CIRCULARLY-POLARIZED OMNIDIRECTIONAL ANTENNA*

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Summary—This paper describes a circularly-polarized antenna which has been developed specifically for ground station use in airport-to-airplane communication. After briefly considering the necessary field conditions in space to bring about circular polarization, a combination of a vertical dipole and a horizontal loop antenna is treated theoretically. An equivalent arrangement using four dipoles is also studied and a number of factors influencing the performance are displayed.

The theoretical treatment is followed by a description of an antenna which was constructed according to the principles outlined. Test results show that the antenna produced a substantially circularly-polarized wave over a rather wide frequency range without readjustment.

INTRODUCTION

EXPERIENCE in airport-to-airplane communication has indicated a need for more reliable communication, free from random polarization changes caused by banking of the aircraft and from amplitude variations due to ground reflections. It has been suggested that a circularly-polarized antenna at the ground station would help to stabilize signal transmission, and permit maximum freedom of choice of antenna location on the aircraft.

The antenna described in this paper is the result of an extensive investigation which included experiments with slotted cylinder radiators, dipole and loop combinations, and spiral radiators.

THEORETICAL CONSIDERATIONS

(a) *A Circularly-Polarized Wave*

A circularly-polarized wave may quite properly be considered as made up of a vertically-polarized wave imposed on a horizontally-polarized wave with both waves traveling in the same direction. At any chosen point, the fields of the two waves are in time quadrature with one another.

The electric field intensity of the vertically-polarized wave is represented by the expression $e_V = A \cdot \sin \omega t$ (1)

This field intensity component is vertical.

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* Decimal Classification: R320.

The electric field intensity of the horizontally-polarized wave has the same peak value, but differs in phase by 90 degrees. This component, which is horizontal, is given by $e_H = A \cdot \cos \omega t$ (2)

At any given instant of time, the resultant field intensity vector has a magnitude equal to $\sqrt{e_V^2 + e_H^2} = A$, and this vector makes an angle α with the horizontal where

$$\tan \alpha = \frac{e_V}{e_H} = \tan \omega t \tag{3}$$

The field intensity vector is seen to be constant in magnitude and rotates in the plane of the wave at synchronous speed.

When the observer looks in the direction of travel of the wave and sees the vector rotating clockwise, the wave is said to be right-hand circularly polarized. When the vector rotates counterclockwise, the wave is left-hand circularly polarized.[1]

(b) *The Combination of a Vertical Dipole and a Horizontal Loop*

A horizontal loop antenna, with a vertical half-wave dipole piercing the center of the loop, may be used to produce a circularly-polarized wave.

At a remote point in the horizontal plane, the vertical half-wave dipole produces a vertical electric field given by

$$E_V = \frac{j60 I_V}{r} \epsilon^{-jkr} \tag{4}$$

The horizontal loop produces a horizontal electric field at the same point.

$$E_H = \frac{-60\pi kR \cdot J_1(kR)}{r} I_H \epsilon^{-jkr} \tag{5}$$

where I_V = the current at the center of the dipole,

I_H = the current in the loop,

λ = the wavelength, $k = 2\pi/\lambda$,

r = the distance from the antenna to the remote point,

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[1] Standards on Radio Wave Propagation, (Definition of Terms—p. 2), Institute of Radio Engineers, New York, N. Y., 1942.

R = the radius of the loop,

$J_1(kR)$ = the Bessel function of the first kind and first order.

It may be seen from equations (4) and (5) that the vertical and horizontal fields are in phase quadrature, when the currents in the loop and the dipole are in phase.

To make the two field components be equal to achieve circular polarization, the following relation must be satisfied:

$$I_V/I_H = \pi kR \cdot J_1(kR) \tag{6}$$

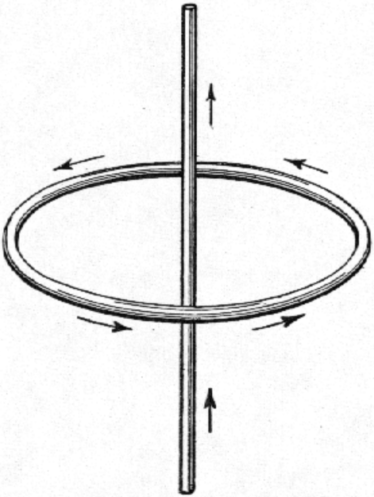

Fig. 1—Current flow relationships in a horizontal loop and a vertical dipole which radiate a right-hand circularly-polarized wave.

Typical values of this ratio, as a function of the radius of the loop, are given below:

R/λ	I_V/I_H
0.05	0.152
0.10	0.587
0.15	1.25
0.20	2.02
0.25	2.8

When the currents in the loop and dipole flow as shown in Figure 1, the resultant wave is right-hand circularly polarized.

While this combination of a loop and a dipole appears to be a simple arrangement, one soon finds that the necessary plumbing to achieve the proper current division while maintaining the currents in phase is quite elaborate and the adjustments are critical. This is particularly true when a wide band of frequencies is used.

(c) *An Equivalent Arrangement*

An arrangement which produces the same result but which is not difficult to attain has been proposed by Lindenblad.[2, 3] His plan may be described best in two steps. First, several vertical dipoles are disposed uniformly about the periphery of a circle which lies in the horizontal plane. Then each dipole is rotated about its center point, with the rotation taking place in a vertical plane which is tangent to the imaginary circle. Each dipole is rotated in the same angular direction. Figure 2 may help to clarify the description. Here four dipoles are used and the heavy arrows represent the direction of current flow in the dipoles. The vertical components of these currents are shown, all pointing upward and acting somewhat as a single vertical radiator. The horizontal components may be seen to flow just as the currents in a continuous loop antenna flow.

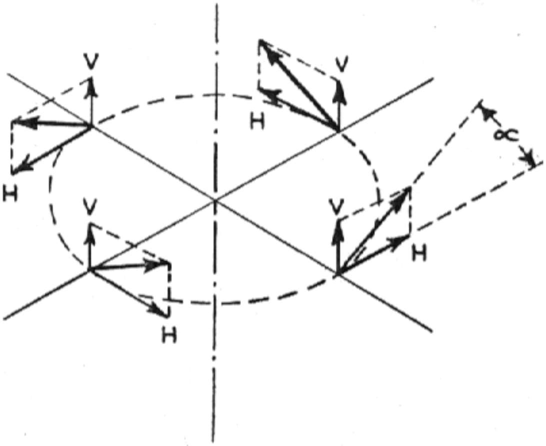

Fig. 2—The effective-current components in the slanted-dipole antenna arrangement.

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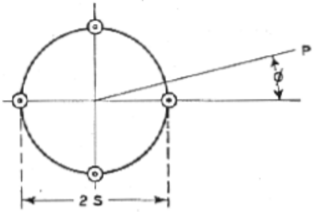
[2] N. E. Lindenblad, "Antennas and Transmission Lines at the Empire State Television Station", *Communications*, Vol. 21, No. 4, pp. 13-14, April, 1941.

[3] N. E. Lindenblad, U. S. Patent 2,217,911.

Figure 3 shows the plan view with the vertical current components all in phase, and the lower part of the same diagram shows the plan view for the horizontal current components.

PLAN VIEW-VERTICAL POLARIZATION



PLAN VIEW-HORIZONTAL POLARIZATION

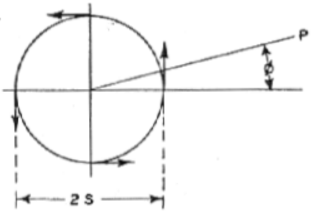


Fig. 3—Plan views showing the relative disposition of the vertical and horizontal components of antenna current.

Using the four radiators shown in Figures 2 and 3, we may write the expressions for the vertical and horizontal components of electric field at a remote point P thus:

$$E_V = j \frac{120\, I \epsilon^{-jkr}}{r} \cdot \sin \alpha \cos \theta \left[\cos (kS \cos \phi \cos \theta) + \cos (kS \sin \phi \cos \theta) \right] \tag{7}$$

and

$$E_H = \frac{-120\, I \epsilon^{-jkr}}{r} \cdot \cos \alpha \left[\cos \phi \sin (kS \cos \phi \cos \theta) + \sin \phi \sin (kS \sin \phi \cos \theta) \right] \tag{8}$$

where $S =$ the radius of the circle on which the antennas are located

$\alpha =$ the angle between each radiator and the horizontal plane

$\phi =$ the angle that locates the point P in the horizontal plane

$\theta =$ the angle which locates the point P in the vertical plane. (When this angle is zero, the point lies in the horizontal plane.)

$I =$ the current in each radiator.

The symbols k and r have been defined earlier in this paper.

Digressing for a moment, the case is considered where the dimension S is very small compared to a wavelength. Then the following approximations may be used:

$$\cos\,(kS \cdot \cos\phi\cos\theta) \doteq 1$$

$$\cos\,(kS \cdot \sin\phi\cos\theta) \doteq 1$$

$$\sin\,(kS \cdot \cos\phi\cos\theta) \doteq kS \cdot \cos\phi\cos\theta$$

$$\sin\,(kS \cdot \sin\phi\cos\theta) \doteq kS \cdot \sin\phi\cos\theta$$

and (7) becomes

$$E_V = j\,\frac{120\,I\epsilon^{-jkr}}{r} \cdot 2\sin\alpha\cos\theta \tag{9}$$

while (8) takes the form

$$E_H = \frac{-\,120\,I\epsilon^{-jkr}}{r} \cdot \cos\alpha\,[kS\cos^2\phi\cos\theta + kS\sin^2\phi\cos\theta]$$

$$= \frac{-\,120\,I\epsilon^{-jkr}}{r} \cdot kS\cos\alpha\cos\theta \tag{10}$$

Equations (9) and (10) show that, for small values of S, both the vertical and horizontal components of electric field are independent of the angle ϕ. In other words, the radiation pattern is uniformly circular. Both vertical patterns vary simply as $\cos\theta$. Hence, if we satisfy the condition

$$2 \cdot \sin\alpha = kS\cos\alpha$$

or

$$\tan\alpha = kS/2 \tag{11}$$

the radiated field will be circularly polarized at all points in space.

When the dimension S is not sufficiently small, perfect circular polarization will not be achieved at all points. However, elliptical polarization which closely approaches circular polarization may be readily obtained. For example, if it is desired to insure true circular polarization in the horizontal plane at positions corresponding to values of ϕ equal to 0, 90, 180, and 270 degrees, it is merely necessary to satisfy the relation

$$\sin\alpha\,[1+\cos(kS)] = \cos\alpha\,\sin(kS)$$

or

$$\tan\alpha = \tan(kS/2) \tag{12}$$

To obtain circular polarization at points corresponding to ϕ equal to 45, 135, 225, and 315 degrees, it is necessary to satisfy the relation

$$\tan\alpha = \frac{1}{\sqrt{2}}\tan\left(\frac{kS}{\sqrt{2}}\right) \tag{13}$$

The relation between the tilt angle of the dipoles and the dimension S may be seen in the following tabulation.

S (wavelengths)	kS (degrees)	α (degrees) From equation (12)	α (degrees) From equation (13)
0	0	0	0
0.0833	30	15°	15° 22′
0.166	60	30°	32° 55′
0.25	90	45°	55°

DESCRIPTION OF A CIRCULARLY-POLARIZED ANTENNA

An antenna has been constructed, following the basic design principles established by Lindenblad, and is shown in Figure 4. The antenna consists of four in-phase dipoles arranged on the circumference of a circle having a diameter of approximately one-third wavelength. Hence kS is 60 degrees, so from Equation (12) it is found necessary to incline each dipole at an angle of 30 degrees from the horizontal plane.

Each of the four dipoles is fed with a RG-11U solid-dielectric coaxial cable placed inside one of the two tubular support legs, with the cables each one-quarter wave in length at the mid-band frequency of operation. The inner conductor of the cable extends through a protecting end seal to the end of the other support leg, providing a balanced feed to the dipole. This method of securing balanced feed is illustrated in Figure 5.

The impedance offered to the transmission line at this point consists of the antenna impedance shunted by the inductive reactance of

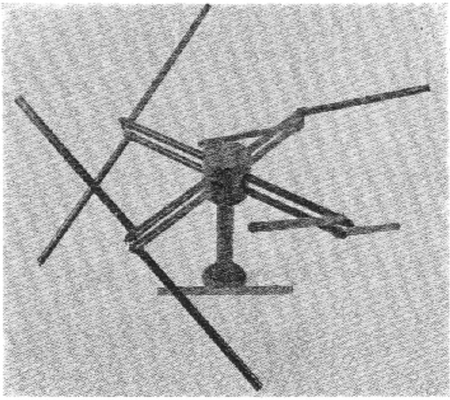


Fig. 4—The development model designed to operate over the frequency range from 110 to 132 megacycles. (This model radiates a left-hand circularly-polarized wave.)

the parallel-bar support legs. The dipoles are made somewhat less than a half wave, so the antenna impedance consists of a resistive component and a capacitive reactance. The dimensions were so chosen that the inductive reactance of the support legs just parallel-resonated the dipole. In addition, at resonance the resistance of the combination is 100 ohms. The RG-11U cable has a characteristic impedance of 72 ohms. Hence, the impedance looking into the quarter-wave section which feeds the dipole is approximately 52 ohms. It is of interest to

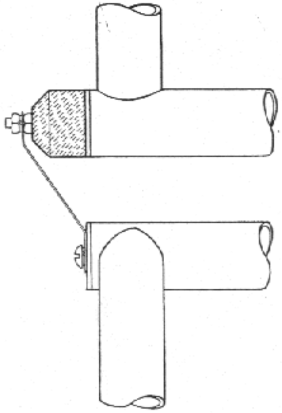


Fig. 5—The method used to secure balanced feed of the dipole from a concentric transmission line.

note that the velocity in this solid-dielectric cable is two-thirds of the velocity of radio waves in free space so the quarter wavelength of cable has an actual physical length of one-sixth of a free-space wavelength and thus just reaches from the end-seal of the dipole to the center of the large cylinder shown in Figure 4. The four cables join in this cylinder. Since they are all in parallel, they offer a resistance of 13 ohms. A quarter-wave transformer with a characteristic impedance of 26 ohms is contained in the central vertical support post. This transformer steps the 13-ohm resistance up to 52 ohms. Thus an impedance match is offered to the 52-ohm feed line which leads from the transmitter to the antenna. The result is a well-matched antenna radiating a substantially circularly-polarized wave. Equal currents in the dipoles, all in phase, are obtained simply from the symmetrical construction and depend in no way upon the method of securing an impedance match.

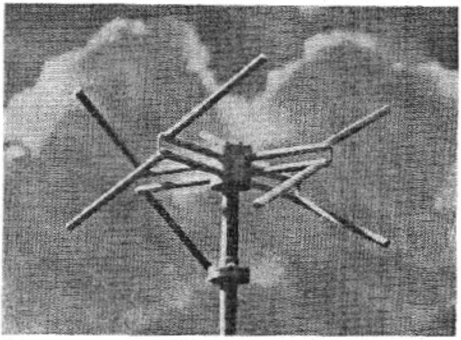


Fig. 6—A very small model of the circularly-polarized antenna. (This model radiates a right-hand circularly-polarized wave.)

While it is true that the central support pole lies in the field of the antenna, tests proved that it was not necessary to use a quarter-wave sleeve around the support pole to secure the desired radiation characteristics.

The weight of the completed antenna is less than 30 pounds, exclusive of the mounting pole and feed line.

An inspection of Figures 1 and 4 reveals that the antenna shown in Figure 4 will radiate a left-hand circularly-polarized wave. A small model of this type of antenna is shown in Figure 6. This model is constructed to yield a right-hand circularly-polarized wave.

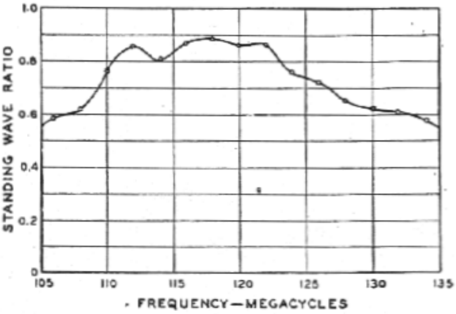


Fig. 7—The measured standing-wave ratio as a function of frequency.

TEST RESULTS

The antenna was designed to cover a band of frequencies lying between 110 and 132 megacycles. The standing-wave ratio on the main feed line, as a function of frequency, is shown in Figure 7. It may be seen that the standing-wave ratio is better than 0.5 over the entire band.

To learn how well circular polarization had been achieved, a transmitter was connected to the antenna and a dipole at the receiver was rotated on a horizontal axis. This test was made at many points around the antenna and at several frequencies. Figure 8 shows typical results. A possible explanation of the departure of the measured curve from a perfect circle is the slight shading or shielding effect experienced by

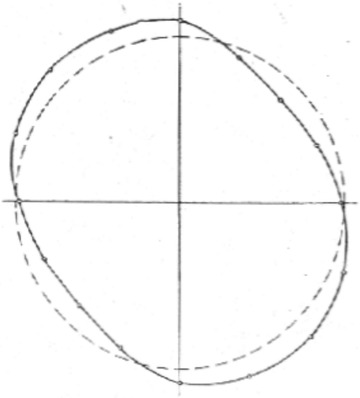


Fig. 8—Experimental data showed the close approach to a true circularly-polarized wave.

the radiators or portions of radiators farthest from the receiver, behind the central pipe support and cable connector box.

Vertical radiation patterns were found to obey the cos θ law rather well throughout the band of frequencies.

Radiation patterns in the horizontal plane were measured at a number of frequencies. The patterns were found to be essentially circular for all frequencies in the band. Typical measurements taken at 122 megacycles are shown in the tabulation below. The theoretical values were calculated from Equations (7) and (8).

Angle ϕ (degrees)	Horizontally-polarized field		Vertically-polarized field	
	Theoretical	Measured	Theoretical	Measured
0	1.0	1.0	1.0	1.02
22.5	1.05		0.992	
45	1.095	1.015	0.976	1.042
67.5	1.05		0.992	
90	1.0	0.98	1.0	1.042
135	1.095	1.015	0.976	1.065
180	1.0	1.0	1.0	1.075
225	1.095	1.015	0.976	1.052
270	1.0	0.98	1.0	1.032
315	1.095	1.015	0.976	1.032

CONCLUSION

The antenna described in this paper produces a substantially circularly-polarized wave over a rather wide frequency range without readjustment. In fact, the initial adjustments are far from critical.

The signal radiated by this antenna may be received on a dipole or loop antenna. The receiving antenna may be oriented in any position, with the reservation that the receiving antenna does not have a null in its pattern at this position. For example, a dipole could be rotated about a horizontal axis and receive a substantially constant signal if this axis coincides with the line from the transmitter to the receiver. However, if the rotation were such that the receiving antenna assumed a position which coincided with the axis mentioned above, no signal would be received.

If a circularly-polarized antenna is used to receive the circularly-polarized wave, it is necessary that both antennas be capable of producing a right-hand circularly-polarized wave or that they both be capable of producing a left-hand circularly-polarized wave. For example, if the transmitting antenna were the one shown in Figure 4 and the receiving antenna similar to the antenna of Figure 6, the receiving antenna would be blind to the transmitter.