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The calculation of ionospheric absorption with modern computers

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Abstract

New outcomes are proposed for ionospheric absorption starting from the Appleton–Hartree formula, in its complete form. The range of applicability is discussed for the approximate formulae, which are usually employed in the calculation of non-deviative absorption coefficient. These results were achieved by performing a more refined approximation that is valid under quasi-longitudinal (QL) propagation conditions. The more refined QL approximation and the usually employed non-deviative absorption are compared with that derived from a complete formulation. Their expressions, nothing complicated, can usefully be implemented in a software program running on modern computers. Moreover, the importance of considering Booker's rule is highlighted. A radio link of ground range $D = 1000$ km was also simulated using ray tracing for a sample daytime ionosphere. Finally, some estimations of the integrated absorption for the radio link considered are provided for different frequencies.

Keywords: Appleton–Hartree formula; More refined quasi-longitudinal approximation; Usually employed non-deviative absorption; Booker's rule

1. Introduction

When the ionospheric radio sounding technique was developed, the first recorded ionograms showed variations in amplitude of the received signal. It was immediately evident that ionospheric absorption occurred at lower altitudes, below those at which the electron density was sufficient to give rise to reflection (Pillet, 1960). Initially it was assumed that this absorption took place in the E region, and several studies were carried out, recording the amplitude of waves reflected from the F region, for both vertical and oblique incidence (Booker, 1935; White and Brown, 1936).

However, already in 1930, Appleton and Ratcliffe measured echo intensity after reflection from the E region, and concluded that the absorption occurs far below the level of reflection. In this way they discovered the existence of a distinct region, which they named the D region.

There was also significant progress in theoretical studies, including the contribution of Booker (1935). He demonstrated that a radio wave can be absorbed even at a level where the refractive index is slightly different from the unit. In practice, this region corresponded to the D region previously proposed by Appleton and Ratcliffe. Other experimental results confirmed the hypothesis of the existence of the D region, with the absorption properties mentioned above. For example, Farmer and Ratcliffe (1935) found a sharp increase in the reflection coefficient during the evening hours, which was attributed to the decreasing absorption coefficient in the D region at dusk.

Ever since the first formulation of the magneto-ionic theory, which is controversially attributed to Appleton and Ratcliffe (1930) or Lassen (1926), it was clear that collisions between electrons and neutral molecules influenced the local absorption coefficient of radio waves.

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The magneto-ionic theory, in principle, allowed direct derivation of the local absorption coefficients for both the ordinary and the extraordinary, while also taking into account the presence of the magnetic field and collisions. These details can be studied by referring to the well known early publications of Ratcliffe (1959) and Budden (1961).

However, the formulae that can be derived are complicated and difficult to interpret. The focus of interest was therefore an approximate formula, which will be discussed in the following sections. This takes into account that, in most cases propagation takes place in QL approximation, and for non-deviative absorption $\mu \approx 1$ can be assumed, μ being the real part of the refractive index n. It was thus not considered necessary to substantially revise the theory of non-deviative absorption.

In high frequency (HF) radio propagation, the application of the approximate formula has also been proposed in recent studies, to assess for example the state of the D and E regions by establishing the local absorption coefficients of the ordinary and extraordinary components of radio waves, and making use of space-based facilities (Zuev and Nagorskiy, 2012). The effects of HF absorption in the ionosphere of Mars were also numerically simulated using the same approximate formula (Withers, 2011; Varun et al., 2012).

In the present paper, it is proposed that this mode of operation is no longer justified in all the applications, like for example riometry. A typical frequency used with this technique is 30 MHz, with which absorption changes of about 0.1 dB can be measured. Instead, it is preferable to use the exact formulation or even a more refined QL approximation for all the applications designed in the HF band, such that $\omega \gg \omega_p$, ω being the angular frequency of the radio wave considered and ω_p the plasma frequency.

Moreover, in this paper, an eikonal based ray tracing procedure was used to evaluate the ray path linking two sites 1000 km apart. Some limitations were imposed for simplifying the ray tracing computation. Azzarone et al. (2012) and Settimi et al. (2013, 2014) have already overcome these limitations, applying the more elaborate Haselgrove's (1955) ray theory and the Jones and Stephenson's (1975) method for ray tracing, which takes into account even the curvature of Earth's surface, and that the ionospheric medium can be characterized by large horizontal gradients.

Finally, in the paper, it is proved our ultimate purpose of underlining that, at any rate in some practical applications, the more refined QL approximation can be used, while the usually employed non-deviative absorption can lead to significant errors in the estimation of absorption. The expression of such QL approximation, nothing complicated, can usefully be implemented in a software program running on modern computers.

2. The classical and generalized magneto-ionic theories

In the initial formulation of magneto-ionic theory, a frictional term is utilized that does not depend on the root-mean-square electron velocity and the electron velocity distribution. It represents a first approximation of the effective collision frequency due to the collisions between electrons and neutrals. Later, several studies were published that strived to improve this aspect of the theory.

Originally, Phelps and Pack (1959) measured the collision cross-section σ for electrons in the nitrogen N_2 — the most abundant atmospheric constituent up to 100 km — establishing that it is proportional to the root-mean-square electron velocity v_{rms}. Consequently, Sen and Wyller (1960) generalized the Appleton–Hartree magneto-ionic theory including a Maxwellian velocity distribution of the electrons (a), and extending the findings of Phelps and Pack (1959) to all constituents of air (b). However, Sen and Wyller (1960) made several key mistakes, later remedied by Manchester (1965). A valuable approximation of the generalized magneto-ionic theory exists in Flood (1980).

The momentum collision frequency ν of electrons with neutrals can be simply expressed by the product of pressure p times a constant α. Based on both laboratory and ionospheric data α can be estimated as $\alpha = 6.41 \times 10^5\ \mathrm{m^2\ s^{-1}\ N^{-1}}$ (Thrane and Piggott, 1966; Friedrich and Torkar, 1983; Singer et al., 2011).

Detailed information about data of the pressure can be obtained using the global climatology of atmospheric parameters from the Committee on Space Research (COSPAR) International Reference Atmosphere (CIRA-86) project. As recommended by the COSPAR, the CIRA-86 provides empirical models of atmospheric temperatures and densities. A global climatology of atmospheric temperature, zonal velocity and geo-potential height was derived from a combination of satellite, radiosonde and ground-based measurements (Rees, 1988; Rees et al., 1990; Keating, 1996). The reference atmosphere extends from pole to pole and 0–120 km. CIRA-86 consists of tables of the monthly mean values of temperature and zonal wind with almost global coverage (80°N–80°S). Two files were compiled by Fleming et al. (1988), one in pressure coordinates including also the geo-potential heights, and one in height coordinates including also the pressure values.

The atmosphere in the E and D layers consists mainly of nitrogen N_2 (about 78%), with atomic and molecular oxygen O_2 as the next most important constituents. The relatively large cross section for N_2 makes it likely, as a first-order approximation, that the height variation of collision frequency ν is proportional to the partial pressure of the N_2. Experiments show that the cross section for O_2 also varies by the square root of T so that the two contributions can be combined (Davies, 1990).

When there is complete mixing of the atmospheric gases the following relationship holds:

$$\frac{dp}{p} = \frac{d\rho_N}{\rho_N} + \frac{dT}{T} = -\frac{dH}{H}, \tag{1}$$

where p is the total pressure, ρ_N the number density, T the absolute temperature of molecules, and $H = k_B T/mg$ the