THE FOUR-LOOP VOR ANTENNA

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THE FOUR-LOOP VOR ANTENNA

SUMMARY

In an effort to improve the accuracy of the VHF omnirange (VOR), a new four-loop antenna system which incorporates a means to reduce polarization errors was developed by the Technical Development and Evaluation Center of the Civil Aeronautics Administration This report describes the antenna, the method of exciting the loops, and the flight tests and measurements

The improvements in a VOR using the four-loop instead of the conventional five-loop antenna are best illustrated by comparing the results of flight tests The maximum polarization error measured on flight checks of the four-loop VOR with polarizer was ±0 7° compared to ±2 1° for the five-loop VOR The maximum bearing error obtained with the four-loop VOR was ±0 75° The cone, or region over the top of the station, of the four-loop VOR is very narrow and provides excellent position indication over the station This is displayed on the TO-FROM meter by a movement of the pointer from the TO to the FROM position as the aircraft passes over the VOR

INTRODUCTION

The present CAA VHF omnirange in use on the Federal Airways uses a five-loop antenna system [1] This system has given very satisfactory service, but with the development of new techniques in flying the VOR and the development of course-line and pictorial computers, greater accuracy was desired The principal objectives were to improve the cone characteristics and to reduce the polarization error to a negligible value A more difficult problem studied was that of reducing the bearing error

The irregularities in the cone of the five-loop VOR are known to be a result of the fact that the carrier loop is at a different height above the counterpoise than are the sideband loops An excellent cone having the desired characteristics was obtained by removing the fifth loop and feeding carrier power through a bridge network to the sideband loops

Since Uskon cloth was effective in reducing polarization error from the five-loop antenna, it was also tried on the four-loop but was found to have little effect Other methods, such as a cage of aluminum rods entirely surrounding the loops, substantially eliminated polarization error, but the structure was large, expensive, and would require excessive maintenance A satisfactory means of reducing such error was devised in the development of a polarizer This is small enough to be installed as a part of the antenna array and requires only minor modifications to the present antenna shelters The development and application of such a polarizer to the five-loop VOR array, although possible, was not pursued because there would still remain the problem of improving the cone characteristics

This report presents the results of the development and operational tests conducted at TDEC on the four-loop VOR antenna system Except for the antenna, standard VOR equipment and a 35-foot diameter counterpoise 15 feet in height were used for the tests Results from similar tests on a standard five-loop VOR at the same site are included for comparison

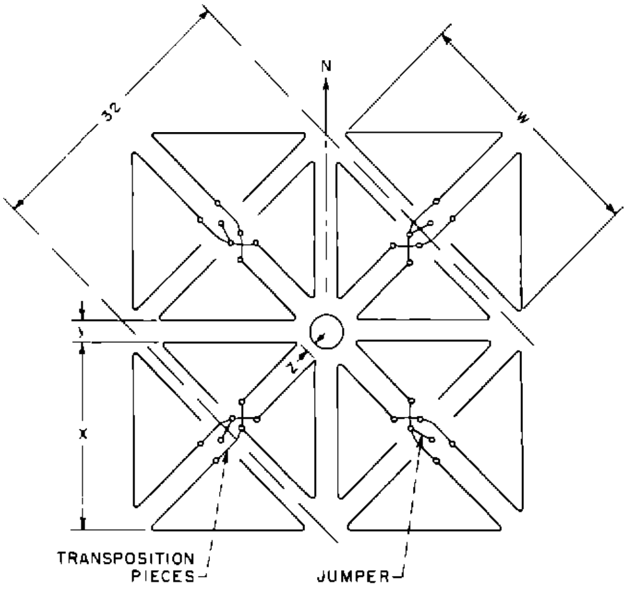
DESCRIPTION

The new antenna array is composed of four loops such as those now used as sideband antennas at a standard VOR facility The loops are mounted at the corners of a square, as shown in Fig 1, and are 48 inches (approximately one-half wavelength) above the counterpoise Each diagonal pair of loops is driven from an output of a goniometer and produces a figure-of-eight pattern in space All four loops are simultaneously driven in phase with carrier frequency currents Modulating this carrier is a 9960-cycle per second (cps) subcarrier which in turn is frequency-modulated with a 30-cps signal

In order to excite the four loops simultaneously from three separate generators, a double bridge circuit is employed This permits isolation of one generator from the others The double VHF bridge is made of RG-8/U coaxial cable and Type N fittings Fig 2 shows a schematic diagram of the bridges and the connections to the loops

A successful means of reducing vertically polarized radiation was obtained through use of a parasitically excited array, called a polarizer, mounted above the four loops on

[1] H C Hurley, S R Anderson, and H F Keary, "The CAA VHF Omnirange," CAA Technical Development Report No 113, June 1950



ANT TYPE	FREQ MC	DIMENSIONS (INCHES) W	x	y	z
B	112 115	25 5/8	20 3/16	2 7/16	1 3/8
C	115 118	25 1/16	19 11/16	2 15/16	1 5/8

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Fig 1 Four-Loop Array Connection Diagram

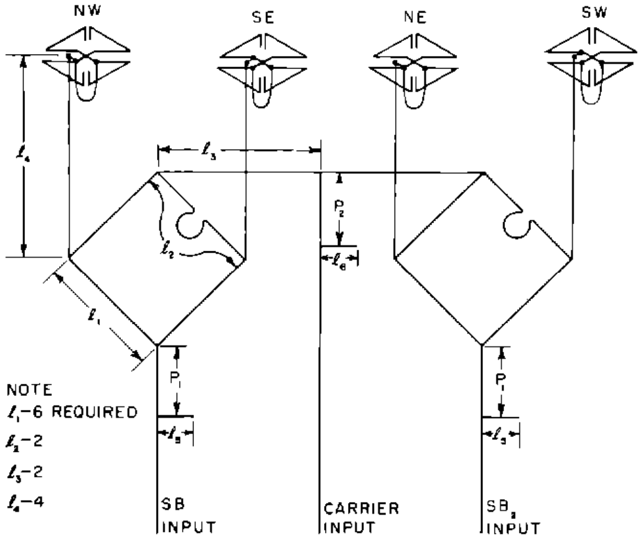

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Fig 2 Schematic Diagram of R-F Bridges and Loop Connections

the DME antenna pedestal as illustrated in Fig 3 The polarizer consists of four vertical elements of 3/4-inch outside diameter (OD) aluminum tubing 27 to 29 inches in length These elements are fastened at the lower end to a hub of cast aluminum The hub provides rigid support for the rods, and no other means of support is necessary

In order to accommodate the polarizer, it was necessary to modify the antenna shelter The vertical rods protrude through the top opening, which is used for ventilation, making it necessary to provide an extension for the rain shield This extension is 13 1/2 inches long, 18 7/8 inches in diameter, and is made of the same material as the antenna shelter A sketch of the antennas, polarizer, and modified shelter is shown in Fig 4 A photograph of the four-loop antenna is shown in Fig 5

MEASUREMENTS

Tests conducted to determine the operational characteristics of the four-loop antenna array included field-strength measurements to obtain horizontal plane patterns, impedance measurements to determine impedance matching requirements, and course deviation indicator (CDI) readings to determine the polarization and bearing errors

The lengths of the transmission lines which join the two bridges and the lines which join the loops to the bridges were adjusted for minimum standing-wave ratios The standing-wave measurements were made at the carrier and sideband inputs to the bridges and use a slotted line and probe detector Figs 6 and 7 show a plot of the line lengths versus the frequency, and Fig 8 is a plot of the standing-wave ratios which were measured The bridge inputs were matched with open stubs to the carrier and sideband feed lines Fig 9 shows the values of stub lengths and their positions, as those values are determined from the voltage standing-wave ratio (VSWR) measurements

Horizontal plane patterns of each sideband pair of loops were obtained by feeding radio-frequency (r-f) power directly to each sideband input and plotting the relative field strength for each 20° position of the array through 360° The patterns obtained are shown in Fig 10 The nulls obtained were separated 180° ±0 5° The carrier horizontal plane pattern was obtained by feeding r-f power to all four loops at the carrier input of the bridges and by plotting the relative field strength for each 40° position of the array through 360° The relative field strength was nearly constant at each setting of the array, and it is plotted in Fig 10

Bearing error checks were made by comparing the variable phase with a phase

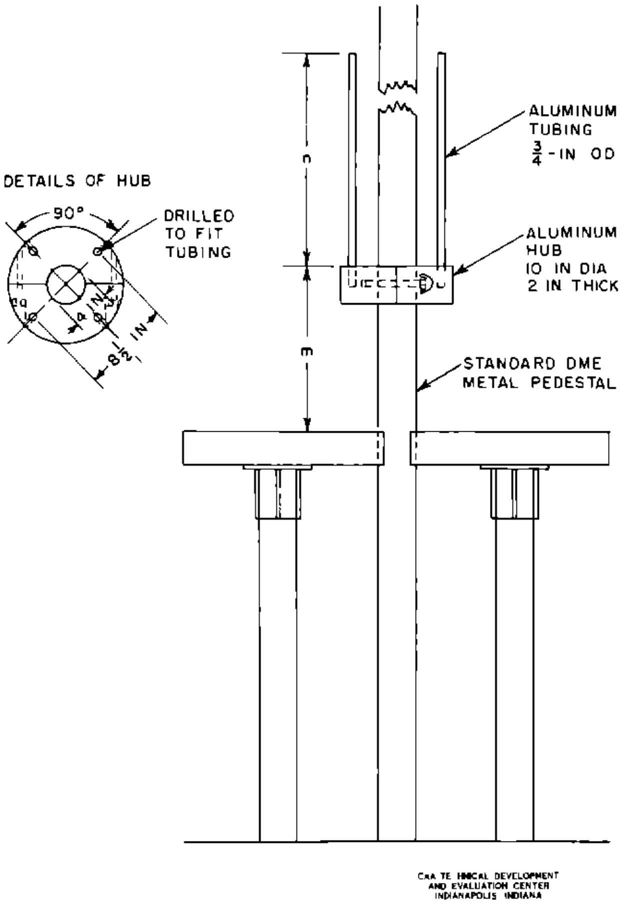

Fig 3 Polarizer for Reducing Polarization Error

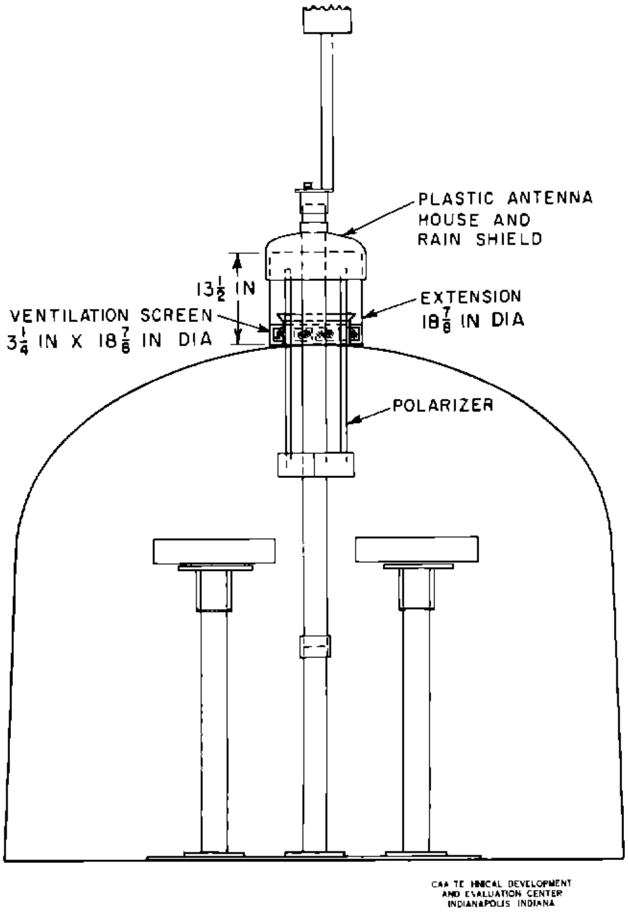

Fig 4 Modification of Antenna Shelter

standard and rotating the antenna array This method was used because the measurements are very accurate and provide a precise method of comparing the bearing errors of different types of antenna arrays The variable phase voltage was taken from the monitor and compared with the voltage from the phase standard on an oscilloscope The antenna array was rotated at intervals of 20°, and the error was taken as the difference between the array angular reading and that of the phase standard The maximum error observed was ±1 75° The shape of the error curve is quadrantal and indicates a difference of 5 per cent in amplitude between the figure-of-eight patterns The amplitudes were equalized by inserting a short length of RG-21/U attenuating coaxial cable at the output of the goniometer The same length of RG-8/U was inserted at the other output to keep the electrical lengths of the lines equal With balanced figure-of-eight patterns, the bearing error was reduced from a maximum error of ±1 75° to 0 75° Fig 11 shows the bearing-error curves before and after the figure-of-eight patterns were equalized

Fig 12 shows the polarization error measured when the station was operating on 114 8 megacycles (Mc) and with the polarizer adjusted to the dimensions obtained from the curves in Fig 13 These measurements were made in accordance with a procedure developed at this Center and described in another report [2] The polarization error was plotted for each 20° rotation of the array through 360°, with the antenna array plate making good contact with the counterpoise at each setting The maximum polarization error measured was ±0 8° For comparison purposes, the polarization error measured on a standard five-loop array using Uskon

[2] S R Anderson and W A Law, "The Measurement of VOR Polarization Errors," CAA Technical Development Report No 202, May 1953

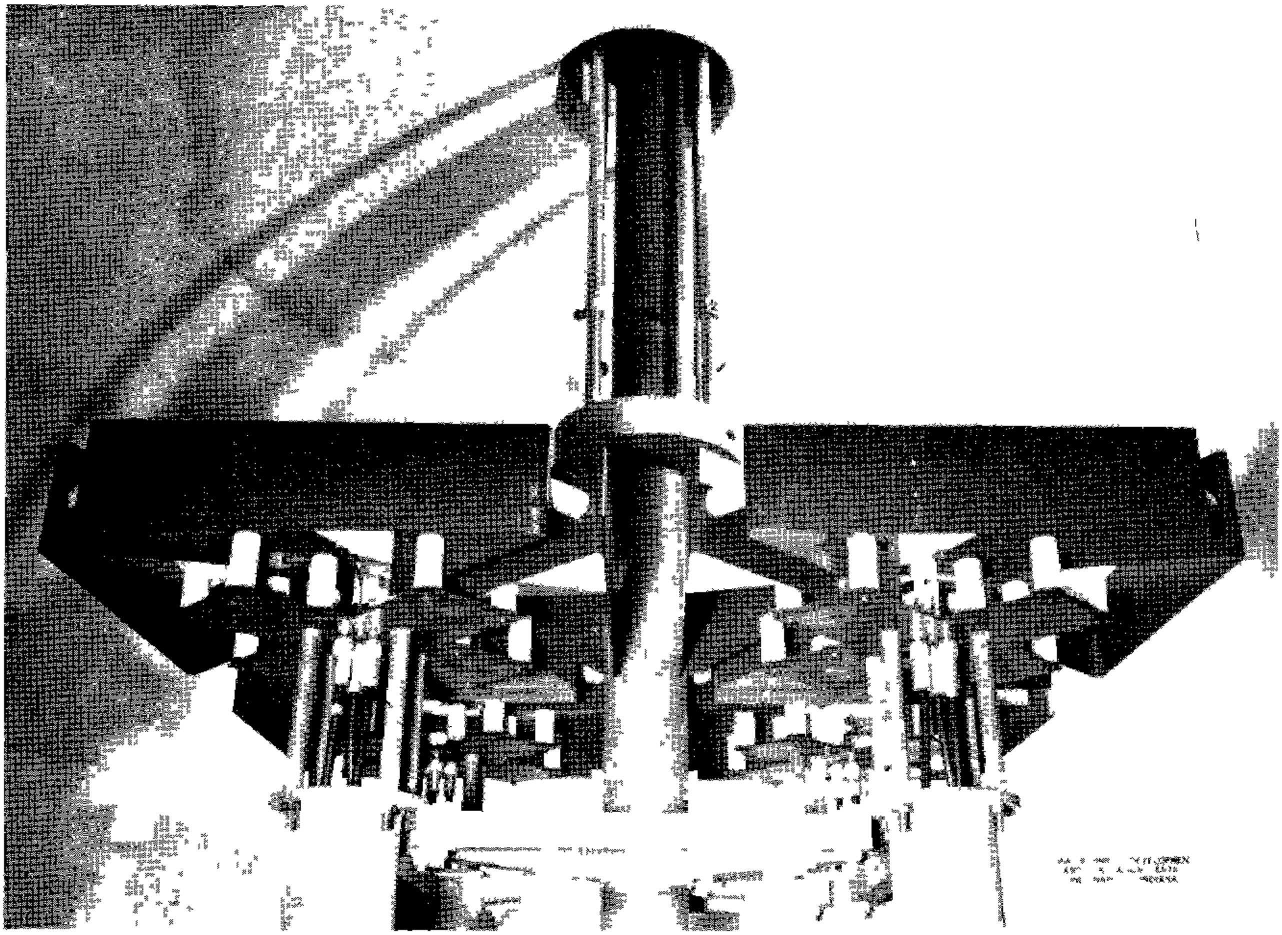

Fig 5 Four-Loop Antenna and Polarizer

cloth around the pedestals is shown in Fig 14 The maximum polarization error in this case was ±2 9°

Flight checks were conducted and included polarization checks, distance range, and cone measurements Standard procedures were used in the flight checks, and only brief mention of the methods will be given here

Three polarization checks including 30° wing rock, 360° circle, and "eight-ways-over-a-point" were conducted [3] These tests were made approximately 20 miles from the VOR at an altitude of 1,000 feet above ground in a Douglas C-47 aircraft using a Collins 51R-1 receiver and a tail-mounted Type V-109 antenna The average errors for the four-loop and five-loop antennas supported on a counterpoise 15 feet high and 35 feet in diameter are given in Table I

The effectiveness of the polarizer in reducing the polarization errors of the four-loop antenna is indicated by the data in Table I

The distance range of a VOR is here defined as the distance in statute miles from the VOR at which place the course width in degrees becomes double the course width measured at ten miles from the VOR The average distance ranges for the four- and five-loop antennas were 56 and 61 miles, respectively

Cone elevation angle measurements [4] were made on radial flights across the VOR by recording the currents of the CDI and the TO-FROM indicator Cone elevation angle measurements for the four- and five-loop antennas are shown in Table II Recordings of the TO-FROM indications are reproduced in Fig 15 One of the outstanding features of the four-loop antenna is the excellent

[3] Ibid , pp 8-9

[4] Thomas S Wonnell, "Mountain-Top VOR Site Flight Tests," CAA Technical Development Report No 139, March 1951

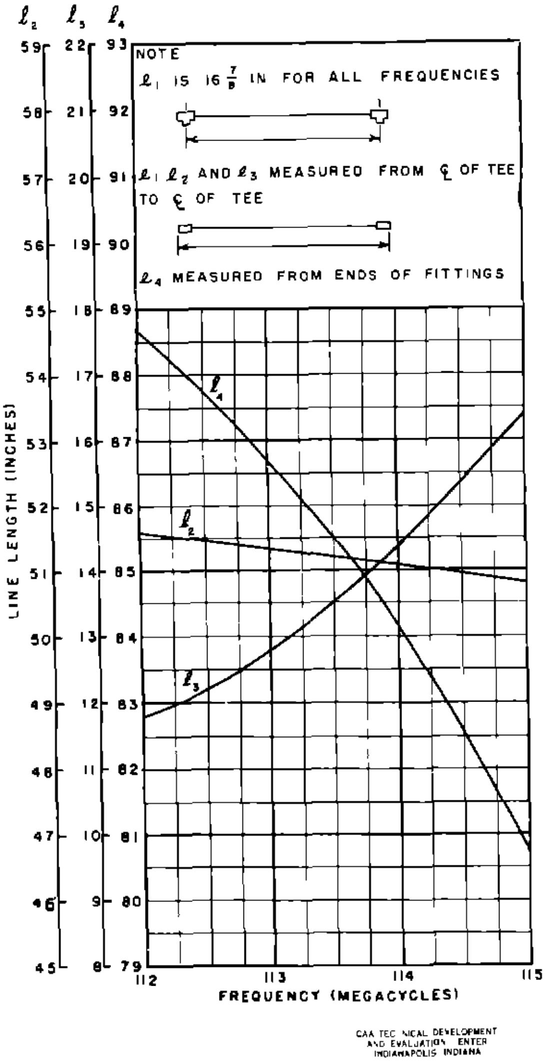

Fig 6 Line Lengths Using Band B Loops

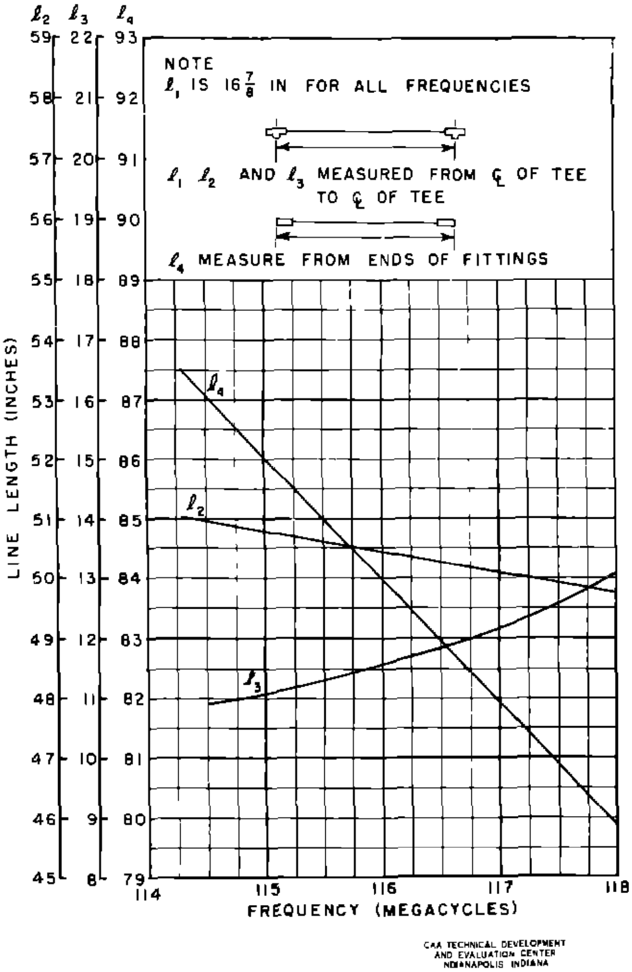

Fig 7 Line Lengths Using Band C Loops

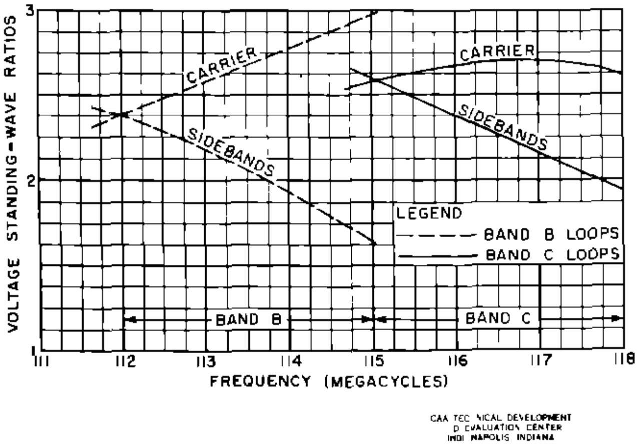

Fig 8 Voltage Standing-Wave Ratios Measured at Bridge Inputs Before Adding Matching Stubs

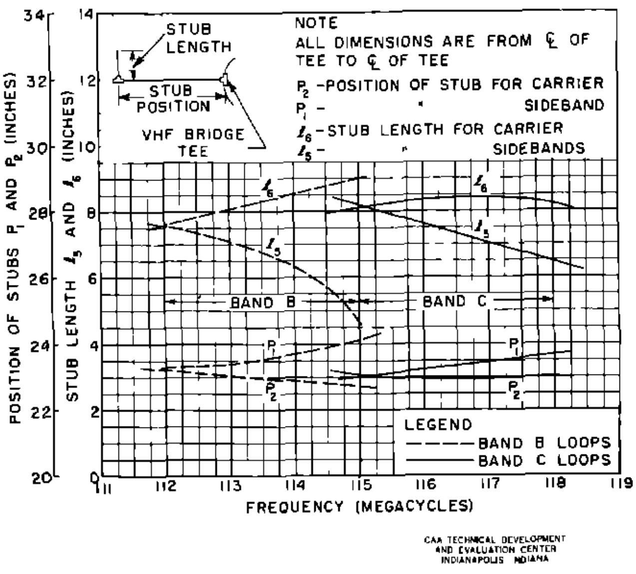

Fig 9 Impedance Matching Data

TABLE I

POLARIZATION ERROR FOR FOUR-LOOP AND FIVE-LOOP ANTENNAS

Type of Flight Check	Four-Loop Antenna		Five-Loop Antenna	
	Without Polarizer (degrees)	With Polarizer (degrees)	Without Uskon Cloth (degrees)	With Uskon Cloth (degrees)
30° wing rock	±1 6	±0 5	±0 8	±0 75
360° circle	±2 0	±0 7	±3 1	±2 10
Eight-ways-over-a-point	±1 0	±0 6	±3 5	±0 75

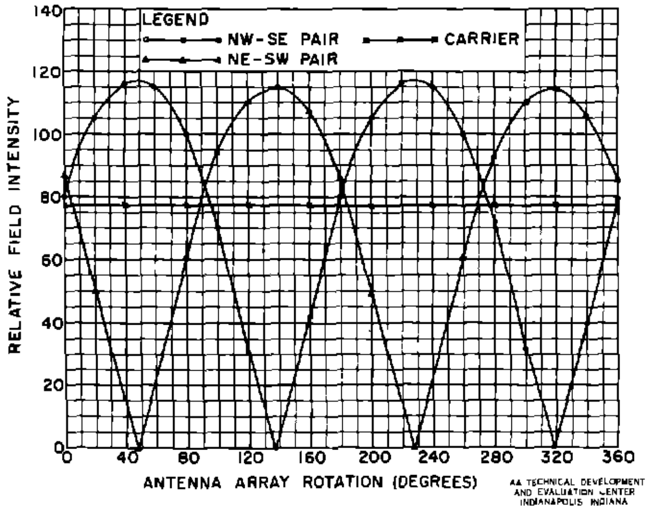

Fig 10 Sideband and Carrier Horizontal Plane Patterns

position indication produced by the action of the TO-FROM meter when passing over the station As shown in Fig 15, the action of the TO-FROM indicator when passing over the VOR employing the four-loop antenna is one smooth movement of the indicator from the TO position to the FROM position and

TABLE II

CONE ELEVATION ANGLE MEASUREMENTS

Indicator	Five-Loop Antenna (degrees)	Four-Loop Antenna (degrees)
CDI	50 0	75
TO-FROM	49 5	86

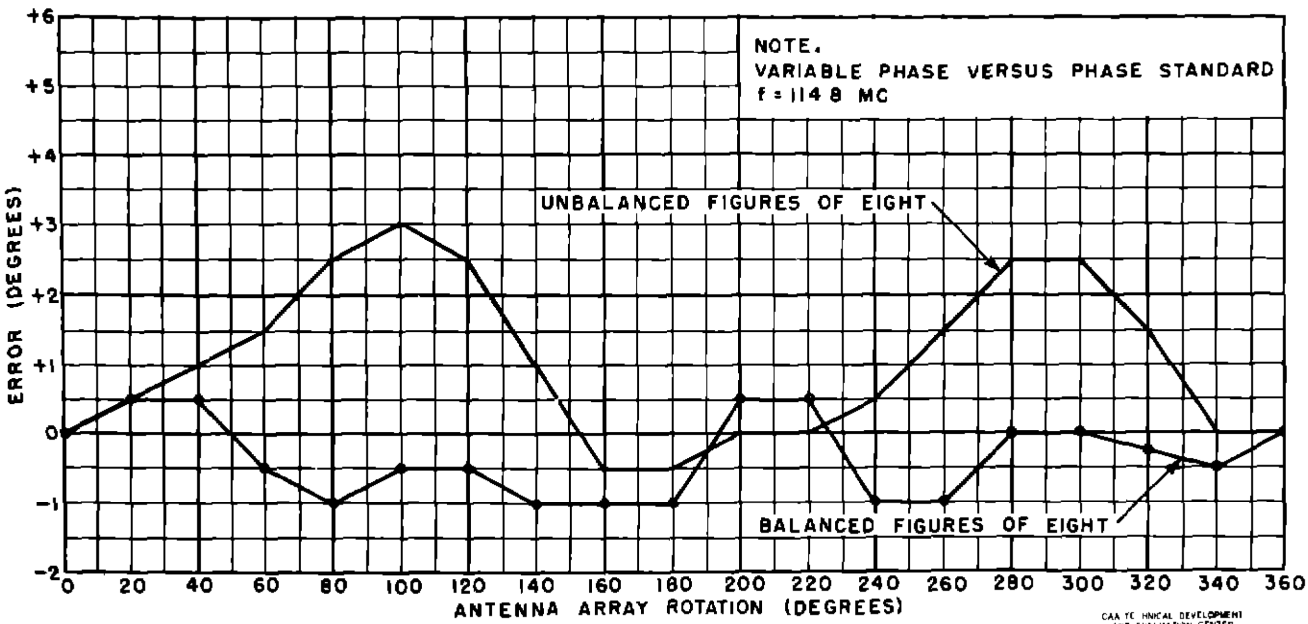

Fig 11 Bearing-Error Curves of Four-Loop Array, Ground Check

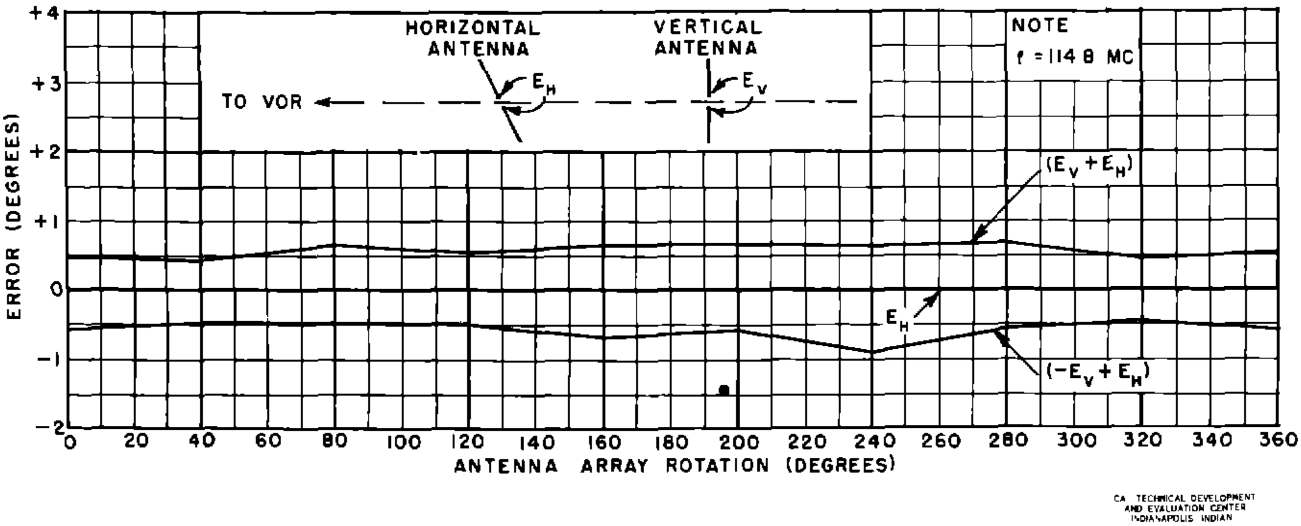

Fig 12 Polarization-Error Curve of Four-Loop Omnirange Antenna, Ground Check

provides a precise check when the aircraft is directly over the station

THEORY OF THE R-F BRIDGE

In order to excite the four-loop antenna from three different generators, it was necessary to have a means of isolating the circuits and of maintaining proper phase relations Two r-f bridges which were made of RG-8/U cable were used for this purpose A schematic diagram of a bridge is shown in Fig 16

Three arms of the bridge ℓ_1 are 90° in length at 115 Mc, and the fourth arm $\ell_2 = \ell_1 + 180°$ at the operating frequency A length of 90° for ℓ_1 provided the lowest VSWR on the sideband lines before matching Sideband energy is supplied to the bridge at point a where it divides, and equal amounts will flow through ab and ad The voltages appearing at b and d will be equal in magnitude and phase The voltages traveling through bc and dc will arrive 180° out of phase at point c, since dc is 180° longer The resultant voltage at c will be zero Since a virtual short circuit exists at c, no sideband energy will flow out of the bridge at this point Carrier energy is supplied to the bridge at point c where it divides, and equal amounts flow through cb and cd Carrier voltages at b and d will be equal in magnitude but 180° out of phase This phase relationship is necessary in order that the carrier loop currents will be in phase The jumpers at the feed points of the southeast and southwest loops are connected for a phase reversal as on the five-loop array Carrier voltages

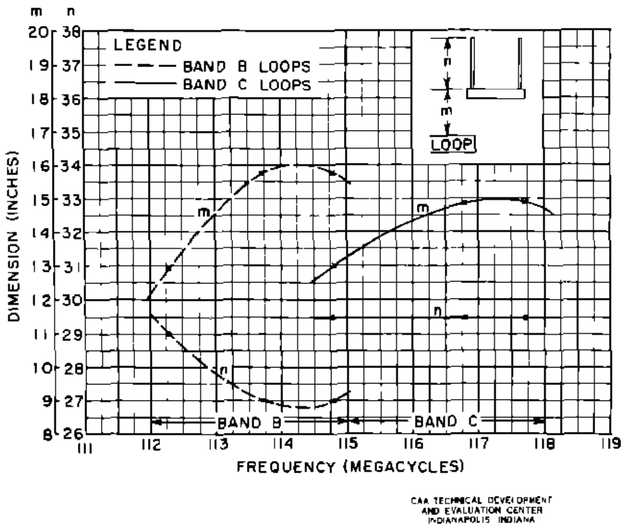

Fig 13 Dimensions of Polarizer

at point a will arrive 180° out of phase, and the resulting voltage will be zero The virtual short circuit to carrier voltage at point a will prevent energy from flowing into the sideband input lines The complete diagram is shown in Fig 2 It can be seen that complete isolation of the carrier and sideband inputs and proper phase relationships are accomplished through the use of the bridges

THE DEVELOPMENT OF THE POLARIZER

Fig 17 is a theoretical plot of the 30-cps sideband electric field intensity, relative amplitude, and r-f phase angle at any point on the vertical axis of the four-loop array

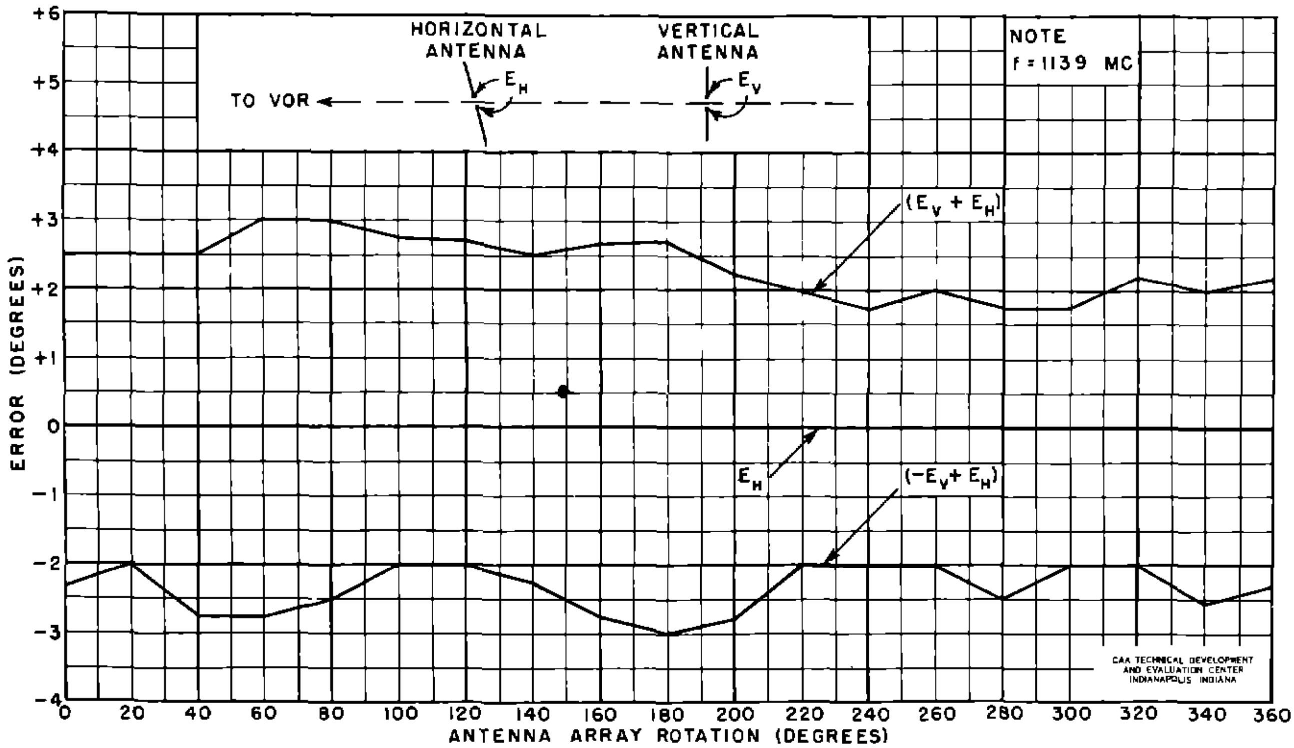

Fig 14 Polarization-Error Curve of Standard Five-Loop Omnirange Antenna, Ground Check

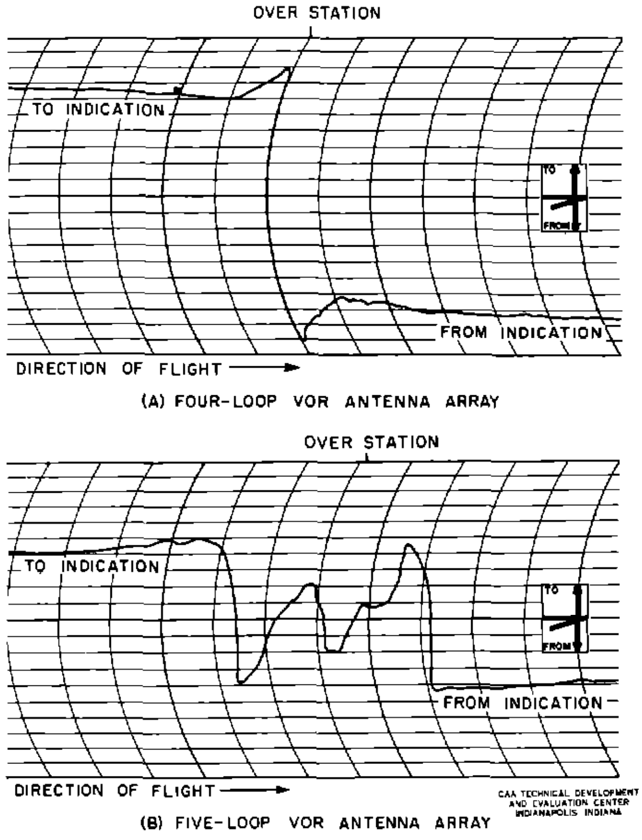

Fig 15 TO-FROM Indicator Recordings of Four-Loop and Five-Loop Antenna Arrays

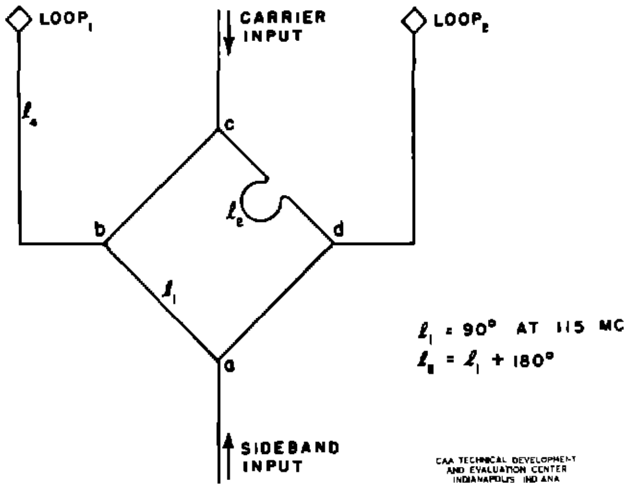

Fig 16 A Schematic Representation of an R-F Bridge

from the counterpoise level to approximately 80 inches above the counterpoise Fig 18 shows the situation in which the counterpoise is in the xy plane, the four-loop array is shown with the loops 48 inches above the counterpoise, and an electric vector (which is always horizontal) is shown on the vertical axis of the array The carrier input to the four-loop array is zero, the goniometer is stopped, and the two outputs of the goniometer feed the 30-cps sideband inputs of the array,

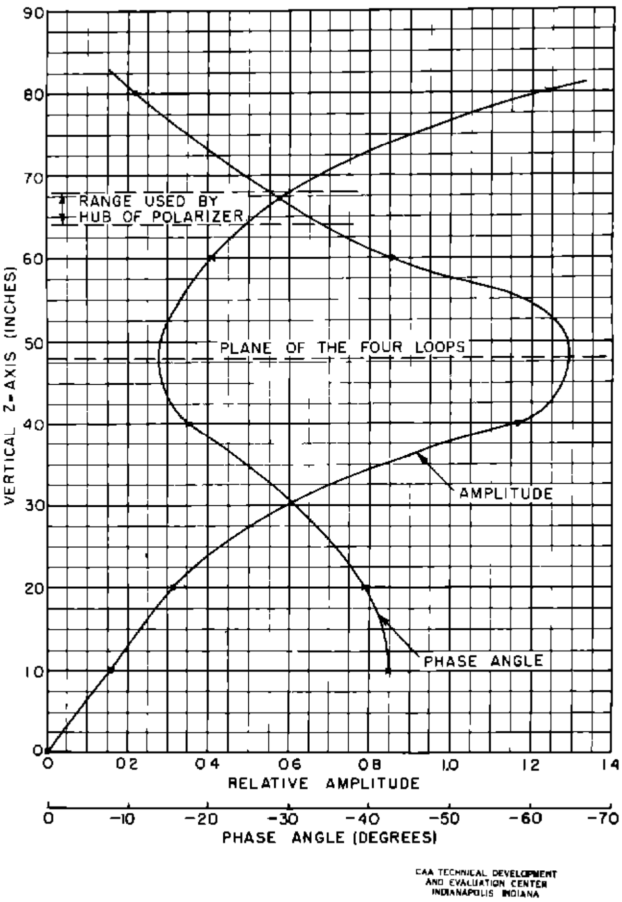

Fig 17 Theoretical Determination of the Phase Angle and Amplitude of the 30-cps Sideband Electric Vector Versus Position on the Axis of a Four-Loop Antenna

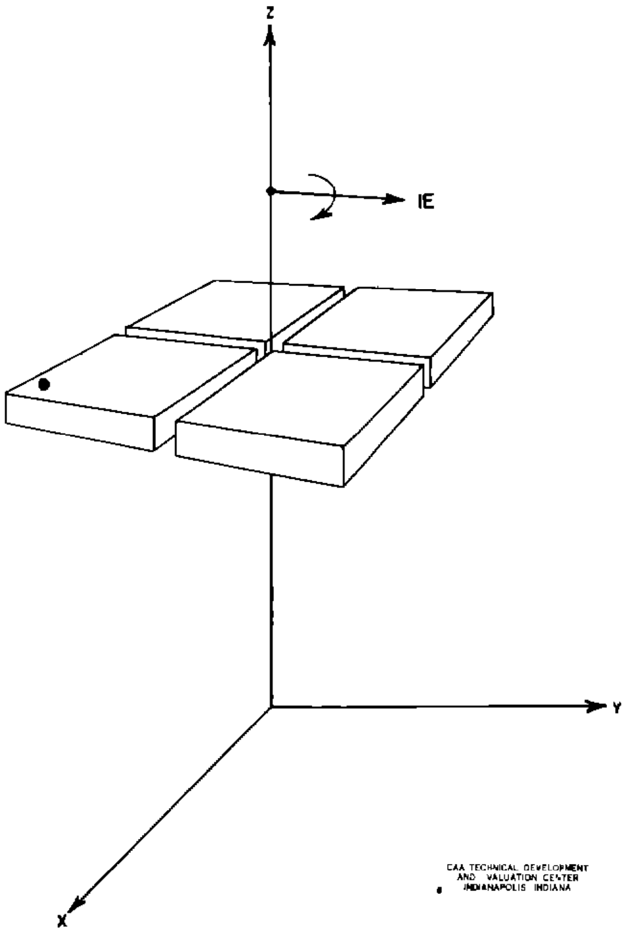

Fig 18 An Illustration of the 30-cps Sideband Electric Vector of the Four-Loop Array

as in normal operation The electric vector IE, shown in Fig 18, is of carrier frequency, and its direction depends on the goniometer rotor position When the goniometer is turned by hand in the normal direction, the electric vector will rotate clockwise as shown When the goniometer is revolving at 1800 revolutions per minute (rpm), the electric vector will spin at this rate with the Z-axis as a center The electric field so produced consists of 30-cps sideband energy with the 30-cps phase angle directly proportional to the azimuth angle.

Placing two short conductors, as shown in Fig 19, on the Z-axis will cause to be produced across the ends of both conductors a potential difference which is proportional to the electric vector that is in line with the conductor The potential difference has the same 30-cps phase angle, r-f phase angle, and amplitude as the electric vector

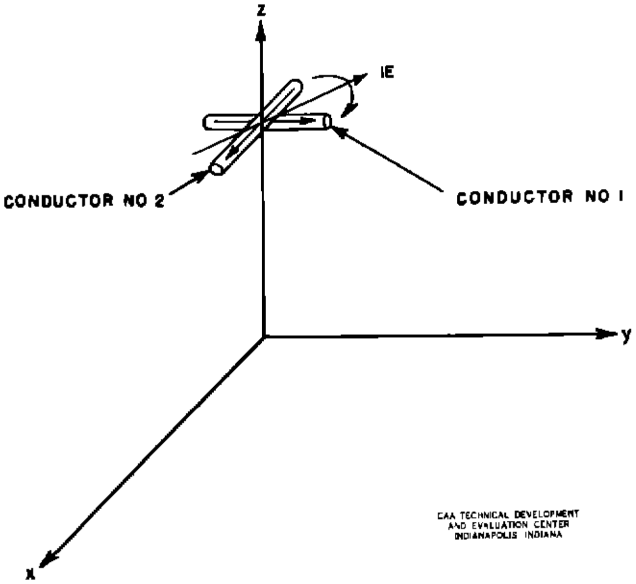

Fig 19 Two Horizontal Conductors Located on the Axis of the Four-Loop Array

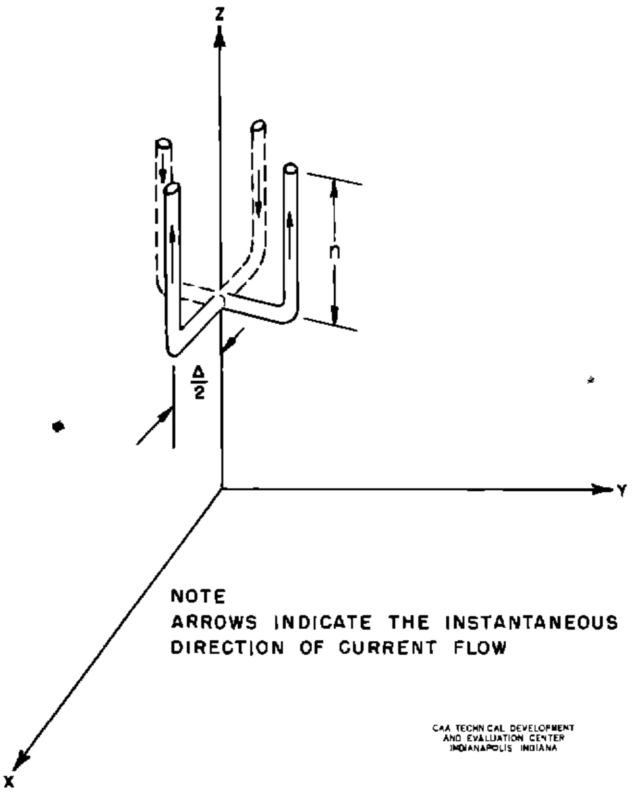

Fig 20 The Polarizer on the Axis of the Four-Loop Array

Fig 20 shows vertical extensions added to the horizontal conductors These horizontal conductors may be considered as generators, and each pair of vertical extensions may be considered as a balanced transmission line Fig 21 illustrates this way of looking at the polarizer From transmission-line theory, the current that flows through the hub is

$$I_g = +j \frac{E_g}{Z_0} \tan Gn \qquad (1)$$

where

I_g = generator or hub current in amperes,

j = $\sqrt{-1}$

E_g = generator voltage, voltage developed across the hub, in volts,

Z_0 = characteristic impedance of the transmission line formed by diagonally opposite elements, in ohms,

G = $\frac{2\pi}{\lambda}$, in degrees per inch,

n = length of the polarizer elements in inches

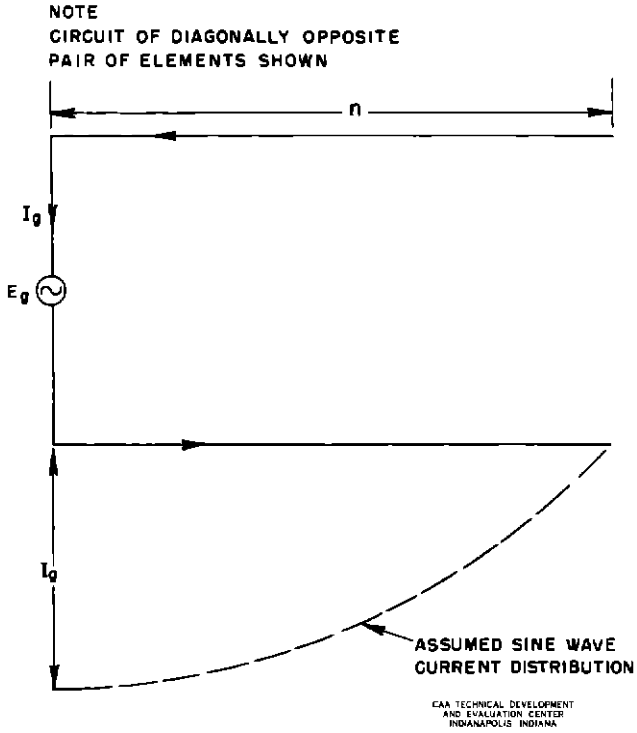

Fig 21 An Equivalent Circuit of the Polarizer

The generator voltage is determined as

$$E_g = \Delta E \qquad (2)$$

where

Δ = spacing between diagonally opposite elements in inches,

E = electric field intensity at the hub in volts per inch

Combining Equations (1) and (2)

$$I_g = +j \frac{\Delta E}{Z_0} \tan Gn \qquad (3)$$

Fig 22 is a plan view of the polarizer showing the currents in the vertical elements The electric fields radiated by the four elements combine at a distant point in the horizontal plane to give

$$F_V = K_1 \Delta I_g \cos(\rho t - 90° - \phi) \qquad (4)$$

where

F_V = electric field intensity, vertically polarized, from the polarizer, in volts per inch,

K_1 = constant,

$\frac{\rho}{2\pi}$ = modulation frequency, 30-cps,

t = time in seconds,

ϕ = azimuth angle in degrees

Substituting Equation (3) into Equation (4)

$$F_V = K_2 \frac{\Delta^2 E}{Z_0} \tan Gn \cos(\rho t - 90° - \phi) \quad (5)$$

where

K_2 = constant

The corresponding expression for the electric field intensity radiated by the loops is of the form

$$F_H = K_3 \cos(\rho t - \phi) \quad (6)$$

where

F_H = electric field intensity, horizontally polarized, from the loops in volts per inch,

K_3 = constant

A comparison of Equations (5) and (6) makes clear that the bearing information contained in the two fields is in quadrature The currents flowing in the loops produce the horizontally polarized distant field F_H, and the currents also produce a near field which drives currents through the polarizer The polarizer currents in turn produce a vertically polarized distant field F_V

The vertically polarized wave, normally radiated by the four-loop array and believed to be from the loop pedestals, may be expressed by an equation similar to Equation (5), therefore if the variables Δ, Z_0, n, and others and the field E (in which the hub is located) are properly chosen, the field of the polarizer may be made to cancel the field from the pedestals Variables Δ and Z_0 were determined during the development of the polarizer Variables E and n are those used in adjusting the polarizer

A study of Equation (5) and Figs 20 and 21 shows that the polarizer may be operated in another mode, Gn < 90°, provided that the polarizer is turned over (that the elements hang down from the hub) However, the hub current will be seen to reverse Flight tests have proved that this reversed hub current causes the TO-FROM indicator to present false indications from the time an aircraft leaves an elevation angle of 80° to the time one assumes an elevation angle of 80° on the other side of the station

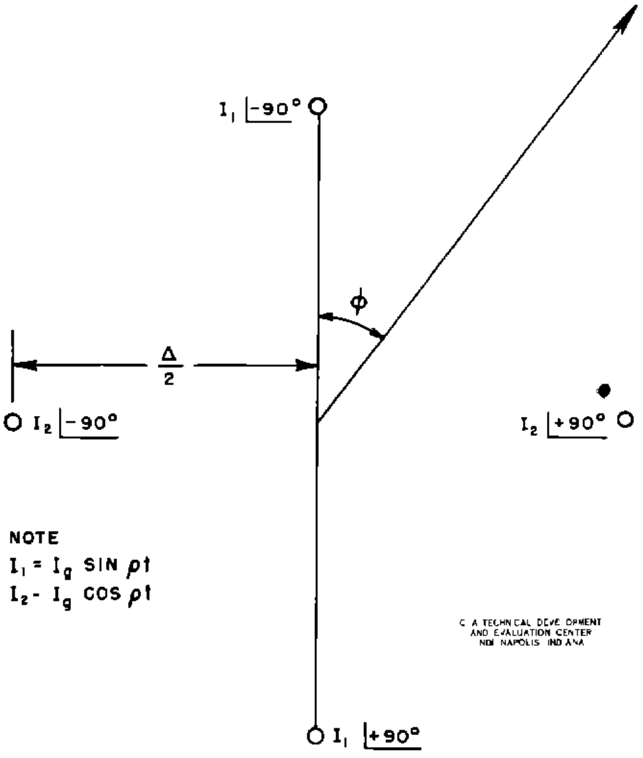

Fig 22 Plan View of Polarizer Illustrating Phase Angle and Amplitude of Currents

The procedure for adjusting the polarizer may be described by reference to Figs 23A, B, and C where the vector (Fig 23A) represents the polarization error measured from a four-loop array with the polarizer removed The measurement is made by the use of a polariscope described in another report[5]

Fig 23B shows the situation with the polarizer in place and set arbitrarily The vector labeled "pedestals" is taken from Fig 23A, the vector labeled "resultant" is measured with the polariscope with regard to magnitude and angle, and the vector labeled "polarizer" is obtained by completing the vector diagram A study of Fig 23B indicates that, in order for the polarizer vector to cancel the pedestals vector, the polarizer vector must be rotated counterclockwise and lengthened Reference to Fig 17 indicates that lowering the polarizer will increase the amplitude of the polarizer vector and decrease its negative phase angle Equation (5) indicates that shortening n will increase the length of the polarizer vector, Gn > 90°, without introducing a phase change The

[5] Anderson and Law, op cit

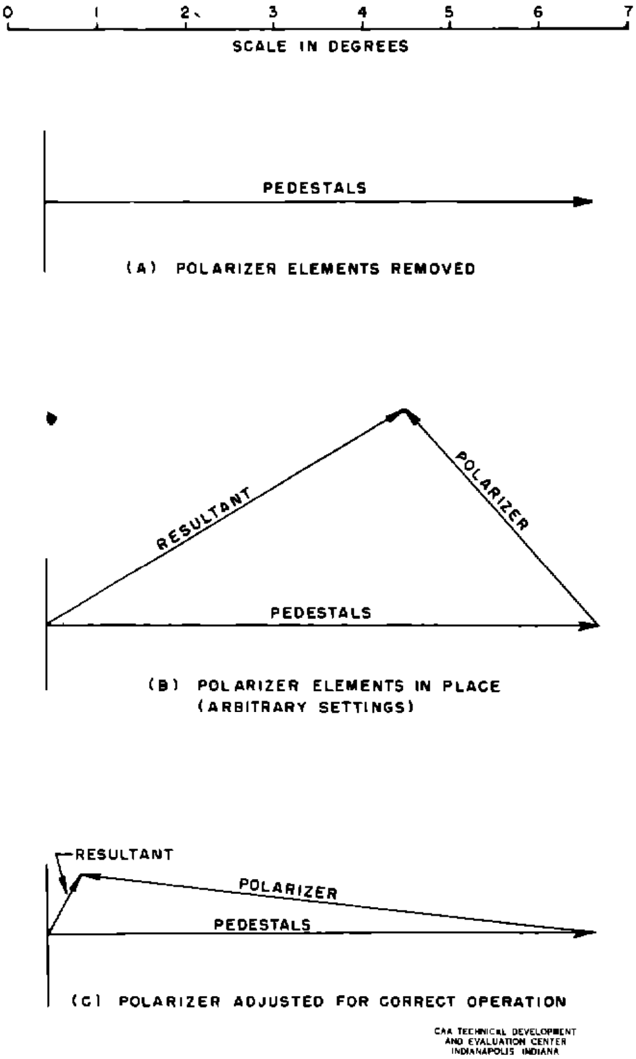

Fig 23 Vector Diagrams Used During the Adjustment of the Polarizer

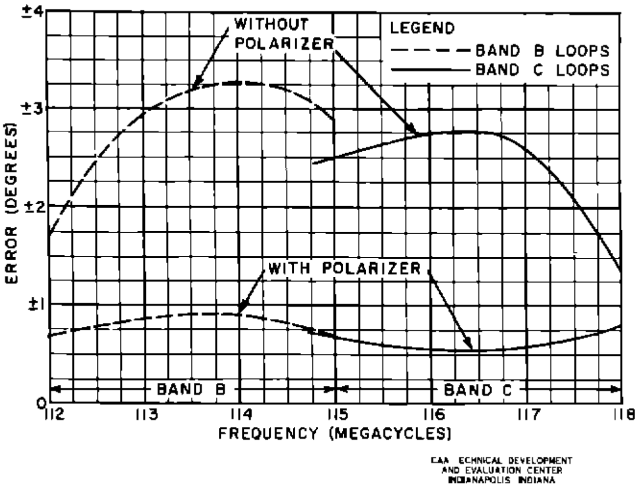

Fig 24 Polarization Error* Versus Frequency

* Maximum Error Measured Throughout 360° Rotation of Antenna Array

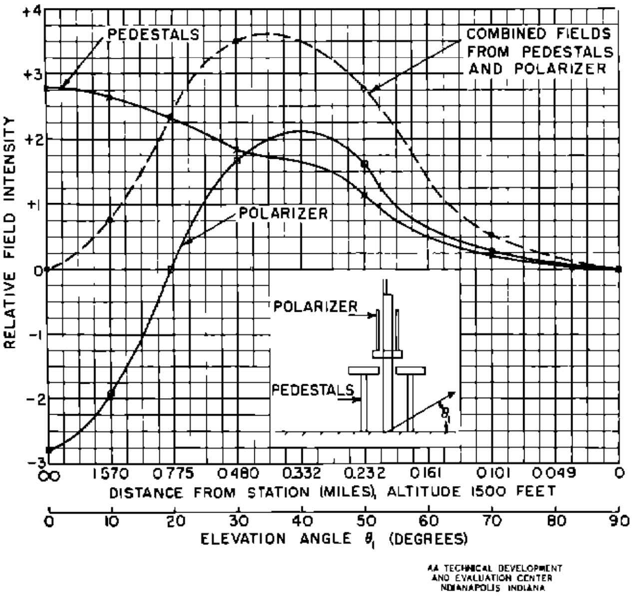

Fig 25 Theoretical Vertical Plane Field Strength Patterns of the Polarizer and the Four-Loop Pedestals

polarizer vector is brought to the favorable position shown in Fig 23C by varying the location of the polarizer and the length of its elements After satisfactory cancellation is obtained, the polarization error is measured at other azimuths from the VOR in order to make sure that it is small at all azimuths A limit of ±1° polarization error, as measured by means of the polariscope, has been found satisfactory This limitation restricts the polarization error observed in aircraft to a negligible amount Fig 24 illustrates the polarization error of the four-loop VOR antenna measured with the polariscope at various frequencies with and without the polarizer

The discussion so far has been confined to the horizontal plane which contains the four-loop array The field radiated by the polarizer is adjusted to cancel the field radiated by the pedestals at small elevation angles Since the two sources of radiation (polarizer and pedestals) are at different heights above the counterpoise, the respective vertical plane patterns have different shapes Therefore, making the patterns coincident at low elevation angles results in inequality at high elevation angles Fig 25 illustrates the two patterns which are obtained when they are adjusted for cancellation at an elevation angle of 0° An improvement in polarization error is realized below 19 5° Above this angle, an increase in polarization error is indicated Almost all of the flying is done below 10° where a marked improvement in polarization error is realized, as indicated by the second abscissa scale With the addition of the polarizer to the four-loop antenna, no deterioration of cone quality has been observed in flight tests Satisfactory operation of the polarizer could not be accomplished when the polarizer was located below the loops

It should be pointed out that in the development of the polarizer it was found necessary to have good electrical bonding between all surfaces in the antenna system, including the counterpoise For example, poor contact between the array base plate and the counterpoise or an opening in the counterpoise may cause a large polarization error at some azimuths while it is negligible at others

CONCLUSIONS

The results of the flight and ground tests indicate that more accurate information is to be obtained from a VOR using a four-loop antenna than from one using a five-loop antenna

A very narrow cone above the VOR is obtained with the four-loop antenna This narrow cone produces an excellent position indication by the action of the TO-FROM meter when an aircraft is flying over the VOR

The polarization error of the four-loop VOR with the polarizer is so small that little could be gained by further reduction

The azimuth accuracy was found to be ±1° or less for a number of four-loop VOR installations This is a measure of the accuracy of the antennas only and does not include site errors

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