FOR CHRONOGRAPHS

Two thyratrons provide a simple switching system that permits amplification in a succeeding amplifier when the first pulse is received, blocks the amplifier when the second pulse is received. Readily substituted for more complicated gate circuits

in the circuit is 150 volts negative with respect to chassis or ground.

Operation is as follows: The first pulse from the shaper with a +30 volt positive crest ignites thyratron T_1, the control grid of which is biased to −30 volts, but fails to ignite thyratron T_2, whose grid potential is −82 volts. When T_1 fires, its cathode potential jumps to +73 volts, which after a time delay through R_3 and C_3, biases the grid of T_2 to −32 volts so that the second pulse of +30 volts from the shaper can ignite the second tube.

The action can be followed by noting that the voltages at various points in the circuit before T_1 fires are indicated in parenthesis, the voltage at the same points after T_1 fires are indicated in boxes and after both tubes, T_1 and T_2, have fired by brackets. Arrows between these numerical values indicate the ignition of one or the other thyratron.

Tubes T_1 and T_2 are gas thyratrons such as type 2050 or 2051 which, once fired, continue to glow until plate voltage is removed by opening the reset switch. The neon lamp may be a type 991 and is used to indicate the condition of the circuit. The lamp glows when the circuit is reset and is ready to function.

The conditions at the grid of vacuum tube T_3 are such that, before T_1 has ignited and after T_2 is ignited, the voltage is sufficiently negative to prevent amplification in T_3. When T_1 has ignited but before T_2 has ignited, the grid voltage is sufficiently positive to permit amplification.

Circuit Details

Figure 4 shows a modification which has been applied to a chronograph of another type, in which the gate circuit output voltage is applied to the suppressor grid of a pentode tube. This circuit is basically the same as that of Fig. 3, differing chiefly in that the level of the control voltage delivered is raised to approximately 130 volts during the gate-open part of the operating cycle.

In both Figs. 3 and 4, R_3 and C_3 should be designed to give the desired delay so that the control grid of T_2 will become armed or ready to be operated after the proper time interval. In the case of the chronographs used for measuring time of flight of projectiles, a preferred coil spacing is, say, 30 feet, so that a 3000-foot-per-second velocity will exhibit a time of flight of 0.01 second, or 1000 cycles of the 100-kc oscillator. The arming time under this condition should be about 0.001 second, so values of R_3 and C_3 should yield a time-constant product of $R_3C_3 = 1000$ microsecond. Thus suitable values are $R_3 = 100{,}000$ ohms and $C_3 = 10^{-8}$ farad or 0.01 microfarad. These are the values which were employed in the experimental model and later installed permanently in three chronograph instruments.

Capacitors C_1 and C_2 may be any suitable size, dependent upon the shape of the pulses from the control input line. In the chronographs to which these circuits were applied, $C_1 = C_2 = 0.00025$ microfarad.

While the accent has been placed upon application of this type of circuit to chronographs, there are obviously numerous other applications in which a device such as that described can be used.

The writer wishes to acknowledge the cooperation of Major P. W. Klipsch, under whose general supervision this work was done.

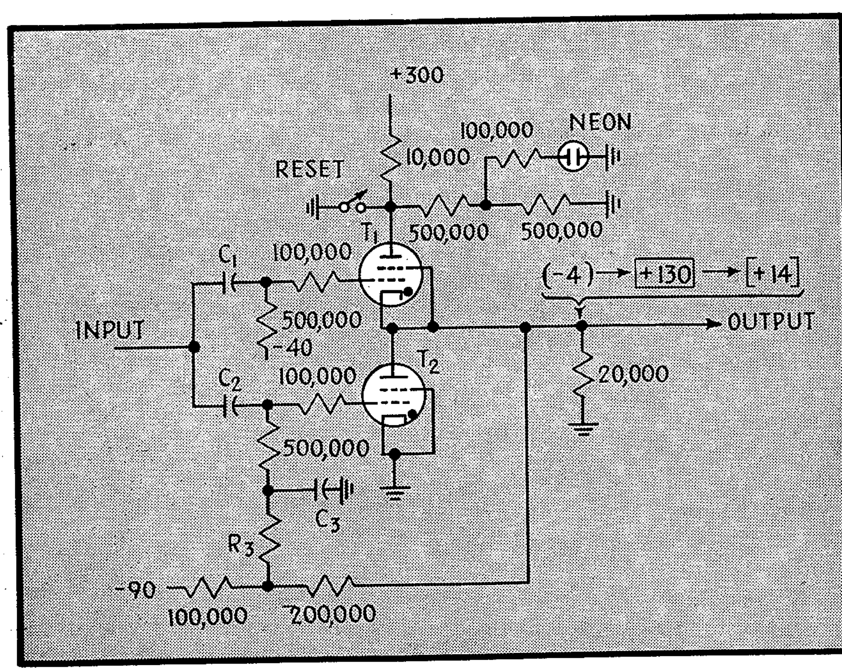

FIG. 4—Modification of the gate circuit, in which sufficient output voltage is developed to operate the suppressor grid of a pentode in another chronograph

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PROPAGATION

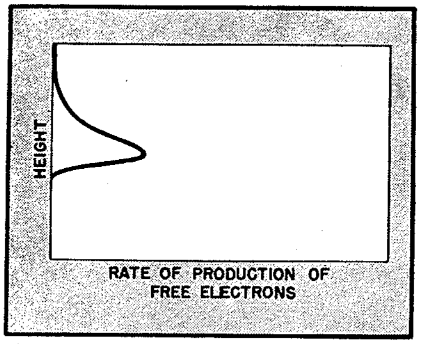

FIG. 1—Chapman curve showing vertical distribution of free electrons

2-Mc Sky-Wave

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THE ionosphere is usually defined as "that region of the earth's atmosphere which is ionized sufficiently to affect the propagation of radio waves." For practical purposes it may be thought of as all the atmosphere above the stratosphere, or, more specifically, the atmosphere between 30 and 300 miles above the surface of the earth.

The atmosphere at such heights consists primarily of the same constituents as at sea level, nitrogen and oxygen. Above 60 miles the oxygen presumably exists in atomic rather than molecular form because the ultraviolet light from the sun disassociates the atoms much faster than they recombine. Nitrogen may be disassociated at, say, 200 miles but the evidence for that is less clear.

There is little to indicate that the heavier elements settle out at the lower altitudes. Probably all the components of the atmosphere are quite well mixed, except for the change from molecular to atomic oxygen at 60 miles. It may be that hydrogen and helium escape into space; there is no strong evidence that they form much of the upper air.

The pressure at which these gases exist decreases exponentially with increasing height to very small values. At 60 miles it is about one millionth of the sea level pressure, while at 200 miles it is probably thousands of times again as small. The mean free path, at 60 miles height, may be taken as one centimeter while at 200 miles it may be as much as a mile or more. This mean free path is the distance a particle—molecule, atom, heavy ion or electron—will travel, on the average, before it collides with another particle. It is a very important quantity.

The temperatures in the ionosphere are high. This does not mean that there is much heat in the upper air, because there are very few particles to contain heat, but it does mean that the particles travel rapidly. At sea-level temperatures the air molecules travel at about 0.5 kilometer per second, while at 200 miles altitude they move several times as fast. The temperature, after falling to about −70 F in the stratosphere, increases to nearly the sea-level value at about 30 miles. Then there is a sharp drop to about −140 F at 50 miles. Above that the temperature (velocity of particles) rises rapidly to somewhat more than 80 F at 60 miles and to perhaps 1,400 F at 200 miles.

Production of Ionization

If a certain wavelength of solar ultraviolet light excites one of the electrons in an atom so that it breaks away from the atom and exists alone, the atom is ionized. The electron may be called a negative ion and the positively-charged remnant of the atom is called a heavy or positive ion. The electron is small and light. It will travel, independent of the heavy ion, at great speed until it finds another heavy ion with which it can unite or until it finds an atom or molecule to which it can stick temporarily.

Let us assume that ultraviolet light of some ionizing wavelength is falling upon the atmosphere. There will be, in general, enough energy at this wavelength to penetrate some distance into the air but not enough to reach the surface of the earth before it has all been expended in ionization. At several hundred miles above the surface very little ionization will be produced because there are very few atoms there to absorb the energy. The ionization will therefore increase as the height decreases because there is more and more material which can be ionized. As the height decreases further, however, a substantial fraction of the original ultraviolet energy has been used up so that, although the number of atoms continues to increase very rapidly, the number of electrons set free does not increase so rapidly. At still lower heights the number of free electrons actually begins to diminish and, lower yet, decreases to zero when all of the suitable incoming energy has been used up.

This behavior can be calculated, under certain simplifying assumptions, and gives a curve of the shape of Fig. 1 which is known as the Chapman distribution. The height at which the free electrons are produced and the thickness of the layer of electrons depend upon the kind of ionizing energy, the kind of atoms which are ionized and the temperature of the air. The number of free electrons produced depends upon the same things but especially upon the total energy available in the ionizing ultraviolet light.

The true picture of the vertical distribution of free electrons is much more complicated. A separate distribution, of the form of Fig. 1, is produced for every combination of ionizing ultraviolet wavelength and atomic constituent in the atmosphere. Many of these distributions overlap

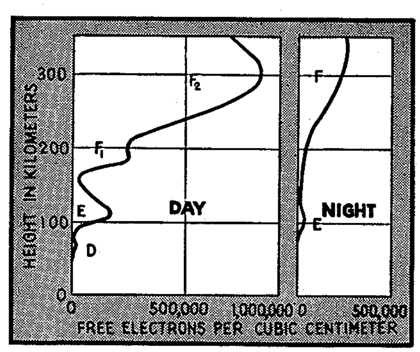

FIG. 2—Night and day distribution of free electrons showing disappearance of the *D* layer and combination of the F_1 and F_2 layers at night

*This paper is based on work done for the Office of Scientific Research and Development under Contract OEMsr-262 with the Radiation Laboratory, Massachusetts Institute of Technology

Transmission

A simplified review of present ionospheric knowledge and a critical survey of the information resulting from an empirical use of the night-time *E* layer. Its relative stability, as disclosed by loran operations, is little affected by ordinary disturbing phenomena

each other but some are quite well separated. Furthermore, these Chapman curves define the rate at which free electrons are produced. There is some diffusion from the heights at which they are produced and the electrons at lower levels recombine faster than those above. Both of these factors operate to cause the heights at which the density of ionization is maximum to be greater than the heights at which the electrons are set free most rapidly.

Formation of Layers

Figure 2 shows the approximate distribution of free electrons as they exist by day and by night. The maximum at about 250 km is called the *F* layer, or Appleton layer. The small bump on the lower side appears only in the day time in the summer, because it recombines quickly at night and is swamped in the body of the *F* layer in the winter. When it appears it is called the F_1 layer and the remainder of the *F* region is known as the F_2 layer. The *F* layer varies greatly in height, thickness, and density of ionization.

The *E*, or Kennelly-Heaviside layer at about 100 km, is much more stable. Its density of ionization follows the altitude of the sun quite closely, except that some ionization remains throughout the night when the sunlight does not fall on the layer. We shall be primarily concerned with the *E* layer.

The tail of the E layer, perhaps at about 70 km above the earth, sometimes shows a small maximum which is called the *D* layer. The density is low, so that only low frequency waves can be reflected from it. The *D* layer is primarily of importance because it absorbs energy from radio waves.

Reflection

If a radio wave penetrates obliquely into the ionosphere the phase velocity, which determines the direction of the wave front, increases as the index of refraction decreases. At the same time the group velocity, which is the velocity with which the energy travels, decreases in the same ratio. Thus the upper part of the wave front travels faster as the wave penetrates into an ionized layer because the density of ionization is increasing. The wave is therefore refracted so that it curves back toward the earth, but it travels more slowly while being refracted.

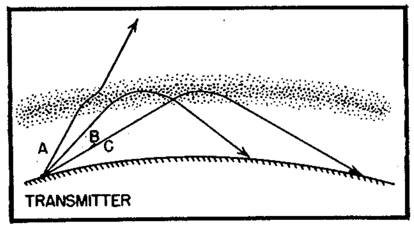

FIG. 3—A simplified representation of an ionospheric layer showing the effects of rays entering at different angles. Ray A has left the earth at too steep an angle to be turned back

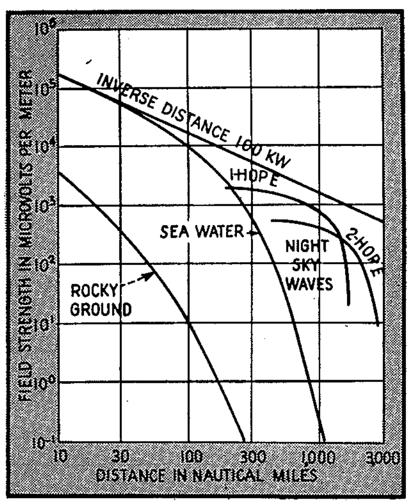

FIG. 4—Field strength as a function of distance from a 100-kw transmitter, over sea water and rocky ground. The 1-hop *E* sky waves can not be safely used beyond 1,400 miles because their strength falls rapidly below those of the 2-hop *E*

In Fig. 3 we have postulated an ionospheric layer whose density (number of free electrons per cubic centimeter) is roughly indicated by the density of dots. Three rays of radio frequency energy are shown entering the layer. If the frequency is such that reflection can occur at oblique incidence but not at vertical incidence on the layer the behavior will be as shown. A ray C departing at a small angle to the horizontal will only require a modest amount of refraction before it is turned parallel to the surface of the earth. It will therefore not need to penetrate far into the layer and will span a long range in a single hop. Another ray, B, departing more steeply from the earth will penetrate the layer more deeply because it must be turned through a greater angle. If the required bending cannot be achieved, because the frequency or departure angle is too high or the density of the layer is too low, the ray A will penetrate the layer, traveling on a path which is concave downward until the height of maximum ionization is reached and concave upward beyond that height. This ray, of course, leaves the earth completely unless it is turned back later by a higher layer. The effect of the penetration is to establish the well known skip distance within which sky-wave signals are not received. Outside a layer, rays travel straight lines.

Single-Hop Limit

There is a definite maximum range which can be spanned by single hop transmission. This is the distance covered by a ray departing horizontally (or as nearly horizontally as antenna radiation can be effective) and is about 1,500 miles in the case of *E*-layer transmission. At greater distances the signal is cut off by the earth itself. This shadow effect can be seen clearly in the sharp drop in the 1-hop sky-wave field-intensity curve of Fig. 4.

A rough. diagram indicating the typical action of both *E* and *F* layers

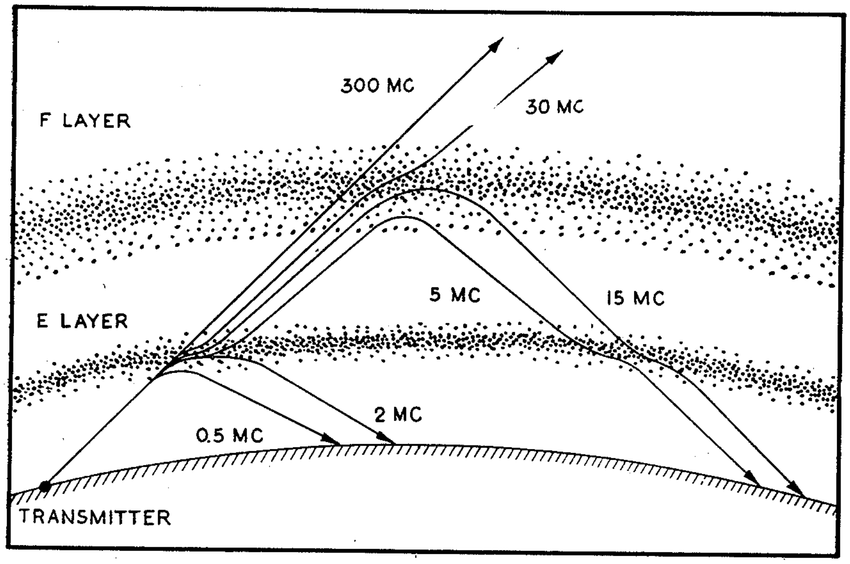

FIG. 5—Typical behavior of rays at various frequencies in the *E* and *F* layers. At the higher frequencies the rays are less affected by the ionosphere

is given in Fig. 5. Here we have assumed a number of rays at different radio frequencies, all departing from a transmitter along the same path. The medium frequencies shown, 500 kc and 2 mc, are both reflected by the *E* layer, but the 2-mc ray penetrates much more deeply and travels somewhat farther. At 5 mc, the ray is refracted strongly in the *E* layer but does penetrate it, and is easily reflected by the *F* layer. The 15-mc ray is less affected by the *E* layer and penetrates more deeply into the *F* layer, but the general behavior is much the same as at 5 mc. Thirty mc, however, is too high a frequency to be returned, under the conditions we have postulated. The ray passes the *E* layer with very little refraction, and is refracted strongly by the *F* layer but without being turned back toward the earth. The energy at this and all higher frequencies, such as 300 mc, escapes into space. As the frequency increases the deviation of the ray in the layers decreases until at microwave or optical frequencies the effect of the ionization is not at all perceptible.

The whole structure of Fig. 5 depends upon the density of ionization in the layers and upon the angle of departure of the original rays. At a lower angle the 5-mc ray might often be reflected from the *E* layer while the 30-mc ray would be returned from the *F* region.

The reflection of radio waves in the ionospheric layers is only half of the process of radio transmission by sky waves. The absorption of energy from the waves is of at least the same importance.

Absorption

Some mention was made above of the mean free path of an electron (or other particle) in the upper atmosphere. This quantity, or more properly the inversely-varying collisional frequency, controls the energy lost by a radio wave. While there may be a million free electrons per cc in a highly ionized layer there are typically a million times as many neutral atoms or molecules with one of which an electron may collide at any instant. Suppose, for example, that on the average an electron can move freely only for a millionth of a second before bumping into a heavy atom. If the electron is being vibrated by a radio frequency field at 1 mc there is only about one chance in two that the electron can complete a cycle of oscillation before its motion is interfered with.

The collision is important for this reason. Some energy is abstracted from the radio wave to provide the kinetic energy contained in the moving electrons. This energy is, in effect, lost to the radio wave only for a half cycle because the moving electron, since it constitutes a moving charge, reradiates an electro-magnetic field whose energy is equal to the energy absorbed by the electron. As the radio wave passes through the ionosphere the energy reradiated by all the electrons adds in phase to constitute a wave traveling in the same direction as the original wave. If the electrons can move freely, tiny elements of the energy in the wave flow back and forth between electrostatic and kinetic states, but the total energy in the wave remains the same.

Energy Lost by Collision

If, however, an electron rebounds from an atom while temporarily carrying some of the energy two things happen. One is that the direction of motion of the electron is changed. The energy is then reradiated in a different orientation, so that the phase relation with the radiation from other electrons is damaged. Even more serious is a real loss of radio frequency energy because the atom is accelerated slightly and carries off part of the kinetic energy which had been loaned to the electron. This energy is completely lost to the radio wave and remains in the atmosphere in the form of increased kinetic energy, or heat.

If the probability of collision and loss of energy is high enough the radio wave will be completely attenuated in the ionized layer. The degree of absorption is less as the frequency is increased because the electrons are more likely to be able to complete their half cycles of oscillation before a collision occurs. In the *F* layer there is little collisional friction because the mean free paths are long and the collisional frequency is low. In the *E* layer collisions are frequent enough so that waves of frequency below 2 or 3 mc are completely absorbed in the daytime. At night the density of ionization in the *E* layer decreases to perhaps a tenth of the daytime value. The absorption goes down to low values because the chance of a collision between an electron and some other particle is similarly reduced.

We may summarize the situation thus: Ionization is needed to reflect radio waves but ionization at low heights in the atmosphere absorbs energy from the waves. The higher the frequency the stronger the ionization required for reflection and the less the absorption.

Little Ionization at Night

Since most ionization in the atmosphere is produced by the action of ultraviolet light from the sun there is little new ionization created at night. The free electrons recombine, but slowly enough so that a substantial number of them remains throughout the night. Thus the maximum ionization occurs at or soon after noon and the minimum at sunrise. Similarly the ionization is more intense in summer than in winter because the sun shines more perpendicularly upon the atmosphere and the ionization increases as does the temperature.

Whether radio transmission is better by day or by night, in winter or in summer, is a question of frequency. At high frequencies, say 20 mc, the weak ionization may prevent sky-wave transmission completely in the winter or at night, while in summer or daytime the stronger ionization will support transmission when absorption is so small as to be unimportant. At broadcast frequencies, absorption is complete in the daytime so that only ground wave ranges are useful. At night, long distance transmission is possible, and the decreased absorption in the winter makes communication better than in the summer.

2-mc Sky-wave Loran Transmissions

During the war, much practical information was obtained from the use of E-layer transmissions which extended the night-time range of the loran navigational system. The balance of this paper describes some of the phenomena encountered.

Figure 6 shows typical variations of the critical frequencies (which are proportional to the square roots of the maximum densities of ionization) in the E and F regions throughout the day. Recombination is slow in

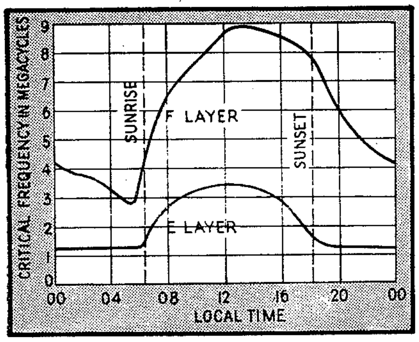

FIG. 6—Critical frequencies for the *E* and *F* layers at various times of the day. These plots are particularly important in showing that ionization in the *E* layer is not entirely dependent upon solar radiation

the F region that the maximum occurs well after noon although all of the ionizing energy appears to come directly from the sun. The smooth decrease throughout the night is another manifestation of the fact that some free electrons have lifetimes of many hours in the F layer.

The behavior of the E layer at night is not understood. At the height of the E layer complete recombination takes only a few minutes, so that the density of ionization adapts itself very quickly, in the daytime, to the amount of energy being received from the sun. The E layer curve of Fig. 6, between sunrise and sunset is nearly proportional to the fourth root of the cosine of the sun's distance from the zenith. This is so exactly true that without question the ionization would go almost to zero at night if ultraviolet

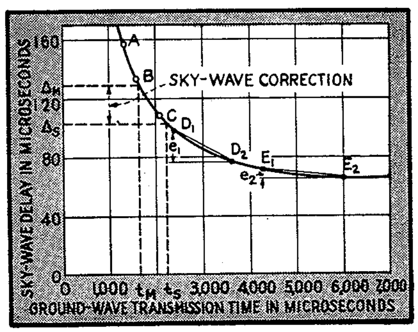

FIG. 7—Delay in reception of a sky wave after reception of a ground wave from the same transmitter is shown as a function of distance of the receiving point from the transmitter. The curve has been calculated to distances beyond ground-wave reception in terms of the travel time of radio waves

light from the sun were its only source.

The energy brought into the earth's atmosphere by meteoric bombardment may possibly be enough to sustain this night-time ionization.[1] In any case, meteoric effects are definitely perceptible and certainly cause many of the variations in the density and distribution of free electrons in the E layer even though they are probably not the major cause of the ionization. The random variations in the density of the E layer are of the first importance in the propagation of loran signals by sky waves, because they control the errors of the system.

Sky-wave Delay

The transmission time of a sky wave is greater than the transmis-

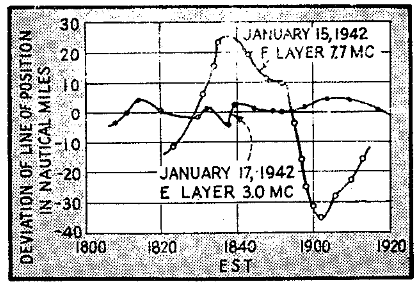

FIG. 8—Apparent deviation of a line of position with time using signals reflected from the *E* and *F* layers. As a result of this study, the *E* layer was chosen for loran work

sion time of the ground wave, primarily because of the greater distance traveled but also because the wave travels more slowly during the process of refraction. The difference between the two times is called the sky-wave delay. The delay observed at a point very near the transmitter (if penetration does not occur) is essentially equal to the transmission time of the sky wave. As the distance increases the transmission time of the the sky wave increases but the transmission time of the ground wave increases more rapidly. The delay therefore decreases as the distance of transmission increases and, in fact, becomes very nearly constant at distances of a thousand miles or more. Figure 7 shows the standard delay curve for loran, which is drawn for reflection from the E layer. The curve is a mean for night conditions at a frequency just below 2 mc. It is never drawn back to zero distance because a 2-mc wave nearly always penetrates the night-time E layer at short distances and because the delay becomes more variable as the distance decreases. At distances less than 1,200 μ sec (about 200 nautical miles) the delay is completely unreliable. Fortunately for loran the ground-wave service of the system is ordinarily available at distances up to those at which the E-layer transmission becomes satisfactory.

The stability of the reflection becomes greater at longer distances partly because grazing reflection is better than reflection at a steep angle, but primarily because a change in the height of reflection does not greatly change the total distance traveled by the ray. At a distance of a thousand miles the length of the sky-wave path increases only 1.78 miles for a change in the height of

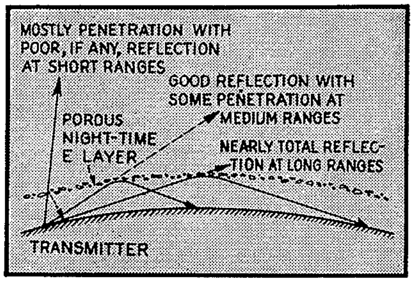

FIG. 9—The porous character of the night-time *E* layer is illustrated by the reflection at long ranges, the penetration at short distances

reflection of 5 miles. This is a change in the time of transmission of less than 10 μsec or about one-fifth of the corresponding change at a short distance.

Large-area Layer Variation

Variations of five miles in the height of reflection are rare but do occur at times. Their effect upon standard loran is not too large because such an extreme variation is likely to exist over a large area. It will therefore operate to increase (or decrease) the transmission times from both stations of a pair so that the time difference measured by the navigator does not vary as much as the individual delays.

The discussion in the last few paragraphs has been specifically applicable to the *E* layer. Only this layer is used in loran because the *F* layer is too variable to permit prediction of the times of transmission with the necessary accuracy. A comparison between the layers is given in Fig. 8 which shows the apparent variation of the line of position through a point in Bermuda. These observations were made as part of first experiments on loran. For obvious reasons work involving the *F* layer was discontinued after that time. The example shown is typical of the behavior of both layers although the time of day was not favorable to maximum stability of either. The average deviations of the line of position are 18 miles for the *F* layer and 2 miles for the *E*. The distance was 625 miles from the stations, so that the equivalent average errors in the bearing of Bermuda, as seen from near New York, were 1.7 deg for the *F*-layer experiment and 0.2 deg for the *E*-layer.

As will be seen from the notation on Fig. 8, the layer can be selected by proper choice of frequency. At the time of these experiments 7.7 mc penetrated the *E* layer while 3.0 mc did not. The loran frequency is chosen as one which will be reflected by the *E* layer at all times at all distances which will not be adequately served by ground waves. It is possible that frequencies as high as 2.5 mc might satisfy this criterion, but both ground-wave range and sky-wave stability are improved by using lower frequencies. (The lower limit of frequency, incidentally, is that at which it becomes too difficult to generate and radiate a sufficiently short pulse for loran purposes. With the criteria adopted for standard loran, this frequency is probably about 1 mc).

Choice of Loran Frequency

It should be noted that the last paragraph did not state that signals at the loran frequency would not penetrate the *E* layer. They almost always do penetrate at short distances and part of the energy usually penetrates the layer at long distances. This seems to be because, in contradiction of what has been suggested above, the *E* layer is not really a smooth homogeneous layer at night, although it is in the daytime. At night the layer is porous, even gauzy. It seems to consist of many nuclei or clouds of ionization chiefly at about the same height—a little below the height of the daytime or normal *E* layer—with either spaces or patches of sparse ionization between them. The density of the ionization in the clouds is not very great so that 2-mc rays pass vertically through the layer partly because of penetration of the clouds and partly by passing between them. At more grazing angles the probability of passing through the spaces becomes smaller and usually goes nearly to zero for transmission over the longer distances. A diagram showing this effect is given in Fig. 9.

In general some energy will be reflected by the porous night-time *E* layer and some will pass through it and be reflected from the *F* layer. Multiple-hop transmission is possible in both cases so that the pattern of received pulses may be very complex. The structure of some of these components of the received pattern is shown in Fig. 10A. The way the corresponding signals look on a linear time base is indicated at B. This diagram is idealized.

The spotty character of the night-time *E* layer gives rise to pulses whose shape is not the same as that of the pulses when they leave the transmitter. Several of the small clouds of ionization in the neighborhood of the midpoint of the transmission path may reflect the pulse. While each reflection may be a complete and perfect reproduction of the transmitted pulse, the overlapping components arriving at the receiver may combine to give a very complex

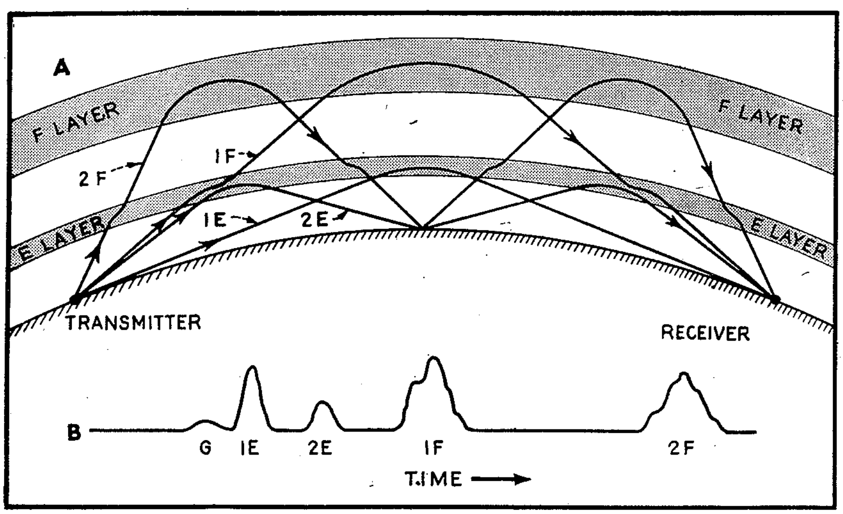

FIG. 10—Multiple-path transmissions occur in many combinations, only a few of which are shown. Their appearance on the loran indicator scope is suggested at B. Only the ground wave, G, and the 1-hop *E* will have any semblance of stability over a period of time

form indeed. This is particularly true at very short distances, say up to 100 miles, where often a family of ten or a dozen contiguous or overlapping pulses may be seen. As the range increases the weak multiple pulses move toward each other and coalesce into a single strong pulse which occasionally has a more or less serious distortion of its shape. Figure 11 shows some of the typical reflection patterns received between, say, 100 and 400 miles from a loran transmitter. The reason for not using sky waves at very short distances is clear.

The Delay Curve

The standard technique in loran is to measure to the first visible component of a pulse even though the pulse be complex. As seen in Fig. 11B this may be quite different from measuring to the dominant component. This decision was first made on theoretical grounds and was based on the belief that if a pulse should be simultaneously reflected from a number of clouds of ionization the part arriving first must travel by the simplest and most direct path and should therefore be the most reliable. This thesis has been amply confirmed by experiment, as measurements made on the first component exhibit smaller mean deviations than those made in any other way.

At the start of the loran program the night-time E layer was scarcely known to exist and its properties could not be predicted. It was necessary, therefore, in the interest of speed, to determine the necessary factors empirically. More than this has not yet been done. Fortunately the layer was found to be remarkably stable. That is, its characteristics change very little from one hour of the night to another. More surprisingly, the properties of the layer seem to be essentially the same at all latitudes, and to vary only simply and moderately between winter and summer. These auspicious discoveries greatly facilitated the use of sky waves for loran.

The delay curve already cited was determined by making loran observations on sky waves at accurately known points and comparing the observed readings with time differences calculated (for the locations where they could not be directly measured) in terms of ground-wave transmission.

Charts and tables for Standard loran are computed in ground-wave time differences even though the distances are so great that ground waves cannot be received.

Sky-wave Corrections

A correction must be applied when sky waves are used. The correction can be read from the sky-wave delay curve if the distances to the two stations are known. Suppose that t_M in Fig. 7 represents the distance of the navigator from the master station while t_S is the distance from the slave. The first-hop E layer sky wave from the master will arrive Δ_M μsec after the ground wave and the corresponding slave pulse will be Δ_S μsec later than its ground wave. Since the navigator measures the time difference between the M and S pulses his sky-wave reading will differ from his ground-wave reading (if he has made one) by $(\Delta_M - \Delta_S)$ μsec. This amount is the sky-wave correction. In this case (closer to the master station) the sky-wave reading is smaller than the ground-wave reading. The correction is therefore called positive, so that when it is added to the sky-wave reading the ground-wave time difference, which is shown on the charts, will be obtained.

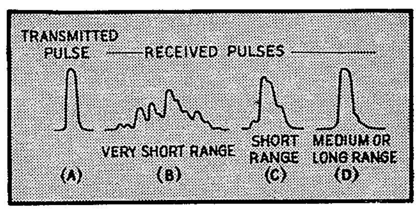

FIG. 11—Within 100 miles of a transmitter the pulses reflected from the E layer are complex and useless for accurate timing techniques. At 300-400 miles, the pulses have achieved sufficient stability

The sky-wave corrections can, of course, be calculated easily at the time the charts are prepared. They are ordinarily exhibited on the charts as small numbers printed at the intersections of the whole degrees of latitude and longitude. The magnitude of the corrections is small so that interpolation by inspection is adequate. On the centerline of the pair and at long distances from both stations the corrections are zero because the master and slave delays cancel each other.

The delay curve was constructed through study of many thousands of loran sky-wave readings made at various distances from the stations. At short ranges both sky and ground waves could be received. Measurements of both against the ground wave of the other station of the pair gave two average readings whose difference was the delay at the distance of the station whose sky wave was used. Points derived in this way are shown at A, B, and C of Fig. 7. For longer ranges, where ground waves could not be used, an inverse process had to be employed. The sky-wave readings of a pair were averaged and compared with the calculated ground-wave reading at the monitor station. The discrepancy (e_1 or e_2 in the figure) was, of course, the sky-wave correction. Since the two distances were known, the correction gave the slope of a chord of the delay curve, as shown at $D_1 - D_2$ or $E_1 - E_2$. Many lines of this slope could be drawn in an effort to find the vertical position of the line which would fit its end points into a smooth curve with the end points of other similar lines at other distances. If enough observations are available, at enough distances, the curve can easily be constructed.

Empirical Formula for Delay

The curve which, after three years experience in various latitudes, seems to be the best average approximation to the true values has been shown in Fig. 7. This curve is described by the equation: delay in μsec

$$= D + 0.3\left(\frac{7{,}000 - t}{1{,}000}\right)^3 + 0.18 \times 10^{-6}\left(\frac{7{,}000 - t}{1{,}000}\right)^{11}$$

D is the minimum sky-wave delay which varies between 65 μsec in the winter and 75 μsec in the summer

t is the transmission time of the ground wave in μsec

This formula applies for distances less than about 1,130 nautical miles (where $t = 7{,}000$). For greater distances the delay equals D. This equation has no mathematical justification.

As shown by the variation of the quantity D, the layer height is somewhat greater in the summer. However, the delay curve, for all practical purposes, simply moves upward so that the correction, which is always the difference between two delays, is not affected. There is an error introduced by this change in two cases; when the navigator may occasionally wish to measure the time difference between a sky wave and a ground wave, and in the case of the synchronization path in SS Loran[2, 3] which will be discussed below.

The only significant latitude effect which has been isolated is that the

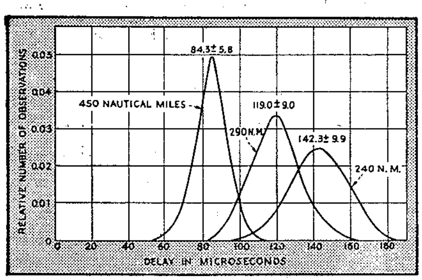

FIG. 12—As shown by the three sets of observations, the average sky-wave delay diminishes as distance from the transmitter increases and the spread of readings decreases proportionately

delay curve may be used at shorter distances at low latitudes. That is, near the equator fairly reliable operation may be had at as little as 150 nautical miles, while at 45 deg latitude about 250 miles is the minimum safe distance. The curve itself does not seem to vary appreciably over the range from 25 N to 63 N within which it has been carefully checked.

Variation in the Sky-Wave Delay

Since we propose to examine closely the averages and the mean deviations of the sky-wave delay and sky-wave corrections, it is necessary to test the accuracy with which transmitter synchronism can be maintained. An example, somewhat better than normal, is given by readings from a pair of stations in the Northwest Atlantic Chain observed at a monitor station where the computed reading was 3510.6 μsec. The mean, as is usual, agrees with the computation within 0.2 or 0.3 μsec, and the average deviation is of the order of 0.6 μsec. A series of sky-wave readings usually shows an average deviation at least four or five times as great. It is, therefore, nearly always satisfactory to assume that the synchronism of the transmitting stations is rigid and that any deviations observed are the result of variations in sky-wave propagation. Exceptions to this assumption are usually obvious.

Three distribution curves of observations of the sky-wave delay are given in Fig. 12. The curves are drawn to have the same area and exhibit clearly the two important facts of sky-wave transmission for loran. The average delay diminishes as the distance increases, as shown by the delay curve, and the spread of the readings also decreases in about the same proportion. The probable errors in this set of observations are: 9.9 μsec at 240 nautical miles, 9.0 μsec at 290 nautical miles, 5.8 μsec at 450 nautical miles. The first two are somewhat below the normal scatter at these distances.

Layer Height Correlations

At long distances it is impossible to measure delay directly. Distribution curves of the sky-wave reading (not delay) compared with the computed reading at distances of 870 and 1,350 nautical miles show that the corresponding probable errors are 2.1 and 2.4 μsec, although a smaller error would be expected at the greater distance. These are errors in the sky-wave *correction.* As remarked above, major changes in the height of reflection of a sky wave may be expected to affect both transmission paths in the same way and therefore to cancel to some extent. In other words, there should be a correlation between the two delay patterns, and the errors of a sky-wave measurement would be smaller than if the two reflection points behaved independently. For instance, the probable error of delay at a thousand miles averages about 3.9 μsec. If every point in the reflecting layer varied independently, the probable error of a sky-wave reading would be about $\sqrt{2} \times 3.9$ μsec, or 5.5 μsec. Actually, for base-line lengths of about 250 or 300 miles, the probable error of a reading is usually between 1.5 and 2.0 μsec for a thousand-mile range. This indicates a fair degree of correlation in the behavior of the layer at points separated by a hundred miles or more.

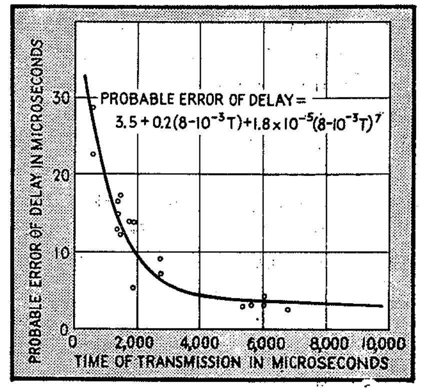

FIG. 13—Probable error of delay has been determined by actual observations at monitor stations of various pairs of transmitters

The probable error of *delay* is shown in Fig. 13 as determined from monitor station readings on many different pairs of stations. The points for ranges greater than could be served by ground waves were determined during the American trials of the SS Loran system.[2, 3] The equation given on the diagram defines the smooth curve but has no other significance.

If no correlation existed between the layer heights at the two points of reflection, the probable error of a sky-wave reading would be found by taking the square root of the sum of the squares of the two values of probable error of delay for the two distances involved. Since there is a correlation, an estimate of the probable error of a reading can be made by multiplying the no-correlation value by a factor smaller than unity which can be obtained by experiment. This factor is given in Fig. 14 where it is plotted against the electrical length of the base line. The positive slope means simply that the greater the separation of the stations the less the variations in delay tend to cancel each other. The factor, "Probable error of synchronization", is given in the equation on the figure because sometimes, as in SS Loran, the absolute accuracy of synchronism cannot be assumed. In SS Loran, of course, the probable error of synchronization is equal to the probable error of delay at the distance separating the stations.

Sky-wave Accuracy Patterns

The accuracy (or average error) with which a sky-wave loran reading can be made can be estimated by the method of the preceding section. This average timing error may or may not correspond to a significant number of miles depending upon the distance from the stations and their orientation with respect to the navigator.

Ordinary geometrical methods permit the calculation of the number of miles corresponding to a change in reading of one microsecond. These formulas may be combined with the methods of this article to yield the average error of a sky-wave reading in miles.

The probable error of a sky-wave line of position (in nautical miles) varies over the service area of a loran pair, whether standard or SS. It is of special interest to note that the errors increase very slowly with distance along the center line of the pair. This is because the timing errors are nearly inversely proportional to distance and almost cancel the increasing geometrical error. Beyond the 1,400 mile limit or within 250 miles of the stations it is not safe to use sky waves because of ambiguity in the first case and erratic behavior in the second.

The accuracy of SS Loran is greater than the sky wave accuracy of standard loran, because the long base lines greatly improve the geometrical accuracy, or miles per μsec of timing error. The timing error itself is not so good as in a standard loran, primarily because of sky-wave variations on the synchronizing path, but the timing error is not increased as much as the geometrical factors are improved. The total area served by an SS pair is not so great but the errors are smaller and more constant except along the base line extensions.

Sporadic E-Region Ionization

One of the outstanding anomalies in the *E* region is the existence of sporadic ionization. This takes the form of clouds of free electrons, at a very constant height, which are sporadic in both time and space. They may appear at any time, day or night, and last for a few minutes or for hours. Their size may be anything up to hundreds of miles across. They sometimes appear to move with very great velocities and at other times they seem nearly stationary. The density of ionization is often low but occasionally is very great indeed—even greater than is ever observed in the *F* layer. On at least one occasion the density has been observed to be enough to reflect signals up to 110 mc over a thousand-mile path.

These clouds are probably caused by corpuscular bombardment of the atmosphere by particles shot off by the sun, in much the same way that northern lights are formed. While sporadic *E*-region ionization may appear at any time, it is most likely in the summer and at times of sunspot maximum. It is most probable at high latitudes and is very seldom if ever observed at the magnetic equator—again like the aurora.

In the early days of loran it was feared that signals from one station of a pair might be reflected from a cloud of sporadic *E* ionization while the other signals would be transmitted by the normal night-time *E* layer, thus leading to large and unpredictable errors. Fortunately this is not the case, apparently because the normal reflections occur at a height somewhat below that of the sporadic *E*, so that the signals never are propagated by the sporadic clouds.

At very short distances sporadic *E*-region ionization frequently does cause strong steady reflections. Since the height of reflection differs from the normal, this contributes to the unreliability of sky-wave transmission at short distances at 2 mc.

The best evidence to this effect is given in the table which exhibits the average value and probable error of sky-wave readings when sporadic *E* ionization is and is not present. These data were taken in Ottawa, Canada, by the Canadian Navy, in May, June, and July, 1943, the season of maximum sporadic ionization. During this period the sporadic *E* layer appeared about one-third of the time at Ottawa. Of course there is no proof that sporadic ionization existed at the points of reflection at the same time they were observed at Ottawa, but it is more likely to have existed there then than when it was not observed at Ottawa. As the table shows, there was no significant change in the loran reading at times when sporadic *E*-region ionization was observed. The probable errors (or average errors) of the readings were actually smaller at those times, but the difference is not large enough to be significant except in the sense that it may be taken as proof that the errors were not larger in the presence of sporadic ionization.

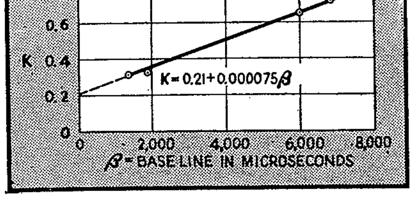

FIG. 14—The increasing value of the correlation factor, *K*, indicates that as the separation of transmitters increases, variations in delay tend to cancel less. This also shows that over great distances the ionosphere does not move uniformly

Effect of Sporadic *E* on Loran Readings

Pair	Normal		
	No. of Observations	Mean Reading	Probable Error
MF	561	2932.1	3.2
MB	422	3816.3	4.4
DB	368	1342.5	3.7
	1351		

Pair	During Sporadic *E*			Computed Reading
	No. of Obser-vations	Mean Reading	Probable Error	
MF	305	2932.6	2.9	2932.4
MB	256	3816.8	3.6	3814.7
DB	206	1341.8	3.1	1342.4
	767			

Magnetic Activity

The effect of sudden or large variations in the earth's magnetic field upon loran transmissions is known, but will not be discussed in this paper. It seems, however, that none of the ordinary phenomena which disturb radio transmissions have any appreciable effect upon the accuracy of loran sky-wave readings, although the reliability of the service may suffer in operating too near the magnetic pole.

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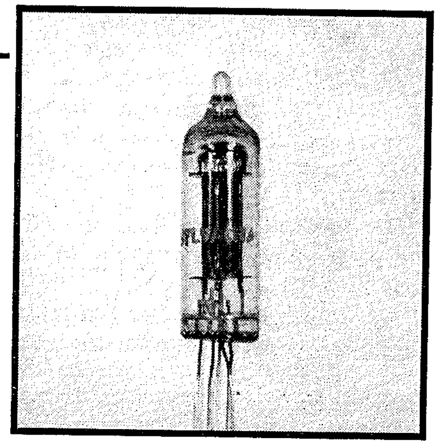
Circuits for SUB-MINIATURE TUBE



Actual-size photograph of 6K4 triode illustrates its small size

Electrical and mechanical characteristics of subminiature triode suit it for use in audio and radio-frequency stages of compact commercial equipment. Circuits are suggested and design data presented for very high frequency line oscillators.

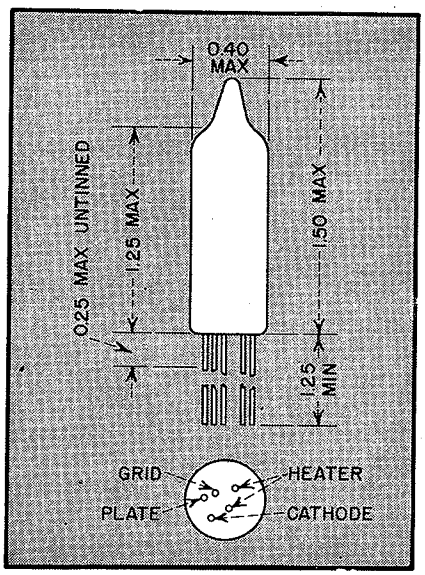


FIG. 1—Physical dimensions of small, baseless 6K4

In applications where bulk, and weight of electronic equipment are limited, a physically small tube has the advantage of compactness over other tubes. The dimensions of one such midget tube, or midgetron, are shown in Fig. 1. In addition, the mechanical characteristics of the Sylvania 6K4 fit it for use in locations subject to vibration. Thus it is excellent for use in aircraft, railroad rolling stock, and factories.

The leads are brought straight through the button stem, thereby simplifying tube assembly and contributing to its high frequency performance. The tube has the electrical characteristics listed in Table I, which enable it to be used in an oscillator at frequencies well into the hundreds of megacycles. The cathode provides the high plate current necessary for high mutual conductance.

Audio Amplifier

For operation at the lower frequencies, the 6K4 plate and transfer characteristics shown in Fig. 2 and 3 are average. From them circuits can be designed in the usual way and performance predicted. Table II gives typical circuit values for a conventional resistance-capacitance coupled amplifier.

Table I—Electrical Characteristics of the 6K4

Direct Interelectrode Capacitances (No Shield)	
Grid to Plate	2.2 $\mu\mu f$
Grid to Cathode	2.4 $\mu\mu f$
Plate to Cathode	0.85 $\mu\mu f$
Maximum Electrical Ratings (Open Air)	
Plate Potential	250 volts max
Plate Dissipation	3.0 watts max
Heater to Cathode Potential	100 volts max
Cathode Current	20 ma max

In a multivibrator circuit, the 6K4, because of its relatively low amplification factor and high plate current at zero grid bias, provides a large square-wave voltage and is not critical to loading. Thus the tube can be used in timing and counting circuits.

For connection, the tinned, flexible leads of the tube are soldered directly into the circuit. Although the tube is sufficiently strong mechanically to survive any normal dropping or vibration, it should be held in position by a grommet or mounting shield. A convenient mounting method is to wedge the top and bottom of the tube envelope into grommets that are not quite large enough to slip over the envelope. The grommets can be mounted on angle brackets or in the chassis. Another mounting method is to form a metal strap around the tube. The strap acts as both support and shield. In severely vibrating locations to reduce microphonics, the tube can be wrapped in rubber before being clamped by the strap. The tube leads themselves should not be relied upon for support, and should be slack enough to permit normal tube motion in its support.

Radio-Frequency Oscillator

The 6K4 was designed to have an amplification factor of the order of