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A SIMPLIFIED THEORY OF ELF PROPAGATION IN ITS EARTH-IONOSPHERE --ETC(U)
1980 H G BOOKER N00014-78-C-0682

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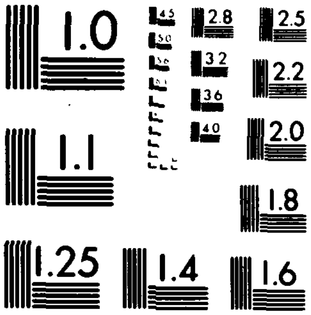

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A simplified theory of ELF propagation in its Earth-ionosphere transmission line and its worldwide application. Supplement,

Since the termination of Contract N00014-78-C-0682 discussions have continued with the Naval Ocean Systems Center for the purpose of comparing the results obtained in Report N00014-78-C-0682-0001 with those obtained using the NOSC computer program.

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It has transpired that the NOSC calculations presented in Table 5 were made for a magnetic dip of 75° rather than for a magnetic latitude of 75°, and that the profiles of electron density used was not completely identical with those given in Tables 1 and 2. The corrected version of Table 5 is presented below.

(10) Henry G./Booker

The NOSC computer program has confirmed that non-reciprocity in the ELF band is not introduced in the refracting stratum near the bottom of the ionosphere. It is introduced higher up where the direction of phase propagation is almost vertical.

It has been determined that the effect of a slightly off-vertical angle for the direction of phase propagation in the ionosphere in the ELF band does in fact cause the non-reciprocity obtained by Pappert and Moler (1974). The electromagnetic reason for this has been identified and is described below.

The fact that off-vertical angles of less than a degree for the direction of phase propagation have noticeable effects raises the question of how precisely the stratification of the ionosphere may be assumed to be horizontal. This question is discussed below.

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In the version of Chapter 4 of Report N00014-78-C-0682-0001 that is being submitted for publication in a journal, the wording of Sections 9 et seq, beginning on page 52, has been modified as shown below. In what follows, paper I refers to Chapter 3 of Report N00014-78-C-0682-0001.

9. Comparison with the NOSC computer program -- high latitudes

The method of calculation described in I and applied in this paper was designed primarily to reveal the physics of ELF propagation. As a method for

Table 4

Effect on c/v and α (db Mm^{-1}) of various degrees of enhanced ionization below the E region in the polar cap

(Magnetic latitude = 75°)

Frequency (hertz)	Day profiles (Figs. 2, 4 and 6)				Night profiles (Figs. 3, 5 and 7)			
	0	1	2	3	0	1	2	3
7.5	1.34 0.14	1.39 0.17	1.36 0.24	1.34 0.20	F region is involved		1.34 0.18	1.41 0.16
45	1.26 0.48	1.31 0.68	1.23 0.84	1.22 0.73	1.11 0.39	1.14 0.65	1.18 0.86	1.28 0.78
75	1.25 0.73	1.29 1.24	1.20 1.24	1.20 1.08	1.12 0.45	1.14 0.94	1.18 1.26	1.25 1.22

Table 5

Calculations using the NOSC computer program for comparison with Table 4

Frequency (hertz)	Day profiles (Figs. 2, 4 and 6)				Night profiles (Figs. 3, 5 and 7)			
	0	1	2	3	0	1	2	3
7.5	1.34 0.13	1.38 0.18	1.31 0.23	1.32 0.18	F region is involved		1.35 0.17	1.43 0.17
45	1.26 0.49	1.27 0.81	1.20 0.71	1.21 0.67	1.13 0.31	1.15 0.66	1.21 0.80	1.31 0.88
75	1.25 0.77	1.24 1.43	1.18 1.05	1.19 1.01	1.14 0.38	1.16 1.35	1.19 1.66	1.27 1.53

calculating the numerical values of c/v and α it is only approximate. Let us compare these values with those obtained using the computer program of the Naval Ocean Systems Center (Pappert and Moler 1974, 1978). In this method the only errors are those arising from digitization of the profiles. The computer was provided with the analytic profiles in Figures 2 and 3 described by Tables 1 and 2, and with the other analytic profiles in Figures 4-7 described by corresponding Tables. The computer digitizes these profiles at variable intervals of height determined by the NOSC program. However, one can specify the maximum permissible digitization interval.

Calculations were performed using maximum permissible digitization intervals of 1 km and 4 km. It was found that results are identical to better than 1%, and often to better than 0.1%. This demonstrates that the NOSC computer program does an excellent job of selecting small digitization intervals where they are needed.

Using the analytical profiles of Figures 2-7 in the NOSC computer program, calculations were performed for a magnetic latitude of 75° corresponding to those presented in Table 4 for the approximate theory described in I. Results are given in Table 5 (Ferguson, private communication). The values in Table 5 are averages of those for west-east and east-west transmission but, at a latitude of 75°, the two sets of values differ by less than 1%. Comparison of Tables 4 and 5 shows that, while the numbers are not identical, trends are the same. The comments about the effect of disturbance on the polar ionosphere made in the previous section on the basis of Table 4 are unchanged if use is made of Table 5 instead.

In judging the importance of the differences between corresponding entries in Tables 4 and 5, it is desirable to have a feeling for how much results are changed if minor modifications are made in the ionospheric profiles. Instead of using the analytic profiles in Figures 2-7, values were read visually from the graphs (Pappert and Moler, private communication). Readings were made at multiples of 5 km in height but, in order to improve the representation of the sharp gradient on the under side of the E region, an additional reading was made at 82 km (day) and 91 km (night). Linear interpolation in the logarithm of the particle density was used between the visually read values. Keeping all other parameters the same, the NOSC computer program was used to make calculations both for the analytic profiles (Ferguson, private communication) and for the visual approximations to these profiles (Pappert and Moler, private communication). The percentage changes in $(c/v)-1$ and α caused by use of visual approximation to the analytical profiles are shown in Table 6.

The changes in $(c/v)-1$ and α appearing in Table 6 are quite noticeable. Yet, from the standpoint of ionospheric physics, the difference between the two sets of profiles compared in Table 6 is trivial. Larger differences are likely to arise from the natural fluctuations in ionospheric profiles associated with the existence of acoustic gravity waves in the atmosphere. Furthermore, the modification of profiles explored in Table 6 is almost certainly small compared with the errors of profile involved in any worldwide model of the ionosphere currently available. One is forced to conclude that all calculations of $(c/v)-1$ and α, however carefully performed, are in reality rough estimates. Only the trends are reasonably reliable.

Against this background, let us examine more closely the errors caused by using the approximate theory described in I in place of the more accurate theory used in the NOSC computer program. Let us calculate the percentage errors in $(c/v)-1$ and α caused by using Table 4 in place of Table 5. The results are shown in Table 7. In calculating the percentage errors, use was made of versions of Tables 4 and 5 carrying an additional significant figure. In calculating the mean and rms values at the bottom of Table 7 use was made of entries in the Table having one additional significant figure. The same is true for Table 6.

Comparison of Table 7 with Table 6 shows that the mean error in $(c/v)-1$ and α caused by using the approximate theory described in I is less than the mean

Table 6

Percentage changes in (c/v)-1 and α

caused by visual approximation to the analytic profiles

Frequency	Day profiles (Figs. 2, 4 and 6)				Night profiles (Figs. 3, 5 and 7)			
(hertz)	0	1	2	3	0	1	2	3
7.5	-1	-2	+2	+1	F region		+7	0
	-5	-4	0	-3	is involved		+5	-3
45	+2	0	+1	+2	+9	+9	+7	+5
	-3	+5	+3	0	+7	+9	+11	-10
75	+2	-4	0	+2	+6	+22	+7	+7
	+3	+8	+2	0	+4	+5	+15	-6

Mean value = 2.9%. RMS value = 6.4%.

Table 7

Percentage errors in (c/v)-1 and α

caused by use of the approximate theory

Frequency	Day profiles (Figs. 2, 4 and 6)				Night profiles (Figs. 3, 5 and 7)			
(hertz)	0	1	2	3	0	1	2	3
7.5	-1	+4	+16	+7	F region		-2	-3
	+7	-2	+8	+12	is involved		+4	-4
45	+1	+13	+12	+7	-14	-7	-12	-8
	-3	-16	+19	+8	+25	-1	+8	-12
75	+2	+20	+12	+8	-10	-12	-4	-6
	-6	-14	+18	+8	+17	-30	-24	-20

Mean value = 0.4%. RMS value = 11.6%.

error caused by using visual approximation to the analytic profiles. Even the rms error is only twice as big. Remembering how small the modification of profile is that is explored in Table 6 using the NOSC computer program, it follows that the error caused by using the approximate theory described in I is almost certainly less than the error caused by the uncertainty in ionospheric profiles.

10. Comparison with the NOSC computer program -- low latitudes

Let us now examine transmission along the magnetic equator. In these circumstances the NOSC computer program gives different values for west-east transmission and for east-west transmission (Pappert and Moler, 1974). In this paper we obtain no difference between west-east and east-west transmission because of the assumption in I that phase is propagated vertically in the ionosphere in the ELF band. A numerical comparison is presented in Table 8 between calculations made with the NOSC computer program (Ferguson, private communication) and the calculations presented in this paper on the basis of the theory described in I.

We see that differences occur between NOSC (W-E), NOSC (E-W) and this paper. Calculations of joule heating as a function of height (cf Pappert and Moler 1978) show that, in all three cases, there is a maximum of absorption in a refracting stratum near the bottom of the ionosphere and a second maximum in a reflecting stratum at a higher level. Moreover, the heights at which both of these maxima occur are closely the same in all three cases. The differences in the rates of attenuation in the Earth-ionosphere transmission line do not arise in the refracting stratum at the bottom of the ionosphere. They arise instead from slight differences in the directions of phase propagation above the refracting stratum. For NOSC (W-E) the direction of phase propagation in the transmitted wave is slightly off-vertical in the easterly direction, for NOSC (E-W) it is slightly off-vertical in the westerly direction, and in this paper it is not off-vertical at all.

Table 8

Values of c/v and α (db Mm^{-1}) for transmission along the magnetic equator

Frequency (hertz)	Noon, equinox (Fig. 2)			Night (Fig. 4)		
	NOSC W-E	NOSC E-W	This paper	NOSC W-E	NOSC E-W	This paper
7.5	1.30	1.30	1.30	1.16	1.15	1.18
	0.071	0.075	0.074	0.14	0.14	0.16
45	1.25	1.24	1.25	1.11	1.09	1.11
	0.40	0.47	0.33	0.32	0.43	0.37
75	1.24	1.23	1.24	1.10	1.07	1.10
	0.72	0.88	0.53	0.42	0.65	0.48

In the VLF band, off-vertical angles for the direction of phase propagation in the ionosphere amount to many degrees, but at the low-frequency end of the ELF band they are less than a degree. It is remarkable that such small changes in the direction of phase propagation in the ionosphere can have an influence as large as that shown in Table 8. This arises as follows.

For propagation along the magnetic equator, the difference between west-east and east-west transmission has nothing to do with interference between the O and X waves, because only the X wave is involved. There is not even any coupling between the O and X waves. The non-reciprocity occurs because the electric vector for the X wave is elliptically polarized in the vertical plane of transmission (Barber and Crombie 1959). In switching from west-east transmission to east-west transmission, all features are reflected in the magnetic meridian except the direction of rotation in the polarization ellipse; this is controlled by the direction of the Earth's magnetic field. Moreover, the ellipse for the transmitted wave is very elongated in the direction of phase propagation. Consequently a small off-vertical angle causes the large electric vibration in the direction of phase propagation to have a horizontal component comparable with that arising from the small electric vibration transverse to the direction of phase propagation, thereby affecting the impedance looking perpendicular to the stratification.

It has to be remembered that ELF propagation at a particular latitude Λ does not depend solely on the calculation at Λ but on an average over a range of latitudes in the neighborhood of Λ. This is because of the large free-space wavelength λ_0. For transmission along the equator at 75 Hz, for example, a strip $\lambda_0/(2\pi)$ in width extends from latitude 3°N to latitude 3°S. But at 75 Hz vertical propagation of phase in the reflecting stratum on the under side of the E region changes from quasi-transverse to quasi-longitudinal for a departure from the magnetic equator substantially less than 3° of latitude. Even if the ionization density is horizontally stratified in the neighborhood of the magnetic equator, the same is not true for the refractive index. Indeed, at the low-frequency end of the ELF band, the quasi-transverse portion of the D and E regions behaves as much like a diffracting wedge as it does like a horizontally stratified medium.

It should not be assumed that, when vertical propagation becomes quasi-longitudinal, the difference between west-east and east-west transmission disappears. In the ELF band the hydromagnetic approximation to the magneto-ionic theory is applicable in the ionosphere. The high conductivity along the Earth's magnetic field prevents the development of any important electric field except perpendicular to the imposed magnetic field. Consequently the electric ellipses for the O and X waves have planes approximately perpendicular to the Earth's magnetic field (Booker and Dyce 1965, Booker 1975). For vertical propagation of phase in mid-latitudes, the horizontal projection of an electric ellipse is closely circular but, in the reflecting stratum, the ellipse itself is closely perpendicular to the Earth's magnetic field. Consequently it has a projection onto a vertical east-west plane, and this leads to some non-reciprocity. As one moves to lower latitudes, the horizontal projection remains almost circular but the plane of the ellipse turns with the Earth's magnetic field. In consequence the ellipse becomes very elongated in the direction of phase propagation even though propagation is still quasi-longitudinal. Very close to the magnetic equator, vertical propagation of phase finally changes to quasi-transverse, but the electronic collisional frequency ν_e then plays a major role because, even in the reflecting stratum on the under side of the E region, ν_e is not small compared with the angular wave-frequency. The upshot is that non-reciprocity maximizes at a low but non-zero magnetic latitude. This is the explanation of the results obtained by Pappert and Moler (1974).

In spite of calculations showing a difference between west-east and east-west transmission at low latitudes, it is nevertheless doubtful whether non-reciprocity materializes in practice at the low-frequency end of the ELF band. The phenomenon is caused by off-vertical angles of less than a degree for the direction of phase propagation. Noticeable effects associated with such small off-vertical angles constitute a challenge to the assumption of strict horizontal stratification in the ionosphere. Fluctuations in the stratification occur in both time and space, and they cause the direction of phase propagation in the transmitted wave to be slightly spread. The effect is likely to be important because the wavelengths of radio waves in the reflecting stratum at ELF are comparable with wavelengths involved in acoustic gravity waves in the atmosphere. What is needed is, not the behavior of the transmitted wave in the unique direction calculated on the basis of strict horizontal stratification, but an average behavior for directions within a cone whose angle is controlled by the fluctuation in the angle of tilt of the stratification. Consequently the difference between west-east and east-west transmission is likely to be smeared out at the low-frequency end of the ELF band, but not in the VLF band where off-vertical angles are larger.

In the ELF band it would be feasible to assume appropriate statistics for fluctuation in the tilt of the stratification, to deduce an average impedance looking vertically upwards, and to use the height-variation of the average impedance as a basis for calculation. However, even the non-fluctuating part of the ionospheric profile is only known well enough to permit a rough estimate of the rate of attenuation in the Earth-ionosphere transmission line. It may be doubted whether it is worthwhile to attempt greater propagational accuracy at the low-frequency end of the ELF band than that obtained in this paper using the method described in I. Useful improvement in accuracy depends less on employing precision in the propagational calculation than on improving the worldwide model used for the ionosphere.

11. Conclusion

It is concluded that the method of investigating ELF propagation in the Earth-ionosphere transmission line described in I and applied in this paper (i) gives more physical insight than any other method currently available, (ii) requires less effort than any other profile-based method currently available, and (iii) provides all the accuracy that can usefully be employed at the low-frequency end of the ELF band in the D and E regions pending major improvement in our knowledge of the worldwide behavior of the ionosphere.

However, to handle reflection from the F region at the low-frequency end of the ELF band at night, further development of the method is needed. Between the E and F regions some coupling can take place between the O and X waves at frequencies less than the ionic gyro-frequency. The extent and consequences of this coupling need to be investigated.

12. Acknowledgments

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