April 17, 1934. J. S. STONE 1,954,898

RADIO RECEIVING SYSTEM

Filed June 10, 1930 3 Sheets-Sheet 1

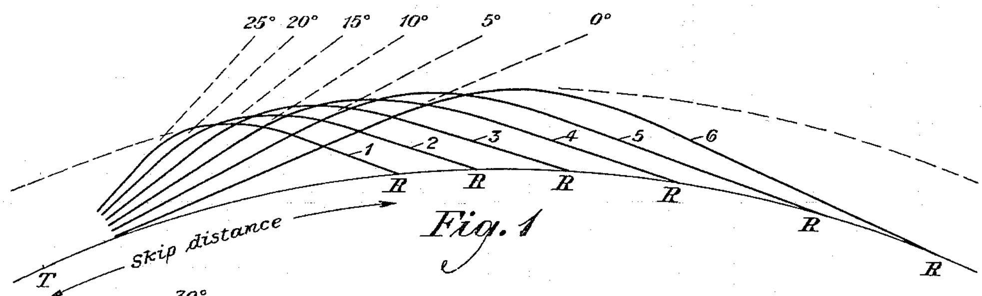

Fig. 1

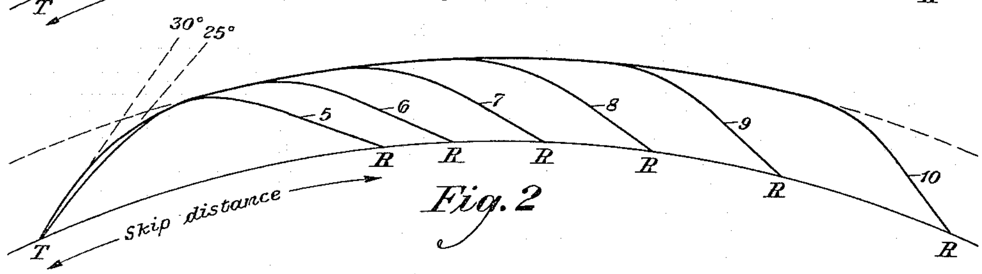

Fig. 2

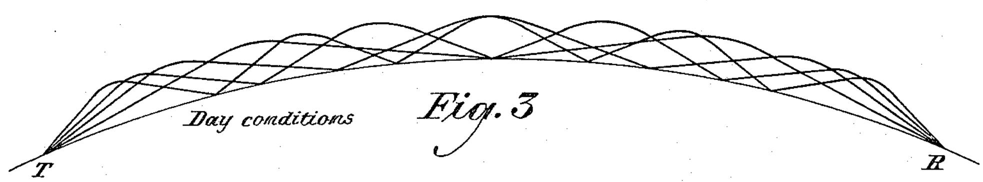

Fig. 3

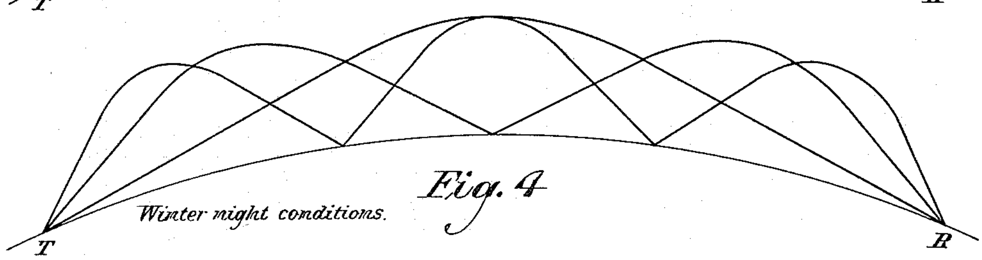

Fig. 4

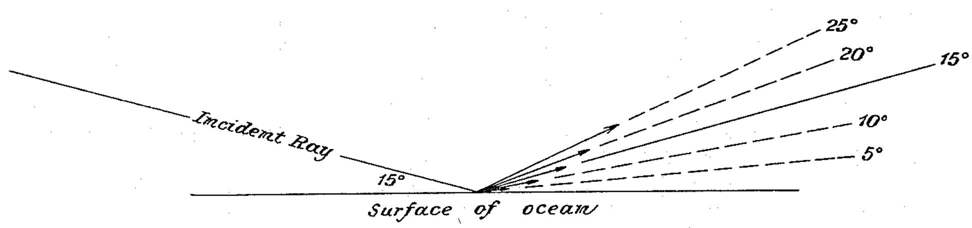

Fig. 5

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April 17, 1934. J. S. STONE 1,954,898

RADIO RECEIVING SYSTEM

Filed June 10, 1930 3 Sheets-Sheet 2

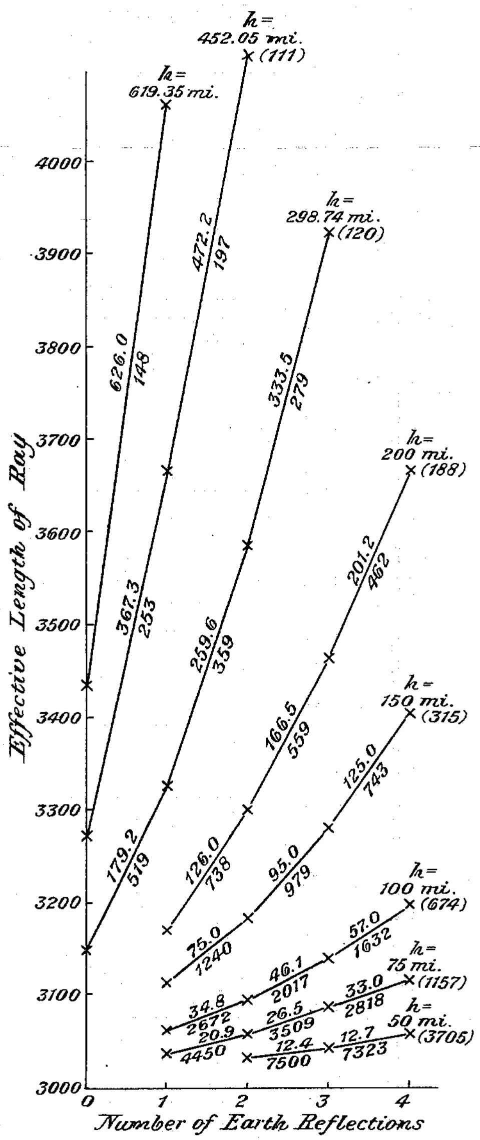

Fig. 6

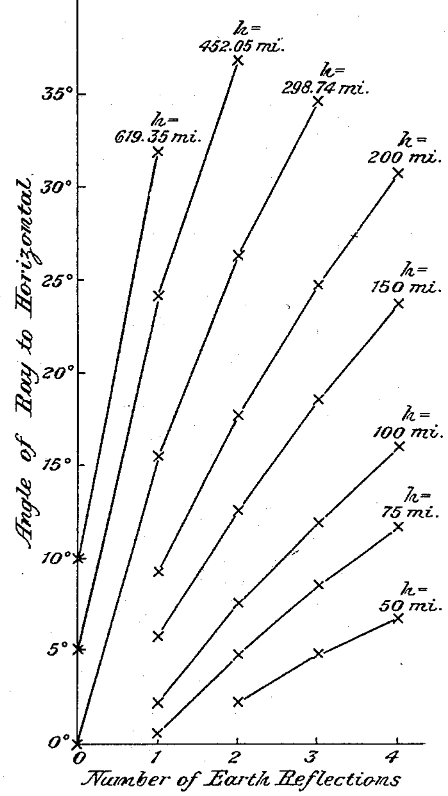

Fig. 7

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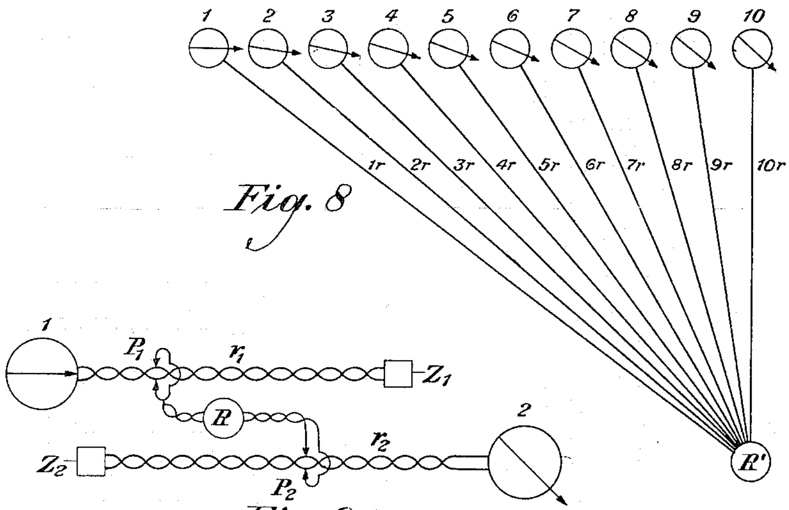

Fig. 8

Fig. 9

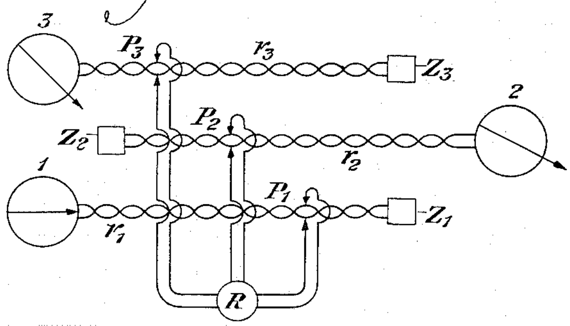

Fig. 10

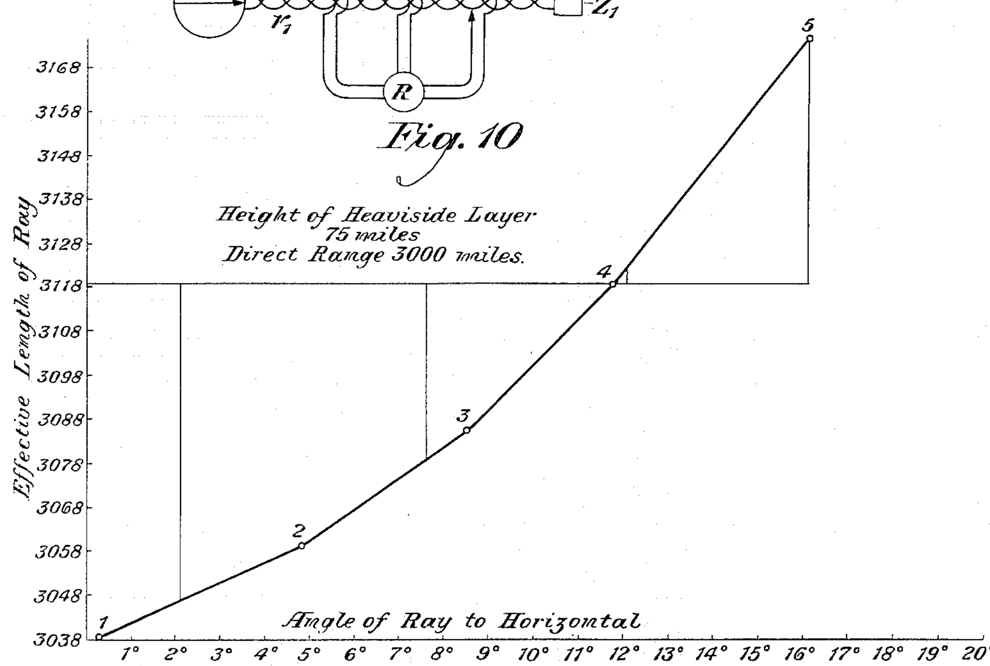

Fig. 11

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UNITED STATES PATENT OFFICE

1,954,898

RADIO RECEIVING SYSTEM

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Application June 10, 1930, Serial No. 460,172

11 Claims. (Cl. 250—11)

It is one of the principal objects of my invention to provide a radio receiving system adapted to obviate certain objectionable effects of signal distortion. Another object is to provide a system of directionally selective antennas or antenna systems and associated apparatus combined to make proper allowance for the difference of phase of received components of the signal energy, and thereby to make correction for the signal distortion due to such difference. Another object is to provide a plurality of antennas or antenna systems, each directionally selective in a vertical plane, the directions being different, and to provide respective phase shifters and central apparatus, all combined and adjusted to give undistorted reception notwithstanding the conditions that ordinarily cause the objectionable phenomenon of distortion. In the following specification I shall point out certain scientific principles involved in an explanation and understanding of my invention; then I shall disclose a few embodiments of the invention by way of example to illustrate its principles. It will be understood that this disclosure will be specific to the examples chosen for presentation and that the scope of the invention will be indicated in the appended claims.

Figure 1 is an elevation diagram showing rays once reflected by the Heaviside layer; Fig. 2 is another diagram showing the course of the rays sent at angles to the horizontal somewhat greater than for Fig. 1; Fig. 3 is a diagram showing several ray paths determined by earth reflections a different number of times; this figure is for daytime conditions and Fig. 4 is by way of contrast for winter night conditions; Fig. 5 is a diagram showing the effect of scattering at reflection by the ocean surface; Fig. 6 is a coordinate diagram for a direct range of 3000 miles showing the relation of the number of earth reflections, effective length of ray and other data; Fig. 7 is a similar diagram with the angle of incidence of the ray presented instead of its effective length; Fig. 8 is an elevation diagram of receiving apparatus embodying the principle of my invention; Figs. 9 and 10 are diagrams indicating how phase equalization may be effected in the system of Fig. 8; and Fig. 11 is a coordinate diagram showing the relation of effective length of ray and angle of incidence at a direct range of 3000 miles and with the Heaviside layer at 75 miles effective height.

My invention relates to radio signaling and signal distortion due to interference (partial or complete) between identical simple harmonic components of the signal that reach the receiver from the transmitter by different ray paths of different "effective" lengths. A difference of effective lengths of two ray paths that will produce signal distortion in the transmission of speech will be at least 35 miles. This may be contrasted with the fact that a difference of a few meters in lengths of ray paths may produce ordinary fading due to interference at radio frequencies. The kind of interference at audio frequencies to which I here direct attention shifts aperiodically along the scale of audible frequencies, though the higher frequency components of the signal or telephone current are the more likely to suffer fluctuations of amplitude, and these fluctuations of amplitude are likely to be more pronounced for the higher frequency components of the telephone current than for the lower frequency components. Such distortion is not serious for radio telegraphy but it may seriously impair the quality of speech and music. The different ray paths mentioned above are determined in great measure by the "Heaviside layer", the stratum of the upper atmosphere where the sunlight ionizes the molecules of air without the prompt recombination that occurs at lower levels. Referring to Figure 1, the waves transmitted from the transmitter T at angles to the horizontal less than the critical angle, in this instance 25 degrees are refracted down to the earth by the Heaviside layer. At somewhat greater angles, between 25 degrees and 30 degrees, there may be transmission of the character indicated in Fig. 2. Here the rays penetrate farther into the Heaviside layer and may progress to a comparatively long distance from the transmitter before they are bent down to the earth. At considerable distances from the transmitter, say 3000 miles, these waves of the class of Fig. 2 will, in general, be of comparatively low energy intensity, and may be neglected. At higher angles, above the critical angle which is here taken as 30 degrees, the radiation will pass out into space and be lost to the earth. The "skip distance" shown in Figs. 1 and 2 is the interval between the transmitter and the nearest point on the earth's surface at which a reflected wave may be received. Reception will be weaker and more variable in time at points a little within the skip distance than at points a little beyond its limit.

The altitude of the Heaviside layer varies from time to time over a range whose limits are roughly in the ratio of 2 to 1 or more. The effective level of the layer rises at night and descends with daylight; and its height is also subject to a seasonal change. Fig. 3 represents a case of daytime transmission from T to R. Of all the radiation from T, there are four rays shown that reach R. One of these has been reflected from the earth once, another twice, another three times, and another four times. In Fig. 4 a case of winter night transmission is depicted. Here, there are three rays; one reaches the receiving station R once refracted from the Heaviside layer and having suffered no reflection from the earth's surface, another has been reflected from the earth's surface once, and another twice.

Each reflection involves loss of energy according to a geometrical progression law, hence the received rays that have been reflected a great number of times may be of so little intensity that they may be neglected at the receiving station.

Waves which are too close to the resonant wave length of 214 meters suffer great attenuation in the Heaviside layer. Hence for transmissions to distances of, say, in the neighborhood of 3000 miles or more, these wave lengths must be avoided; this rules out the band of wave lengths from about 150 meters to about 600 meters. This band of wave lengths separates the long range short-wave radio from the long range long-wave radio.

Outside the band surrounding the resonance wave length of 214 meters, the refractions by the Heaviside layer are attended with very little scattering. But the scattering is more serious for the reflections at the earth's surface, more particularly the ocean's surface, for of course our interest in long distance radio lies principally in transoceanic transmission. Scattering becomes serious only for those cases in which the dimensions of the surface irregularities are comparable with the wave length. As the result of a careful study I have found that for radio wave lengths not very short, the scattering is inconsiderable for ordinary ocean waves as distinguished from swells. For ocean swells of dimensions given on good authority, I have carefully computed the scattering effects. The nature of my results may be sufficiently indicated by one example. For a swell 20 feet high (crest relatively to trough) and 400 feet long (crest to crest), the scattering is as indicated in Fig. 5. In this case, the direction of motion of the swells is the same as, or opposite to, the direction of transmission of the radio waves. Having regard to intensity, the reflected, scattered rays lie principally at a larger angle to the horizontal than the incident ray. The effect of scattering by the ocean surface will be somewhat to modify the diagrams of Figs. 3 and 4, but the modification will not be serious except for wave lengths below 50 meters and when there is unusually stormy weather at sea.

The distance traversed by the waves by any path from the transmitter to the receiver will be longer than the direct measure along an arc of a great circle of the earth's surface. For any such longer path there will be an "effective length" such that the time of transmittal of the signal along it will be the same as along a straight line of that length in empty space. I have made a careful study of effective lengths for various cases, and shall present some of the results and point out their application. Briefly stated with reference to Figs. 3 and 4, it is the differences of the effective lengths along the paths from T to R that occasion the signal distortion mentioned earlier in this specification. A particular ray length may fluctuate, but this in itself will not be a cause of appreciable signal distortion, which is due rather to the inequality of the relative lengths of several different paths. The effective length of a wave path from the transmitter to the receiver is given by the following formula,

$$l_N=\frac{1}{k}[R\tan k\alpha+(h-R\ \mathrm{ex\ sec}\ k\alpha)\sin k\alpha]\sec\theta_N$$

where

$$\tan\theta_N=\frac{(h-R\ \mathrm{ex\ sec}\ k\alpha)\cos k\alpha}{R\tan k\alpha+(h-R\ \mathrm{ex\ sec}\ k\alpha)\sin k\alpha}$$

In this formula l_N is the effective length of the path of the ray which suffers N reflections from the ocean surface in transit from the transmission to the receiver; also θ_N is the angle of inclination to the horizontal of the path of the same ray at the earth's surface;

$$k=\frac{1}{2}(N+1);\ \alpha=360°\times\frac{\text{range}}{2\pi R};$$

R is the earth's radius, which will be taken as 4000 miles; and h is the effective height of the Heaviside layer; that is the height at which the incident and reflected rays intersect if produced straight from the portions thereof near the earth (this height is so nearly the same for different angles that it may be assumed to be constant).

From the foregoing formula I have computed the effective lengths and angles of inclination to the horizontal of the rays reaching a receiver from a transmitter 3000 miles distant, when the intervening earth's surface is calm ocean, and at various effective heights of the Heaviside layer from 50 miles to 619.35 miles. The results are presented in the diagrams of Figs. 6 and 7. For the lesser values of the height of the Heaviside layer, no ray unreflected from the earth's surface is possible, and when this height is as little as 50 miles, no ray only once reflected from the earth's surface is possible. These limitations are indicated in Figs. 6 and 7, where the curves are broken off at their lower left ends. For some of the greater values of the height of the Heaviside layer, the angles of inclination are so great that in general the rays for these cases will not be returned to the earth by the Heaviside layer, but will go through it and on through space away from the earth; this is indicated by the breaking off of some of the curves at their upper right ends.

The numerals written above each curve in Fig. 6 give the difference of effective length for the two paths indicated by the points adjacent to those numerals on each side. Thus for example on the curve for the Heaviside layer at 100 miles, between the paths for 1 earth reflection and 2 earth reflections there is a difference of length of 34.8 miles.

For each such difference, there will be a certain lowest frequency of interference. These interference frequency numbers are written below the curves in the corresponding locations. Thus for the same example, to the ray-length difference of 34.8 miles there corresponds a lowest interference frequency of 2672 cycles per second. Evidently the suppression of this frequency by interference would seriously impair the quality of music, and would be on the border line of impairment of speech quality.

At the right end of each curve in Fig. 6 there is a numeral in parentheses that gives the lowest interference frequency between the most widely separated ray-paths represented by that curve. When the Heaviside layer is at 100 miles height, we have seen that the difference of effective length for one and two earth reflections is 34.8 miles. Likewise the difference for two and three earth reflections is 46.1 miles, and the difference for three and four is 57.0 miles. Obviously the difference between the ray lengths for one and four earth reflections is the sum of these three differences, which is 137.9 miles. The lowest interference frequency given by this difference of ray-length is 674 cycles, the number in parentheses at the right. This is at a point on the frequency range where it would be highly effective to mutilate or distort speech as well as music.

Figs. 6 and 7 deal with cases of less than five earth reflections. The loss of energy by reflection is so great that we need not consider cases of five and more earth reflections. In this connection it should be noticed that the interference for adjacent ray-paths will usually be more complete than for extreme ray-paths, because the intensities of the interfering components will be less nearly equal in the latter case.

It will readily be learned from Figs. 5 and 6 that the higher the Heaviside layer, the less will be these interfering frequencies. If the Heaviside layer is ever as high as 298.74 miles, in that case the lowest interference frequency will be 120 cycles. Hence daytime transmission will be with less distortion than at night, other things being equal.

While the foregoing study has had relation particularly to a range of 3000 miles, I have extended it to points within 35 miles more and less than 3000 miles, and I find that within this sub-range no great help for distortion due to selective interference can be obtained by the use of spaced "pick-up" antennas.

In a case of transmission such as represented in Fig. 3 or Fig. 4, I provide a receiving system shown in diagram in Fig. 8. This is an elevation, the plane of the paper being the vertical plane that contains the transmitting station and the receiving station. Each numbered unit, such as 1, 2, 3, etc. is a highly directive receiver, its optimum direction making the angle with the horizontal indicated by the associated arrow. Each such unit consists of an antenna or an antenna array and associated apparatus for demodulating the received waves. These receivers 1, 2, 3, etc. have their directions of selectivity in a graded series of angles to the horizontal as indicated by the arrows. The lines 1*r*, 2*r*, 3*r*, etc. represent audio-frequency output circuits from the directionally selective component receivers 1, 2, 3, etc. to the ultimate receiver R'.

Stated briefly, the waves selectively received by any two of the component receivers or antenna systems, say 3 and 7, have come in over paths of different effective lengths; I make the paths 3*r* and 7*r* of different effective lengths, so as to compensate and bring the audio-frequency signals to the receiver R' in the same phase and therefore without interference.

Consider an ideal structure of the character symbolized in Fig. 8, with an infinite number of directionally selective antennas, each of infinite directional selectivity. Then each received ray, at whatever angle to the horizontal, will find its one and only appropriate antenna which will respond to it in full intensity. With the height of the Heaviside layer at 75 miles, there will be four rays received, respectively earth-reflected one, two, three and four times. As shown on Fig. 7 these will come in at angles to the horizontal of 0° 16', 4° 52', 8° 31', and 11° 45'. As shown on Fig. 6, the effective lengths of the corresponding ray-paths are 3038.4 miles, 3059.3 miles, 3085.8 miles and 3118.8 miles. To equalize these, the effective or equivalent lengths of the respective associated slow-conductors to the ultimate receiver R' must be $l'+80.4$ miles, $l'+59.5$ miles, $l'+33.0$ miles and l' miles, where l' is any convenient length in miles.

Under these circumstances the signals transmitted over the four channels extending from the transmitter to the ultimate receiver will traverse the same effective distance, $l'+3118.8$ miles, and will therefore reach that receiver in the same phase. No interference between the simple harmonic components of the signals traversing different channels can occur, and therefore there will be no distortion.

The data for Fig. 11 are taken principally from Figs. 6 and 7; the corresponding angle as abscissa and the effective distance as ordinate being plotted in a point for each number of earth reflections for the Heaviside layer at 75 miles height. Thus, the data for points 1, 2, 3 and 4 are obtained from Figs. 6 and 7, and the data for point 5 are obtained by an additional computation the same as for the data of Figs. 6 and 7. Taking the horizontal line through point 4 in Fig. 11 as the axis of abscissas, we see that the ordinates measured down to the points 1, 2 and 3 are the distances that are mentioned above as added to l' to equalize the effective overall distances from the transmitter to the ultimate receiver.

We have now adjusted the effective lengths of the slow speed conductors connecting four of the antennas to the ultimate receiver, but the remainder of the slow speed conductors may be similarly adjusted by interpolation in Fig. 11. Take the case of the slow speed conductor associated with the antenna directly oriented to receive a ray whose angle of inclination to the horizontal is 4 degrees. From the curve we see that the effective length of the hypothetical ray-path in question is 3055 miles, and the effective length of the corresponding slow speed conductor is the ordinate interval 63.8 miles. In this way all the lengths of all the slow speed conductors are determined.

Thus far we have restricted ourselves to a height for the Heaviside layer of 75 miles; we now investigate how the ideal receiver will operate when the effective height of the Heaviside layer rises to 100 miles and when it falls to 50 miles. From Figs. 6 and 7 we ascertain that at 100 miles we have the values given in the first, second and third columns of the following tabular array.

Number of earth reflections	Angle of ray to horizontal	Effective length of ray-path	Effective length of slow speed conductor	Total effective lengths
		Miles	*Miles*	*Miles*
1	2° 7'	3059.1	$l'+73.3$	$l'+3132.4$
2	7° 35'	3093.9	$l'+40.8$	$l'+3134.7$
3	12° 4'	3140.0	$l'-2.7$	$l'+3138.3$
4	16° 4'	3197.0	$l'-55.7$	$l'+3141.3$

The values in the fourth column are obtained as ordinates in Fig. 11. The values in the fifth column are obtained by adding corresponding values in the third and fourth columns; that is, by adding the corresponding effective lengths for the ray-paths and the slow speed conductors we get the total effective lengths of the four channels, as given in the fifth column. Here the greatest difference of effective lengths of any two paths is 8.7 miles; this corresponds to an interference frequency of 10,450 cycles, which is too high to produce appreciable distortion even in the transmission of music.

In a similar manner we may deal with the operation of the organization when the effective height of the Heaviside layer falls to 50 miles. In this case as shown in Figs. 6 and 7 there are but three rays to be considered at the receiver, those reflected from the earth 2, 3 and 4 times. The result is a maximum difference of 2.7 miles in the effective length of the overall channels, which corresponds to an interference frequency of 34,400 cycles, a frequency far above the limit of audibility. Therefore no distortion can result.

So far we have been considering an ideal organization in which the component receivers or receiving antennas are infinite in number and infinitely directive in the vertical plane. In the practical organization, as diagrammed in Fig. 8, the number of antennas will be finite and proportional to their directivities.

In our example we have assumed a mean effective height of 75 miles for the Heaviside layer to govern the adjustment of the lengths of the slow speed conductors, but in practice, experience will determine the best height of the layer to choose in effecting this adjustment. It may be best not to fix this adjustment once for all, but to vary it to meet the changing conditions of the Heaviside layer.

Figs. 9 and 10 are to indicate how the adjustment of the slow speed conductors may be made. In Fig. 9 there are two directionally selective receivers 1 and 2. The audiofrequency output circuit of each of these two receivers comprises a slow speed conductor *r* that terminates in a reflection absorbing impedance *z*. The ultimate audiofrequency receiver R is connected to these two slow speed conductors by means of the adjustable contact points *p*. Fig. 10 illustrates the same principle extended to the case of three directive antenna systems 1, 2 and 3. From these examples it will be apparent how to connect one ultimate receiver with any number of directive receiving antennas such as 1, 2 and 3 in Fig. 8.

From the discussion of short wave radio transmission given heretofore in this specification, it will be clear that the device represented by Fig. 8 will minimize signal distortion in transoceanic short wave radio transmission when the radio waves are of such lengths as not to be very seriously scattered by the waves of the ocean. In other words, this device will be effective in the case of what I term "moderately short wave transmission". There is no fixed and sharp line of demarcation as to actual wave lengths to be drawn between the two classes of transmission, for the reason that this line of demarcation depends at any moment on the degree of turbulence of the ocean surface. According to the principles here developed, and so far as signal distortion is concerned, it will be practicable to use shorter waves when the ocean surface is relatively calm than when it is storm-racked.

It will be seen that I attribute "selective fading" and consequent distortion to conditions that involve the reception of waves in rays all in the same vertical plane but at different angles to the horizontal and at different phases due to different "effective length" of the ray paths from the transmitter. I meet the situation by setting up a number of antenna systems very sharply directive in the vertical plane of the receiving and transmitting stations but at different angles to the horizontal. Thereby I obtain at the receiving station several distinct components representative of different ray paths which have different down-coming angles at the receiving station. The time lag differences between the signals received on the different antennas are substantially fixed, and I correct for them by passing the output of each antenna through a suitable respective delay circuit so as to make the total time of transmission of the signals from the transmitter to the output end of the delay circuit substantially equal for all the ray paths. Thus I am able to combine the outputs of all the delay circuits without selective fading of the simple harmonic components of the signals received.

I claim:

1. A plurality of radio receivers directionally selective in graded angles of elevation in the same vertical plane, said receivers comprising respective independent demodulators, an ultimate receiver, and respective phase shifters connecting said receivers to said ultimate receiver.

2. A plurality of radio receivers each narrowly selective in a particular direction, these directions all lying in the same vertical plane and making a series of graded angles to the horizontal in that plane, said receivers comprising respective independent demodulators, an ultimate receiver, and respective adjustable delay circuits connecting the said receivers to said ultimate receiver.

3. A plurality of radio receivers each narrowly selective in a particular direction, these directions all lying in the same vertical plane and making a series of graded angles to the horizontal in that plane, an ultimate receiver, respective adjustable delay circuits extending from the said receivers, non-reflective impedances ending said delay circuits, and contacts adjustable along said delay circuits connected to apply the electromotive forces therein to said ultimate receiver.

4. In combination, at a radio receiving station, means to receive and demodulate incoming radio signals in separate channels according to their direction, each channel being of a certain length, means to shift the phase in each channel so as to equalize the overall effective distances of transmission in these channels, and an ultimate receiver to which the energy in each channel is applied after such equalization.

5. In the reception of directionally dephased radio signal components, means for receiving them selectively in separate channels according to their direction, means to effect demodulation and a compensating phase shift in each channel, and an ultimate receiver to which the energy of the channels is delivered.

6. A long range short wave radio transmitting system comprising a transmitting station and a receiving station separated at a relatively great distance compared to the height of the Heaviside layer, whereby transmission is by several ray paths each with a respective different number of earth reflections, and whereby each ray path is incident at the receiving station at a respective different angle to the horizontal, said receiving station comprising respective receivers highly selective in the directions of said angles, each such receiver comprising a respective independent demodulator, an ultimate receiver, and means between it and the respective before-mentioned receivers to equalize the overall effective lengths of the ray paths.

7. The method of obviating selective interference of the simple harmonic components of the signal in radio receiving which consists in receiv-

ing portions of the signal energy in different channels according to the incoming direction of the received waves, demodulating the received energy and adjusting the phase in each channel separately to effect equalization in all channels, and combining the energy in all the channels.

8. The method of receiving long range short wave radio which consists in receiving the signals in separate channels according to their incoming angle of inclination to the horizontal and demodulating and delaying them separately by different adjusted amounts to equalize the delays in transmission, and then combining their energy with full effect for ultimate reception.

9. The method of long range short wave radio transmission which consists in sending radio signals along several different ray paths differing in the number of refractions and reflections by the Heaviside layer and by the earth's surface, receiving these waves in respective different channels, and delaying the transmission in each channel separately by different adjusted amounts to equalize the delays in transmission, and then combining their energy with full effect for ultimate reception.

10. In combination at a radio receiving station, a plurality of separate sets of radio receiving apparatus each set being highly selective in a certain direction, these directions being all different, and all lying in the same vertical plane determined by the receiving station and the transmitting station from which the signals are to be received and these directions being at various angles to the horizontal, whereby each such set separately receives a component at a corresponding angle, and an ultimate audioreceiver connected with all said sets.

11. The method of obviating selective interference due to incoming electric wave components in different directions which consists in separately receiving these components with high directional selectivity in respective independent radio receiving sets, then adjusting the received components in phase, and then assembling their effects in a common audioreceiver.

JOHN STONE STONE.