POLARIZATION ERRORS OF TWO DIFFERENT OMNIRANGE ANTENNA ARRAYS

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SUMMARY

This report describes the results of flight tests on the Youngstown, Ohio, and Indianapolis, Indiana, VHF omniranges in order to obtain comparative data with respect to polarization errors of two distinct types of antenna arrays

The Youngstown omnirange antenna array is comprised of a single loop and two pairs of crossed dipoles The Indianapolis omnirange utilizes a standard five-loop antenna array

The flight tests made on the Youngstown VHF omnirange were duplicated as closely as possible on the Indianapolis omnirange in order that a true comparison of the performance of each station could be made Theoretical considerations predicted a considerable amount of vertical polarization from the Youngstown omnirange due to the use of crossed dipoles in the antenna system Analysis of the five-loop antenna array at the Indianapolis omnirange predicted pure horizontal polarization Polarization errors of considerable magnitude were observed while flight testing the Youngstown omnirange, while the polarization errors observed on the Indianapolis omnirange were correspondingly less, the ratio being about five to one The Youngstown antenna array in its present form is not recommended for use in the omnirange system due to the errors associated with this type of antenna structure

The requirements of the omnirange system make it necessary that any antenna array used in this particular system produce pure horizontal polarization only if it is to become a successful navigational aid

INTRODUCTION

The use of crossed dipoles in the VHF omnirange antenna array was conceived by engineers of the CAA's Office of Federal Airways with the idea of simplifying the installation of the antenna system (See Fig 1)

The idea of using crossed dipoles for VHF antenna arrays is not new Earlier experiments in the development of VHF four-course ranges by the Office of Technical Development indicated considerable polarization errors associated with this type of antenna structure making it necessary to utilize the VHF loop antenna to obtain pure horizontal polarization

While the presence of vertical polarization in a VHF four-course range antenna array is not desirable, it is undesirable to a much greater degree in the omnirange system For this reason the use of loop antennas has become standard for all CAA VHF navigational aids systems, and has proven very satisfactory in the omnirange antenna array at Indianapolis and numerous other locations (See Fig 2). At the request of the Office of Federal Airways, the Office of Technical Development flight tested the Youngstown omnirange with Experimental Station airplane NC-182 The airplane was equipped with V antennas located at the hatch and tail positions The hatch position is on top the fuselage along the center line 144 in from the nose, the tail position is on top the vertical stabilizer

The receiving equipment consisted of a modified RC-103 receiver and converter unit adjusted for operation on 30 cps

THEORETICAL CONSIDERATIONS

Crossed Dipole Array The characteristics of the crossed dipole array may be determined by first considering a single horizontal dipole as shown in Fig 3 The direction of the electric field intensity vector, produced by the dipole, when fed with a generator at the center of the dipole, is obtained by performing the following vector operations[1]

$\mathbf{i}D$ = direction of electric field

$$= \frac{\mathbf{i}r}{|\mathbf{i}r|} \times \left(\mathbf{i}j \times \frac{\mathbf{i}r}{|\mathbf{i}r|} \right) \qquad (1)$$

[1] $\mathbf{i}i$, $\mathbf{i}j$ and $\mathbf{i}k$ are unit vectors

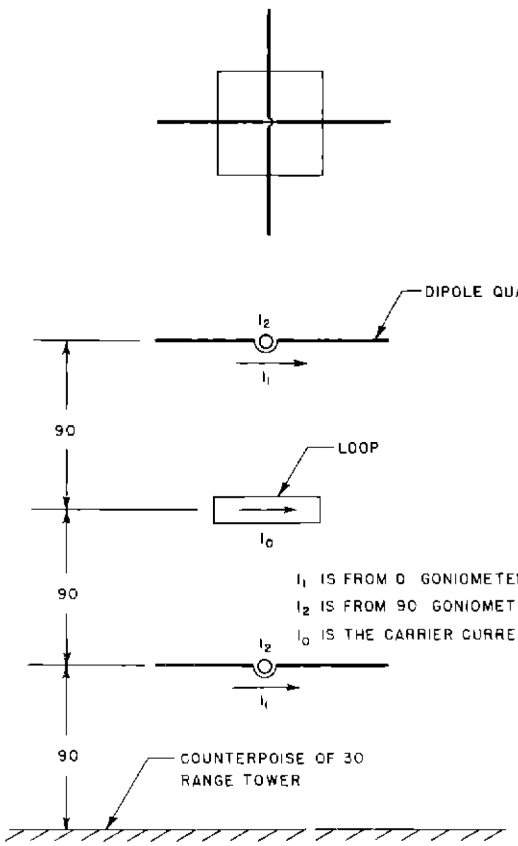

Fig 1 Crossed Dipole Omnirange Antenna Array

$$\mathbf{D} = -\mathbf{i}\cos\phi\sin\phi\sin^2\theta + \mathbf{j}(1-\sin^2\phi\sin^2\theta) - \mathbf{k}\cos\theta\sin\theta\sin\phi \quad (2)$$

$$|\mathbf{D}| = D = \sqrt{1-\sin^2\theta\sin^2\phi} \quad (3)$$

$\mathbf{E}$ = electric field intensity

$$= \frac{\mathbf{D}}{D} E_m \sin\alpha \quad (4)$$

E_m is a constant depending upon the power radiated, the distance, the units, etc It can be shown that

$$\sin\alpha = \sqrt{1-\sin^2\theta\sin^2\phi} \quad (5)$$

Putting (5) into (4) and making use of (2) and (3)

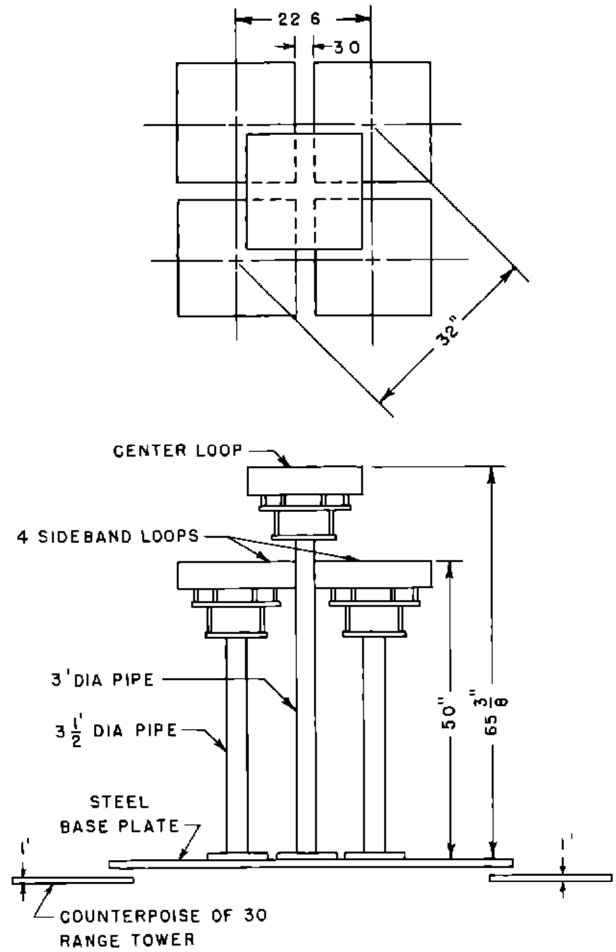

Fig 2 Five-Loop Omnirange Antenna Array

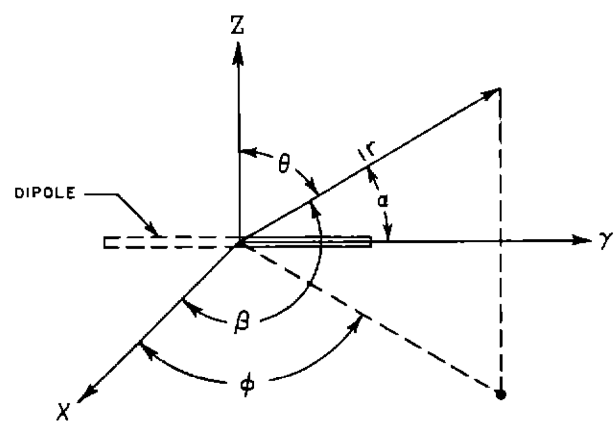

Fig 3 Horizontal Dipole in Coordinate System

$$\mathbf{E} = E_m \Big[-\mathbf{i} \cos\phi \sin\phi \sin^2\theta + \mathbf{j}(1 - \sin^2\phi \sin^2\theta) - \mathbf{k} \cos\theta \sin\theta \sin\phi \Big] \quad (6)$$

Equation (6) may be rewritten in terms of the vertical and horizontal components as follows

$$\mathbf{E}_H = E_m \Big[-\mathbf{i} \cos\phi \sin\phi \sin^2\theta + \mathbf{j}(1 - \sin^2\phi \sin^2\theta) \Big] \quad (7)$$

$$\mathbf{E}_V = + F_m \Big[-\mathbf{k} \cos\theta \sin\theta \sin\phi \Big] \quad (8)$$

$$\left| \mathbf{E}_H \right| = E_H = E_m \sqrt{1 - \sin^2\phi \sin^2\theta (1 + \cos^2\theta)} \quad (9)$$

$$\left| \mathbf{E}_V \right| = E_V = E_m \cos\theta \sin\theta \sin\phi \quad (10)$$

In equation (4), it is assumed that the dipole field intensity varies as $\sin\alpha$ This is true for small dipole lengths and is a good approximation for lengths approaching one-half wavelength

Fig 4 shows two dipoles of the type considered in Fig 3, placed one above the other and parallel to the y-axis The dipoles are excited with equal currents, inphase The field intensity from the two dipoles is then

$$\mathbf{E}_a = \mathbf{E} \left[2 \cos\left(\frac{d}{2} \cos\theta \right) \right] \quad (11)$$

LET $f(\theta) = 2 \cos\left(\frac{d}{2} \cos\theta \right)$ (12)

then $\mathbf{E}_a = \mathbf{E} \, f(\theta)$ (13)

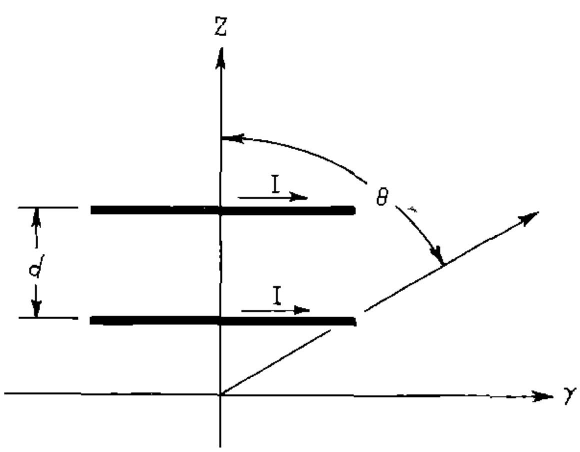

Fig 4 Two Dipole Array

Equation (13) may be expressed in terms of the vertical and horizontal components by making use of equations (7) through (10) as follows

$$\mathbf{E}_a = (\mathbf{E}_V + \mathbf{E}_H) \, f(\theta) \quad (14)$$

$$\mathbf{E}_{aV} = \mathbf{E}_V \, f(\theta) \quad (15)$$

$$\mathbf{E}_{aH} = \mathbf{E}_H \, f(\theta) \quad (16)$$

$$E_{aV} = E_V \, f(\theta) = E_m \cos\theta \sin\theta \sin\phi \, f(\theta) \quad (17)$$

$$E_{aH} = E_H \, f(\theta) = E_m \sqrt{1 - \sin^2\phi \sin^2\theta (1 + \cos^2\theta)} \, f(\theta) \quad (18)$$

The above equations show that the effect of stacking the dipoles is to change the vertical plane characteristics but, in no way alter the relative strength of the vertical component with respect to the horizontal component The horizontal plane patterns, which vary with ϕ, are unaffected by stacking the dipoles except in size

Inspection of equation (17) shows that the vertical component is zero along the horizon and directly above the array and reaches a maximum value depending upon $f(\theta)$ The horizontal plane patterns, horizontal slices through the three-dimensional pattern, are figures-of-eight with maxima at $\phi = 90°$ and $270°$ The horizontal component, equation (18), has a figure-of-eight pattern along the horizon but, it is at right angles to the vertically polarized figure-of-eight The maxima occur at $\phi = 0°$ and $180°$ for the horizontal component

Let $\theta = 90°$, then from equations (17) and (18)

$$E_{aV} = 0 \quad (19)$$

$$E_{aH} = 2 E_m \cos\phi \quad (20)$$

From equations (19) and (20), it can be seen that in the horizontal plane, including the array, a perfect figure-of-eight is obtained, (a cosine wave) and no vertical component This characteristic is desirable for an omnirange If $\theta \neq 90°$, the figure-of-eight pattern of the horizontal component changes from a true cosine shape to a dumbbell, then to a circle, as the z-axis is approached The vertical component is also present, but with a sine pattern (figure-of-eight displaced 90° from that produced by the horizontal component)

From the above considerations, it is apparent that the use of two pairs of elements at right angles to each other and each pair fed from an output of the goniometer associated with the omnirange will produce the desired variable phase radiations of an omnirange in the horizontal plane containing the array only As the receiver is moved to higher and higher angles above the horizon, the pattern of the horizontal component becomes more and more distorted while at the same time a vertically polarized pattern comes into play The vertically polarized pattern would produce a course just 90° removed in space from that of the horizontal component In other words, the same receiver using first the horizontal component would indicate a course N-S for example, while secondly, using just the vertical component, the receiver unchanged would indicate an E-W course Actually, a horizontal V antenna is used for receiving on the aircraft so that the antenna favors reception of the horizontal component However, the skin of the aircraft intercepts energy from both components, and some of this energy is coupled to the V antenna Consequently, as the direction of flight is changed with respect to a fixed point, the amount of vertical component reaching the receiving antenna may vary, depending upon the combined directive pattern of the skin of the aircraft and receiving antenna

If it is assumed that the aircraft receiver responds to both the vertical and the horizontal components present, at its location in space, the following errors would result

Let $\phi = 90°$ in equations (17) and (18) The fields, due to one output of the goniometer are

$$E_{aV1} = \frac{E_m \sin 2\theta}{2} f(\theta) \tag{21}$$

$$E_{aH1} = E_m \cos^2\theta \, f(\theta) \tag{22}$$

The fields, due to the other output of the goniometer, are obtained by setting $\phi = 0°$ in equation (17) and (18)

$$E_{aV2} = 0 \tag{23}$$

$$E_{aH2} = E_m f(\theta) \tag{24}$$

If $\theta \to 90°$, E_{aH1} may be neglected since E_{aH1} is small compared with E_{aV1} The 30-cps phase angle is then,

$$\phi_V = \tan^{-1}\left(\frac{E_{aV1}}{E_{aH2}}\right) = \tan^{-1}\left(\frac{\sin 2\theta}{2}\right) \tag{25}$$

If the vertical field were not present, $\phi_V = 0°$, so that ϕ_V, in effect, is the error due to the presence of the vertical polarization The following tabulation shows how the error varies with θ

θ(degrees)	ϕ_V(degrees)
88	2 0
85	4 95
80	9 85

If we assume that the aircraft receiver responds to the horizontal component only, an error will be produced as the aircraft increases its angle of elevation due to a distortion of the figure-of-eight pattern

Let $\phi = 90°$, then from equation (18) the field due to one output of the goniometer will be

$$E_{aH1} = E_m \cos^2\theta \, f(\theta) \tag{26}$$

By putting $\phi = 0°$ in equation (18) the field in space due to the other output of the goniometer is obtained

$$E_{aH2} = E_m f(\theta) \tag{27}$$

The phase angle of the combined voltages produced in the receiver by fields of equations (26) and (27) is

$$\phi_H = \tan^{-1}\left(\frac{E_{aH1}}{E_{aH2}}\right) = \tan^{-1}(\cos^2\theta) \tag{28}$$

If no distortion in the figure-of-eight pattern were produced $E_{aH1} = 0$, $\Phi_H = 0°$, no error would be present Hence, Φ_H is the error produced by the distortion of the figure-of-eight pattern The chart below indicates how Φ_H varies with θ

θ (degrees)	Φ_H (degrees)
85	0 44
80	1 8
45	26 6
0	45 0

This analysis of the crossed dipole array neglects the effect of the counterpoise and earth Equation (25) is derived on the assumption that the aircraft is located in the null of one figure-of-eight pattern Actually, this equation holds for all directions from the station It is believed that in spite of the simplifying assumptions made in the analysis, effects agreeing with the theory both of the order and magnitude as predicted should exist The flight tests to be described later bear out the validity of this view

Five-Loop Array This array uses loop antennas which theoretically radiate very little or no vertical polarization[2,3] If no vertical polarization is radiated, it is believed that no polarization errors should exist except in those cases where the polarization has been changed by reradiation from trees, buildings, etc Incidentally, reradiation phenomena, would also exist in the case of the crossed dipole array If it is assumed that the loop antennas are not perfect radiators, that they do radiate a small amount of vertical polarization, one would expect quite different characteristics from the loop array, than are predicted for the crossed dipole array The flight tests indicate very little polarization errors for the loop array and, where error is observable, its characteristics are quite different from that predicted for the crossed dipole array

FLIGHT TESTS

In checking for polarization errors, the aircraft is flown on a course away from the omnirange station over a well-defined point, at a predetermined distance from the range site and clearly visible from the cockpit at a known altitude After passing over the check point, the aircraft is turned around and flown across the check point at right angles to the original course After crossing the check point in one direction, the aircraft is turned around and crosses over the check point in the reverse direction If the needle of the cross-pointer instrument (the course recorder gives a true indication of the cross-pointer needle at all times) assumes the same position at the instant the check point is crossed over, in either direction of flight, no polarization errors are present If the cross-pointer needle assumes a different position when crossing over the check point in one direction, as compared with the cross over in the reverse direction, it is evident that polarization errors exist since the course has apparently been shifted when the aircraft changes its direction of flight This is sometimes referred to as "pushing" or "pulling"

Fig 5 shows the location of check points at the Indianapolis omnirange, and Fig 6 indicates the location of check points at Youngstown omnirange

In Tables I and II are tabulated the polarization errors observed in flight for the Youngstown and Indianapolis omnirange stations

Table III is a comparison of the magnitude of the polarization errors observed on the Youngstown and Indianapolis omnirange stations It may be seen from these data that the polarization errors observed on the Youngstown station are approximately five times greater than those observed on the Indianapolis station Also, the polarization error on the Youngstown station increases with an increase in elevation angle, as theory predicts, while this effect is absent for the Indianapolis station

Fig 7 shows recordings taken during flights in two directions, flying a straight ground track directly over the Indianapolis omnirange, using the aircraft tail V and hatch

[2] S R Anderson and H F Keary, "Five-Loop Omni-Directional Radio Range Array Developed for Use On the New York-Chicago Airway" C A A Technical Development Service unpublished Memorandum Report No 9, April 29, 1946

[3] A Alford and A G Kandoian, "Ultra High Frequency Loop Antennas", A I E E Technical Paper 40-45, January 1940

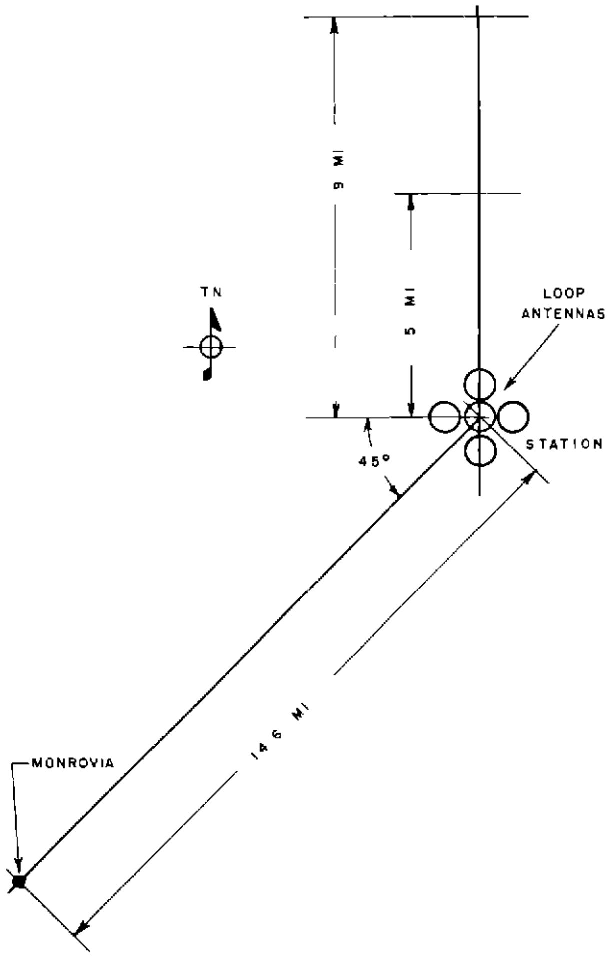

Fig 5 Sketch Showing Location of Check Points for Five-Loop Antenna Array Polarization Flight Tests at Indianapolis, Indiana

receiving antennas The approach to the station is equally good in both directions for either antenna The "cone" is quite narrow and permits a close approach to the omnirange site before the cross-pointer needle deviates from the on-course position

Fig 8 shows recordings made on a similar flight at the Youngstown omnirange under like conditions It will be noted that the tail V antenna gave identical results to that obtained at the Indianapolis omnirange With the hatch V antenna in use, the "cone" was considerably broader and resulted in a more difficult approach to the station due to the sharp course-bends It is believed by the authors that the course-bends observed with the hatch V antenna are due entirely to polarization errors The hatch V antenna appears to be more susceptible to vertical polarization,

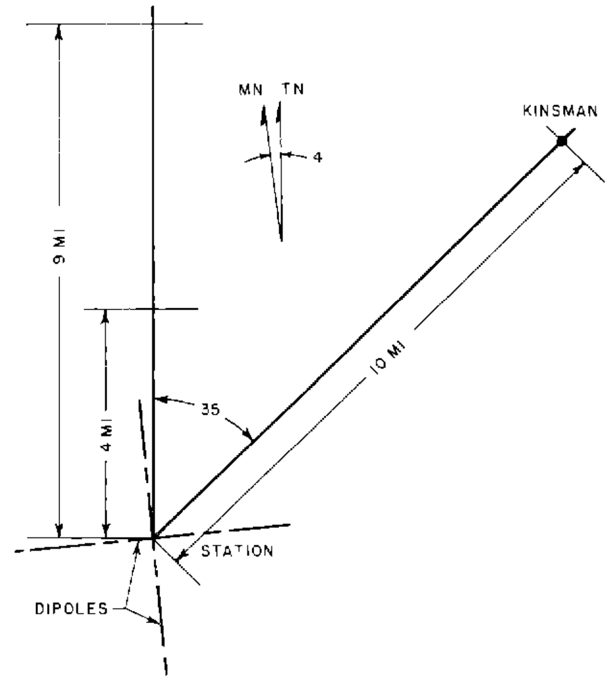

Fig 6 Sketch Showing Location of Check Points for Dipole Antenna Polarization Flight Tests at Youngstown, Ohio

due to its position on the aircraft, than is the tail V antenna

CONCLUSIONS

The theoretical analysis of the crossed dipole array indicates that such an array will produce polarization errors, the magnitude of which depends upon the characteristics of the receiving antenna and its location on the aircraft The flight records of the crossed dipole array prove that even with the best available receiving antenna and location on the aircraft, considerable polarization errors are present Some aircraft require a location comparable to the hatch V location for the receiving antenna, in which case the flight records show an unflyable course over the station for the crossed dipole array It is recommended, in view of the findings presented in this paper, that the crossed dipole array not be used for omnirange stations

The five-loop array, both from theoretical considerations and flight measurements is responsible for little polarization error It is believed from a comparison of the tests on both antenna systems that the five-loop array by far makes the safest and most accurate omnirange

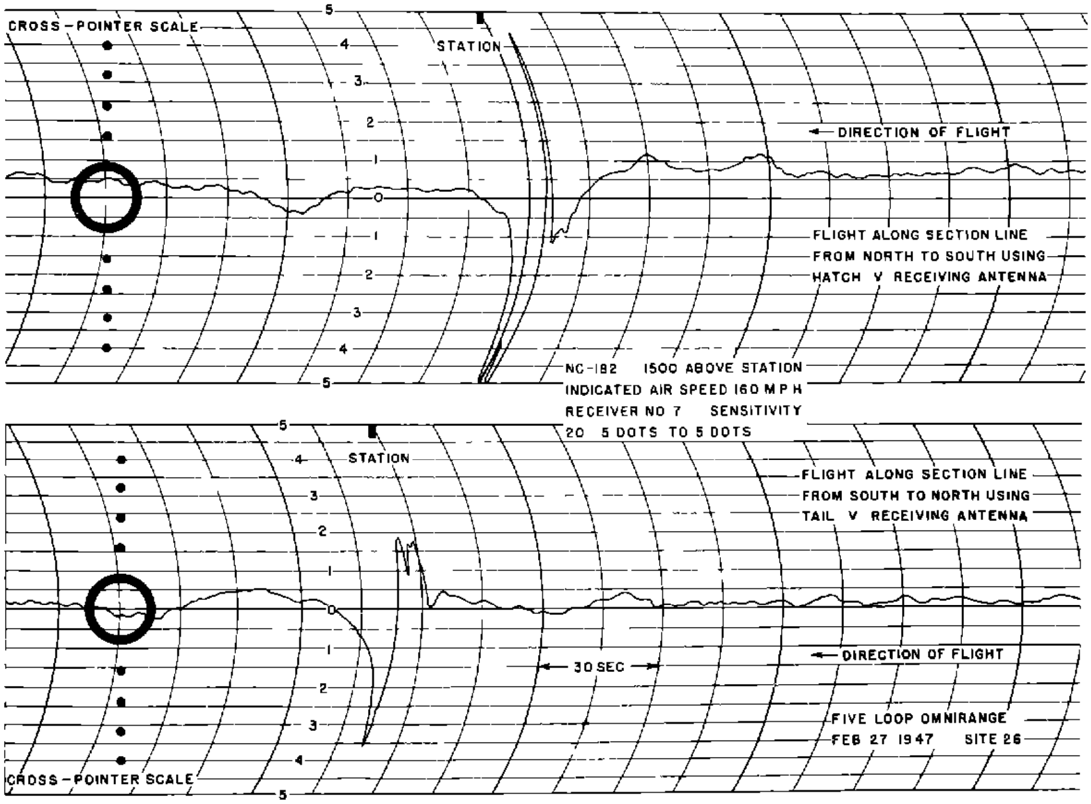

Fig 7 Flight Recording of Indianapolis Radial Flights

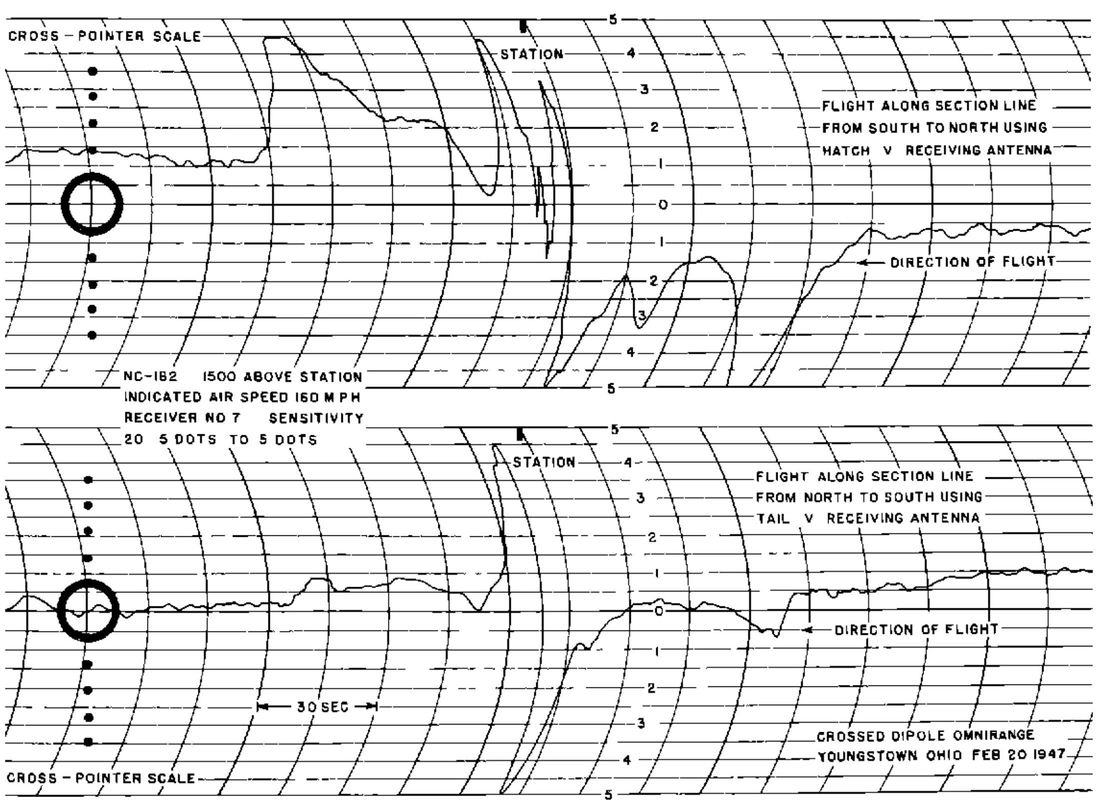

Fig 8 Flight Recording of Youngstown Radial Flights

TABLE 1 TABULATION OF POLARIZATION ERRORS IN YOUNGSTOWN FLIGHT TESTS

Flight Tests on Youngstown, Ohio, Omnirange Using Crossed Dipole Transmitting Antenna and Tail V Receiving Antenna

Location	Direction of Flight	Altitude	Polarization Error in One Direction* (degrees)	Combined Polarization Error (degrees)	Remarks
9 miles North	East	2000	-0 81	3 20	
"	West	2000	+2 39		
"	South	2000	-0 0		
"	North	2000	-0 0	0 0	Radial Flight
"	East	4000	-2.39	4 0	
"	West	4000	+1 61		
4 miles North	West	2000	+5 56		
"	East	2000	-3.3	8 86	
"	South	2000	0 0		
"	North	2000	-1 23	1 23	Radial Flight
10 miles NE	SE	2000	-1 85		
"	NW	2000	+2 42	4.27	
"	NE	2000	0.0		
"	SW	2000	+0 285	0 285	Radial Flight
"	SE	4000	-3 84		
"	NW	4000	+1 36	5 2	

Flight Tests on Youngstown, Ohio, Omnirange Using Crossed Dipole Transmitting Antenna and Hatch V Receiving Antenna

Location	Direction of Flight	Altitude	Polarization Error in One Direction* (degrees)	Combined Polarization Error (degrees)	Remarks
9 miles North	East	2000	-0 81		
"	West	2000	+2 94	3 75	
"	East	4000	-7 29		
"	West	4000	+0 08	7 37	
"	East	4000	-7 79		Agree with previous east run
"	North	4000	-2 44		
"	South	4000	+2 76	5 2	
4 miles North	West	2000	+4 3		
"	East	2000	-8 4	12 7	

* Plus sign indicates meter right
Minus sign indicates meter left

TABLE II TABULATION OF POLARIZATION ERRORS IN INDIANAPOLIS FLIGHT TESTS

Flight Tests on the Indianapolis Omnirange Using a Five-Loop Array for Transmitting and a Tail V Receiving Antenna

Location	Direction of Flight	Height Above Station in Feet	Polarization Error in One Direction* (degrees)	Combined Polarization Error (degrees)
9 miles North	South	2000	0 0	
"	West	2000	+0 67	0 67
"	East	2000	0 0	
"	West	4000	-0 5	0 25
"	East	4000	-0 25	
"	West	4000	0 0	0 25
5 miles North	North	2000	+0 66	0 66
"	South	2000	0 0	
"	North	2000	+1 00	1 0
"	East	2000	-1 17	
"	West	2000	+0 66	1 83
14 6 miles SW	SW	2000	0 0	
"	SF	2000	+0 33	
"	NW	2000	-0 67	1 0
"	SE	4000	+0 67	
"	NW	4000	-1.0	1 67

Flight Tests on the Indianapolis Omnirange Using a Five-Loop Array for Transmitting and Hatch V Receiving Antenna

Location	Direction of Flight	Height Above Station in Feet	Polarization Error in One Direction* (degrees)	Combined Polarization Error (degrees)	
9 miles North	North	2000	0 0		
"	East	2000	+2 0	2 5	
"	West	2000	-0 5		3 15
"	East	2000	+3 3	3 8	
"	West	4000	-0 75		
"	East	4000	+2 5	3 25	

* Plus sign indicates meter deflects right
Minus sign indicates meter deflects left

TABLE 111 TABULATION OF COMPARISON OF INDIANAPOLIS AND YOUNGSTOWN FLIGHT TESTS

A Comparison of Flight Tests on Youngstown and Indianapolis Omnirange Stations Made in NC-182

TAIL

Location	Height Above Station in Feet	Combined Polarization Error (degrees)	
		Youngstown*	Indianapolis**
9 miles North	2000	3 2	0 67
"	4000	4.0	0 25
4 miles North	2000	8 86	-
5 miles North	2000	-	1 88
10 miles NE	2000	4 27	-
14.6 miles SW	2000	-	1 0
"	4000	-	1.67
10 miles NE	4000	5 2	-

HATCH

Location	Height Above Station in Feet	Youngstown*	Indianapolis**
9 miles North	2000	3 75	3 15
"	4000	7 37	3.25

*This station used crossed dipole transmitting antennas
**This is the Experimental Station site, using a five-loop array