Wave Propagation

9-1 Radio Waves

Nature of radio waves — Radio waves are electromagnetic waves, consisting of traveling electrostatic and electromagnetic fields so related to each other that the energy is evenly divided between the two, and with the lines of force in the two fields at right angles to each other in a plane perpendicular to the direction of propagation, as shown in Fig. 901. Except for the difference in order of wavelength, they have the same nature as light waves, travel with the same speed (300,000,000 meters per second in space), and, similarly to light, can be reflected, refracted and diffracted.

Polarization — The polarization of a radio wave is taken as the direction of the lines of force in the electrostatic field. If the direction of the electrostatic component is perpendicular to the earth the wave is said to be *vertically polarized*, while if the electrostatic component is parallel to the earth the wave is *horizontally polarized*. The electromagnetic component, being at right angles to the electrostatic, therefore has its lines of force vertical when the wave is horizontally polarized and horizontal when the wave is vertically polarized.

Reflection — Radio waves may be reflected from any sharply defined discontinuity, of suitable characteristics and dimensions, in the medium in which they are propagated. Any good conductor meets this requirement, provided its dimensions are at least comparable with the wavelength. The surface of the earth also forms such a discontinuity, and waves are readily reflected from the earth.

Refraction — Refraction of radio waves is similar to the refraction of light; that is, the wave is bent when moving obliquely into a region having a different refractive index from that of the region it leaves. This bending results because the velocity of propagation differs in the two regions, so that the part of the wavefront which enters first travels faster or slower than the part which enters the new region last, causing the wavefront to turn.

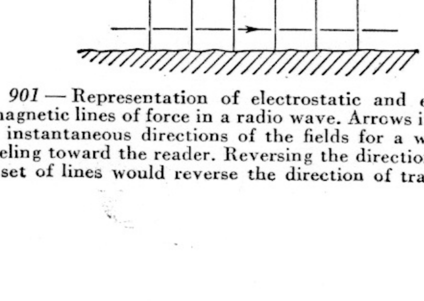


Fig. 901 — Representation of electrostatic and electromagnetic lines of force in a radio wave. Arrows indicate instantaneous directions of the fields for a wave traveling toward the reader. Reversing the direction of one set of lines would reverse the direction of travel.

Diffraction — When a wave grazes the edge of an object in passing, it is bent around the object. This bending is called *diffraction*.

Ground and sky waves — Two types of waves occur, one traveling along the surface of the ground, the other traveling through the atmosphere and having no contact with the ground along most of its path. The former is called the *ground wave*, the latter the *sky wave*. The ground wave dies out rather rapidly but the sky wave can travel great distances, especially on high frequencies (short wavelengths).

Field strength — The intensity of the electrostatic field of the wave is called the *field strength* at the point of measurement. It is usually expressed in microvolts per meter, and is equivalent to the voltage induced in a wire one meter long placed with its axis parallel to the direction of polarization.

9-2 The Ground Wave

Description — The ground wave is continuously in contact with the surface of the earth and, in cases where the distance of transmission makes the curvature of the earth important, is propagated by means of diffraction, with refraction in the lower atmosphere also having some effect. The ground wave is practically independent of seasonal and day and night effects at the higher frequencies (above 1500 kc.).

Polarization — A ground wave must be vertically polarized because the electrostatic field of a horizontally polarized wave would be short-circuited by the ground, which acts as a conductor at the frequencies for which the ground wave is of most interest.

Ground characteristics and losses — The wave induces a current in the ground in traveling along its surface. If the ground were a perfect conductor there would be no loss of energy, but actual ground has appreciable resistance, so that the current flow causes some energy dissipation. This loss must be supplied by the wave, which is correspondingly weakened. Hence, the transmitting range depends upon the ground characteristics. Because sea water is a good conductor, the range will be greater over the ocean than over land. The losses increase with fequency, so that the ground wave is rapidly attenuated at high frequencies and above about 2 Mc. is of little importance except in purely local communication.

Range of ground wave — At frequencies in the vicinity of 2 Mc. the ground-wave range is of the order of 200 miles over average land and perhaps two or three times as far over sea water, for a medium-power transmitter (500 watts or so) using a good antenna. At higher frequencies the range drops off rapidly, and above 4 Mc. the ground wave is useful only for work over quite short distances.

ℂ 9-3 The Ionosphere

Description — Since a sky wave leaving the transmitting antenna has to travel upward with respect to the earth's surface, it would simply continue out into space if its path were not bent sufficiently to bring it back to the earth. The medium which causes such bending is the *ionosphere*, a region in the upper atmosphere where free ions and electrons exist in sufficient quantity to cause a change in the refractive index. Ultraviolet radiation from the sun is considered to be responsible for the ionization. The ionosphere is not a single region but consists of a series of "layers" which occur at different heights, each layer consisting of a central region of ionization which tapers off in intensity both above and below.

Refraction, absorption, reflection — For a given intensity of ionization, the amount of refraction becomes less as the frequency of the wave becomes higher (shorter wavelength). The bending therefore is smaller at high than at low frequencies, and if the frequency is raised to a high-enough value the bending eventually will become too slight to bring the wave back to earth, even when it enters the ionosphere at a very small angle to the "edge" of the ionized zone. At this and higher frequencies long-distance communication becomes impossible.

The greater the intensity of ionization, the greater the bending on a given frequency. Thus an increase in ionization increases the maximum frequency which can be bent sufficiently for long-distance communication. The wave loses some energy in the ionosphere, and this energy loss increases with ionization density and the wavelength. Unusually high ionization may cause complete absorption of the wave energy, especially when the ionization is high in the lower regions of the ionosphere and below the lowest normally useful layer. When the wave is absorbed in the ionosphere it is no more useful for communication than if it had passed through without sufficient bending to bring it back to earth.

In addition to refraction, reflection may take place at the lower boundary of a layer if that boundary is well-defined; i.e., if there is an appreciable change in ionization within a relatively short interval of distance. For waves approaching the layer at or near the perpendicular, the change in ionization must take place within a difference in height comparable to the wavelength, hence reflection is more apt to occur at longer wavelengths (lower frequencies).

Critical frequency — When the frequency is low enough, a wave sent vertically upward to the ionosphere will be bent sufficiently to return to the transmitting point. The highest frequency at which this occurs, for a given state of the ionosphere, is called the *critical frequency*. It serves as an index for transmission conditions, although it is not the highest *useful* frequency since waves which enter the ionosphere at smaller angles than 90 degrees (vertical) will be bent sufficiently to return to earth. The maximum usable frequency, for waves leaving the earth at very small angles to the horizontal, is in the vicinity of three times the critical frequency.

Besides being directly observable, the critical frequency is of more practical interest than the ionization density because it includes the effects of absorption as well as refraction.

Virtual height — Although a layer is a region of considerable depth it is convenient to assign to it a definite height, called the *virtual height*. The virtual height is the height from

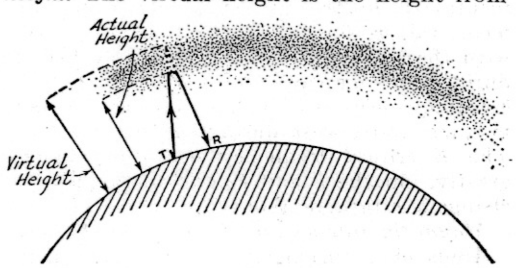


Fig. 902 — **Showing bending in the ionosphere and the echo or reflection method of determining virtual height.**

which a pure reflection would give the same effect as the refraction which actually takes place. This is illustrated in Fig. 902. The wave traveling upward is bent back over a path having appreciable radius of turning, and a measurable interval of time is consumed in the turning process. The virtual height is the height of a triangle formed as shown, having equal sides of a total length equivalent to the time taken for the wave to travel from T to R.

The E layer — The lowest normally useful layer is called the E layer. Its average height (maximum ionization) is about 70 miles. The ionization density is greatest around local noon, and the layer is only weakly ionized at night when the radiation from the sun is not present. This is because the air at this height is sufficiently dense so that free ions and electrons very quickly meet and recombine.

The F, F_1 and F_2 layers — The second principal layer is the F, which is at a height of about 175 miles at night. In this region the air is so thin that recombination of ions and electrons takes place very slowly, since the particles can travel relatively great distances before meeting. The ionization decreases after sundown, reaching a minimum just before sunrise. In the daytime the F layer splits into two layers, the F_1 and F_2, at average virtual heights of about 140 miles for the F_1 and 200 miles for the F_2. These are most highly ionized at about local noon, and merge again at sunset into the F layer.

Seasonal effects — In addition to day and night variations, there are also seasonal changes in the ionosphere as the quantity of radiation received from the sun changes. Thus the E layer has higher critical frequencies in the summer (about 4 Mc., average, in daytime) than in the winter, when the critical frequency is near 3 Mc. The F layer shows little variation, the critical frequency being of the order of 4 to 5 Mc. in the evening. The F_1 layer, which has a critical frequency in the neighborhood of 5 Mc. in summer, usually disappears in winter. The critical frequencies are highest in the F_2 layer in winter (11 to 12 Mc.) and lowest in summer (around 7 Mc.). The virtual height of the F_2 layer is also less in winter (about 185 miles) than in summer (average 250 miles).

In the spring and fall a transition period occurs, and conditions in the ionosphere are more variable at these times of the year.

Sunspot cycles — The critical frequencies mentioned in the preceding paragraph are mean values, since the ionization also varies with the 11-year sunspot cycle, being higher during times of greatest sunspot activity. Critical frequencies are highest during sunspot maxima and lowest during sunspot minima. The E critical frequency does not change greatly, but the F and F_2 critical frequencies change in a ratio of about 2 to 1.

Magnetic storms and other disturbances — Unusual disturbances in the earth's magnetic field (magnetic storms) usually are accompanied by disturbances in the ionosphere, when the layers apparently break up and expand. Usually there is also an increase in absorption during such a period. Radio transmission is poor and there is a drop in critical frequencies, so that lower frequencies must be used. Such a storm may last for several days.

Unusually high ionization in the region of the atmosphere below the normal ionosphere may increase absorption to such an extent that sky-wave transmission becomes impossible on high frequencies. The length of such a disturbance may be several hours, with a gradual falling off of transmission conditions at the beginning and an equally gradual building up at the end of the period. *Fadeouts*, similar to the above in effect, are caused by sudden disturbances on the sun. Characterized by very rapid ionization, with sky-wave transmission disappearing almost instantly, they occur only during daylight and do not last as long as the first type.

9-4 The Sky Wave

Wave angle (angle of radiation) — The smaller the angle at which the wave leaves the earth, the smaller the bending required in the ionosphere to bring it back and, in general, the greater the distance between the point where it leaves the earth and that at which it returns (§ 9-3). This is shown in Fig. 903. The vertical angle which the wave makes with a tangent to the earth is called the *wave angle* or *angle of radiation*, the latter term being used more in connection with transmitting than with receiving.

Skip distance — Since more bending is required to return the wave to earth when the wave angle is high, it is found that at high frequencies the refraction frequently is not great enough to give the required bending unless the wave angle is smaller than a certain angle, called the *critical angle*. This is shown in Fig. 903, where wave angles A and lower give useful signals but waves sent at higher angles travel through the layer and do not return. The distance between T and R_1 is, therefore, the shortest possible distance over which sky-wave communication can be carried on. The area between the end of the useful ground wave and the beginning of sky-wave reception is called the *skip zone*. The skip distance depends upon the frequency and the state of the ionosphere, and is greater the higher the transmitting frequency and the lower the critical frequency (§ 9-3). It depends also upon the height of the layer in which the refraction takes place, the higher layers giving longer distances for the same wave angle. The wave angles at the transmitting and receiving points are usually, although not necessarily, approximately the same for a given wave path.

It is readily possible for the sky wave to pass through the E layer and be refracted back to earth from the F, F_1 or F_2 layers. This is because the critical frequencies are higher in the latter layers, so that a signal too high in frequency to be returned by the E layer can still come back from the F_1, F_2 or F, depending

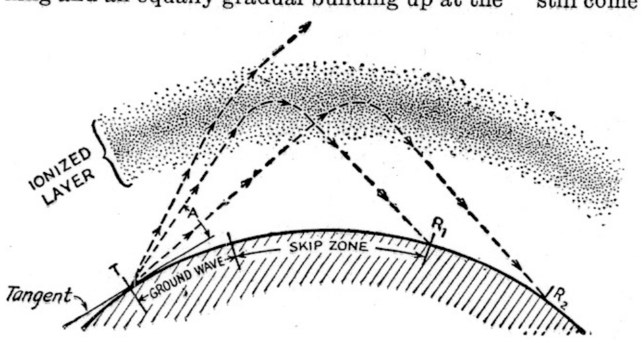


Fig. 903 — Refraction of sky waves, showing the critical wave angle and the skip zone. Waves leaving the transmitter at angles above the critical (greater than A) are not bent enough to be returned to earth. As the angle is increased, the waves return to earth at increasingly greater distances. Below a certain minimum angle (less than A) the waves do not ever return to earth.

upon the time of day and the conditions existing. Depending upon the wave angle and the frequency, it is also possible to carry on communication via either the E or F_1-F_2 layers on the same frequency.

Multi-hop transmission — On returning to earth the wave can be reflected (§ 9-1) upward and travel again to the ionosphere, where refraction once more takes place, again with bending back to the earth. This process, which can be repeated several times, is necessary for transmission over great distances because of the limited heights of the layers and the curvature of the earth, since at the lowest useful wave angles (of the order of a few degrees, waves at smaller angles generally being absorbed rapidly at high frequencies by being in contact with the earth) the maximum one-hop distance is about 1250 miles with refraction from the E layer and around 2500 miles from the F_2 layer. Ground losses absorb some of the energy from the wave on reflection, the amount of loss varying with the type of ground and being least for reflection from sea water. When the distance permits it is better to have one hop rather than several, since the multiple reflections introduce losses which are higher than those caused by the ionosphere.

Fading — Two or more parts of the wave may follow slightly different paths in traveling to the receiving point, in which case the difference in path lengths will cause a phase difference to exist between the wave components at the receiving antenna. The field strength therefore may have any value between the numerical sum of the components (when they are all in phase) and zero (when there are only two components and they are exactly out of phase). Since the paths change from time to time, this causes a variation in signal strength called *fading*. Fading also can result from the combination of single-hop and multi-hop waves, or the combination of a ground wave and sky wave. The latter condition gives rise to an area of severe fading near the limiting distance of the ground wave, better reception being obtained at both shorter and longer distances where one component or the other is considerably stronger. Fading may be rapid or slow, the former type usually resulting from rapidly changing conditions in the ionosphere, the latter occurring when transmission conditions are relatively stable.

¶ 9-5 Very-High-Frequency Propagation

Direct ray — In the very-high-frequency portion of the spectrum (above 30 Mc.), the bending of the waves in the normal ionosphere layers is so slight that the sky wave (§ 9-4) does not ordinarily play any part in communication. The ground-wave (§ 9-2) range also is extremely limited, because of high absorption in the ground at these frequencies. Normal v.h.f. transmission is by means of a *direct ray*, or wave traveling directly from the transmitter to the receiver through the atmosphere. Since the energy lost in ground absorption by a wave

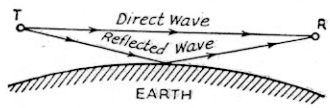


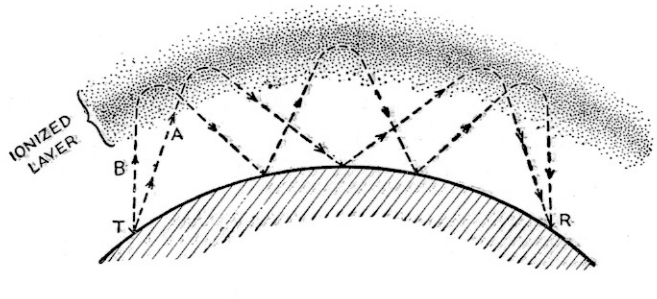
Fig. 905 — Showing how both direct and reflected waves may be received simultaneously in v.h.f. transmission.

traveling close to the ground decreases very rapidly with its height in wavelengths above ground, a very-high-frequency wave can be relatively close (in physical height) to the ground without suffering the absorption effects which would occur at the same physical heights with longer wavelengths.

Since the wave travels practically in a straight line, the maximum signal strength can be obtained only when there is an unobstructed atmospheric path between the transmitter and receiver. This means that the transmitting and receiving points should be sufficiently high to provide such a path, and on long paths the curvature of the earth as well as the intervening terrain must be taken into account.

Reflected ray — In addition to the direct ray, part of the wave strikes the ground between the transmitter and receiver and is reflected upward at a slight angle, producing a *reflected-ray* component at the receiver. This is shown in Fig. 905. The reflected ray is more or less out of phase with the direct ray, hence the net field strength at the receiving point is less than that of the direct ray alone. The canceling effect of the reflected ray depends upon the heights of the transmitter and receiver above the point of reflection, the ground losses when reflection takes place, and the frequency, decreasing with an increase in any of these.

Fig. 904 — Multi-hop transmission, showing two- and three-hop paths. A high-angle wave may be reflected upward from the ground and then refracted again to appear at the receiving point, R (two-hop transmission). If the angle of the wave is high enough, the process may be repeated several times.



Atmospheric refraction — There is normally some change in the refractive index of the air with height above ground, its nature being such as to cause the waves to bend slightly towards the ground. Where curvature of the earth must be considered, this has the effect of lengthening the distance over which it is possible to transmit a direct ray. It is convenient to consider the effect of this "normal" refraction as equivalent to an increase in the earth's radius, in determining the transmitting and receiving heights necessary to provide a clear path for the wave. The equivalent radius, taking refraction into account, is 4/3 the actual radius.

Range vs. height — The height required to provide a clear path ("line of sight") over level ground from an elevated transmitting point to a receiving point on the surface, not including the effect of refraction, is

$$h = \frac{d^2}{1.51}$$

where h is the height in feet and d the distance in miles. Conversely, the line of sight distance in miles for a given height in feet is equal to $1.23\sqrt{h}$. Taking refraction into account, this equation becomes $1.41\sqrt{h}$. Fig. 906 gives the answer directly when one quantity is known.

When transmitter and receiver both are elevated, the maximum direct-ray distance to ground level as given by the formulas can be determined separately for each. Adding together the two distances so obtained will give the maximum distance by which they can be separated for direct-ray communication. This is shown in Fig. 907.

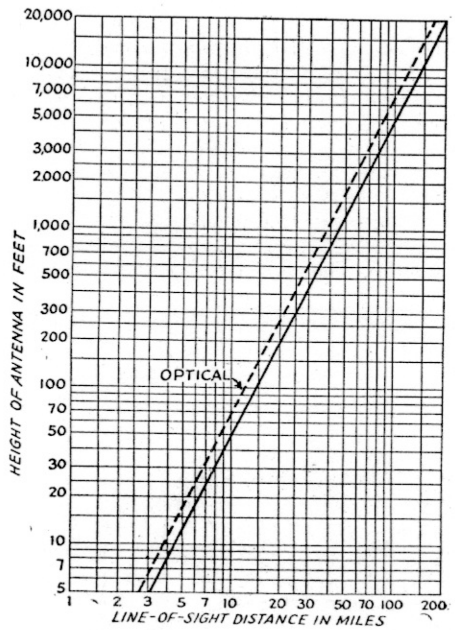


Fig. 906 — Chart for determining line-of-sight distance for v.h.f. transmission. The solid line includes effect of refraction, while the dotted line is the optical distance.

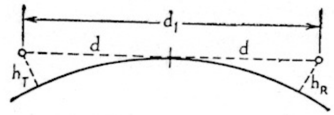


Fig. 907 — Method of determining total line-of-sight distance when both transmitter and receiver are elevated, based on Fig. 906. Since only earth curvature is taken into account in Fig. 906, irregularities in the ground between the transmitting and receiving points must be considered when computing each actual path.

Diffraction — At distances beyond the direct-ray path the wave is diffracted around the curvature of the earth. The diffracted wave is attenuated very rapidly, so that beyond the maximum direct-ray distance the signal strength decreases considerably faster with distance than it does within the direct-ray or line-of-sight path.

ℂ 9-6 Troposphere Refraction

Temperature inversions — The refractive index of the lower atmosphere depends principally upon the temperature, moisture content, and pressure. Of the three, only temperature differences cause a large enough change in refractive index to refract very-high frequency waves in such a way as to extend the distance range beyond the normal direct-ray and diffracted-wave ranges discussed in the preceding section. This occurs when there is a "temperature inversion," or a layer of warm air over cooler air near the ground. Temperature inversions are relatively frequent in the summer, and usually occur at heights from a few thousand feet to two miles or so above the ground.

Lower atmosphere bending — When there is a sufficiently marked temperature inversion, i.e., a rapid rise of temperature with height, a wave is refracted back to earth in much the same way as in the ionosphere, although the cause of the change in refractive index is different. The amount of bending is small compared to the bending in the ionosphere. Consequently, the wave angle (§ 9-4) must be quite low (zero or nearly so), but since the bending takes place at a low altitude it is possible to extend the range of v.h.f. signals to several hundred miles when both transmitter and receiver are well below the line of sight.

Fig. 908 illustrates the conditions existing when the air is "normal" and when a temperature inversion is present. Since the bending is relatively small it is advantageous to have as much height as possible at both the receiving and transmitting points, even though these heights may be considerably less than those necessary for "line-of-sight" transmission.

Frequency effects — The amount of bending is greater at longer wavelengths (lower frequencies) but is not usually observed at frequencies much below 28 Mc., partly because it is masked by other effects. The upper limit of frequency at which useful bending ceases is not known, but transmission by this means is frequent on 56 and 112 Mc.

9-7 Sporadic-E Ionization

Description — Under certain conditions small regions or "patches" of unusually dense ionization may appear in the *E* layer of the ionosphere, for reasons not yet clearly understood. This is known as *sporadic-E* ionization, and the change in refractive index in such a patch or cloud frequently is great enough to cause waves having frequencies as high as 60 Mc. to be bent back to earth. The dimensions of a sporadic-*E* cloud are relatively small, hence communication by means of it is restricted to transmitting and receiving localities so situated with respect to the cloud and to each other that a refracted wave path is possible.

The abnormal ionization usually disappears in the course of a few hours. Sporadic-*E* ionization is more frequent in the summer than in the winter, and may occur at any time of the day or night.

Transmission characteristics — Sporadic-*E* refraction may take place at all frequencies up to the region of 60 Mc. At the present time there are no known cases of such refraction on 112 Mc. When sporadic-*E* ionization is present skip distance is greatly reduced (when a wavepath via the cloud is possible to a given receiving location) on the frequencies where transmission normally is by means of the F, F_1 and F_2 layers; that is, from about 3.5 to 30 Mc. at night. The skip zone may in fact disappear entirely over most of the high-frequency spectrum, since the critical frequencies may rise to as high as 12 Mc. for sporadic-*E* refraction.

At very-high frequencies the bending is relatively small compared to lower frequencies, and only wave angles of the order of 5 degrees and less are useful in most cases. The transmitting and receiving points thus must be sufficiently distant from the cloud to enable a wave leaving the transmitter at such angles to strike it, and the cloud should be approximately on, and near the center of, the line joining the transmitter and receiver. Unless the ionization is extremely intense, the minimum distance of transmission on 56 Mc. is of the order of 800 miles and the maximum distance about 1250 miles.

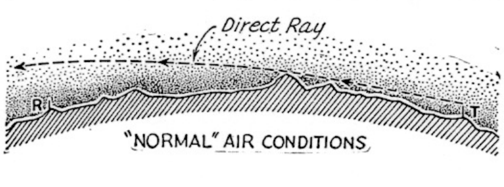


Fig. 908 — Illustrating the effect of a temperature inversion in extending the range of v.h.f. signals.

Multi-hop transmission by means of two sporadic-*E* clouds properly situated with respect to a transmitter and receiver is possible, but rather rare. Distances up to 2500 miles or so have been attained on 56 Mc. by this means.

9-8 Optimum Wave Angles

One of the requirements in high-frequency radio transmission is to send a wave to the ionosphere in such a way that it will have the best chance of being returned to earth. This is chiefly a matter of the angle at which the wave enters the layer, although in some cases polarization may be of importance. Furthermore, the desirable conditions may change considerably with frequency.

The desirable conditions for waves of different frequencies can be summarized as follows, in terms of the various amateur bands:

1.75 Mc. — Low-angle radiation is indicated for the longer distances. High-angle radiation may cause fading toward the limit of the ground-wave signal, because the downcoming waves add in random phase to the ground wave. Vertical polarization is to be preferred.

3.5 Mc. — As at 1.75 Mc., waves at all angles of radiation usually will be reflected, so that no energy is lost by high-angle radiation. However, the lower-angle waves will, in general, give the greatest distances. Polarization on this band is not of great importance.

7 Mc. — Under most conditions, angles of radiation up to about 45 degrees will be returned to earth; during the sunspot maximum still higher angles are useful. It is best to concentrate the radiation below 45 degrees. Polarization is not important, except that losses probably will be higher with vertical polarization.

14 Mc. — For long-distance transmission, most of the energy should be concentrated at angles below about 20 degrees. Higher angles are useful for comparatively short distances (300–400 miles), although 30 degrees is about the maximum useful angle. Aside from the probable higher losses with vertical polarization, the polarization may be of any type.

28 Mc. — Angles of 10 degrees or less are most useful. As in the case of 14 Mc., polarization is not important.

56 Mc. — The lowest possible angle of radiation is most useful for all types of transmission. Vertical polarization has been chiefly used for line-of-sight and lower atmosphere transmission, although horizontal polarization may be slightly better for long distances. In any event, the *same* polarization should be used at both transmitter and receiver.

Higher frequencies — The relatively small amount of data indicates that, as in the case of 56 Mc. optical and lower-atmosphere transmission, either horizontal or vertical polarization may be used, so long as the same type is employed at both ends of the circuit.