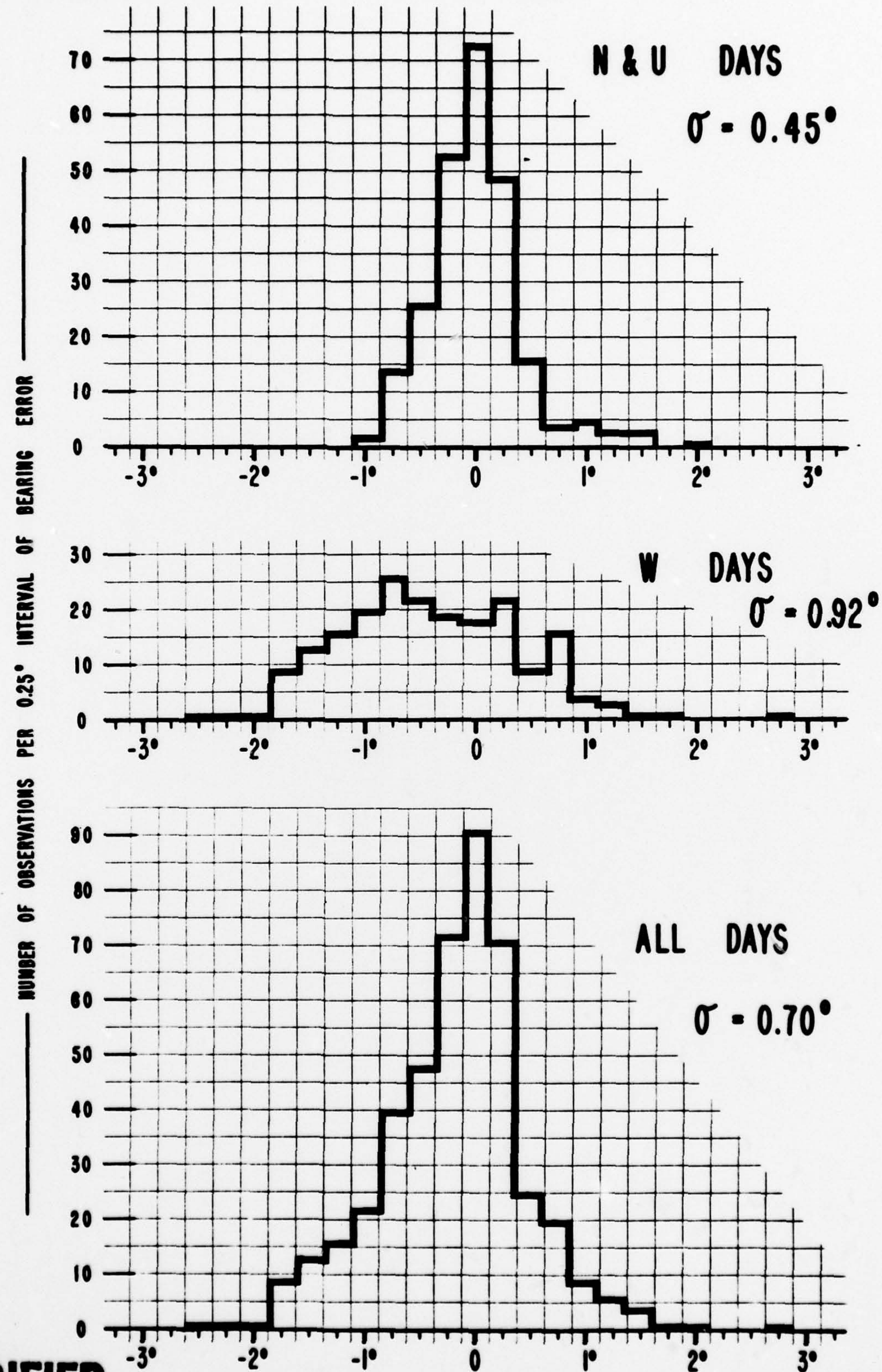

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Figure 4 BEARING ERROR HISTOGRAMS

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VIEW OF PART OF FOX FERRY ANTENNA

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Figure 5