Report No. FAA-RD-71-25

DEVELOPMENT AND EVALUATION OF A DOUBLE SIDEBAND DOPPLER VOR SYSTEM WITH HIGH LEVEL REFERENCE MODULATION

Virgil E. Willey
National Aviation Facilities Experimental Cent
Atlantic City, New Jersey 08405

JUNE 1971

FINAL REPORT

Availability is unlimited. Document may be released to the Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia 22151, for sale to the public.

Prepared for

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

Systems Research & Development Service

Washington D. C., 20590

172

The contents of this report reflect the views of the National Aviation Facilities Experimental Center, Atlantic City, New Jersey, which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policy of the Department of Transportation. This report does not constitute a standard, specification or regulation.

The Federal Aviation Administration is responsible for the promotion, regulation and safety of civil aviation and for the development and operation of a common system of air navigation and air traffic control facilities which provides for the safe and efficient use of airspace by both civil and military aircraft.

The National Aviation Facilities Experimental Center maintains laboratories, facilities, skills and services to support FAA research, development and implementation programs through analysis, experimentation and evaluation of aviation concepts, procedures, systems and equipment.

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FAA-RD-71-25		

4. Title and Subtitle	5. Report Date
DEVELOPMENT AND EVALUATION OF A DOUBLE SIDEBAND DOPPLER VOR SYSTEM WITH HIGH LEVEL REFERENCE MODULATION	June 1971
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Virgil E. Willey	FAA-NA-71-36
9. Performing Organization Name and Address	10. Work Unit No.
National Aviation Facilities Experimental Center Atlantic City, New Jersey 08405	
	11. Contract or Grant No. Project No. 330-011-01X
	13. Type of Report and Period Covered Final Report November 1962 - May 1971
12. Sponsoring Agency Name and Address FEDERAL AVIATION ADMINISTRATION Systems Research & Development Service Washington, D. C. 20590	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report describes the development and evaluation of an improved Doppler VOR System which will provide improvement of receiver compatibility with existing receiving equipment and reduction of station bearing error with some additional reduction of "siting effects" and a reduction of counterpoise size. A new method of providing the 30 Hz amplitude modulation of the carrier, applicable to either the present Single Sideband or the Double Sideband Doppler VOR System for increased carrier power is also described.

17. Key Words	18. Distribution Statement
Double Sideband Doppler VOR High Level Modulation for Doppler VOR Doppler VOR	Availability is unlimited. Document may be released to the National Technical Information Service, Springfield, Virginia 22151, for sale to the public.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	178	

Form DOT F 1700.7 (8-69)

PREFACE

The project manager acknowledges the project guidance and technical assistance provided by Robert B. Flint, RD-331 and by the personnel of the Model Shop for their timely and efficient work in the counterpoise reduction. Acknowledgements are also due to the many technicians, pilots, and support personnel who contributed to the project effort.

BLANK PAGE

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

Figure | | Page

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

INTRODUCTION

Purpose

The purpose of this project was to develop a Double Sideband Doppler VOR System and evaluate the effectiveness to improve airborne receiver compatibility over that of the present Single Sideband Doppler System.

A secondary purpose was to determine a feasible technique of providing more efficient modulation for the reference signal as a means of increasing radiated power and thereby increase Doppler VOR (DVOR) operating range to that of the Conventional VOR.

General

Project effort has resulted in an improved Doppler VOR System known as the Double Sideband Doppler VOR System, and a new technique (high level modulation system) for providing the reference 30 Hz amplitude modulation of the carrier at an increase of radiated carrier power which is applicable to either the present Single Sideband or the Double Sideband Doppler VOR System. Each of the two systems will be discussed in separate sections of this report. The equipment development will be briefly discussed in the third section of this report.

SECTION I

DOUBLE SIDEBAND DOPPLER VOR SYSTEM

BLANK PAGE

Background

There are many VOR and VORTAC facilities presently operating with restricted services due to certain site effects from objects which are physically or economically impractical to remove. There are requirements for new facilities for which there are no suitable sites available for a Conventional VOR or VORTAC. The endeavor to reduce the siting problem of the Conventional VOR has resulted in the use of the doppler principle in the generation of the 30 Hz frequency modulation of the 9960 Hz subcarrier.

The feasibility of the Doppler VOR (References 1 and 2) was proven in 1958, and was integrated in the National Airspace System (NAS) by Selection Order 1010. 5, dated August 27, 1964. The Doppler VOR System does provide a navigational facility where operational requirements cannot be met by the Conventional VOR System. It has the advantage of having much less susceptibility to course deterioration due to siting conditions. This is due to the basic manner in which the variable phase voltage is produced. Improvement in receiver compatibility and reduction of station bearing error, with some additional reduction of "siting effects" and counterpoise size, can be achieved with a Dual Channel Subcarrier Doppler VOR.

DISCUSSION

General

In the development of the Doppler VOR, it was necessary to have system compatibility with existing airborne receiving equipment. The compatibility of the Doppler VOR is dependent upon many factors involved in the generation of the signals of the transmitter and in the processing of the signals at the reception point.

Each of the various types of navigational receivers currently in existence processes the Doppler VOR signals differently. This is due to varied receiver design parameters among the various manufacturers of navigational receivers.

The major receiver design parameters which affect receiver compatibility are the degree of limiting in the frequency modulation circuitry (9960 FM Channel), the bandpass characteristics of the radio frequency and intermediate frequency amplifying stages, the type and characteristics of the limiter and discriminator used, the point of the receiver circuitry at which the AM and FM modulations are separated, and the characteristics of the signal filters used in the processing of the information portion of the received signal. The limitation of "compatibility without receiver modification" places the burden of receiver compatibility at the signal source, the Doppler VOR.

At the signal source, receiver compatibility and station error are primarily determined by the smoothness achieved in the simulated rotation of the sideband antenna and the circularity of its radiation pattern. These are determined by the sideband radiation system composed of the sideband antenna, the distributor, and the counterpoise, all of which affect the radiated signal.

In order to establish a relationship between the Doppler VOR radiation system and receiver compatibility, as well as station error and to discuss means of improvement, a comparison of how the navigational signals for the two VOR systems are generated is briefly reviewed.

Specifications

The specifications for a VOR ground system are, in part, that it contain two modulation voltages having a frequency of 30 Hz. In order to keep those voltages separate and distinct, so that they may eventually be compared in phase angle by the receiver, one is transmitted as 30 Hz amplitude modulation, while the second is applied to a 9960 Hz subcarrier as frequency modulation, and the subcarrier transmitted as amplitude modulation. One of these voltages must have a phase which varies directly with azimuth angle, while the other must have a phase which is constant with azimuth.

VOR specifications require that the characteristics of the frequency-modulated subcarrier be as follows: Center Frequency - 9960 Hz; Deviation - ±480 Hz; Modulation Frequency - 30 Hz.

Navigational Signal Generation

Conventional VOR: The radiated signal from the Conventional VOR is composed of a carrier frequency which is amplitude-modulated by two audio frequencies, one a 30 Hz and the other a 9960 Hz subcarrier which is frequency-modulated $\pm$480 Hz at a 30 Hz rate.

The 9960 Hz is generated by a tone wheel with proper spacing of the teeth to provide a frequency deviation of $\pm$480 Hz at a 30 Hz rate. The carrier energy is amplitude-modulated by this 9960 Hz and is radiated by the carrier antenna. This 9960 Hz is a subcarrier and when processed by the FM circuitry of the receiver, produces a 30 Hz signal. The phase of this 30 Hz signal is the same in all azimuths and therefore is known as the reference phase signal.

The 30 Hz amplitude modulation of the carrier energy is accomplished by a technique known as "Space Modulation," wherein a portion of the modulated carrier energy is stripped of its modulation and fed to a rotating capacitive goniometer. The goniometer has sine and cosine outputs which energize the sideband array, producing a rotating figure-of-eight pattern. The figure-of-eight pattern combines in space with the circular carrier pattern to produce a rotating limacon, where $R = A\ (1 + m \sin \theta)$ and m(modulation index) = 0.30, while A is equal to the carrier level. The phase of the 30 Hz AM component of this signal varies with azimuth and is appropriately known as the variable phase signal.

When this signal is detected and processed by the AM channel of the navigational receiver, a 30 Hz signal is obtained, the phase of which, when compared to the 30 Hz reference signal from the FM channel of the receiver, will provide azimuth information relative to the point of radiation. A block diagram of the VOR modulation system is given in Figure 1. The RF spectrum is illustrated in Figure 2a.

Doppler VOR: In the present Doppler VOR, the 30 Hz AM signal is generated by the use of the same type of capacity goniometer as used in the VOR. Unmodulated power from the carrier is supplied to the input. However, only one of the outputs is used to supply power to a modulation bridge for modulation of the carrier. The other output is connected to a dummy load to maintain a balanced load to the goniometer. A simplified block diagram of the 30 Hz amplitude modulation system is given in Figure 3. We now have the carrier energy amplitude

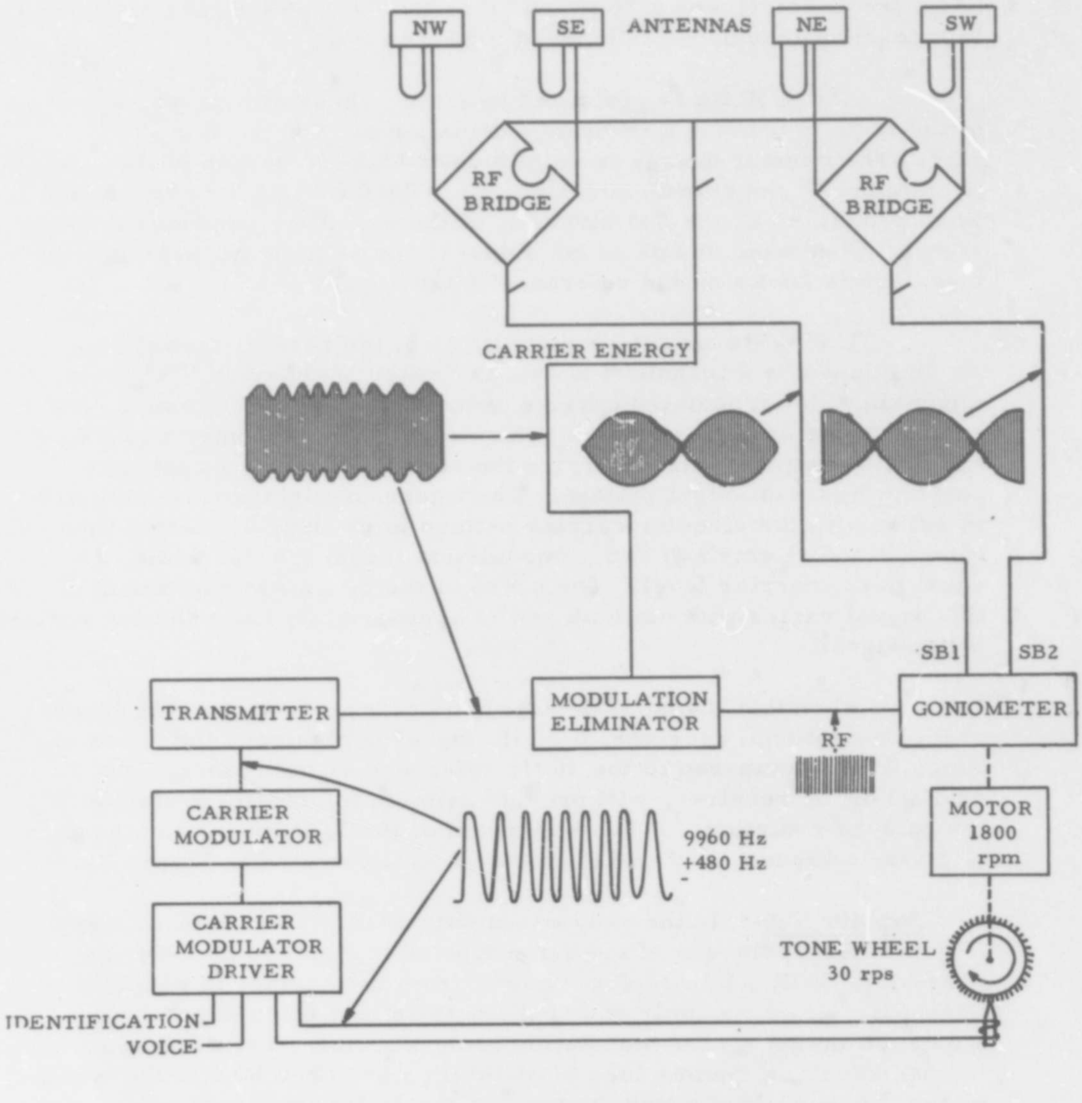
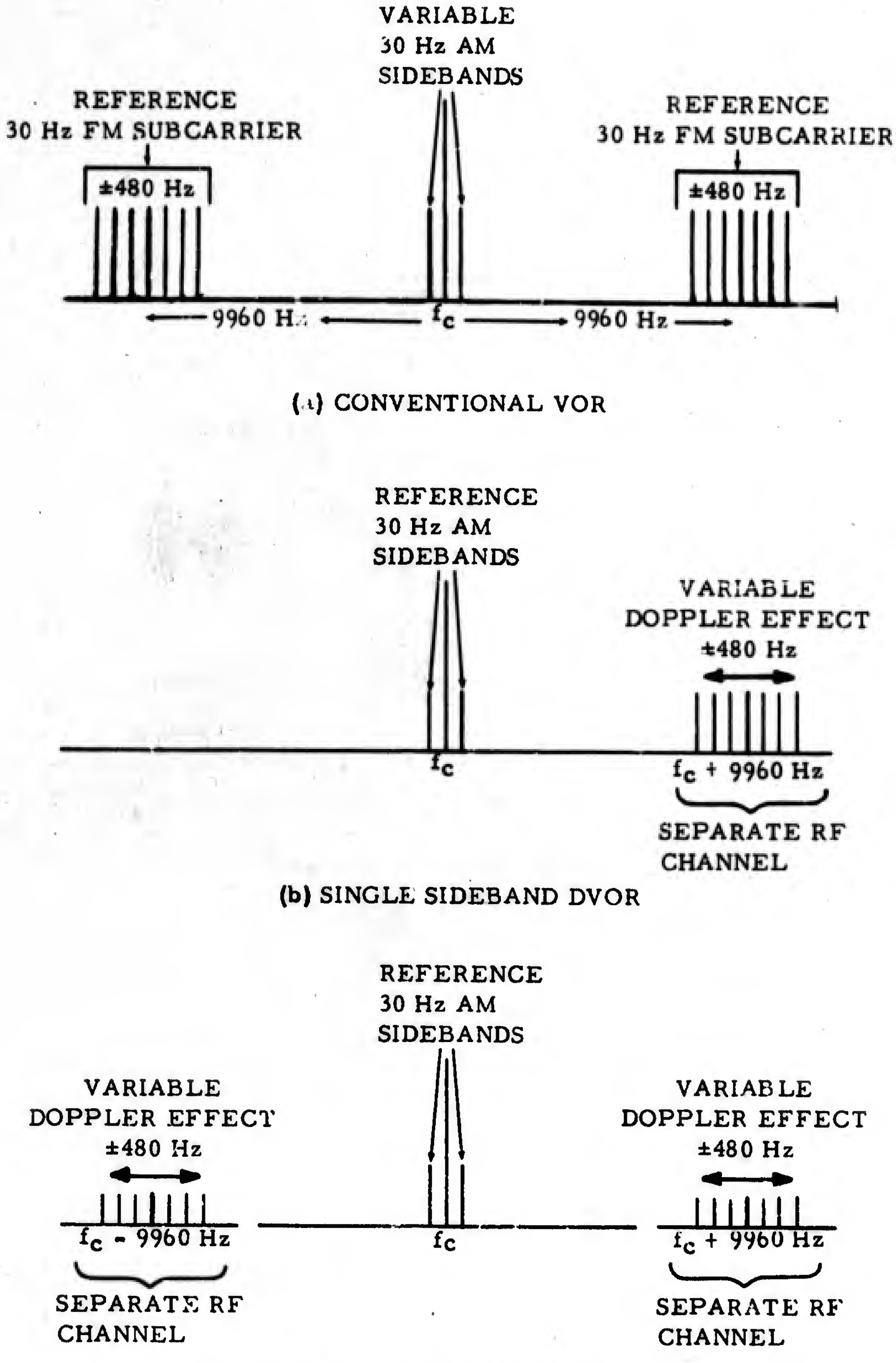


Figure 1. CONVENTIONAL VOR MODULATION SYSTEM



(a) CONVENTIONAL VOR

(b) SINGLE SIDEBAND DVOR

(c) DOUBLE SIDEBAND DVOR

Figure 2. RF SPECTRUM OF VOR MODULATION SYSTEMS

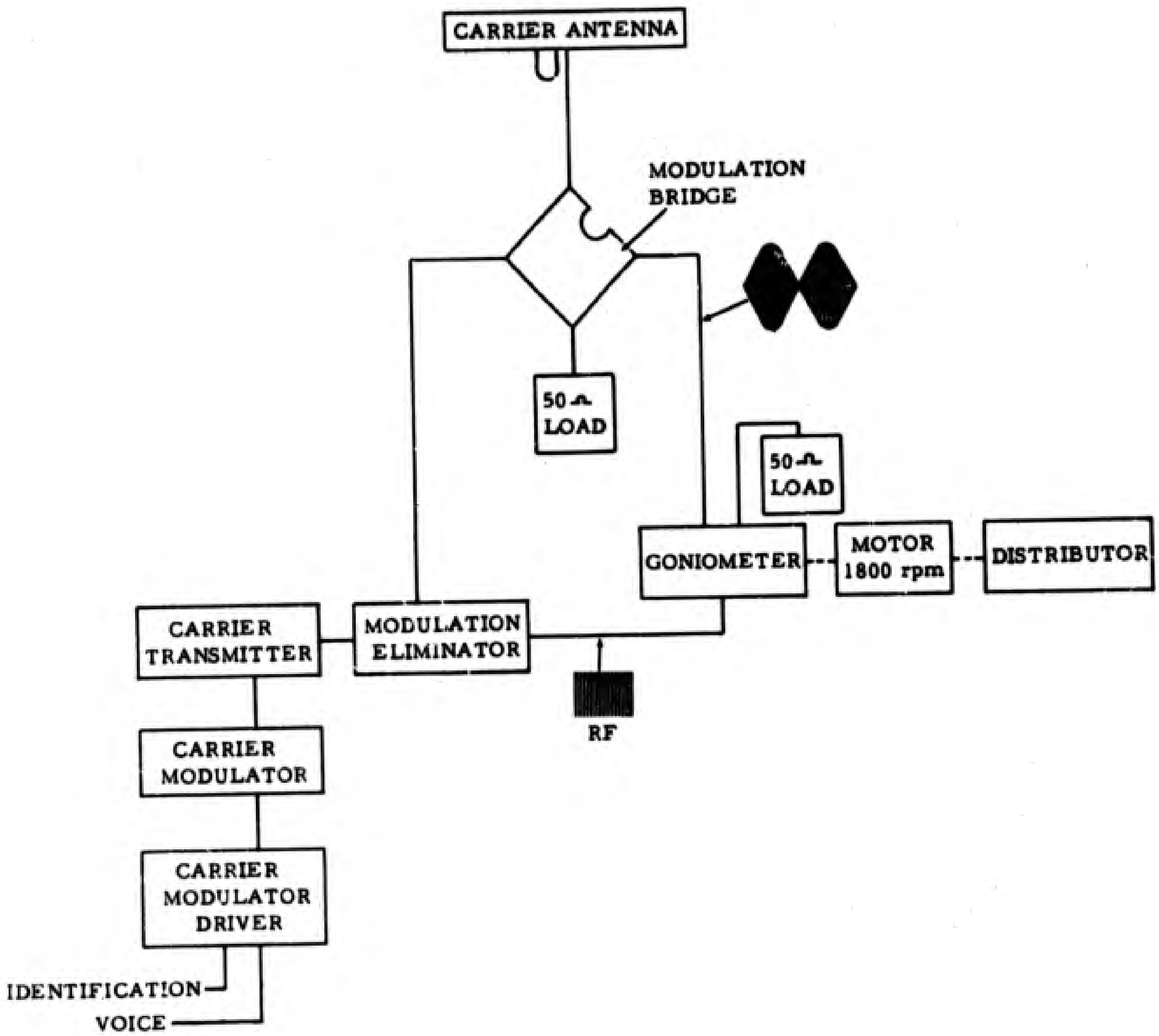


Figure 3. BLOCK DIAGRAM OF THE DVOR 30 HZ AM MODULATION SYSTEM

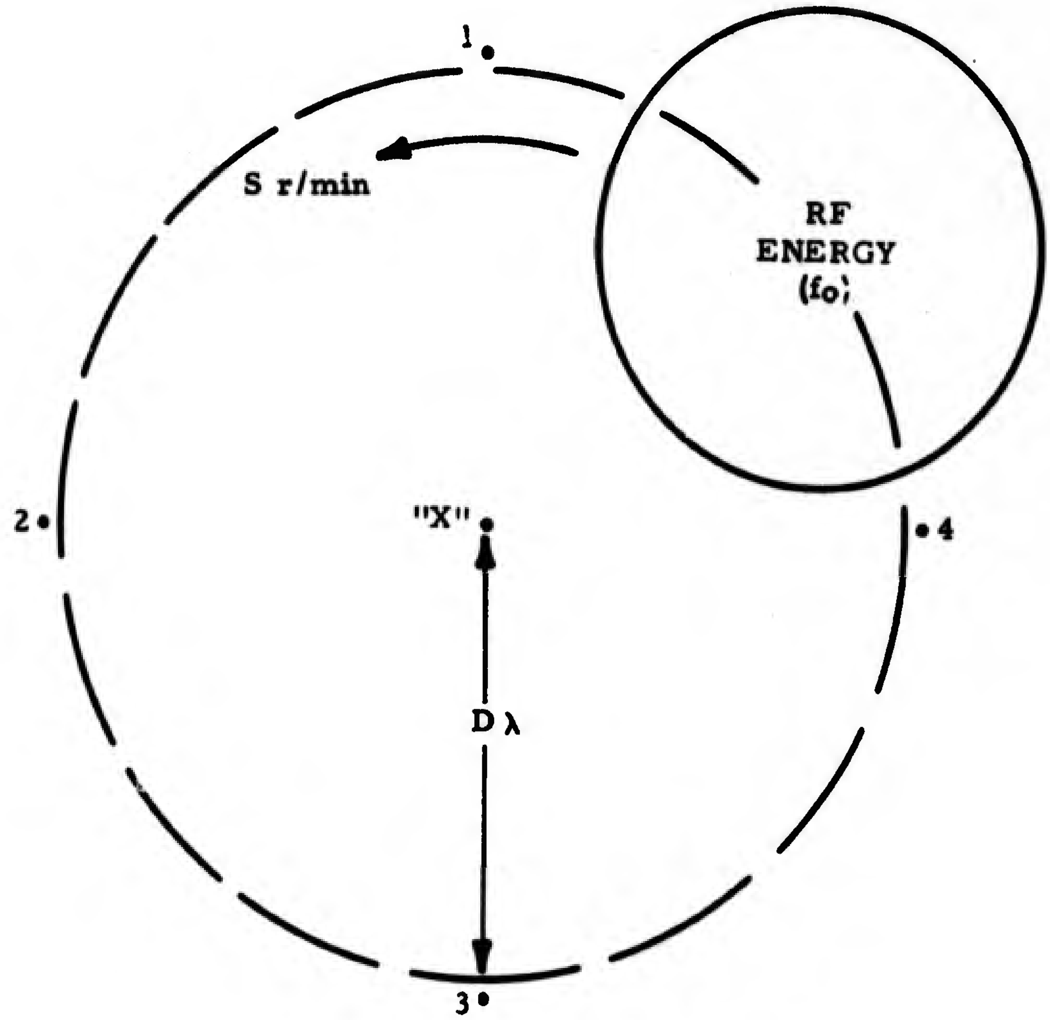
modulated in a manner that when detected and processed by the navigational receiver, a 30 Hz AM signal is produced, the phase of which does not vary with azimuth. Therefore, this 30 Hz AM signal now becomes the reference signal.

The generation of the 9960 Hz makes use of a heterodyne technique. This technique can be explained if we suppose an antenna is placed in the vicinity of the carrier antenna. The carrier antenna is energized at a frequency of f_c and the other antenna at a frequency which is different from f_c by 9960 Hz (f_o). As these two frequencies are within the bandpass of the receiver, a 9960 Hz heterodyne signal is detected.

The frequency modulation of the 9960 Hz signal is accomplished by the "Doppler Effect." The "Doppler Effect" is a well-known phenomenon wherein the received frequency of periodic wave radiation from a moving source is altered by this movement; that is, if the source is moving towards the receiver, the received frequency will be higher than the radiated frequency and conversely, will be lower when the source is moving away. This is illustrated in the classic example of the change in pitch of a train whistle as it passes the listener.

In the Doppler VOR, a single antenna could conceivably be rotated about an axis in order to create the moving radiator. (In practice, quasi-rotation is resorted to.) Figure 4 illustrates this principle, where a signal of frequency f_o is radiated from an antenna rotating about point "X" at a rate S r/min, and at a distance D wave lengths from X. The received frequency will therefore be above, below, or equal to f_o, depending on whether the rotating antenna is moving toward, away from, or at right angles to a line to the receiver. The deviation from f_o is proportional to the product of "D" and "S." Since the frequency modulation deviation cycle must occur once every thirtieth second, "S" is fixed at 30 Hz or 1800 r/min. In order to produce a deviation of ± 480 Hz, "D" must be approximately 2.5 wave lengths, or about 22 feet at the mean VOR operating frequency of 115 MHz. In the illustration, the frequency of the received voltage at point "A" is f_o, $f_o + 480$ Hz, f_o, $f_o - 480$ Hz, as the antenna rotates past points 1, 2, 3, and 4, respectively.

To complete the specified characteristics of the frequency-modulated subcarrier, it is necessary to add a fixed antenna at point "X." This antenna also has a circular radiation pattern at frequency f_c, wherein



"A" • OBSERVER

Figure 4. ILLUSTRATION OF THE DOPPLER EFFECT PRODUCED BY A ROTATING ANTENNA

the difference between f_o and f_c is 9960 Hz. The beating of these two signals in the receiver effectively produces a carrier (f_c) which is amplitude-modulated by a 9960 Hz subcarrier that, in turn, is frequency modulated by the doppler effect.

Since any reference point (e. g., the high frequency) in the frequency deviation cycle varies with the azimuth of the receiver, the phase of the 30 Hz component of the subcarrier also varies directly with azimuth, and this voltage becomes the "variable" phase voltage. The fixed phase, or "reference" phase voltage, is established by amplitude-modulating the carrier radiated from the central antenna with a 30 Hz voltage. Since these two components have interchanged roles with respect to which is the "reference" phase voltage and which is the "variable" phase voltage, it is necessary that the moving antenna be rotated in a counter-clockwise direction. Since the receiver does not recognize the interchange of terms, but responds only to the relative phase between the two voltages, it is appropriate to refer to these voltages by their relationship to the carrier. Therefore, they will be referred to hereafter as the "AM 30 Hz voltage" and the "FM 30 Hz voltage." (The terms "variable voltage" and "reference voltage" continue to denote the voltage which varies in phase with azimuth, and the voltage which has a fixed phase, respectively. However, in "Doppler VOR" discussion, confusion due to the former association of these terms with ground and airborne circuits necessitates using them in conjunction with those terms engendered above.)

As indicated above, the antenna must rotate at 1800 r/min at the end of an arm 22 feet long. Obviously, this would be extremely difficult to accomplish physically. Instead, 50 antennas are equally spaced around the periphery of a circle 22 feet in radius. These are fed in succession by a distributor rotating at 1800 r/min which presently employs a capacitor coupling, and feeds approximately half of a sinusoidal pattern. This produces a pattern which has a nearly constant amplitude and angular velocity as it rotates. Since a single rotating antenna is not actually employed, the nomenclature for this system might more correctly be "Quasi-Doppler VOR."

The basic specifications for the frequency-modulated subcarrier with a center frequency of 9960 Hz, with a deviation of $\pm$ 480 Hz at a modulation frequency of 30 Hz have been fulfilled. The frequency spectrum of the Doppler VOR at point "A" described above is illustrated in Figure 2b.

A carrier frequency is received which is amplitude-modulated by two audio frequencies, one a 30 Hz signal, the phase of which is fixed in all points in azimuth, and a 9960 Hz subcarrier frequency-modulated $\pm$480 Hz at a rate of 30 Hz, the phase of which varies with azimuth. The receiver produces 30 Hz FM signal from the 9960 Hz subcarrier, the phase of which provides azimuth information relative to the point of radiation when compared to the 30 Hz AM signal.

The "hetrodyne-Doppler effect" technique used in the generation of the 9960 Hz subcarrier and 30 Hz FM results in reduced susceptibility to course deterioration from obstacles around the site such as trees, buildings, etc. This is due to the fact that the variable phase is now contained in the subcarrier frequency-modulated signal. For bearing error (at the receiving point) to exist, there must be a combination of "right bearing" (direct) information with "wrong bearing" (reflected or reradiated) information. For the latter, the frequency deviation cycle is displaced in time from that of the former. If a reflected voltage, shifted 90^{o} in phase of deviation cycle, with an amplitude of one-twentieth of the direct voltage added to the direct voltage, it would have little or no effect on the instantaneous frequency of the direct voltage. This effect, known as the "frequency modulation capture effect," has been experienced in communications transmission on interfering frequency modulation transmissions, where the stronger signal takes over. The antenna aperture is related to this effect, in that, with greater aperture, the overriding of unwanted signals is greater, since the frequency modulation deviation is greater.

As indicated earlier, receiver compatibility at the signal source is dependent upon the smoothness achieved in the Quasi-Doppler VOR, hereafter referred to as Doppler VOR, and the circulatory of the sideband radiation pattern. These are dependent upon the radiation system, composed of the sideband antennas, distributor, and counterpoise. Each will be discussed in relation to its effect on the smoothness of the simulated motion, improvements accomplished, and areas of possible improvements.

<u>Distributor</u> - The distributor, the heart of the Doppler VOR, is a simple mechanical (but very complex electrical) device which couples RF energy from the transmitter to each of the sideband antennas in succession. A photograph of a typical distributor is given in Figure 5, with exploded views of the distributor head in Figures 6, 7, and 8. There

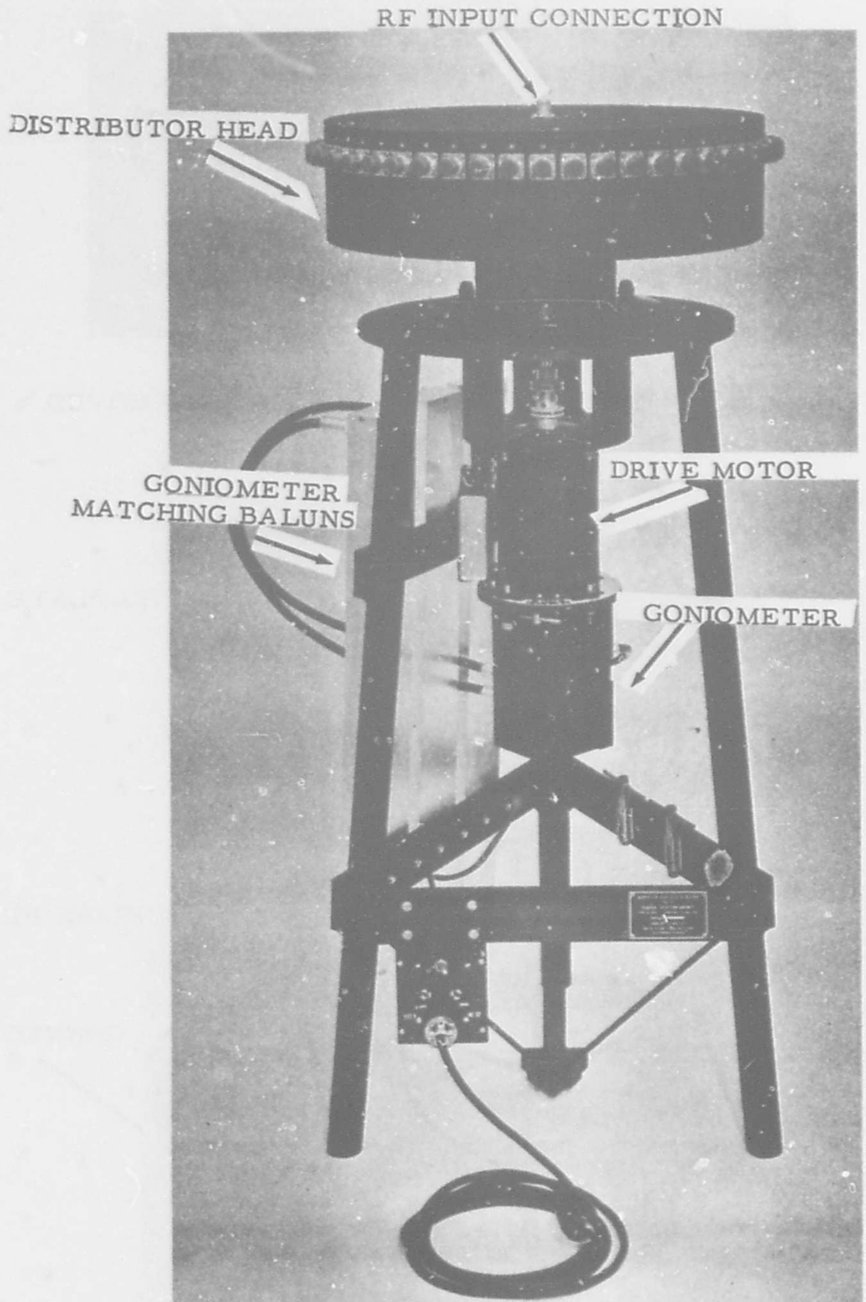


Figure 5. ASSEMBLY OF TYPICAL SINGLE SIDEBAND DOPPLER VOR DISTRIBUTOR

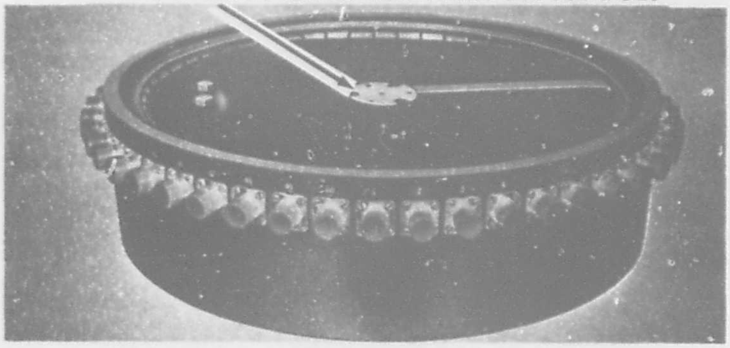


Figure 6. DISTRIBUTOR HEAD WITH COVER REMOVED

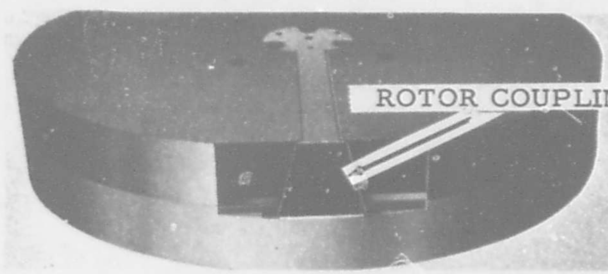


Figure 7. DISTRIBUTOR ROTOR

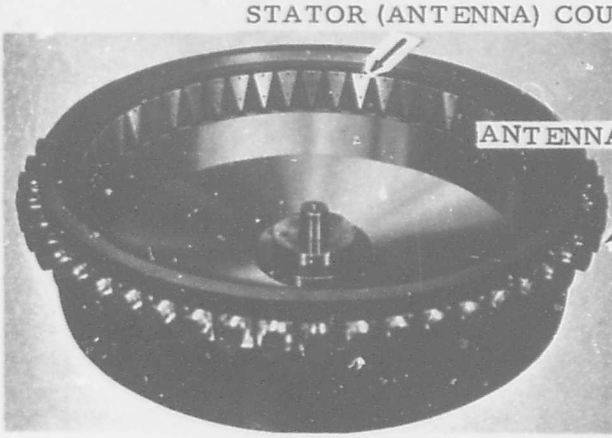


Figure 8. DISTRIBUTOR HEAD WITH COVER AND ROTOR REMOVED

are several factors in distributor design and performance which produce undesirable effects in the generation of the rotating sideband antenna pattern. These factors concern blending, transmitter loading and leakage. The distributor, as it rotates, will feed only one antenna, begin to decrease that level, and feed the next antenna a small amount, and continue the process until only the second antenna is fed. The variation in level fed to an antenna, versus the distributor rotational angle, is referred to as the "blending function." The blending of the distributor outputs are illustrated in Figures 9 and 10. Nonideal blending will produce several effects.

In order to achieve smooth simulated rotation of the sideband antenna, it is necessary that the ratio of the levels fed to the two antennas have a specific value for a given position of the distributor. When this criteria is not met, the instantaneous antenna position will be incorrect for points between full feed to each of the successive antennas. Correct position will also be realized when the two antennas are fed equal amounts. An incorrect blending function will, for example, cause the antenna to increasingly lag as the rotor proceeds from the position of feeding one antenna only. As the rotor midposition is reached, the antenna position will again be correct. Following this, the antenna position will follow a similar cycle, except that it will lead its correct position. As a result, an extraneous FM is produced. It occurs at a rate of 1500 Hz, since there are 50 antennas, and the distributor rotates at 30 Hz. The highest deviation is determined by the rate at which the antenna must travel to restore it to its correct position following the lag portion of the cycle, which is, in turn, dependent on the degree of the lag. This extraneous deviation is a maximum near the point where the normal deviation reaches its maximum deviation of 480 Hz. It reduces to zero where the normal deviation is zero, since there can be no error in the relative motion when there is no relative motion. The result of this extraneous deviation is to produce a 1500 Hz ripple on the 30 Hz output of the 9960 Hz receiver discriminator. If the amplitude is small, no error results, since it can readily be filtered from the 30 Hz voltage. If the amplitude is relatively large, appreciable error can be produced in a receiver by exceeding the bandpass of the 9960 Hz discriminator. (In the early days of Doppler VOR development, the peak combined deviation reached over 700 Hz, and produced several degrees of error in a receiver which had a relatively narrow discriminator bandpass.) The FAA Doppler VOR uses a blending function of $y = k \sin^{0.836} x$, where

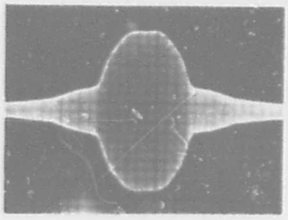


Figure 9. SINGLE OUTPUT WAVE FORM

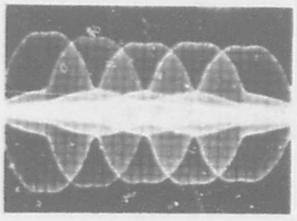


Figure 10. BLENDING OF FIVE OUTPUT WAVE FORMS

y is the maximum amplitude fed to a given antenna, k is determined by the amount of RF fed into the distributor, and x varies from 0° to 180°, while the rotor moves from feeding maximum to the previous antenna, through feeding maximum to a given antenna, and on to feeding the maximum to the following antenna. This relatively simple blending function produces a theoretical maximum deviation of 492 Hz. If the number of antennas were to be changed significantly, the spacing would change and a different exponent value for the sin x would be required.

A second consideration of distributor design is phase change of the RF fed to the antenna as the rotor moves past a given output. This phase change has the effect of lengthening and shortening the radius arm of the rotating antenna, thereby also producing an extraneous 1500 Hz FM component. The phase of the 1500 Hz ripple voltage on the 30 Hz will depend on the nature of the phase change. It may, therefore, have any phase relation with respect to the 1500 Hz ripple produced by imperfect blending. The resultant ripple in the FAA Doppler VOR is about 15 percent and does not produce any significant error.

The blending function can also produce amplitude modulation on the sideband, and thus on the 9960 Hz subcarrier. This modulation also depends on the combination of blending function and spacing between sideband antennas. To explain this mechanism, it may be considered that the blending function is such as to supply 70 percent of the peak value when two antennas are fed equally, assuming also that the antennas are spaced 90°. When the receiver is located on a radial in line with the pair of antennas, the sideband will alternate between relative levels of 1.0 and 1.4, producing significant amplitude modulation. When the antenna moves to place the receiver on a line perpendicular to the antenna radial, the amplitude remains constant at 1.0. Thus, this amplitude modulation varies from zero to 17 percent, depending upon antenna position. This is approximately the level measured in the FAA Doppler VOR. It does not produce error, since it occurs at a 1500 Hz rate.

Variation in transmitter loading may also affect the blending function, and thereby the 1500 Hz FM and 1500 Hz AM. The distributor load is highly reactive by ordinary standards. Both the conductance and the susceptance of the load vary with rotor position. In order to minimize this loading variation, isolation between the distributor and the transmitter is provided by use of a dummy load and power divider, as illustrated in Figure 11.

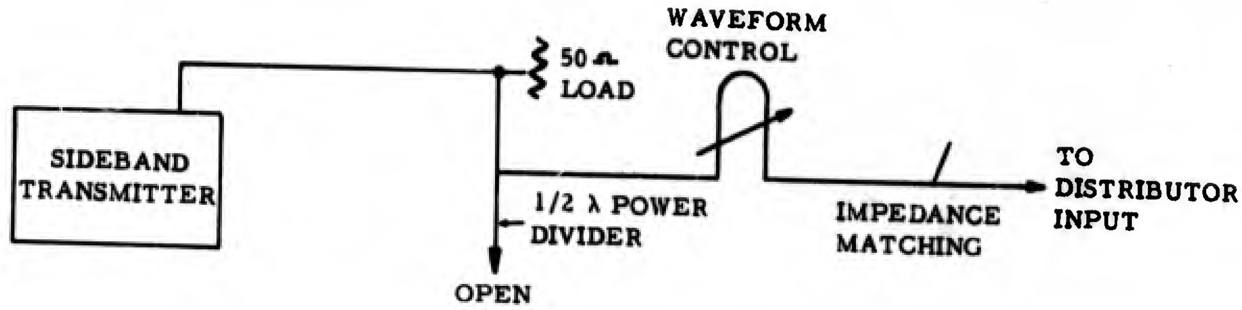


Figure 11. METHOD OF ISOLATION OF THE SIDEBAND TRANSMITTER FROM THE VARYING LOAD IMPEDANCE OF THE DISTRIBUTOR

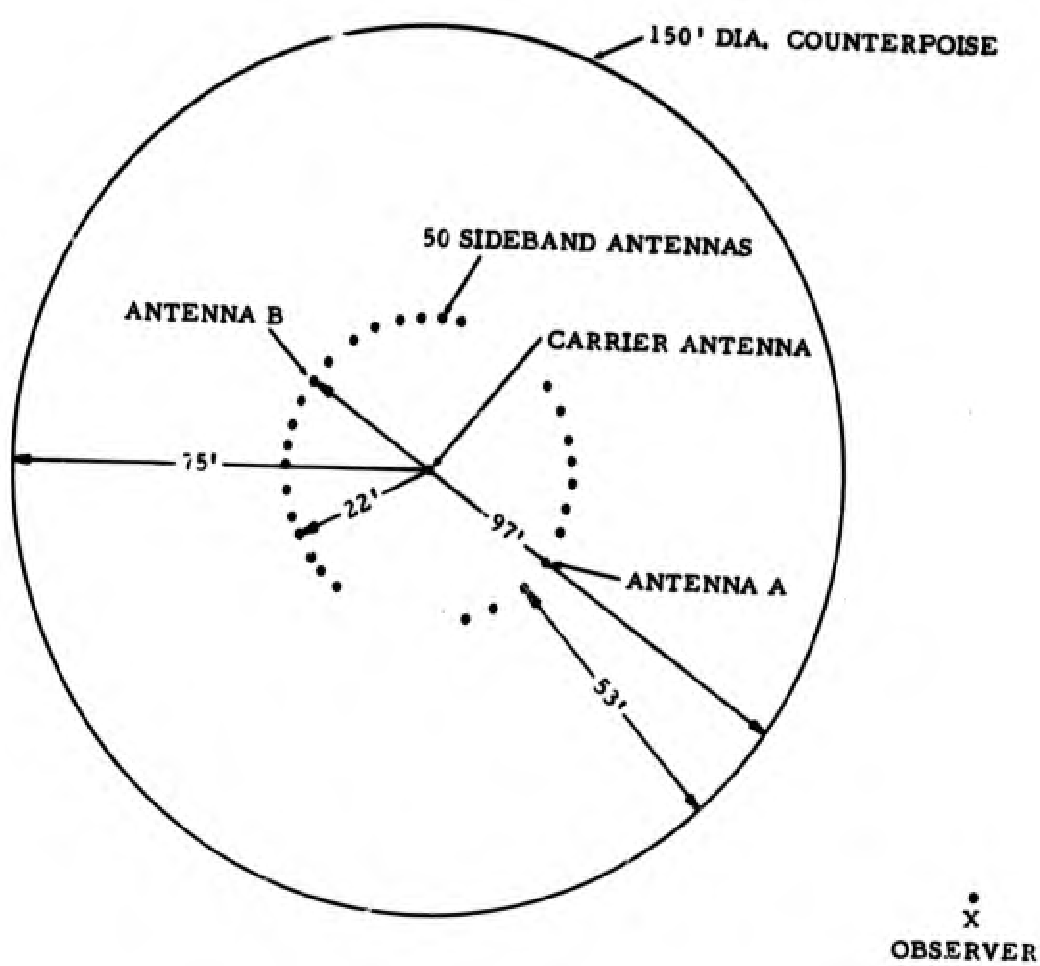


Figure 12. ILLUSTRATION OF COUNTERPOISE MODULATION DUE TO THE CHANGE IN THE EFFECTIVE COUNTERPOISE SIZE

The distributor may also contribute to nonideal performance (i. e., a constant amplitude, circular sideband pattern rotating at constant velocity) through insufficient isolation of outputs. In the FAA Doppler VOR, sufficient leakage exists to produce measurable currents out to two antennas on either side of the one being fed. The sideband is, therefore, radiated from an array, rather than a single antenna. The pattern is noncircular, being elongated in the radial direction. In addition, the array becomes alternately concave and complex, causing the elongation to be more in one direction than in the other direction. The resultant radiation pattern in the single sideband Doppler VOR produces a 9960 Hz subcarrier envelope which is amplitude-modulated with a 30 Hz voltage.

A theoretical analysis determined that the ideal blending function would be $y = \frac{\sin x}{x}$. Since this is an infinite series, it was necessary to modify this function. A triangular weighing function was used to limit the number of lobes to three. A seven-plate rotor was built which included alternate 180° phase shifts and capacitive voltage dividers to provide the necessary outputs. Tests indicated that this complex distributor did not provide any significant reduction in error (Reference 9).

Antenna - The standard Alford loop antennas are used in the Doppler VOR. Due to their large physical size and the required close spacing, high parasitic currents are generated in the antennas adjacent to the "fed" antenna. These induced currents add to the leakage currents in the distributor to further aggravate the noncircularity of the sideband pattern, thereby further increasing the 30 Hz AM of the subcarrier. These parasitic currents have been reduced by modification of the antenna (Reference 3) and by cutting the coaxial lines which connect the distributor to the antennas to a length that will result in maximum input impedance to the induction voltage. Procedures for determination of the correct coaxial line length are given in agency order I MP 6790. 5. Any further reduction of the parasitic currents will probably require a redesign of the antennas or weather protection domes which cover each antenna. It has been suggested that these domes be made of "lossy" material to produce a signal attenuation of X in the forward direction. The induction voltage for the adjacent antenna would then experience an attenuation of 2X. The parasitics are reduced by the square of the attenuation factor. That is, for example, if the attenuation reduces the field strength by one-half, the parasitics will be reduced to one-quarter.

Counterpoise - The 150-foot diameter counterpoise, presently used for the Doppler VOR, was determined to be the minimum size for acceptable receiver compatibility and indicated receiver station error for all classes of receivers. For the more sophisticated receivers, a smaller counterpoise could be used. A finite counterpoise produces a 30 Hz amplitude modulation on the subcarrier which is in phase with the 30 Hz AM produced by the array pattern from induced antenna currents. The mechanism can best be explained by referring to Figure 12 in which the 150-foot counterpoise and the ring of sideband antennas are illustrated. For an observer, at point X in space, only 53 feet of counterpoise are used when antenna A is excited. When antenna B is excited, 97 feet of counterpoise are used. This difference in the effective counterpoise size as each of the sideband antennas are excited, results in a variation of the field intensity. The variance of the field intensity caused by the eccentricity effect of the counterpoise will be noted in Figure 13. As each of the sideband antennas are excited at a 30 Hz rate, a 30 Hz amplitude modulation of the rotating 9960 Hz sideband energy, which contains the variable phase signal that heterodynes with the carrier, is produced. An average value of 6.5 percent counterpoise modulation was measured at the NAFEC Doppler VOR facility. This measurement was made by exciting antennas A and B alternately with pure RF energy as an aircraft flew a radial through points A and B, recording the field strength of each antenna as it was energized. Cross-modulation of the 30 Hz AM signal (reference phase) radiated nondirectionally from the carrier antenna occurs in the receiver AM detector, resulting in a duantal error.

One solution at some commissioned DVOR facilities to reduce the effects of this modulation is the use of the error cancelling technique of supplying a small signal of proper magnitude and phase from the unused output of the goniometer to a 4-loop array. This solution has two prominent disadvantages. One is that the amount of error cancellation signal injected into the carrier antenna will not be correct for all receiver types. The amount of error cancellation signal required for one group of receiver types could result in overcorrection to another group of receivers. The second disadvantage is that the error cancellation technique requires the use of the standard 4-loop carrier array in lieu of a single antenna. While the technique does function, it must be considered as an interim solution.

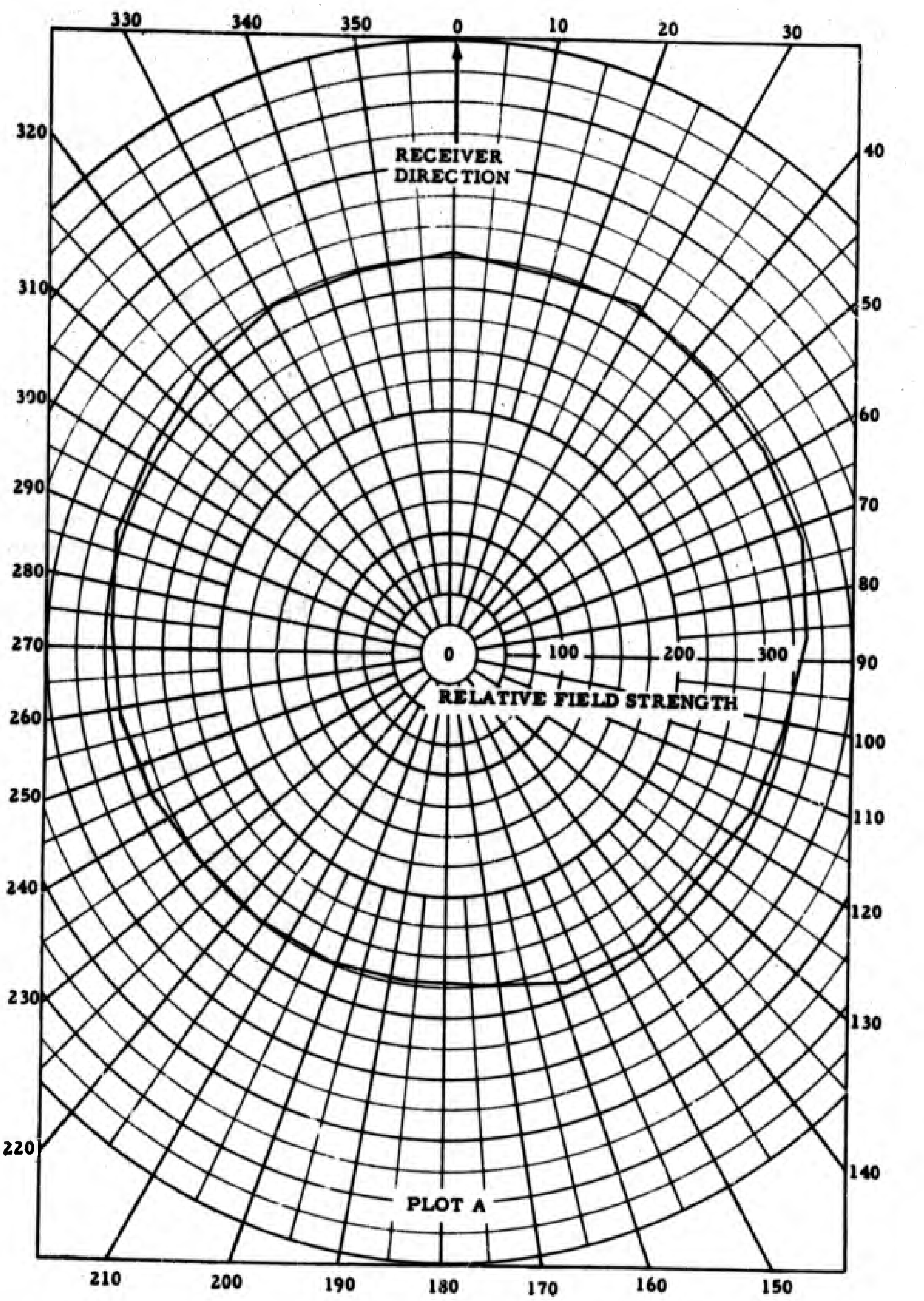


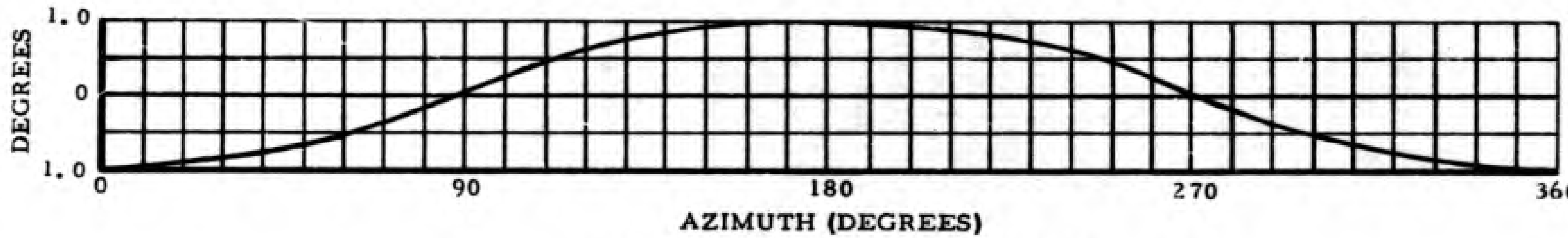
Figure 13. VARIATION IN FIELD STRENGTH OF ONE ANTENNA CAUSED BY ECCENTRICITY EFFECT OF 150-FOOT DIAMETER COUNTERPOISE

From the foregoing discussion of "cause and effect" of problems with the antenna, distributor, and counterpoise, it appears at this time that any improvement of these components for improved station error and receiver compatibility would require a long development effort and a high expenditure of funds. Any immediate improvements to the present Doppler VOR System must then come from the modification of, or additions to, the radiated signals.

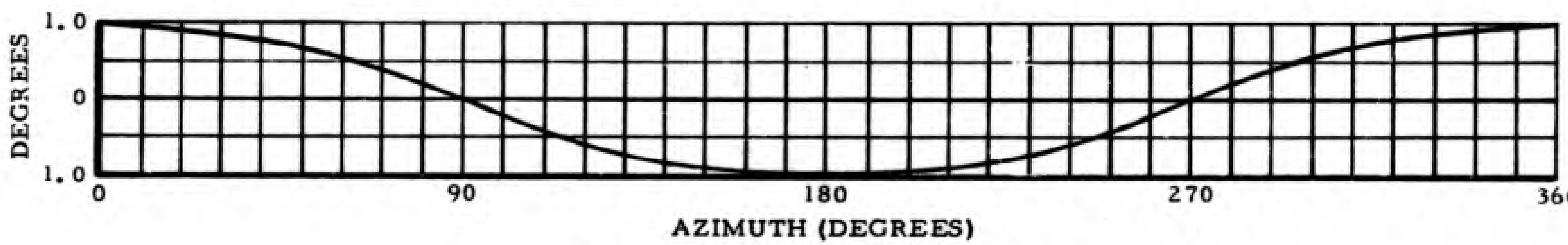
As indicated above, the major cause of station error and receiver incompatibility of the present Doppler VOR System is the cross-modulation of the 30 Hz AM signal radiated nondirectionally from the carrier antenna. This results from the amplitude modulation of the rotating sideband due to the eccentricity effect of the counterpoise as explained on page 22. The phase relationship of the cross-modulation signal to the reference phase signal is such that the characteristic station error curve departs from the ideal zero error to a single cycle or duantal shape as illustrated in Figure 14a.

Referring to Figure 2a, RF spectrum of the Conventional VOR, and Figure 2b, RF spectrum of the Doppler VOR, we note that Conventional VOR has a carrier frequency of f_c and upper and lower sidebands, a product of amplitude modulation of the carrier by a 30 Hz and a 9960 Hz signal, and that the Doppler VOR has a carrier of f_c, upper and lower sidebands, a product of amplitude modulation of the carrier by a 30 Hz signal. However, an additional RF channel spaced 9960 Hz from the carrier has been added to provide the 9960 Hz subcarrier. This channel has been standardized to be 9960 Hz above f_c. In reality, the present Doppler VOR is a system composed of a carrier with 30 Hz double sidebands and a single channel subcarrier. For simplicity, the present Doppler VOR System, which makes use of a single channel subcarrier, will be referred to as a Single Sideband Doppler VOR (SSDVOR) and the term upper or lower sideband will be used to denote the relation of the subcarrier channel to the carrier frequency; i. e., upper sideband being f_c + 9960 Hz and lower sideband being f_c - 9960 Hz.

When the SSDVOR system makes use of the lower sideband (subcarrier channel frequency of f_c - 9960 Hz) the resultant



(a) UPPER SIDEBAND (f_c + 9960 Hz)



(b) LOWER SIDEBAND (f_c - 9960 Hz)

Figure 14. CHARACTERISTIC STATION ERROR

shape of the station error curves is as illustrated in Figure 14b. By comparing the station error curves in Figures 14a and 14b, one can see that the runout error for the SSDVOR system, when the sideband energy is f_c + 9960 Hz (upper sideband), is positive at 180° and negative at 0°; whereas, sideband energy of f_c - 9960 Hz (lower sideband) is a reversed error curve; i. e., negative at 180° and positive at 0°.

Suppose then a DVOR system is established with dual channel subcarriers radiating both f_c + 9960 Hz and f_c - 9960 Hz. The frequency spectrum of such a system given in Figure 2c, when compared to the frequency spectrum of the Conventional VOR given in Figure 14a, shows that they are similar. By the addition of another subcarrier channel, which is 9960 Hz lower in frequency than the carrier, we have produced an RF spectrum similar to the one for which the receivers were designed. As we have applied the term of Single Sideband Doppler VOR (SSDVOR) to the system which makes use of single subchannel operating at f_c + 9960 Hz, then it is appropriate to use the term Double Sideband Doppler VOR (DSDVOR) to denote a system which makes use of two subcarriers with frequencies of f_c + 9960 Hz and f_c - 9960 Hz.

From the foregoing discussion, it is logical to expect improved performance with the DSDVOR System; i. e., the station error curve must lie between those of the upper sideband only and those of the lower sideband only.

Double Sideband Doppler VOR System

A block diagram of a DSDVOR System is given in Figure 15. Comparison of the DSDVOR System with the SSDVOR can be made by referring to the block diagram of the SSDVOR given in Figure 16.

In comparison of the two Doppler VOR Systems, it is noted that conversion of the single sideband system to a double sideband system requires only the addition of another sideband transmitter operating on f_c - 9960 Hz, the use of a dual input distributor with a double bar rotor, and the addition of an Automatic Phase Control (APC) to maintain the correct RF phase relationship between the two 9960 Hz RF sidebands and the carrier.

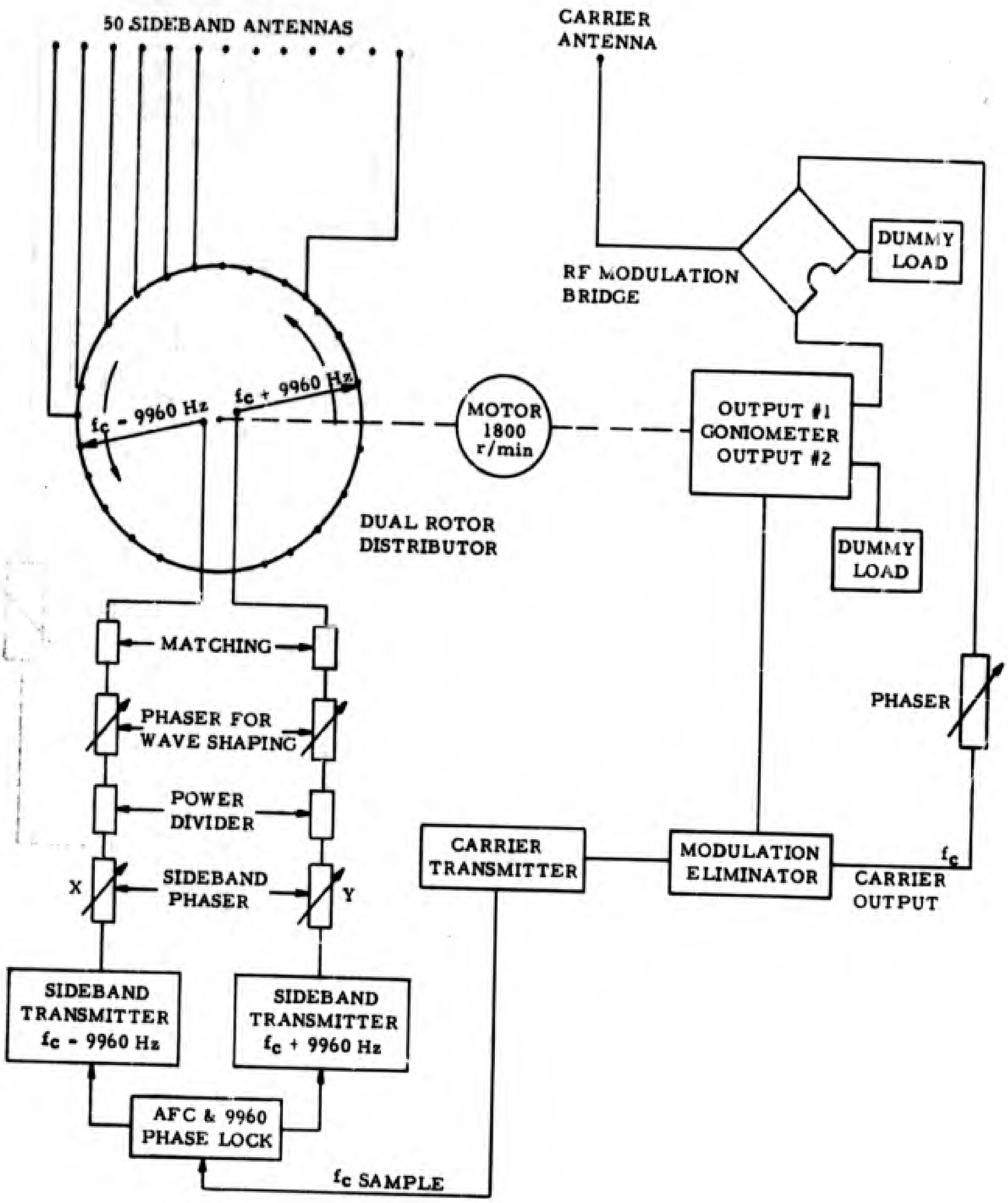


Figure 15. SIMPLIFIED BLOCK DIAGRAM OF DSDVOR SYSTEM

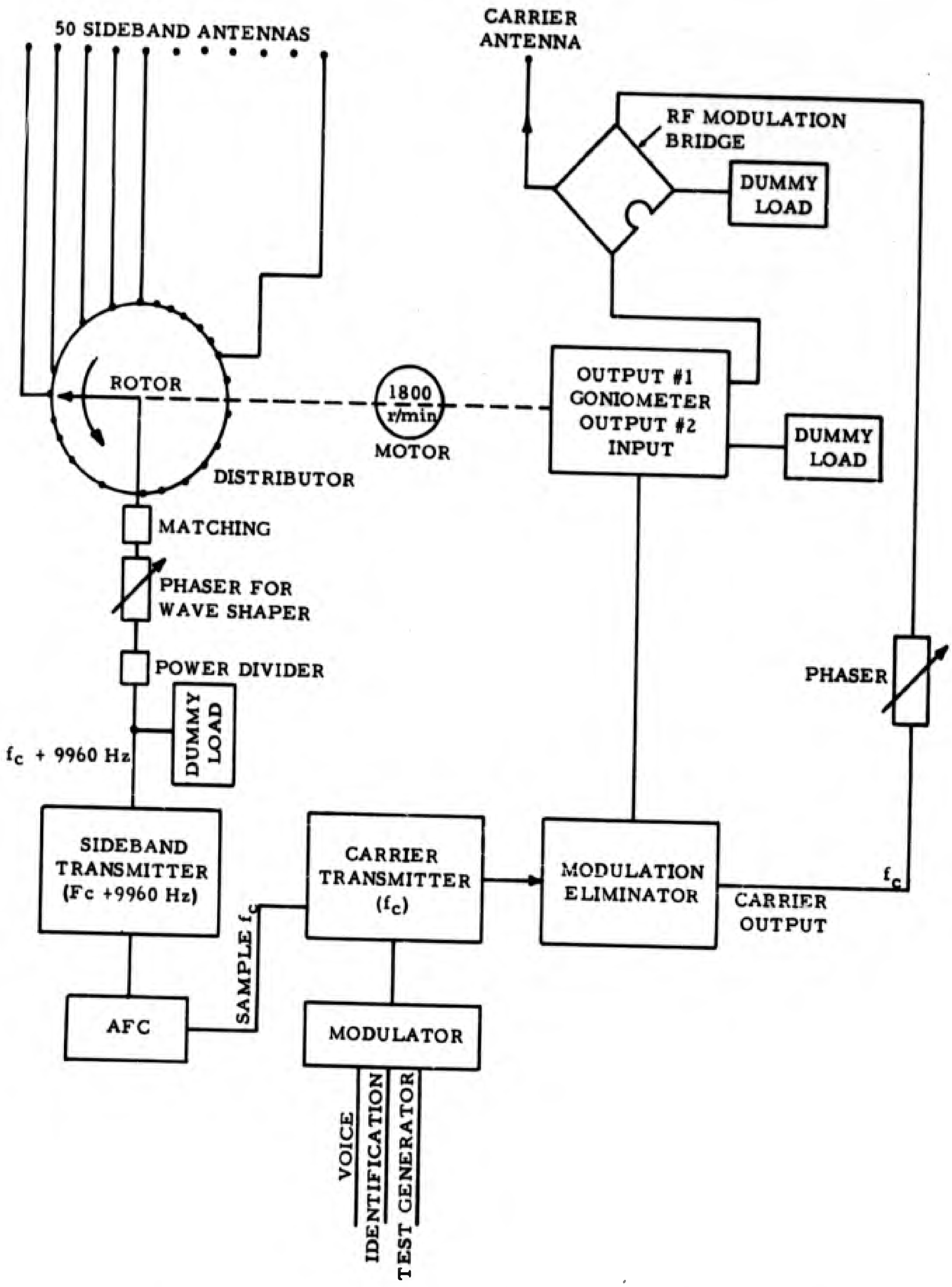


Figure 16. SIMPLIFIED BLOCK DIAGRAM OF SSDVOR SYSTEM

The improvement of the DSDVOR over the SSDVOR is primarily due to the reduction of the 30 Hz cross-modulation of the signal as it appears at the second detector of the VOR receiver. This can be best explained by considering the effects of the cross-modulation of the 9960 Hz sideband energy on the 30 Hz AM reference phase modulation. As previously explained, the DSDVOR System is in reality a dual 9960 Hz channel system in which each channel (sideband) contains redundant information. The redundancy of the two sidebands referring to Figure 14, is due to the upper channel (f_c + 9960 Hz sideband) energy being radiated on one side of the array simultaneously with the radiation of the lower channel (f_c - 9960 Hz sideband) from the opposite side of the array. The frequency modulation signals on each sideband, due to the Doppler effect, are in phase. The cross-modulation that is present due to the 30 Hz AM component on each sideband is out of phase.

The predominant cross-modulation frequency which is most detrimental to the SSDVOR System is the cross-modulation from the 30 Hz AM on the 9960 Hz entering the 30 Hz reference channel of the VOR receiver. Due to simultaneous radiation of the subcarrier being emitted from diametrically opposite points of the counterpoise in the DSDVOR System, this undesirable amplitude modulation of the 9960 Hz subcarrier is considerably lower and has a predominant frequency of 60 Hz. While this will show a reduction of the indicated station error for all receivers, the greatest reduction will be noted in those receivers that have second detector circuits with the greatest amount of distortion.

Refer again to Figure 14 and consider the error curve for the Single Sideband (f_c + 9960 Hz) DVOR System given in a. The observed runout error is positive at 180° and negative at 0°. For an SSDVOR System where the sideband is f_c - 9960 Hz, the error curve reverses shape; i. e., negative at 180° and positive at 0°. Therefore, it follows that the resultant station accuracy is improved when both the upper (f_c + 9960 Hz) sideband and the lower (f_c - 9960 Hz) sideband are used.

Much of the remaining site effects on the Doppler VOR are due to transient effects of cross-modulation from reflection-caused amplitude modulation of the 9960 Hz sideband. The use of a double sideband emission reduces the magnitude of these effects since each sideband is at a different frequency and radiates from opposite sides of the antenna array. The redundancy of the two 9960 Hz sidebands tends to smooth out the level of the 9960 Hz audio at the second detector resulting in less course roughness.

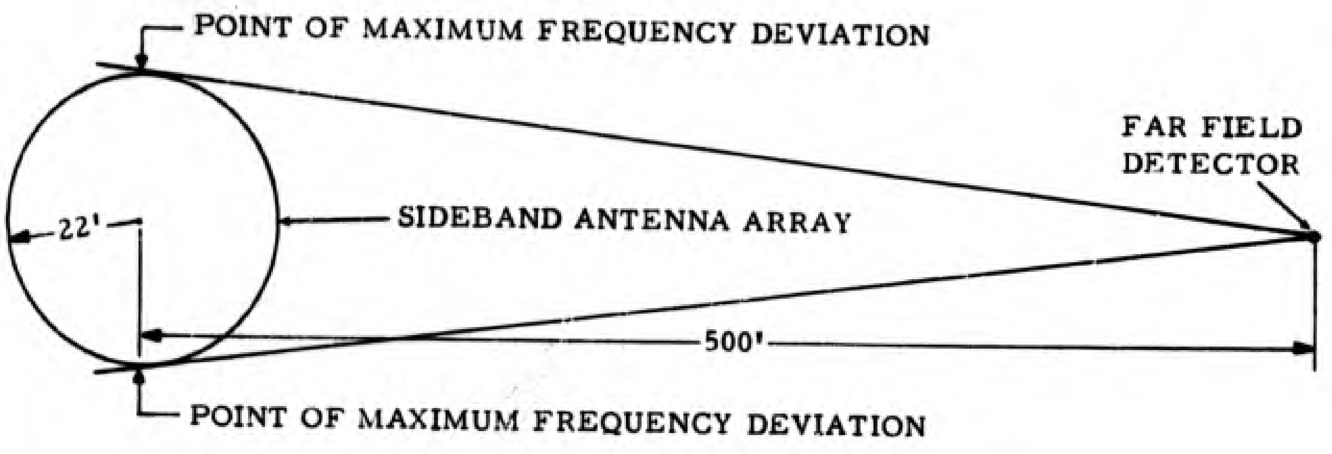
The requirement of a large counterpoise for the SSDVOR System, as previously explained, was due to the cross-modulation resulting from the eccentricity of the pattern of the sideband radiation. In the DSDVOR System, amplitude modulation of the detected 9960 Hz sidebands has been reduced by virtue of the fact that sideband radiation emanates from diametrically opposite points of the counterpoise. Therefore, a reduction in counterpoise size for the DSDVOR System should be possible. A reduction of 33 percent of the counterpoise diameter from 150 feet to 100 feet would reduce the counterpoise area by approximately 56 percent. When extending the 52-foot counterpoise of a Conventional VOR the required additional area is reduced 63 percent.

System Adjustment:

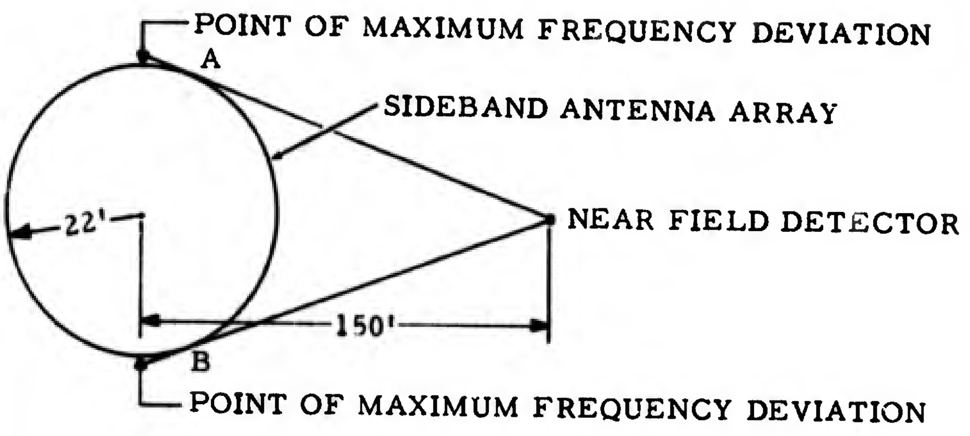
General - The SSDVOR System adjustments are sufficiently explained in the agency's orders pertaining to the Doppler VOR System and the manufacturer's equipment instruction manuals. Therefore, only those adjustments peculiar to the DSDVOR System will be discussed.

Distributor - The input impedance of each distributor input should be adjusted for minimum voltage standing wave ratio (VSWR). The sideband output wave shape should be adjusted for the best blending function and minimum 1500 Hz spikes on the 9960 Hz using the same procedures as for the SSDVOR System. The shape of the two output waves should be as nearly identical as is possible.

Phasing - The two sidebands should be phased for the best 9960 Hz pattern and maximum amplitude of the 9960 Hz signal as indicated by the monitor. A far-field detector will be required for sideband phasing. The two sideband phasers (X and Y of Figure 15) should be adjusted for an in-phase condition of the sideband energy at the points of maximum frequency deviation of the 9960 Hz signal as illustrated in Figure 17a. If a near-field detector is used, a false indication of the in-phase condition of the sideband energy will be indicated, because the sideband phasers, X and Y, are adjusted for an in-phase condition of the sideband energy at points A and B of Figure 17b. These are not the points of maximum frequency deviation of the 9960 Hz energy as seen by a receiver at a distance.



(a) CORRECT PHASING



(b) INCORRECT PHASING

Figure 17. EFFECT OF FIELD DETECTOR LOCATION ON PHASING

9960 Hz Modulation Level - The output of the sideband transmitter of the SSDVOR System, is adjusted to produce an indicated 9960 Hz level of the monitor to that value obtained when the carrier transmitter is modulated to a depth of 30 percent by the 9960 Hz signal from the VOR test generator.

In the Double Sideband System there are two sideband transmitters (f_c + 9960 Hz and f_c - 9960 Hz) which contribute to the total sideband energy. Therefore, the output level of each sideband transmitter is adjusted to be equal as indicated by the level of the 9960 Hz channel of the VOR monitor. It is then adjusted to the value, the sum of which is equal to the indicated level obtained when the carrier transmitter is modulated by the VOR test generator to give 30 percent modulation of the carrier frequency.

System Monitoring: The DSDVOR System will not present any monitoring problems. The monitoring of course alignment can be accomplished with a Conventional VOR monitor, as with the present Single Sideband System.

The sideband radiation can be monitored with a type FA-8142 Doppler VOR sideband antenna monitor, as in the present Single Sideband System. Only sideband input to the distributor need be monitored in order to detect a fault in the sideband antenna system. Tests of the FA-8142 prototype sideband antenna monitor for the DSDVOR System are given in Report NA-69-19 (Reference 8).

It is theorized that an auxiliary 9960 Hz frequency deviation monitor, as used in present SSDVOR System will not be necessary in the DSDVOR System. This theory is based on the DSDVOR requirement for proper phasing of each sideband with the carrier and the circuitry used to achieve proper phasing.

The crystal frequency of each sideband oscillator, whose circuitry is designed to prevent tuning to the wrong sideband, is the same as the carrier frequency, but is "pulled" to the proper sideband frequency by means of a dc voltage applied to a varactor diode (voltage variable capacitor). The sideband oscillator frequency would return to the carrier frequency during a varactor voltage failure. Since each sideband contributes one-half the total sideband energy, the loss of one sideband would cause the monitor to alarm, due to the reduction of the 9960 Hz level.

This effect was confirmed by tests in which the dc voltage was removed from the varactor diodes.

The two 9960 Hz sidebands maintain proper phase relationship to the carrier by an Automatic Frequency Control/Automatic Phase Control (AFC/APC) unit. The AFC/APC unit is comprised of a phase-error detector circuit which compares the phase of the 9960 Hz sideband to a crystal-controlled 9960 Hz reference. Any phase deviation produces a dc error voltage which is applied to the varactor diode of the oscillator, causing an instantaneous change in the frequency of the oscillator which will correct the phase error and return the dc error voltage to normal. Failure of the AFC/APC unit or the 9960 Hz reference would result in the loss of the dc error voltage. With the loss of the dc error voltage, the sideband frequency would no longer track the carrier frequency by a difference of exactly 9960 Hz, resulting in a constant monitor alarm, because the random frequency will not be within the bandpass of the monitor's 9960 Hz filter for a duration that would correct the monitor alarm.

This has been confirmed by tests in which one sideband was operating normally and the dc error voltage of the other sideband was replaced by a battery voltage, the value of which was adjusted to produce an instantaneous 9960 Hz sideband. With this fixed dc voltage, the random drift of the carrier and sideband frequencies produced a constant monitor alarm due to the reduction of the 9960 Hz level.

System Tests:

Preliminary Tests - The Doppler VORTAC test bed facility was used in the early stages of equipment development and tests of the DSDVOR System. This test bed facility consisted of a standard 50 sideband antenna SSDVOR System with a 150-foot diameter counterpoise and an offset TACAN antenna. Upon receipt of the feasibility model of the DSDVOR equipment from the contractor, the SSDVOR System was converted to a DSDVOR System in a manner which would provide a quick selection of either SSDVOR, DSDVOR, or Conventional VOR operation for tests and comparison of systems.

The first tests of the DSDVOR System were to determine from an operational standpoint how critical the phasing and the power ratio of the two sideband channels were to system performance. Consequently, upon completion of the equipment installation and system adjustments to provide a DSDVOR System, tests were made to determine the effects to system performance of maladjustments of the sideband phasing and effect of unbalanced sideband power.

The tests were conducted by making theodolite-controlled 5-nmi orbital flights of the DSDVOR System with the normal sideband power and with an unbalance of 6 dB. This value was chosen to be the "worst case," as this is the value which would cause a monitor alarm due to low 9960 Hz modulation. The course deviation indicator (CDI) action of four receivers, a Bendix MN85FA, a Wilcox 706A, a Collins 51R3, and a 51R4, were recorded. The results are shown in Figures 18 and 19.

The same procedures and equipment were used to determine the effect to the system performance with the sidebands misphased in steps of $\pm 15^{\circ}$, $\pm 30^{\circ}$, and $\pm 43^{\circ}$. The results of these tests are given in Figures 20, 21, 22, and 23.

Doppler VOR No. 2 test bed facility was used for the major portion of the system tests, as this test bed facility provided a means of rotating the entire antenna array for static tests. The counterpoise was of a design which facilitated reduction of the size for those tests based on counterpoise size.

Many hours of flight time were saved in the early development stages by the extensive use of the rotating antenna array to simulate actual flight. This not only provided a savings in flight test cost but also had the advantages that the effects of reflecting objects are fixed in azimuth and that the rotation of the antenna array could be stopped for investigation of any portion of the azimuth signals. In addition, with the motion of the receivers and recording system stopped, the recording time response was equal for all receivers.

The recording time response is the time required for a CDI signal change to be indicated on the recorder and involves not only the mechanics of the recorder but includes the impedance time constant of the receiver CDI and the recording system. The recording time response varies with receiver types and aircraft speed. The effect of the unequal recording time response is an apparent shift of the zero axis of the station error curve. While the error is small for most navigation receivers, it can be as large as 0.75° for some of the less sophisticated receivers. This was determined by making theodolite-controlled 5-nmi orbital flights at a constant speed in both a counterclockwise direction and in a clockwise direction and noting the difference of the indicated azimuth points on the recordings for each type of receiver.

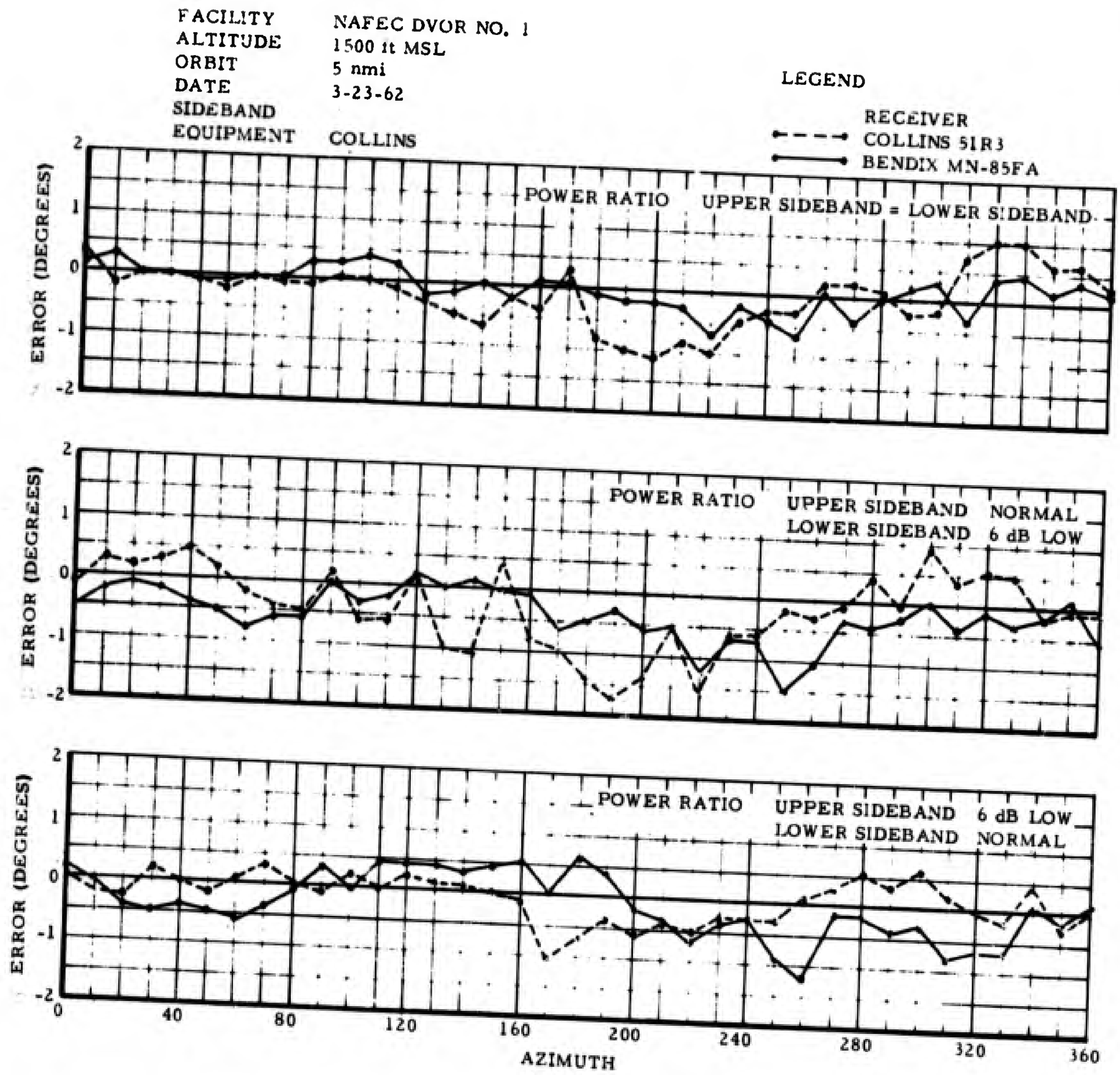


Figure 18. INDICATED SYSTEM ERROR AS A FUNCTION OF SIDEBAND POWER RATIO

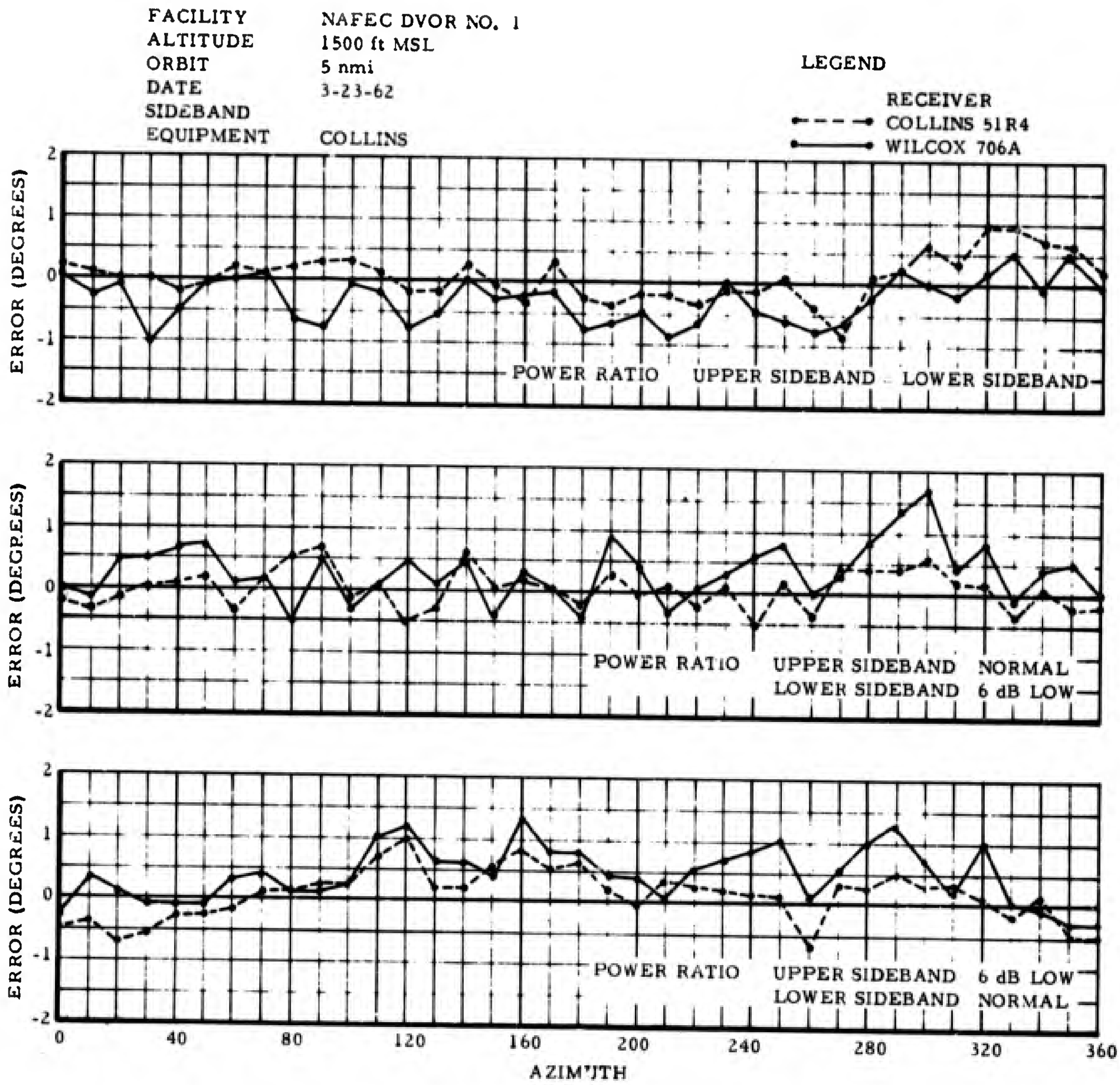


Figure 19. INDICATED STATION ERROR AS A FUNCTION OF SIDEBAND POWER RATIO

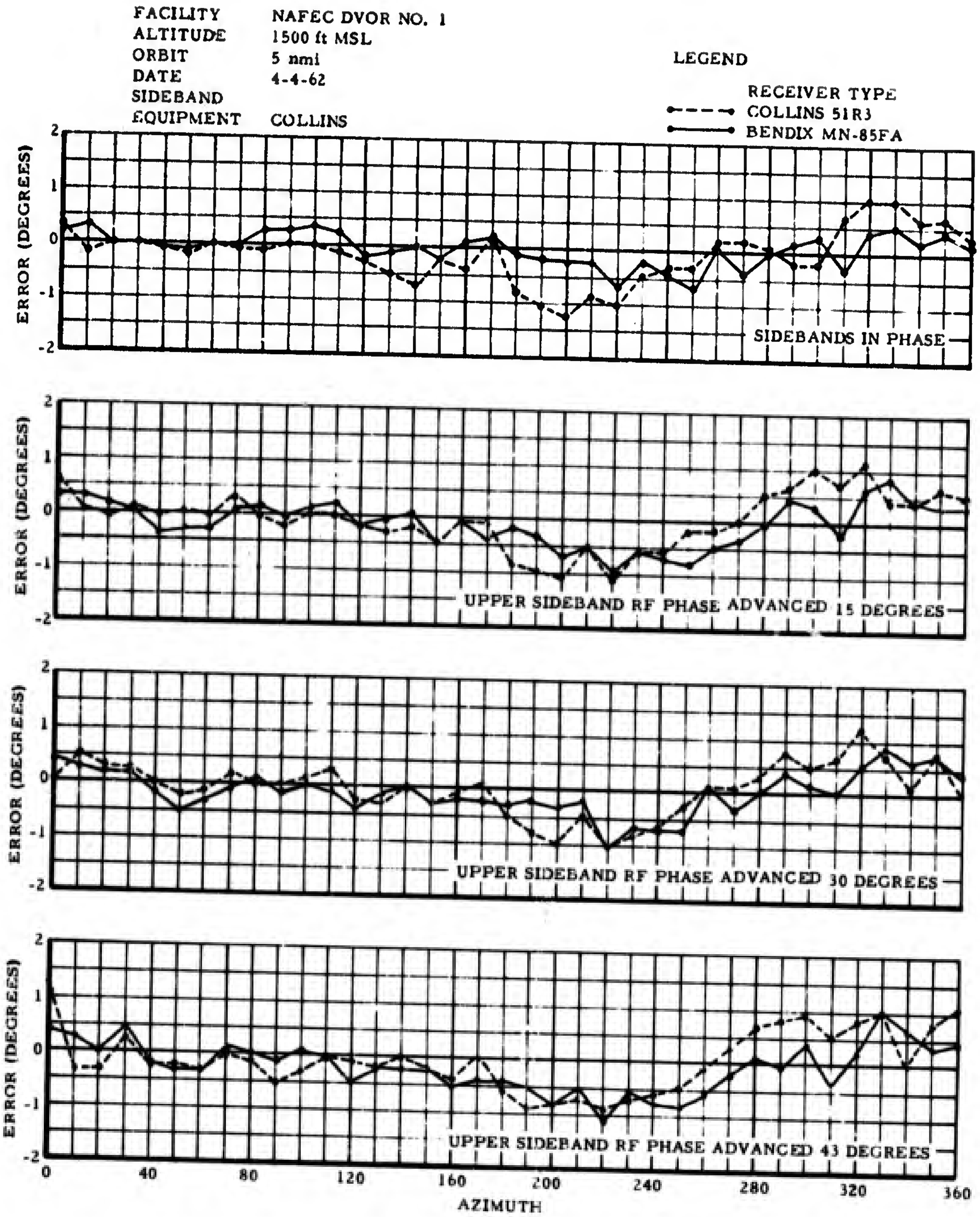


Figure 20. COMPARISON OF INDICATED STATION ERROR AS UPPER SIDEBAND RF PHASE IS ADVANCED (COLLINS 51R3 AND BENDIX MN-85FA)

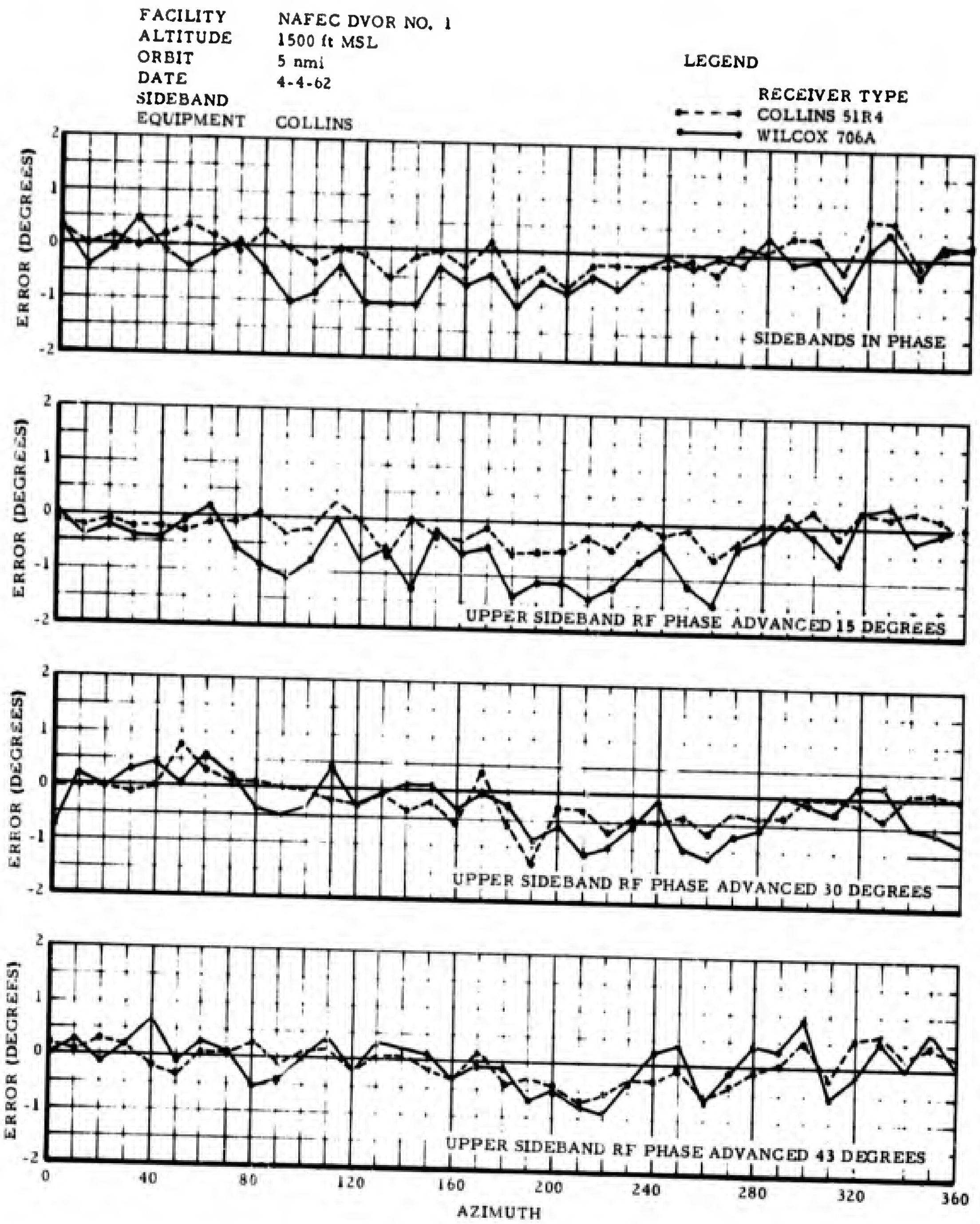


Figure 21. COMPARISON OF INDICATED STATION ERROR AS RF PHASE OF UPPER SIDEBAND IS ADVANCED (COLLINS 51R4 AND WILCOX 706A)

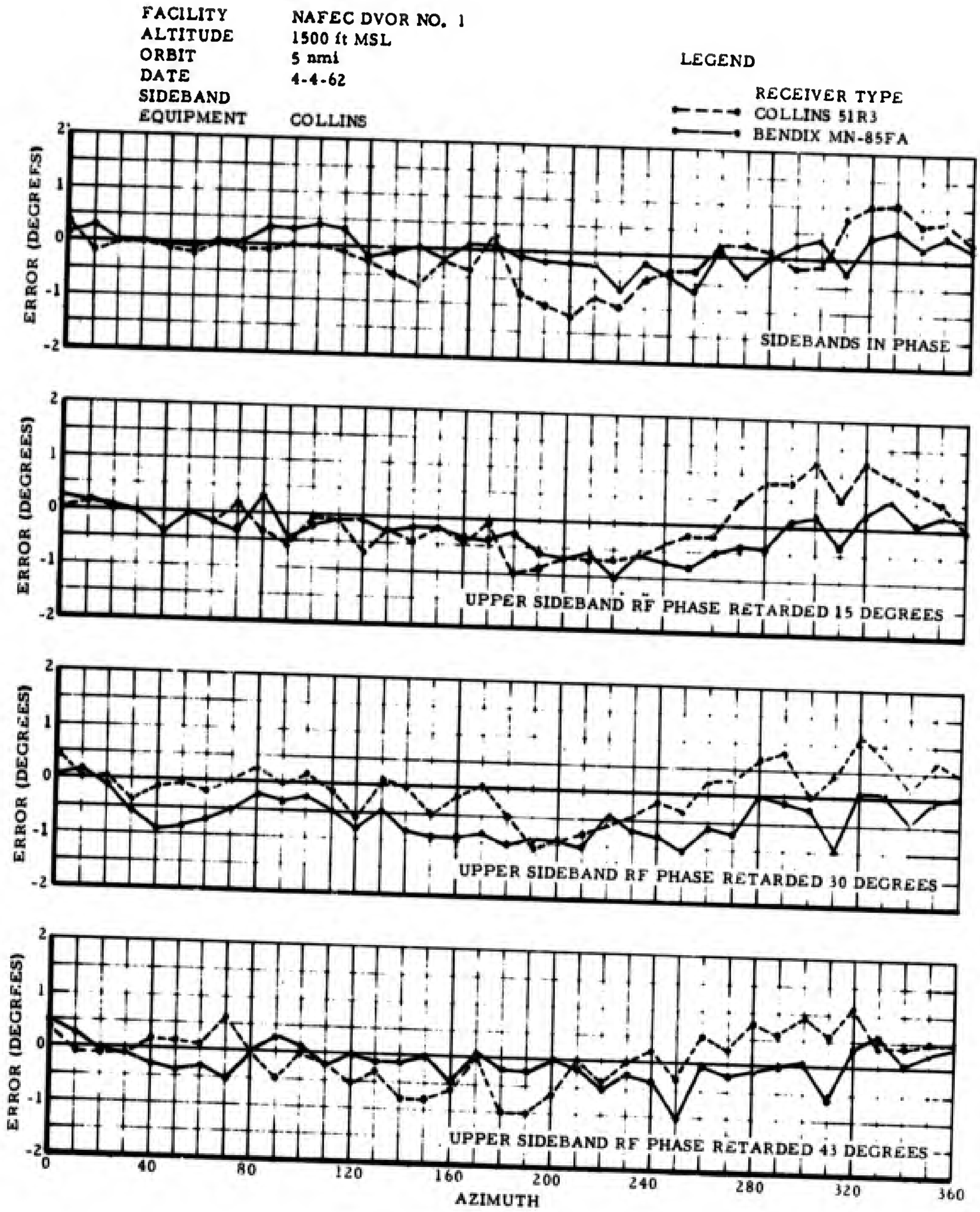


Figure 22. COMPARISON OF INDICATED STATION ERROR AS RF PHASE OF UPPER SIDEBAND IS RETARDED (COLLINS 51R3 AND BENDIX MN-85FA)

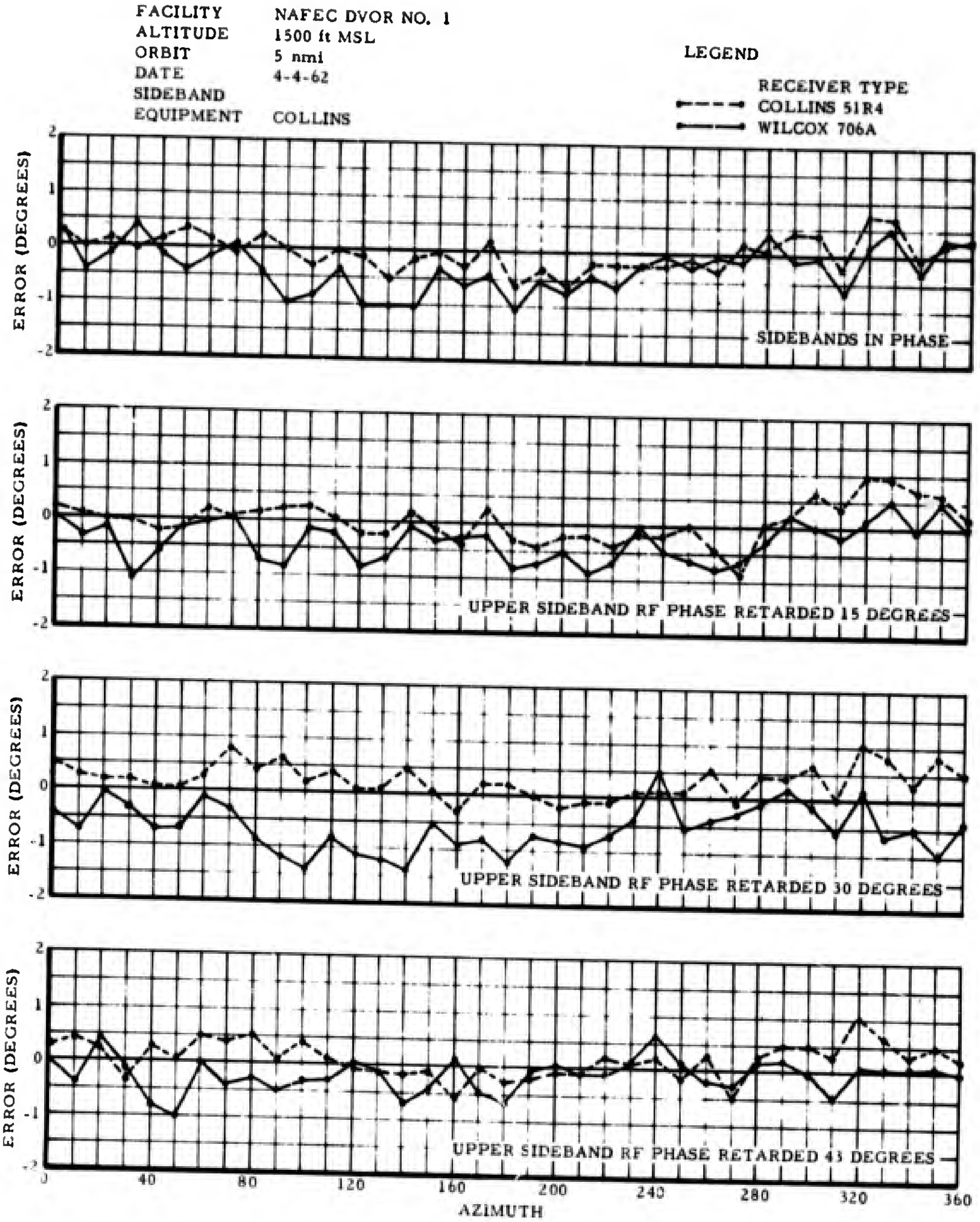


Figure 23. COMPARISON OF INDICATED STATION ERROR AS RF PHASE OF THE UPPER SIDEBAND IS RETARDED (COLLINS 51R4 AND WILCOX 706A)

Upon receipt of the prototype sideband equipment from the contractor, the equipment was installed in the Doppler No. 2 facility in a manner which would provide a means of quick change from one VOR system to another; i. e., SSDVOR, DSDVOR, or Conventional VOR for a comparison of systems. A block diagram of the prototype DSDVOR System used for the following tests is given in Figure 15. The lower sideband equipment was disabled for those tests requiring signal sideband operation.

Static Tests - Static tests were made by rotating the DVOR antenna array and stopping in 10° increments as determined by accurately measured mechanical marks placed on the edge of the rotating portion of the counterpoise. The DVOR signals were received by 10 navigational receivers located approximately 1.4 nmi from the DVOR. The omnibearing selectors (OBS) of the receivers were adjusted for an on course indication. The DVOR signal was then replaced with a signal of the same amplitude from receiver calibration generator. The phase generator was then adjusted for an on course indication for each of the 10 receivers. The difference between the indicated angle of the phase generation and the counterpoise position became the indicated station error for that particular receiver. The procedure was repeated for each 10° of 360° azimuth. The results were plotted to provide a station error curve for each of the 10 receivers. The same tests were performed on the SSDVOR, DSDVOR, and Conventional VOR Systems for a comparison of receiver reaction under identical test procedures. Typical results are given in Figures 24 through 38. Static tests could not be accomplished as the counterpoise reduced in size due to failure of the drive mechanism which rotated the antenna array.

Flight Tests - Flight tests were made using 10 navigational receivers, representative of a cross-section of the air carrier, executive, and general aviation types. The simultaneous recording of the CDI action of each of the receivers, operating from a single antenna, was made possible by the use of an RF amplifier and a signal distribution pad. The signal distribution pad provided isolation and impedance matching of the receiver inputs. The gain of the RF amplifier, connected between the antenna and the signal distribution pad, was adjusted to provide a signal level to the receiver inputs equal to the level which would normally appear at the antenna terminals with one receiver load.

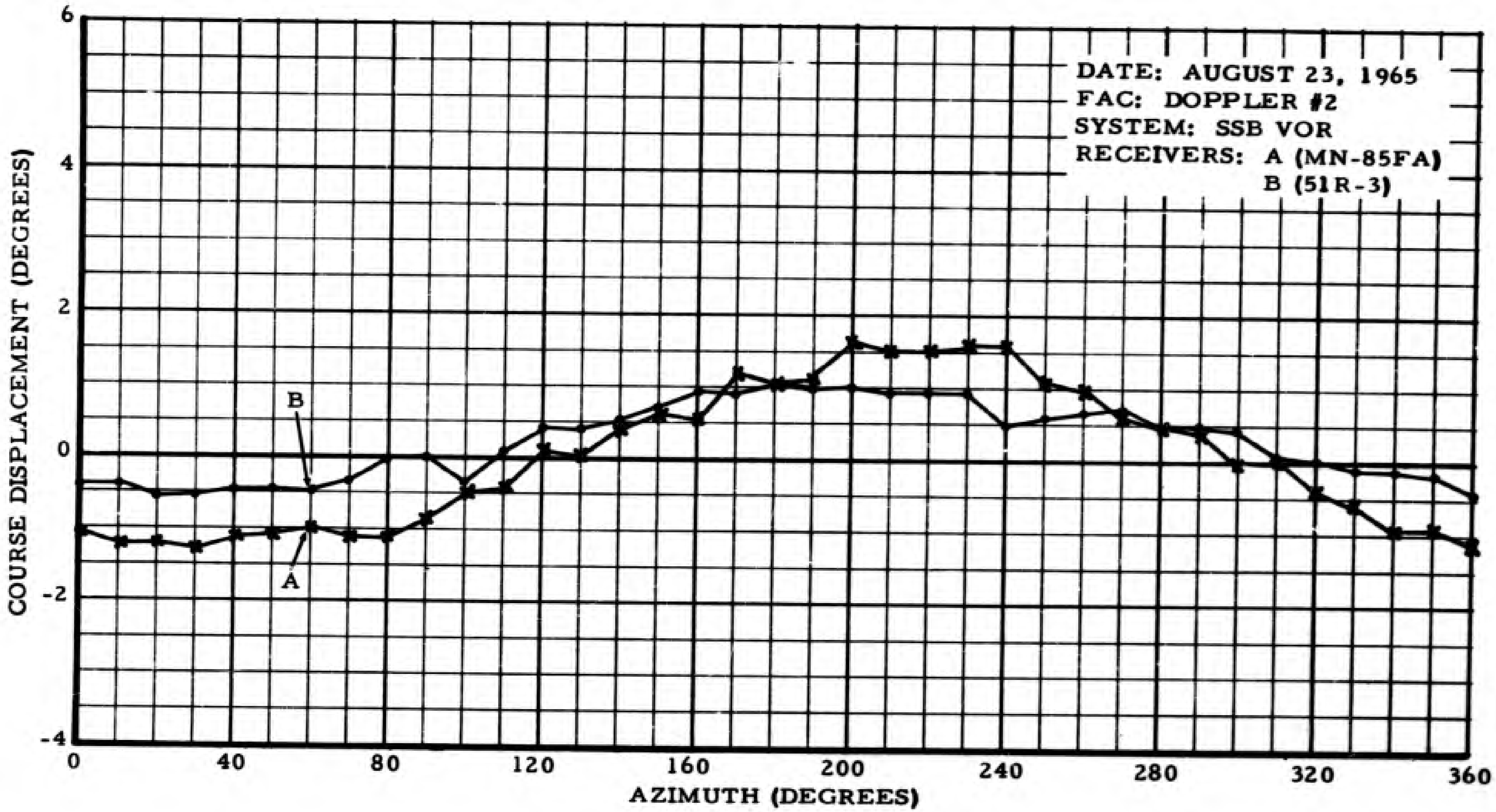


Figure 24. INDICATED STATION ERROR WITH TYPE MN-85FA (A) AND 51R3 (B) RECEIVERS FROM SSDVOR STATIC TESTS

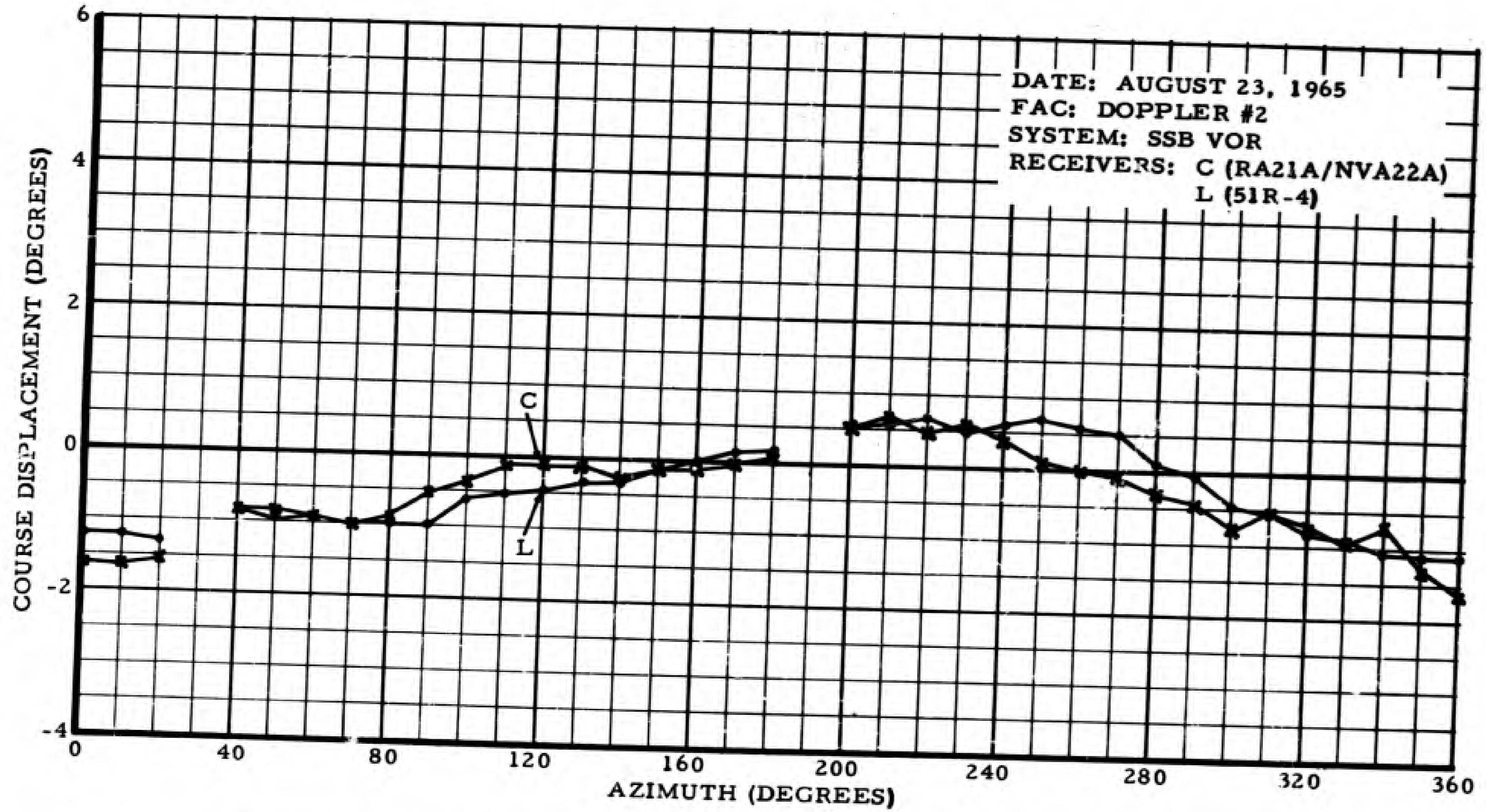


Figure 25. INDICATED STATION ERROR WITH TYPE RA-21A/NVA22A (C) AND 51R4 (L) RECEIVERS FROM SSDVOR STATIC TESTS

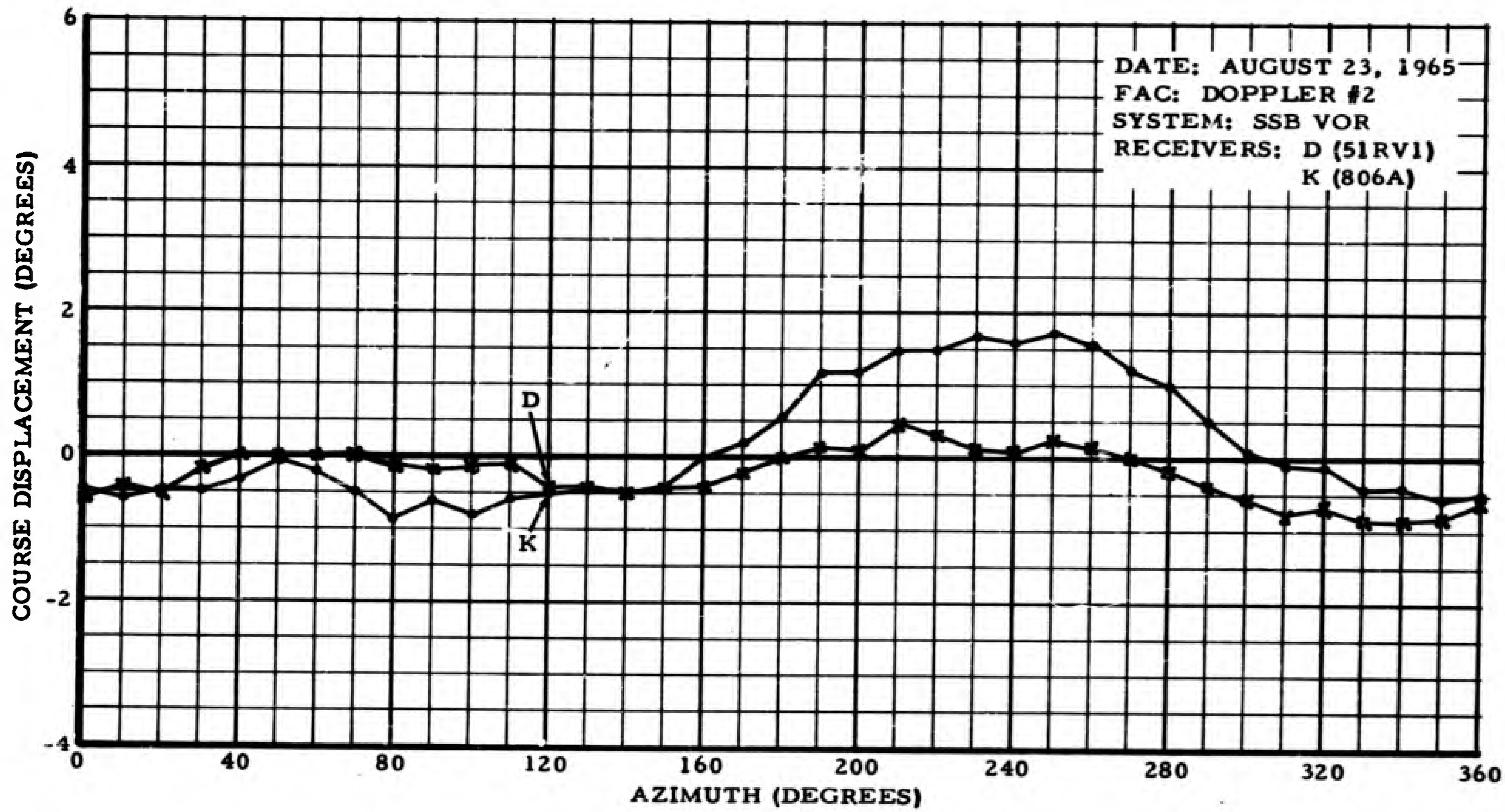


Figure 26. INDICATED STATION ERROR WITH TYPE 51RV1 (D) AND 806A (K) RECEIVERS FROM SSDVOR STATIC TESTS

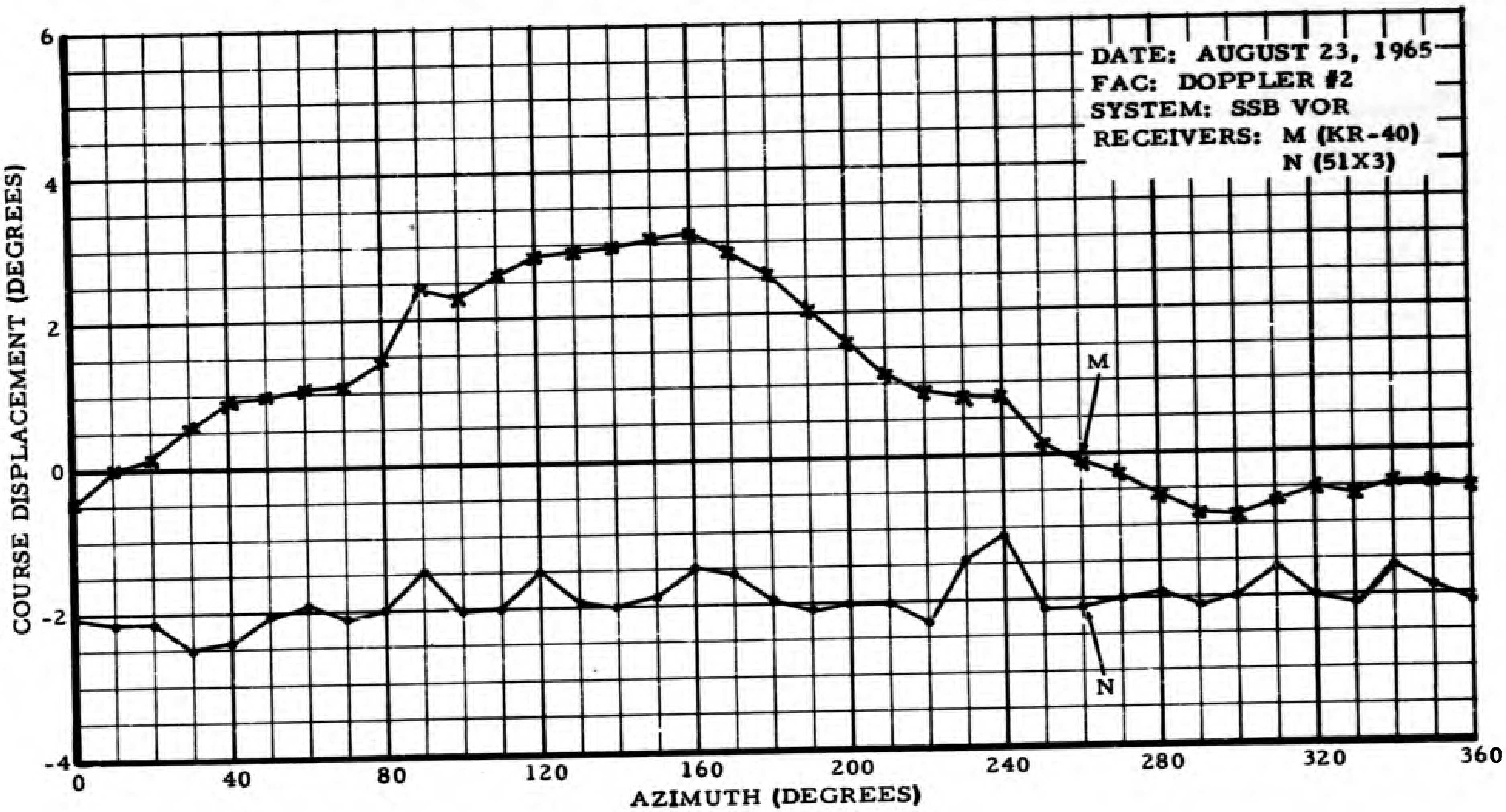


Figure 27. INDICATED STATION ERROR WITH TYPE KR-40 (M) AND 51X3 (N) RECEIVERS FROM SSDVOR STATIC TESTS

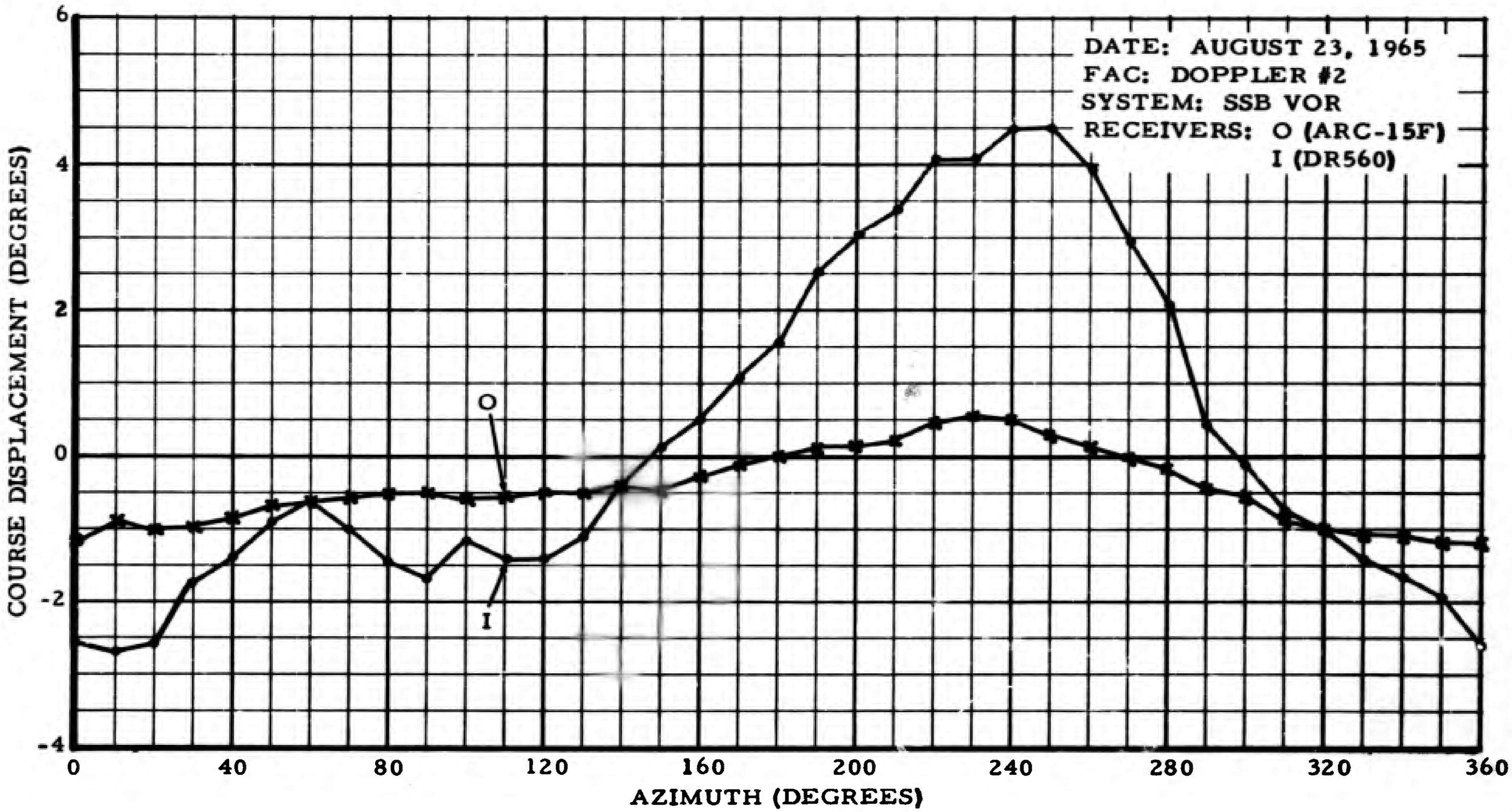


Figure 28. INDICATED STATION ERROR WITH TYPE ARC-15F (O) AND DR560 (I) RECEIVERS FROM SSDVOR STATIC TESTS

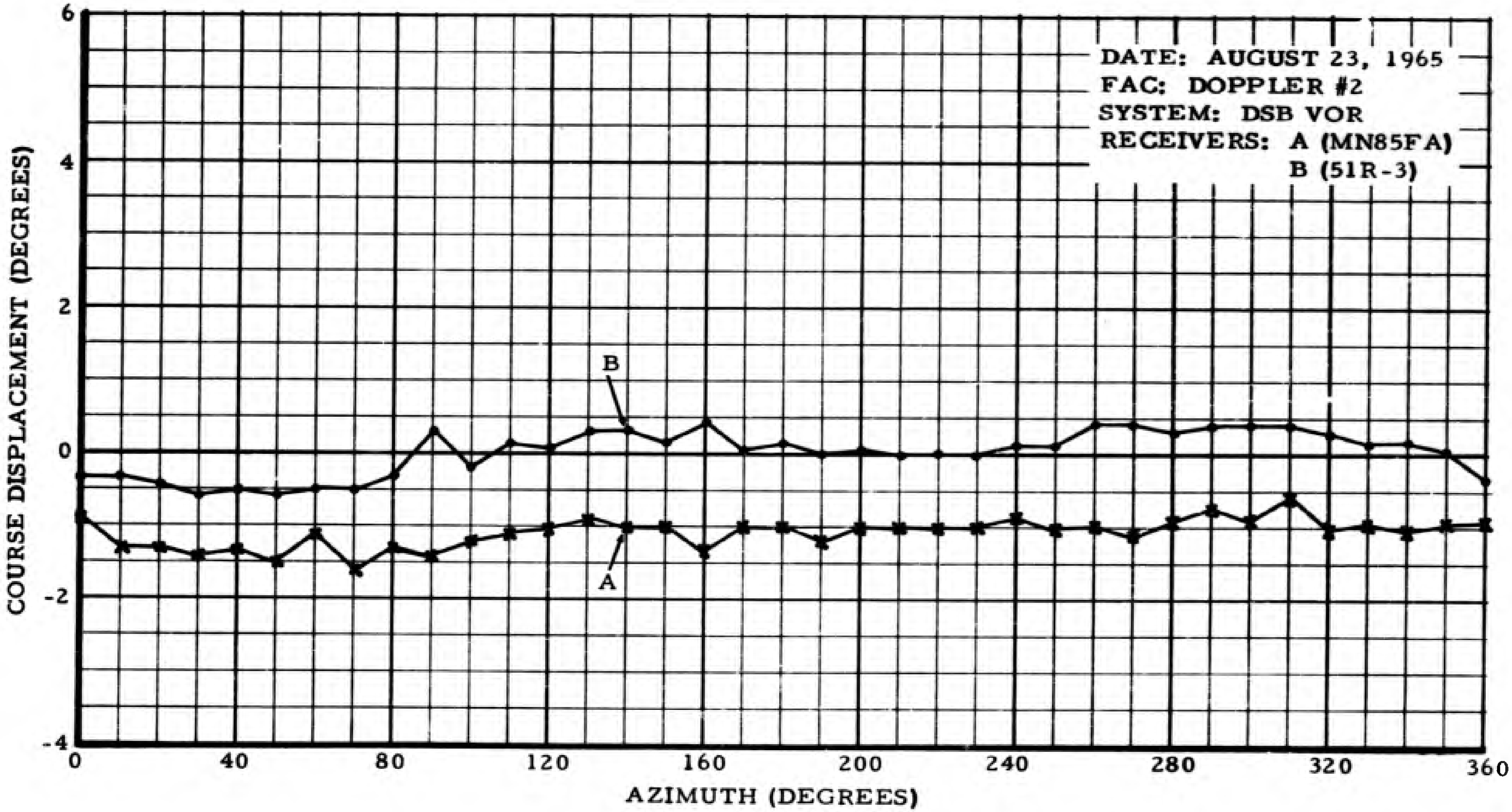


Figure 29. INDICATED STATION ERROR WITH TYPE MN-85FA (A) AND 51R3 (B) RECEIVERS FROM DSDVOR STATIC TESTS

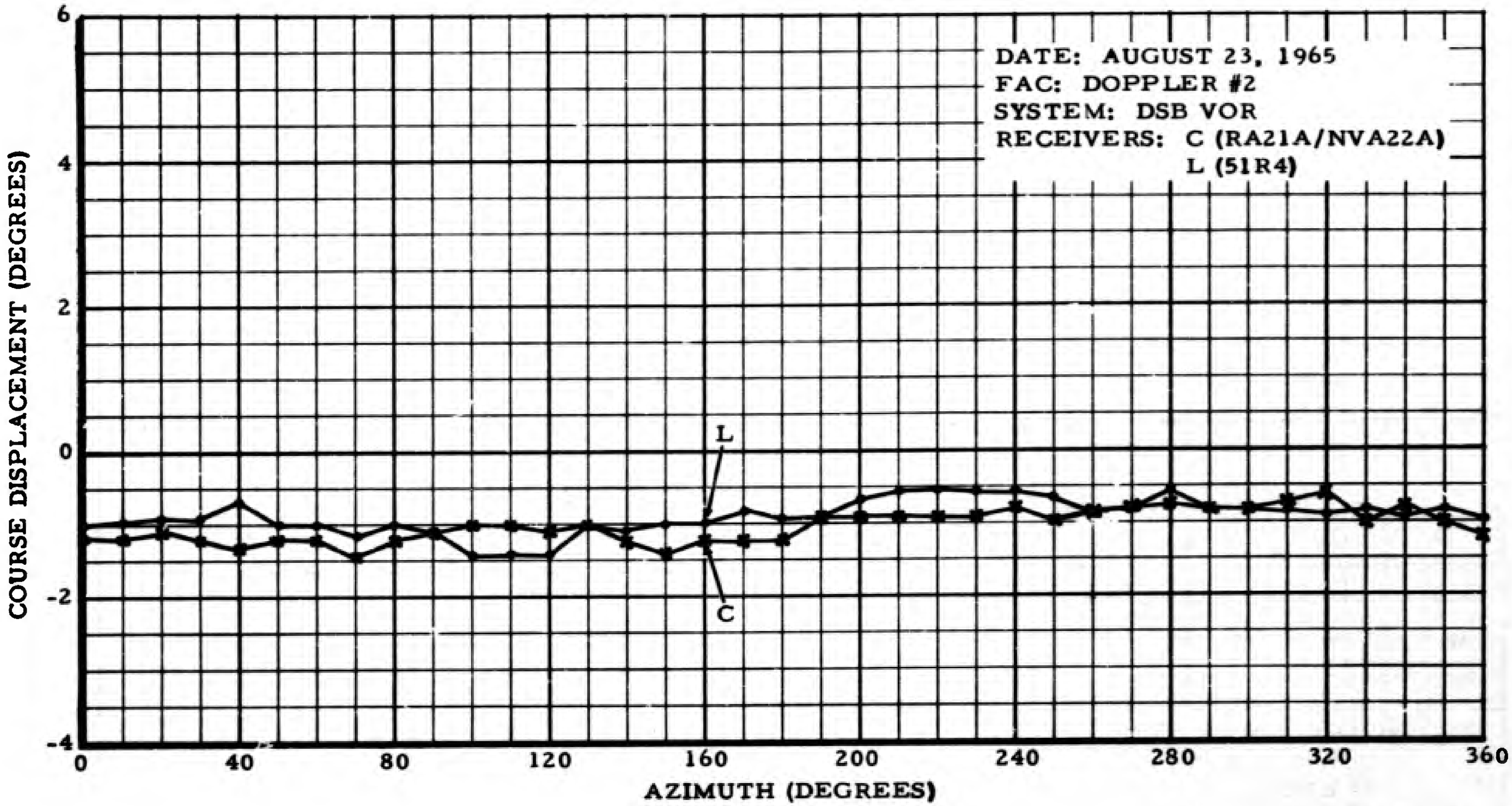


Figure 30. INDICATED STATION ERROR WITH TYPE RA-21A/NVA22A (C) AND 51R4 (L) RECEIVERS FROM DSDVOR STATIC TESTS

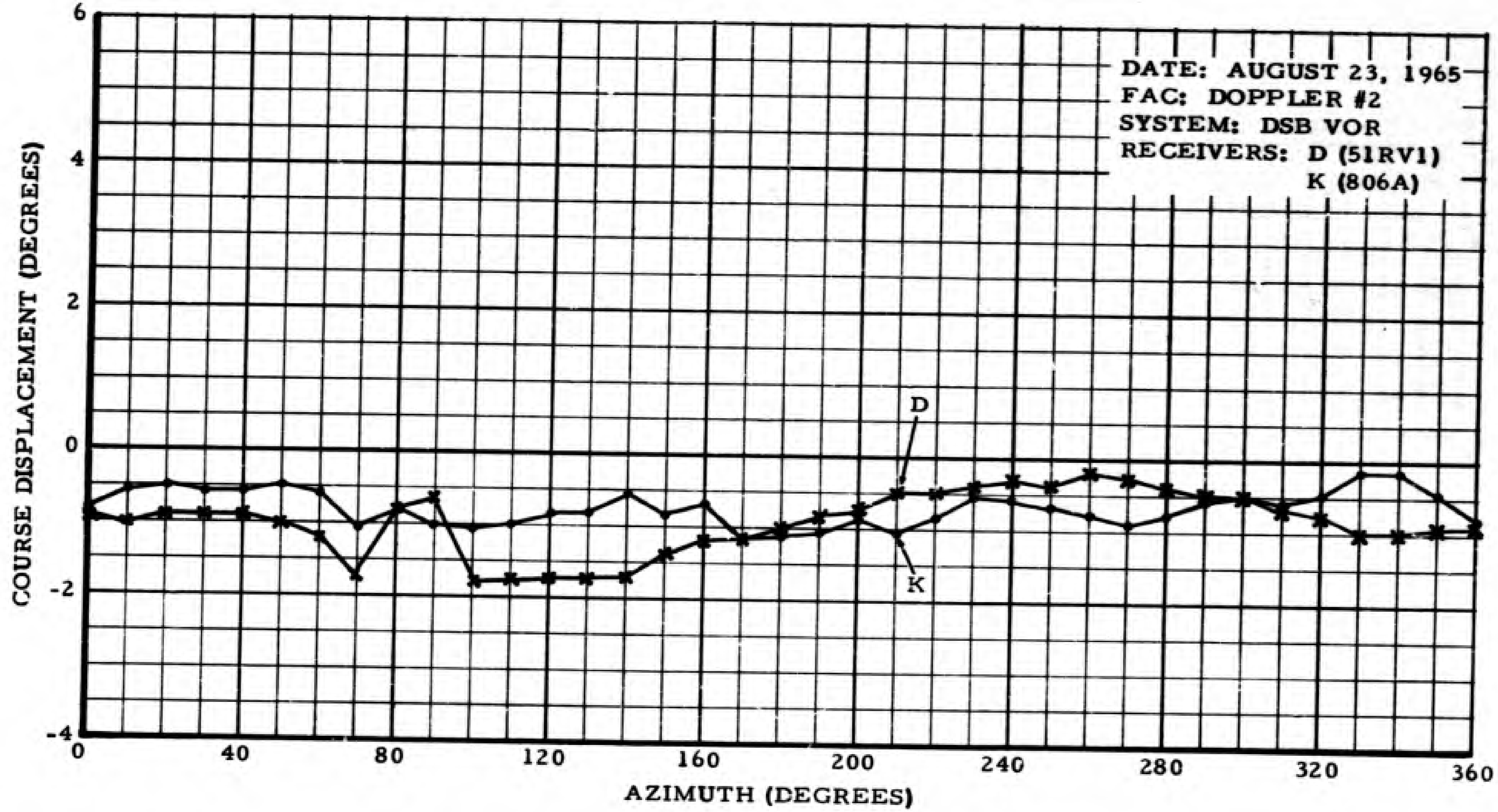


Figure 31. INDICATED STATION ERROR WITH TYPE 51RV1 (D) AND 806A (K) RECEIVERS FROM DSDVOR STATIC TESTS

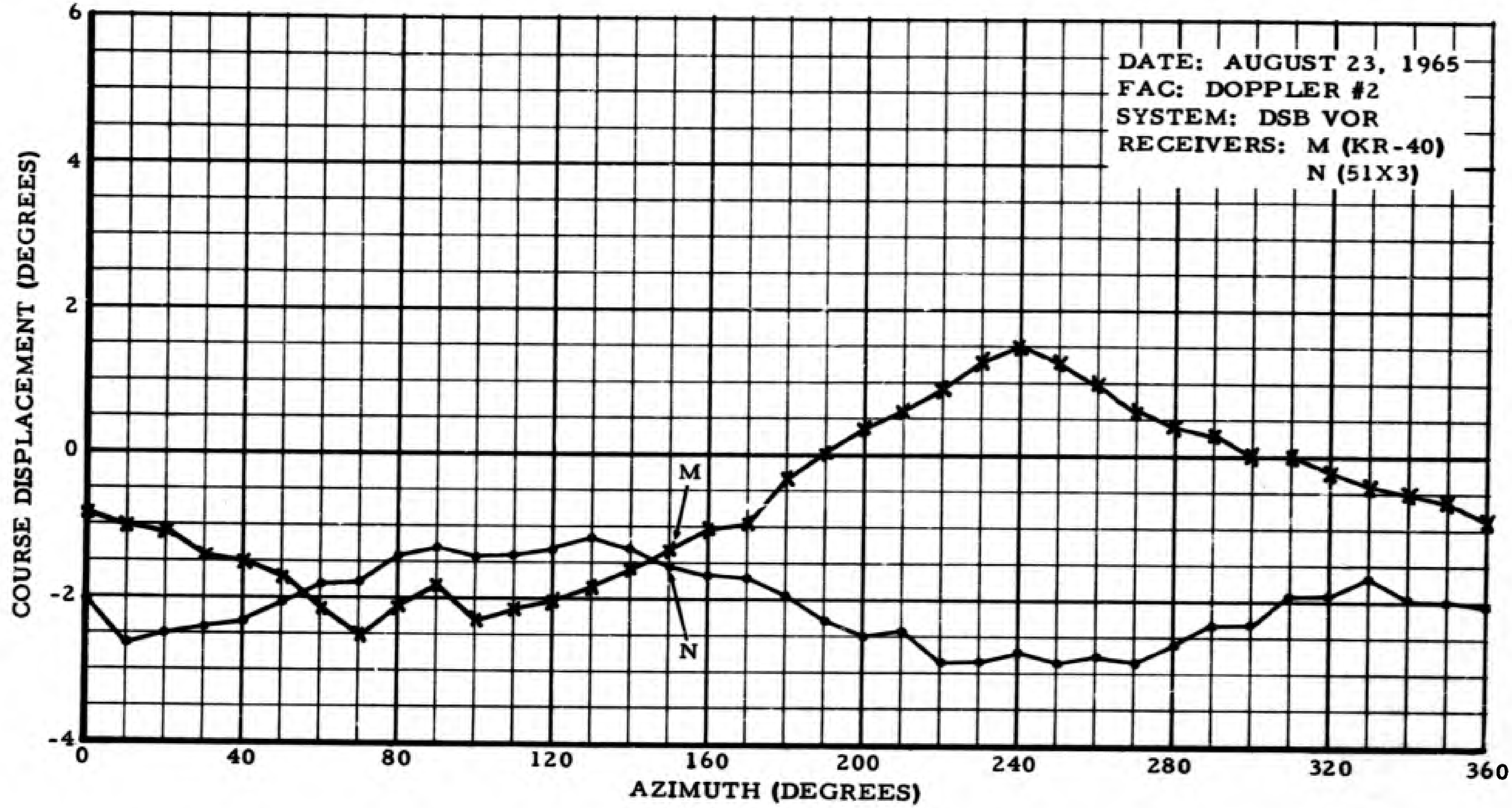


Figure 32. INDICATED STATION ERROR WITH TYPE KR-40 (M) AND 51X3 (N) RECEIVERS FROM DSDVOR STATIC TESTS

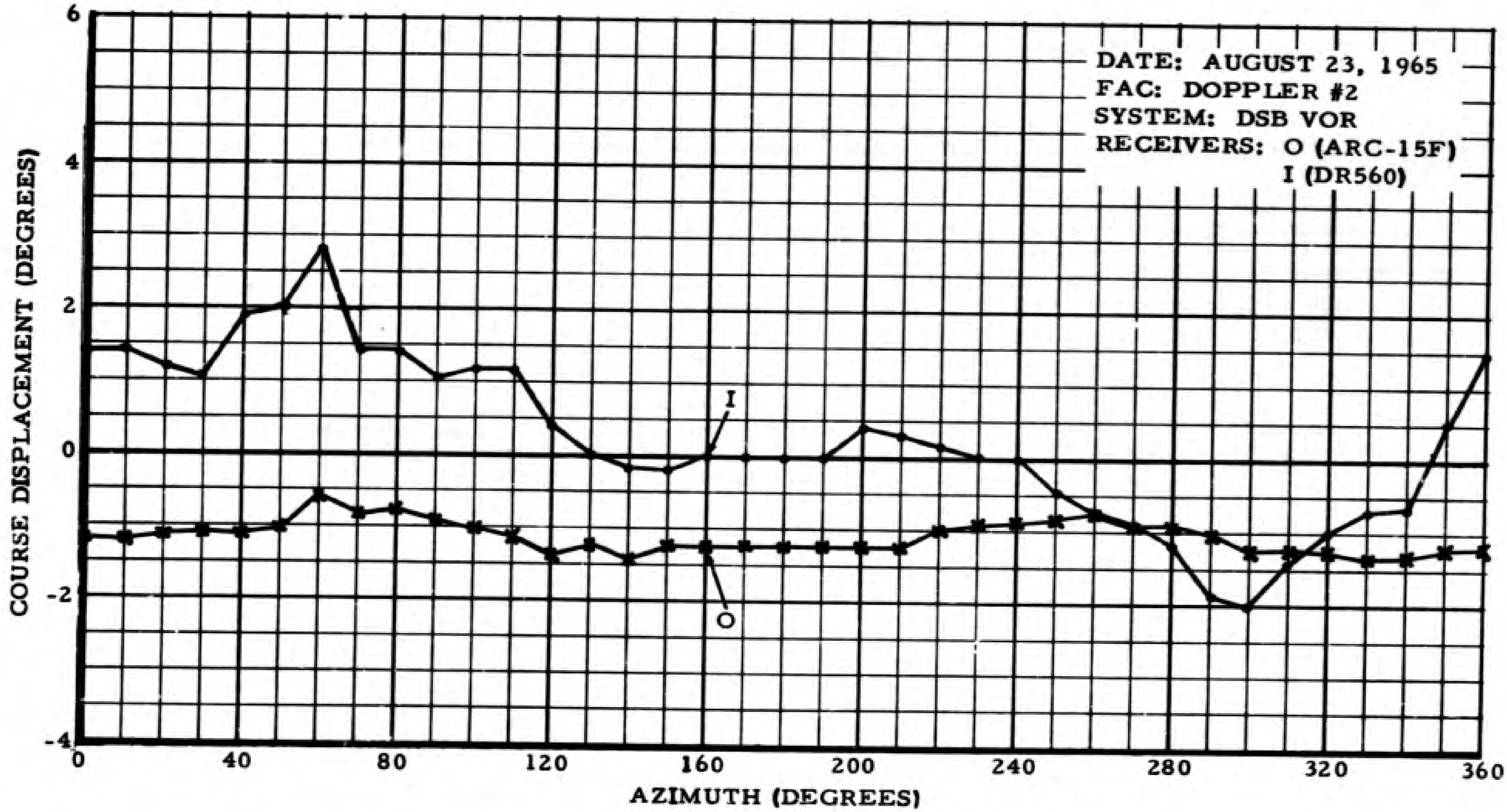


Figure 33. INDICATED STATION ERROR WITH TYPE ARC-15F (O) AND DR560 (I) RECEIVERS FROM DSDVOR STATIC TESTS

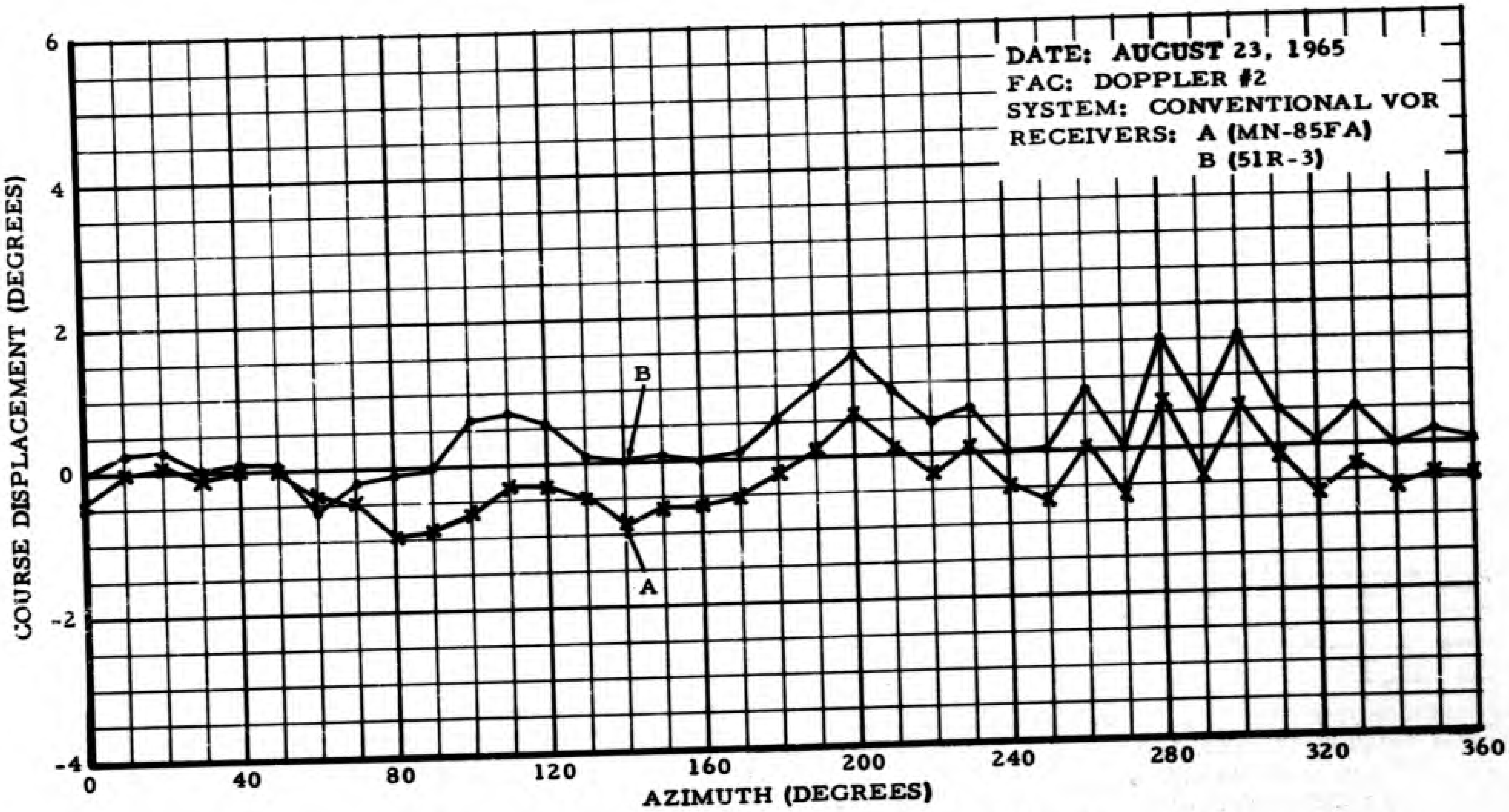


Figure 34. INDICATED STATION ERROR WITH TYPE MN-85FA (A) AND 51R3 (B) RECEIVERS FROM CONVENTIONAL VOR STATIC TESTS

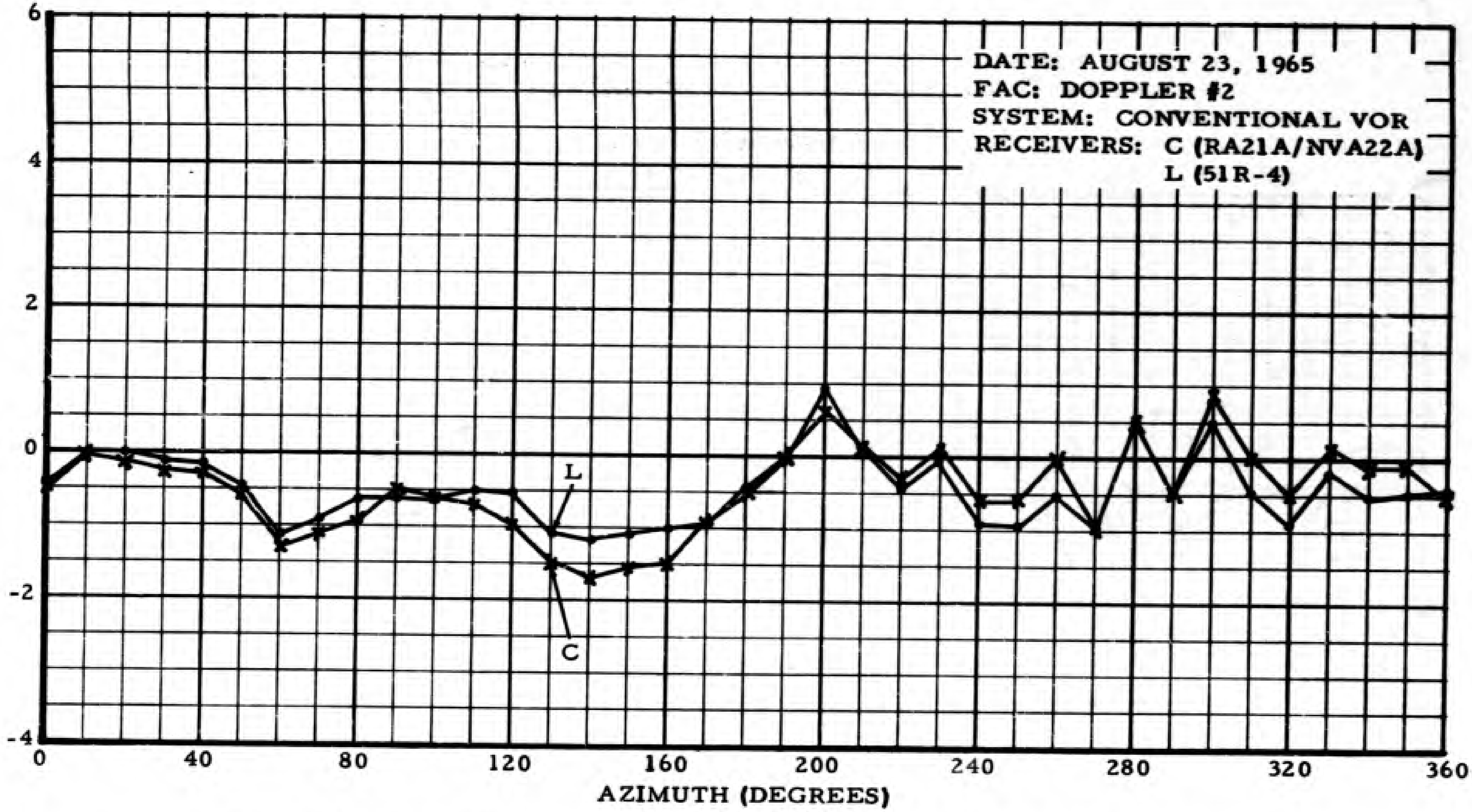


Figure 35. INDICATED STATION ERROR WITH TYPE RA-21A/NVA22A (C) AND 51R4 (L) RECEIVERS FROM CONVENTIONAL VOR STATIC TESTS

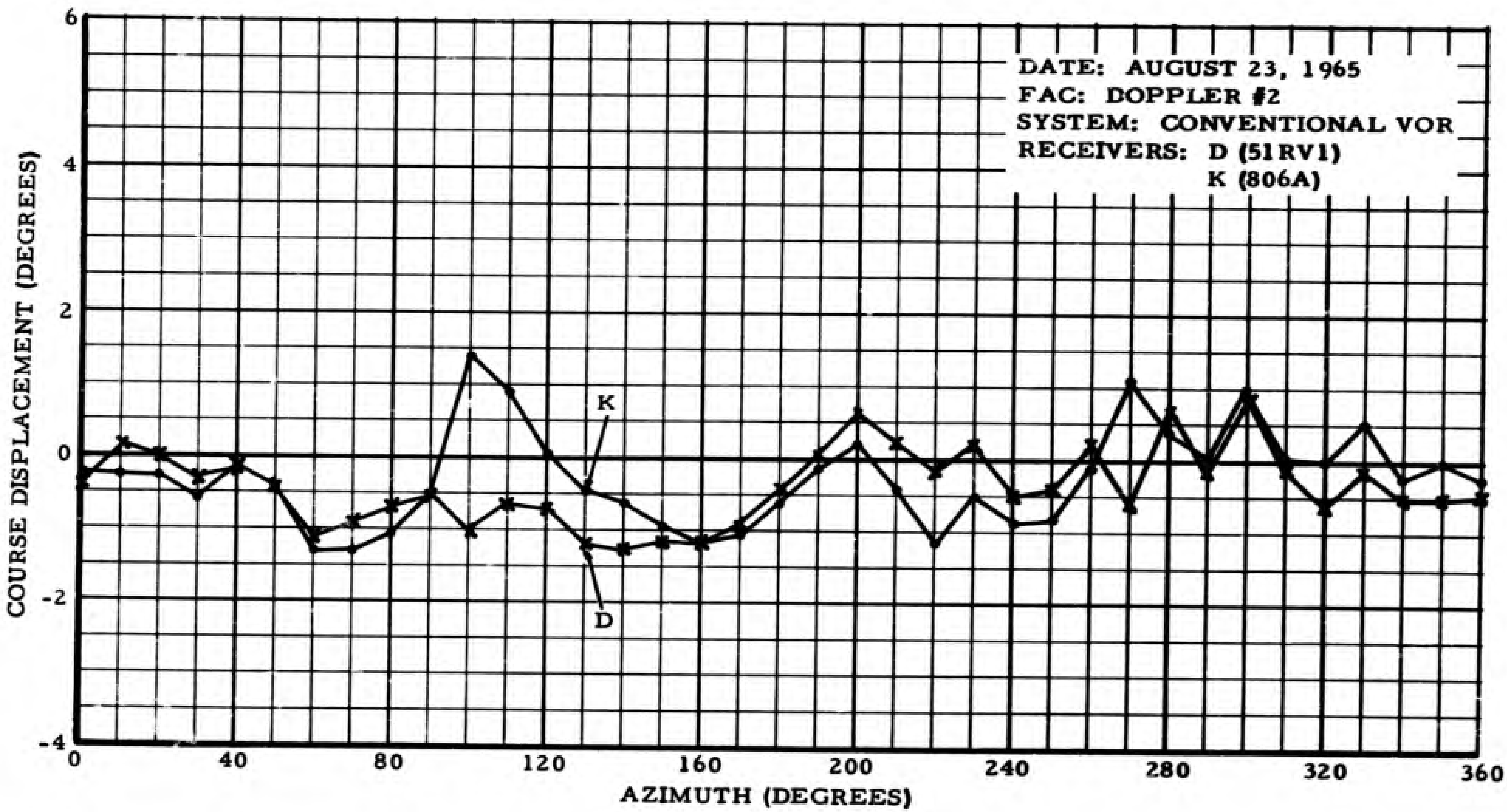


Figure 36. INDICATED STATION ERROR WITH TYPE 51RV1 (D) AND 806A (K) RECEIVERS FROM CONVENTIONAL VOR STATIC TESTS

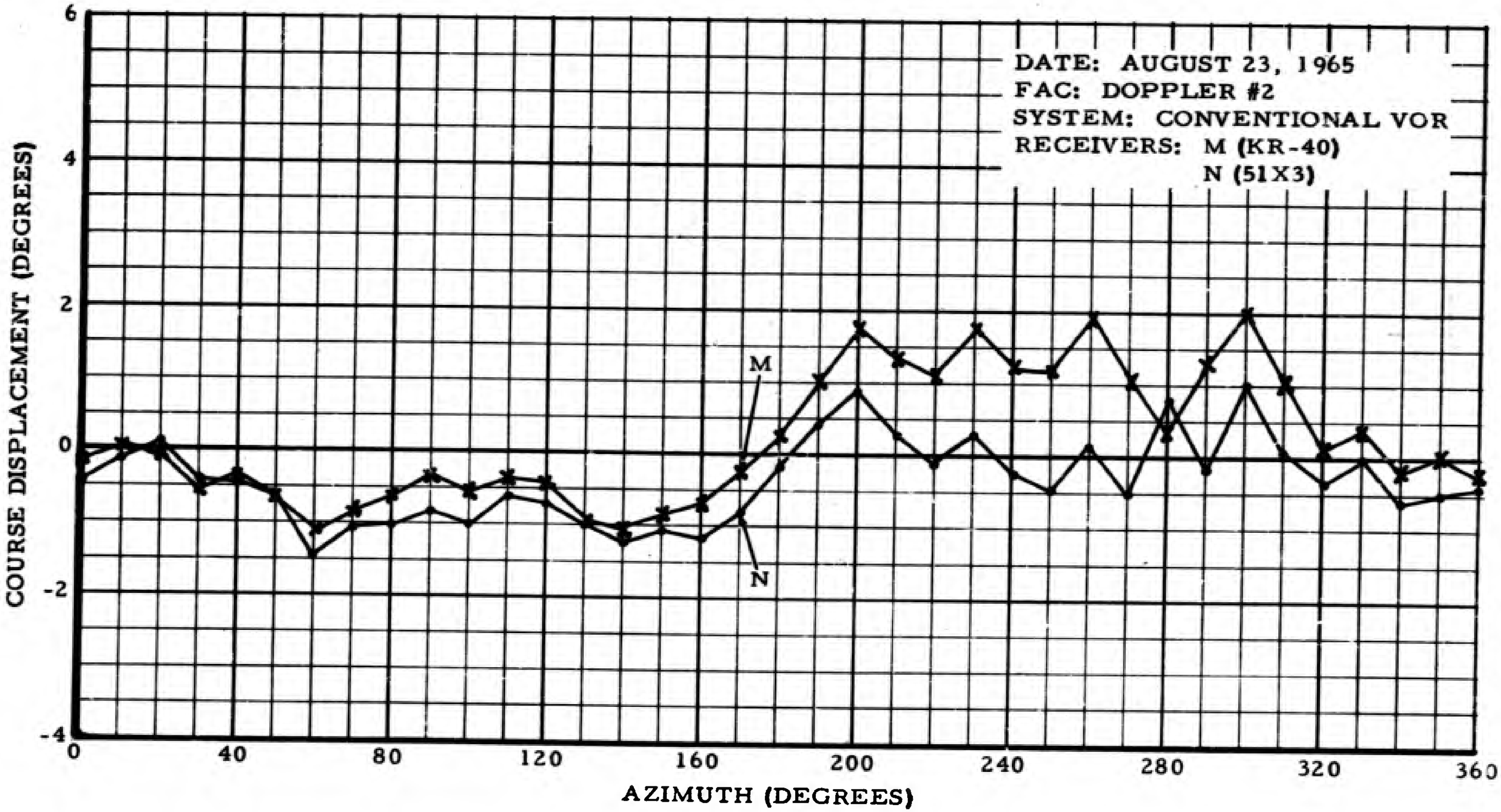


Figure 37. INDICATED STATION ERROR WITH TYPE KR-40 (M) AND 51X3 (N) RECEIVERS FROM CONVENTIONAL VOR STATIC TESTS

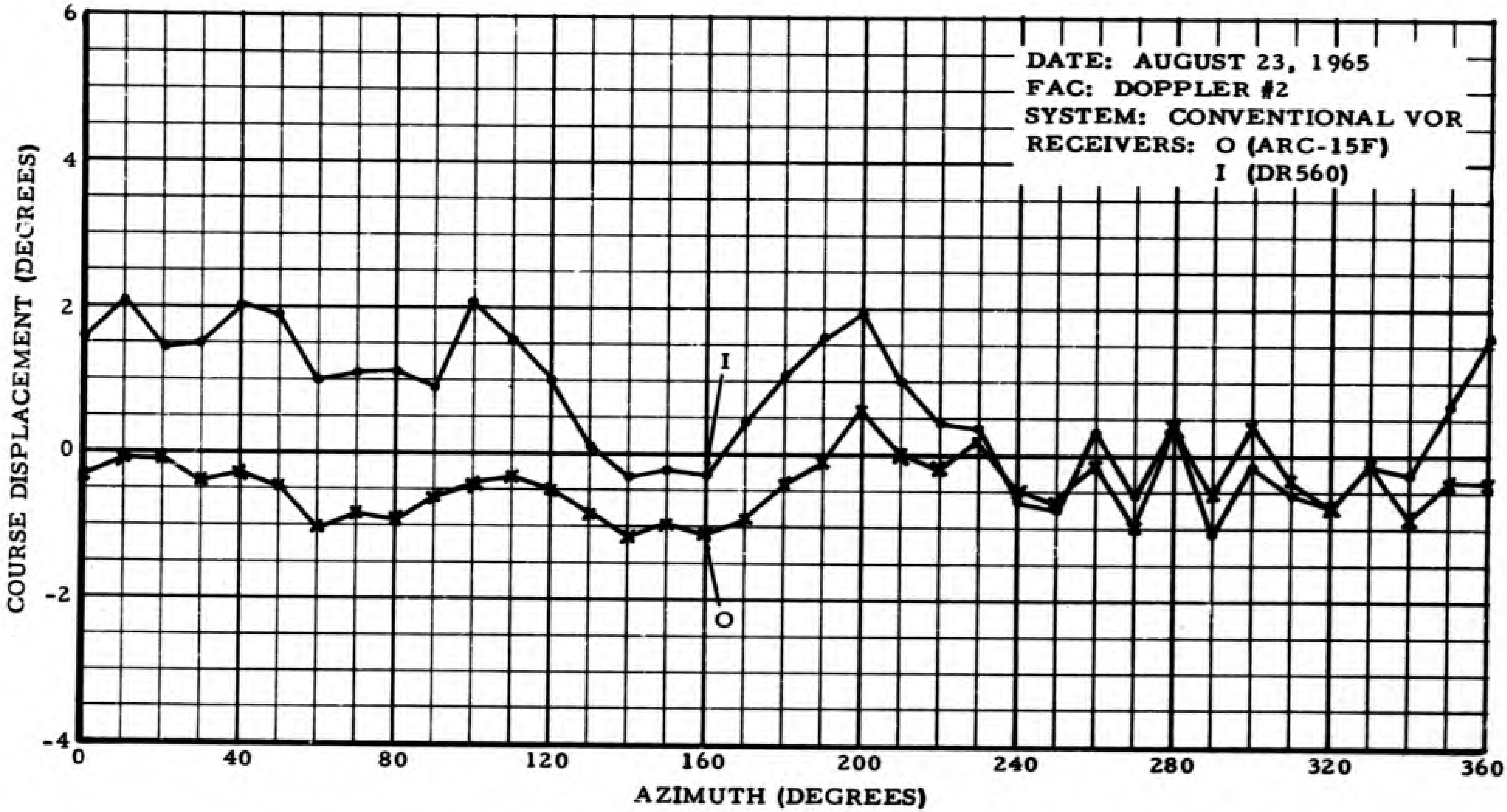


Figure 38. INDICATED STATION ERROR WITH TYPE ARC-15F (O) AND DR-560 (I) RECEIVERS FROM CONVENTIONAL VOR STATIC TESTS

Azimuth reference marks on the CDI recording of each receiver were made by tracking the test aircraft with a theodolite which automatically transmitted a tone for each 10^o of azimuth. Theodolite-controlled 5-nmi orbital flight tests were made to determine station error and receiver compatibility for each counterpoise size. Two orbits were flown for each test to ascertain repeatability. The SSDVOR, DSDVOR, and Conventional VOR Systems were flight-tested to provide a comparison of the VOR systems.

Upon completion of the reassembly of the counterpoise to the 100-foot size, the flight tests were repeated. In addition, tests were made to determine the effects to the DVOR System of a TACAN antenna mounted coaxially above the carrier array. A problem encountered in the mounting of the TACAN antenna was that the hemispherical dome covering the DVOR antenna array did not lend itself to the installation of the TACAN antenna without extensive construction effort. In order to provide a quick, simple test, a simulated TACAN mounting base composed of an aluminum drum of the same physical size as the TACAN mounting base was fabricated. The drum was assembled in the dome and installed 16 feet above the counterpoise by extending the iron pipe used to support the VOR polarizer.

To determine scalloping due to "site effects" for each VOR system and counterpoise size, 20-nmi orbital flight tests were made. The CDI action of each of the 10 receivers was recorded. From these recordings, the maximum scalloping for each 10^o of azimuth was obtained and plotted. Counterpoise size has little effect on scalloping; therefore, only the data obtained for the 150', 100', and 60' sizes are given as representative of the test results.

Signal Evaluation Airborne Laboratory (SEAL) Receiver Tests - Additional flight tests, utilizing a special navigational receiver, were made for comparison of the three VOR system performances. The specialized receiver was a prototype unit of the SEAL System undergoing test and evaluation for use in flight inspection service. This receiver was chosen because the design objectives of a highly accurate, instrumentation quality unit required for flight inspection application would give comparison of systems performance with the best receiver available, and would also afford a performance comparison of the SEAL receiver and the more sophisticated receivers used in the previous flight tests.

Several departures from existing commercial receiver designs were incorporated in the SEAL receiver to obtain a high degree of accuracy. Generally, these included the development of:

1. An IF amplifier with low cross-modulation and flat response beyond the subcarrier sideband,

2. A highly linear IF detector,

3. AGC circuits giving smoothly changing logarithmic AGC voltages and stiffer control on the detector output level,

4. Matched phase response of the filters for the 30 Hz signal,

5. Digital circuits for accurate phase comparison of the two 30 Hz filters,

6. Linear amplitude filters and rectifiers for separating and detecting pertinent audio components, and,

7. Provision for manual tuning of the local oscillator for placement of the IF frequency in the center of the IF filters.

Complete design consideration and development of the SEAL receiver are given in Report Number RD-67-4 (Reference 4).

To obtain a high degree of readout in azimuth accuracy, departures were made from existing commercial design in the processing of the VOR navigation signals. In the SEAL system, the navigational signals from the SEAL receiver are sampled at a rate of 30 times per second and converted from analog form to digital form to provide digital readout of azimuth and for recording on magnetic tape for computer processing of the VOR station error at a later date. An output is also available for analog readout of azimuth, derived by converting the digital information to analog form, for operation of the presently used instrumentation.

In normal use, the SEAL system aircraft position is determined by an inertial system; only the SEAL receiver was available for the Doppler VOR tests. However, aircraft position was determined by the theodolite method. Two 6-nmi orbital flight tests were made of each VOR system; i. e., SSDVOR, DSDVOR, and Conventional VOR Systems. For performance comparison, six air carrier receiver types were used with SEAL receiver. The analog output of the SEAL receiver was recorded in the conventional manner for direct comparison with the data obtained from the six air carrier types of receivers. At each 10° of azimuth as measured by the theodolite, marks were made on recordings of the CDI action of the six air carrier receivers tested and on the digital recording of the SEAL receiver data. The digital output of the SEAL receiver was recorded by the use of a Hewlett Packard Model 562A digital printer to provide data for comparison of VOR system performance.

Test Results and Analysis: The primary objective of the DSDVOR System is to reduce cross-modulation of the signal at the second detector of the receiver. This will provide improved receiver compatibility, reduction of station error, reduction of counterpoise size, and a possible reduction in course roughness and scalloping. The test data indicate minimal reduction in scalloping.

Static Tests -

A. Cross-Modulation Reduction - Individual station error curves (Figures 24 through 38), as indicated by each of the 10 receivers, have been plotted from the data obtained in the previously mentioned static tests. By comparing the characteristic shape of the error curves for the DSDVOR System with those of the SSDVOR System (noting the absence of the SSDVOR inherent duantal shape in the DSDVOR curves) it is readily apparent that the DSDVOR System does, in fact, produce less cross-modulation of the signal at the second detector of the navigational receivers than the SSDVOR System.

B. Receiver Compatibility - Receiver compatibility is difficult to define in absolute terms. Only by comparing the reactions of receivers of different design with the signal of the systems under test can a determination be made of receiver compatibility. Accordingly, the individual receiver error curves were combined to provide a composite error curve for system comparison, and are given in Figures 39, 40, and 41, for the SSDVOR, DSDVOR, and the Conventional VOR, respectively. Examination of these curves revealed that the maximum total error spread for the SSDVOR System was 7.2° and 5.1° for the DSDVOR System. The Conventional VOR maximum error spread was 3.8°.

The dispersion of the receiver error curves are greater in the SSDVOR System than in the DSDVOR System. The receivers which contributed most to the wide dispersion of the error curves in both of the DVOR Systems were the least sophisticated (receivers, I and M). These same receivers also contributed to the wide dispersion of the error curves in the Conventional VOR System.

C. Station Error Reduction - A tabulation of each system error, as indicated by each of the 10 receivers, is given in Figure 42 from which it can be noted that the DSDVOR System has less station error than the SSDVOR.

D. Siting Effects - In the above tests the receiver remained fixed in azimuth and the antenna array rotated to provide a change of azimuth signals; therefore, the effects of reflecting objects also remain at a constant azimuth. Consequently, "siting effects" data could not be obtained from these tests.

Flight Tests - Due to the long span of time between the accomplishment of the preliminary static tests and the flight tests, several receivers used in the static tests were not available for the flight tests. Other receivers in the same category of classification were substituted to provide, as near as possible, a cross-section representation of the air carrier, executive, and general aviation types. When receiver failures occured during a flight and no data were obtained, the receiver was either repaired or another receiver of the same or similar type (receiver "E" being substituted for receiver "K") was substituted for the next step in the flight test program.

Individual station error curves for each counterpoise size, as indicated by each of the 10 receivers, were plotted from the data obtained from the 5-nmi orbital flight tests of the three VOR systems; i. e., Conventional VOR, SSDVOR, and DSDVOR Systems.

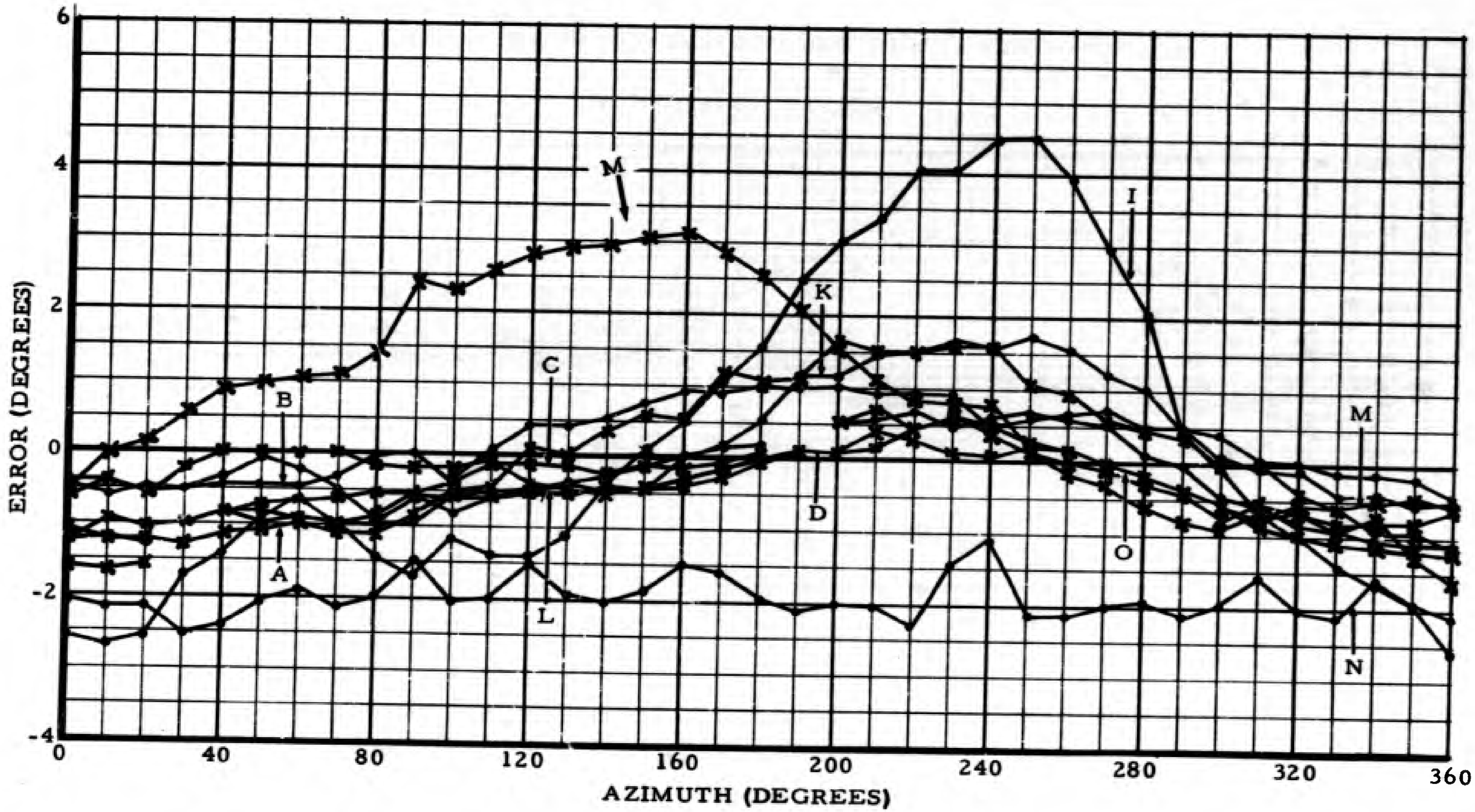


Figure 39. COMPOSITE INDICATED STATION ERROR FROM SSDVOR STATIC TESTS

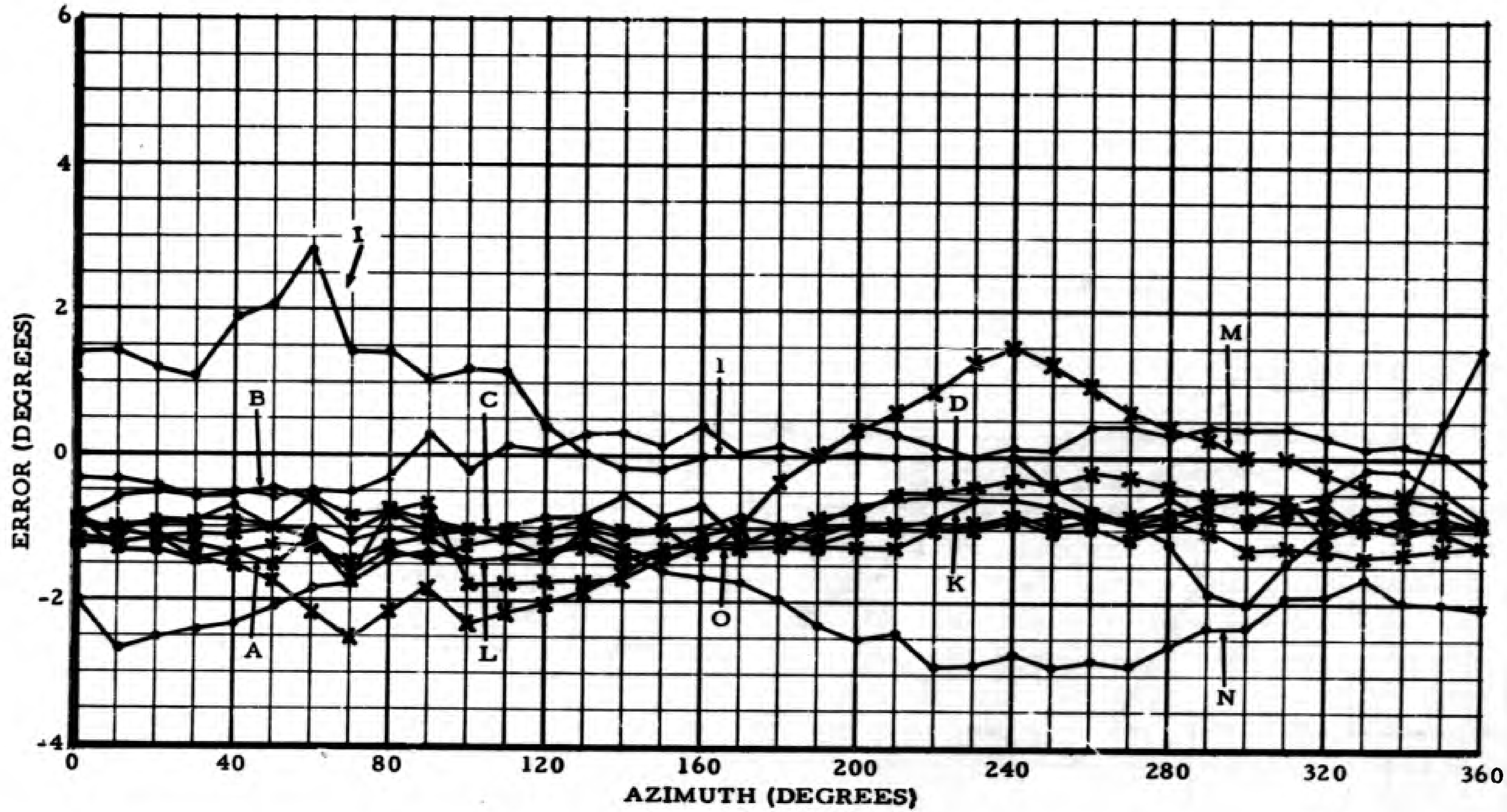


Figure 40. COMPOSITE INDICATED STATION ERROR FROM DSDVOR STATIC TESTS

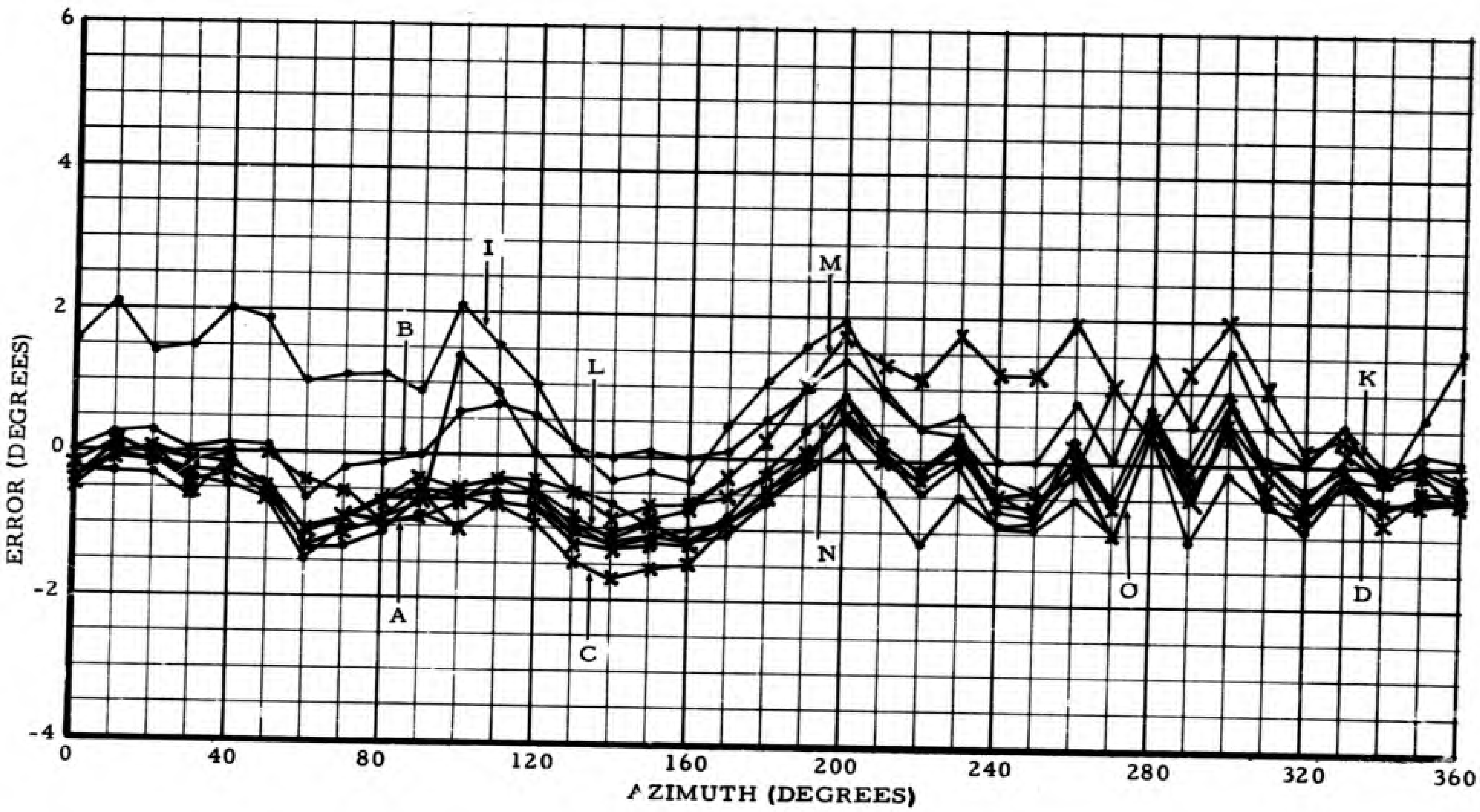


Figure 41. COMPOSITE INDICATED STATION ERROR FROM CONVENTIONAL VOR STATIC TESTS

RECEIVERS	SSDVOR SYSTEM	DSDVOR SYSTEM	CONVENTIONAL VOR SYSTEM
A MN-85FA	2.9	1.0	1.0
B 51R-3	1.6	1.0	2.1
C RA21A/NVA22A	2.4	0.8	2.5
D 51RV1	1.2	1.6	2.1
I DR-560	7.2	4.8	3.2
K 806A	2.1	1.0	2.7
L 51R-4	2.0	0.7	2.0
M KR-40	4.0	4.0	3.1
N 51-X3	1.4	1.2	2.5
O ARC-15F	1.8	0.8	1.8

Figure 42. MAGNITUDE OF RECEIVER ERROR SPREAD (AZIMUTH DEGREES) FROM STATIC TESTS

A tabulation of the indicated station error on each receiver for the three VOR systems with each counterpoise size is given for comparison of receivers and systems. Station error curves for each VOR system, as indicated by each of the 10 receivers, are included for the more pertinent counterpoise diameters of 150 feet and 100 feet to provide a clear illustration and for comparison of receiver response to the signal of the three VOR systems.

Composite station error curves for each VOR system, as indicated by each of the individual receivers, were made from the flight test data obtained for each counterpoise size. Receiver I failed during the flight for the 60-foot counterpoise diameter tests. A projection of the anticipated error curve, based on the receiver's reaction to previous steps in the reduction of the counterpoise size, is shown (by the dotted lines) on the composite curves for the 60-foot counterpoise tests of the two Doppler VOR Systems.

As previously stated, the prime objectives of the DSDVOR System are improved receiver compatibility, reduced station error, reduction of counterpoise size, and minor improvement in the siting effects. These improvements were to be achieved by a reduction of the cross-modulation caused by the "counterpoise effect." The achievement of the objectives of the DSDVOR System is revealed by the following analysis of the flight test data.

According to the previously stated theory, the duantal shape of the station error curve for the SSDVOR System is due to the cross-modulation caused by the "counterpoise effect." If the theory is correct, reduction of the counterpoise size would increase the cross-modulation resulting in larger errors as the counterpoise is reduced in size. Reviewing the composite station error curve for the SSDVOR given in Figures 43, 46, 49, 52, 55, it can be noted that as the counterpoise size was reduced, the amount of station error increased and the duantal shape became greater with a reduction of counterpoise size. Based on these facts, the stated theory is true.

Accordingly, the DSDVOR System should provide a reduction in the station error and improvement in receiver compatibility. The composite station error curves for the DSDVOR System given in Figures 44, 47, 50, 53, and 56, reveal the absence of the duantal shape of the error curves. The dispersion of the curves is less when compared to the SSDVOR System with the same counterpoise size, given in Figures 43, 46, 49, 52, and 55. For comparison, composite station error curves for the Conventional VOR are given in Figures 45, 48, 51, 54, and 57. The reduction of station error achieved by the DSDVOR System is revealed by the comparison of the individual receiver errors, tabulated in Figure 58.

Further demonstration of the improvement of the DSDVOR System can be noted by comparison of the station error curves, as indicated by the individual receiver for each of the VOR systems, given in Figures 59 through 68 for the 150-foot diameter counterpoise, and given in Figures 69 through 78 for the 100-foot diameter counterpoise. These figures also provide a graphic illustration of the receiver response to the various VOR signals.

To determine the minimum size counterpoise required for the DSDVOR System, the values of the error spreads are tabulated in Figure 49 (error spread versus counterpoise size). For system comparison, graphs were made of the two Doppler VOR and Conventional VOR systems. These graphs are presented in Figures 79, 80, and 81, for the SSDVOR, DSDVOR, and the Conventional VOR Systems, respectively. Referring to the graphic presentation of error spread of the SSDVOR System given in Figure 79, it can be noted that as the counterpoise diameter is decreased, the error spread becomes greater at an increasing rate for each step of counterpoise reduction. The DSDVOR System, presented in Figure 80, had a lower rate of increase of error spread as the counterpoise diameter was decreased with virtually no increase in the error spread between the diameters of 100 feet and 150 feet. The dispersion of the error spread curves is less for the DSDVOR than the SSDVOR System, with the less sophisticated receivers (I and J) contributing most to the dispersion of the curves. The dispersion of the curves for the balance of receivers is less than for the Conventional VOR System (Figure 81).

The smaller dispersion of the error curves for the DSDVOR System as compared to the SSDVOR System is further evidence of improved receiver compatibility provided by the DSDVOR System.

Based on the above statements, the counterpoise size for the DSDVOR System can be reduced to 100 feet in diameter and still provide improved receiver compatibility and less station error than the SSDVOR System with a 150-foot diameter counterpoise.

FACILITY: NAFEC DVOR#2
ORBIT: 5 nmi 1500 ft. MSL
DATE: 9/25/68
SIDEBAND EQUIP: WILCOX WITH HIGH LEVEL MODULATION
COUNTERPOISE DIAMETER: 150 ft.
FREQUENCY: 111.9 MHz

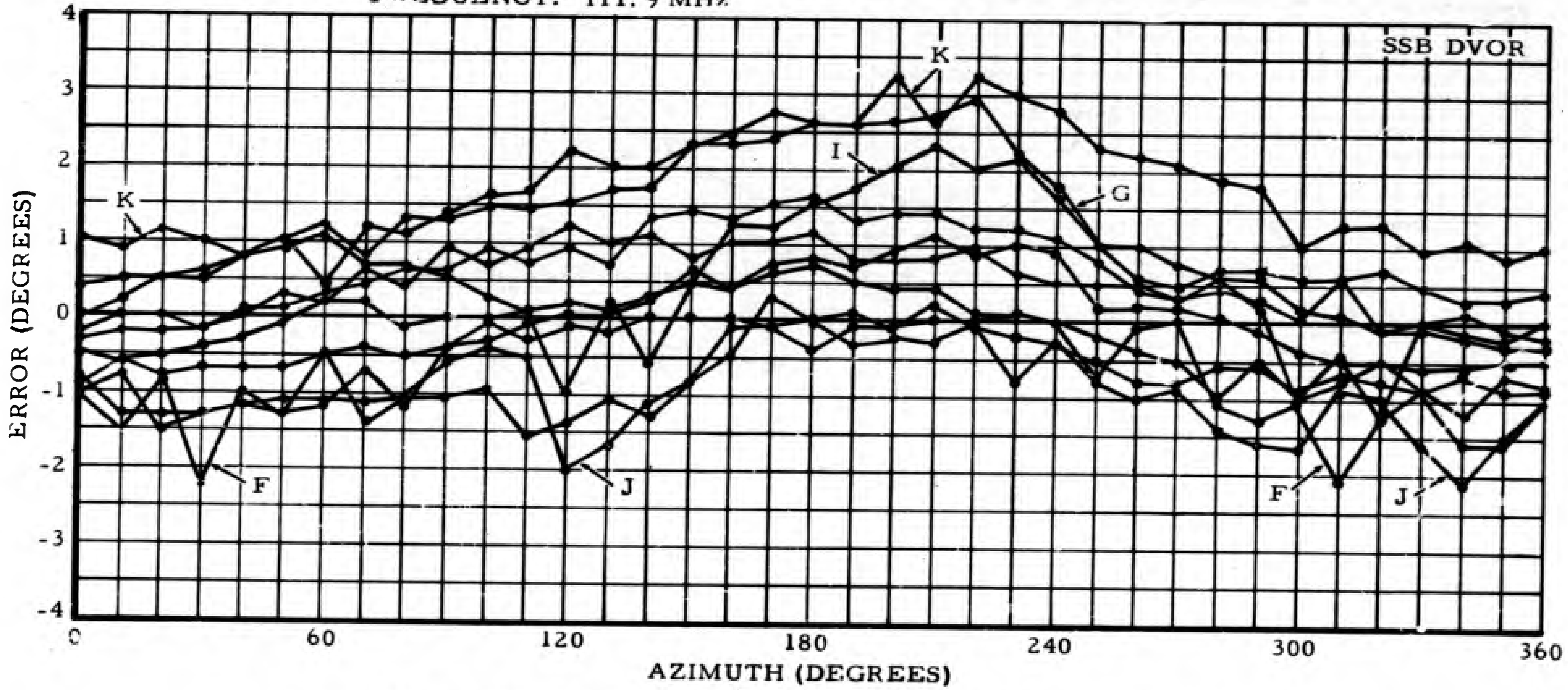


Figure 43. COMPOSITE INDICATED STATION ERROR FROM SSDVOR, 150-FOOT COUNTERPOISE

FACILITY: NAFEC DVOR#2
ORBIT: 5 nmi 1500 ft. MSL
DATE: 9/25/68
SIDEBAND EQUIP: WILCOX WITH HIGH LEVEL MODULATION
COUNTERPOISE DIAMETER: 150 ft.
FREQUENCY: 111.9 MHz

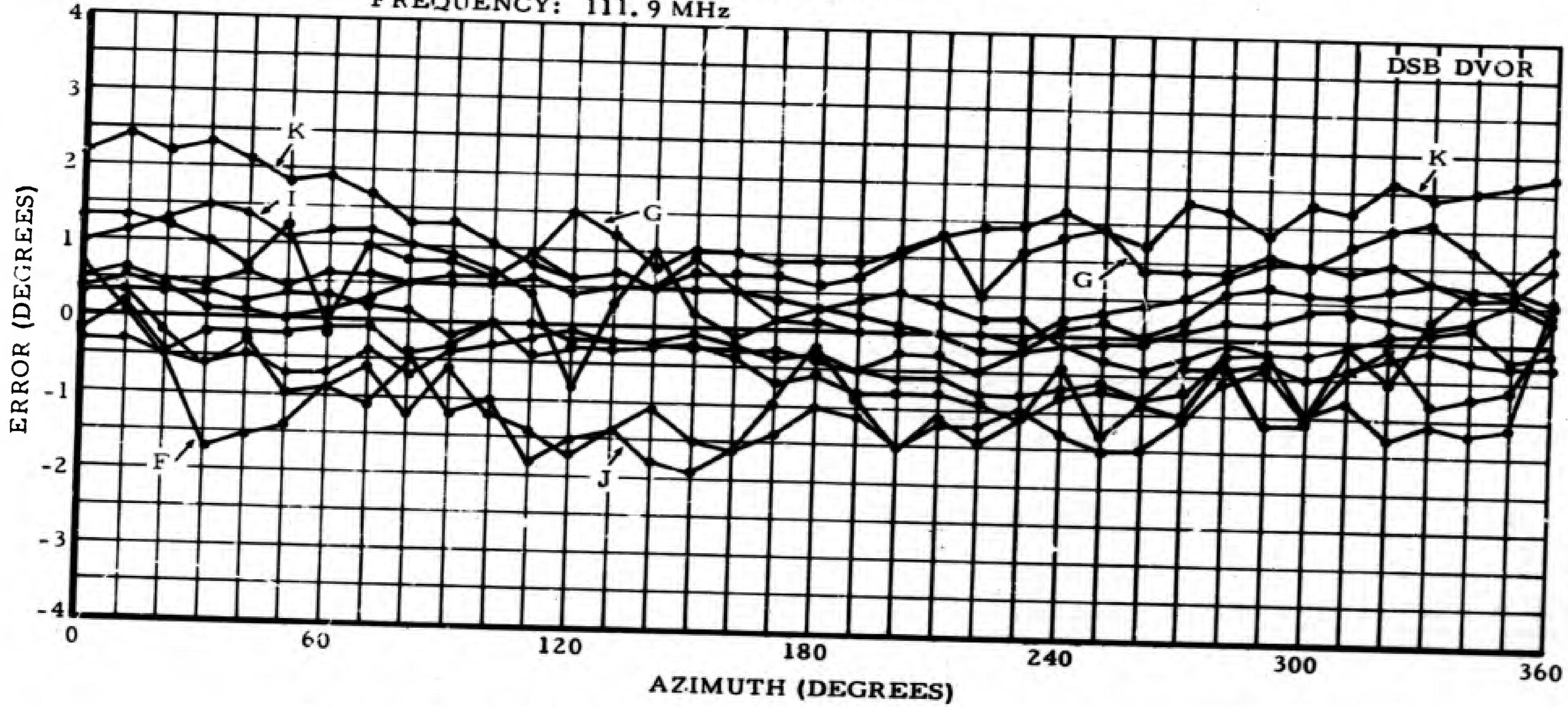


Figure 44. COMPOSITE INDICATED STATION ERROR WITH DSDVOR, 150-FOOT COUNTERPOISE

FACILITY: NAFEC DVOR#2
ORBIT: 5 nmi 1500 ft. MSL
DATE: 9/25/68
SIDEBAND EQUIP: WILCOX WITH HIGH LEVEL MODULATION
COUNTERPOISE DIAMETER: 150 ft.
FREQUENCY: 111.9 MHz

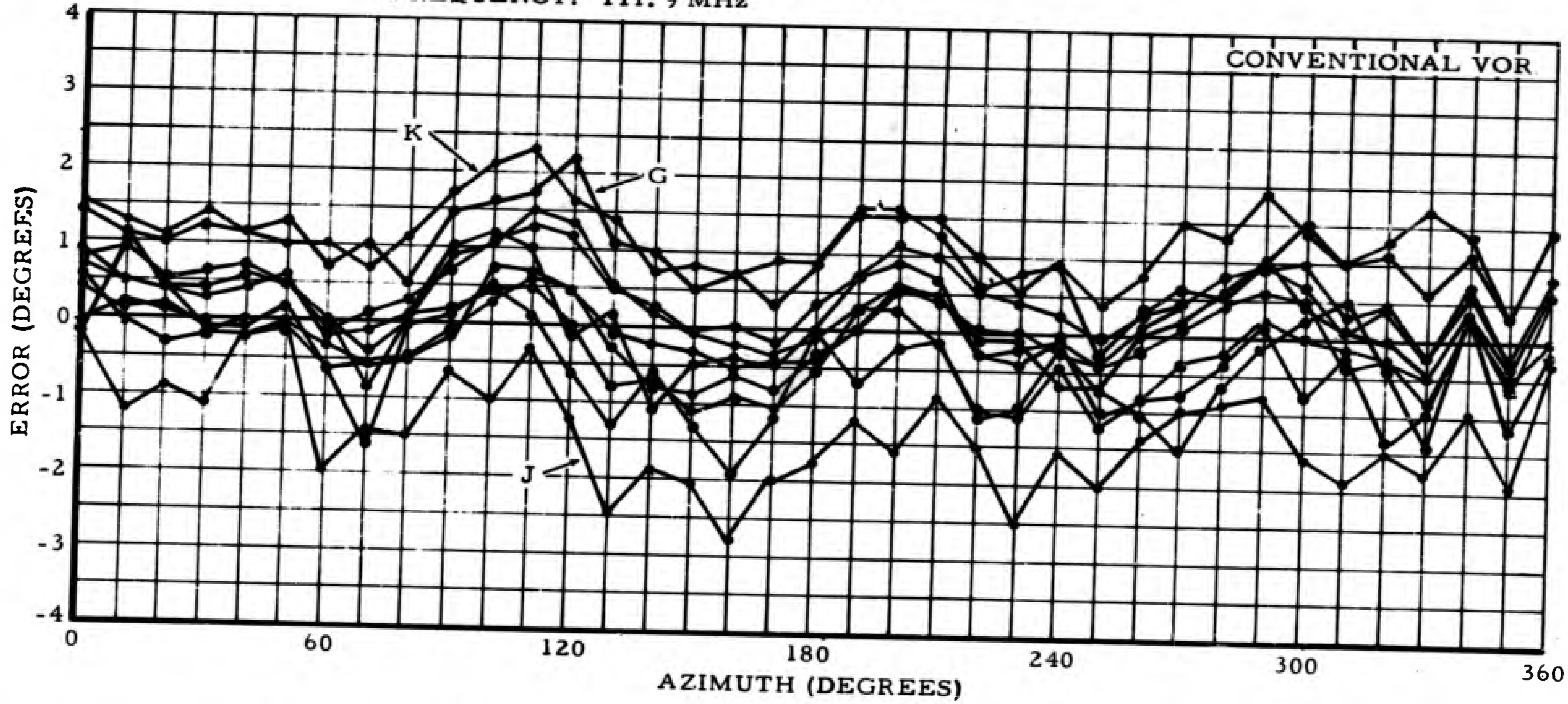


Figure 45. COMPOSITE INDICATED STATION ERROR WITH CONVENTIONAL VOR, 150-FOOT COUNTERPOISE

FACILITY: NAFEC DVOR#2
ORBIT: 5 nmi 1500 ft. MSL
DATE: 11/15/68
FREQUENCY: 111.9 MHz
SIDEBAND EQUIP: WILCOX WITH HIGH LEVEL MODULATION
COUNTERPOISE DIAMETER: 120 ft.

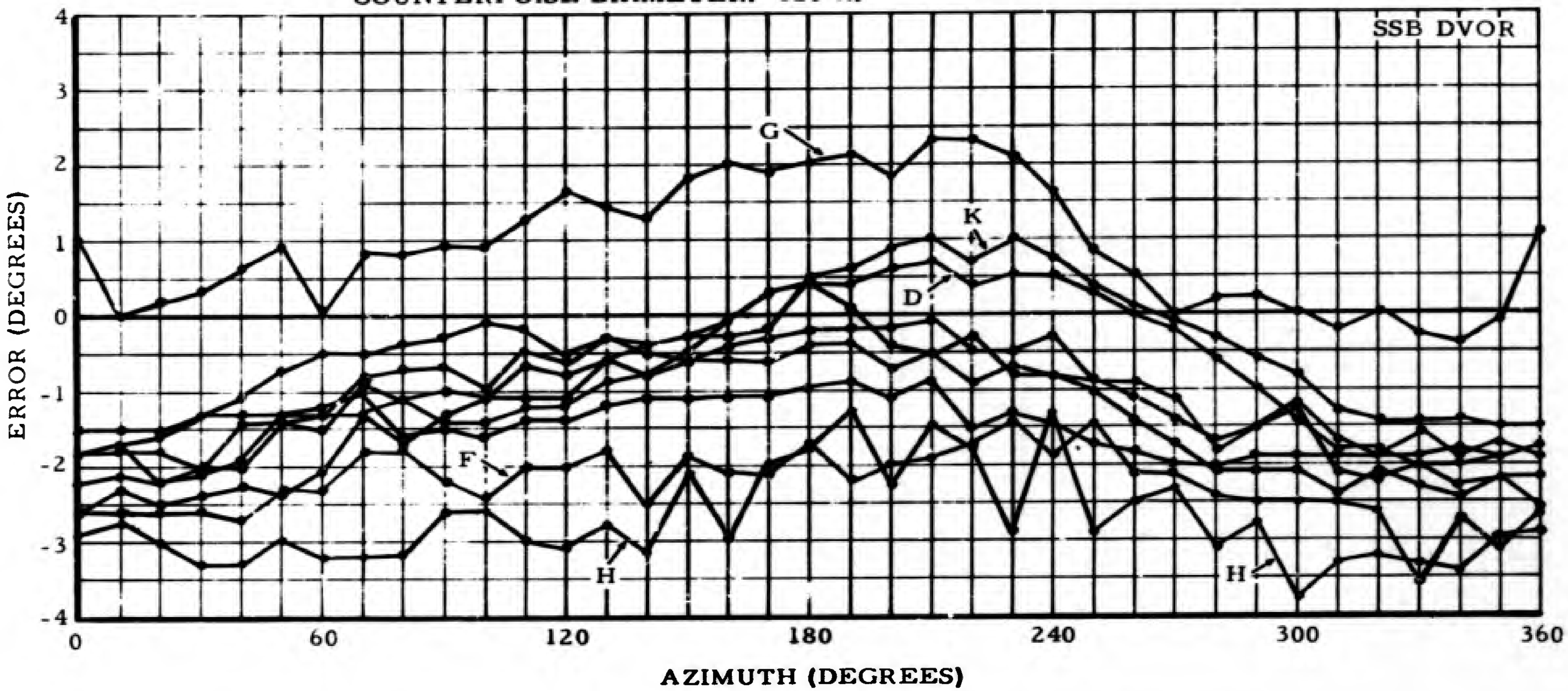


Figure 46. COMPOSITE INDICATED STATION ERROR WITH SSDVOR, 120-FOOT COUNTERPOISE

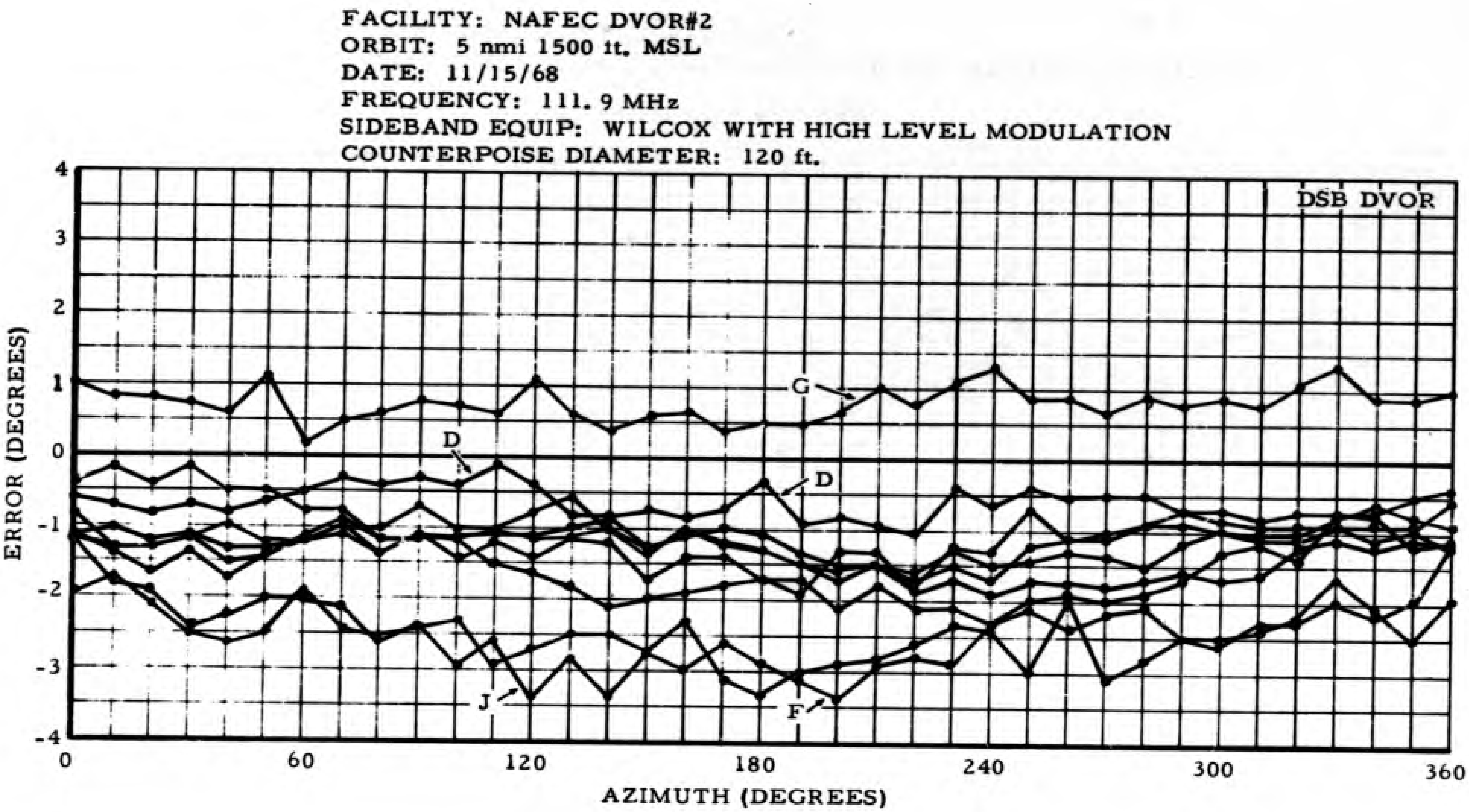


Figure 47. COMPOSITE INDICATED STATION ERROR WITH DSDVOR, 120-FOOT COUNTERPOISE

FACILITY: NAFEC DVOR#2
ORBIT: 5 nmi 1500 ft. MSL
DATE: 11/15/68
FREQUENCY: 111.9 MHz
SIDEBAND EQUIP: WILCOX WITH HIGH LEVEL MODULATION
COUNTERPOISE DIAMETER: 120 ft.

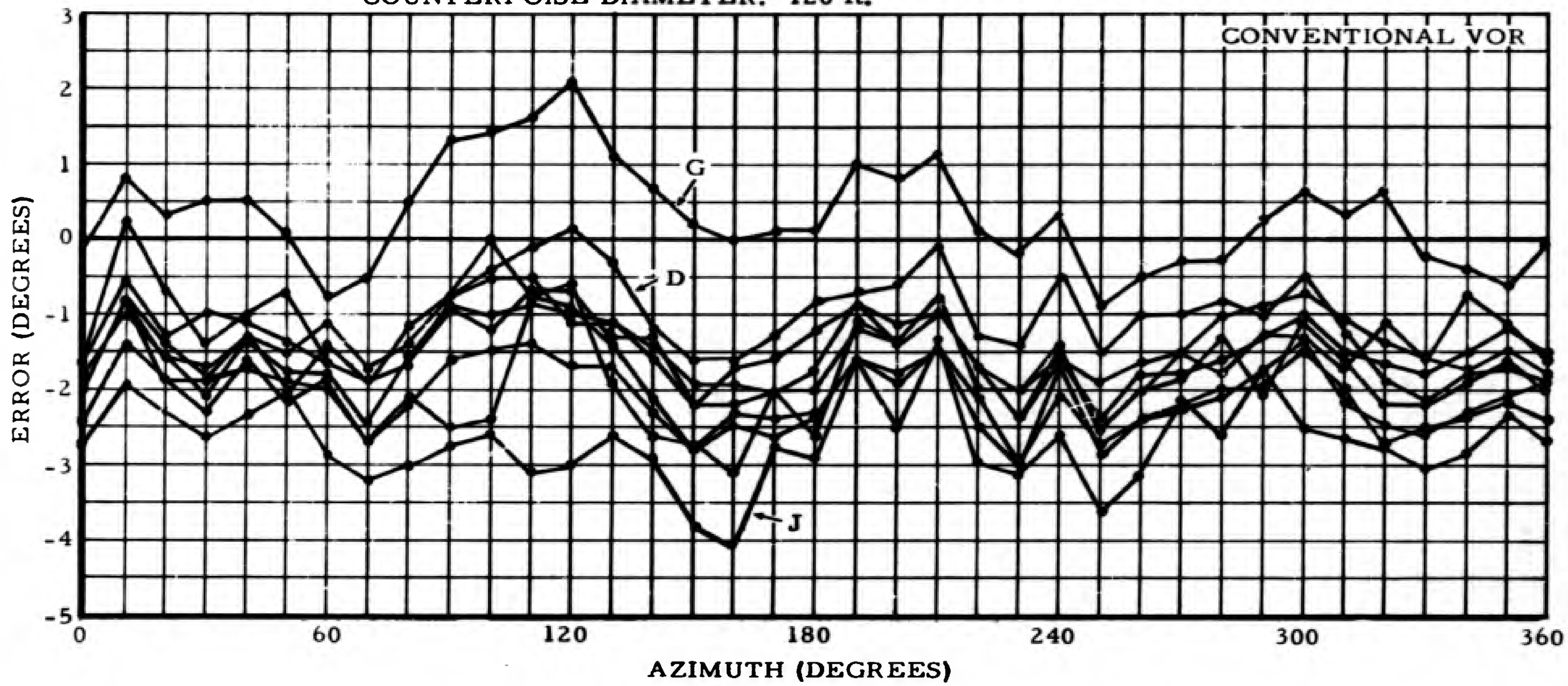


Figure 48. COMPOSITE INDICATED STATION ERROR WITH CONVENTIONAL VOR, 120-FOOT COUNTERPOISE

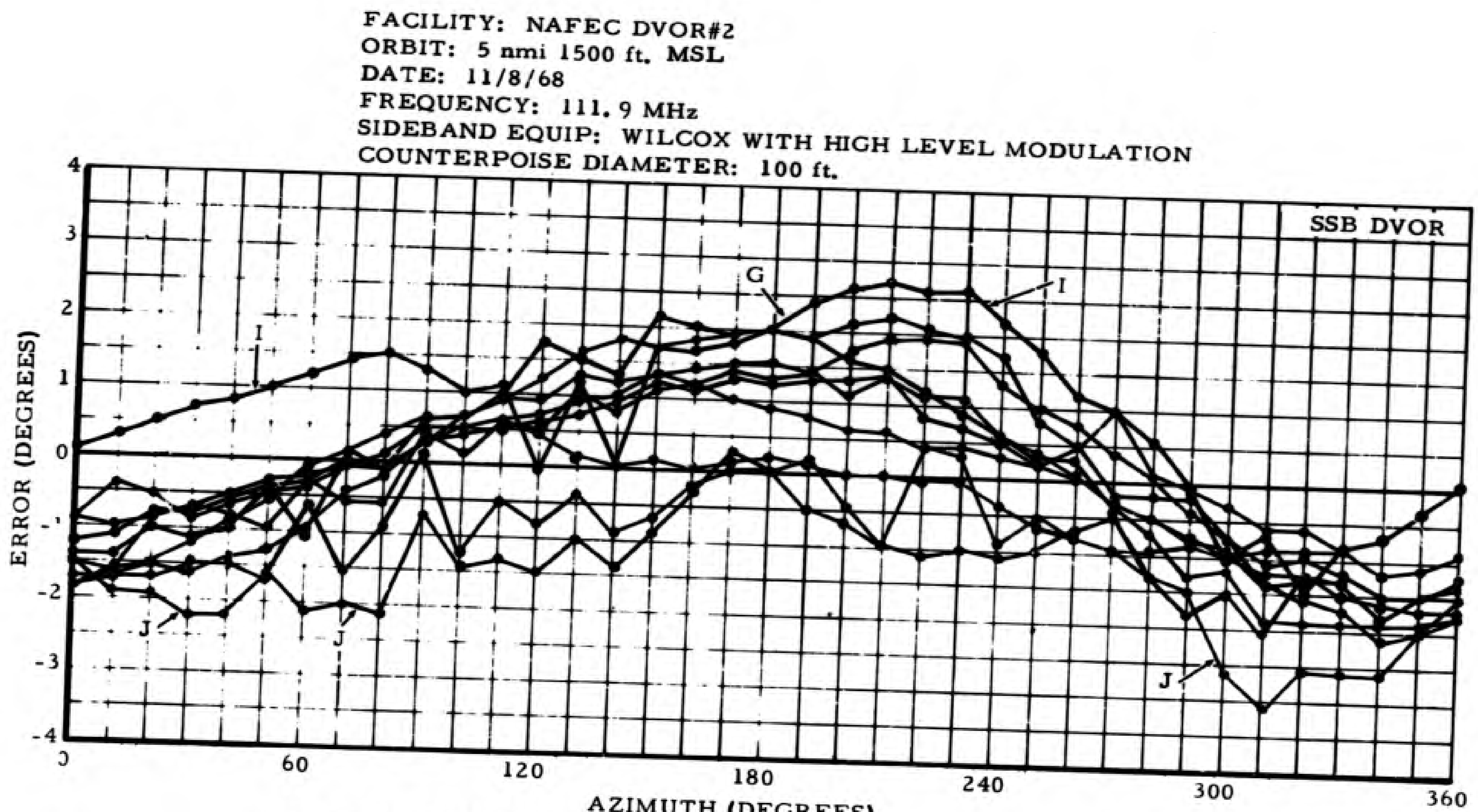


Figure 49. COMPOSITE INDICATED STATION ERROR WITH SSDVOR, 100-FOOT COUNTERPOISE

FACILITY: NAFEC DVOR#2
ORBIT: 5 nmi 1500 ft. MSL
DATE: 11/8/68
FREQUENCY: 111.9 MHz
SIDEBAND EQUIP: WILCOX WITH HIGH LEVEL MODULATION
COUNTERPOISE DIAMETER: 100 ft.

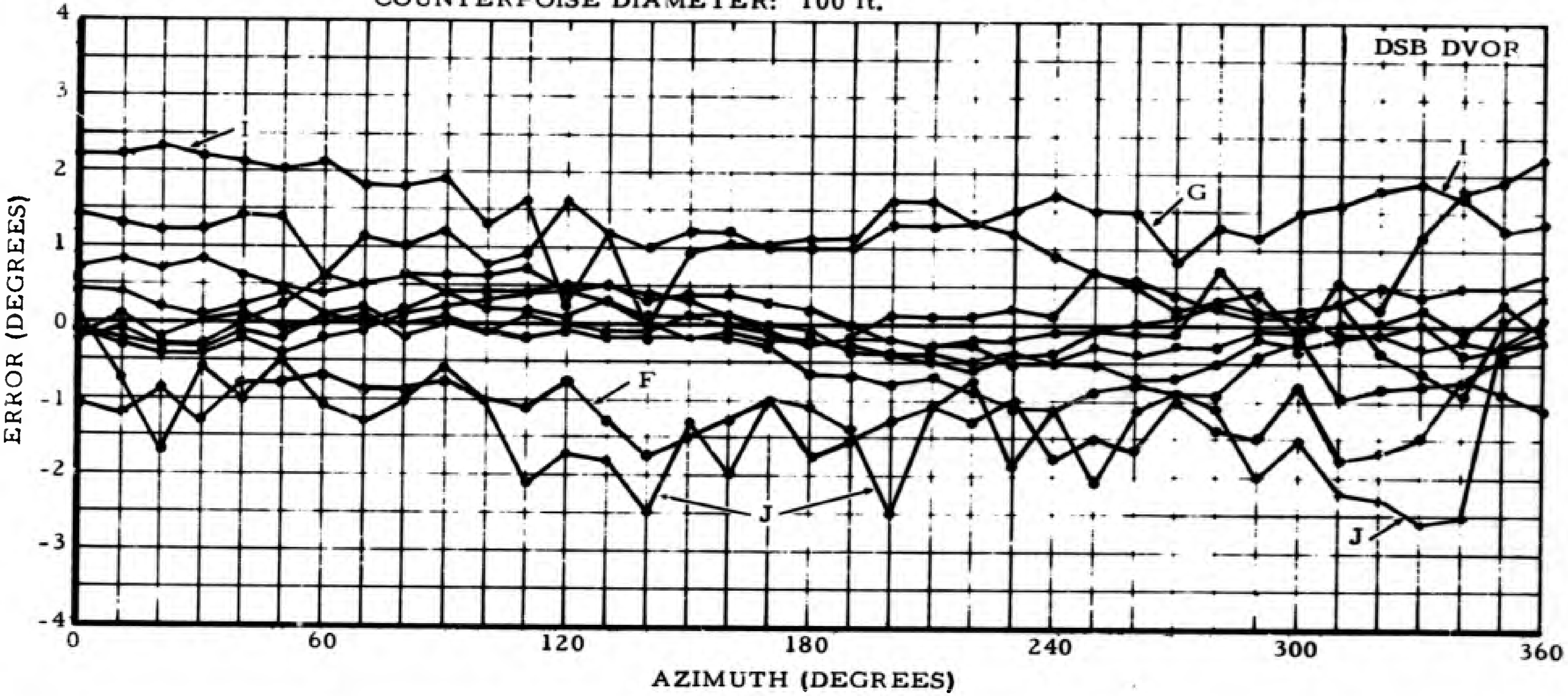


Figure 50. COMPOSITE INDICATED STATION ERROR WITH DSDVOR, 100-FOOT COUNTERPOISE

FACILITY: NAFEC DVOR#2
ORBIT: 5 nmi 1500 ft. MSL
DATE: 11/8/68
FREQUENCY: 111.9 MHz
SIDEBAND EQUIP: WILCOX WITH HIGH LEVEL MODULATION
COUNTERPOISE DIAMETER: 100 ft.

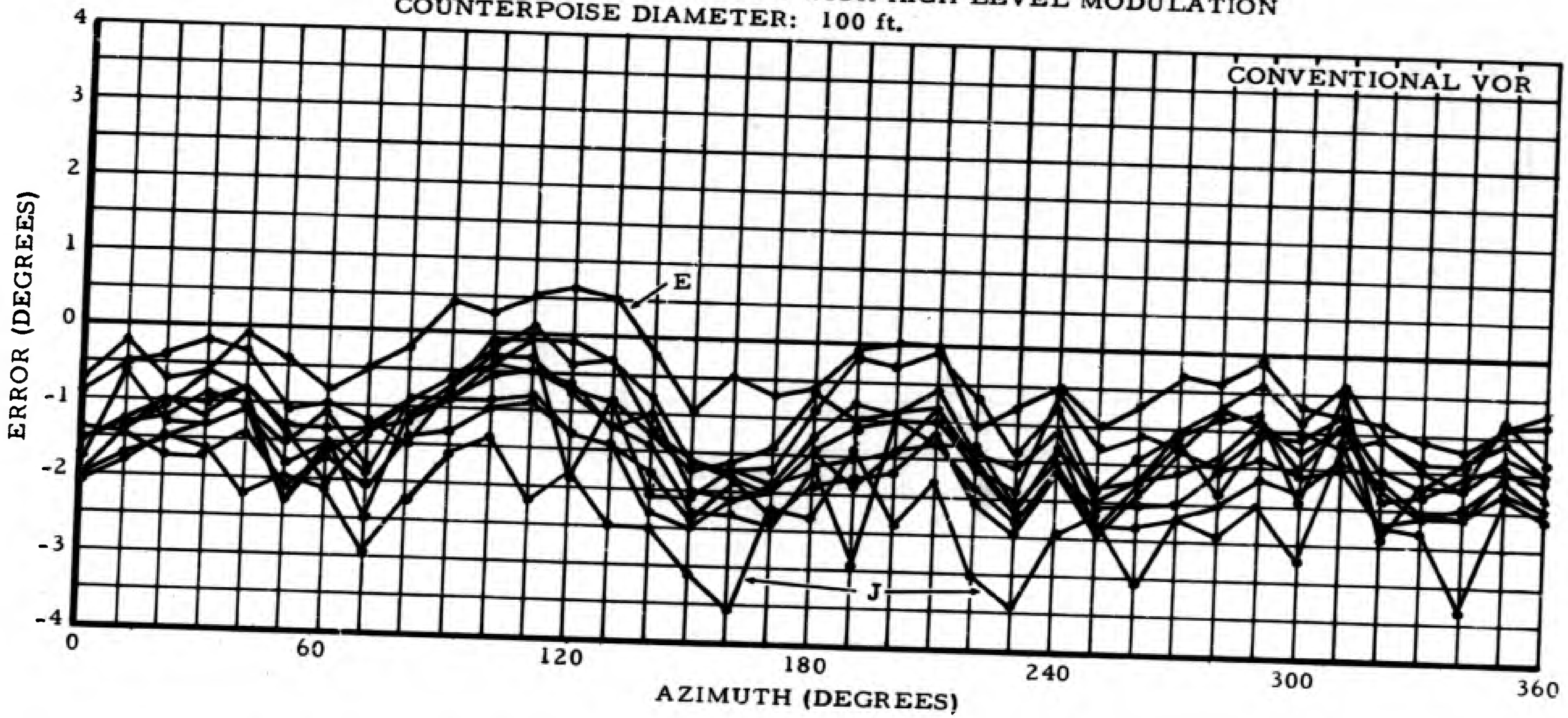


Figure 51. COMPOSITE INDICATED STATION ERROR WITH CONVENTIONAL VOR, 100-FOOT COUNTERPOISE

FACILITY: NAFEC DVOR#2
ORBIT: 5 nmi 1500 ft. MSL
DATE: 11/15/68
FREQUENCY: 111.9 MHz
SIDEBAND EQUIP: WILCOX WITH HIGH LEVEL MODULATION
COUNTERPOISE DIAMETER: 80 ft.

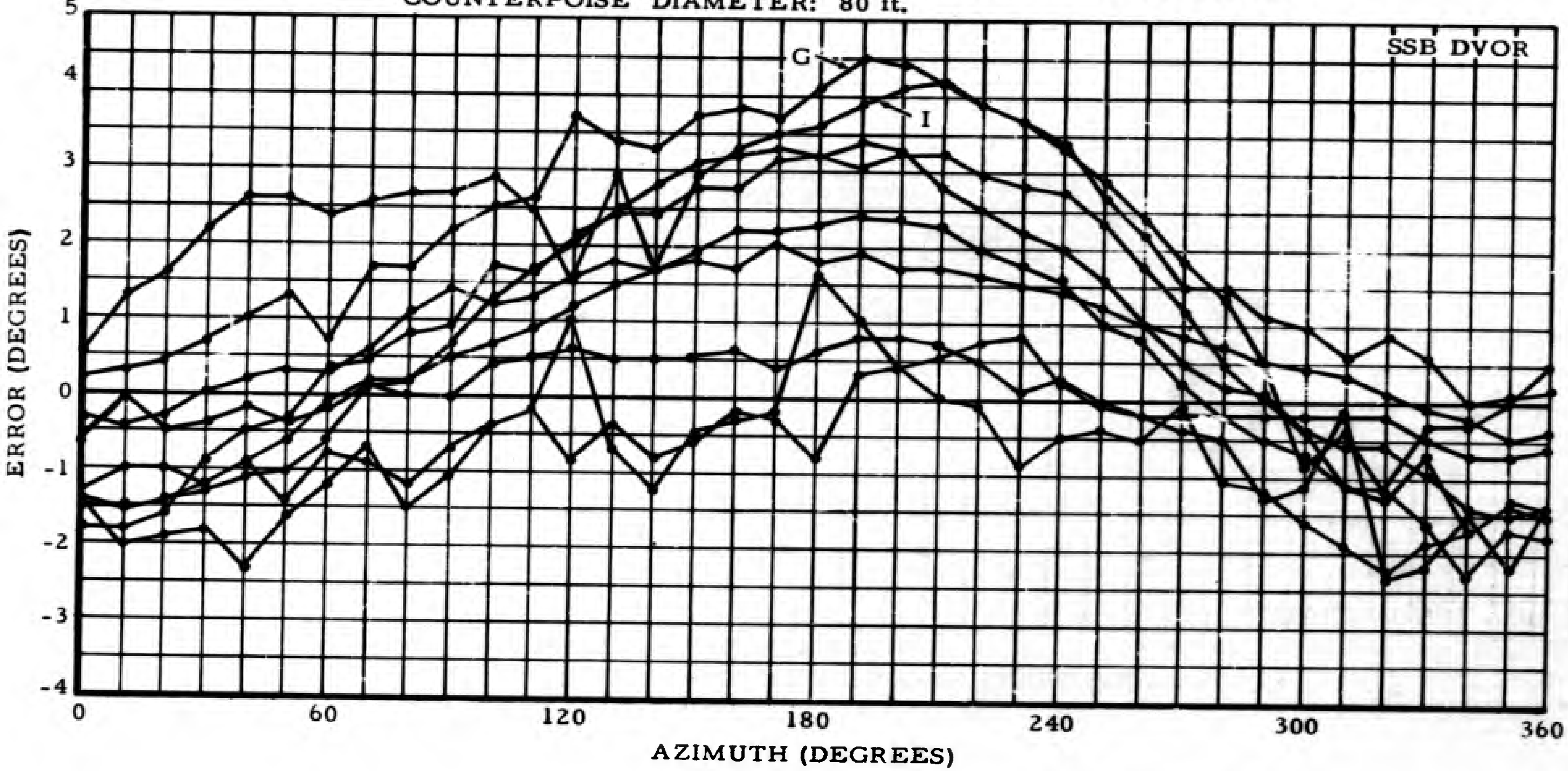


Figure 52. COMPOSITE INDICATED STATION ERROR WITH SSDVOR, 80-FOOT COUNTERPOISE

FACILITY: NAFEC DVOR#2
ORBIT: 5 nmi 1500 ft. MSL
DATE: 11/15/68
FREQUENCY: 111. 9 MHz
SIDEBAND EQUIP: WILCOX WITH HIGH LEVEL MODULATION
COUNTERPOISE DIAMETER: 80 ft.

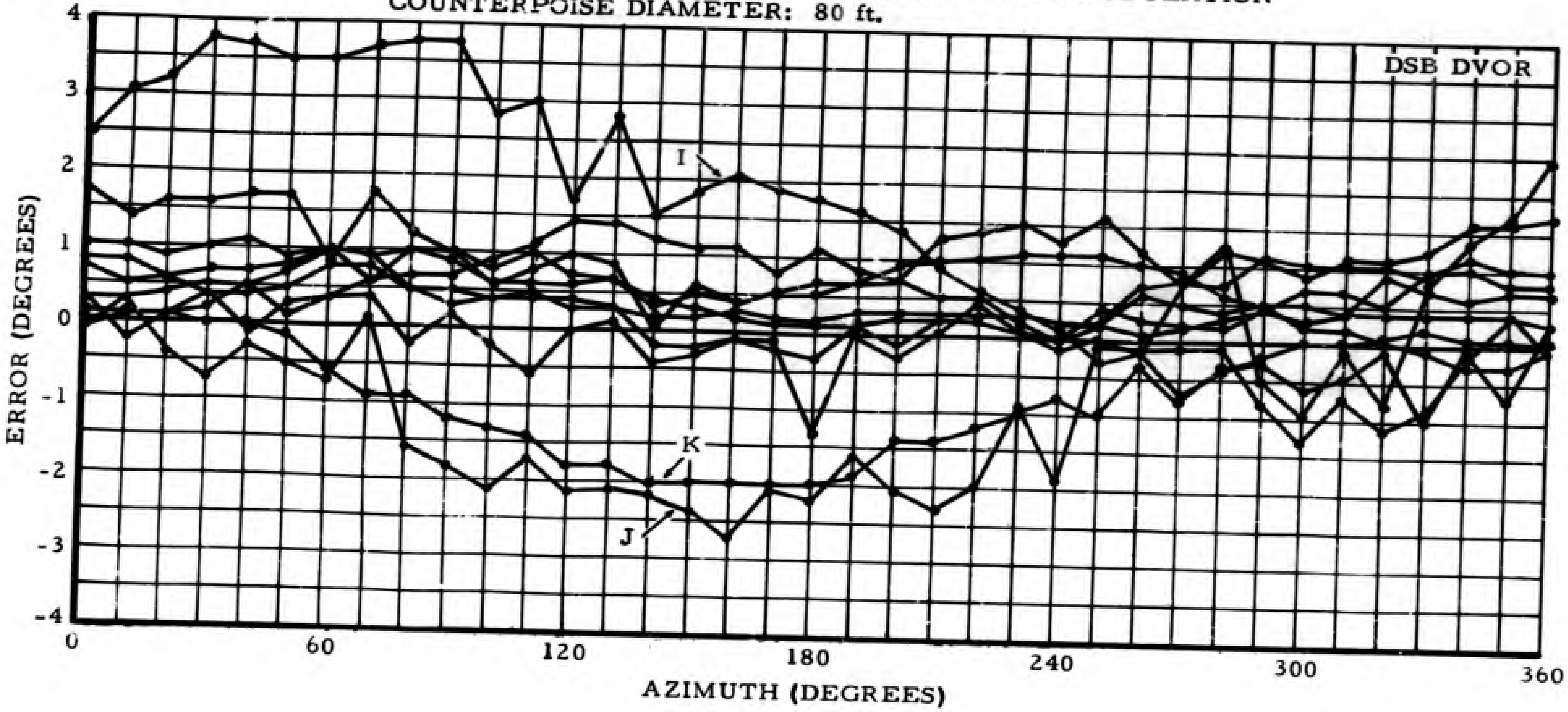


Figure 53. COMPOSITE INDICATED STATION ERROR WITH DSDVOR, 80-FOOT COUNTERPOISE

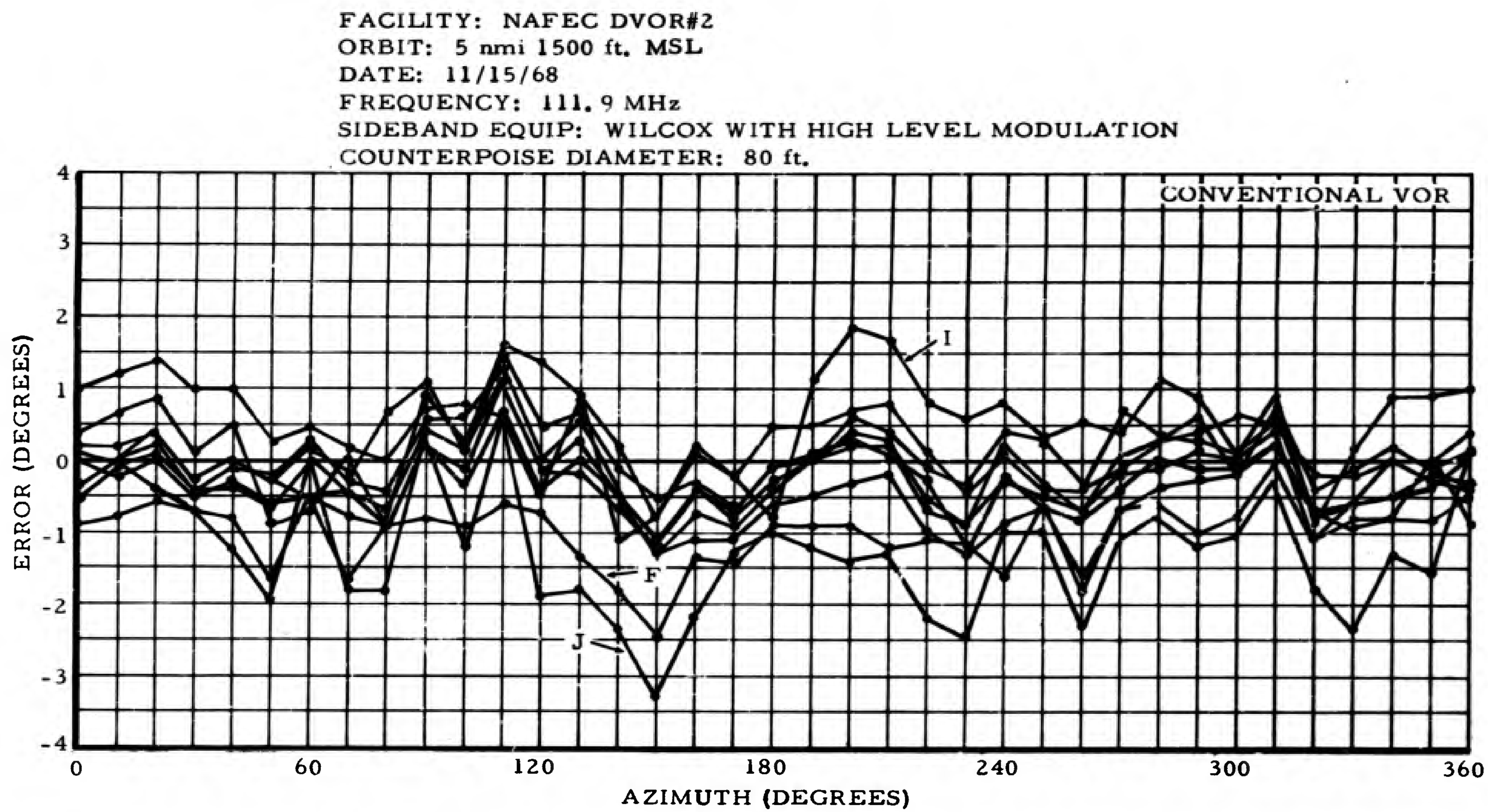


Figure 54. COMPOSITE INDICATED STATION ERROR WITH CONVENTIONAL VOR, 80-FOOT COUNTERPOISE

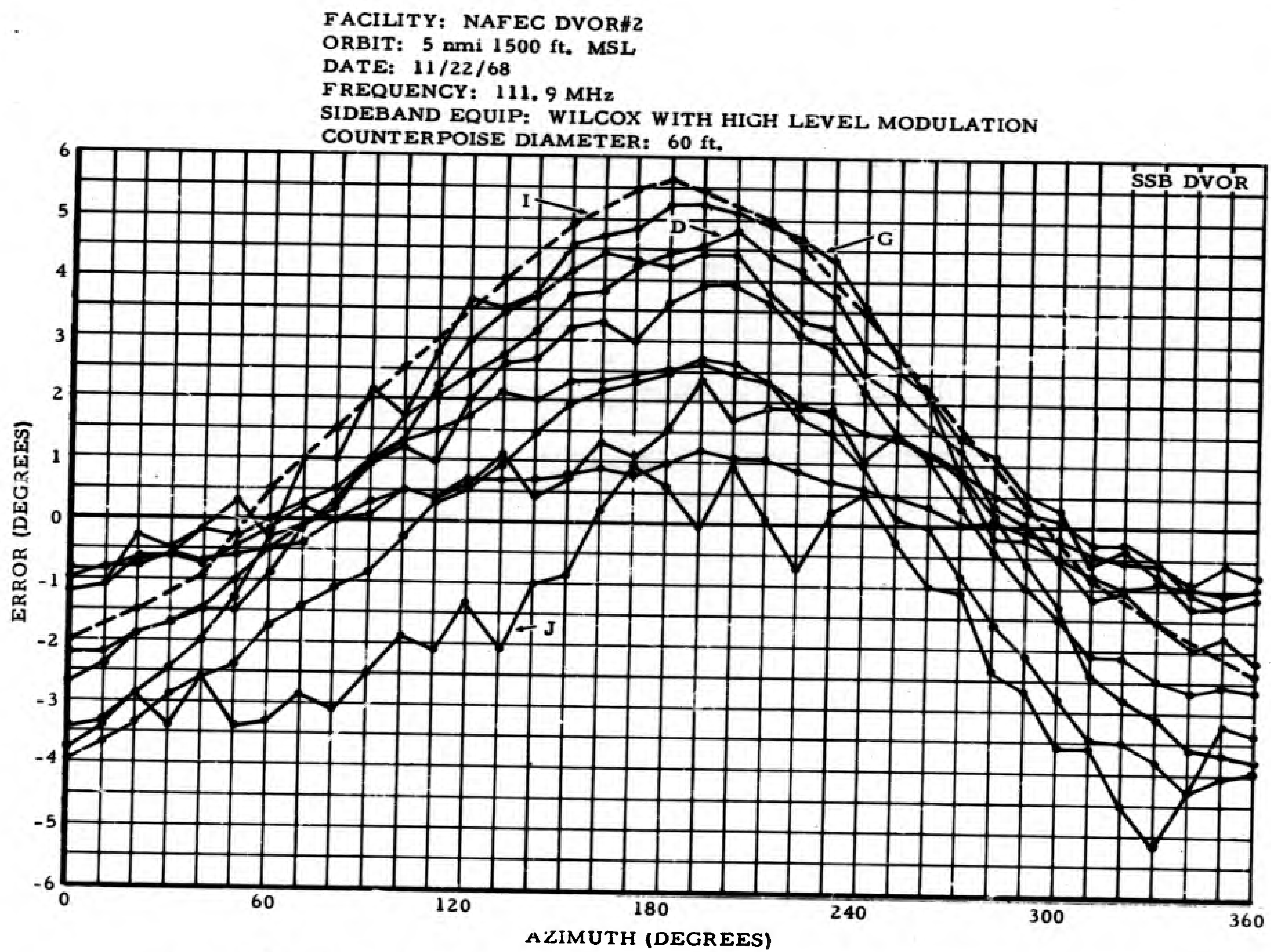


Figure 55. COMPOSITE INDICATED STATION ERROR WITH SSDVOR, 60-FOOT COUNTERPOISE

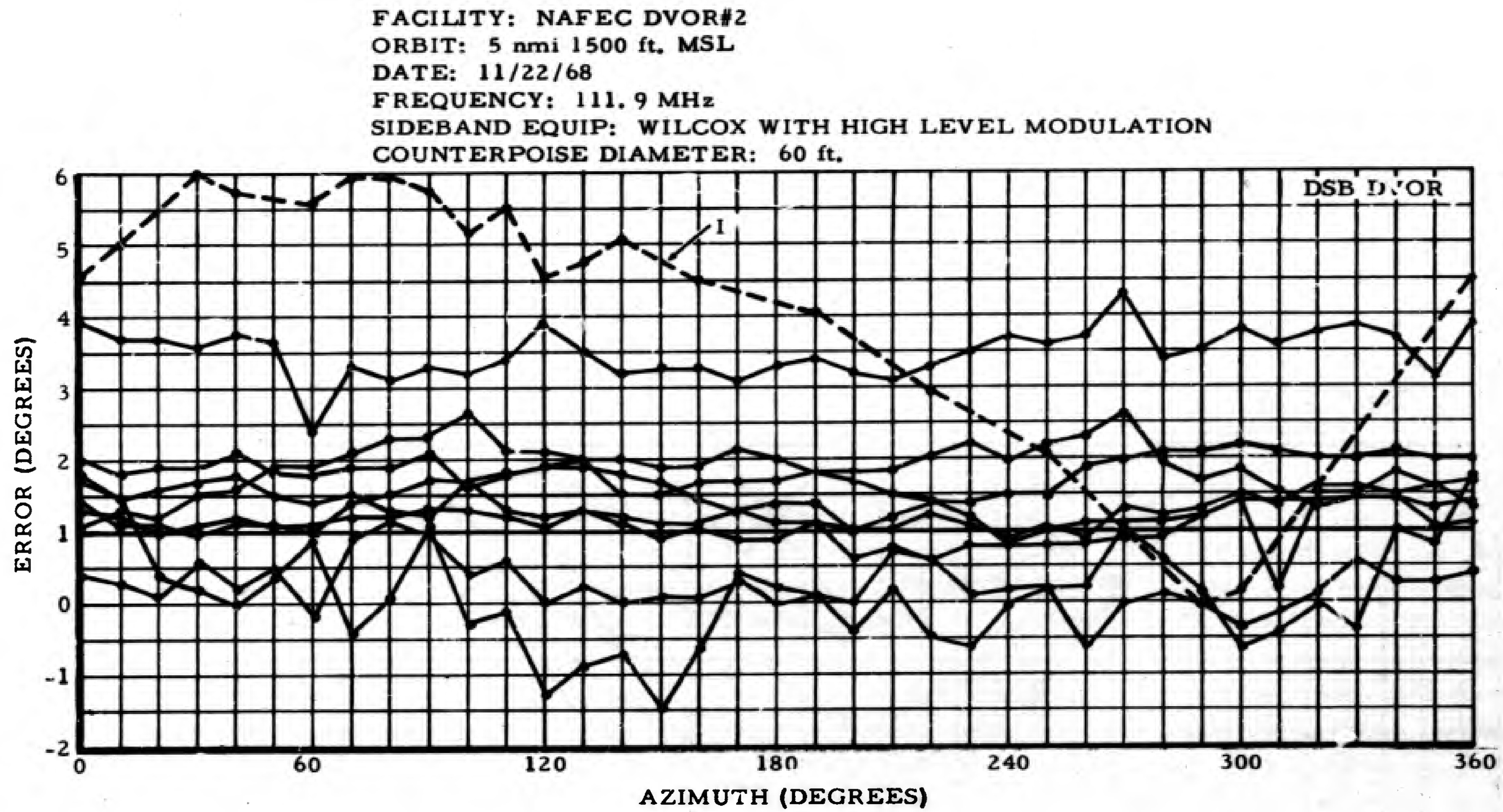


Figure 56. COMPOSITE INDICATED STATION ERROR WITH DSDVOR, 60-FOOT COUNTERPOISE

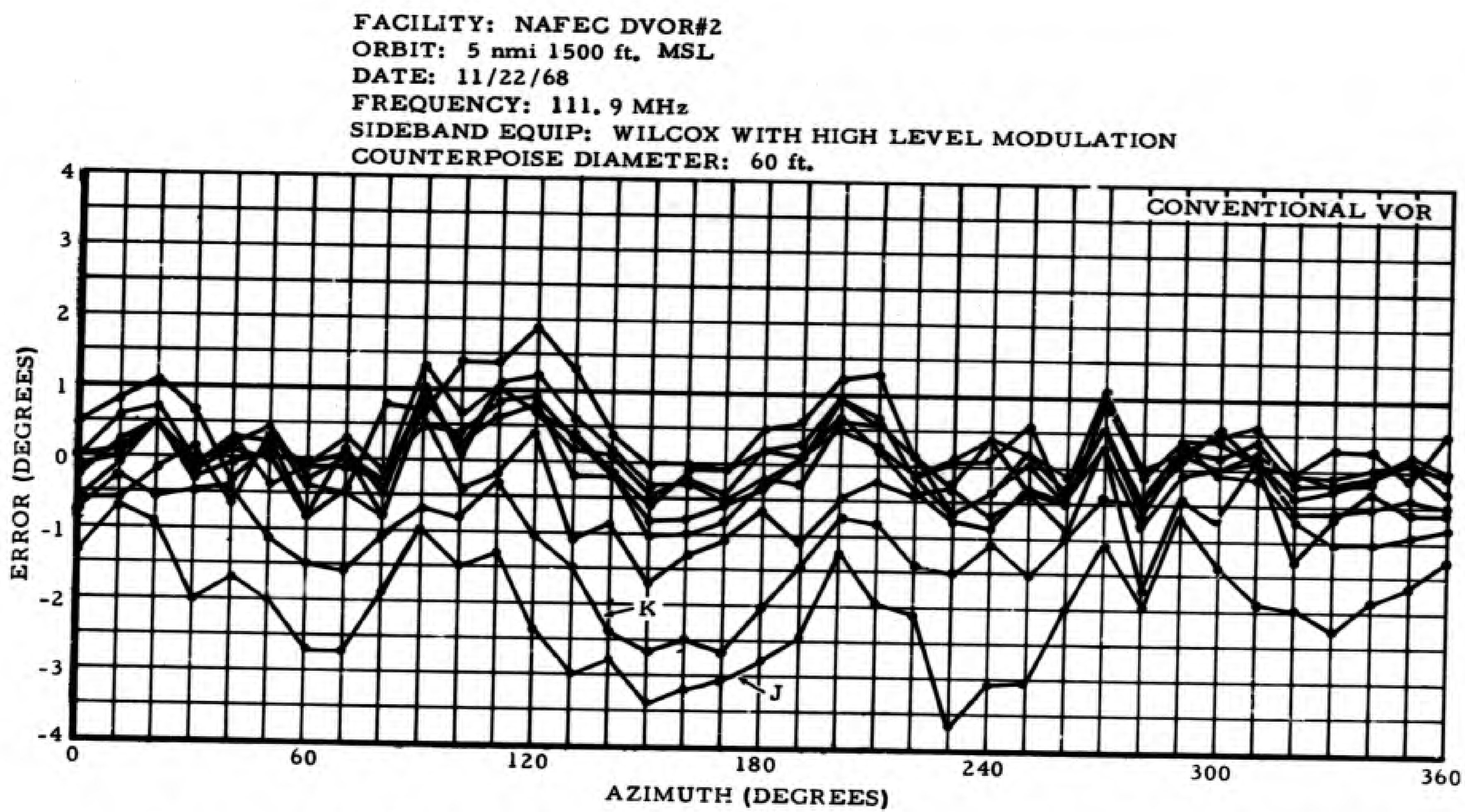


Figure 57. COMPOSITE INDICATED STATION ERROR WITH CONVENTIONAL VOR, 60-FOOT COUNTERPOISE

RECEIVER TOTAL ERROR SPREAD

Ctpse Size	Date	SYSTEM	A MN-85FA		B 51R3		C RA-21A		F KX-160		I DR-560		G ARC-15G		D 51RV1		J MARK-12		H 51X2B		K 806A		E 805A	
		Orbit	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
150'	09/25/68	Single Sideband	2.0	2.3	1.8	1.8	1.1	1.1	2.3	2.2	3.5	3.6	2.6	2.4	1.7	1.8	2.4	2.0	1.5	1.7	2.4	2.6		
	09/25/68	Double Sideband	0.7	1.0	1.0	1.0	1.3	1.2	2.4	2.4	2.6	2.8	1.8	1.6	1.0	1.3	2.2	2.1	1.1	1.3	1.9	2.0		
	09/25/68	Conventional VOR	1.5	2.0	1.6	1.5	1.7	1.6	3.0	2.2	2.6	2.4	2.5	2.5	1.7	1.9	2.7	3.1	1.9	2.0	2.1	2.0		
120'	10/31/68	Single Sideband	2.8	3.0	2.0	2.2	1.2	1.3	1.6	2.2	4.4	4.1	3.2	2.7	2.7	2.7	2.8	2.7	2.5	2.5	2.7	2.5		
	10/31/68	Double Sideband	1.1	1.1	1.1	1.0	1.3	1.4	1.3	1.7	No data		2.0	1.1	1.1	0.9	2.0	2.2	1.2	1.1	2.0	1.9		
	10/31/68	Conventional VOR	2.1	1.7	2.1	1.6	2.1	1.9	2.2	3.3	3.4	3.1	4.0	3.0	2.3	2.2	2.3	2.8	2.7	1.9	2.0	2.2		
100'	10/08/68	Single Sideband	3.8	3.8	3.0	3.2	1.4	1.8	2.4	2.5	4.4	4.2	4.1	3.7	4.0	4.0	3.5	3.4	2.6	2.5	RECEIVER FAILED	RECEIVER FAILED		
	06/16/69	Repeat	3.0	3.1	2.0	2.2	1.8	1.7	2.5	2.3	5.2	4.9	2.9	3.3	3.9	3.9	3.6	-	2.2	2.4			3.3	3.3
	10/08/68	Double Sideband	-	1.2	-	0.8	-	1.2	-	1.1	-	2.9	-	1.3	-	1.0	-	2.7	-	1.4				
	06/16/69	Repeat	0.9	1.0	1.3	1.1	1.5	1.7	1.5	1.8	2.0	1.8	1.6	1.7	1.2	0.9	2.3	2.3	1.9	1.4			1.6	1.1
	11/08/68	Conventional VOR	1.5	2.0	1.7	1.6	2.7	2.1	2.8	2.4	2.3	2.3	2.9	2.2	2.3	2.1	2.7	2.5	2.7	2.3				
	06/16/69	Repeat	1.8	1.7	1.7	1.7	2.3	1.9	2.2	2.4	2.5	3.5	2.5	2.7	1.9	1.9	-	2.2	2.1	2.2			1.9	1.8
80'	11/15/68	Single Sideband	4.9	5.0	4.1	4.1	1.5	1.6	3.1	2.5	5.4	5.1	4.5	4.8	5.5	5.9	3.9	4.4	2.5	2.4				
	11/15/68	Double Sideband	1.3	1.2	0.7	0.7	1.6	1.6	1.7	2.0	4.8	4.0	1.9	2.2	1.6	1.2	3.3	3.5	1.2	1.2				
	11/15/68	Conventional VOR	2.3	2.1	2.3	1.9	2.3	2.0	2.5	2.1	2.9	3.1	2.5	2.4	2.6	2.6	3.8	2.9	2.4	2.5				
60'	11/22/68	Single Sideband	6.7	6.6	6.9	6.6	2.1	2.1	3.4	3.4	-	-	6.5	6.5	9.1	8.6	4.7	6.1	3.8	3.9				
	03/28/69	Repeat	3.8	4.0	3.1	3.3	2.0	2.0	3.1	3.0	7.2	7.2	5.4	5.6	8.1	7.6	5.5	6.3	4.1	3.7			7.0	7.0
	11/22/68	Double Sideband	1.3	1.4	1.0	0.7	1.5	1.3	1.8	1.7	-	-	2.7	2.7	2.1	1.4	3.9	3.2	1.3	1.0				
		Repeat	1.2	1.3	1.5	1.6	1.6	1.8	2.3	2.2	1.7	2.3	1.4	1.7	1.4	1.1	2.7	2.7	1.6	1.5			2.2	1.0
	11/22/68	Conventional VOR	1.9	1.9	1.9	1.6	2.1	1.8	2.8	2.3	-	-	3.0	2.7	2.5	2.0	3.4	3.0	2.0	1.9				
		Repeat	2.5	2.4	2.8	2.5	2.5	2.4	2.9	2.8	2.9	3.3	3.3	3.7	2.7	2.4	3.9	2.4	2.4	2.6			3.3	2.4

Figure 58. MAGNITUDE OF RECEIVER ERROR SPREAD (IN AZIMUTH DEGREES) FOR VARIOUS COUNTERPOISE DIAMETERS

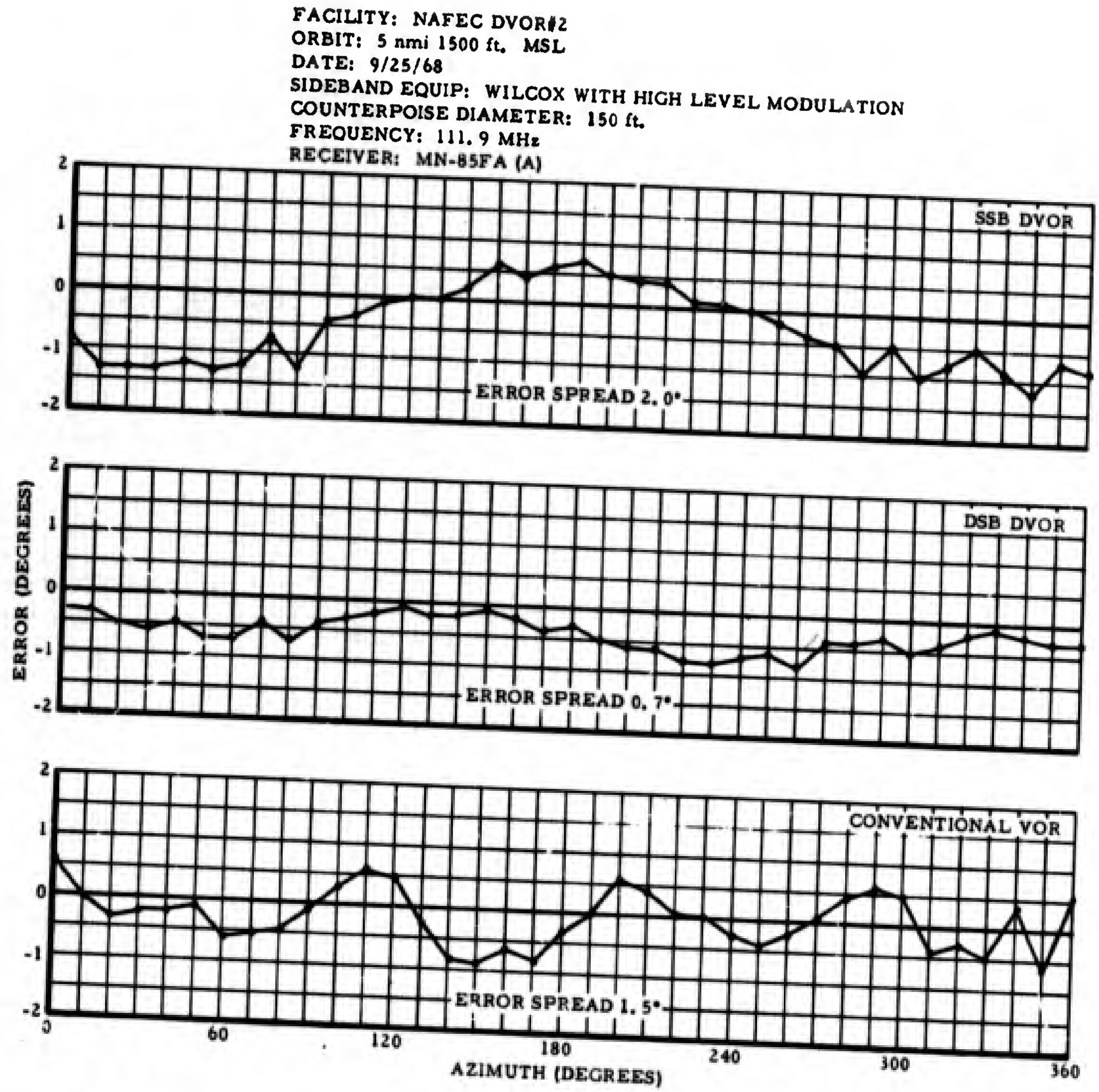


Figure 59. INDICATED STATION ERROR WITH TYPE MN-85FA (A) RECEIVER, 150-FOOT COUNTERPOISE

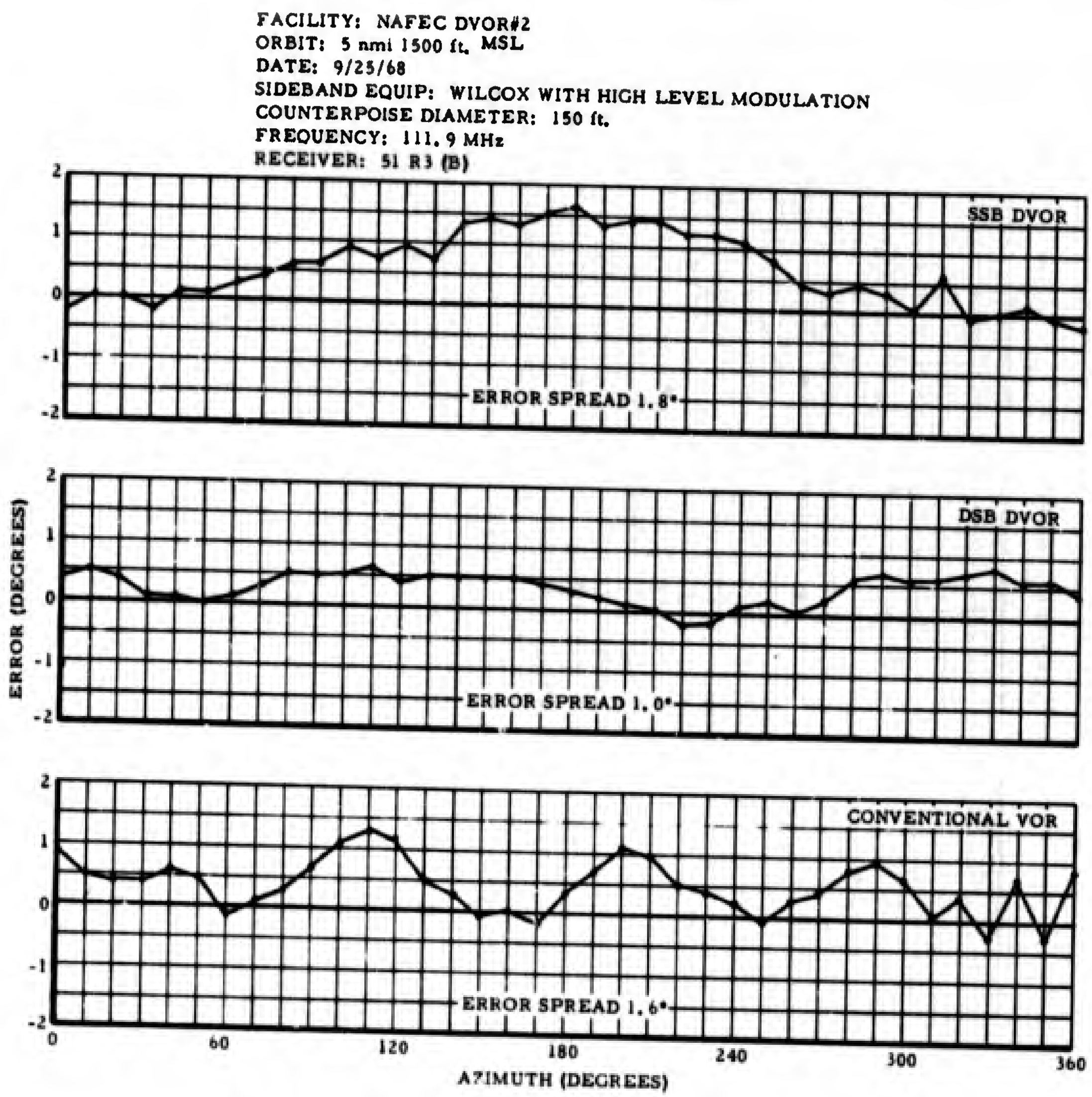


Figure 60. INDICATED STATION ERROR WITH TYPE 51R3 (B) RECEIVER, 150-FOOT COUNTERPOISE

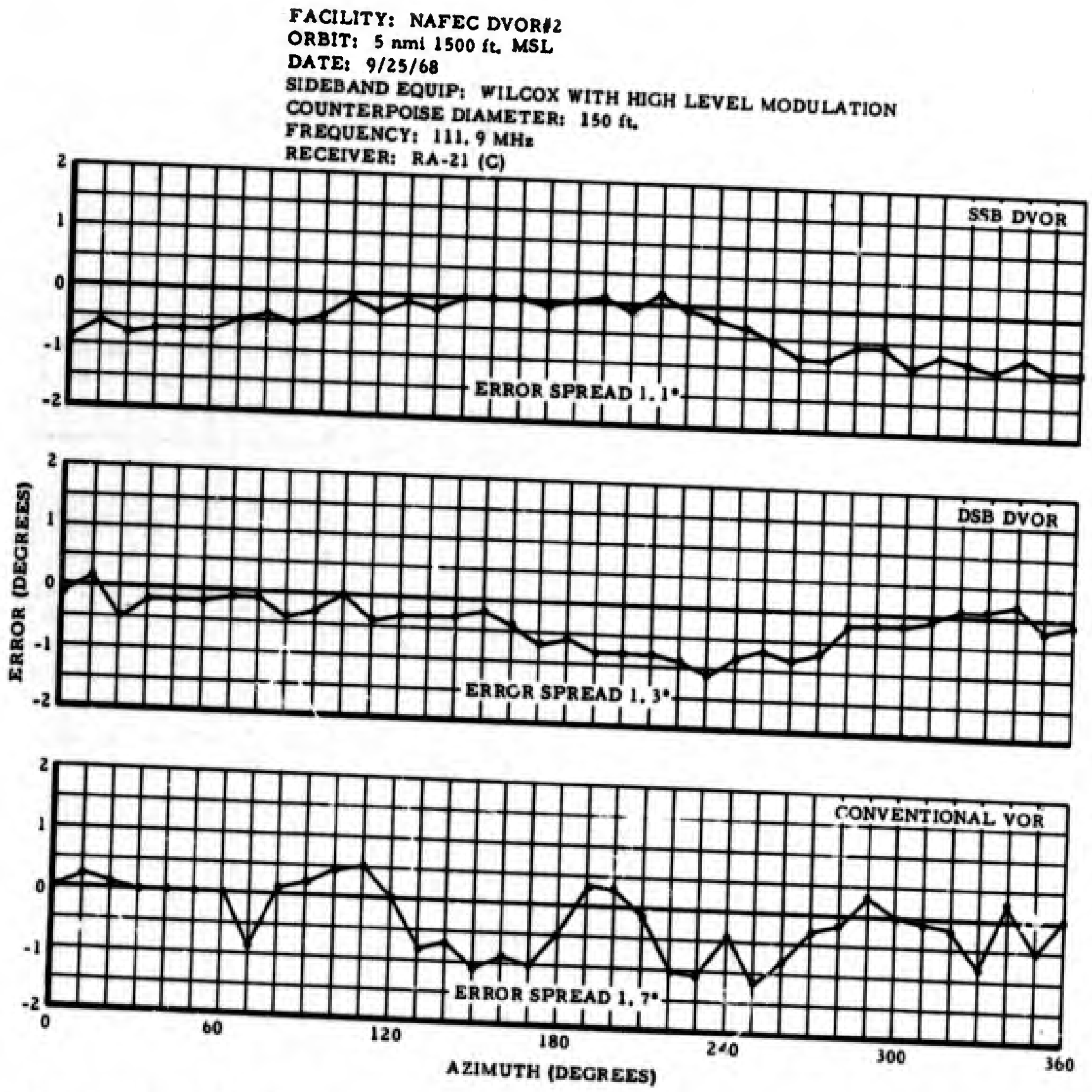


Figure 61. INDICATED STATION ERROR WITH TYPE RA-21A (C) RECEIVER, 150-FOOT COUNTERPOISE

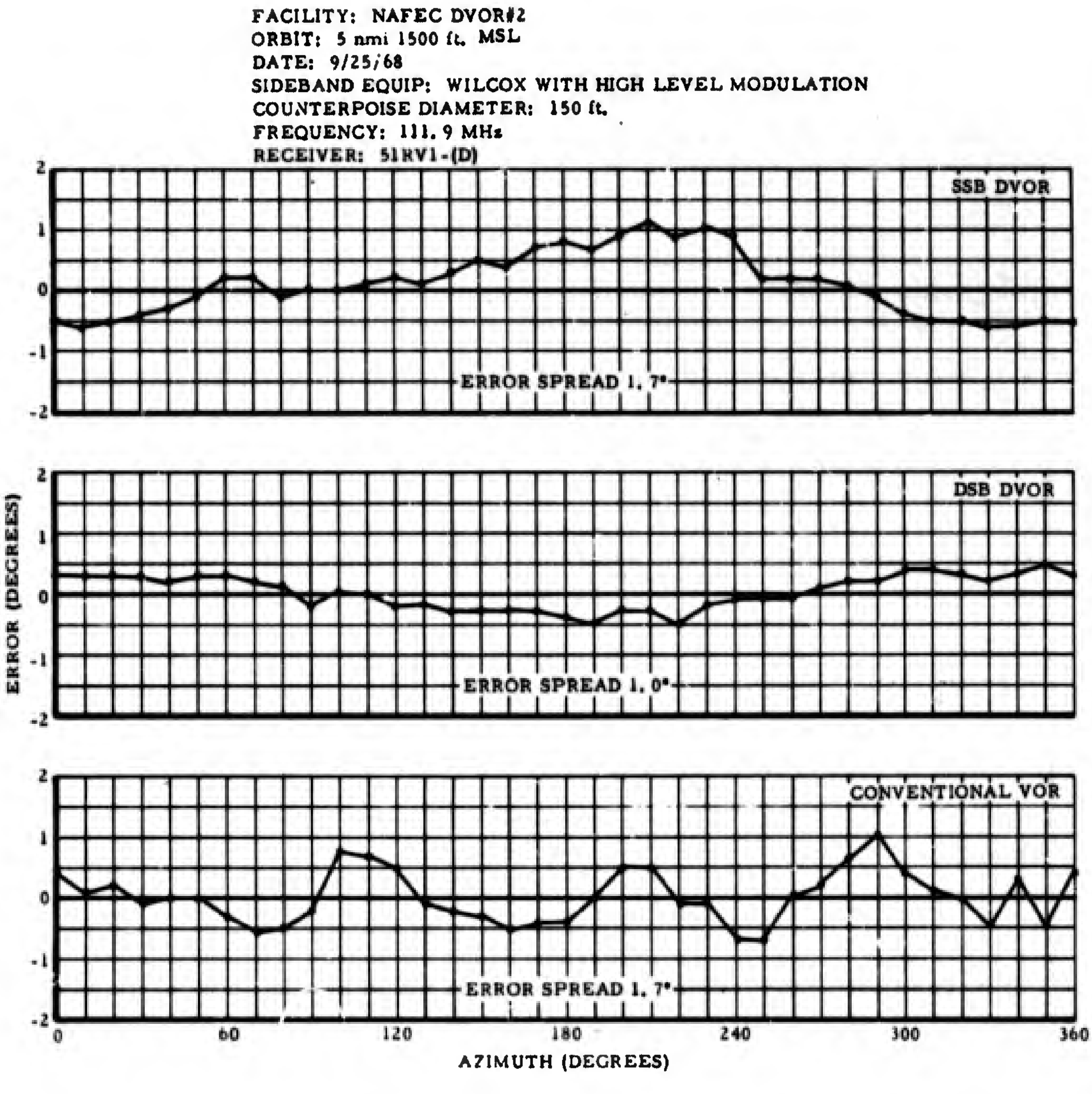


Figure 62. INDICATED STATION ERROR WITH TYPE 51RV1 (D) RECEIVER, 150-FOOT COUNTERPOISE

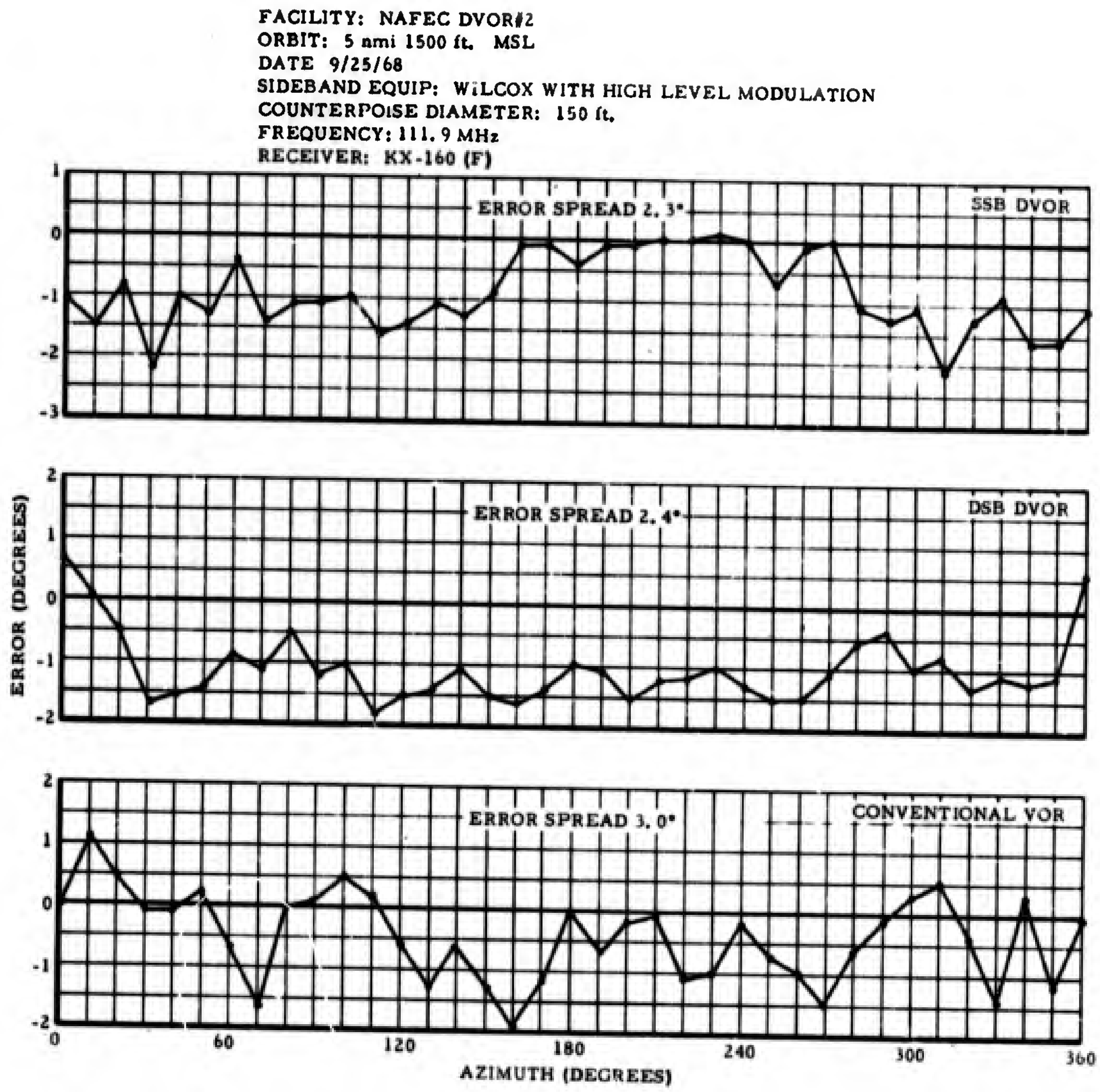


Figure 63. INDICATED STATION ERROR WITH TYPE KX-160 (F) RECEIVER, 150-FOOT COUNTERPOISE

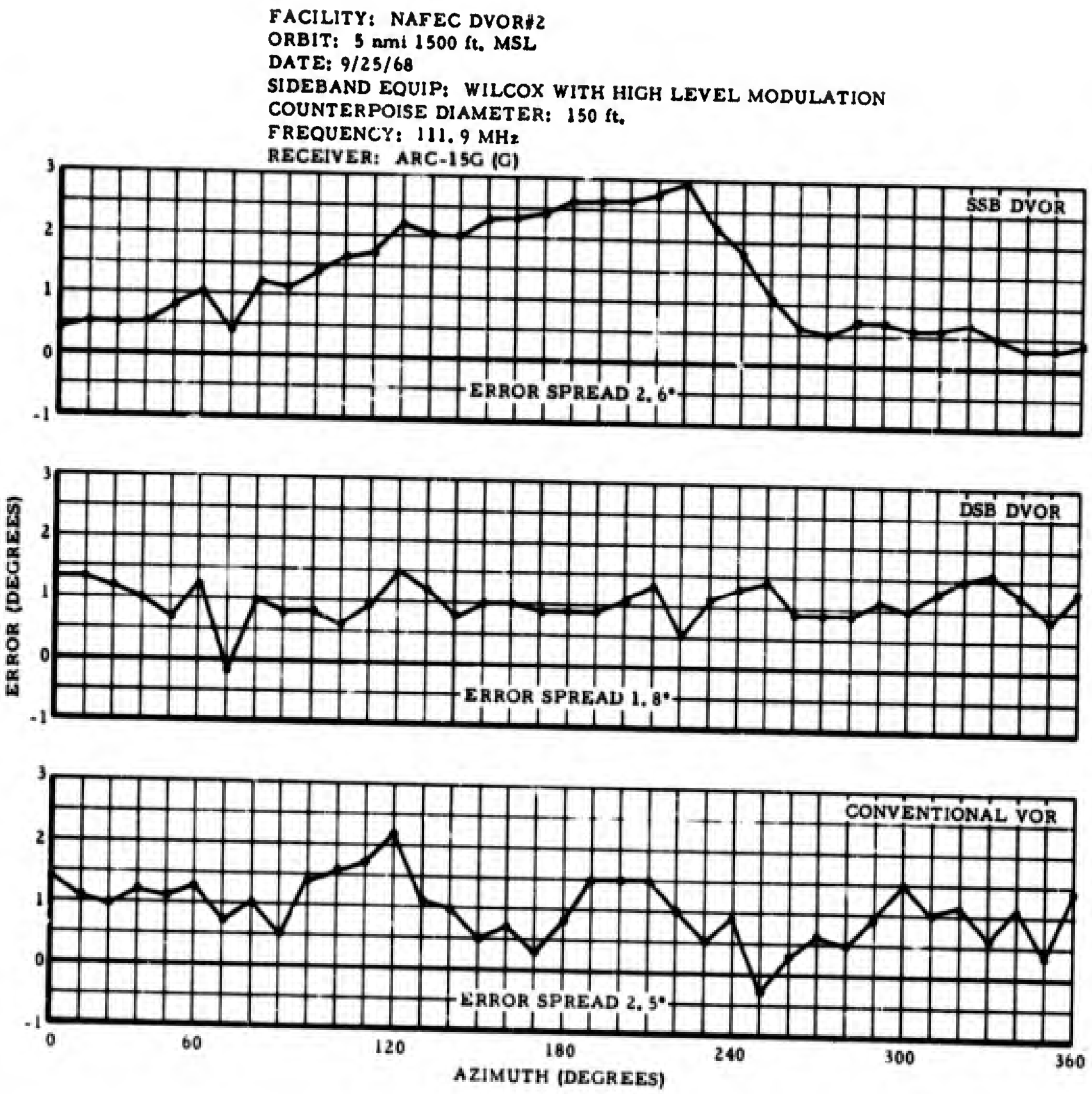


Figure 64. INDICATED STATION ERROR WITH TYPE ARC-15G (G) RECEIVER, 150-FOOT COUNTERPOISE

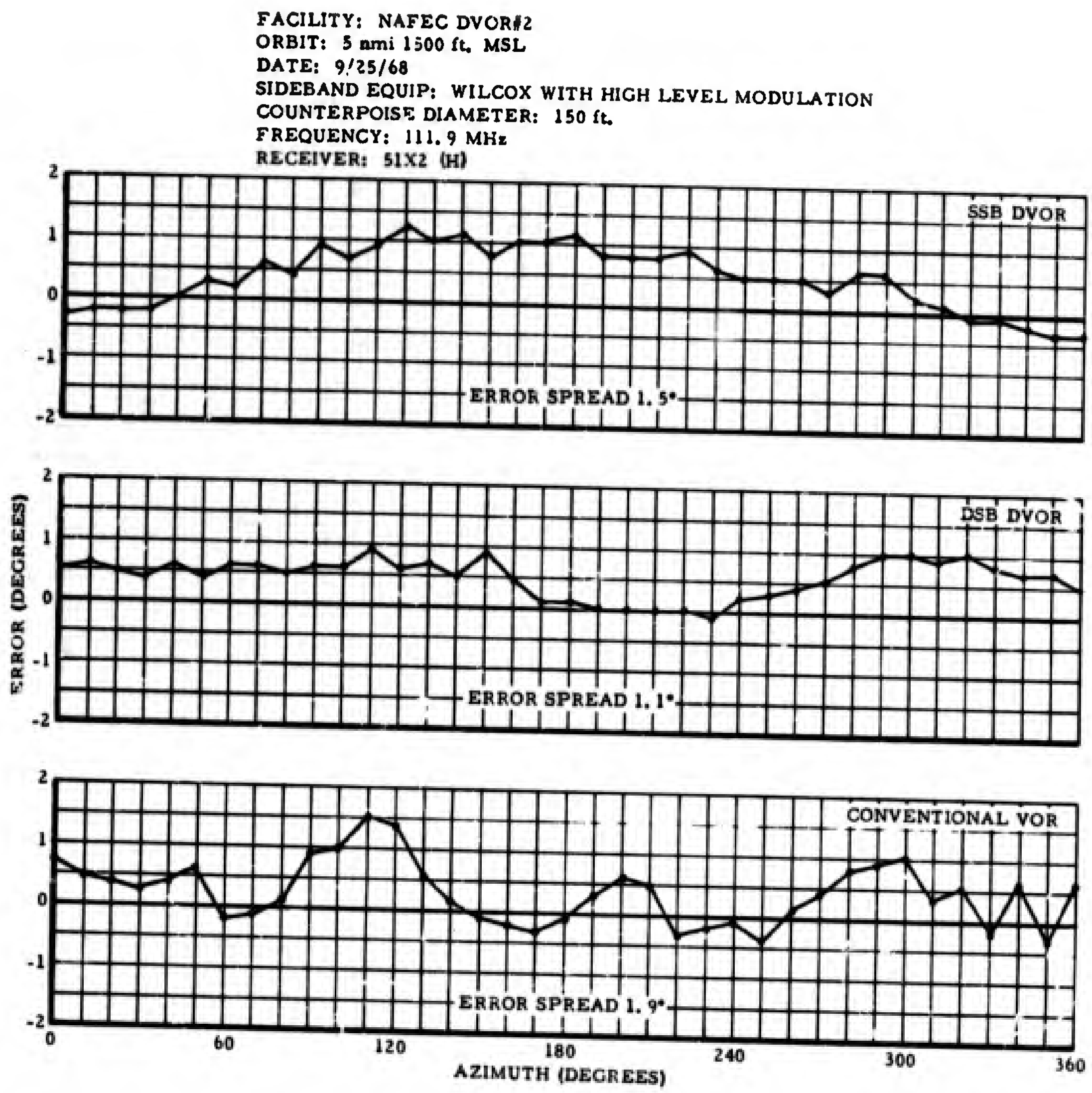


Figure 65. INDICATED STATION ERROR WITH TYPE 51X2 (H) RECEIVER, 150-FOOT COUNTERPOISE

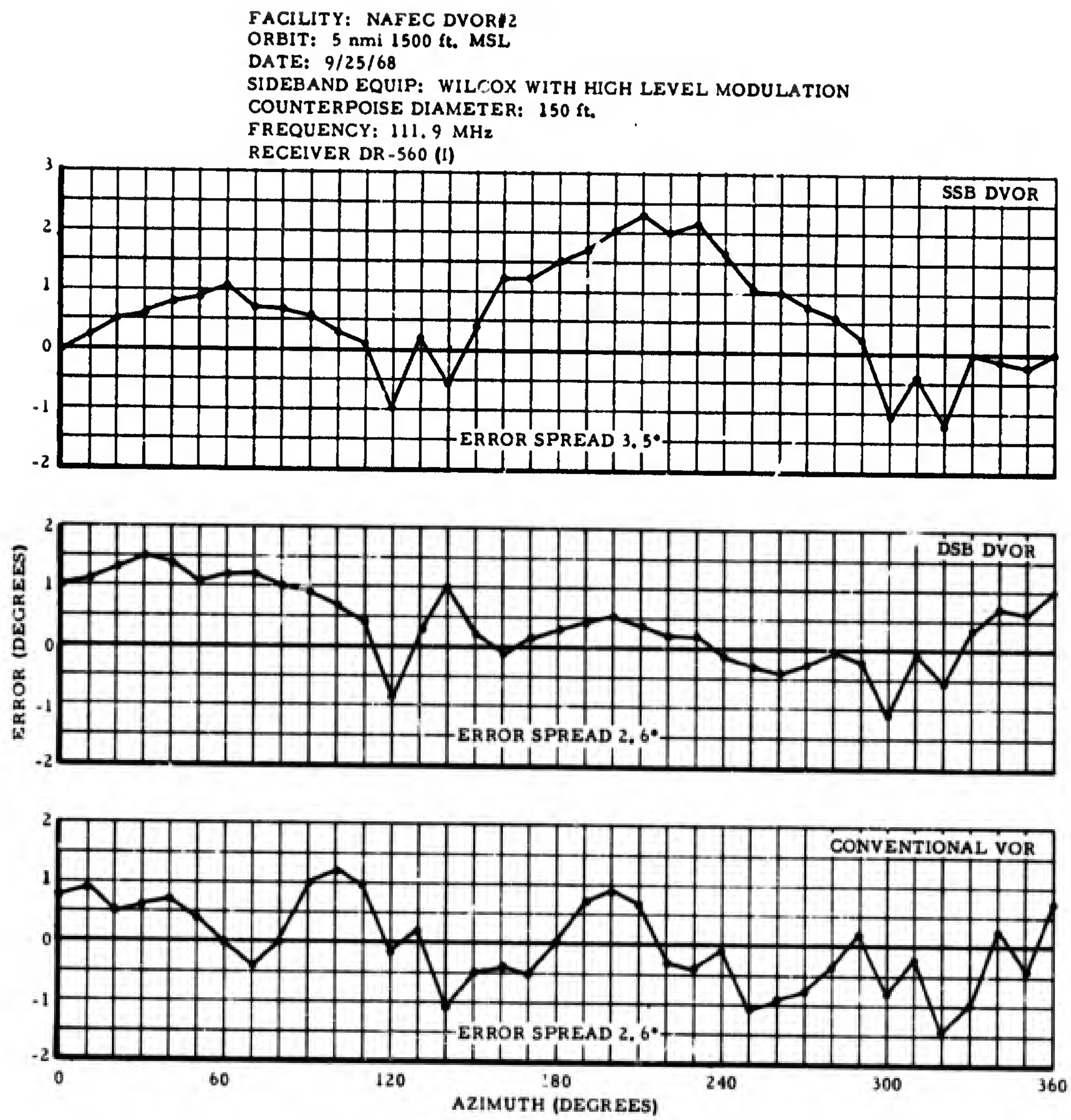


Figure 66. INDICATED STATION ERROR WITH TYPE DR-560 (I) RECEIVER, 150-FOOT COUNTERPOISE

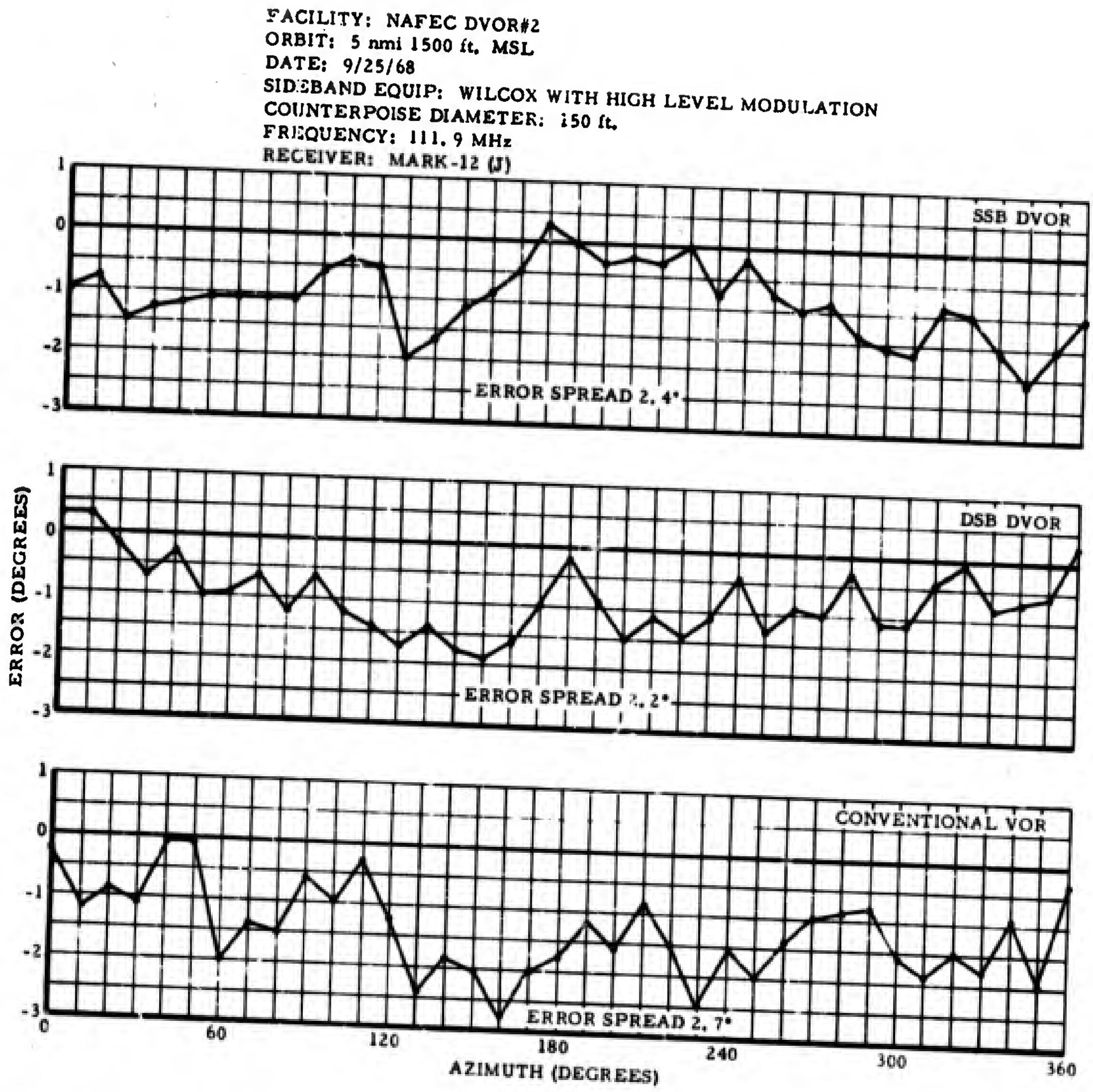


Figure 67. INDICATED STATION ERROR WITH TYPE MARK-12 (J) RECEIVER, 150-FOOT COUNTERPOISE

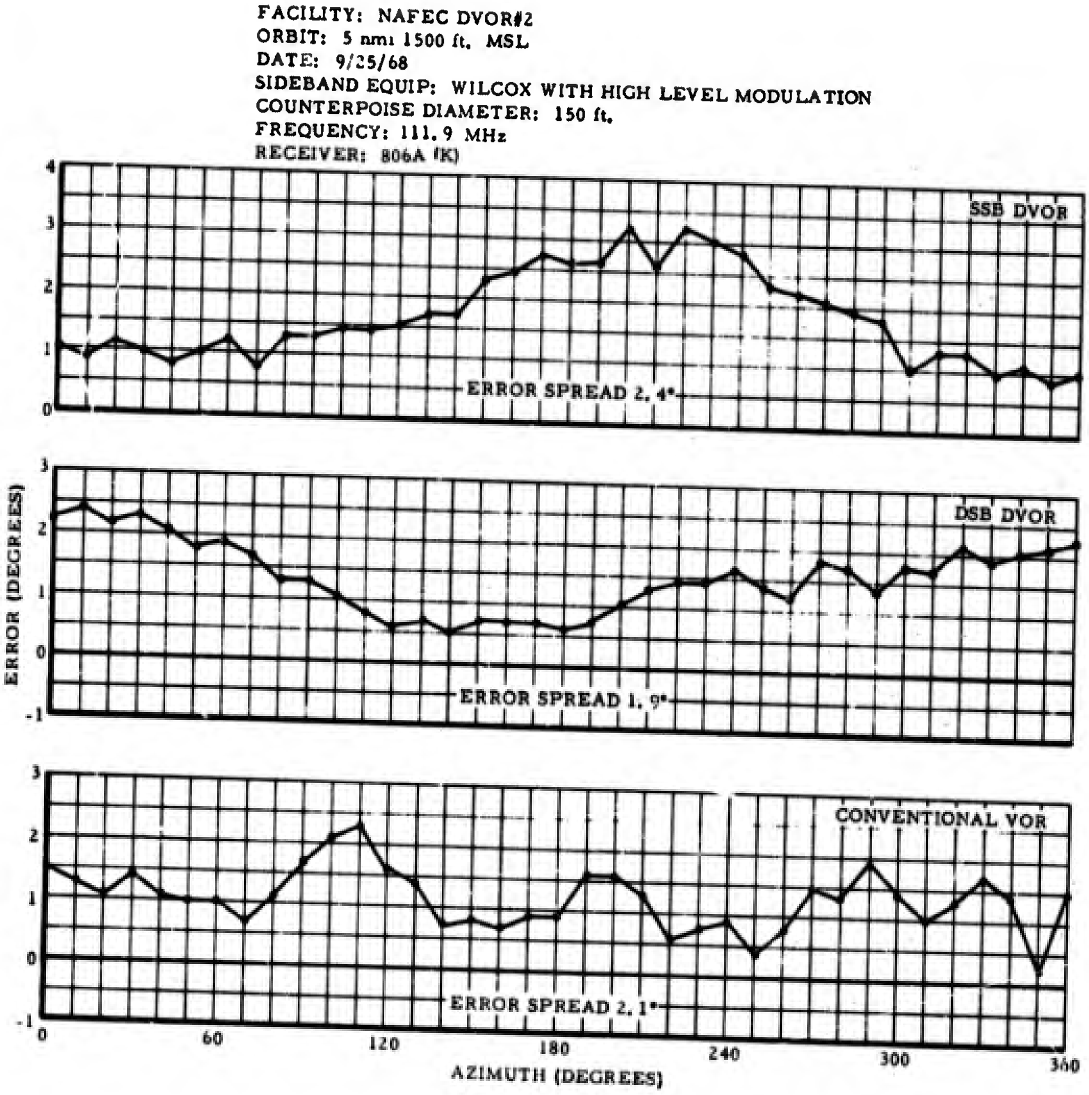


Figure 68. INDICATED STATION ERROR WITH TYPE 806A (K) RECEIVER, 150-FOOT COUNTERPOISE

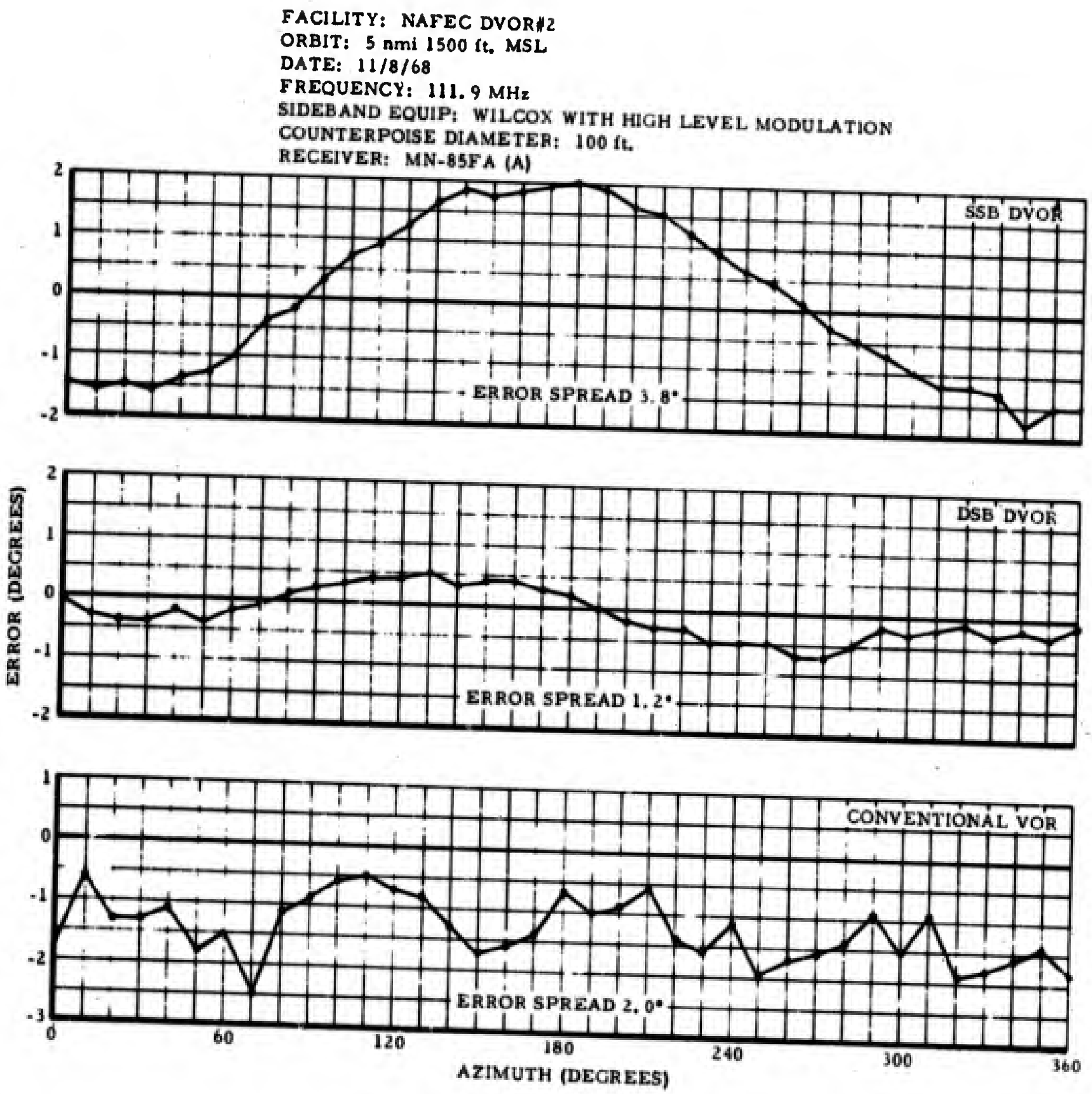


Figure 69. INDICATED STATION ERROR WITH TYPE MN-85FA (A) RECEIVER, 100-FOOT COUNTERPOISE

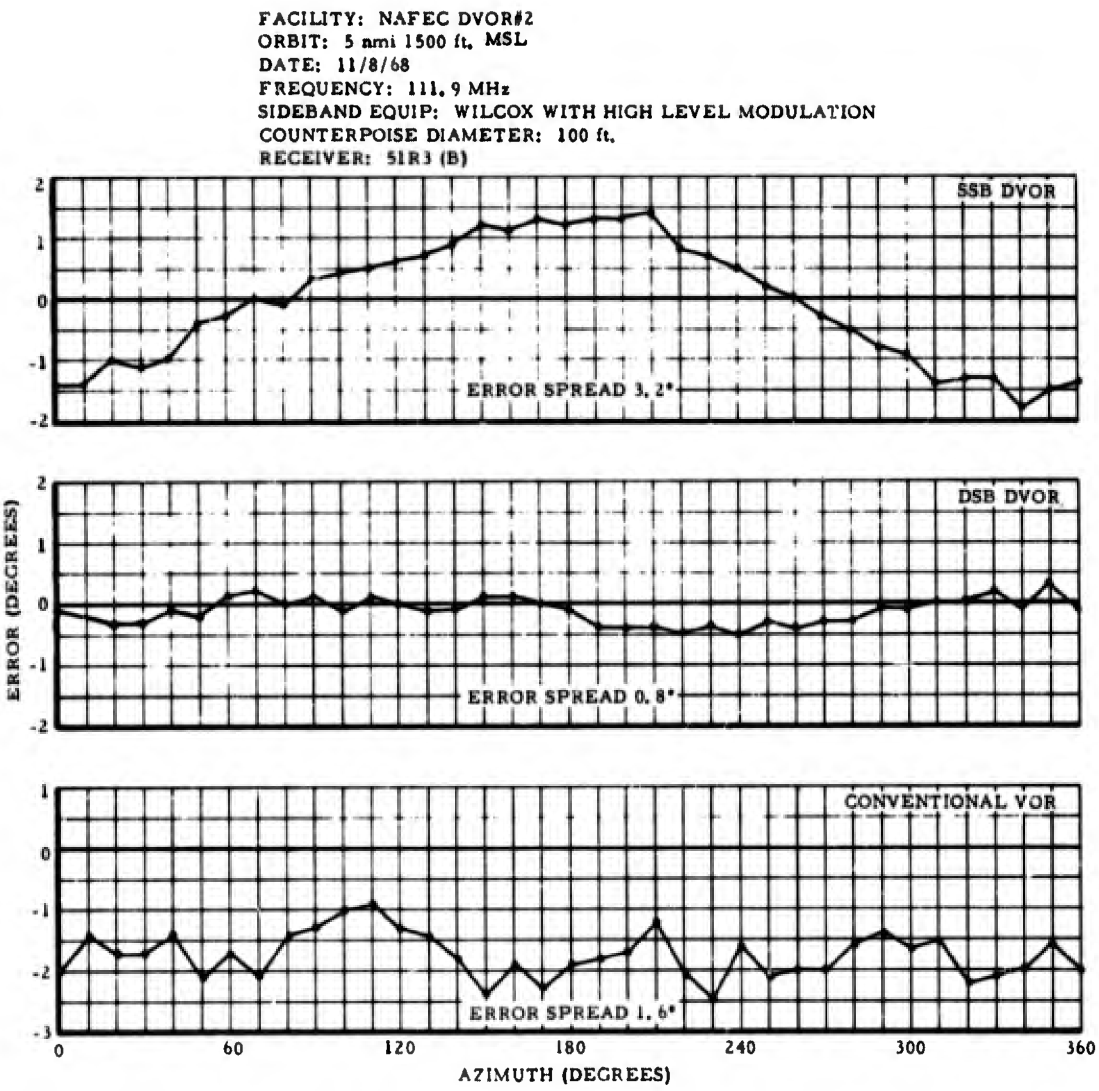


Figure 70. INDICATED STATION ERROR WITH TYPE 51R3 (B) RECEIVER, 100-FOOT COUNTERPOISE

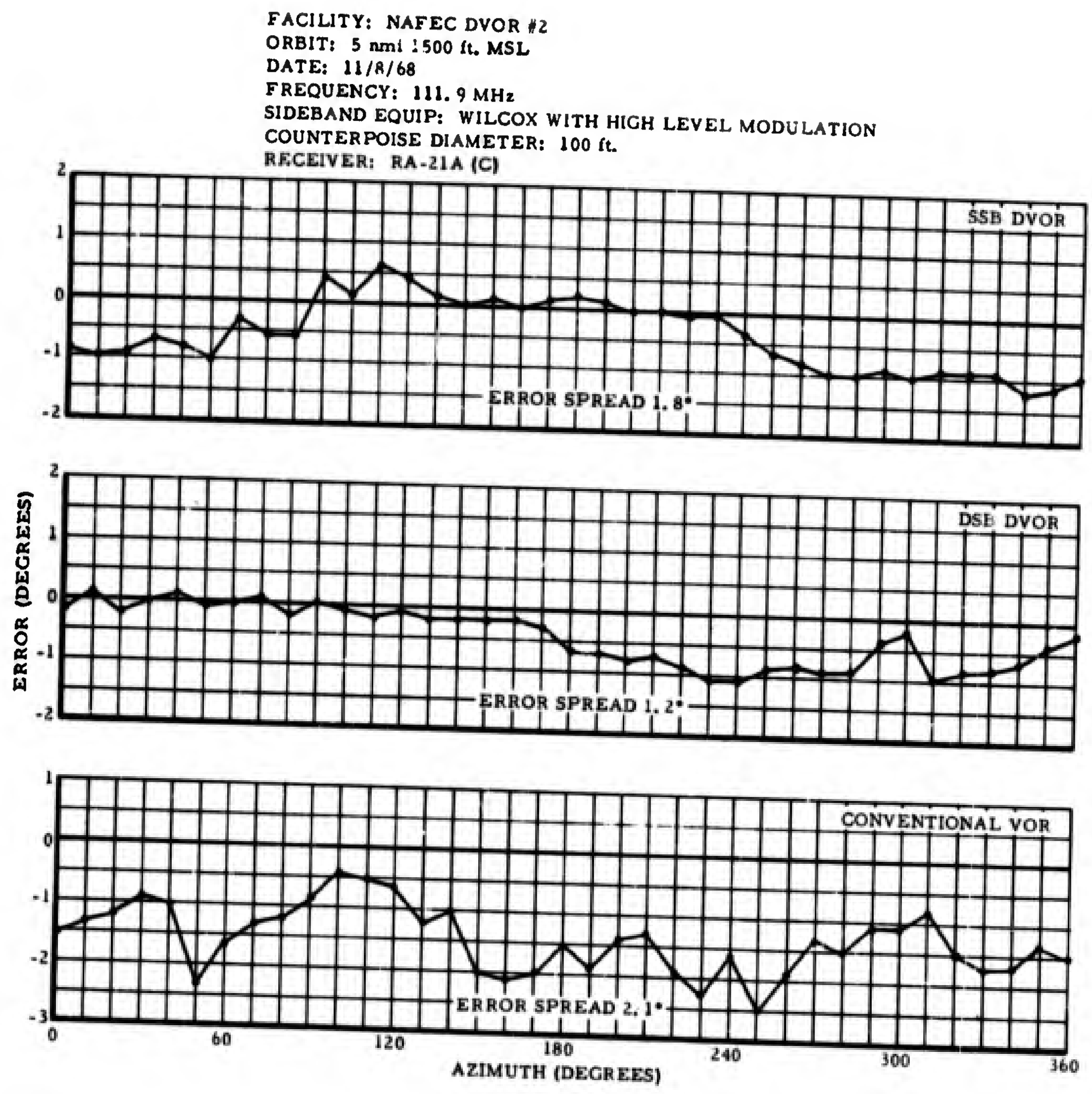


Figure 71. INDICATED STATION ERROR WITH TYPE RA-21A (C) RECEIVER, 100-FOOT COUNTERPOISE

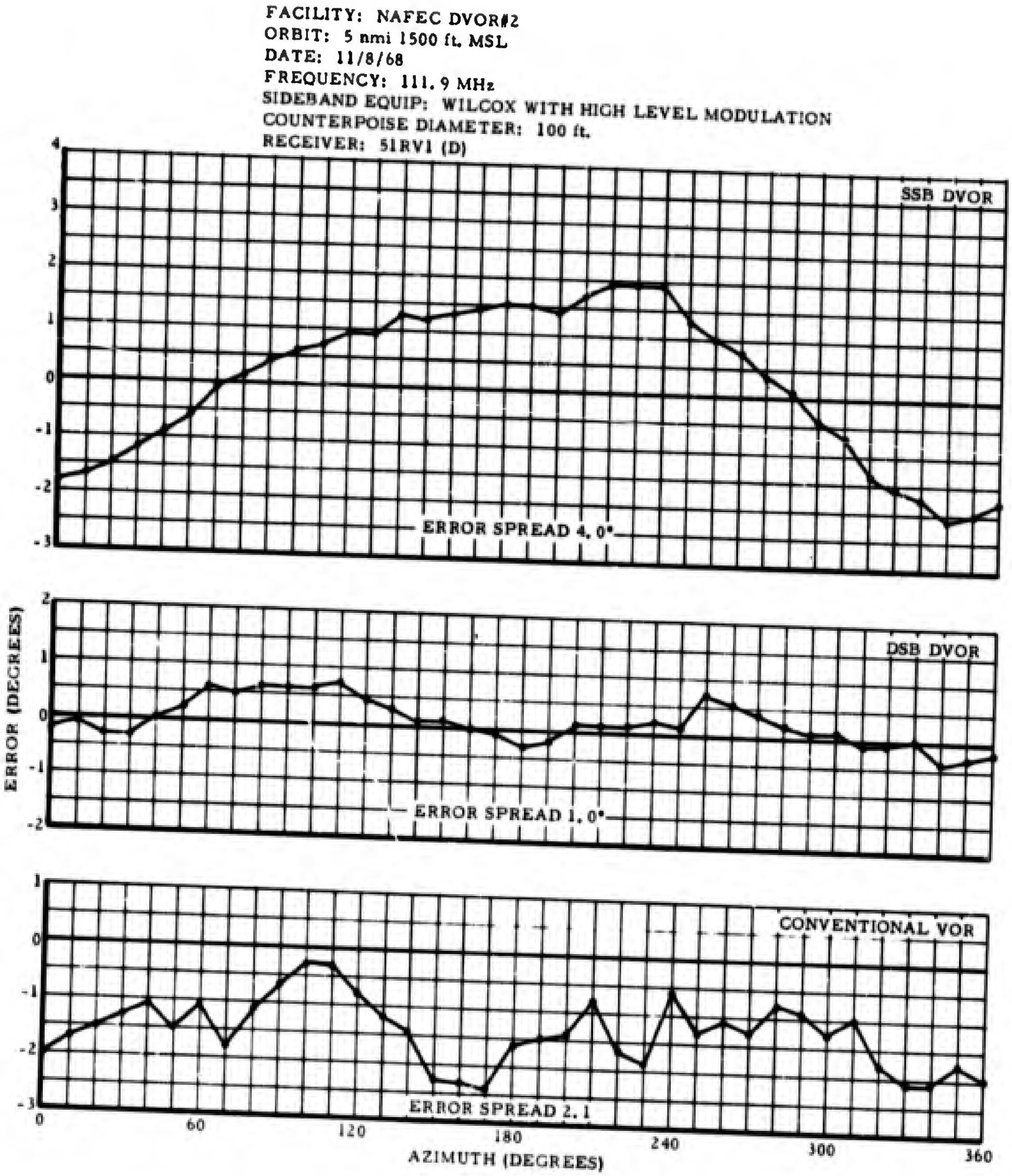


Figure 72. INDICATED STATION ERROR WITH TYPE 51RV1 (D) RECEIVER, 100-FOOT COUNTERPOISE

FACILITY: NAFEC DVOR#2
ORBIT: 5 nmi 1500 ft. MSL
DATE: 11/8/68
FREQUENCY: 111.9 MHz
SIDEBAND EQUIP: WILCOX WITH HIGH LEVEL MODULATION
COUNTERPOISE DIAMETER: 100 ft.
RECEIVER: 805A (E)

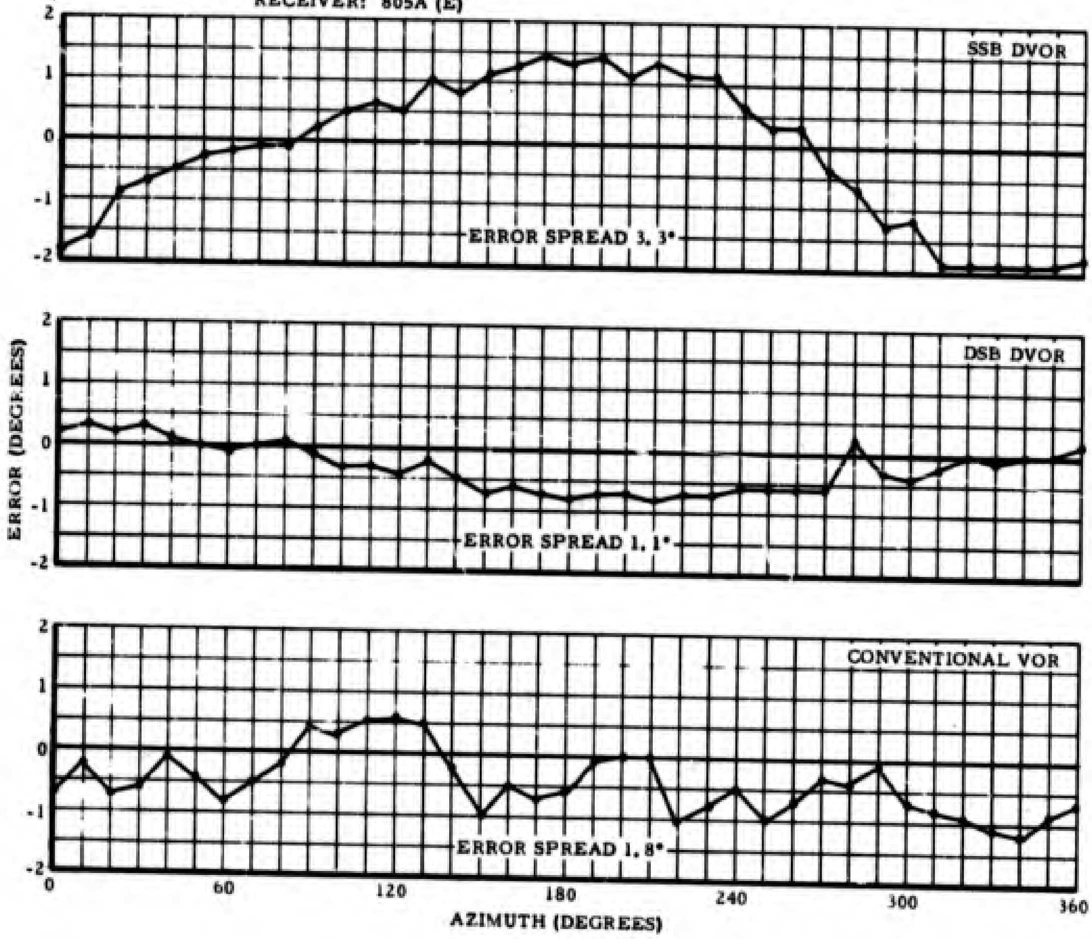


Figure 73. INDICATED STATION ERROR WITH TYPE 805A (E) RECEIVER, 100-FOOT COUNTERPOISE

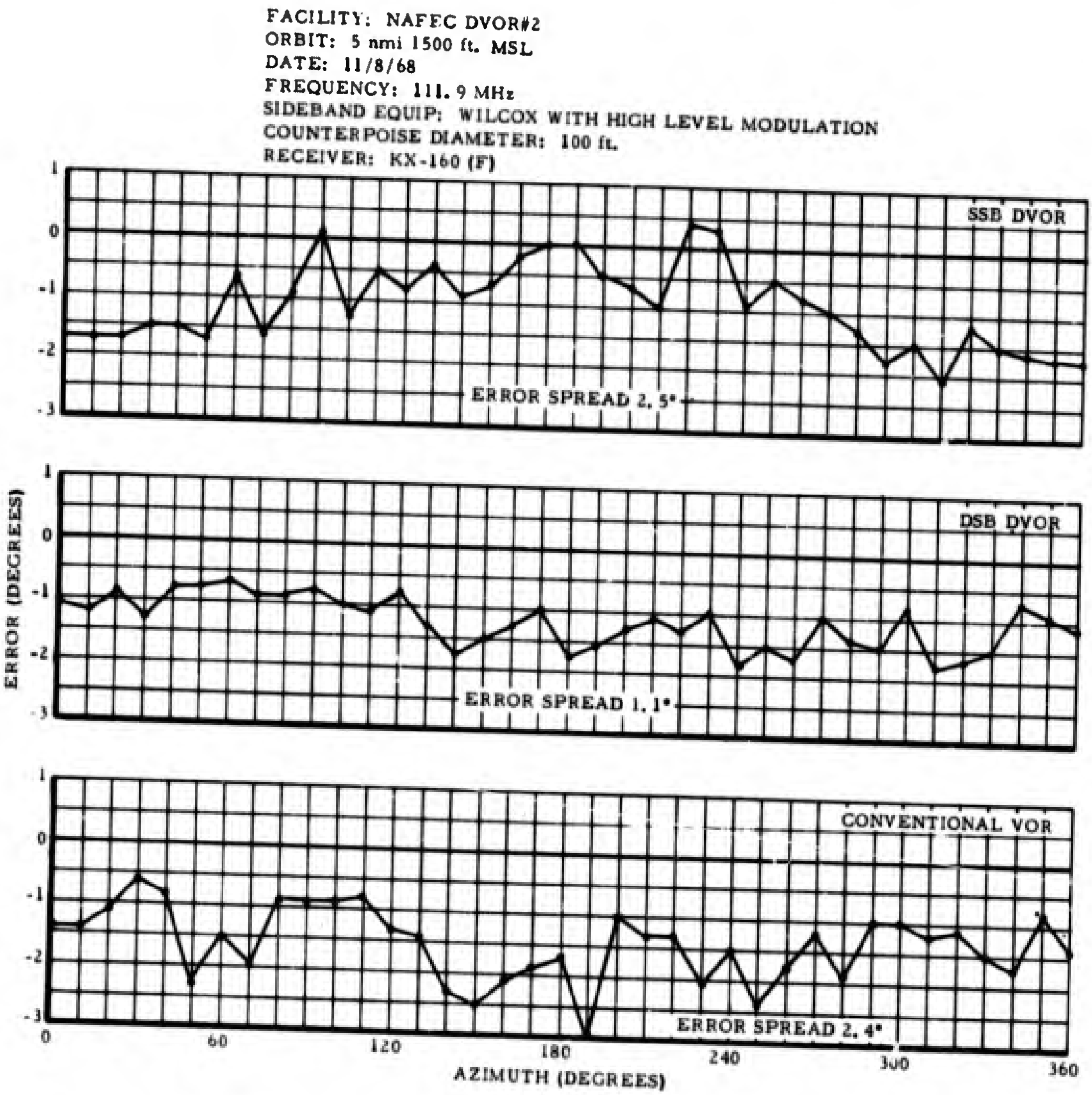


Figure 74. INDICATED STATION ERROR WITH TYPE KX-160 (F) RECEIVER, 100-FOOT COUNTERPOISE

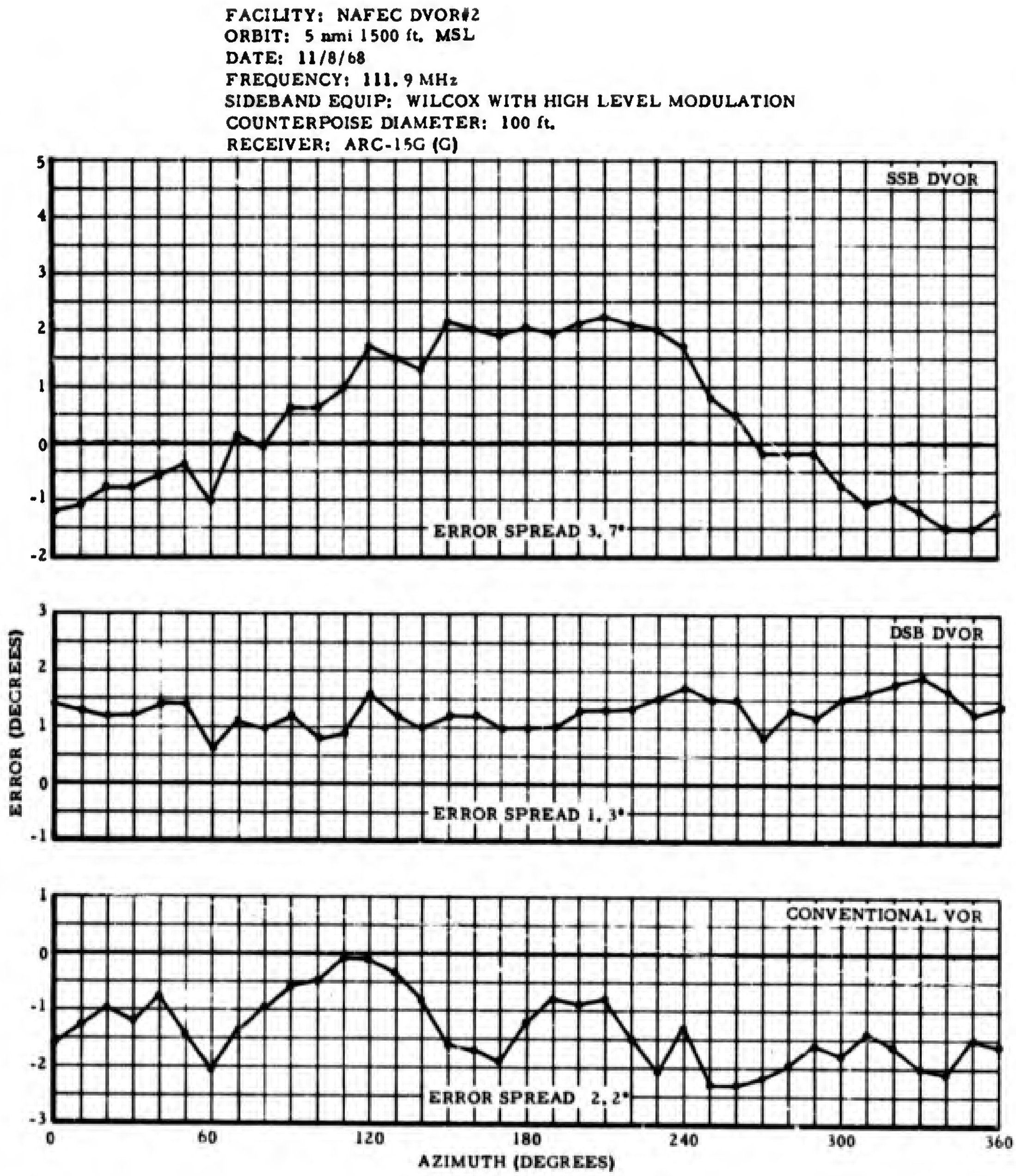


Figure 75. INDICATED STATION ERROR WITH TYPE ARC-15G (G) RECEIVER, 100-FOOT COUNTERPOISE

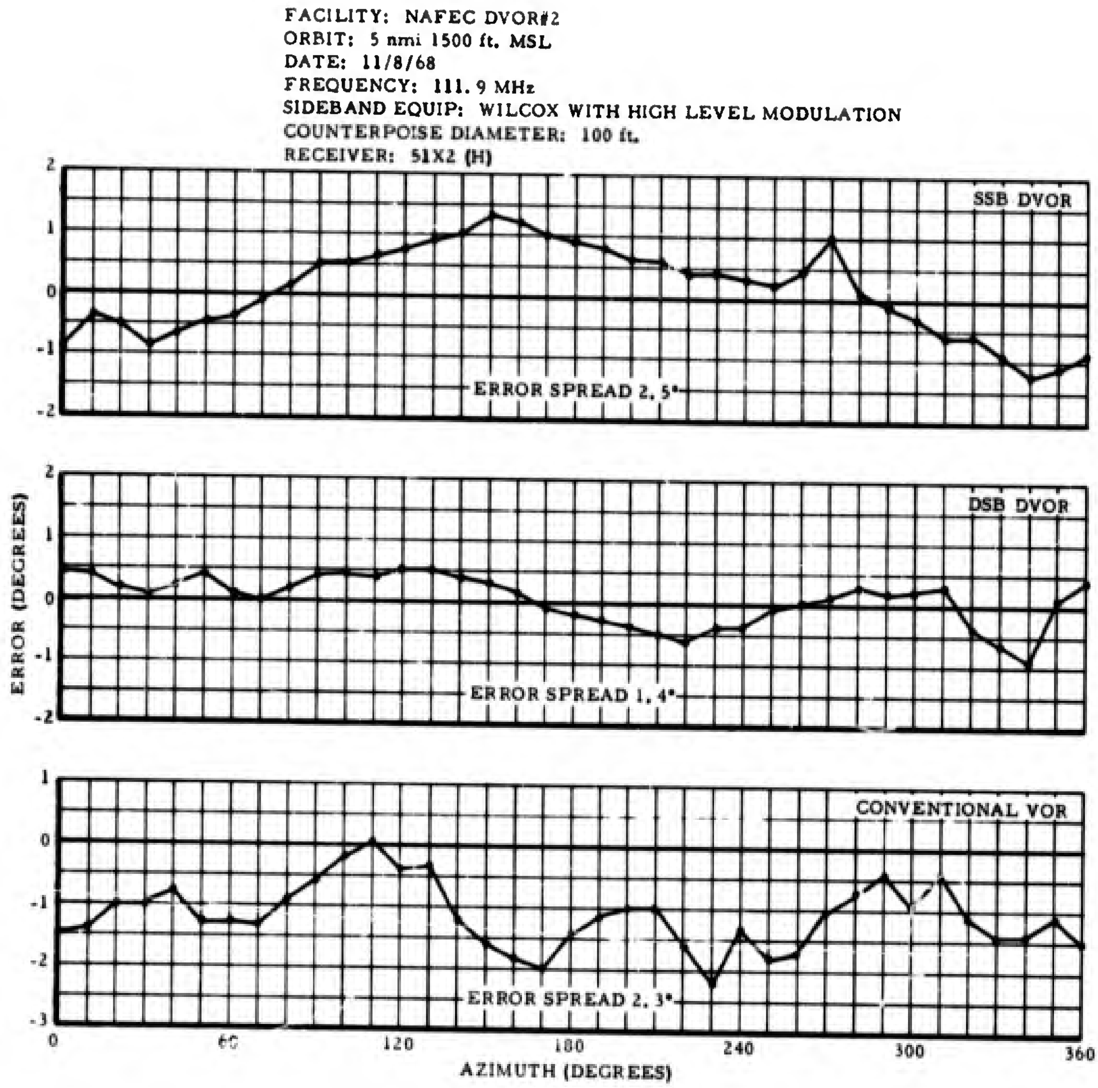


Figure 76. INDICATED STATION ERROR WITH TYPE 51X2 (H) RECEIVER, 100-FOOT COUNTERPOISE

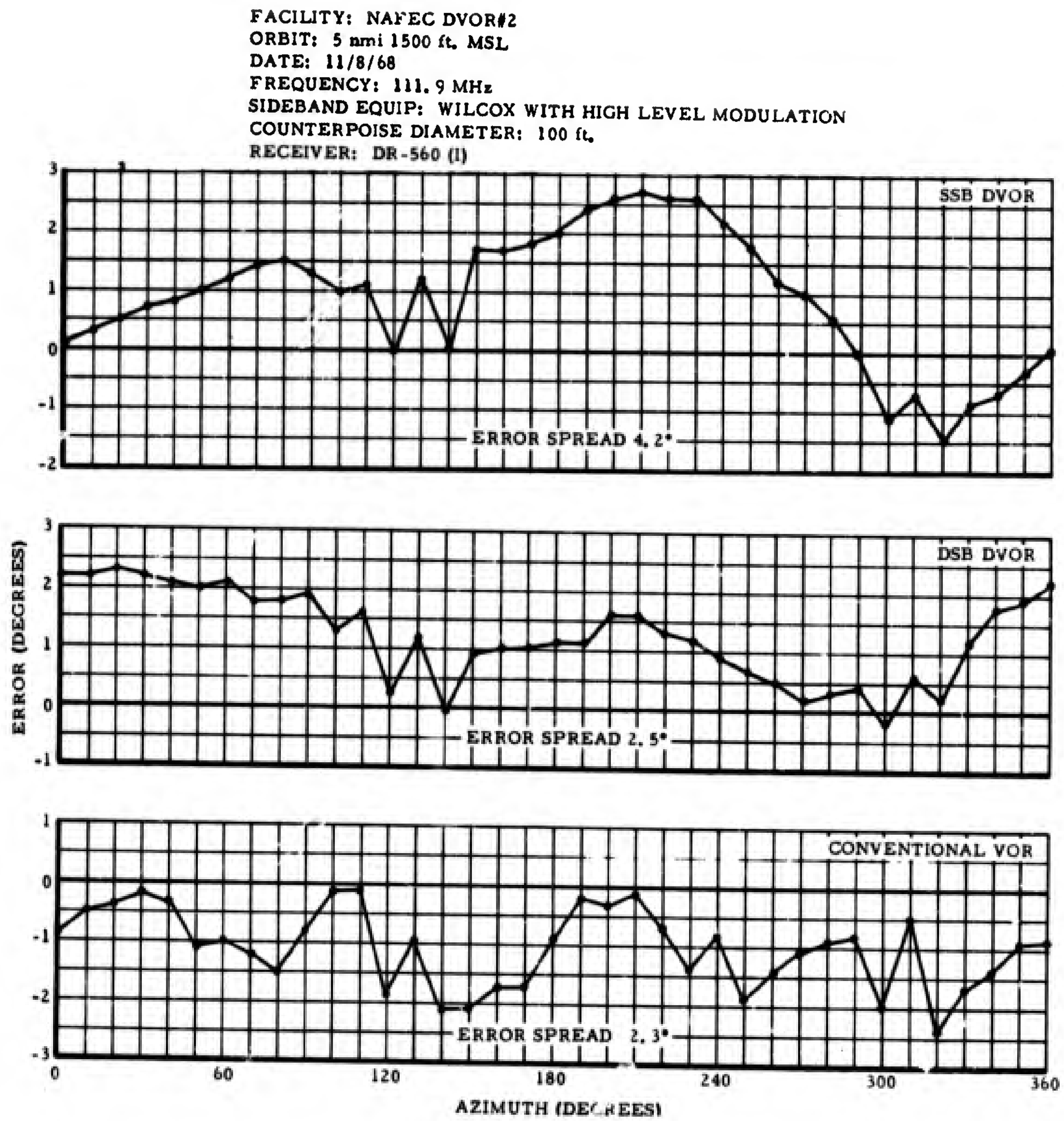


Figure 77. INDICATED STATION ERROR WITH TYPE DR-560 (I) RECEIVER, 100-FOOT COUNTERPOISE

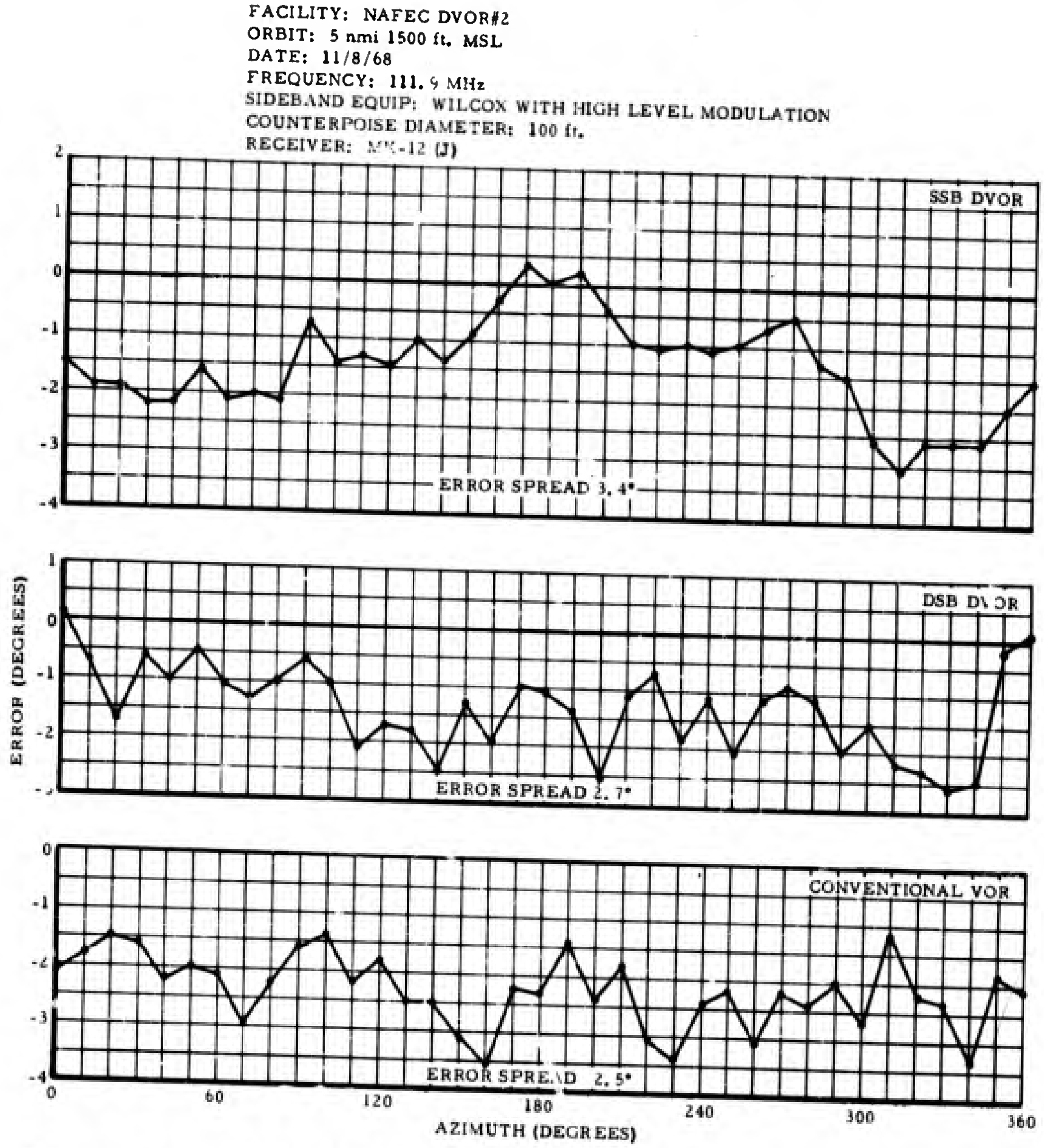


Figure 78. INDICATED STATION ERROR WITH TYPE MK-12 (J) RECEIVER, 100-FOOT COUNTERPOISE

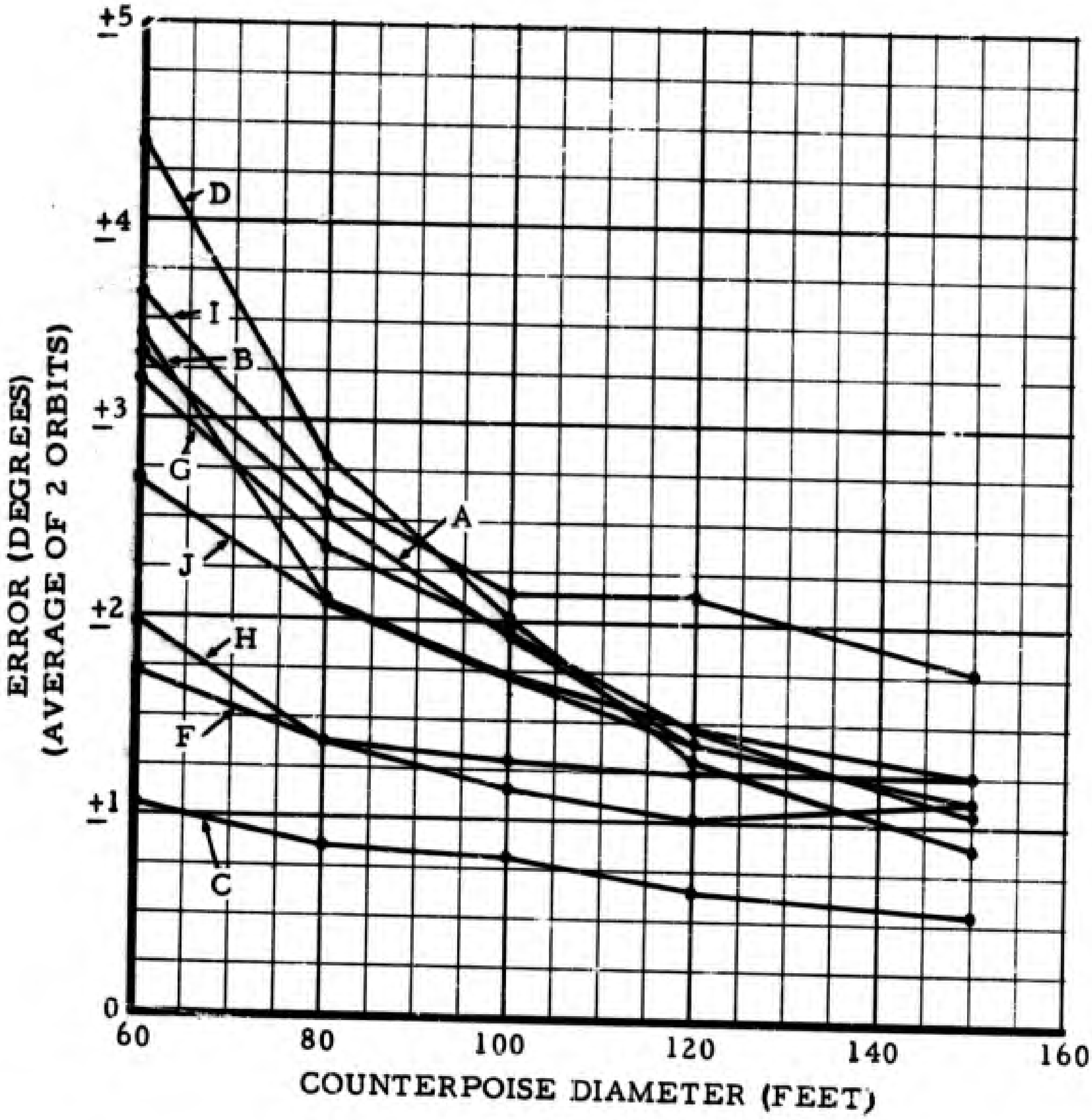


Figure 79. COMPOSITE INDICATED STATION ERROR WITH SSDVOR, VARIOUS COUNTERPOISE DIAMETERS

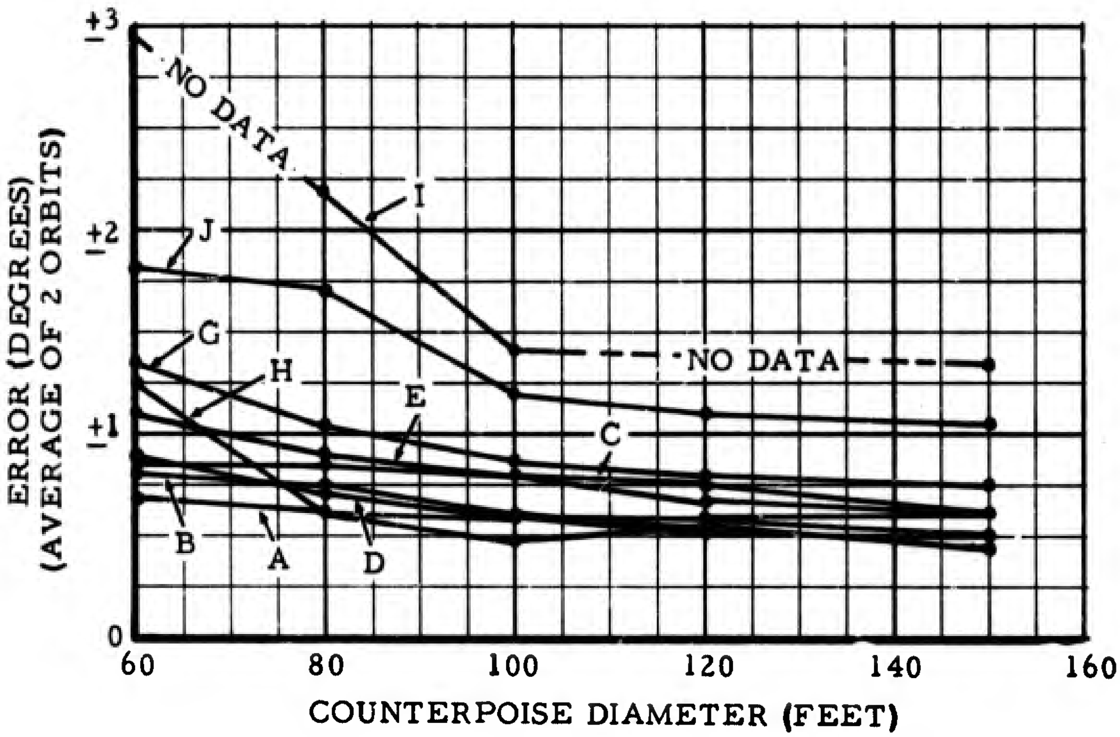


Figure 80. COMPOSITE INDICATED STATION ERROR WITH DSDVOR, VARIOUS COUNTERPOISE DIAMETERS

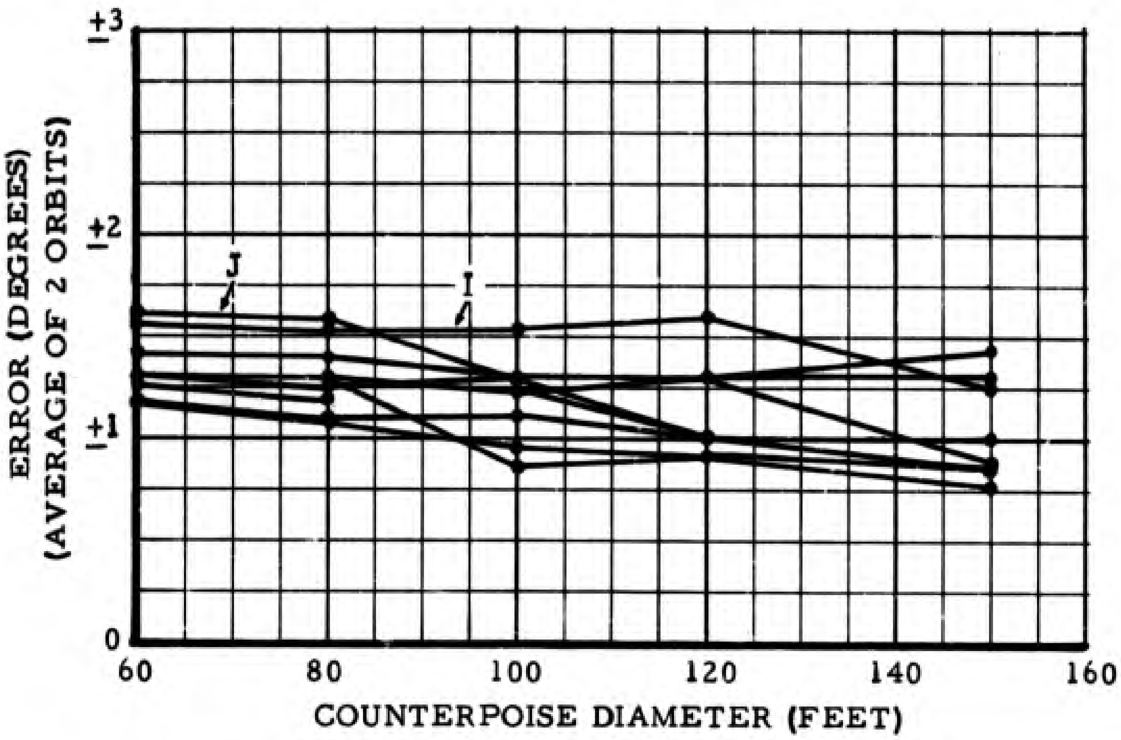


Figure 81. COMPOSITE INDICATED STATION ERROR WITH CONVENTIONAL VOR, VARIOUS COUNTERPOISE DIAMETERS

From the data obtained of the 20-nmi orbital flight tests, the maximum scalloping for each 10° of azimuth is plotted in Figures 82 through 91. By averaging the maximum value of scalloping for each 10° of azimuth, a single value is established for each VOR system. The system with the lowest average value would be the least susceptible to site effects. The results, tabulated in Figure 92, provide a comparison of system and individual receiver reaction to siting effects. These data and the graphs of Figures 82 through 91 indicate that the DSDVOR System is slightly less susceptible to site effects than the SSDVOR System, and there is very little difference in performance at counterpoise diameters of 150 feet and 100 feet.

SEAL Receiver Tests - A tabulation of total error spread of each receiver, obtained from the 6-nmi orbital flight tests of the three VOR systems, is shown in Figure 93 for a comparison of indicated station error. Analog and digital performances of the SEAL receiver are compared with that of the air carrier receivers tested The station error curves for each of the three VOR systems, as indicated by the individual air carrier receivers and by the analog output of the SEAL receiver are given in Figures 94 through 100. Composite indicated station error curves for the three VOR systems, given in Figures 101 through 103, were made from the output data of the individual receivers to compare receiver compatibility.

The digital data, plotted in Figure 104, of the three VOR systems, taken from a 6-nmi orbital flight give indication of the SEAL receiver performance.

Coaxially Located TACAN Antenna Test - Results of tests to coaxially locate a TACAN antenna with Doppler VOR, using a simulated antenna mounting base were inconclusive. A coaxially located TACAN antenna would have to be installed at a Doppler test facility to conclusively determine feasibility. This test should be conducted when a standard DSDVOR counterpoise size is established. Since manpower and funds to accomplish this task were not within the scope of the DSDVOR project, this was not done. To perform tests of the TACAN antenna under the DSDVOR project would have unnecessarily delayed the completion of the DSDVOR test.

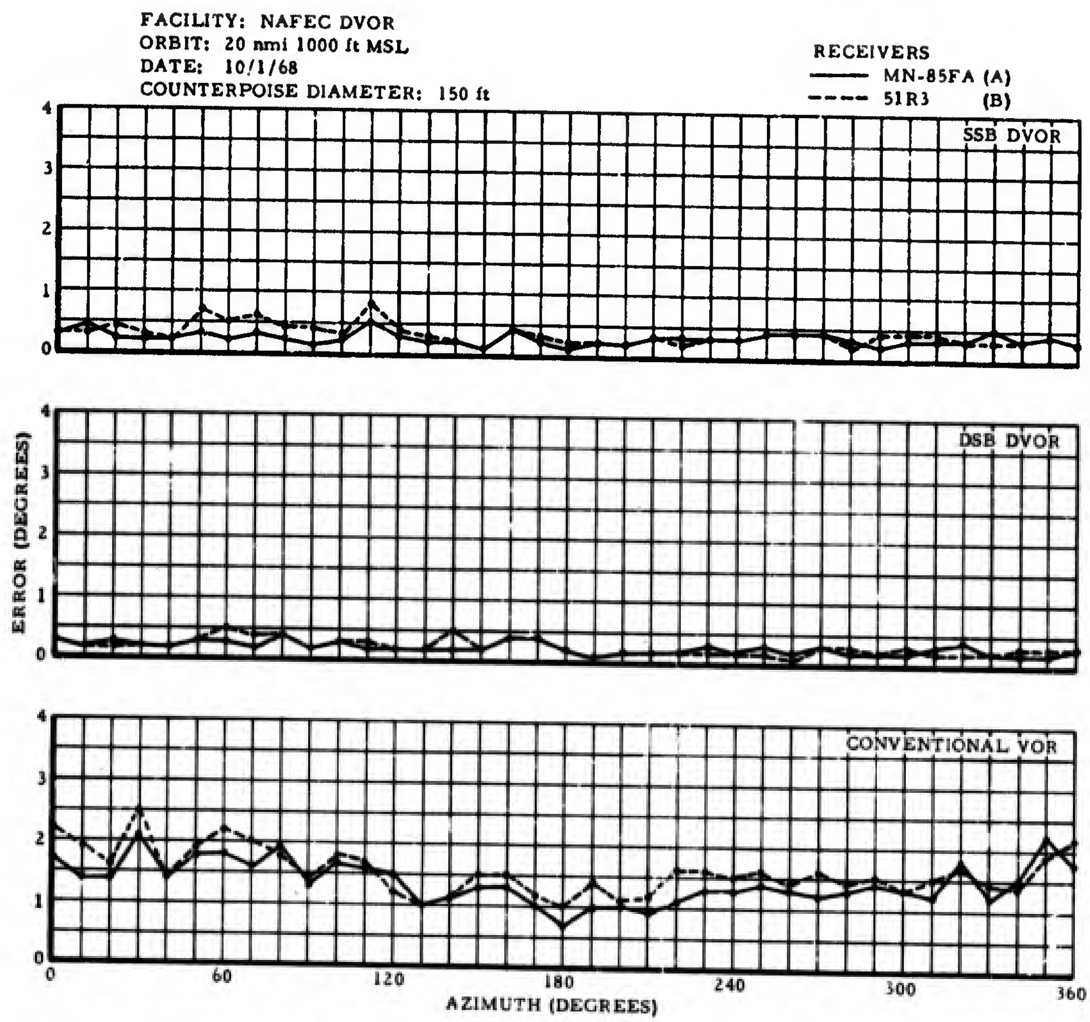


Figure 82. MAX'MUM SCALLOPING PER 10° SECTOR WITH TYPE MN-85FA (A) AND 51R3 (B) RECEIVERS, 150-FOOT COUNTERPOISE

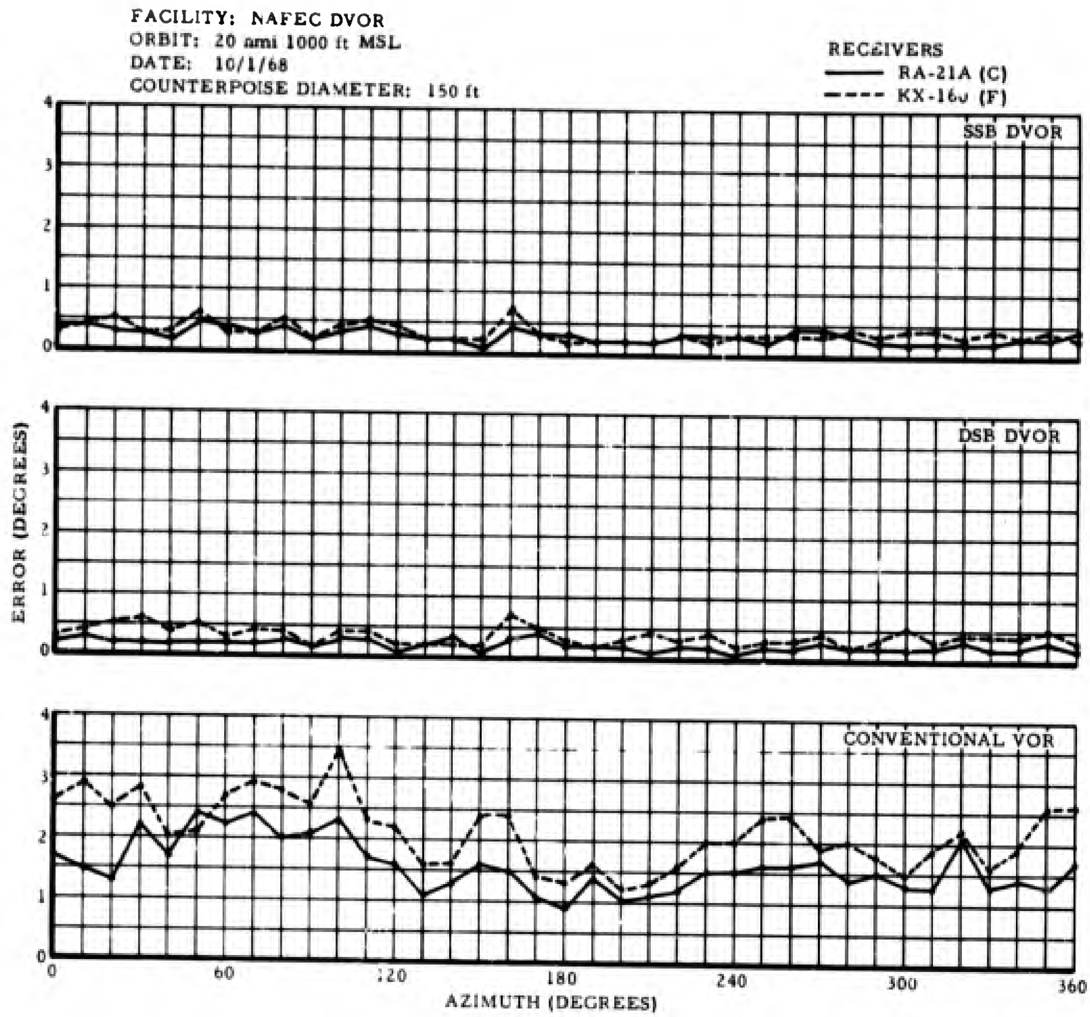


Figure 83. MAXIMUM SCALLOPING PER 10° SECTOR WITH TYPE RA-21A (C) AND KX-160 (F) RECEIVERS, 150-FOOT COUNTERPOISE

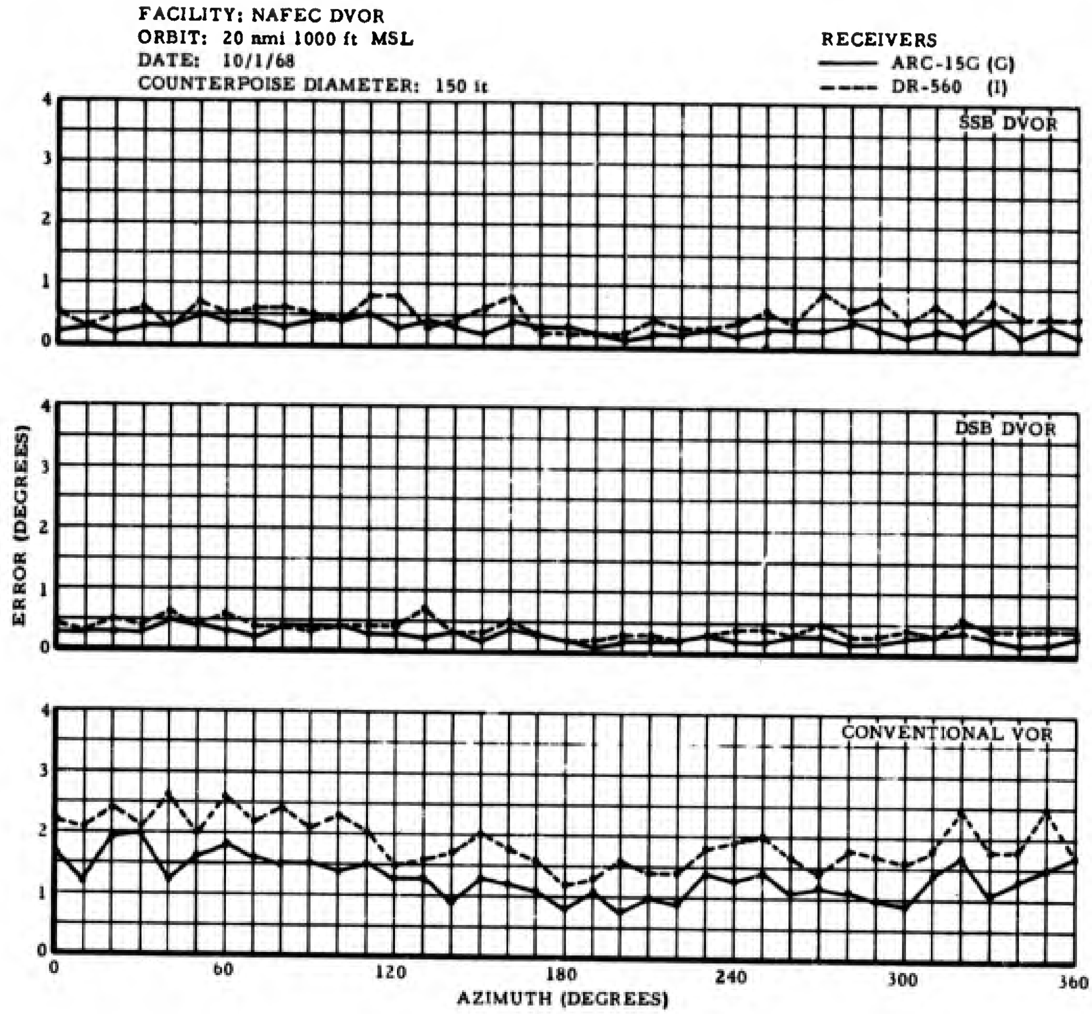


Figure 84. MAXIMUM SCALLOPING PER 10° SECTOR WITH TYPE ARC-15G (G) AND DR-560 (I) RECEIVERS, 150-FOOT COUNTERPOISE

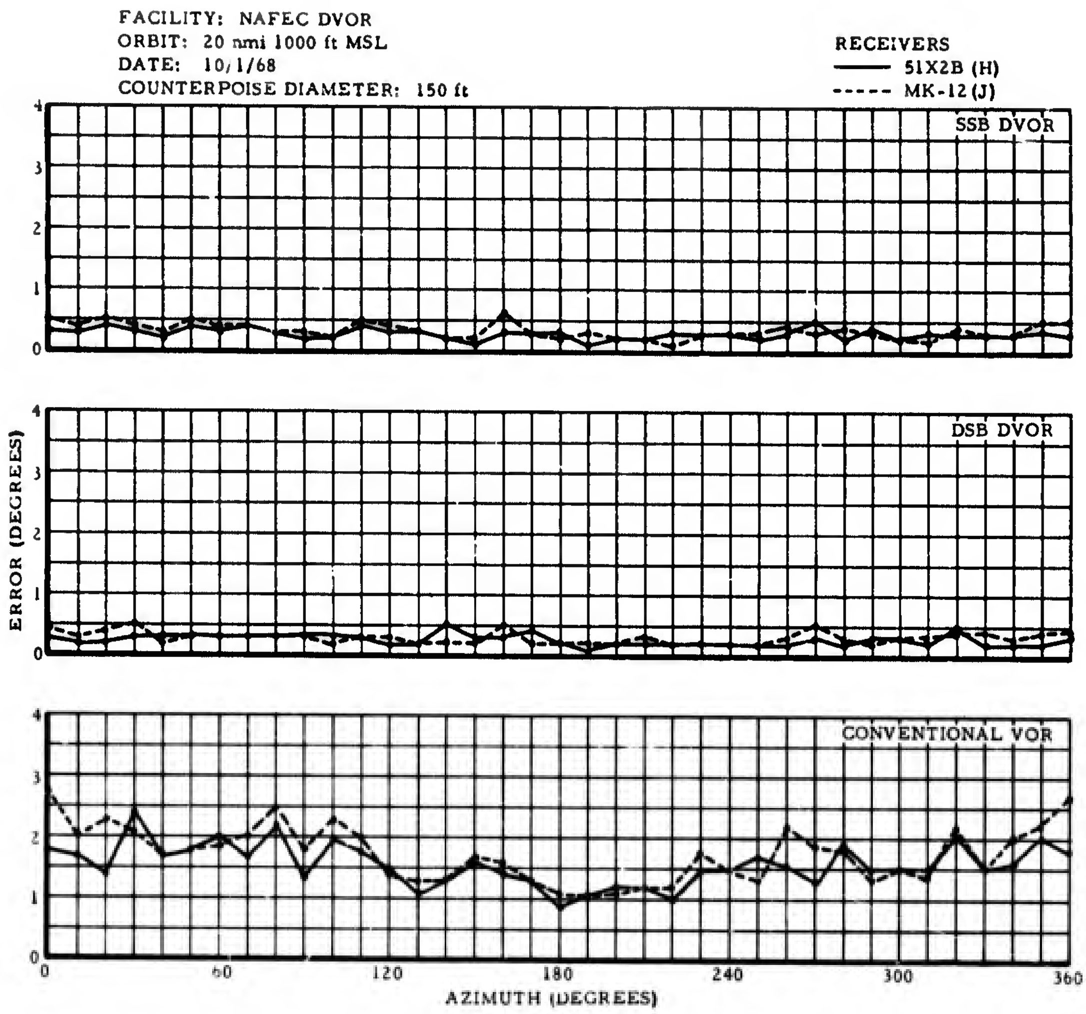


Figure 85. MAXIMUM SCALLOPING PER 10° SECTOR WITH TYPE 51X2B (H) AND MK-12 (J) RECEIVERS, 150-FOOT COUNTERPOISE

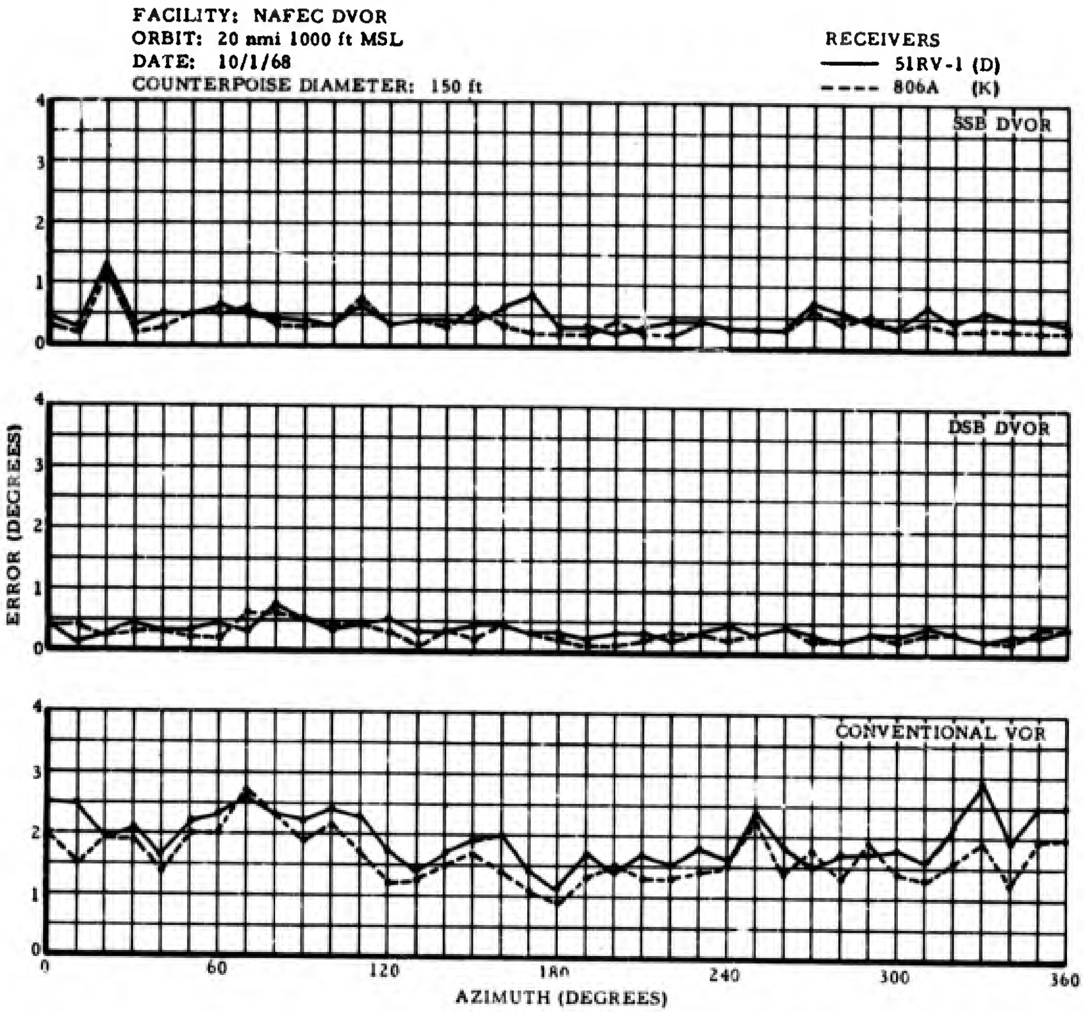


Figure 86. MAXIMUM SCALLOPING PER 10° SECTOR WITH TYPE 51RV1 (D) AND 806A (K) RECEIVERS, 150-FOOT COUNTERPOISE

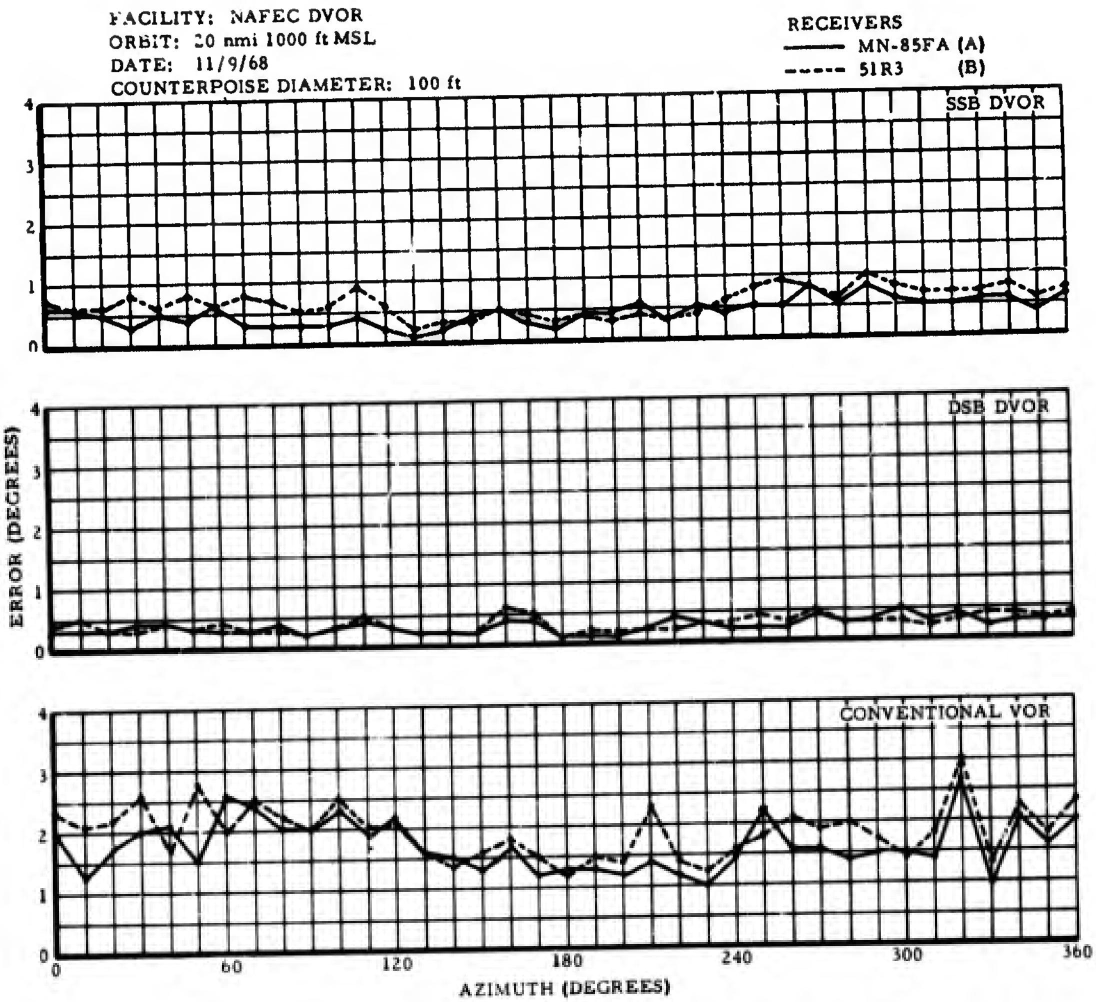


Figure 87. MAXIMUM SCALLOPING PER 10° SECTOR WITH TYPE MN-85FA (A) AND 51R3 (B) RECEIVERS, 100-FOOT COUNTERPOISE

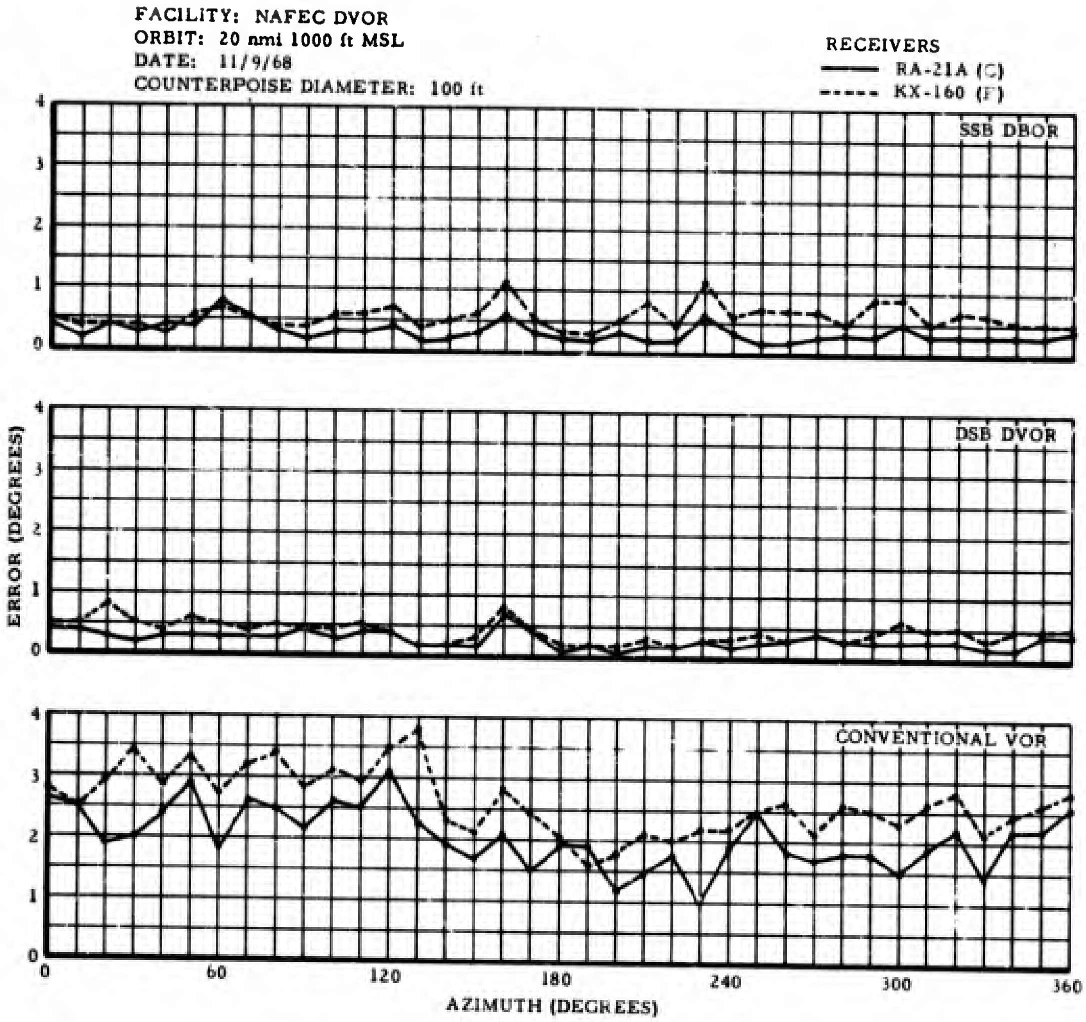


Figure 88. MAXIMUM SCALLOPING PER 10° SECTOR WITH TYPE RA-21A (C) AND KX-160 (F) RECEIVERS, 100-FOOT COUNTERPOISE

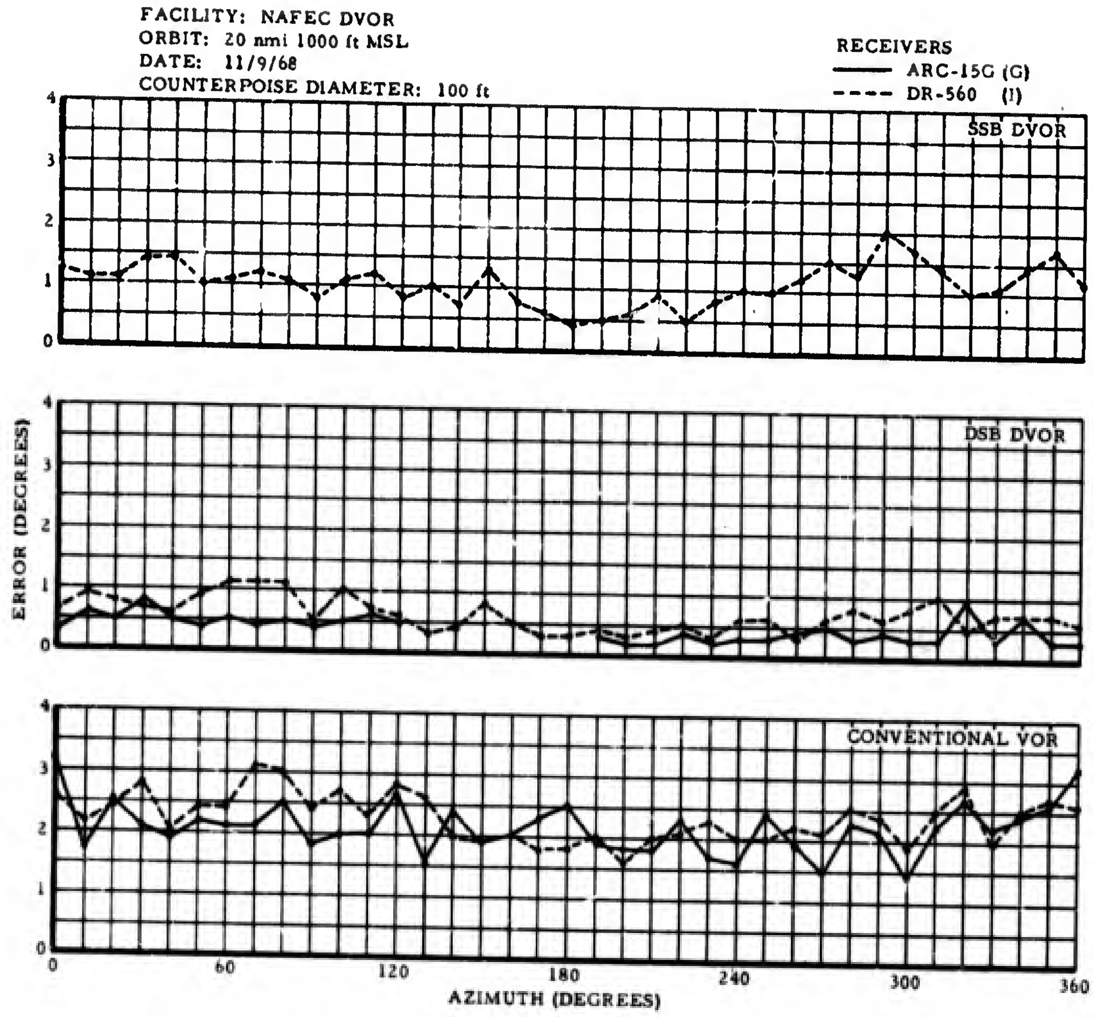


Figure 89. MAXIMUM SCALLOPING PER 10° SECTOR WITH TYPE ARC-15G (G) AND DR-560 (I) RECEIVERS, 100-FOOT COUNTERPOISE

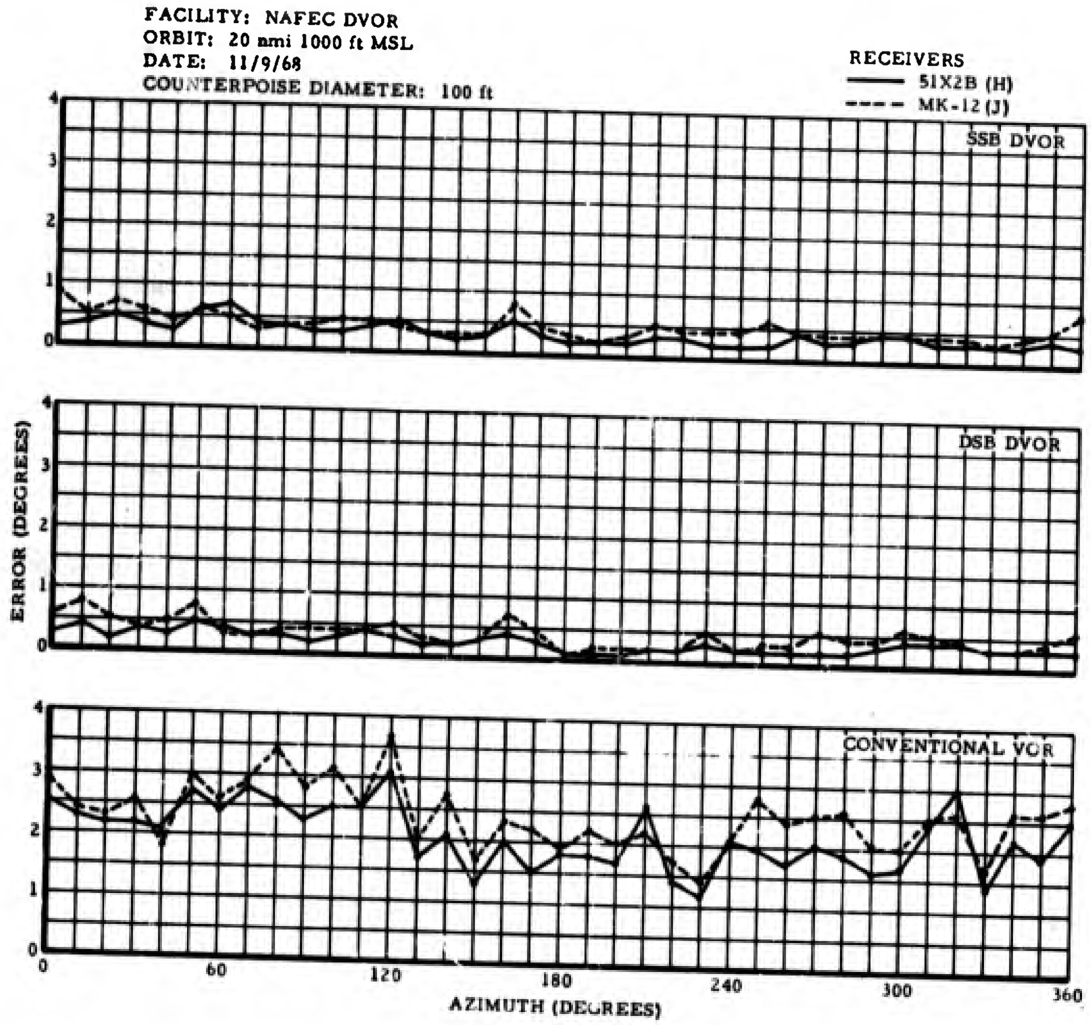


Figure 90. MAXIMUM SCALLOPING PER 10° SECTOR WITH TYPE 51X2B (H) AND MK-12 (J) RECEIVERS, 100-FOOT COUNTERPOISE

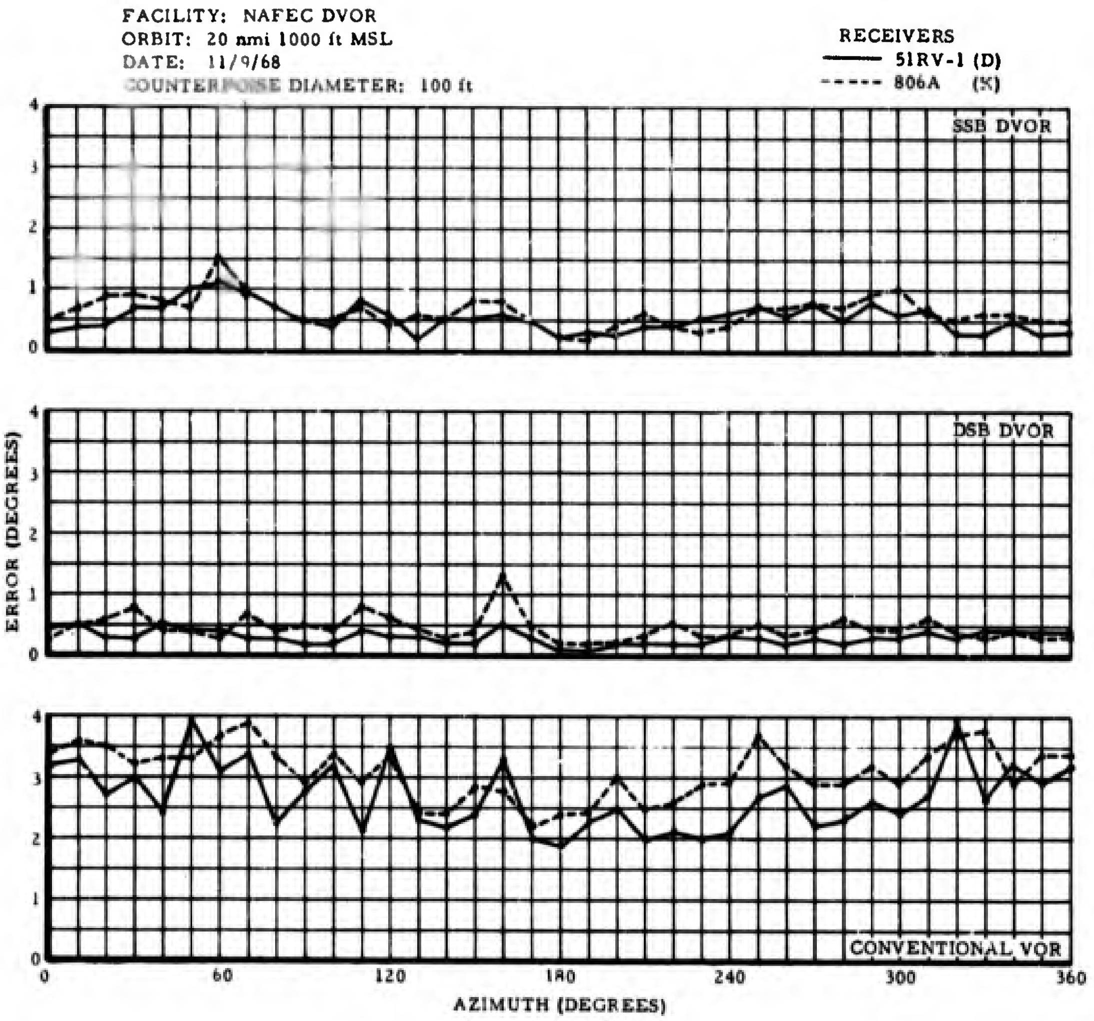


Figure 91. MAXIMUM SCALLOPING PER 10° SECTOR WITH TYPE 51RV1 (D) AND 806A (K) RECEIVERS, 100-FOOT COUNTERPOISE

THE AVERAGE VALUE OF MAXIMUM SCALLOPING

Receiver Code	A	B	C	F	I	G	D	J	H	K
Receiver Type	MN-85FA	51R3	RA21A	KX-160	DR-560	ARC-15G	51RV1	MARK-12	51X2B	806A
Counterpoise Diameter - 150'										
SSDVOR SYSTEM	0.3	0.3	0.3	0.3	0.5	0.3	0.4	0.3	0.3	0.4
DSDVOR SYSTEM	0.2	0.2	0.2	0.4	0.4	0.3	0.3	0.3	0.3	0.3
CONVENTIONAL VOR SYSTEM	1.4	1.5	1.6	2.1	1.9	1.3	1.9	1.7	1.6	1.6
Counterpoise Diameter - 100'										
SSDVOR SYSTEM	0.4	0.6	0.3	0.6	1.0	---	0.5	0.4	0.3	0.6
DSDVOR SYSTEM	0.3	0.3	0.3	0.4	0.6	0.4	0.3	0.4	0.3	0.4
CONVENTIONAL VOR SYSTEM	1.7	1.9	2.0	2.6	2.3	2.1	2.7	2.4	2.0	3.0

Figure 92. TABULATION OF THE AVERAGE VALUES OF MAXIMUM SCALLOPING

RECEIVER TOTAL ERROR SPREAD

SYSTEM		SINGLE SIDEBAND DOPPLER VOR			DOUBLE SIDEBAND DOPPLER VOR			CONVENTIONAL VOR		
Receiver Type	Orbit Number	Error Spread Total	Mean Error $\overline{X}$	Standard Deviation	Error Spread Total	Mean Error $\overline{X}$	Standard Deviation	Error Spread Total	Mean Error $\overline{X}$	Standard Deviation
MN-85FA A	1	2.2°	1.74°	0.65°	0.6°	1.59°	0.16°	3.4°	-1.06°	0.83°
	2	2.2°	1.65°	0.71°	0.8°	1.59°	0.21°	4.2°	-1.18°	0.97°
51R3 B	1	1.5°	1.59°	0.41°	0.6°	1.48°	0.16°	3.5°	-0.94°	0.82°
	2	1.5°	1.57°	0.49°	1.1°	1.57°	0.25°	3.8°	-0.96°	0.89°
RA-21A C	1	1.3°	1.90°	0.35°	1.4°	1.70°	0.35°	2.8°	-1.10°	0.65°
	2	1.0°	1.88°	0.35°	No Data			3.2°	-1.09°	0.78°
51RV1 D	1	2.3°	1.98°	0.65°	0.8°	2.33°	0.16°	3.4°	-1.06°	0.73°
	2	2.5°	2.51°	0.76°	0.7°	2.34°	0.19°	2.9°	-1.23°	0.74°
Wilcox 805A E	1	1.9°	2.21°	0.46°	0.9°	2.00°	0.29°	3.3°	-0.58°	0.76°
	2	1.6°	2.25°	0.47°	1.1°	2.12°	0.29°	3.6°	-0.60°	0.81°
51X2B H	1	1.2°	1.69°	0.30°	1.0°	1.62°	0.26°	3.2°	-1.05°	0.72°
	2	1.4°	1.67°	0.36°	No Data			3.9°	-1.19°	0.81°
SEAL Analog	1	1.3°	2.63°	0.40°	0.8°	2.16°	0.22°	4.4°	-0.33°	0.82°
	2	1.6°	2.61°	0.50°	0.8°	2.27°	0.23°	3.7°	-0.29°	0.80°
SEAL Digital	1	2.8°	3.09°	0.51°	2.0°	2.43°	0.31°	7.9°	-0.02°	1.12°
	2	2.9°	3.07°	0.53°	2.1°	2.57°	0.38°	7.1°	-0.08°	1.14°

Figure 93. TABULATION OF INDICATED SYSTEM ERROR

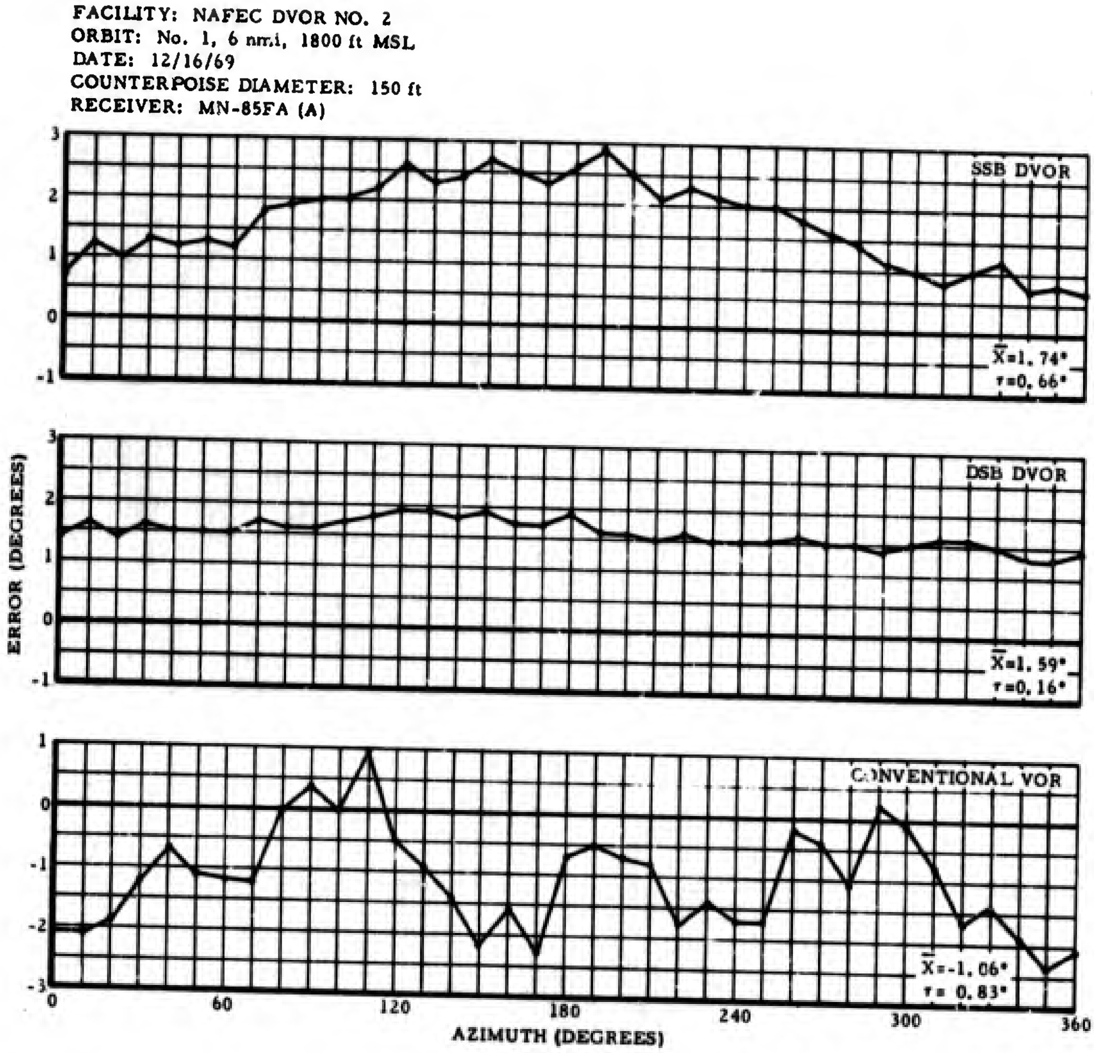


Figure 94. INDICATED STATION ERROR WITH TYPE MN-85FA (A) RECEIVER, 150-FOOT COUNTERPOISE

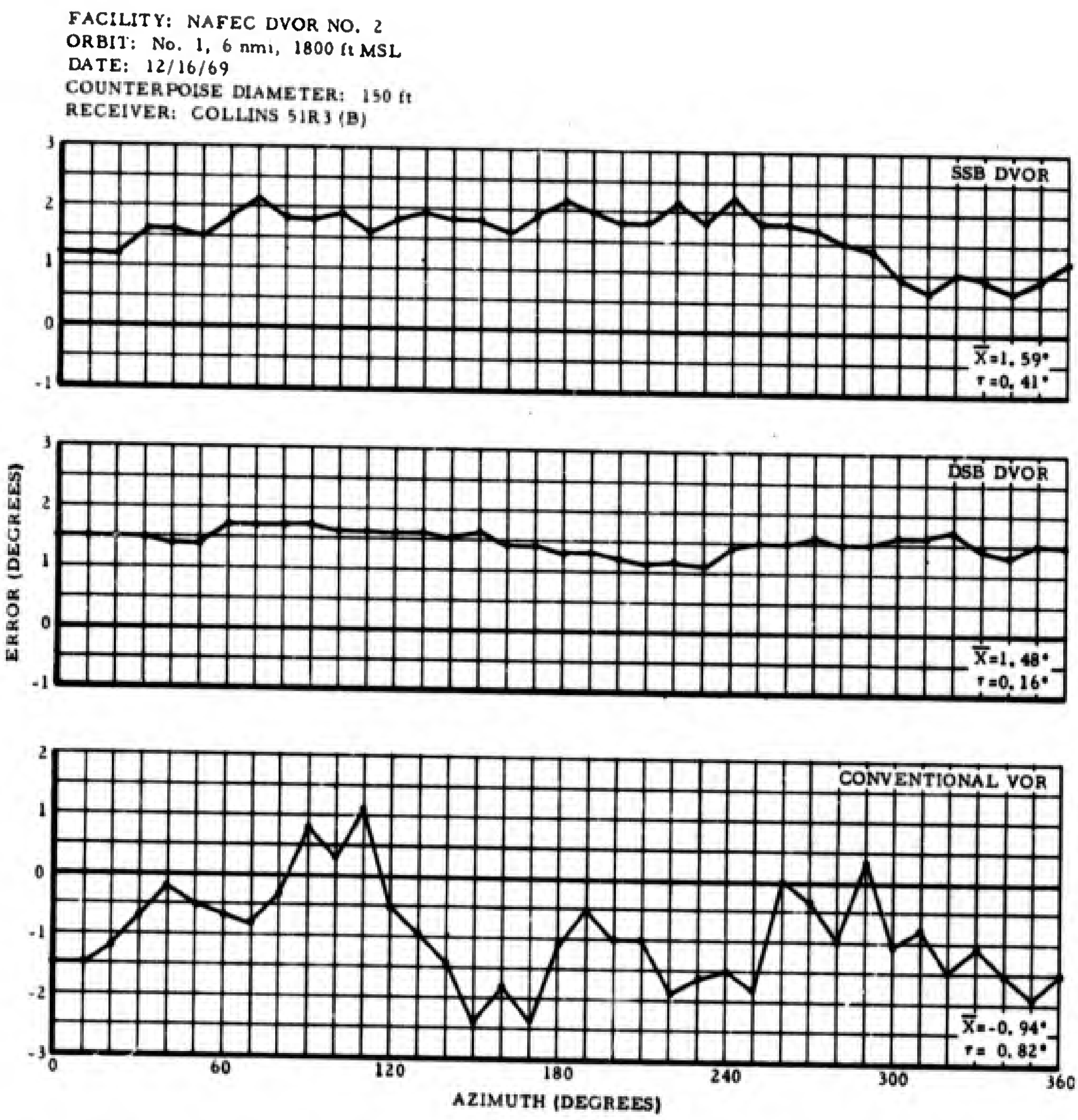


Figure 95. INDICATED STATION ERROR WITH TYPE 51R3 (B) RECEIVER, 150-FOOT COUNTERPOISE

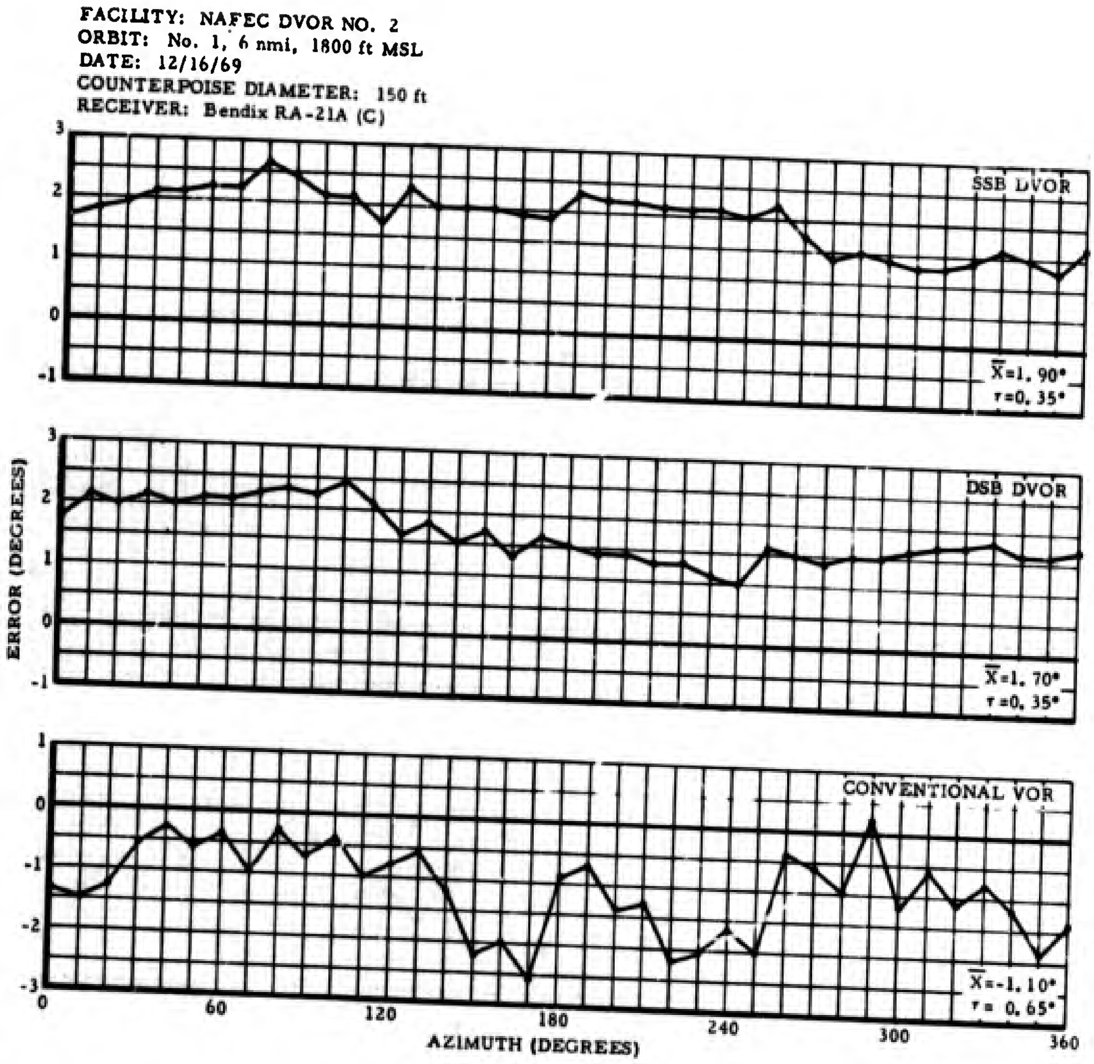


Figure 96. INDICATED STATION ERROR WITH TYPE RA-21A (C) RECEIVER, 150-FOOT COUNTERPOISE

FACILITY: NAFEC DVOR NO. 2
ORBIT: No. 1, 6 nmi, 1800 ft MSL
DATE: 12/16/69
COUNTERPOISE DIAMETER: 150 ft
RECEIVER: Collins 51RV1 (D)

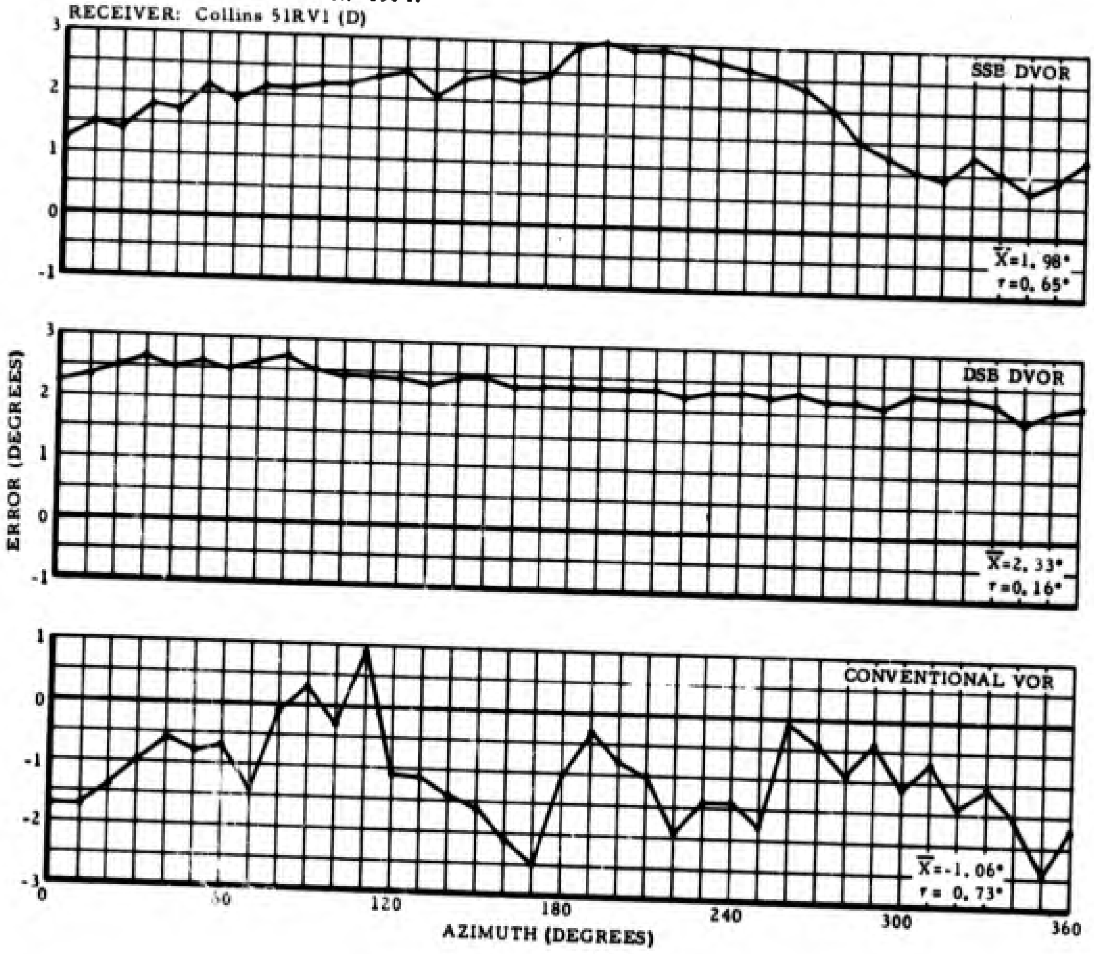


Figure 97. INDICATED STATION ERROR WITH TYPE 51RV1 (D) RECEIVER, 150-FOOT COUNTERPOISE

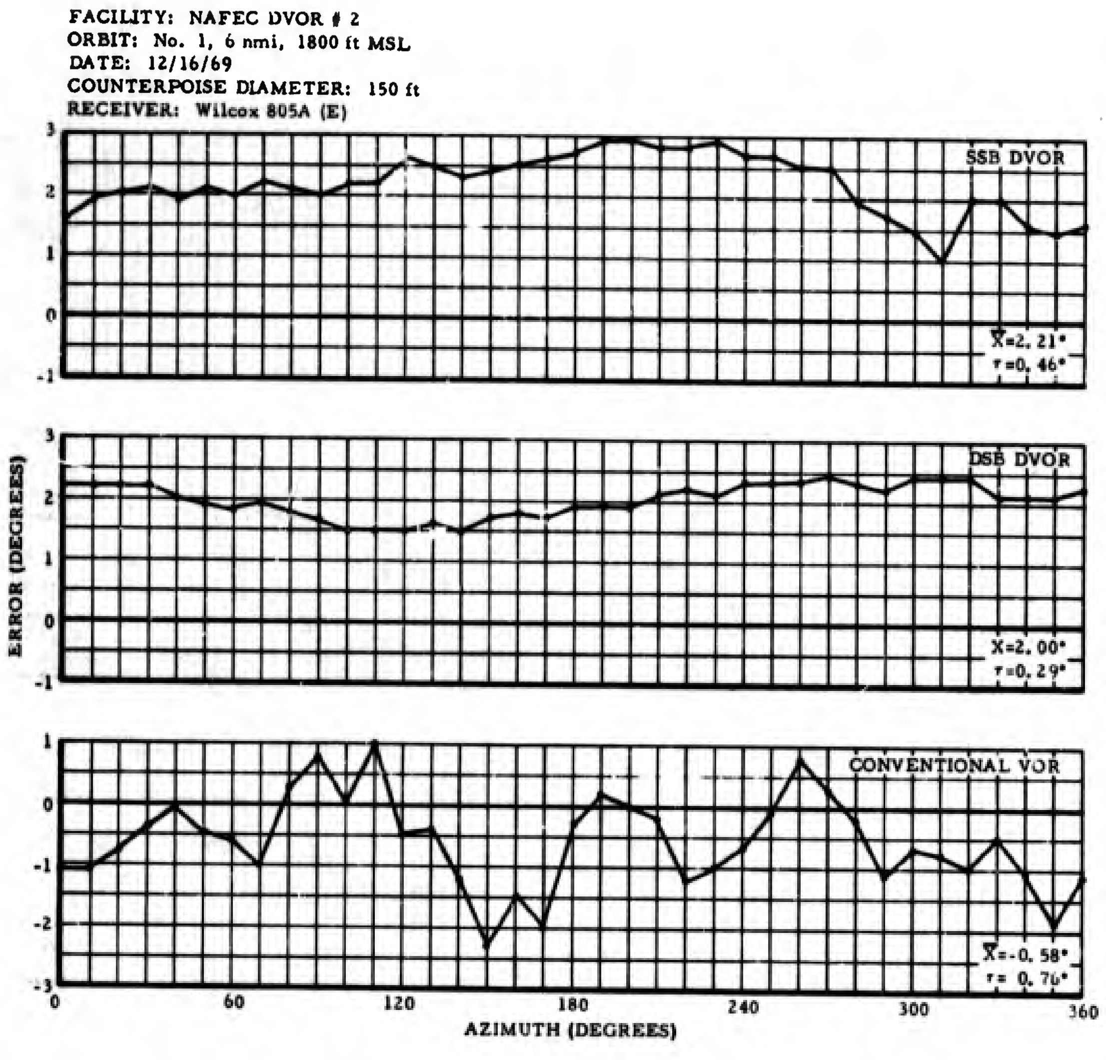


Figure 98. INDICATED STATION ERROR WITH TYPE 805A (E) RECEIVER, 150-FOOT COUNTERPOISE

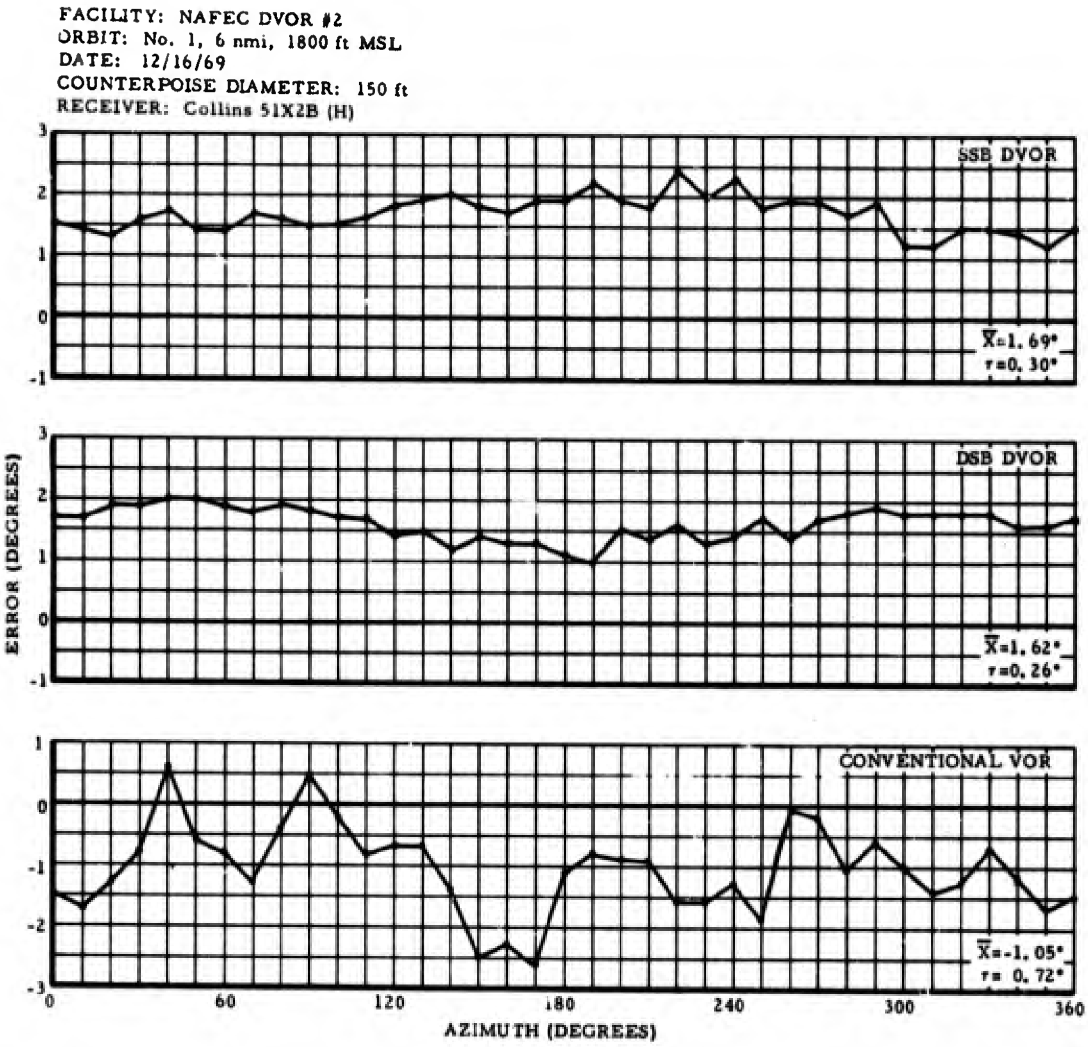


Figure 99. INDICATED STATION ERROR WITH TYPE 51X2B (H) RECEIVER, 150-FOOT COUNTERPOISE

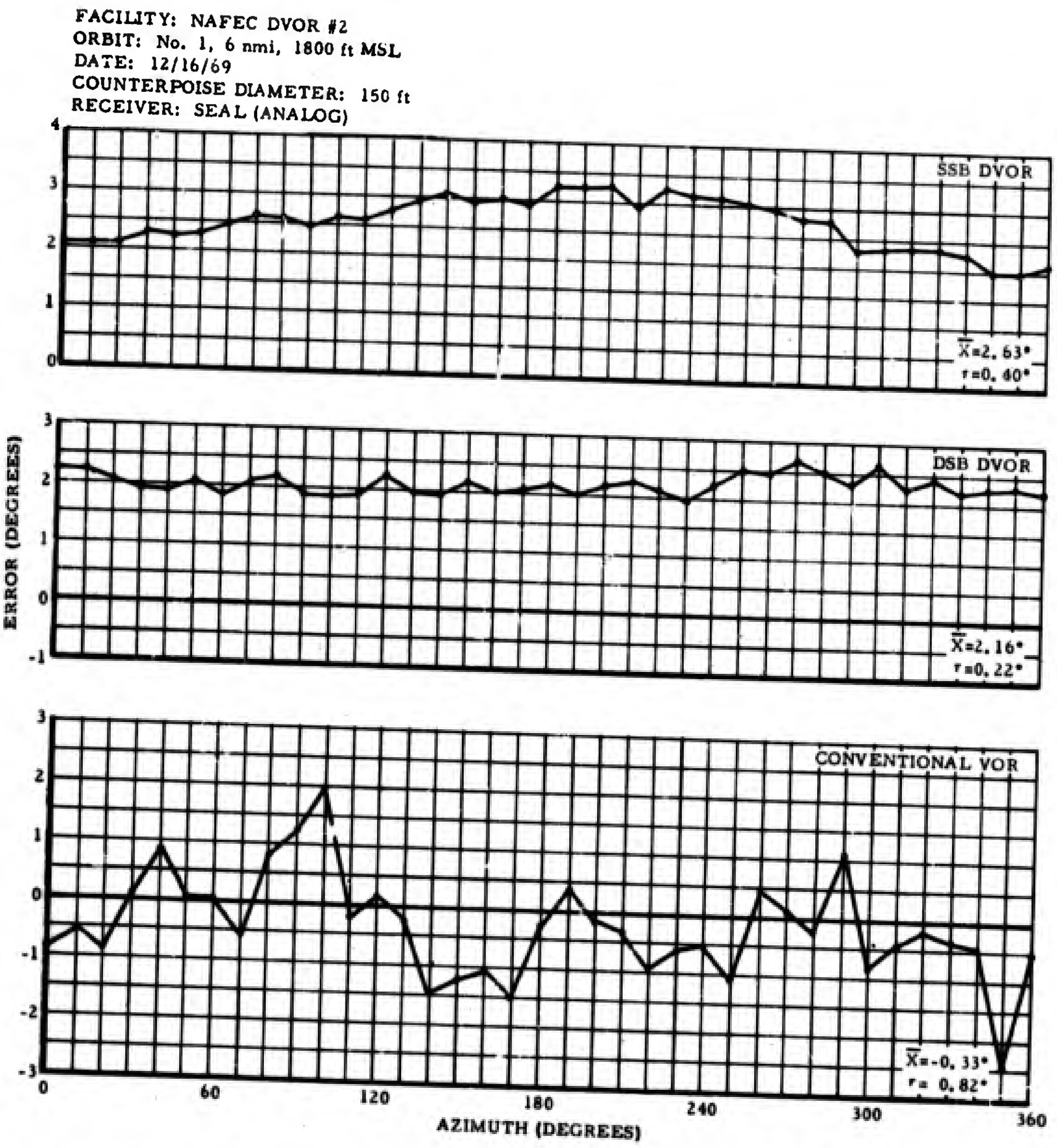


Figure 100. INDICATED STATION ERROR WITH ANALOG OUTPUT OF SEAL RECEIVER, 150-FOOT COUNTERPOISE

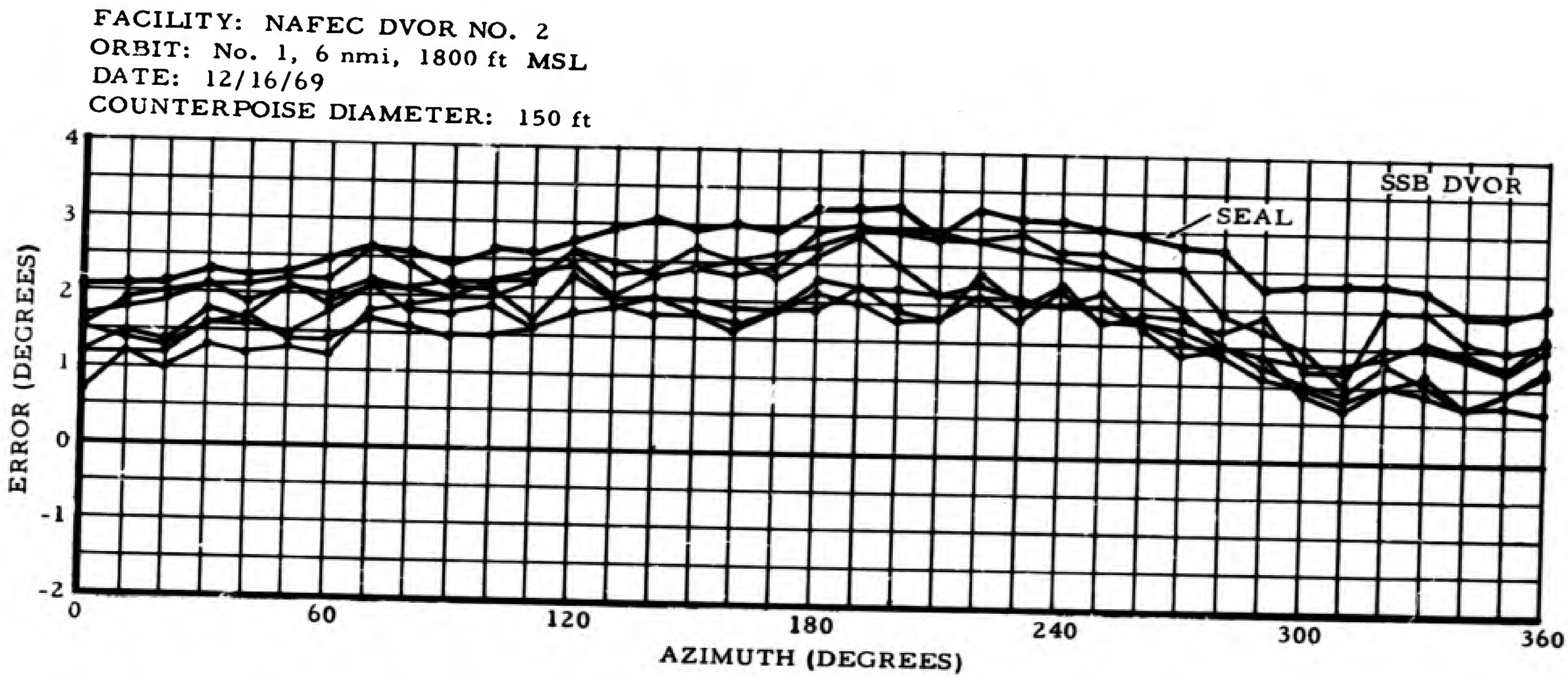


Figure 101. COMPOSITE INDICATED STATION ERROR ON SSDVOR

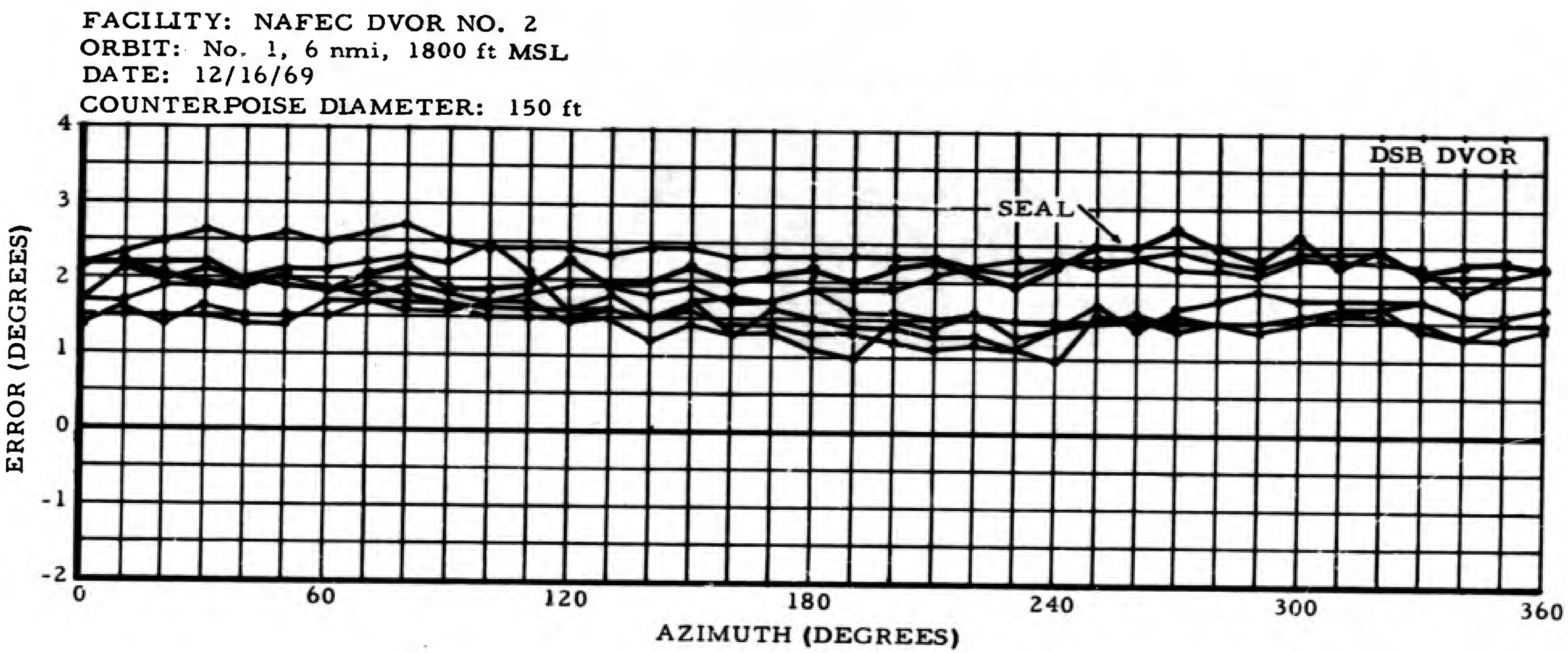


Figure 102. COMPOSITE INDICATED STATION ERROR ON DSDVOR

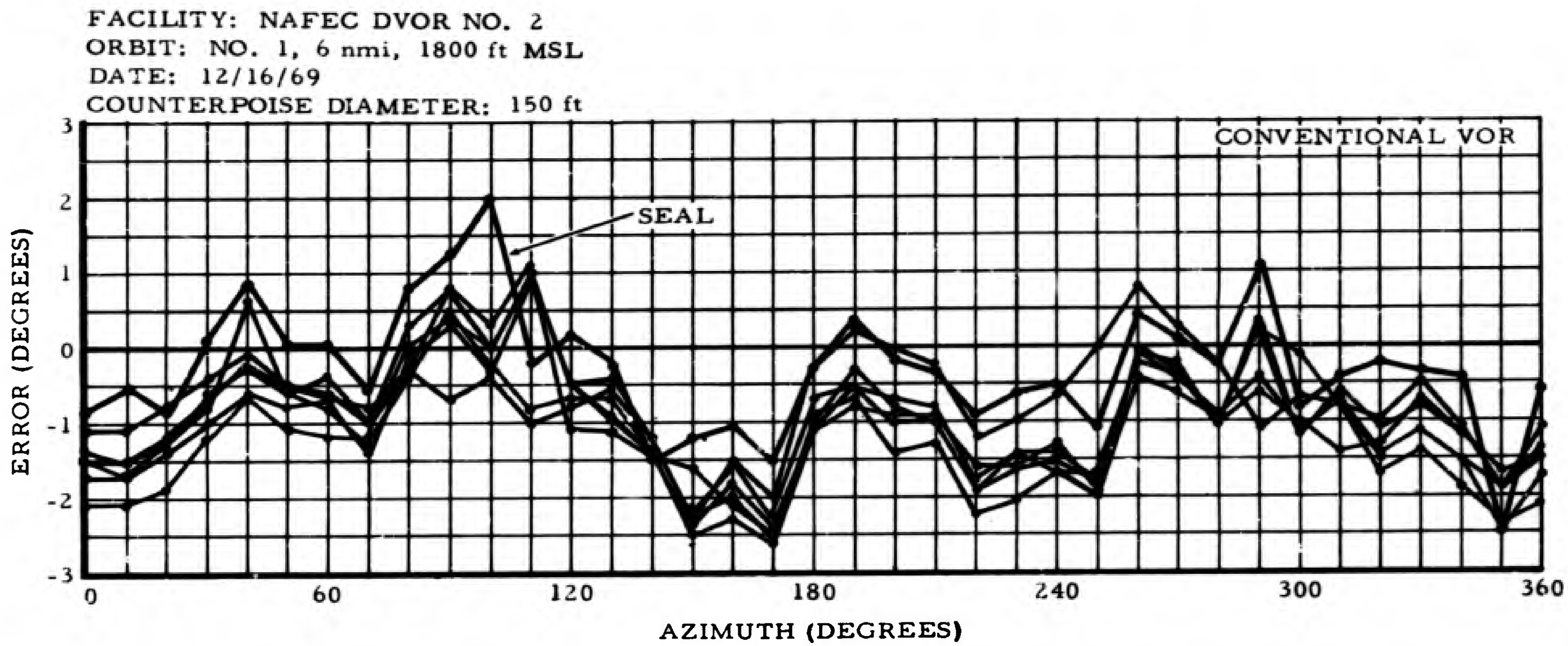


Figure 103. COMPOSITE INDICATED STATION ERROR ON CONVENTIONAL VOR

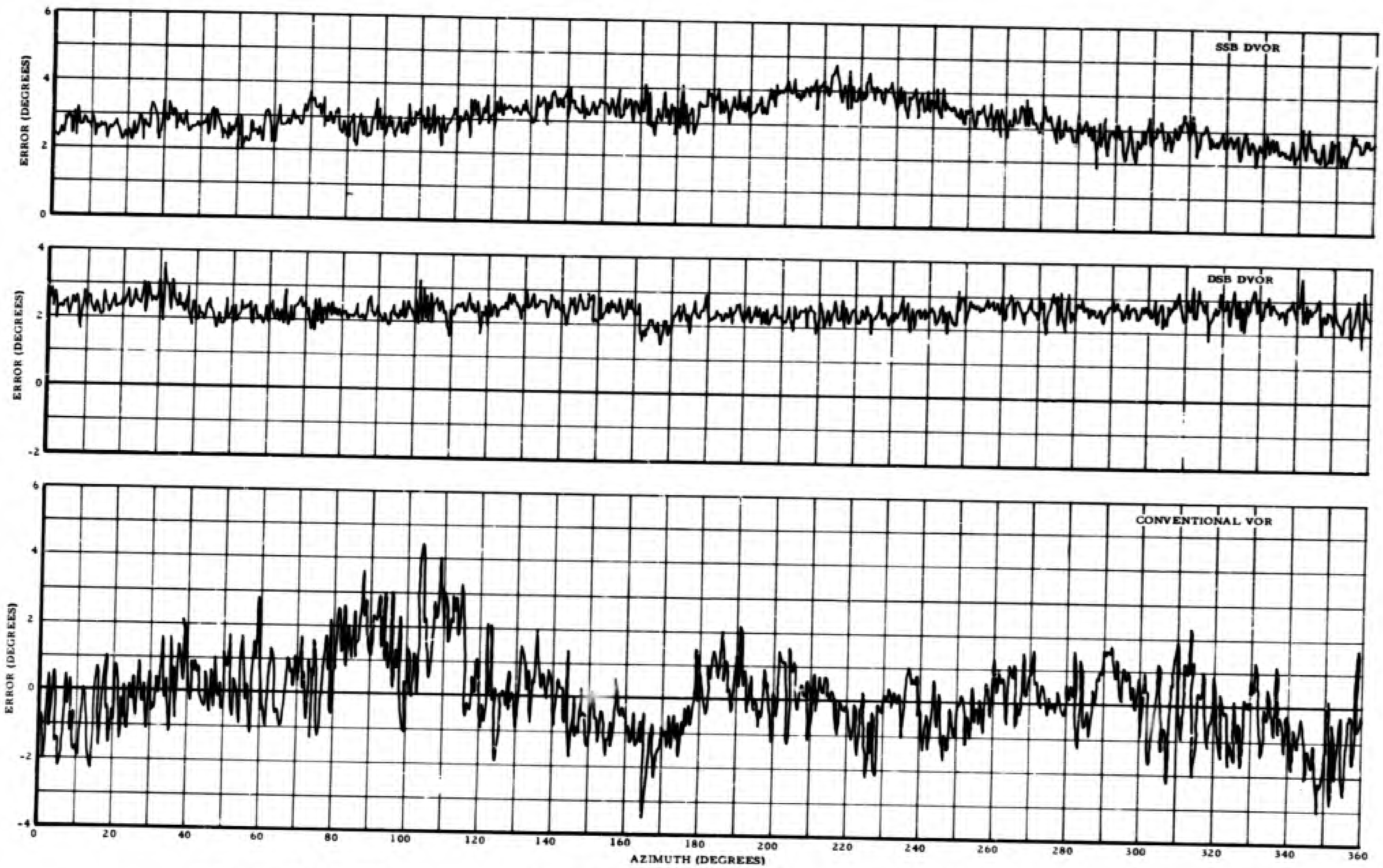


Figure 104. INDICATED STATION ERROR WITH DIGITAL OUTPUT OF SEAL RECEIVER, 150-FOOT COUNTERPOISE

SECTION II

HIGH LEVEL MODULATION SYSTEM

Background

The present type of commissioned Doppler VOR System utilizes a modulation eliminator, a capacitive goniometer, two 50-ohm loads, and an RF bridge, as illustrated in Figure 3, to provide the 30 Hz reference modulation of the carrier energy. The RF power loss, due to this method of providing the 30 Hz reference modulation, results in approximately one-half the carrier power of the Conventional VOR System. The field intensity at low elevation angles is further reduced by the large counterpoise. The reduced carrier power of the Doppler VOR System results in a reduction of the usable range. To make the Doppler VOR System more advantageous, the field intensity should be increased to equal that of the Conventional VOR.

DISCUSSION

One method of making the field intensity of the Doppler VOR equal to that of Conventional VOR is to increase the carrier power to overcome modulation losses. This would require approximately twice the power rating of the present carrier transmitter. Obviously, this would not only be costly but would have the disadvantage of requiring a special carrier transmitter for the Doppler facilities. Therefore, to increase the effective radiated carrier energy of present equipment, the efficiency of the 30 Hz amplitude modulation system must be increased.

The present method in use to provide the 30 Hz amplitude modulation of the carrier energy for the Doppler VOR System is a conversion of the modulation method used in the Conventional VOR System. Although this method is inefficient, the equipment was readily available and provided an interim method until more efficient equipment could be developed.

In the Conventional VOR the use of the capacity goniometer to provide space modulation of the carrier energy was necessary to provide a 30 Hz AM signal, the phase of which varied with azimuth (30 Hz variable signal). In the Doppler VOR the 30 Hz amplitude modulation of the carrier energy generates the fixed phase or reference signal. As the system requirements are for a fixed phase 30 Hz AM signal, high level modulation of the carrier transmitter with a 30 Hz voltage is possible if a means is provided to maintain a constant phase angle of the 30 Hz transmitted signal. This requirement can be fulfilled with an APC unit, illustrated in the simplified block diagram of Figure 105. APC of the transmitted 30 Hz AM signal is necessary because a slight variation in tuning of the transmitter's modulated stage causes a small impedance change, resulting in a change of the phase angle of the transmitted 30 Hz AM signal. This would result in a change in the course alignment for the Doppler VOR System.

Description

Referring again to the simplified block diagram of the APC unit given in Figure 105, it can be noted that a 30 Hz reference voltage is derived from an alternator attached to the distributor drive motor. The 30 Hz voltage is supplied to the phase comparator block and through the phase shifter and modulator to the carrier transmitter where the carrier energy is modulated by the 30 Hz signal. A sample of the modulated RF energy supplied to the carrier antenna is demodulated to obtain a 30 Hz voltage which is supplied to the phase comparator, where the phase of the detected 30 Hz is compared to the phase of the 30 Hz reference input. An "out of phase" condition will generate an error voltage which will shift the phase of the 30 Hz reference voltage being supplied to the modulator. A balance will be achieved when the detected 30 Hz voltage is in phase with the 30 Hz reference voltage under which condition there will be a zero error voltage. Detailed circuits and functions are described in FAA Report No. RD-65-45, "Development of a Prototype Double Sideband Doppler VOR Transmitter Carrier Modulator." One can see by analysis of the block diagram of the APC unit of Figure 105, that any phase change due to components or circuit adjustments throughout the entire modulation circuitry including the transmitter will be corrected.

A block diagram of a DSDVOR System, which makes use of the high level modulation system, is given in Figure 106. It will be observed that the capacity goniometer has been replaced with a 30 Hz generator. The modulation bridge and balancing load with its 3 dB carrier power loss and the modulation eliminator with its contribution to carrier power loss are no longer required. The carrier modulator driver and carrier modulator have been replaced with a redesigned modulator which includes the circuitry for the APC function.

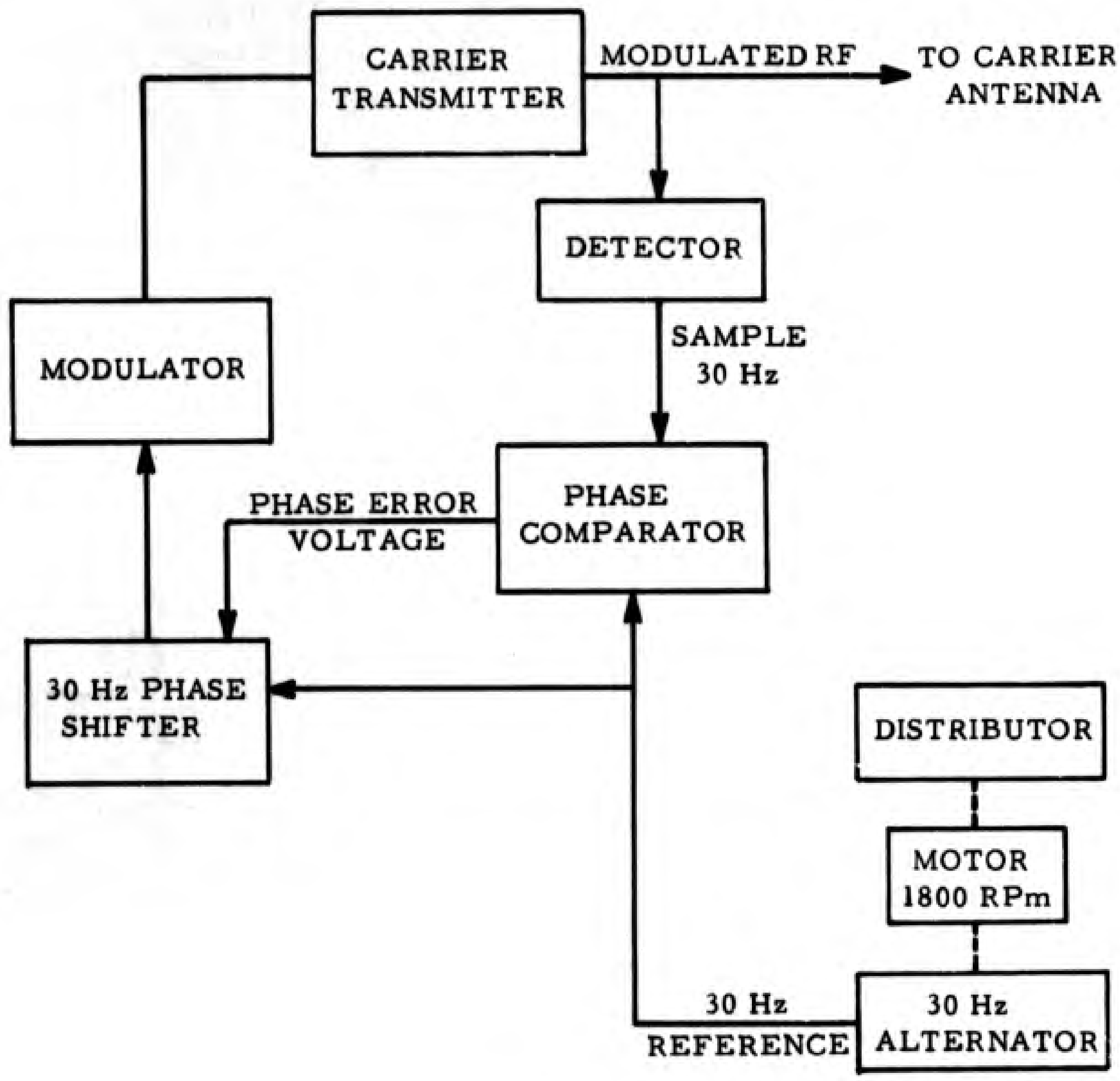


Figure 105. SIMPLIFIED BLOCK DIAGRAM OF AUTOMATIC PHASE CONTROL UNIT OF THE 30 HZ REFERENCE

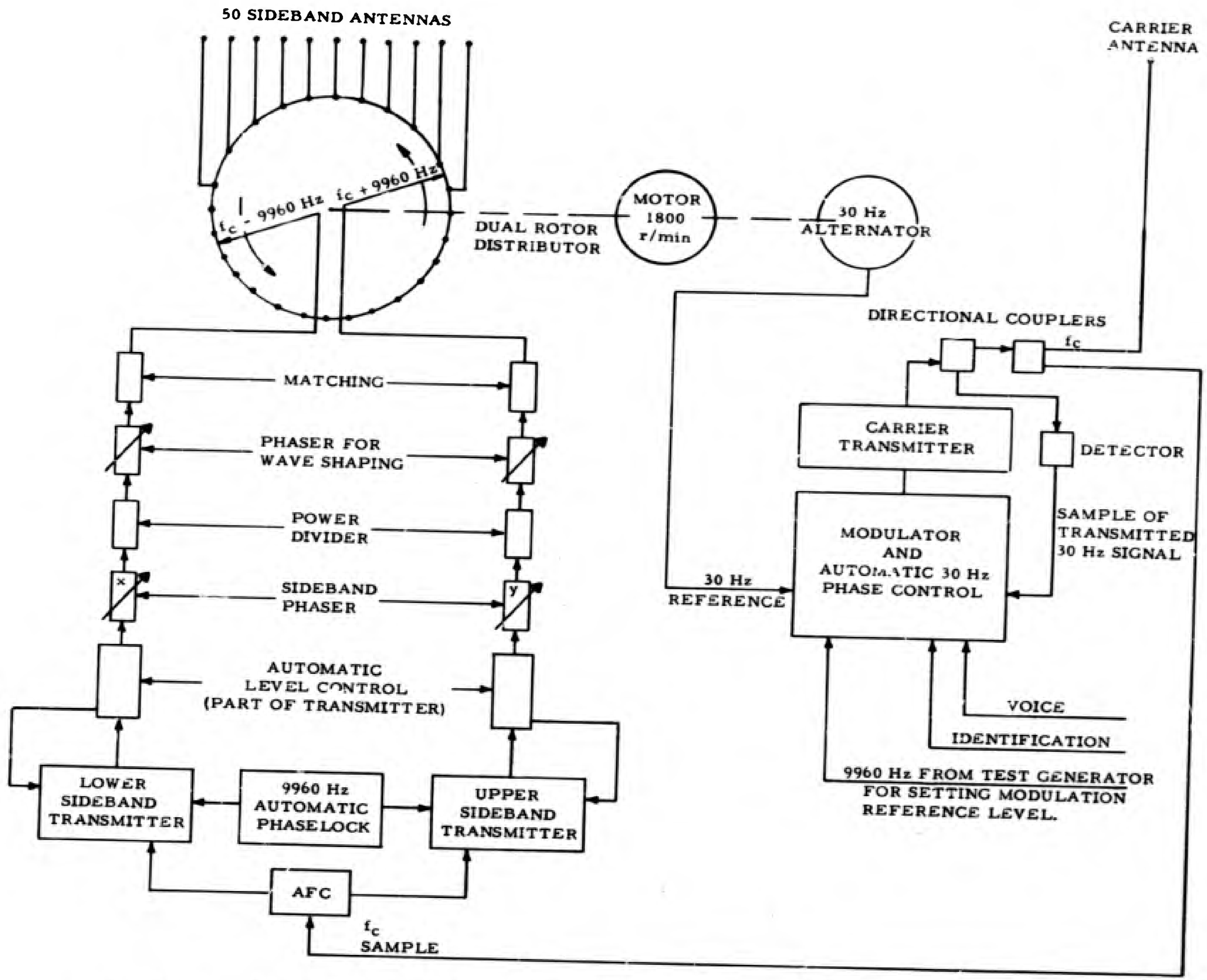


Figure 106. BLOCK DIAGRAM OF DSDVOR WITH HIGH LEVEL MODULATION

Redesign of the carrier modulator driver and the carrier modulator was necessary since they were not designed to pass a 30 Hz signal. In the redesign of these units, it was possible by the use of solid-state circuitry to combine their functions into one unit including the APC. The panel space required for the new modulator is the same as the combined space requirements of the carrier modulator driver and carrier modulator units.

As the 30 Hz AM modulation is independent of the 9960 Hz generation, the high level modulation techniques will function on either the SSDVOR or DSDVOR Systems.

Flight Tests

The data from flight tests of the SSDVOR and DSDVOR Systems, as outlined under Flight Tests of Section I, were obtained with the high level modulation equipment installed and operating as an integral unit of the Doppler VOR Systems.

SECTION III

EQUIPMENT DEVELOPMENT

DISCUSSION

Double Sideband Transmitters

System Requirements: In the DSDVOR, the generation of the sideband pair ($f_c \pm 9960$ Hz) by separate transmitters requires careful consideration of modulation fundamentals. The basic equation for double sideband amplitude modulation

$$\left(e(t) = E \sin (W_c t + \phi) + \frac{ME}{2} \sin \left[(e_c + e_m) t + \phi \right] + \frac{ME}{2} \sin \left[(e_c - e_m) t + \phi \right] \right)$$

states that amplitude modulation of a carrier by a sine wave adds two additional sinusoidal components which are displaced equally in frequency (above and below) to the carrier. The displacement from the carrier frequency is equal to the frequency of the modulating sinusoid. Pure amplitude modulation will exist only when the phase angle between the upper sideband and the carrier is opposite in sign and equal in magnitude to the phase angle between the lower sideband and the carrier as illustrated in the vector diagram of Figure 107. Since the method of generating and radiating the separate sidebands in the DSDVOR System is unique and since the separate sidebands must be dealt with in separate circuits and delivered to separate feed systems, care must be taken to produce a spectrum which does in fact meet the above conditions. To assure that a spectrum will be produced which meets the above conditions, the separate sideband transmitters must have automatic frequency control (AFC) circuitry to maintain the upper sideband energy at 9960 Hz above the carrier frequency and the lower sideband at 9960 Hz below the carrier frequency. Any shift in the carrier frequency must produce an equivalent shift in both sideband frequencies with respect to the carrier. To maintain the correct phase relationship between the two 9960 Hz RF sidebands and the carrier, APC circuitry is required. In addition, to maintain the RF level of each sideband transmitter to a preset value an automatic level control (ALC) is required.

Background (Historical): The requirements for dual-channel heterodyne sideband generation for the DSDVOR System are formidable in appearance; yet the techniques to accomplish the desired results are numerous. The problem then was not how to meet the system requirements from a technical standpoint, but was the selection of a technique which would provide the greatest reliability and minimum equipment with the least complexity for ease of adjustment.

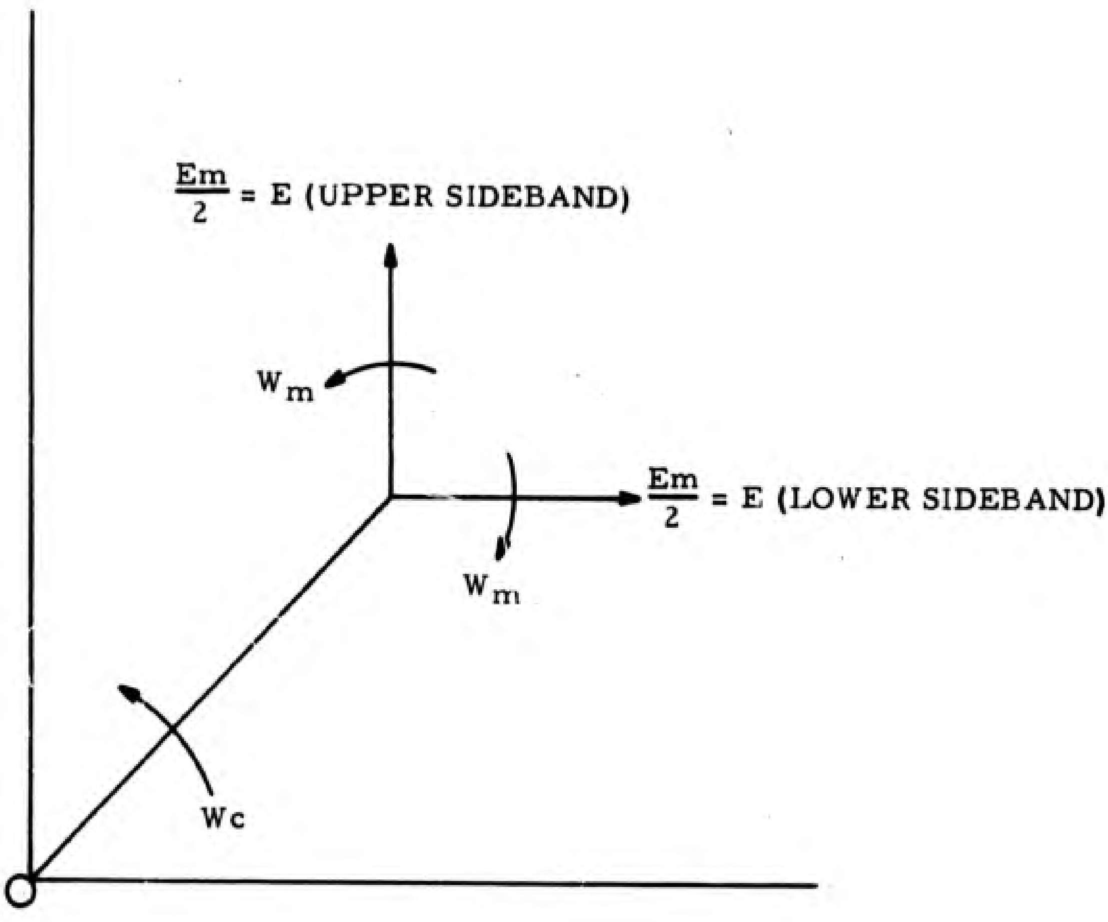


Figure 107. VECTOR DIAGRAM OF DSDVOR 9960 HZ AM MODULATION

Accordingly, SRDS issued a proposal for the design and development of feasibility models of double sideband transmitting equipment. Contracts were subsequently awarded to Collins Radio Company of Cedar Rapids, Iowa, and to Hazeltine Technical Development Center of Indianapolis, Indiana. Each of the two contractors was to use a different technique in the generation of the double sideband energy. The Collins equipment made use of the heterodyne-balanced modulator filter technique in the generation of the upper and lower sideband energy. The equipment is described in detail in Report Number AD 432 709 (Reference 6). The Hazeltine equipment made use of the AFC technique in which the sidebands are developed and controlled independently. Each AFC circuit performs a phase comparison between a common reference 9960 Hz and the 9960 Hz heterodyne between one sideband and the carrier to develop an error control voltage which is applied as a correction to the voltage-tuned oscillator of the associated sideband transmitter. Complete details of the circuits and equipments are given in Report No. AD 612 423 (Reference 7).

The best circuit features of the two feasibility models of double sideband transmitter equipments were used in writing the specifications for a prototype model. The development of the prototype double sideband transmitter was awarded to the Wilcox Electric Company, Kansas City, Missouri, under Contract FA-WA-4646.

Tests: Factory inspection and tests were conducted in detail for assurance of compliance with the contract specification and performance criteria. NAFEC tests were therefore limited to evaluation of operational deficiencies with the equipment installed and functioning as an integral part of the DSDVOR System. Deficiencies noted and comments follow:

1. The most annoying deficiency encountered in the equipment operation was not one of circuit design, but the selection of hardware. The dials used for the tuning of the transmitter continuously gave trouble due to slippage of the friction drive.

2. Under certain combinations of output coupling adjustment and grid drive value, there is a very slight indication of double dip in the plate current of the final RF stage as this stage is tuned through

resonance. No indication of oscillation in the circuit could be detected; nor could any detrimental effect to system performance be detected.

3. In adjusting L-306 of the frequency control unit through its range of adjustment, little, if any, effect to the waveform amplitude could be detected. This adjustment could perhaps be a factory-fixed adjustment.

4. The adjustment of the trimmer capacitor (reference number C-190) of the lower sideband is very critical since only 180° of rotation cover its full value. A piston-type of capacitor should be used to provide many turns of rotation to cover the range of capacity. This would give less capacity change per degree of shaft rotation.

5. The installation of a meter in each of the two sideband channels of the frequency control unit to indicate "lock-on" and departure from "lock-on" would provide ease of adjustment and maintenance. The meter could be driven by feedback from the error voltage derived from the phase detectors used to control the voltage applied to the voltage-tuned sideband oscillators.

The adjustment required for frequency and phase alignment would be made easier by the use of a frequency counter. However, the system is not difficult to adjust when the instruction book procedures are followed step by step with a knowledge of what is to be achieved for each adjustment.

Failures which have occurred during 3 years of intermittent operation of two units of equipment, other than normal tube replacements, are:

1. One failure of capacitor (reference number C-190).

2. One failure of the diode rectifier (reference number CR-509) of the high voltage supply.

3. Two failures of diode rectifiers (reference number CR-503 and CR-504) of the bias supply.

The number of components could be reduced by the use of solid-state devices, particularly in the frequency control unit. The advances and improvements made in solid-state devices since the design of present equipment warrant consideration of their usage in future equipment procurement.

High Level Modulation Equipment

System Requirements: The system requires an amplitude-modulated 30 Hz reference phase voltage obtainable by high level modulation of the carrier energy requiring a modulation system capable of passing a 30 Hz voltage without distortion. In addition, the circuitry must provide APC, as previously discussed, to correct any phase change in the transmitted 30 Hz which may occur due to perturbation in the modulation systems.

Background: The concept of modulating the carrier energy from a 30 Hz voltage source to provide the reference phase voltage for the Doppler VOR System dates back to the early development effort of the SSDVOR. The first tests were conducted in August 1958, at Charleston, South Carolina, by the Technical Development Center of the former Civil Aeronautics Administration during siting tests of the present Doppler VOR System. Although the modulation system components were not designed to pass a 30 Hz signal without distortion, the tests indicated that with a modulator designed to pass a 30 Hz signal and with the inclusion of APC circuitry for phase stabilization of the transmitted 30 Hz reference phase signal, the technique of high level modulation of the carrier energy was feasible. Development of a modulator with APC of the 30 Hz voltage would be necessary before implementation of the high level reference modulation techniques.

In September 1959, the Systems Research and Development Service awarded Contract Number FAA/BRD-143 to the Servo Corporation of America for the development of an SSDVOR System and the development of a high level reference modulation technique. Due to difficulties and delays in the development program, the contract was not completed successfully. Upon delivery of equipment from the contract, tests and development of the high level reference modulation technique were continued as an "in house" effort at NAFEC, culminating in the development of the specifications for a prototype production model.

In June 1963, Systems Research and Development Service awarded Contract Number FA-WA-4646 to the Wilcox Electric Company for the development of prototype production models of a carrier modulator which included an APC circuit for the high level reference modulation of the carrier transmitter. Development effort and circuit details are given in their Report Number RD-65-44 (Reference 5), "Development of Prototype Double Sideband Doppler VOR Transmitter and Carrier Modulator."

Tests: Tests were conducted at the manufacturer's plant for compliance with contract specifications. The results of these tests are included in the aforementioned report. Tests at NAFEC, limited to notation of operational deficiencies during the 3 years of intermittent operation of two units of equipment, yield no major operational deficiencies. However, for future equipment procurement, consideration should be given to the following:

1. The circuit design requires a large time constant for the 30 Hz phase control loop. This results in long periods of waiting for lock-on to occur during alignment. The inclusion of a push-type switch to remove a large portion of the capacitance of C-116 to reduce the phase control lock-on response time would allow adjustments without the long periods of waiting for lock-on to occur. This was brought to the attention of the contractor and has been included as a recommendation in their development report.

2. In the adjustment of the static and dynamic response of the modulator, it is necessary to remove one lead from each of the capacitors C-203 and C-204. This is not only awkward and inconvenient, but also places wear and mechanical strain on the capacitor terminals, which after repeated adjustments may result in failure of the capacitors. An improved method to remove capacitors from the circuit should be devised for production models.

3. Test points for hum measurements should be brought out to test points instead of the use of leads attached to circuit components.

While the above may appear trivial, when one considers the 4CX250B modulator tube life of only 1,000 hours before replacement, the reduction of maintenance time would warrant consideration of the above changes.

In addition, the modulator is of a hybrid design making use of solid-state devices for the low signal level stages and vacuum tubes for the high signal stages, because at the time of design there were no large power transistors capable of the required output. With the advances in the "state-of-the-art," consideration should be given to an all solid-state modulator. This would not only reduce the physical size but would eliminate the high voltage power supply required for the modulator tubes and would reduce the maintenance time associated with the modulator tube replacement.

Failures: To date the only modulator component failures, other than normal tube replacement, which have occurred for the two units in operation are as follows:

1. Two transistor failures (reference number Q125, type 2N2498).

2. One output transformer failure (reference number T-201) due to internal short.

3. The 30 Hz AM level control potentiometer (reference number R-185) of both equipments became noisy and required replacement.

4. One failure of the 4XC250B tube socket due to a short.

5. The safety air switch would occasionally fail to operate due to insufficient air flow past the 4XC250B modulator tubes.

Distributors

System Requirements: Briefly stated, the function of the distributor is to couple sideband energy to each of the sideband antennas, in succession, to produce simulated motion. A detailed discussion is given in Section I.

Background: The problems of distributor design for the DSDVOR System are greater than those of the SSDVOR System, since provision must be made for coupling two separate isolated sideband signals to separate rotors. The simple expedient used in the single sideband distributor of mounting a metal disc in the center of the rotor, as shown in Figure 6, to form one plate of a coupling capacitor will not work on a distributor requiring dual inputs.

The use of capacitive rings as a means of coupling energy to the rotor coupling bars will, in addition to increasing the leakage to adjacent antenna outputs, present problems in maintaining the RF energy at the same relative phase angle as it is coupled, in succession, to each of the outputs. This can best be explained if we assume that the rotor coupling ring feed point for the antenna coupling bar is positioned directly opposite the energy feed point of the stator ring. The RF phase angle of the energized antenna is measured as θ. Then the rotor is moved mechanically 180° to energize the opposite antenna. The RF phase angle measured at this antenna becomes θ plus the electrical distance around the coupling ring.

From the foregoing discussion, it is apparent that the design problems of a dual-channel distributor are both mechanical and electrical requiring development effort for a solution. Therefore, Contract Number FAA/BRD-376, awarded to Hazeltine Corporation for the development of Double Sideband Doppler VOR equipment, included the development of a dual-channel distributor. This contract was subsequently terminated when it became apparent that the distributor would require an excessively large drive motor due to the large mass of the rotor. Details of their development effort are given in Report Number AD 612423 (Reference 7).

Also included in Contract Number FAA/BRD-404, awarded to Collins Radio Company of Cedar Rapids, Iowa, for the development of Doppler VOR Dual Sideband equipment, was the development of a dual-channel distributor. A photograph of the distributor is given in Figure 108. Various parts of the distributor are given in Figures 109 through 112. Development details of the Collins dual-channel distributor are given in Report Number AD 432709 (Reference 6).

The termination of the Hazeltine distributor development left only one approach to solution of the design problems of a dual-channel distributor. It was desired to have at least two approaches to the design problems, and since the Jansky and Bailey Division of Atlantic Research Corporation of Alexandria, Virginia, had successfully produced a single-channel distributor, Contract Number FAA/ARDS-560 was modified to include the effort necessary for modification of one of their production models of the single-channel distributor to a dual-channel unit. Subsequently added to the contract was the fabrication of a 52-output dual-channel distributor for use in a multi-lobe Precision VOR - Doppler VOR project.

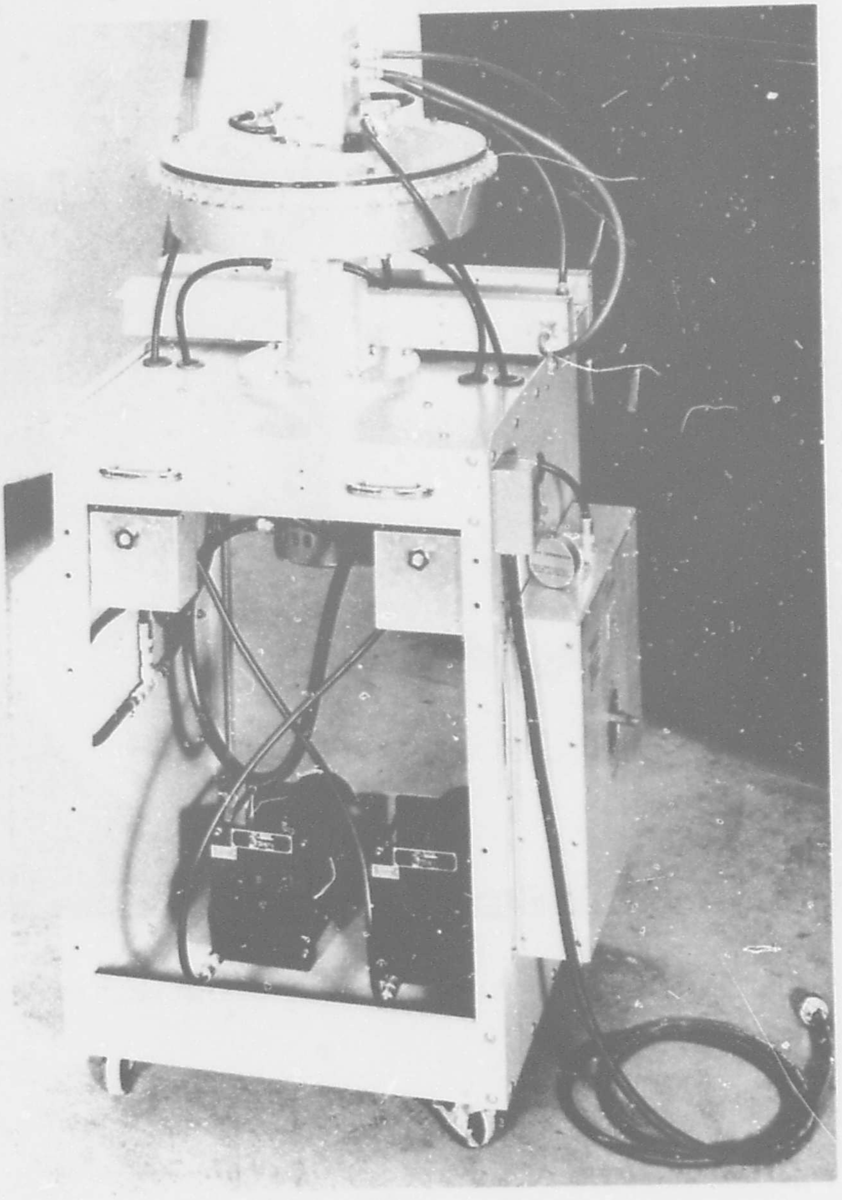


Figure 108. PHOTOGRAPH OF COLLINS VOR DISTRIBUTOR AND CART

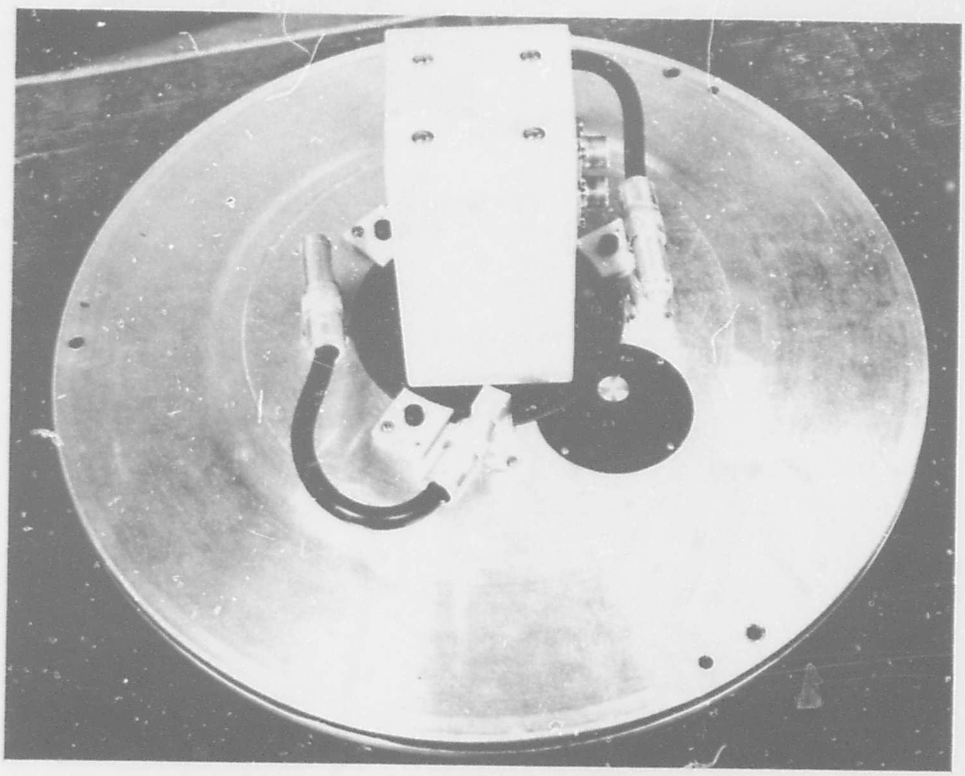


Figure 109. VOR DISTRIBUTOR, TOP COVER WITH GONIOMETER ATTACHED

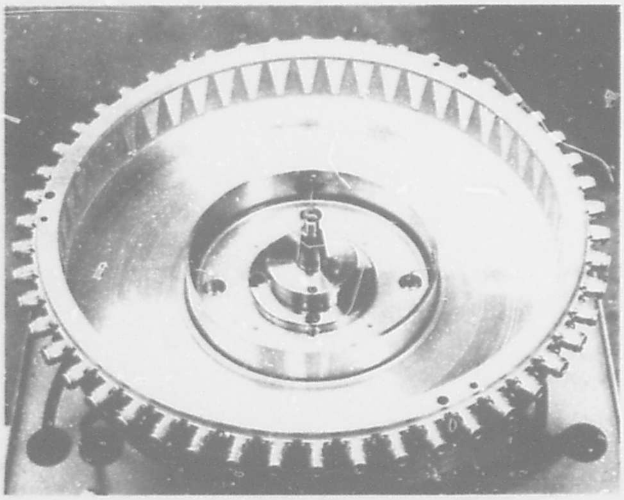


Figure 110. VOR DISTRIBUTOR, ROTOR REMOVED

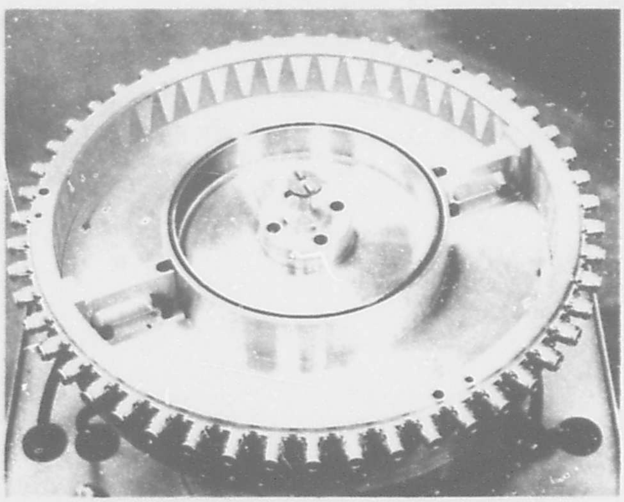


Figure 111. VOR DISTRIBUTOR, ROTOR ATTACHED

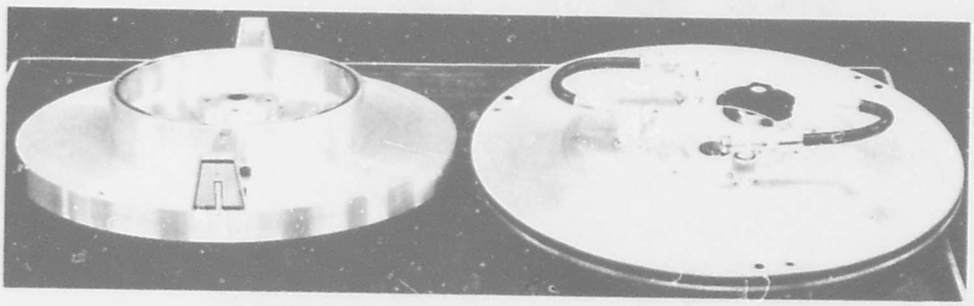


Figure 112. VOR DISTRIBUTOR, ROTOR ASSEMBLY AND TOP COVER

The necessary modification of the Jansky and Bailey distributor from single sideband to double sideband operation required only the redesign of the rotor to provide two output coupling bars, and the redesign of the input coupling system to provide dual input capability. The redesigned input coupling had two cylindrical capacitors in tandem. The capacitors are approximately 1 inch in diameter, 1 inch long, and are spaced 1 inch apart. The stator portion of the cylindrical input coupling capacitor is secured to the distributor cover plate, as shown in Figure 113. The stator fits inside the rotor portion of the input coupling capacitor. The rotor portion of the input coupling capacitor is mounted on the distributor rotor as shown in Figure 114.

Details of distributor development by Atlantic Research Corporation are given in FAA Report No. FAA-RD-69-68, (Reference 9).

Tests:

Hazeltine Distributor - No tests were made because the unit was not completed.

Collins Distributor - Most of the early development effort of the DSDVOR System made use of the Collins distributor. Tests were made of the Collins distributor, and the results compared with similar test results made of a Jansky and Bailey single sideband distributor, Type No. FA-5632, Serial No. 42, which was the design standard for production models presently used in the SSDVOR System. The results of the comparison are as follows:

1. Output Voltage Variation - The Collins distributor exhibited an output voltage variation of $\pm$ 6 percent compared to $\pm$ 3 percent variation of the Jansky and Bailey standard distributor.

2. Adjacent Output Isolation - The RF leakage from the driver output into the adjacent outputs averaged -26.1 dB for the upper sideband and -26.9 dB for the lower sideband, compared to -33.4 dB for the single-channel Jansky and Bailey standard distributor. Plots of output voltage variation and of isolation of antenna outputs are given in Figures 115 and 116, respectively.

3. Sideband Isolation - A comparison of the isolation between the two sideband channels of the Collins distributor cannot be made with the Jansky and Bailey standard distributor, as the latter is of a single-channel design. The isolation between the two sideband channels measured approximately -27 dB.

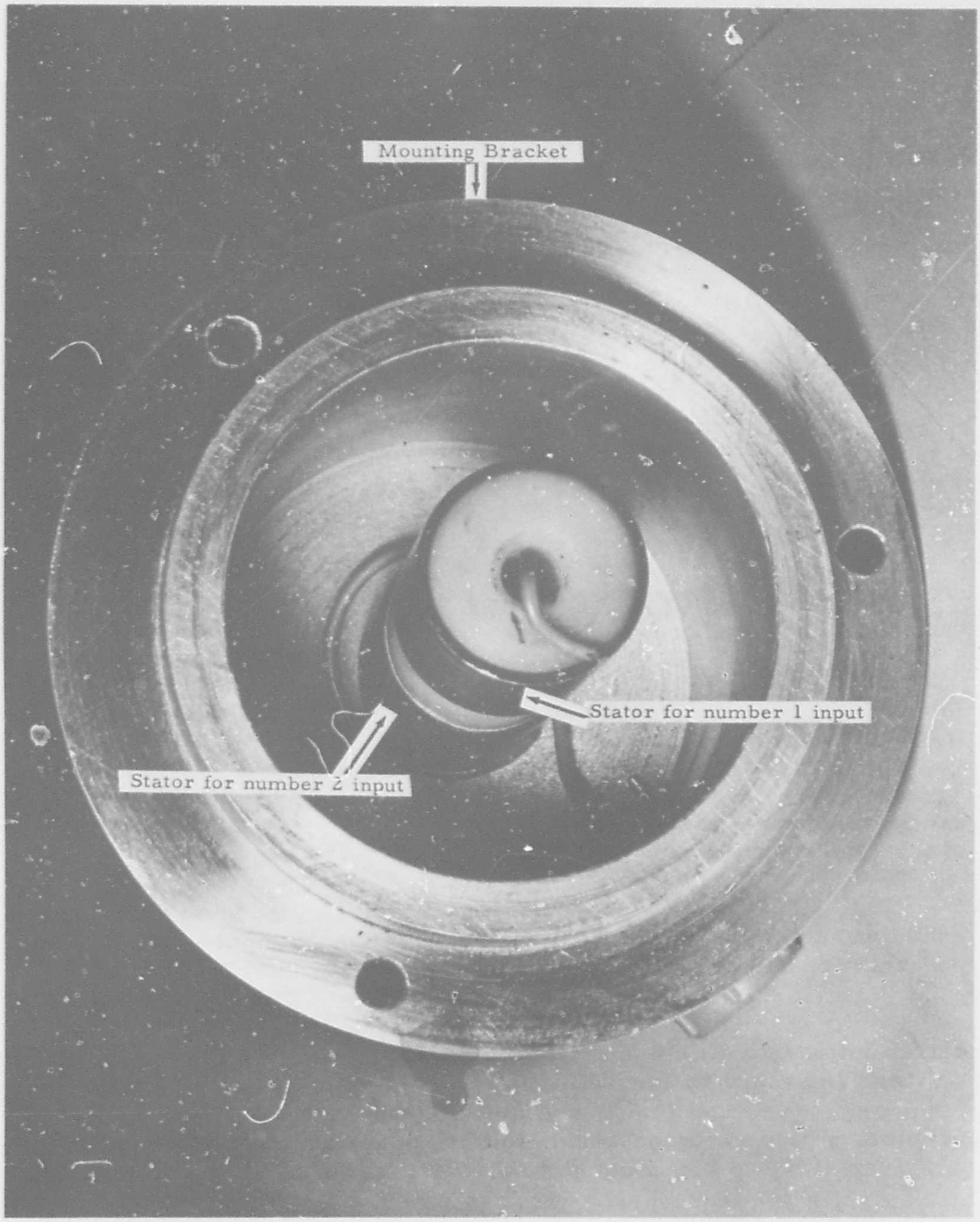


Figure 113. STATOR OF THE INPUT COUPLING CAPACITOR AND MOUNTING BRACKET OF THE JANSKY AND BAILEY DOUBLE SIDEBAND DISTRIBUTOR

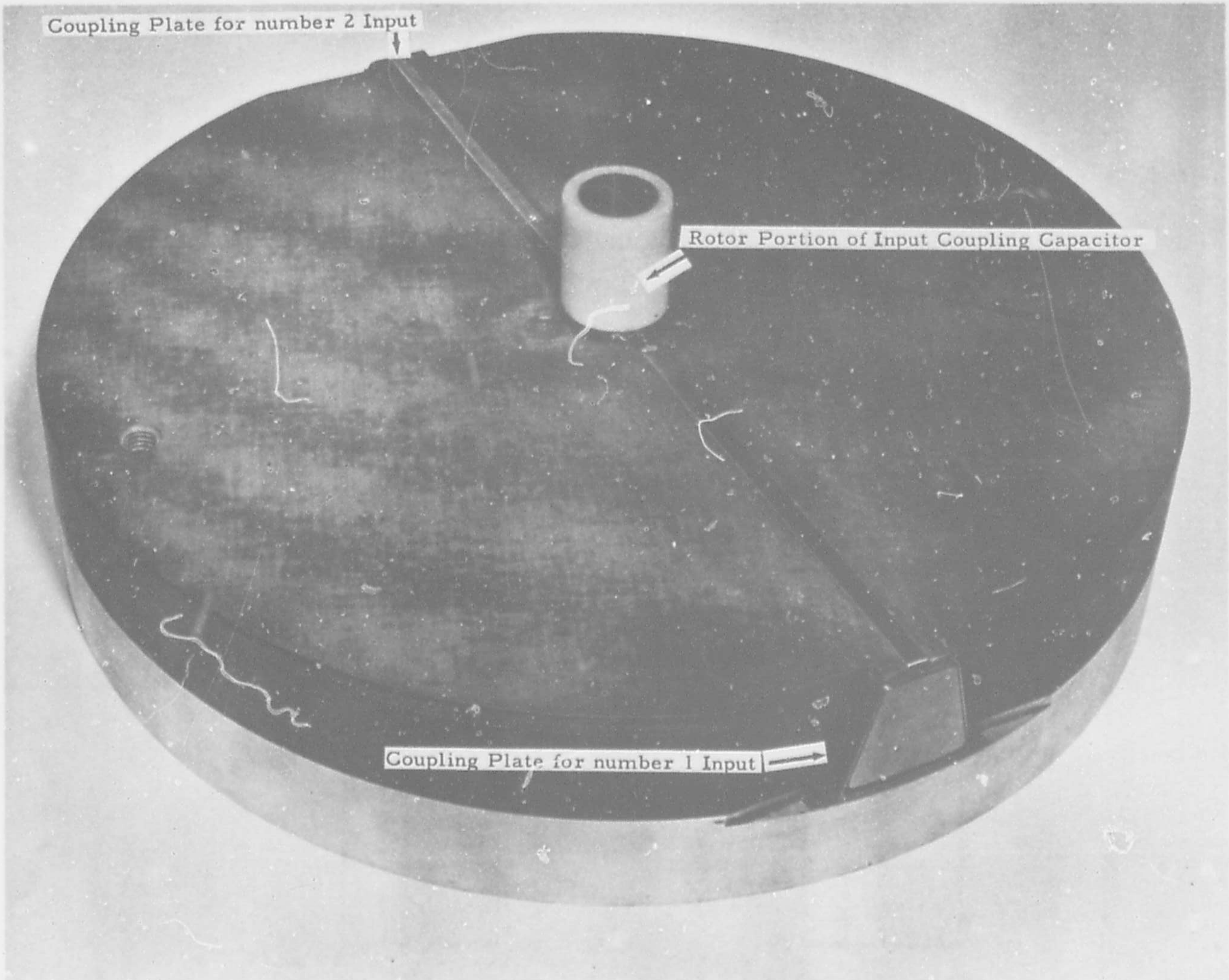
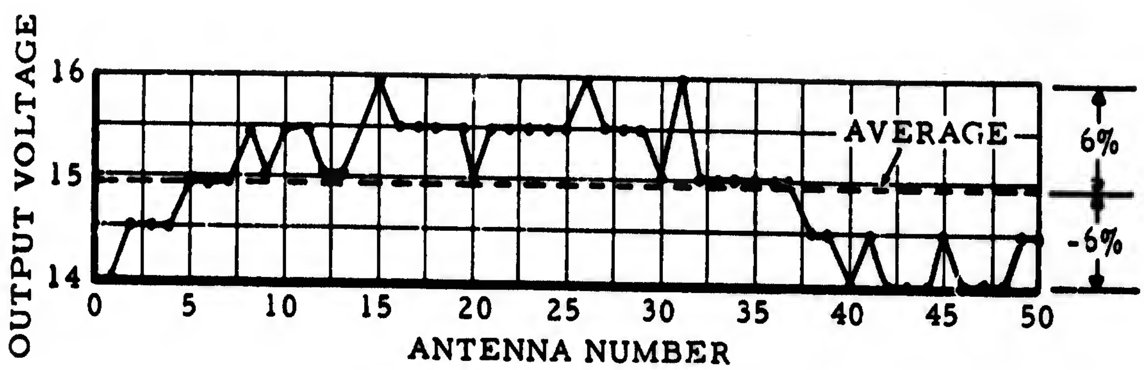
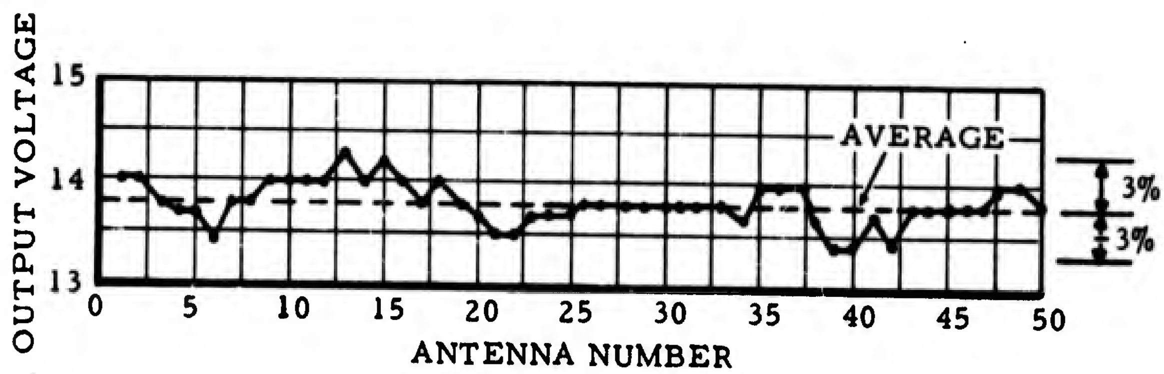


Figure 114. ROTOR OF JANSKY AND BAILEY DOUBLE SIDEBAND DISTRIBUTOR



COLLINS DISTRIBUTOR GAP SPACING = .008"



JANSKY-BAILEY DISTRIBUTOR SERIAL NO. 42 GAP SPACING = .008"

Figure 115. COMPARISON OF VARIATION IN OUTPUT VOLTAGE

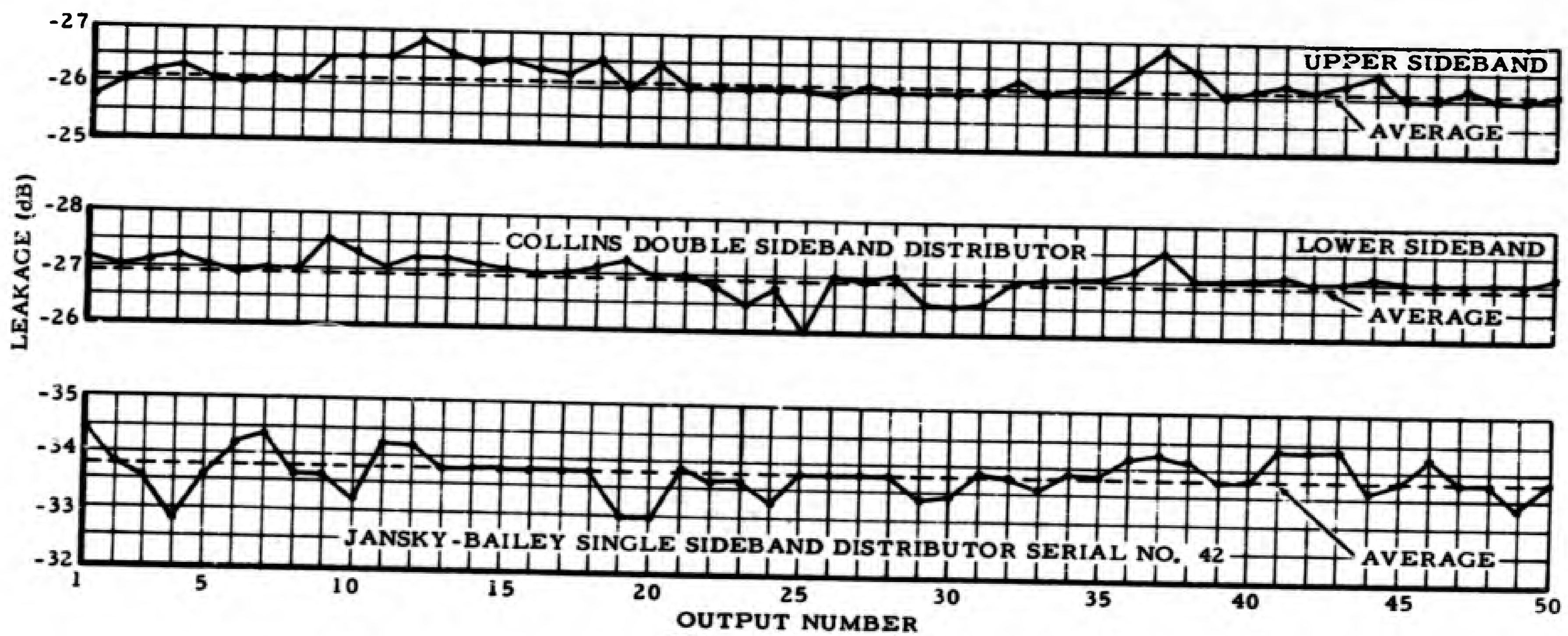


Figure 116. COMPARISON OF RF LEAKAGE FROM DRIVEN OUTPUT INTO ADJACENT OUTPUTS

Jansky and Bailey Dual-Channel 50-Output Distributor - This distributor design was the same as the standard Jansky and Bailey single-channel design with the exception of dual-rotors and the method of input coupling. Tests were limited to sample measurements of the first adjacent output isolation, measurement of the sideband channel isolation, and measurement of the VSWR of each sideband channel input.

1. First Adjacent Output Isolation - The average of four sample measurements of the first adjacent outputs indicated an isolation of -35.7 dB for one channel, and a -34.5 dB for the other channel.

2. Sideband Channel Isolation - The isolation of Channel 1 from Channel 2 was -26 dB, but isolation of Channel 2 from Channel 1 was -25.4 dB. The difference in the isolation is due to the difference in the stray capacitance.

3. Input Voltage Standing Wave Ratio - The input VSWR, with the distributor running, indicated a value of approximately 12.9:1 for each channel on a through line wattmeter. With the input line "matched," the input VSWR was 1.37 to 1 for Channel 1 and 1.4 to 1 for Channel 2, measured with only the measured channel energized. With both channels energized, these values were 1.8:1 and 2.2:1, respectively. All measurements were made at a frequency of 113.0 MHz.

Jansky and Bailey Dual-Channel 52-Output Distributor - This distributor design was the same as the Jansky and Bailey dual-channel 50-output distributor, with the exception that it provided 52 outputs. The measurements made of the Jansky and Bailey 50-output dual-channel distributor were repeated for Jansky and Bailey dual-channel 52-output distributor, using the same technique and frequency.

1. First Adjacent Output Isolation - The first adjacent output isolation measured -34.5 dB for one channel and -33 dB for the other channel.

2. Sideband Channel Isolation - The isolation of Channel 1 from Channel 2 was -22.5 dB and Channel 2 from Channel 1 was -21.1 dB.

3. Input Standing Wave Ratio - The input VSWR for each channel was approximately 13.2:1. Under "matched" conditions, the VSWR for the input of Channel 1 was 1.6:1 and 1.7 for Channel 2. With both channels energized, these values were 1.65:1 for Channel 1 and 2.2:1 for Channel 2.

Operational Deficiencies

It is difficult to draw a fine line separating operational deficiencies, in the true sense, from design problems when basic standards are being established, such as in the development of the dual-channel distributor.

Collins Distributor: The design of the input coupling capacitor of the Collins distributor achieves a small increase in the isolation between sideband channels when compared to the Jansky and Bailey distributor. The first adjacent output isolation of the Collins distributor was less than the Jansky and Bailey distributor. The output voltage variation of the Collins distributor was greater than compared to the standard single-channel distributor. The input coupling capacitive rings of the Collins distributor are of a design which requires multiple feed points. These feed points are connected together by means of coaxial connectors, which present a possible source of trouble.

Improvement of the adjacent output isolation and the reduction of the variation in the output voltage could possibly be achieved in production models to make the Collins distributor comparable with the Jansky and Bailey distributor. However, it appears that the design of the Collins distributor, requiring more extensive machine work than the simple design of the Jansky and Bailey distributor, would increase the cost of production models without any major gain over the technical characteristics of the Jansky and Bailey distributor.

Jansky and Bailey Distributors: The isolation between sideband channels was less in the Jansky and Bailey distributors than in the Collins distributor; however, the difference was small. Improvement could possibly be achieved on production models. Suggested modifications to increase the sideband channel isolation are: (1) shielding the rotor coupling, (2) placing a ring at ground potential between the coupling rings of the rotor, and (3) placing a grounded metallic disc between the stator coupler rings. These modifications would increase, by a small amount, the RF losses of the distributor due to the shunt capacitance and would possibly require a redesign of the rotor impedance matching scheme.

In the present design there appears to be a high RF current mode at the coupling rings. This is assumed from tests which required a large amount of RF energy to be coupled to the sideband antenna. In these tests, the lead connecting the distributor input to the lower stator of the coupling capacitor melted. This lead is routed through the center of the upper stator coupling capacitor. In addition, the heat generated at the lower coupling capacitor was sufficient to expand the metal of the coupling capacitor and distort the insulated support of the stator position of the coupling capacitor causing metal-to-metal contact of the stator to the rotor. The feed wire was replaced with a length of teflon-insulated coaxial cable and the power reduced to complete the tests at normal power levels (less than 10 watts); no heating problem was experienced.

In another test involving a dual-channel rotor to produce a $\frac{\sin \pi x}{\pi x}$ wave shape function, the same problems were encountered, but no damage was experienced to the feed line. In this test, operation for normal power was delivered to the antenna system; however, the input power was high due to the RF losses in the $\frac{\sin \pi x}{\pi x}$ rotor. In both tests trouble was experienced with the lower coupling capacitor rings. These two failures of the lower coupling capacitor were the only failures experienced, and are mentioned only as points of consideration in future development design, and should not be considered as operational deviciencies.

SUMMARY

Analysis of the tests conducted of the Double Sideband Doppler VOR System showed that the added sideband to the RF spectrum of the Single Sideband Doppler VOR System reduced the counterpoise modulation, thereby increasing receiver compatibility with increased station accuracy and a reduction of counterpoise size.

The high level modulation technique for the 30 Hz reference signal was feasible for either the Double Sideband Doppler VOR System or the presently used Single Sideband Doppler VOR System. This increased the field intensity of either Doppler VOR System to equal that of the Conventional VOR.

Additional improvements of the VOR systems, other than small improvements gained from improved components, required non-compatible changes in the method of transmitting the reference and/or variable signals.

CONCLUSIONS

Based on the test results, it is concluded that:

1. The Double Sideband Doppler VOR System (DSDVOR) is effective in improving compatibility with airborne receivers over that of the present Single Sideband Doppler VOR System (SSDVOR). The total dispersion of all data from the overall group of 10 different types of typical receivers used in the test was reduced in the case of the DSDVOR when compared to the SSDVOR at all counterpoise sizes from the present standard 150-foot diameter to the reduced 60-foot diameter.

2. The DSDVOR will reduce station error over that of the present SSDVOR. A reduction of approximately 50 percent, based on the average of the total error of the 10 receivers tested, can be achieved with counterpoise diameters from 100 to 150 feet.

3. A reduction in the counterpoise diameter from 150 feet to 100 feet can be achieved without sacrificing receiver compatibility and the low station error obtained with the 150-foot counterpoise. A reduction of 33 percent of counterpoise diameter will reduce the required counterpoise extension area 63 percent.

4. The high level reference modulation technique tested is feasible as a method of increasing the radiated carrier power, for either DSDVOR or SSDVOR systems, to that of the Conventional VOR.

5. Specifications for procurement of double sideband equipment for field use can be based on the final equipment tested. This includes the following:

a. Double Sideband transmitters.

b. Double Sideband distributer if minor improvements of the input coupling are made.

c. High-level reference modulator.

d. Modification to carrier transmitter.

REFERENCES

1. S. R. Anderson and Robert B. Flint, The CAA Doppler Omnirange, Technical Development Report No. 392, April 1959.

2. The Navigational Aids Engineering Division, Federal Aviation Agency, Performance of Doppler VOR at Difficult Sites, staff study, February 9, 1959.

3. S. E. Taggart, Modification of Standard Alford Loop Antenna for Use on Doppler VOR, Final Report Task No. 115-02-06T, February 1, 1961, AD258735.

4. Airborne Instruments Laboratory Division of Cutler-Hammer, Inc. Deer Park, Long Island, New York, VOR/Localizer Flight Inspection Receiver, Final Report No. RD-67-4, January 1967, AD649250.

5. Wilcox Electric Co., Inc., Kansas City, Missouri, Development of Prototype Double Sideband Doppler VOR Transmitter and Carrier Modulator, Final Report No. RD-65-44, March 1967, AD651160.

6. Collins Radio Company, Cedar Rapids, Iowa, VOR Dual Sideband Equipment, Final Report, Contract FAA/BRD-404, CER 1669A, December, 1963, AD432709.

7. Hazeltine, Corp., Hazeltine Electronics Division, Little Neck, New York, Double Sideband Doppler VOR Equipment, Final Report, Contract FAA/BRD-376, Report 10143, October 1964, AD612423.

8. Virgil E. Willey, Evaluation of Prototype Doppler VOR Sideband Antenna Monitor, Final Report No. RD-69-27, June 1969.

9. Atlantic Research Corporation, Jansky and Bailey Engineering Department, Alexandria, Virginia, Multi-bar Rotor Doppler VOR Distributor, Final Report No. RD-69-68, March 1970.