My present invention relates to a diversity transmission system for short-wave signaling beyond the radio horizon, in which the provisions of the so-called "forward scattering" technique are utilized.

In accordance with a recently developed technique, a beam of high-frequency energy from a directive transmitting antenna "illuminates" an atmospheric volume above the radio horizon, thereby exciting columns of ionic scattering present in greater or less abundance in said volume. The main lobe of the directive pattern of a transmitting antenna is trained upon the same volume where, by the latter antenna "sees" the excited particles and is energized as a result thereof.

The strength of the received signal is subject to more or less predictable long-term (diurnal and seasonal) variations and also to random fluctuations; fading of the signal for periods of the order of several minutes is not uncommon. This situation may be improved by diversity transmission, a standard system of this type comprising a pair of receiving antennas spaced apart along a line transverse to the general direction of the signal path. Diversity signaling by means of different carrier frequencies has been suggested in principle but appears not to have been explored heretofore to any extent.

The present invention has for its general object the provision of an improved diversity transmission system of the character set forth by means of which, apart from a reduction in signal fluctuation, a better overall ratio of received to transmitted power can be obtained. According to one aspect of this invention, I provide a transmitting antenna and a plurality of receiving antennas whose main lobes are trained upon the transmitted beam so as to intersect the latter at spaced-apart locations. The spacing of the intersections serves to minimize correlation between the two incoming beams but, at the same time, introduces a phase difference between the outputs of the several receiving antennas unless the latter are so positioned that the total path length between the transmitting antenna and each receiving antenna is the same. In the last-mentioned case it may be desirable to employ differential amplification at the receiving points to compensate for diversities in scattering angle.

Where a positioning of the receiving antennas to equalize the path lengths is impractical, the invention proposes to introduce delay means between the several receiving antennas and a common output circuit therefor, such delay means being preferably inserted in the audio or signal-frequency path of one or more of these antennas and being designed to compensate for the path-length difference.

Another feature of my invention resides in the provision of a plurality of directive transmitting antennas whose beams intersect the main lobe of each receiving antenna at spaced-apart locations, delay means being included, if necessary, between the signal source and one or more of the transmitters. If several transmitting antennas as well as several receiving antennas are provided, it is advantageous to maintain all the outgoing beams and also all the incoming beams substantially parallel to one another so that the intersections of any pair of the former with any pair of the latter define a parallelogram, the problem of compensating for path-length differences being thereby considerably simplified. It will be understood that with such arrangement each receiver obtains power from each transmitter, the power ratio in a system according to the invention being thus capable of considerably exceeding that of conventional systems.

It is also an object of my invention to provide an arrangement for frequency diversification which is particularly useful in combination with a multi-beam transmission system as outlined above. In accordance with this aspect of my invention, I provide a source of two carrier frequencies \( F_1 \) and \( F_2 \) which are so related to each other that half their difference, or \( F_2 - F_1 \), is of the order of the highest signal frequency to be transmitted, such signal frequency being of course substantially lower than either carrier frequency. The linear superposition of these two carriers will then give rise to a carrier \( F_1 + F_2/2 \), the amplitude-modulated by the aforementioned halved difference frequency, this resultant carrier thus reaching a peak or near-peak at least once during each signal-frequency cycle regardless of any spurious phase shifts between the two original carriers. The signal in this case may, for example, comprise a train of pulses each of a duration substantially equal to a cycle of the difference frequency \( F_1 - F_2 \).

The above and other objects, features and advantages of the invention will become more fully apparent from the following detailed description, reference being had to the accompanying drawings in which:

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**Fig. 1** illustrates schematically a "beyond-the-horizon" transmission system according to the invention, utilizing a plurality of transmitting and receiving beams shown in elevation and intersecting within a terrestrial great-circle plane;

**Fig. 2** is a diagram of one of the beam intersections shown in **Fig. 1**;

**Fig. 3** shows, schematically, an optional spatial arrangement of the beams of **Fig. 1** as view from the line III--III thereof;

**Fig. 4** is a schematic illustration similar to **Fig. 1** but showing a single transmitted beam associated with a pair of received beams; and

**Fig. 5** is a set of graphs illustrating the use of frequency diversity in the system of **Fig. 1** or **Fig. 4**.

In **Fig. 1** there are shown a pair of highly directive, horizontal transmitting antennas 11 and 12 geographically spaced from each other, the main lobes of their respective beams being indicated at \( A_1 \) and \( A_2 \). These lobes are directed, within a great-circle plane of the earth \( E \) or at a small inclination relative to such plane, toward a region well above the radio horizon as seen from antennas 11 and 12, e.g. in the upper troposphere or the lower ionosphere. The spacing of the antennas 11, 12, is large enough to maintain these lobes well separated from each other throughout the region of interest. The lobes \( A_1, A_2 \) will be referred to hereinafter as the "outgoing" or "transmitted" beams.

The main lobes \( B_1, B_2 \) of the directive patterns of a pair of horizontal receiving antennas 21 and 22, similarly spaced from each other, are trained from the opposite direction upon the aforementioned region above the radio horizon; lobes \( B_1 \) and \( B_2 \) will be referred to hereinafter as the "incoming" or "received" beams.

The beams \( A_1, A_2 \) intersect the beams \( B_1, B_2 \) at an obtuse angle, their intersections defining four separate scattering volumes whose cross sections in the vertical...
or great-circle plane have been indicated by vertical hatching; these volumes are designated $V_{1,1}$ (beams $A_1$, $B_1$), $V_{2,1}$ (beams $A_2$, $B_2$), $V_{1,2}$ (beams $A_3$, $B_3$) and $V_{2,2}$ (beams $A_4$, $B_4$).

Subject to whatever corrections may be required to allow for earth curvature and atmospheric refraction, pursuant to conventional practice, the following geometric relationships obtain: Let $S$ be the distance between antenna 11 and volume $V_{1,1}$, $S'$ the distance between antenna 12 and volume $V_{2,1}$, $R$ the distance between antenna 21 and volume $V_{2,1}$, and $R' + r'$ the distance between antenna 22 and volume $V_{1,2}$; also, let the center spacing between volumes $V_{1,1}$, $V_{2,1}$ (as well as between volumes $V_{1,2}$, $V_{2,2}$) be $s''$ and the center spacing between volumes $V_{1,1}$, $V_{1,2}$ (as well as between volumes $V_{2,1}$, $V_{2,2}$) be $r'$. The length of the signal path from either transmitting antenna to either receiving antenna will then be:

$$d' = z \cdot dx \cdot dy \cdot \cos \alpha \left( \frac{t - z \cos \alpha + y \sin \alpha}{c} \right)$$

(1)

where $\omega / 2\pi = F$ is the operating frequency of the transmitting antenna, $z$ being considered a constant for any particular frequency. This current will produce at the remote receiving antenna a voltage component

$$d' = \frac{2\sigma z}{R} \cos \alpha \left( \frac{t - z \cos \alpha + y \sin \alpha + \alpha R - z \cos \alpha}{c} \right)$$

(2)

from this we obtain by double integration, between the limits $x_1 = z \cos \alpha / \sin \alpha$ and $x_2 = (\alpha + \cos \alpha) / \sin \alpha$ for $x$ and between the limits $y_1 = 0$ and $y_2 = b$ for $y$, the following expression for the voltage vector $E$ at the receiving antenna:

$$E = \frac{2\sigma z \sin \alpha}{K'}$$

(3)

wherein

$$K' = \frac{\sin \alpha}{c} \tan \alpha / 2$$

(4)

and

$$K'' = \frac{b\sigma}{c} \tan \alpha / 2$$

(5)

It should be observed at this point that, in order for Assumption 2, supra, to be approximately valid, the value of $\alpha$ must be considerably greater than zero.

We may now examine the four parameters $z$, $K'$, $K''$ and $K$ with regard to their contributions to the phenomenon of fading.

The magnitude of $z$ is dependent upon such constant factors as the transmitter distance $S$ and the carrier frequency $F$ (which, disregarding the existence of sidebands, we shall consider invariable) as well as upon such variables as the electron density or the degree of ionization in the scattering volume. Since we have based our calculations upon a supposedly uniformly conductive medium and since changes in the average conductivity of an actual medium occur only at a relatively slow rate, we may assume that the parameter $z$ is responsible for the diurnal and seasonal variations in signal strength.

The coefficient

$$\frac{2\sigma z \sin \alpha}{\omega R(1 - \cos \alpha)^2}$$

is to be termed hereinafter the “amplitude factor”; note
that the magnitude of \( \sin \alpha/(1-\cos \alpha)^2 \) decreases rather rapidly with increasing scattering angles \( \alpha \), in keeping with experimental results.

The parameters \( K' \) and \( K'' \) are identical in form except that the former is related to the width \( a \) of the incoming beam and the latter to the width \( b \) of the outgoing one. Theoretically, on the basis of our oversimplified model we might expect both of these parameters to remain constant if we disregard the slight variability of the pulsation \( \omega \). From a practical viewpoint, however, we must remember that the beam widths \( a \) and \( b \) are not, in fact, sharply defined and that minor and transitory atmospheric changes in the path of either beam \( A \) or \( B \) may modify the effective values thereof. Taking \( K' \) as an example, we note from Equation 4 that its magnitude will go to zero whenever

\[
\frac{a \omega}{c} \tan \alpha/2 = 2 \frac{b \omega}{c} \tan \alpha/2
\]

reaches a whole multiple of \( \pi \), thus whenever a \( \tan \alpha/2 \) equals an integral number of half-wavelengths \( \lambda/2 \). If Equation 3, supra, reflects at least approximately the qualitative aspects of the scattering phenomena, and if we are justified in assuming that \( a \) and \( b \) are not simple geometrical dimensions, as in our model, but are in fact complex mathematical operators based upon unstable arguments, we can expect random fluctuations of \( K' \) and \( K'' \) between zero and unity to occur and to produce proportional variations in the strength of the received field such as are actually encountered in short-term fading.

The parameters \( K' \) and \( K'' \) may, therefore, be referred to as the "outgoing fading factor" and the "incoming fading factor," respectively.

The parameter \( K \) may be considered as subject to variations similar to those of the fading factors; this parameter, however, influences only the phase and not the amplitude of the incoming wave, it being convenient, therefore, to refer to it as the "phase factor." Let us now pass from the consideration of a single pair of beams, as in Fig. 2, to that of three or more beams intersecting as in Fig. 1. Taking, for example, the two transmitted beams \( A_1 \) and \( A_2 \) and the received beam \( B_1 \) we are faced with two scattering volumes \( V_{1,1} \) and \( V_{1,2} \) each adapted to give rise to a respective voltage vector \( E_{1,1} \), \( E_{1,2} \) at the receiving antenna \( 21 \). Similarly, the combination of beams \( A_1 \) and \( A_2 \) with received beam \( B_2 \) provides two scattering volumes \( V_{2,1} \), \( V_{2,2} \) each adapted to produce a respective voltage vector \( E_{2,1} \), \( E_{2,2} \) at antenna \( 22 \). Complete fading will occur only if all four of these vectors vanish simultaneously.

We shall assume that the distances \( s' \) and \( s'' \) are small with respect to \( S \) and \( R \) and/or are compensated at the sending station by a higher degree of amplification at transmitter \( 20 \) compared to transmitter \( 19 \); similarly, that the distances \( r' \) and \( r'' \) are small with respect to \( S \) and \( R \) and/or are compensated at the receiving station by a higher degree of amplification at receiver \( 26 \) compared to receiver \( 24 \). We can then consider the amplitude factors of all the aforementioned voltage vectors to be of the same order of magnitude.

If we apply the theory of our rigid, oversimplified model to each of the four scattering volumes in Fig. 1, we find the outgoing fading factor to have a value

\[
K'_{1} = \sin \frac{a_1 \omega}{c} \tan \alpha/2
\]

for the two scattering volumes \( V_{1,1}, V_{1,2} \) and to have a value

\[
K'_{2} = \sin \frac{a_2 \omega}{c} \tan \alpha/2
\]

for the two other scattering volumes \( V_{2,1}, V_{2,2} \) where \( a_1 \) and \( a_2 \) are the widths of beams \( A_1 \) and \( A_2 \), respectively.

Similarly, we find the incoming fading factor to have a value

\[
K''_{1} = \sin \frac{b_1 \omega}{c} \tan \alpha/2
\]

for the two scattering volumes \( V_{1,1}, V_{2,1} \) and to have a value

\[
K''_{2} = \sin \frac{b_2 \omega}{c} \tan \alpha/2
\]

for the remaining two scattering volumes \( V_{1,2}, V_{2,2} \) where \( b_1 \) and \( b_2 \) are the widths of beams \( B_1 \) and \( B_2 \), respectively. These factors are paired in the combinations \( K'_{1} K''_{1} \) for vector \( E_{1,1} \), \( K'_{2} K''_{2} \) for vector \( E_{2,1} \) and \( K'_{1} K''_{2} \) for vector \( E_{2,2} \). It will thus be seen that complete fading requires that at least three of these four factors go to zero simultaneously.

In a practical system we can expect the outgoing fading factors of, say, volumes \( V_{1,1}, V_{1,2} \) or the incoming fading factors of, say, volumes \( V_{1,1}, V_{2,1} \) not to be identical but to exhibit more or less strong correlation, possibly diminishing with increasing spacing of these volumes from each other. The likelihood of total fading is thereby reduced still further.

There is, on the other hand, the further possibility of fading through an adverse combination of phase factors where incoming waves from two or more scattering areas are received simultaneously. Thus it is conceivable, for example, that phase factor

\[
K_{11} = \frac{a_1 - b_1}{2c} \tan \alpha/2
\]

differs from phase factor

\[
K_{12} = \frac{a_2 - b_2}{2c} \tan \alpha/2
\]

at intersections \( V_{1,1} \) and \( V_{2,1} \) respectively, by a multiple or \( \pi \) at the very time when fading factor \( K''_{11} \) is zero or when a similar relationship exists between the phase factors \( K_{12} \) and \( K_{22} \) at intersections \( V_{1,2} \) and \( V_{2,2} \) in which case there would be no signal at either receiving antenna \( 21 \), \( 22 \). The probability of signal cancellation on one incoming beam, occurring at a time of equal amplitudes and opposite phase angles of the wave energy picked up from two outgoing beams, is roughly as low as that of the simultaneous fading of signals from two scattering volumes; the probability of such cancellation occurring on two incoming beams simultaneously is, of course, very slight.

In Fig. 3 I have shown how the beams \( A_1, A_2, B_1 \) and \( B_2 \) which have hitherto considered as co-planar, may be slightly offset with respect to one another so that the axis of each transmitted beam passes between the axes of the two received beams and vice versa. The great circle plane has been indicated at \( G \); the intersections of all four beams lie substantially in that plane. As will be apparent from this figure, any change in axial distance between a transmitted beam and a received beam will vary the dimensions \( a \) and \( b \) of the scattering volume \( V \) (Fig. 2) in the region of their intersection. To the extent that the fading factors \( K'_{11}, K'_{12} \) are in fact determined by these dimensions, the amplitude of the received wave will be affected by slight shifts in the path of the transmitted and/or the received beam due, for example, to movements of the boundary between atmospheric layers of different electron density.

With the arrangement of Fig. 3, any downward deflection of beam \( A_1 \) or upward deflection of beam \( A_2 \) will increase the scattering volume at its intersection with beam \( B_1 \) but decrease the scattering volume at its intersection with beam \( B_2 \); the converse will be true upon a displacement in the opposite direction. Inasmuch as there is no direct relationship between the size of the scattering volume and the amplitude of the received wave, it will
be understood that the purpose of this arrangement is not simple compensation but diminution of the correlation between conjugate intersections, e.g., as represented by volumes $V_{11}$, $V_{1}$, or volumes $V_{21}$, $V_{2}$. An analogous effect is produced in the event of upward or downward deflection of either receiving beam $B_{1}$ or $B_{2}$ as viewed in Fig. 3.

In Fig. 4 I have shown a similar system to that of Fig. 1 but having only a single outgoing beam $A$, originating at a transmitting antenna 111 and intersecting at $V_{11}$ and $V_{2}$, respectively, with incoming beams $B_{1}$ and $B_{2}$ terminating at receiving antennas 121, 122. The beams $B_{1}$ and $B_{2}$ are, furthermore, not parallel yet cross each other in such manner that the total path length from transmitting antenna 111 to either receiving antenna 121, 122 is the same. Thus, with $S$ representing the distance between antenna 111 and intersection $V_{11}$, and with $b$ being the spacing between intersections $V_{1}$ and $V_{2}$, it will be seen that antenna 121 is located on a circle centered on $V_{1}$ whose radius is $R-2b$ whereas antenna 122 is located on a circle centered on $V_{2}$ whose radius is $R$. The need for a delay network at the receiving station is thereby eliminated. The beams $B_{1}$ and $B_{2}$ may be axially offset with respect to beam $A$ in the manner illustrated in Fig. 3.

For reasons to be discussed in connection with Fig. 5, I have provided at the transmitting station a pair of oscillators 117, 118 generating respectively frequencies $F_{1}$ and $F_{2}$ and working into modulators 116, 114 which also receive the output of a signal source 113. Modulators 114, 116 feed a transmitter 119 connected to antenna 111. The receiving station includes a receiver 124, connected to antenna 121 and working into a demodulator 123, as well as a receiver 126, connected to antenna 122 and working into a demodulator 125. The outputs of the two demodulators is combined in a load circuit 128. Owing to the less favorable scattering angle of beam $B_{2}$ it may be desirable to make the amplifying equipment of receiver 126 more powerful than that of receiver 124, as indicated symbolically in the drawing.

It will be assumed that the carrier frequencies $F_{1}$ and $F_{2}$, while being sufficiently close together to fall within the range of operating frequencies of antennas 111 and 121, 122, have been selected so that their difference $(F_{1}-F_{2})/2$ is of the same order as or greater than the highest significant frequency $f$ in the output of signal source 113.

Suppose that the output of source 113 is a train of pulses $P$ of width $T$, as shown in graph (a) of Fig. 5, and that one pulse is received for an interval $2T$ is important but not the shape of the pulse nor its exact time position within such interval. The wave designated $F_{2}$ represents the fundamental frequency of the pulse train when the pulses follow one another at their most rapid rate, i.e., at the rate $1/2T$, and constitutes in effect the highest significant frequency to be transmitted. Carrier $F_{2}$, Fig. 5(b), and carrier $F_{2}$, Fig. 5(c), differs by one cycle within period $T$, hence $F_{1}-F_{2}=1/T$ and, since $F_{2}=1/2T$, $(F_{1}-F_{2})/2=f$. Each of these carriers is modulated by pulse $P$ so as to be suppressed except during the period $T$ between the pulses and $F_{1}$.

Fig. 5(d) shows the result of a linear superposition of carriers $F_{1}$ and $F_{2}$. Given equal amplitudes of the component carriers, the resultant wave has, as is known, the form of a carrier of frequency $(F_{1}+F_{2})/2$ amplitude-modulated with a frequency $(F_{1}-F_{2})/2$ but with phase-reversal of the modulating signal and frequency occurring at intervals $1/(F_{1}-F_{2})=T$. Period $T$ should, of course, be large in comparison with the maximum phase delay to be encountered on the transmission path between antennas 111 and 121, 122. Even if a substantial phase shift should occur on each of the carriers $F_{1}$ and $F_{2}$, we may assume that the relative phase displacement between these carriers will not exceed a small fraction of $T$ so that approximate coincidence will be maintained between them.

By virtue of their difference in frequency, however, the probability of both carriers fading simultaneously is considerably less than that of either carrier fading separately; whenever such fading by one carrier takes place, the other carrier will continue to deliver the signal.

If both carriers are received simultaneously with approximately equal amplitude, the incoming wave will have the form shown in Fig. 5(d) except that, owing to relative phase shift, the peaks of that wave may coincide with some different portion of the interval $T-F_{1}$, this phase shift being a full cycle of either carrier frequency or a fraction thereof, or even more than one cycle, a peak or near-peak of the composite wave will always occur within that interval so long as the minimum frequency spacing specified above is observed. Greater fidelity is, of course, obtained if the difference between the carrier frequencies is increased; thus, if the input signal were not the pulse $P$ but the wave $F_{2}$ itself, it would be desirable to make $(F_{1}-F_{2})$ equal to three to four times $f_{0}$, rather than to $2f_{0}$ since the amplitude of a sinusoidal wave rises to half its peak and higher during two-thirds and to more than 70% thereof during one-half of a cycle.

The outputs of signal source 13, oscillator 17 and oscillator 18 in Fig. 1 may likewise be of the character illustrated in Fig. 5, graphs (a), (b) and (c). In such case the two carriers will be transmitted separately and utilized as $A_{1}$, $A_{2}$ and $B_{1}$ and $B_{2}$ or carrier frequency. Due to an unfavorable combination of phase factors as discussed above, will be completely eliminated.

It will be understood that, if desired, more than two transmitting and/or receiving antennas may be provided by simple extension of the principles herein disclosed. The invention is, furthermore, susceptible of numerous modifications and adaptations without departing from the spirit and scope of the appended claims.

I claim:

1. A radiowave signaling system comprising a source of high-frequency wave energy, a plurality of spaced-apart transmitting antennas connected to said source, a plurality of spaced-apart receiving antennas positioned beyond the radio horizon of said transmitting antennas, all of said antennas having reflector axes lying substantially in the same vertical plane and forming substantially a closed circuit for said wave energy connected to said receiving antennas; the reflector axis of each of said transmitting antennas being trained upon a region above said radio horizon, the reflector axis of each of said receiving antennas being trained upon said region and intercepting the reflector axis of each transmitting antenna, thereby defining a number of spaced-apart scattering volumes equal to the number of transmitting antennas times the number of receiving antennas; said source of energy including first equalizing means for substantially compensating for differences in the respective distances between said scattering volumes and said transmitting antennas; said utilization circuit including second equalizing means for substantially compensating for differences in the respective distances between said scattering volumes and said receiving antennas; the axes of said transmitting antennas and the axes of said receiving antennas being so close to mutual parallelism that the intersections of any two of the first-mentioned axes with any two of the last-mentioned axes substantially define a parallelogram.

2. A system according to claim 1, wherein said first and second equalizing means each include amplifier means of different power connected to different ones of said transmitting antennas and to different ones of said receiving antennas, respectively.

3. A radiowave signaling system comprising a source of high-frequency wave energy, a pair of geographically
separated transmitting antennas connected to said source and provided with a pair of first reflector axes trained in the same general direction upon an elevated region, a source of low-frequency signals connected to modulate the high-frequency wave energy of said transmitting antennas, a pair of geographically separated receiving antennas provided with a pair of second reflector axes trained in the same general direction upon said elevated region, all of said antennas being so positioned substantially in the same vertical plane that each of said first reflector axes is skew to and passes between said second reflector axes while each of said second reflector axes is skew to and passes between said first reflector axes, a common utilization circuit connected to said receiving antennas for recovering said low-frequency signals, and equalizing means connected between said signal source and said utilization circuit, in series with the several signaling paths extending between said transmitting antennas and said receiving antennas, for substantially compensating for differences in the effective lengths of said signaling paths.

4. A radiowave signaling system comprising a source of high-frequency wave energy, a pair of geographically separated transmitting antennas connected to said source and provided with a pair of first reflector axes trained in the same general direction upon an elevated region, a source of low-frequency signals connected to modulate the high-frequency wave energy of said transmitting antennas, a pair of geographically separated receiving antennas provided with a pair of second reflector axes trained in the same general direction upon said elevated region, a common utilization circuit connected to said receiving antennas for recovering said low-frequency signals, and equalizing means connected between said signal source and said utilization circuit, in series with the several signaling paths extending between said transmitting antennas and said receiving antennas, for substantially compensating for differences in the effective lengths of said signaling paths.