ELF Propagation Update

PETER R. BANNISTER, MEMBER, IEEE

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***Abstract*—Extremely low frequency (ELF) electromagnetic waves have a remarkable ability to propagate with very little attenuation in the earth–ionosphere waveguide. The resulting fields are also able to propagate to moderately great depths in the ocean in spite of the higher conductivity of seawater. The principal drawback in the use of ELF for communication is the inherent inefficiency of the transmitting antenna. Indeed the waves do, however, penetrate to deeply submerged submarines when all other methods fail. This paper presents a tutorial overview on ELF propagation in the earth–ionosphere waveguide. Simple form approximate expressions (relating ELF propagation constants to realistic ionospheric conductivity profiles) are compared with experimentally derived results for both daytime and nighttime propagation conditions. Some anomalous ELF propagation results, along with their probable causes, are also discussed.**

I. INTRODUCTION

THE extremely low frequency (ELF) band (30-300 Hz) has serious deficiencies compared with conventional radio frequencies. It is characterized by a very restricted bandwidth (low data rates) and an extremely large wavelength (inefficient antennas). For special applications, however, involving some of the propagation paths conducted through rock or seawater, it offers the possibility of communication where conventional bands offer none. In the case of long-range communication with submerged submarines, it can also provide low-loss highly stable propagation in the earth–ionosphere waveguide.

It is the purpose of this paper to present a general overview of ELF propagation. We will also compare simple form approximate expressions (relating ELF propagation constants to realistic ionospheric conductivity profiles) with experimentally derived results for both daytime and nighttime propagation conditions. ELF propagation during disturbed ionospheric conditions will also be discussed.

II. PROPAGATION IN THE EARTH-IONOSPHERE WAVEGUIDE

The energy of propagating radio waves with frequencies below 300 kHz is principally confined to the shell between the earth and the ionosphere; this space is frequently denoted as the terrestrial waveguide. For long waves, the effective waveguide height h is comparable to a free-space wavelength λ and the characteristics of wave propagation are determined by the properties of the guide boundaries.

A number of propagating modes have distinct cutoff frequencies similar to those in the microwave range. However, unlike the highly conducting guides of the microwave range, the upper boundary of the terrestrial waveguide is diffuse and a poor conductor; the finite conductivity of the earth's surface is also important. In the ELF range, h is less than λ and only one waveguide mode propagates. For VLF, h exceeds λ and there are several propagating modes. In the LF range, the number of significant propagating modes may exceed twenty.

Several field representations can be used to characterize the terrestrial propagation of radio waves. The fields in a uniform spherical shell between the earth and ionosphere can be expressed as a summation of spherical harmonics, which involves Legendre polynomials and spherical Bessel functions of integer order n. This series converges very slowly. The number of terms required is of the order of $10k_0a$, where $k_0 = 2\pi/\lambda$ and a is the radius of the earth. Although this series is directly applicable in the ELF range, its exceedingly slow convergence may preclude its use at LF.

The Watson transformation changes the series of spherical harmonics into a residue, or mode series, where the fields are expressed using Legendre functions and spherical Bessel functions of complex order ν. Each term of the mode series can be identified as an azimuthal wave propagating in the $\theta(=\rho/a)$ direction with a distinct phase velocity and attenuation rate.

At ELF, h is of the order of 45 to 90 km. Because h is much less than λ, the waveguide is below cutoff for all but the lowest order mode (i.e., the TEM mode). The electric and magnetic fields are wholly transverse to the direction of propagation in the TEM mode, with the electric field vertical and uniform and the magnetic field horizontal and uniform. In practice, inhomogeneities and nonuniform surface conditions perturb the ideal TEM field configuration and the result is the quasi-TEM mode.

Attenuation in the earth–ionosphere waveguide at ELF for the quasi-TEM mode is low, on the order of 1 or 2 dB/Mm. The effective conductivity of the ionosphere (10^{-5}-10^{-7} S/m) is usually much lower than that of the ground (10^{-4}-5 S/m), and so the surface impedance of the ground is typically much smaller than the surface impedance of the ionosphere. Thus the attenuation in the guide is attributable mainly to power absorption by the ionosphere.

The same principles apply to radiation and propagation in the earth–ionosphere waveguide that apply to radiation and propagation above a conducting half-space. The significant difference is the attenuation of the fields in the atmosphere.

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The author is with the U.S. Naval Underwater Systems Center, New London, CT 06320.

In the case of the simple conducting half-space, the principal field is essentially detached from the half-space, with the result that the weakening it experiences as a result of leakage of its power down into the ground is negligible, for practical purposes. In the case of the waveguide, on the other hand, the wave is bounded above and below by finitely conducting media and is, therefore, strongly coupled to them. The rate of power loss into the conducting media is then no longer negligible compared with the total power carried by the propagating field within the guide. The effect is clearly stated in the expression for the waveguide attenuation rate α, where α is seen to be inversely proportional to h. In physical terms, this states that the rate of power leakage out of the guide is proportional only to the intensity of the field in the guide, whereas the rate of power flow along the guide is proportional to the intensity of the field and to the volume of the guide. Thus as the guide decreases in height, the constant power leakage is being subtracted from a smaller total power flow. More rapid depletion is the result [1].

Apart from this difference, the same principles apply. The launching of the principal field from a vertical electric current source and a horizontal magnetic current source proceeds as though the walls were perfectly conducting. (The same is true of a horizontal electric current source if it is mathematically represented by its equivalent horizontal magnetic current source.) The principal fields then propagate away from the source region with either negligible attenuation, in the case of the half-space, or small but definite attenuation in the case of the guide.

Thus the principal fields directly provide the vertical electric field E_v and horizontal magnetic field H_h at the field point. Secondary field components arise because the surface impedance η_g of the ground is not zero. Therefore, the horizontal electric field is equal to $\eta_g H_h$ and perpendicular to the horizontal magnetic field, while the vertical magnetic field is related to the circulation of the horizontal electric field. The specific value of the vertical magnetic field is often uncertain, since it is sensitive to the lateral rate of change of surface impedance. It should be noted that the secondary fields are very small in absolute magnitude compared with the principal fields and are of no practical significance, except in the immediate vicinity of the surface. They are fundamentally important at the surface, however, because certain ELF antennas depend upon the existence of the secondary field [1].

When the source of the field point is buried, the vertical field components suffer a jump-discontinuity as the field point descends through the surface, (the level depends on the permittivity, or permeability contrast between the ground and the atmosphere). The horizontal field components, on the other hand, are continuous. Further increases in depth reduces their amplitude in an exponential fashion for a homogeneous ground and, in a more complicated but calculable manner, for a layered ground structure. Completely parallel remarks apply to burying the sources.

The preceding few paragraphs have described the propagation of ELF waves in a planar parallel plate waveguide model of the earth-ionosphere guide. The attenuation in that guide is low enough, however, for round-the-world propagation to occur. The planar model is therefore, inadequate when the distance from the source to the field point is of the same magnitude as, or greater than, the radius a of the earth.

The general nature of ELF propagation around the earth has been the subject of theoretical study for many years and is, apparently, well understood. The texts by Wait [2], Galejs [3], and Burrows [1] describe the theory in the form accepted today and provide a bibliography of earlier work. Reference may also made made to a Special Issue of the IEEE TRANSACTIONS ON COMMUNICATIONS edited by Wait [4], review papers by Bernstein *et al.* [5] and Wait [6], and a collection of papers by Bannister *et al.* [7].

There are a number of effects attributable to the curvature of the earth's surface that might be significant. For example, the curvature of the guide may modify the relationship between the various field quantities by introducing a marked radial dependence. Second, the energy guided between the walls has a constant height of wavefront but a width of wavefront that is smaller than if the guide were planar. Thus the guide curvature has the effect of channeling the same amount of power flux through a small cross section, (an effect known as spherical focusing). The result is an increase in the power flux density and, therefore, in field quantities. Third, the closure of the guide around the earth changes it from an infinite structure into a finite one. The field does not simply propagate continuously away from the field point to infinity, as it does in the planar model. Instead, it eventually returns to the source point after one complete encirclement of the earth. In principle, the field continues to circulate indefinitely. This means that the field at any point is the sum of the field at the point arising from propagation over the shorter great-circle path from the source, and that arising from propagation over the longer great-circle path. Subsequent encirclements by the two waves propagating in opposite directions may also contribute. Moreover, if the frequency is such that the wave phase changes by $2\pi n$ (where n is an integer) when it completes one complete circuit, the closed guide is a cavity-in-resonance. A fourth effect is the geomagnetic field, which varies in intensity and direction as the point of observation moves about the earth. At any single location, the geomagnetic field interacts with the changed particles of the ionosphere to produce, in effect, an anisotropic conducting medium. Since the tensor describing the conductivity is not symmetrical, electromagnetic processes involving the ionosphere will not occur in strict conformity with the reciprocity theorem. This effect is made more complicated by the variation in direction of the geomagnetic field from place to place [1].

It turns out that the first and fourth of these possible effects are not of practical significance. The ionospheric height is of the order of 45-90 km, which is only about one-hundreth of the earth's radius. Thus no local effects attributable to the earth's curvature are observed. Also, the electrical mismatch between the atmosphere and the ionosphere is so large at ELF, and the transition between them so abrupt, that very little penetration of the ionosphere occurs. Thus the ionosphere acts so much like a perfect reflector that any effect of the anistrophy on the guided ELF wave can be shown theoretically to be small [2], [3], and has been measured to be so experimentally [5], [7]-[9].

Since the local effect of the curvature is small, the wave propagates in the curved guide with the same parameters as it would in the planar guide. The only effect of the spherical focusing, therefore, is to increase the power flux density in accordance with the reduction in the area of the wavefront. The width of the wavefront, at a great circle distance from the source, is smaller by the factor $\sin(\rho/a)/(\rho/a)$ than it would have been at the same range ρ in a planar guide. Therefore, the power flux density is increased at this distance by the reciprocal of this factor, and the field quantities by the reciprocal of its square root [1].

III. FIELD STRENGTH CALCULATIONS

The expressions most often employed for calculating the fields in the earth-ionosphere waveguide (radiated by sources near the surface) are based upon a simple theoretical model that assumes the earth and ionosphere to be sharply bounded and homogeneous. The ionosphere, however, which has a greater influence on propagation than does the ground, is neither homogeneous nor sharply bounded. Therefore, a question arises concerning the usefulness of a simple model.

It is necessary to know whether there are simple curves showing the variation with frequency of parameters equivalent to those the h, S, and η_g parameters of the simple theory, that can be used to calculate the fields with sufficient accuracy for communication system design. (The real part of S is c/v, the ratio of the speed of light in free space to the wave speed in the guide. The imaginary part of S is proportional to the attenuation rate in the guide.) The real ionosphere may be essentially different in its properties from a well-behaved sharply bounded model. In fact, theoretical calculations using certain layered ionospheric structures have provided propagation data exhibiting resonant absorption and strong dispersion [3], [10]-[13]. On the other hand, experimental measurements of the properties of the guide have consistently shown them to be, *on the average*, relatively stable and predictable and, in particular, to be accurately represented by the simple formulas [1].

The experimental corroboration of the simple formulas does not, of course, mean that the ionosphere is actually sharply bounded and homogenous; direct measurements of its conductivity profile show that it is not. Rather, the corroboration supports the view that, over the frequency range of interest, simple curves exist of parameters equivalent to h, η_g, and S that can be used in the formulas to obtain accurate field estimates.

The next question to be asked about the simple theory is whether the parameters (e.g., the effective ionospheric reflection height and propagation constant it requires as input) can be readily obtained. It seems likely, based on the theoretical work of Jones [14], [15]; Greifinger and Greifinger [16]-[18]; Booker [19]; Behroozi-Toosi and Booker [20], and the experimental propagation measurements of Ginsberg [21]; Bannister [7], [8], [22]-[24]; Bannister and Williams [25]; Bannister *et al.* [26]; and White and William [9] that they could be calculated accurately if enough ionospheric data were available. However, the calculation would not be wholly convincing without periodic experimental vertification. The experimental verification in itself is a measurement of the parameters, and so establishes their magnitudes and behavior in time and space directly. Then the interpretation in terms of ionospheric physics is superfluous, apart from the reassurance that it can give that the measurements are consistent with other data [1].

The substantial body of propagation data now available from measurements of sferics (the propagating electromagnetic pulses originating from lightning strokes), from Schumann resonances, and the measurements of signals radiated from man-made sources presents a coherent quantitative description of propagation parameters. Thus for the initial design of an ELF communications system using the earth-ionosphere waveguide, estimates of numerical values to be used for the parameters can be obtained from existing data. Before the final design, however, propagation measurements over the path planned for the system should be made. By using long integration times on reception, together with phase-synchronous detection, one can achieve the required accuracy using a test transmitter that is a smaller version of the one planned for the final system (such as the U.S. Navy's ELF Wisconsin Test Facility (WTF)).

Instead of the parameters h, η_g, and S appearing in the theoretical propagation model, it is convenient to measure a composite of the three called the excitation factor ϵ defined by

$$\epsilon = \left| \frac{\eta_g}{h\sqrt{\omega\mu_0 S}} \right| \tag{1}$$

and also the modified form of S, which is the attenuation factor as defined by

$$\alpha = 0.0290\,\omega\,|\mathrm{Im}\,\{S\}| \tag{2}$$

giving the attenuation in dB/Mm. (It should be noted that the ϵ defined here is not the same as the excitation factor Λ_n used by Wait [2] and Galejs [3] for a different purpose.) The utility of these two factors is demonstrated by substituting them in the asymptotic form for the horizontal electric current source. Thus

$$|(H_\phi)_d| \sim Idl\epsilon \left[\frac{k_0}{2\eta_0}\left(\frac{\omega\mu_0}{2\pi}\right)^{1/2}\right]\left(\frac{\rho/a}{\sin\theta}\right)^{1/2} \cdot \frac{10^{-\alpha\rho/2\times 10^7}}{(k_0\rho)^{1/2}} \cos\phi. \tag{3}$$

There are essentially six distinct factors in this propagation formula. The first is the source strength Idl. The second is ϵ. The third is a collection of free-space parameters, all of which are determined exactly once the frequency is specified. The fourth is the spherical focusing factor. The fifth is the radial propagation loss factor, including both the exponential decay due to absoprtion and the $\rho^{-1/2}$ decay due to spreading. The sixth defines the directional dependence of the radiated field. Once the current moment Idl, frequency ω, and coordinates ρ, ϕ of the field point are specified, only two parameters and left undetermined, i.e., α and ϵ. Thus when these two are evaluated, the field calculation can proceed [1].

Recently, Greifinger and Greifinger [16], [17], Booker [19], and Benroozi-Toosi and Booker [20] have derived simple form approximate expressions for the TEM eigenvalues (propagation constants) for ELF propagation in the earth-ionosphere waveguide. They demonstrated that eigenvalues obtained by their methods were in excellent agreement with full-wave numerically calculated eigenvalues. The Greifinger's showed that the propagation constant depends on four parameters–two altitudes and a scale height associated with each. The lower altitude is the height at which the conduction current parallel to the magnetic field becomes equal to the displacement current. The associated scale height is the local scale height of the parallel conductivity. Under daytime ionospheric conditions, the upper altitude is the height at which the local wavenumber becomes equal to the reciprocal of the local scale height of the refractive index. Under the simplest nighttime conditions, the second set of parameters is replaced by the altitude of the E-region bottom and the local wave number just insde the E-region. The relative phase velocity depends, in first approximation, only on the ratio of the two altitudes. The attenuation rate depends on the other two parameters, as well. The two principal attenuation mechanisms are Joule-heating by longitudinal currents in the vicinity of the lower altitude and energy leakage of the whistler component of the ELF wave at the upper altitude.

In a lesser known publication, the Greifingers [18] have extended the results presented in their earlier two papers [16], [17] to a more general class of ionospheric conductivity profiles. Their expressions allow the rapid computation of ELF phase velocities, attenuation rates, and excitation factors, for a wide range of ionospheric conditions without the necessity of lengthly fullwave computer calculations. The results can be applied to the rapid evaluation of the effects of a variety of ionospheric disturbances, both natural and artificial, on ELF communication systems.

Booker [19], [20] has combined the reflection theory of Booker and Lefeuvre [27] with the Greifingers' treatment [16], [17] of the effect of ionization below the level of reflection. The theory allows for the influence of the earth's magnetic field, reflection from the gradient on the underside of the D-region (or, at night, of a ledge below the E-region), reflection from the gradient on the underside of the E-region, and reflection from the gradient on the topside of the E-region.

We have used [23] the recently developed theory of the Greifingers [16] and the Wait VLF exponential ionospheric conductivity profile [2], [28] to determine TEM propagation constants for ELF daytime propagation in the earth-ionosphere waveguide. We determined that the resulting values of ELF attenuation rate, phase velocity, and approximate ionospheric reflection height are in excellent agreement with measured data.

For daytime propagation, the Greifingers' expressions for α and c/v are

$$c/v \sim 0.985\sqrt{h_1/h_0} \tag{4}$$

and

$$\alpha \sim 0.143 f\sqrt{h_1/h_0}\left(\frac{\zeta_0}{h_0}+\frac{\zeta_1}{h_1}\right), \quad \text{dB/Mm} \tag{5}$$

where h_0 is the altitude where $\sigma = \omega\epsilon_0$, h_1 is the altitude where $4\omega\mu_0\sigma\zeta_1{}^2 = 1$, and ζ_0 and ζ_1 are the conductivity scale heights at altitudes h_0 and h_1, respectively.

From (4) and (5) we can see that the phase constant depends primarily on the two reflecting heights and is essentially independent on the conductivity scale heights. On the other hand, for a single scale-height conductivity profile (i.e., $\zeta_1 = \zeta_0$), the attenuation rate is directly proportional to scale height.

The single scale-height profile employed by Wait [2], [28] for determining VLF propagation parameters is

$$\omega_r(z) = \sigma(z)/\epsilon_0 = 2.5 \times 10^5 \exp\left[(z-H)/\zeta_0\right] \tag{6}$$

where H is the (arbitrary) reference height. The altitudes h_0 and h_1 may be determined from

$$h_0 = H - \zeta_0 \ln\left(\frac{2.5 \times 10^5}{2\pi f}\right) \tag{7}$$

and

$$h_1 = h_0 + 2\zeta_0 \ln\left(\frac{2.39 \times 10^4}{f\zeta_0}\right). \tag{8}$$

Note that in (6), (7), and (8) all heights and scale heights are in kilometers.

The Greifingers [18] have also shown that the effective waveguide height of reflection is roughly h_0, rather than the higher reflecting height h_1. This is in excellent agreement with the effective reflection heights inferred from the Sanguine-Seafarer propagation measurements [8], [23]. The fact that it is the lower height is not really that surprising since the horizontal rate of energy flow is essentially constant up to an altitude h_0, above which it falls off very rapidly with altitude [16]-[18].

The most common values of H and ζ_0 employed in interpreting VLF daytime propagation measurements are H = 70 km and $\zeta_0 = 1/0.3 = 3.33$ km. By using these values in (4), (5), (7), and (8) we can readily determine h_0, h_1, c/v, and α at ELF. For example, at 75 Hz, $h_0 \sim 49.1$ km, $h_1 \sim 79.5$ km, $c/v \sim 1.26$, and $\alpha \sim 1.5$ dB/Mm. Furthermore, at 1000 Hz, $h_0 \sim 57.7$ km, $h_1 \sim 70.8$ km, $c/v \sim 1.10$, and $\alpha \sim 16.6$ dB/Mm.

The theoretically determined values of the ELF daytime attenuation rate are plotted in Fig. 1 for frequencies of 5-2000 Hz. Also plotted are various experimentally determined values of α. These were all determined from controlled source

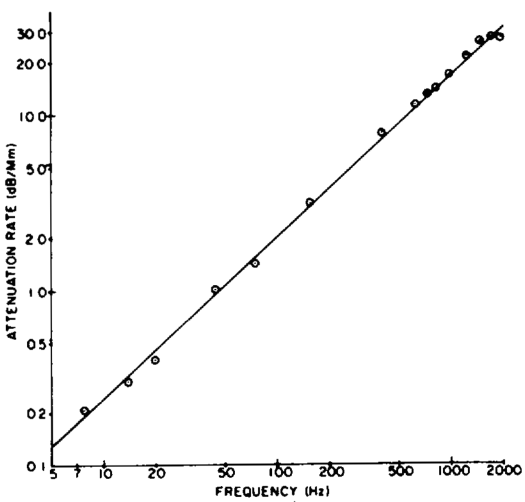

Fig. 1. Comparison of theoretical and experimentally determined ELF daytime attenuation rates. ⊙ Measurements.

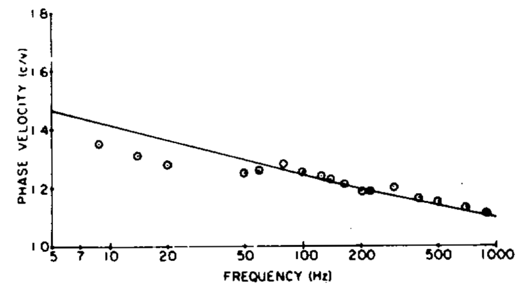

Fig. 2. Comparison of theoretical and experimentally determined ELF daytime phase velocities. ⊙ Measurements.

measurements, except for the 7.8-, 14-, and 20-Hz attenuation rates which were inferred from Schumann resonance measurements [29]. The 45- and 75-Hz data points are average values determined from the 1970–1972 Sanguine/Seafarer propagation measurements [8], the 156-Hz value is from Ginsberg [21], and the 400-Hz value is from Kuhnle and Smith [30]. The 630-to-1950-Hz points were obtained by employing the Navy VLF antenna at Jim Creek, WA, as the source [21]. From Fig. 1 it can be seen that there is excellent agreement throughout the ELF range between the theoretical (employing the Wait expontential ionospheric-conductivity profile) and experimentally determined values of ELF daytime attenuation rates.

The theoretically determined values of the ELF daytime phase velocity are plotted in Fig. 2 for frequencies of 5–1000 Hz. Also plotted are various experimentally determined values of c/v. These values were all determined from measurements of atmospherics. The 7.8-, 14-, and 20-Hz values were inferred from Schumann resonance measurements [29], the 50-to-255-Hz values are from Hughes and Gallenberger [31], and the 300-to-900-Hz measurements are the two station results of Chapman *et al.*, [29]. From Fig. 2, we see that there is excellent agreement between the theoretical and experimentally determined values of c/v for frequencies greater than 50 Hz and fair agreement for frequencies less than 50 Hz.

Under nighttime propagation conditions, a sharp E-region bottom is usually encountered before the altitude h_1 is established. The electron density undergoes a very sharp increase in passing through the bottom, above which it can be quite variable. The Greifingers' [17] have considered the simple model where the density above this botton varies slowly on the scale of the local wavelength. The result is

$$c/v \sim \sqrt{h_E/h_0} \tag{9}$$

and

$$\alpha \sim 0.143 f \sqrt{h_E/h_0} \left(\frac{\zeta_0}{h_0} + \frac{1}{\pi k_0 \eta_E h_E} \right) \tag{10}$$

where h_E is the altitude of the E-region bottom and $k_0 \eta_E$ is the E-region local wavenumber. Comparison with the daytime results (4) and (5) shows that the altitude of the E-region bottom has replaced the frequency dependent altitude h_1 as a parameter, and the local wavelength just inside the E-region has replaced the scale height ζ_1.

We have also employed Waits' nighttime ionospheric conductivity model (with a reference height of 90 km and scale height of $1/0.4 = 2.5$ km) in conjunction with the Greifingers' nighttime theory. We also assumed the height of the E-region bottom was 90 km and its conductivity was approximately 8×10^{-6} S/m.

The theoretically determined values of the ELF nighttime attenuation rate are plotted in Fig. 3 for frequencies of 40–1000 Hz. Also plotted are various experimentally determined values of α. These were all determined from the previously mentioned controlled source measurements. From Fig. 3 we see that, for frequencies from 45 to 800 Hz, there is excellent agreement between the theoretical and experimentally determined values of the ELF nighttime attenuation rates. Also, the 45-, 75-, and 156-Hz effective waveguide reflection heights (approximately 75 km) are in excellent agreement with those inferred from the Sanguine–Seafarer measurements [8].

IV. ANOMALOUS ELF PROPAGATION

On several occasions during the past decade, the 40-to-80-Hz nighttime field strength measured at sites in the northeastern United States (i.e., Connecticut and Mayland) has displayed rapid decreases of from 4 to 8 dB in several hours [7], [8], [32]–[38]. These severe nighttime disturbances sometimes occur during the several days following magnetic storms when similar but less pronounced behavior is found to coincide with phase disturbances on VLF paths across the northern United States.

We have shown [7] that the Connecticut nighttime field strength amplitude was usually at a minimum between 06 00 and 08 00 GMT, whereas the nighttime relative phase was at a maximum 1 h earlier. The time of the lowest nighttime field strengths coincides with the farthest southern displacement of the auroral oval and presumably indicates the time at which precipitated energetic electrons would reach their southernmost extent in the middle latitudes.

These short path (~1.6 Mm) field strength reductions have been speculated to be caused by precipitation of electrons from the radiation belts resulting in enhanced ioniza-

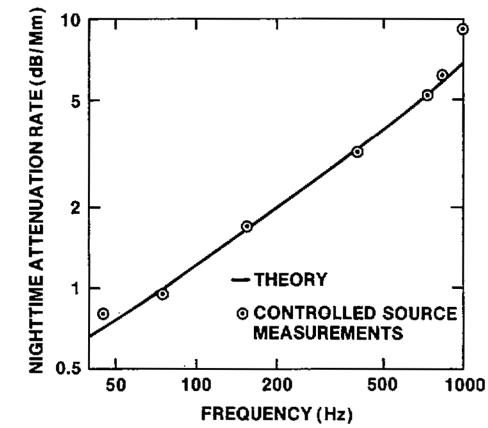

Fig. 3. Comparison of theoretical and experimentally determined ELF nighttime attenuation rates.

tion of the lower atmosphere. Attempts to correlate the anomalous signal strength behavior with geomagnetic indices indicating the degree of disturbed magnetospheric conditions, have met with limited success [39].

Long path ELF field strength propagation data recorded in polar areas also are characterized by periods of abnormally low values [38]. It has also been speculated that these disturbances are due to precipating particles causing enhanced ionization in the lower ionosphere, but no direct relationship has so far been advanced [39].

Simultaneous measurements taken in Connecticut and the North Atlantic area during the magnetically quiet period of early March 1977 (where similar nighttime propagation anomalies occurred 2-4 h apart) have indicated that another cause for some of these anomalies is a moving nocturnal sporadic E-layer [40]-[42].

Some additional examples of the similiarity (in both amplitude and relative phase) of the Connecticut and North Atlantic area (~4.5 Mm from WTF) anomalous nighttime field strengths are presented in Figs. 4 and 5. These data are characterized by the following.

1) Substantial amplitude decreases during the nighttime period of 02 00 ot 06 00 GMT, with the relative phase peaking about an hour before the minimum nighttime amplitude time.

2) Substantial amplitude increases and relative-phase decreases (and then increases) near the end of the nighttime measurement period and the beginning of the sunrise transition period (06 00 to 10 00 GMT).

A comparison of the October 8, 1977, Connecticut and North Atlantic area field strengths is presented in Fig. 4. During October 8, the average North Atlantic area $\Delta\phi$ variation was only 37° compared to 60.5° for the other seven days measured. On the other hand, the average Connecticut $\Delta\phi$ was approximately equal to the monthly average (~21°) [43].

Referring to Fig. 4, we see that from approximately 02 00 to 05 30 GMT the amplitude steadily decreased 4-5 dB at both locations, while the relative phase peaked at 04 30 GMT. Then, the amplitude steadily increased 4-5 dB from 05 00 to 08 00 GMT, while the 04 30 to 07 00 GMT relative

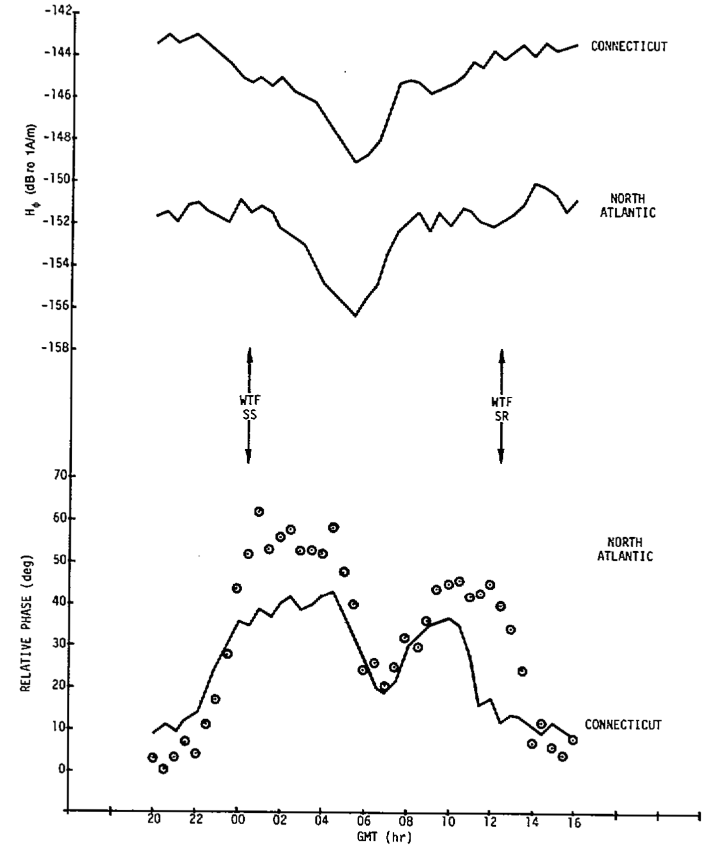

Fig. 4. Comparisons of Connecticut and North Atlantic area field strengths, October 8, 1977.

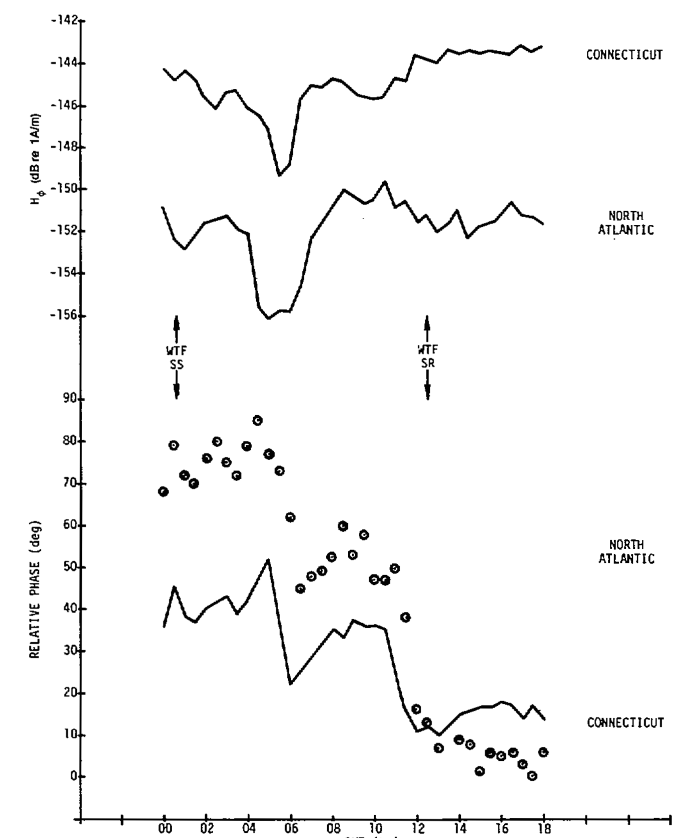

Fig. 5. Comparisons of Connecticut and North Atlantic area field strengths October 9, 1977.

phase decreased $\sim 25^\circ$ in Connecticut and $\sim 40^\circ$ in the North Atlantic. From 07 00 to 10 00 GMT, the relative phase increased $\sim 18^\circ$ in Connecticut and $\sim 25^\circ$ in the North Atlantic, while the 08 00 to 10 00 GMT amplitude decreased $\sim$1 dB. The Connecticut relative phase then decreased to its normal daytime value around WTF sunrise. However, the North Atlantic area relative phase did not start decreasing until WTF sunrise and did not reach its normal daytime value until 2 h later.

A comparison of the October 9, 1977, Connecticut and North Atlantic area field strengths is presented in Fig. 5. From $\sim$03 00 to 05 30 GMT, the field strength at both locations rapidly decreased 4–5 dB, while the relative phase peaked a half hour before the minimum nighttime amplitude time. The $\sim$05 00 to 06 30 GMT relative phase then decreased $\sim 30^\circ$ in Connecticut and $\sim 40^\circ$ in North Atlantic before increasing $\sim 15^\circ$ by 09 00. Meanwhile, the 06 00 to 09 00 GMT field strength rapidly increased 4–5 dB at both locations.

During this same time period, ELF field strength measurements were also taken aboard a submarine located in the Western Pacific at a range of approximately 11.5 mm from WTF. Presented in Fig. 6 are comparisons of the Connecticut, North Atlantic, and Western Pacific 02 00 to 10 00 GMT field strengths for October 8 and 9, 1977. The transmitter, as well as the Connecticut site, was in total darkness from 02 00 to 10 00 GMT, as was the North Atlantic area site until 08 00. On the other hand, the Western Pacific area site was not in total darkness until 08 30 GMT.

The ʘ at each location is the 02 00–10 00 GMT average monthly field-strength value at that location. Note that the 04 00 to 10 00 GMT field-strength plots are similar at all three locations. The time of minimum field-strength amplitude is 05 30 GMT on October 8 and 05 00 to 05 30 GMT on October 9. The difference between the minimum amplitude field strength and the 02 00–10 00 average monthly field strength was 3–4 dB at the Connecticut and North Atlantic area sites and 1.8–2.0 dB at the Western Pacific site. The facts that 1) the field strength was at a minimum at approximately the same time at all three locations and 2) the null was deeper at the total-darkness sites indicate that the propagation anomaly occurred very near the WTF and caused the nighttime excitation factor to decrease.

It has been postulated [36], [37], [44]-[46] that levels of the D-region controlling ELF propagation in the earth-ionosphere waveguide are strongly influenced by energetic electron precipitation. Recently reported measurements [47], [48] are consistent with the theoretical results of Spjeldvik and Thorne [45], [46] regarding ionization caused by precipitation of energetic electrons during the recovery phase of magnetic storms. Because energy particle precipitation into the D-region tends to increase ionization, making the ionosphere more "daylike" by lowering the effective reflecting height and improving excitation, the observed nighttime field strength decreases are in the opposite sense to that which would have been expected.

Larsen *et al.* [39] and Imhof *et al.* [49], from coordinated satellite and ELF field strength measurements, have frounđ that direct particle precipitation into the atmosphere can cause ELF transmission anomalies. In these anomalies the signal strengths may be either attenuated or enhanced depending on the spatial extend and location of the ionization. The effect appears to be due primarily to changes in the excitation factor. Other factors, such as standing wave effects, may also be of importance [37].

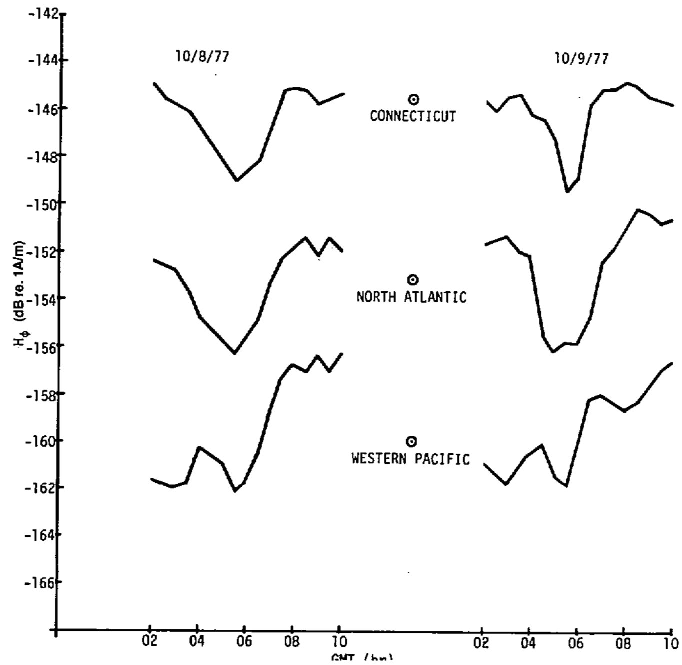

Fig. 6. Comparison of Connecticut, North Atlantic area, and Western Pacific area field strengths (02 00–10 00 GMT), October 8 and 9, 1977.

Barr [10] and Pappert and Moler [11] have also made calculations regarding the influence of a sporadic E-layer that encompasses the nighttime propagation path. They showed that the presence of nocturnal sporadic E produced marked maxima and minima in the propagation characteristics of ELF radio waves. One physical explanation for the enhanced absorption could be in terms of an attenuation resonance between waves reflected from normal E-region heights and from the sporadic E-region. The results of typical theoretical calculations [11] depicting the changes in attenuation rate and phase velocity due to a nocturnal sporadic E-layer are presented in Figs. 7 and 8.

Pappert [13] and Pappert and Shockey [12] have investigated the effects of a more realistically sized path of sporadic E on nighttime propagation in the lower ELF band. Their results indicate that a sporadic E patch 1 by 1 Mm, that causes phase shifts and attenuation rate enhancements consistent with full-wave evaluations, can account for the 6–8-dB fades observed in the Connecticut and Maryland measurements. Patches 1 by 0.5 Mm can account for more commonly observed fades in the 3–4 dB range. Of the cases examined, deepest fades occur when the disturbance falls over the receiver and the depth of the fades in those instances changes very little with the location of the disturbance along the great-circle path connecting transmitter and receiver. In other words, a receiver moving beneath a traveling but otherwise invariant ionospheric disturbance would experience a very nearly constant fade [13].

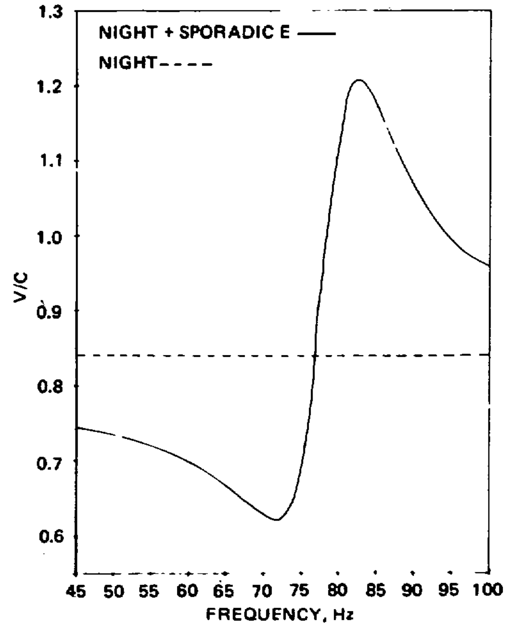

Fig. 7. Comparison of ambient and ambient plus sporadic E attenuation rate versus frequency.

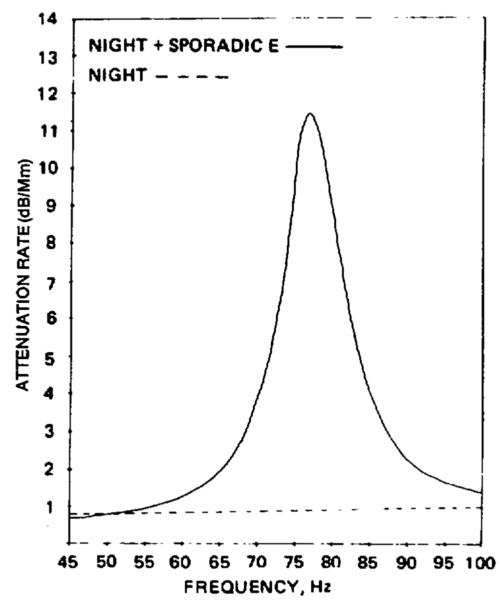

Fig. 8. Comparison of ambient and ambient plus sporadic E-phase velocity versus frequency.

It should be noted that actual measurements of sporadic E conditions have not been made at the receiving sites when WTF was transmitting. Attempts to explain the observed ELF signal fades in terms of absorption due to sporadic E conditions can, therefore, not be conclusive, but the theoretical efforts in this area point out the potential influences of sporadic E on ELF propagation.

Field and Joiner [50] employed in integral equation approach for analyzing propagation in the earth–ionosphere waveguide where conditions change over distances comparable with a Fresnel zone. They derived an expression for the relative errors introduced by neglecting transverse ionospheric gradients over the path and found that full-wave methods must be applied when the effective width of a localized disturbance is less than two-thirds of the width of the first Fresnel zone. They also concluded that the WKB approximation significantly overestimates the propagation anomaly when the disturbance is centered near the propagation path and underestimates the anomaly when the disturbance is centered far off path.

Subsequently, Field and Joiner [51] extended their analysis by analyzing ELF propagation for both widespread and bounded inhomogeneities. Their solutions showed that such a disturbance behaves like a cylindrical lens filling a narrow aperture. Lateral diffraction, focusing, and reflection can cause the transverse electromagnetic (TEM) mode to exhibit a transverse pattern of maxima and minima beyond the disturbance and a standing-wave pattern in front of it. The focusing and diffraction diminish when the transverse dimension of the disturbance approaches the width of the first Fresnel zone, typically, several megameters. Their analysis shows that reflection from widespread inhomogeneities can be important in two situations: first, for great-circle propagation paths that are nearly tangential to the boundary of the disturbed polar cap; and second, when the TEM mode is obliquely incident on the day/night terminator, in which case a phenomenon analogous to internal reflection can occur.

Many types of ionospheric disturbances can cause ELF propagation anomalies. X-rays from solar flares ionize the D- and E-layers of the ionosphere over the sunlit hemisphere. Energetic electrons and protons from solar particle events (SPE's) ionize the polar cap at altitudes well below those from which ELF waves are usually reflected. High-altitude nuclear bursts produce various prompt and delayed ionizing radiations, including γ-rays, β-particles, and neutrons. The γ-rays penetrate to even lower altitudes than energetic protons from a strong SPE, and thus can cause much more severe distortions of the earth–ionosphere waveguide [52].

Extensive calculations for numerous specific disturbances have been made throughout the ELF/VLF research community. Some interesting calculations of the changes in the ELF attenuation rate as well as the Joule heating losses suffered in the ionosphere have been performed by Field [52], [53].

Fig. 9 [52] shows height profiles of electron and positive ion density calculated from models of nominal nuclear environments consisting of widespread high-altitude fission debris. The profiles shown are convenient for calculating the dependence of the waveguide propagation parameters on the intensity of a disturbance. They span a wide range of intensities, but, because propagation depends on ionization height gradient as well as intensity, they do not cover all possible cases. Specific events must therefore be analyzed individually. The "moderate" and "intense" profiles represent levels of ionization typical of strong SPE's as well as spread-debris environments. We can therefore use them to infer effects of both natural and man-made disturbances. Fig. 9 also shows that ions greatly outnumber electrons at the lower altitudes, where they dominate propagation despite their larger mass [52].

Presented in Fig. 10 is a comparison of the 45- and 75-Hz attenuation rate α in disturbed environments [52]. Fig. 10

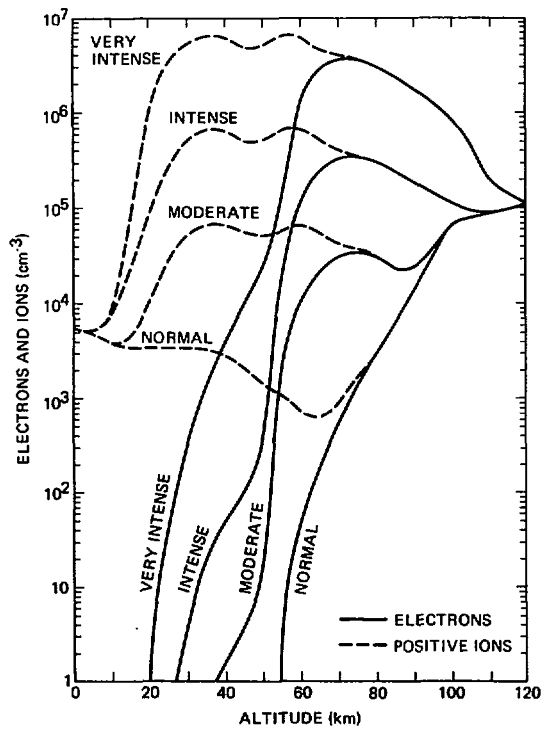

Fig. 9. Electron and ion density profiles for nominal daytime normal and disturbed environments.

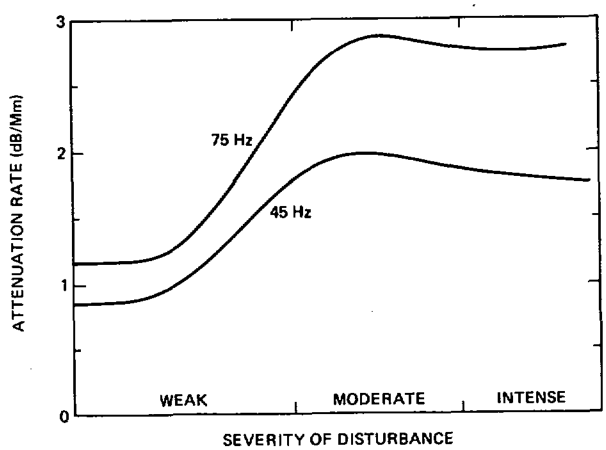

Fig. 10. Attenuation rate in disturbed environments. The intensity of the disturbance varies continuously from normal daytime conditions (extreme left) to very intense (extreme right).

shows that the assumed distributions can cause the attenuation rate to increase by 1 or 2 dB/Mm relative to normal daytime conditions, depending on the frequency. Although the curves span a wide range of intensities, they do not cover all cases because the waveguide characteristics depend on the spectrum of ionizing radiation as well as the intensity. In fact, some calculations show that certain moderate to severe SPE's can cause the attenuation rate to approach 4 dB/Mm at 75 Hz [52].

V. CONCLUSIONS

In this paper, we have presented a tutorial overview on ELF propagation. Much of the material was excerpted from the excellent book *ELF Communications Antennas* by M. L. Burrows [1]. It is recommended reading for anyone seriously interested in ELF communications.

We have also successfully compared simple form approximate expressions (which relate ELF propagation constraints to realistic ionospheric conductivity profiles) with experimentally derived results for both daytime and nighttime propagation conditions.

Additional examples of ELF nighttime propagation anomalies have also been presented. One probable cause of these localized nighttime field-strength reductions (which are certainly not restricted to measurement locations in the northeastern United States) are changes in reflection height along the propagation path (which can lead to standing-wave effects) because of particle bombardment.

Another possible explanation for these anomalous nighttime results is that the receivers are on great-circle paths that are nearly tangential to the disturbed polar cap, in which shadow zones and interference patterns could occur. Another cause for some of these anomalies may be a moving nocturnal sporadic E-layer, but there is as yet no direct evidence supporting this hypothesis.

It now appears that theory has advanced to the point where substantial benefit would result from a concurrent measurement program simultaneously involving nocturnal ELF propagation and sporadic E soundings over and about the propagation path. ELF measurements provide the only means yet of remotely monitoring ionization phenomena in an altitude range not accessible to other techniques and may be extremely useful in untangling the mysteries of this region.

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Peter R. Bannister (M'69), for a photograph and biography please see p. 163 of this issue.