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A Review of Some Features of Radiowave Absorption

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Abstract

Salient features of radiowave absorption theory have been reviewed in this paper. The analysis deals with absorption of radiowaves through the ionosphere using the absorption method – A3 (CW Field Strength) adopting data from the Swiss PTT MNIFTZ 4.1 computer predictions for shortwave transmission. The study gives outstanding formulations, and results, revealing new dimensions to the absorption phenomenon for HF signal predictions in the equatorial ionospheric zone.

1. Introduction

When radiowaves are propagated through the ionosphere, they are absorbed because the free electrons make collisions and lose the ordered vibration energy given them by the waves.

Current researches in radiowave absorption in the neighbourhood of the magnetic equator have been very sparse. Some recent studies on the absorption phenomenon have dealt exclusively on confined environments of rectangular tunnels mainly describing mean path losses against frequency (e.g. Boutin et al, 2008 [1]) while others (e.g. Kveder et al 2002 [2]) investigated problems associated with radiowave absorption and scattering by electrons/ions moving around particles.

Whitehead [3] showed from the noon values of absorption measured at Slough, for the ordinary ray of frequencies 2, 2.4, 4 and 4.8 MHz that, it is possible to separate the contributions to the composite absorption in the ionosphere into the D-, E- and F- region absorptions.

For radiowaves reflected from the E-region, appreciable absorption, according to the author, may take place in three regions:

(a) Near the level of reflection; where a major part of the absorption occurs within a few hundred metres of the level of reflection.
(b) In the D-region; where the refractive index is nearly unity.
(c) In the region about the level where the electronic collision frequency equals the angular frequency of the radiowaves.

In each of the absorbing regions, the actual absorption is a function of the frequency of the incident radiowave.

The basic theory associated with radiowave absorption in the ionosphere is outlined as follows:

We define magneto-ionic medium as a plasma that has an imposed magnetic field, and the theory of interest in the well – known equation describing the propagation of radiowaves in the medium.

A simple form of the theory in which collisions between electrons and other particles (ions and neutrals) are neglected may be considered insignificant in the presence of magnetic field.

The refractive index, n, of the medium is given by the standard equation:

$$n^2 = \mu k - j \left(\frac{\sigma \mu}{\omega k_0} \right) \tag{1}$$

where μ is the relative permeability, k is relative permittivity, σ is conductivity, $\acute{\omega}$ is the angular frequency of the wave, k_0 is the permittivity of free space and

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$$j = \sqrt{-1}$$

The motion of an electron of mass, m, under the action of an electric field, E, is governed by the law of the form:

$$m\ddot{x} = eE \qquad (2)$$

where e is the electron charge and $\ddot{x}$ is the acceleration.

Using the j-operator method to solve equation (2), we have

$$m\ddot{x} = \frac{eE}{j\varpi} \qquad (3)$$

The current density

$$i = Ne\ddot{x} = Ne.\frac{eE}{mj\varpi} \qquad (4)$$

where N is the electron density

From equation (4) above,

$$i = \sigma E$$

where

$$\sigma = \frac{Ne^2}{mj\varpi} = -j\,\frac{Ne^2}{m\varpi} \qquad (5)$$

Substituting for σ in equation (1) gives

$$n^2 = \mu k - j\left(-j\,\frac{Ne^2}{m\varpi}.\frac{\mu}{\varpi k_0}\right)$$

$$n^2 = \mu k - \frac{Ne^2\mu}{mk_0\varpi^2} \qquad (6)$$

In the absence of electrons, the medium behaves like free space. Hence,

$$\mu = 1 = k$$

Equation (6) can now be rewritten as

$$n^2 = 1 - \frac{Ne^2}{mk_0\varpi^2} = 1 - \frac{\varpi^2 n}{\varpi^2} \qquad (7)$$

where $\acute{\omega}^2N = \frac{Ne^2}{mk_0}$ is the angular plasma frequency.

taking account of electron collisions in (2), the equation of motion becomes

$$m\ddot{x} + m\dot{x}v = eE \qquad (8)$$

By the j –operator method, equation (8) now takes the form:

$$-m\varpi^2 x + mvj\varpi x = eE$$

so that

$$x\left(-m\varpi^2 + mvj\varpi\right) = eE \qquad (9)$$

$$\text{The current density}, i = Ne\dot{x} = j\omega Nex$$

$$= j\varpi \, Ne.\frac{eE}{-m\varpi^2 + mj\varpi v}$$

$$= \frac{j\varpi Ne^2}{-m\varpi^2 + mj\varpi v}.E \qquad (10)$$

Substituting for σ in (1), the refractive index changes to:

$$n^2 = 1 + \frac{Ne^2}{\left(m\varpi^2 + j\varpi mv\right)k_0} \qquad (11)$$

The refractive index is no longer purely real, but complex.
Rationalizing the denominator in (11) gives

$$n^2 = 1 + \frac{\left(Ne^2 / k_0\right)\left(-m\varpi^2 - j\varpi mv\right)k_0}{\left(\left(-m\varpi^2\right)^2 + \varpi^2 m^2 v^2\right)k_0}$$

which yields

$$n^2 = 1 - \frac{N_e{}^2}{mk_0}.\frac{1}{\left(\varpi^2 + v^2\right)} - j\frac{Ne^2}{mk_0}.\frac{v}{\left(\varpi^3 + \varpi v^2\right)} \qquad (12)$$

Assuming

$$n = n_0 - jx \qquad (12a)$$

$$n^2 = n_0^2 - x^2 - 2n_0\, jx \qquad (13)$$

Comparing (12) and (13) shows that

$$n_0^2 - X^2 = 1 - \frac{\varpi^2 Nv}{\left(\varpi^2 + v^2\right)} \qquad (14a)$$

and

$$2n_{0X} = -\frac{\varpi^2 NV}{\varpi\left(\varpi^2 + v^2\right)} \qquad (14b)$$

$$\textit{If } n_0^2 >> X^2 \textit{ in}(14a), \textit{ then}$$

$$n_0^2 = 1 - \frac{\varpi^2 N}{\varpi^2 + v^2} \qquad (14c)$$

which implies that

$$\frac{\varpi^2 N}{\varpi^2 + v^2} = 1 - n_0^2 \qquad (14)$$

Again $\quad 2n_0 X.\frac{\varpi}{v} = \frac{\varpi^2 N}{\varpi^2 + v^2}$

Hence,

$$2n_0 X.\frac{\varpi}{V} = 1 - n_0^2$$

$$X = \frac{v}{\varpi} 1 - n_0^2 \frac{1}{2n_0}$$

or

$$X = \frac{v}{2n_0\varpi}\left(1 - n_0^2\right) \qquad (15)$$

Define the absorption coefficient as k,

$$where \qquad K = \frac{\varpi X}{c} = \frac{v}{2n_0 C}\left(1 - n_0^2\right)$$

$$= \frac{v}{2c}\left(\frac{1}{n_0} - n_0\right) \qquad (16)$$

Also, from (14*b*)

$$X = \frac{1}{2n_0} \cdot \frac{\varpi^2 N}{\varpi^2} \cdot \frac{\varpi v}{\varpi^2 + v^2} \qquad (17)$$

Hence, the absorption coefficient, k, is

$$K = \frac{\varpi X}{c} = \frac{\varpi}{c} \cdot \frac{1}{2n_0} \cdot \frac{\varpi v}{\varpi^2 + v^2} \qquad (18)$$

$$= \frac{1}{2n_0^c}\varpi^2 N \frac{v}{\varpi^2 + v^2} \qquad (18a)$$

We note that equation (16) holds only if $n^2_0 >> \chi^2$, that is, absorption is small or non-deviate. It is however shown in equation (18) that χ depends on frequency.

For the D-layer near about 80km, above the earth's surface, $v >> \varpi$, $k = \frac{1}{v}$

For the F-layer above about 180km, $\omega >> v$, hence,

$$K \alpha \frac{v}{\omega^2} \alpha \frac{1}{f^2} \qquad (19)$$

Absorption diminishes with frequency in the non-deviates region. There is also a lot of attenuation when the plasma frequency tends to the critical frequency; that is, $f_N \rightarrow f_\alpha$ This occurs in the deviate region, where in effect, absorption increases with the wave frequency.

The situation is completely different if the medium is ionized. The presence of geomagnetic field makes the medium magneto-active. Electromagnetic waves split into ordinary and extraordinary waves with different refractive indices and absorption coefficients.

According to De et al [4] the problems of propagation through the ionized medium is unsuitable. Therefore, quasi-longitudinal (QL) and quasi-transverse (QT) approximations must be made appropriately.

Some of the major characteristics of absorption have been deduced by comparing results based on experiments or model calculations with other appropriate expressions.

In our approach to the absorption theory, in the QT propagation of radiowaves through the ionosphere, we examine the absorption method – A3 using data from the Swiss PTT **MNIFTZ 4.1** computer predictions of continuous wave field strength measurements for shortwave transmission in the equatorial zone of the ionosphere.

Field strength data of the computer predicting system are said to be conservative (Ugwu, [5], implying that the field strength results obtainable in practice, are expected to be better than the computer prediction. The results are thereafter compared with earlier studies from series of A3 absorption (oblique incidence) measurements on a multi -frequency basis obtained also at a location in the neighbourhood of the magnetic equator, including results from other experiments.

2.0 Basic Formualtions

The Appleton-Hartree magneto-ionic theory (Budden, [6] has long been established as the basis for explaining the various ionospheric phenomena.

The D-region of the ionosphere is probably the principal absorber of radio-waves. Studies have shown that the D-region contributes about 80 – 90 % of the absorption in the ionosphere [Skinner and Wright, [7]; Oyinloye, [8].

The processes and derivations leading to an equation for determining the coefficient of absorption are presented in an earlier work [see Oyekola et al [9]

The final expression for χ in the above study gave

$$X^2 = \left(\frac{1}{2}\right)\left\{\left(\frac{\omega^2 p}{\omega^2+v^2} - 1\right) + \left(\left(1 - \frac{\omega^2 p}{\omega + v^2}\right)^2 + \left(\frac{\omega^2 p}{\omega(\omega^2+v^2)}\right)^2\right\}^{1/2}\right\}^{1/2} \qquad (20)$$

from which the corrected version of the coefficient of absorption was given as:

$$K* = \frac{e^2}{2m\Sigma 0 c}\cdot\frac{1}{X}\cdot\frac{Nv}{\omega^2+v^2} \qquad (21)$$

Detailed results of the above formula can be found in the cited literature [7]

4.0 Absorption Technique A3 Models

Following the work of Appleton [10], the total absorption suffered by HF radiowaves which transverse the Chapman layer and have been reflected without deviative loss from higher layer is given as

$$L = 4.13\left(\frac{4\pi e^2}{mc}\right)(\cos\varphi)^{3/2}\ \frac{N_0 V_0 H}{\omega^2} \qquad (22)$$

where Ψ is the sun's zenith angle, N_0 the maximum electron density at noon; V_0 the electron collisional frequency at the height of maximum ionization at noon for $\Psi = 0$, and H the scale height.

Appleton and Piggott [11] reaffirmed that the variation of ionospheric absorption with frequency is adequately explained by the magneto-ionic theory, where the frequency index, n, equal 2, for non-deviative absorption.

In the equatorial region, however, Skinner and Wright [7], Skinner [12] and Gnanalingam [13] have shown that n is nearly unity (n = 1), whereas using observed data, Oyinloye [8] observed that n has a value of 2.24.

The discrepancies in equatorial radiowave absorption between experimental results and theory prompted Chukwuma [14] to investigate further the level of discrepancy and possibly proffer adequate reasons for these observations. Chukwuma assumed that the absorption of the radio waves in their passage through the ionosphere depends on frequency as

$$L = B + Af^2 \qquad (23)$$

where A and B are constants.

Using regression analysis on absorption data, the author indicated that the high monthly values of the correlated coefficients for equation (23) during the period April – December 1992 could probably be used to verify the claim that absorption may consist of a component which is independent of radiowave frequency. In other words, the discrepancies between experimental results and theory could be due to the fact that in the

mechanism of ionosphere absorption the contributions due to A and B in equation (23) are, in the opinion of Whitehead [3], of the same order and hence for most frequencies seasons and regions, the relationship given by equation (22) cannot be valid.

In an effort to test the validity or otherwise of the absorption law proposed by the two workers (i.e. Whitehead [3] and Chukuwuma, [14], data obtained from the Swiss PTT computer program MNIFTZ 4.1 used in predicting the working parameters (e.g. field strength) of an external broadcasting outfit in Nigeria, were adapted for this study.(see Ugwu, [5])

The field strength measurements for the study were obtained using the A3 circuit. Lagos (6.4^0N, 3.5^0E) – New York (40.8^0N, 74.0^0E) for daytime (0600 – 1800) and night-time (1900 – 0500 LT). The transmitting station on the circuit has consistent transmission schedule and thus satisfies the A3 technique conditionality (Chukwuma [14] and Schwentek [15])

In order to maintain uniformity and consistency, absorption was determined on the multi-frequencies 4.0, 6.0, 8.0, 10.0, 12.0, 15.0 and 12.0, 15.0 and 18.0 MHz from the field strength measurements adopting the expression Schwentek [15].

$$L = 20\log\frac{E(n)}{E(t)} \qquad (24)$$

where E(n) is the night-time field strength and E(t) is the daytime field strength.

To verify the assumption above, we adopt the relationship data calculated from field strength measurements for transmission power 125 kW at the frequency 6.0 MHz, the graph of log L against log *f* was obtained. It is estimated from the line of best fit (Fig. 1), that n = 1.13. Substituting appropriate values in equation (25), the value of A was found to be approximately 118.

Similarly, from the plot of log L against log *f*, using absorption data calculated from field strength values for the transmitter power, 250 k W (Fig. 2), it is observed from the line of best fit that n = 1.16. Again, substituting appropriate values in equation (25) it is easily

$$LogL = \log A - n\log f \qquad (25)$$

seen shown that A is approximately equal to 180.

The above results for the frequency index, n, are also observed to be in good agreement with the findings of Skinner and Wright [7] and Skinner [12] but contrary to the well-known magneto-ionic theory which suggests that n should have a value of 2.

In order to attempt further investigations of the postulations in earlier work (e.g. Whitehead [3], Chukwuma [14], that the variations of absorption of radiowaves are best explained by equation (23), we employ data for n, log A and log *f* for the transmitter powers 125k W and 250 kW at the wave frequency 6.0 MHz. It is observed that the constant B tends towards unity in both cases for the different transmitter powers. In other words, log B = 0 is contrary to the suggestion by Chukwuma [14] that the constants A and B are of the same order of magnitude. The results give credence to the fact that frequency dependence of absorption is appropriately represented by equation (23) as posited by Skinner and Wright and Appleton and Piggott.

Physically, transmitter gain is usually set at 21.5 dB, a figure achievable by curtain array antennas. A signal field strength of 3 mV/m is also required for good reception; this corresponds to 35 dBu (5). (see Ugwu [5]).

Transmitter power exceeding 250 kW is, generally unnecessary as that will not in any way enhance our knowledge of the absorption phenomenon in practice. Furthermore, the upper limits for transmitter power may not exceed 500 k W, because at 100% amplitude modulation, the overall output power will be about 750 kW. The useful power for shortwave transmission is the sideband power, which, for 500 k W transmitter power, is roughly 250 k W at 100% modulation.

For super-power transmitters, maintenance and operational costs will really tug at the limits of Engineering Physics. In addition the huge challenge to engineering practice in the sub-saharah Africa where such limitations are often taken for granted, must come into play, in policy formulations, for shortwave broadcasting. Details will be given in a subsequent contribution.

Conclusion

The absorption phenomenon has been comprehensively analyzed from fundamental principles, culminating in advanced concepts leading to the formulation of an incredible model of the magneto-ionic theory for absorption.

In the study, data from a computer prediction programmer, Swiss **PTT MNIFTZ 4.1,** for field strengths, have been used to study the absorption model – A3, reaffirm in the validity of equatorial radiowave absorption obeying the frequency law of the form originally postulated by Appleton and Piggott in the magneto-ionic theory. The frequency index is found to be approximately equal to unity. This finding is also in good agreement with the results of Skinner and Wright [7] and Skinner [12] but sharply contradicts the observations of Whitehead [3] and Chukwuma [14] that the absorption suffered by radiowaves in their passage through the ionosphere depends on frequency law of the form $L = B + A f^{-2}$, consisting of a component independent of radiowave frequency. It also been established that the dependence of absorption on HF transmitter beyond certain power levels, say 500 k W with the view to overcoming absorption in the equatorial zone of the ionosphere at any frequency is unnecessary as this may tug at the limits of Engineering Physics.

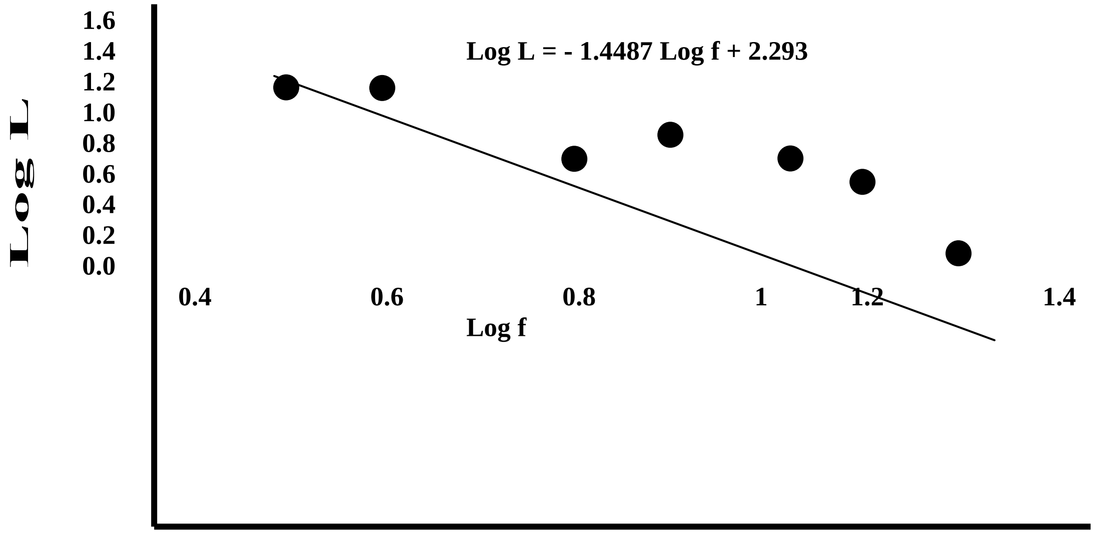

Fig. 1: Log L versus Log f, with transmitter power (= 125 k W)

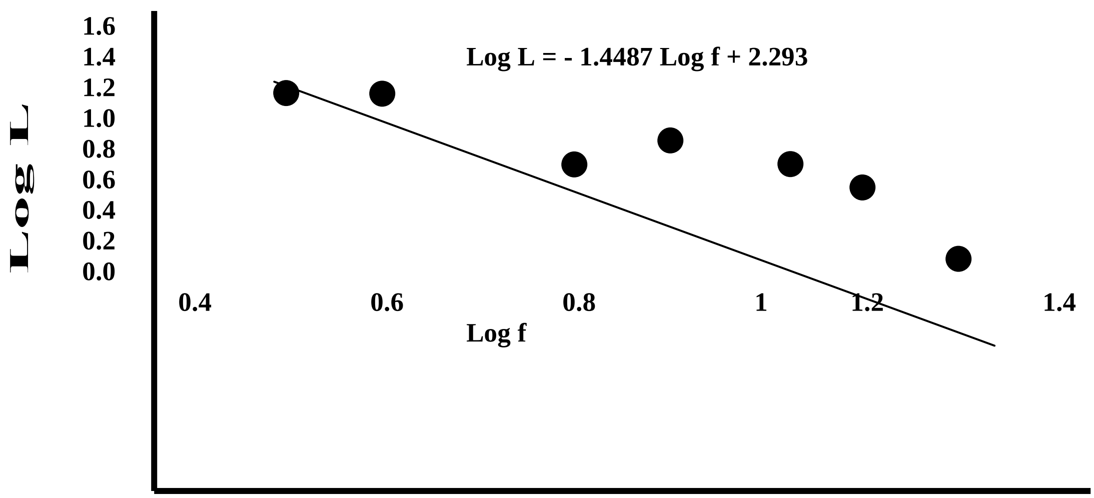

Fig 2: Log L versus Lo g, with transmitter power (= 250 k W)

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