INTERCONTINENTAL COMMUNICATIONS
EMPLOYING OPTIMUM MODE

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In general, one experiences considerable difficulties to communicate by electromagnetic waves between two points which are at or close to the earth's surface, but are separated by an intercontinental distance, on the order of several megameters. This is primarily because of the severe attenuation of the propagating electromagnetic field far beyond the horizon of the transmitting antenna, while the ambient noise at the receive-station remains unaffected with the change of communication range. The diffraction theory advanced by Watson[1] and van der Pol and Bremmer[2] suggest such loss of signal strength well beyond the horizon. Long range communications, however, have been common at high frequencies where the ionospheric reflection or a combination of ionospheric and earth's surface reflections of waves bouncing between the earth and ionosphere are utilized to obtain signals at communicable field-strength levels. Often somewhat unpredictable nature of the ionosphere and the inherent mechanism of propagation utilizing one or more reflections from the ionospheric and earth's surface create skip ranges where reflected signals do not reach the receiver and the diffracted signal around the earth's surface is too weak to be of value for communication purposes. At extremely low, very low and low frequencies (ELF, VLF and LF) communications at long ranges and without "skips" are possible, since the ionospheric and earth's surfaces effectively form a concentric spherical waveguide where guided waves are attenuated at long ranges less rapidly than what is predicted by the diffraction theory.

The attenuation with distance for propagating guided waves is due essentially to losses of signals at the boundary walls of the waveguide, which in this case are ionospheric and earth's surfaces. Since the effective conductivity at the ionospheric surface is usually considerably less than that at the earth's surface, the attenuation suffered by the propagating guided waves at ELF, VLF and LF is primarily due to losses at the ionospheric surface. More particularly, losses in this case occur at regions where there is a low conductivity surface and the magnetic field tangential to the surface is relatively strong. This suggests that out of many modes that can be excited and propagated in the earth-ionosphere waveguide if one, which has an extremely small component of tangential magnetic field at the ionospheric surface and to lesser extent at the earth's surface, is used for long range communication, one may experience a significantly lower attenuation rate with distance. Such a mode exists in fact with an attenuation rate which is on the order of one-hundredth of the attenuation rate in dB per megameter or less than that of the dominant mode in the earth ionosphere waveguide, corresponding to a radial (for spherical earth) or vertical component of electric field. This optimum mode has the added advantage that the relevant ambient atmospheric noise is lower than the corresponding noise level for the dominant mode. Another advantage of the optimum mode communication at long ranges is that the attenuation rate is so low that the communication becomes relatively insensitive with respect to ionospheric height variations during the day and night, or due to natural and man-made ionospheric disturbances. Also, from some test data it appears that noise immunity from atmospheric lightning discharges is increased since lightning often has a predominantly strong vertical electric field component while the optimum mode transmission is characterized by waves having a predominantly strong vertical magnetic field and an ideal receiving antenna designed for the optimum mode signal, rejects the noise corresponding to the vertical component of the electric field.

To illustrate the characteristically low attenuation rate in dB per megameter of the communication distance for the optimum mode, it is noted that the radial component of the vertical magnetic field for the spherical earth geometry, due to a horizontal loop antenna (plane parallel to earth's surface) can be written as

$$H_r = \frac{M}{H\sqrt{d}}\left[\frac{d/a}{\sin d/a}\right]^{\frac{1}{2}} S \tag{1}$$

where M is proportional to the source strength IA, I and A being respectively the loop current and loop area, d is communication distance, a is radius of the earth, H is ionospheric height and

$$S = \sum_{m=1}^{\infty} \mathcal{S}_m \, e^{-i\beta d S_m} S_m^{\frac{1}{2}} f_m(z) \, f_m(z_0) \tag{2}$$

β being 2π/wavelength, S_m and $\mathcal{S}_m$ being modal characteristic functions and $f_m(z)$ and $f_m(z_0)$ being respectively the height-gain functions of the receiving antenna height z and transmitting antenna height z_0.

It is seen from Eqs. (1) and (2) that the field at great distances away from the transmitting antenna varies as $1/\sqrt{d}$, which is characteristic of the guided wave propagation. In addition, the field experiences an exponential attenuation with increasing d, depending on the imaginary part of S_m. Thus, to determine the exponential attenuation rate, one needs to evaluate S_m. Wait[3] has shown that the imaginary part of S_m, corresponding to a horizontal loop radiating antenna, is

$$I_m S_m \simeq -\frac{\Delta}{\beta H}\left(\frac{\pi m}{\beta H}\right)^2 \left[1 - \left(\frac{\pi m}{\beta H}\right)^2\right]^{-\frac{1}{2}} \tag{3}$$

where Δ is a function of the electromagnetic parameters of the ionosphere and the earth.

The mode corresponding to m=1 term in Eq. (2) may be referred to as the optimum mode, since the attentuation due to this mode is the lowest of all possible propagating modes in the earth-ionosphere waveguide. In comparison, the imaginary part of S_m, which determines the exponential attenuation rate for the dominant mode in the earth-ionosphere waveguide, corresponding to a predominantly vertical electric field for the propagating waves, is given as

$$I_m S_m = -\frac{\Delta}{2\beta H} \tag{4}$$

Figure 1 shows a plot of the ratio of exponential attenuation rate in dB per megameter for the optimum mode to that of the dominant mode. It is seen that as H/λ increases, constituting an oversized earth-ionosphere waveguide, the attenuation ratio becomes very small indicating that if the optimum mode is used in such cases, the attenuation rate could be so small as to be negligible. More specifically, the day-time attenuation rate for the dominant mode at 60 KHz is about 2 dB/megameter. For an assumed ionospheric height of 60 Km, the attenuation rate for the optimum mode is less than one-hundredth of a dB/megameter. The significant reduction of attenuation rate for an oversized waveguide is analogous to the attenuation rate for the oversized cylindrical waveguide carrying TE_{01} mode[4].

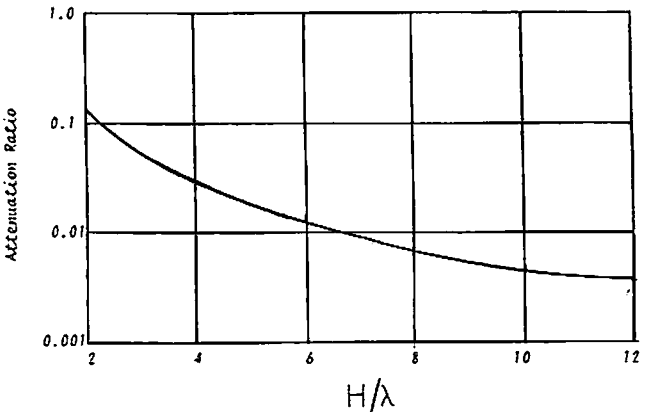

Figure 1. Ratio of optimum mode attenuation rate to dominant mode attenuation rate in dB/megameter as a function of ionospheric height in wavelength.

The striking difference in attenuation rates for the optimum and dominant modes is shown in Figure 2, where relative field strengths for the optimum and dominant modes, as measured in a physical simulation model of the spherical earth-ionosphere waveguide, are plotted as a function of the communication range. As may be noted in Figure 2, the contribution of higher order modes (other than the lowest order mode) in the series of Eq. (2) cannot be ignored when the communication distance is not very far from the transmitting antenna. One thus observes a non-monotonic decrease of the field with distance, because of the different phases of different modes. As the communication range increases, the attenuations for higher order modes increase and consequently their contributions toward S decrease, making the field strength decrease monotonically with distance.

Characteristics of various modes associated with the excitation of the optimum mode are discussed in the paper. The consideration of lower attenuation rate of the field, although most significant, is not exclusive from the viewpoint of communications. The practical and reliable means of excitation of the optimum mode, relevant ambient noise, and means of providing isolation between the transmitting and receiving antenna in a collocated communication terminal also constitute important long-range communication considerations. These aspects of the problem, in general, and means of adaptive isolation between transmitting and receiving antennas, particularly for an airborne communication station, are discussed in the paper.

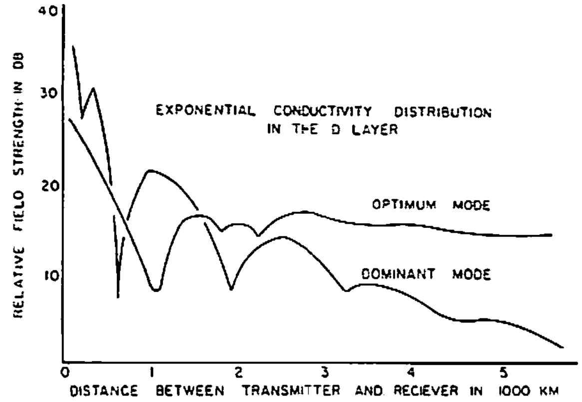

Figure 2. Comparison of relative field strengths for optimum and dominant modes as measured in a physical model simulating spherical earth and ionosphere at 20 Hhz. Ionospheric height is 65 KM.

References

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