of ground reflection will usually be such that the delays associated with ϕ will be greater than those associated with ψ. Assuming sharply beamed antennas ϕ_m is limiting and the delay is 9 microseconds. This corresponds to an available path bandwidth of 110 kc/s. If the transmitting and receiving antenna beamwidths are smaller than bandwidths of the scattering mechanism, still greater bandwidths are in principle available.

Antennas

With the results of the experimental program (Part I) and the discussion of the role of the antennas (Part II), together with the multipath considerations given above, it is possible to establish the characteristics of antenna systems for use in communication applications. For purposes of discussion, Table VI indicates certain desirable characteristics without regard to whether antennas having such characteristics are at present practicable.

TABLE VI
Desirable Antenna Characteristics

Horizontal beamwidth	8 degrees or less
Vertical beamwidth including ground effects	6 degrees or less
Maximum radiation in any minor lobe	At least 40 decibels below radiation in the maximum of the main beam
Radiation efficiency; i.e., ratio of total power radiated to antenna input power	90 per cent or greater
Horizontal orientation of beam	Normally on great-circle bearing between transmitter and receiver
Vertical orientation of beam	85 kilometers above midpoint of great-circle path
Provision for reducing directivity or for varying direction of the beam	For use during periods when scattering is not homogeneous and during periods when scattering from meteoric components will provide higher signal-to-noise ratios
Bandwidth over which characteristics are to be maintained	200 kc/s

Although most of the above set of characteristics are self-explanatory some additional comments are indicated. When a low noise-figure receiver is employed, somewhat lower radiation efficiencies for receiving antennas can be tolerated since the available noise power from galactic sources is much higher than that resulting from internal noise generated in the receiver. For the longer paths, increased vertical directivity is necessary in order to utilize effectively the reduced common scattering volumes. From the common volume point of view, horizontal beamwidths smaller than 8 degrees will not be required for any except the very longest paths. The suggested techniques for varying directivity or for orienting the main beam in directions other than the great circle-bearing have not been tested under operational conditions and a determination of the practical effectiveness of this scheme will require further study and trial. It remains to be seen to what extent antennas having characteristics approaching those envisaged above will find their way into practice.

The use of spaced-antenna receiving diversity is definitely desirable for good communications. From the spaced-antenna observations of envelope correlation between spaced antennas, and from the diversity-distance considerations discussed in Part II, it is concluded that for effective diversity action the component of spacing transverse to the path should not be less than about 10 wavelengths.

The effects of the scattering mechanism with regard to the polarization of the transmitted waves have been considered earlier and it was shown that the scattering losses are somewhat less for horizontal than for vertical polarization. Horizontal polarization is generally to be preferred for additional reasons associated with the reflection characteristics of the ground.[14]

Practical Antenna Siting

A corollary to the observed failure to realize, for a large fraction of the time, antenna gains comparable to the plane-wave gains, is that the additional gain resulting from ground reflection will not be fully realized, even though ideal sites are employed at the transmitter and receiver. The reason for this was discussed in Part II in connection with vertical diversity spacing. Nevertheless there are demonstrable advantages in siting the antennas with respect to a ground surface so that the plane-wave ground-reflection lobe patterns are well formed. In fact, if either antenna is poorly sited, the beams may only partially intersect in the height region where scattering occurs.

For the idealized beam-swinging models discussed in Part II two limiting cases were considered with respect to the transmitting antenna patterns. They were an omnidirectional antenna and an extremely directive antenna. The generalized q-curves representing Case I geometry, in which the effective scattering volume is displaced toward one terminal, are shown in Fig. 46 as a function of α_R. In practice the directivity of the transmitting antenna is intermediate between the two extremes. It is therefore anticipated that slightly greater signal intensities will result if the transmitting and receiving beams are directed toward a point in the scattering stratum slightly displaced in the manner above provided appropriately different directivities are employed at the terminals. While unsymmetrical operation of this kind, employing negligibly increased scattering angles, would represent no disadvantage, it is nevertheless recommended in practice that antenna beams be designed to have their principal lobes directed toward the path midpoint in the ionosphere. The recommended ionospheric height for antenna design and corresponding site selection is 85 kilometers.

Some exceptions to this design recommendation can be made with advantage for paths longer than about 2,200 kilometers. For such extreme path lengths some increase in received signal intensity is likely to be realized with antennas having practical vertical free-space directivities if use is made of heights greater than required to direct the first ground-reflection lobe at the path midpoint in the ionosphere. As the antenna heights increase, ψ_c increases with the increasing depression of the radio horizons. As a consequence the total power radiated into the common volume is increased. Thus, for very long paths greater heights should be used wherever practicable and especially at one terminal if height limitations exist at the other terminal. The design heights indicated for lobe alignment at the path midpoint in the ionosphere should be regarded for paths of extreme length as minimum rather than optimum.

The curves of Fig. 11 show the vertical angle of arrival or departure for various ionospheric midpoint heights as a function of the surface distance between the transmitter and the receiver. They have been found useful in connection with antenna design and siting problems. The values given by these curves have been calculated for elevations near sea level for the assumed condition of no lower atmosphere and for representative radio-wave refraction in mid-latitudes. Some remarks concerning the general applicability of the curves are indicated. First, the refraction corrections decrease with elevation of the terminal above sea level. Secondly, in warm, humid regions, such as many tropical locations, the increase in angle of arrival over that for the case of no lower atmosphere may be about $1\frac{1}{4}$ times the values shown. Thirdly, in polar regions, particularly under winter conditions when the absolute humidity is very low, the increase in angle over that for the case of no lower atmosphere may be only about two-thirds of the values of increase shown. Lastly, the corrections for angles below about one or two degrees may, as a practical matter, be extremely variable, particularly if conditions conducive to superrefraction occur.

In siting an antenna intended to function effectively for small angles of arrival and departure, it is insufficient merely to provide a suitable site on which to perform the construction. Nor is it sufficient simply to have an unobstructed horizon in the desired azimuth for the desired angle of departure or arrival. When the angle of departure or arrival is small, the ground for a considerable distance in front of the antenna plays a critical role in formation of the lobe pattern. The problem of ground-reflection lobes and general requirements for a smooth first Fresnel zone has been given considerable study, particularly with respect to the ground radar siting problem. For the purposes of the following discussion it is assumed that the lowest lobe will be effectively formed when the terrain in front of the antenna is flat and smooth over an area no smaller than the first Fresnel zone. Horizontal polarization only is considered so that lobe formation is not complicated by large variations in the ground-reflection coefficient over the range of angles of interest. Mathematically, the antenna is assumed to be at a point and the ground-reflected wave is assumed to have the same amplitude as the incident wave but to undergo a 180-degree phase change at reflection.

The first Fresnel zone is defined, with the aid of Fig. 64, as the area of ground, assumed smooth and plane, in front of the point antenna A from within which

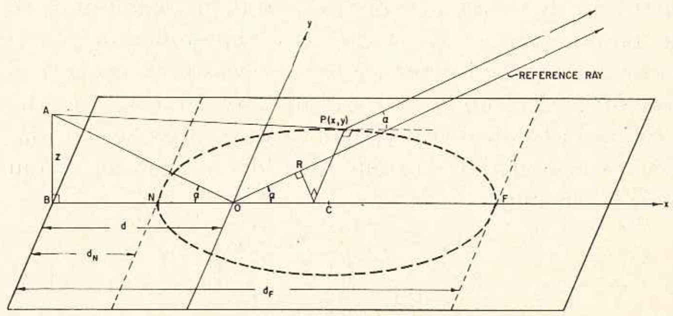

Fig. 64—Geometry of first Fresnel zone.

all secondary wavelets, according to Huygens' principle, contributing to a plane-wave front advancing in the direction of the positive x-axis with an inclination upward of α, differ in phase by 180 degrees or less from a reference ray, obeying strict geometric optics. The origin of the coordinates, O, is situated at the ground-reflection point for the reference ray.

For alignment of the maximum of the first ground-reflection lobe at an angle of elevation α, it is necessary for the point antenna A to be at a height, z, given previously by (43), as follows:

$$z = \frac{\lambda}{4 \sin \alpha},$$

where λ is the wavelength. The distance from the antenna base at B to the geometric ground-reflection point is given by:

$$d = \frac{z}{\tan \alpha}. \quad (44)$$

Now let $P(x, y)$ be a general point obeying the conditions defining the boundary of the first Fresnel zone, so that

$$AP - (AO + OR) = \frac{\lambda}{2}, \quad (45)$$

where R is the point along the reference ray at which the phase comparison is made with the wavelet originating at P.

By using (43) to eliminate λ in (45) and expressing AP, AO, and OR as functions of h, α, and the coordinates x and y, the locus of P is found, after some simplification, to be: