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Earth's magnetic field effect on MUF calculation and consequences for hmF2 trend estimates

Ana G. Elias[a,b,*], Bruno S. Zossi[a,b], Erdal Yiğit[c], Zenon Saavedra[b,d], Blas F. de Haro Barbas[a]

[a] *Laboratorio de Fisica de la Atmosfera, Departamento de Fisica, Facultad de Ciencias Exactas y Tecnología, Universidad Nacional de Tucuman, Av. Independencia 1800, 4000 Tucuman, Argentina*
[b] *Consejo Nacional de Investigaciones Cientificas y Tecnicas, CONICET, Argentina*
[c] *Department of Physics and Astronomy, George Mason University, 4400 University Drive, Fairfax, VA 22030, USA*
[d] *Laboratorio de Telecomunicaciones, Departamento de Electricidad, Electronica y Computacion, Facultad de Ciencias Exactas y Tecnologia, Universidad Nacional de Tucuman, Av. Independencia 1800, 4000 Tucuman, Argentina*

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ABSTRACT

Knowledge of the state of the upper atmosphere, and in particular of the ionosphere, is essential in several applications such as systems used in radio frequency communications, satellite positioning and navigation. In general, these systems depend on the state and evolution of the ionosphere. In all applications involving the ionosphere an essential task is to determine the path and modifications of ray propagation through the ionospheric plasma. The ionospheric refractive index and the maximum usable frequency (MUF) that can be received over a given distance are some key parameters that are crucial for such technological applications. However, currently the representation of these parameters are in general simplified, neglecting the effects of Earth's magnetic field. The value of M(3000)F2, related to the MUF that can be received over 3000 km is routinely scaled from ionograms using a technique which also neglects the geomagnetic field effects assuming a standard simplified propagation model. M(3000)F2 is expected to be affected by a systematic trend linked to the secular variations of Earth's magnetic field. On the other hand, among the upper atmospheric effects expected from increasing greenhouse gases concentration is the lowering of the F2-layer peak density height, hmF2. This ionospheric parameter is usually estimated using the M(3000)F2 factor, so it would also carry this “systematic trend”. In this study, the geomagnetic field effect on MUF estimations is analyzed as well as its impact on hmF2 long-term trend estimations. We find that M(3000)F2 increases when the geomagnetic field is included in its calculation, and hence hmF2, estimated using existing methods involving no magnetic field for M(3000)F2 scaling, would present a weak but steady trend linked to these variations which would increase or compensate the few kilometers decrease (~2 km per decade) expected from greenhouse gases effect.

1. Introduction

The ionosphere is the plasma region of the upper atmosphere that is coupled to meteorological processes from below (Yiğit and Medvedev, 2015) and to space weather effects from above (Yiğit et al., 2016). Ionospheric measurements began in the early 1900s with a high-frequency radar known as ionosonde, which sends vertically short pulses of high-frequency electromagnetic waves. At a certain height these waves are reflected back toward the ground and the ionosonde records the time delay, T, between the transmitted and the received signal (Reinisch et al., 1998). Assuming the signal propagation is at the speed of light in vacuum, c, for the whole path, a virtual height, h′, also called equivalent (or apparent) height, can be estimated from

$$h' = \frac{c}{2}T. \tag{1}$$

The virtual height at a given frequency is then the distance that the electromagnetic wave would have traveled in half the elapsed time T at the speed of light. Since electromagnetic waves within the ionosphere travel more slowly than c, i.e., with group velocity $v_g < c$, the actual height of a reflecting reference layer is smaller than the deduced h′.

Ionograms are produced by varying the wave frequency and then plotting h′ in terms of frequency.

Obtaining the true height electron density profile from ionogram

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[*] Corresponding author at: Laboratorio de Fisica de la Atmosfera, Departamento de Fisica, Facultad de Ciencias Exactas y Tecnología, Universidad Nacional de Tucuman, Av. Independencia 1800, 4000 Tucuman, Argentina.

E-mail addresses: aelias@herrera.unt.edu.ar (A.G. Elias), brunozossi@hotmail.com (B.S. Zossi), eyigit@gmu.edu (E. Yiğit), zsaavedra@herrera.unt.edu.ar (Z. Saavedra), blasdeharo2000@yahoo.com.ar (B.F. de Haro Barbas).

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data is a complex procedure for which several methods have been developed (Scotto et al., 2012). In particular, the peak height of the profile at which the maximum electron density occurs, hmF2, can be estimated in a simple way using its inverse relation to M(3000)F2 factor (Shimazaki, 1955; Bilitza et al., 1979; Dudeney, 1983), which corresponds to the maximum usable frequency (MUF) at which a radio wave can propagate from a given point over a distance of 3000 km divided by foF2.

The most widely used formula is given by Shimazaki (1955) assuming an F2 layer with no underlying ionization, and neglecting the geomagnetic field, that is

$$hmF2 = \frac{1490}{M\,(3000)F2} - 176 \tag{2}$$

A correction ΔM was introduced later to consider a more realistic ionosphere so that Eq. (2) becomes

$$hmF2 = \frac{1490}{M\,(3000)F2 + \Delta M} - 176 \tag{3}$$

Bradley and Dudeney (1973) took into account the underlying ionization and obtained for ΔM the following expression

$$\Delta M = \frac{0.18}{\frac{foF2}{foE} - 1.4} \tag{4}$$

Bilitza et al. (1979) considered in addition the solar activity level through the 12-month running mean sunspot number, R_{12}, and Earth's magnetic field including in the formula the dip latitude, ϕ. ΔM then yields

$$\Delta M = \frac{f_1 \times f_2}{\frac{foF2}{foE} - f_3} + f_4 \tag{5}$$

where

$$f_1 = 0.00232 \quad R_{12} + 0.222 \tag{6}$$

$$f_2 = 1 - \frac{R_{12}}{150} e^{-\emptyset^2/1600} \tag{7}$$

$$f_3 = 1.2 - 0.0116 \quad e^{R_{12}/4.84} \tag{8}$$

$$f_4 = 0.096 \frac{R_{12} - 25}{150} \tag{9}$$

The increasing interest in long-term trends in the upper atmosphere in the context of climate change, mainly attributed to the increasing greenhouse gases concentration, brought the search of long ionospheric data series (encompassing several decades), specially of hmF2. In fact, according to earlier theoretical models (Roble and Dickinson 1989; Rishbeth 1990) the increased concentration of greenhouse gases would induce a cooling in the thermosphere, together with a decrease in air density and a contraction of the upper atmosphere, with a consequent decrease of ionospheric layers. For a hypothetical scenario of doubling of CO_2 a cooling of 30–40 K in the thermosphere was modeled and an hmF2 decrease of 15–20 km. Observations have supported this hypothesis for the actual changes in CO_2 (Qian et al., 2011; Zhang et al., 2011; Lastovicka et al., 2014) but have also suggested that an increase in CO_2 does not completely account for the observed thermospheric temperature trend (Zhang et al., 2016).

In order to assess long-term trends in hmF2, or in any other ionospheric parameter, the solar activity effect must be excluded first since solar variations have a significant impact at F2 region altitudes especially via the associated variability in the direct solar insolation and high-latitude energy and momentum inputs. As the solar activity has a prominent ~11 year periodicity, and considering that trends are more reliable for longer data intervals (Mielich and Bremer, 2013), at least 2 to 3 decades of data are needed in order to obtain statistically significant results. In fact, most of the publications on hmF2 trend analysis use the longer data series available in order to obtain reliable results, with most of the records dating back to the International Geophysical Year 1957, and some with the earliest records since the 1940s (Ulich and Turunen, 1997; Upadhyay and Mahajan, 1998; Mikhailov and Marin, 2001). This requirement on data series length led researchers to use ionospheric characteristics scaled manually from film or paper ionograms made by the ionosondes that preceded the modern digital ionosondes (McNamara, 2008), with the only options for hmF2 estimation through M(3000)F2 or hpF2 that is the virtual height at a frequency equal to 0.834 foF2, which can be used as a substitute for hmF2 (Zolessi and Cander, 2014).

The hmF2 data series that have been analyzed in most of the publications until now, are obtained through the Shimazaki (1955) (Eq. (2)) or Bradeley and Dudeney (1973) formula (Eq. (4)) which uses M(3000)F2 without any consideration of Earth's magnetic field and its variations. Being aware of this limitation, apart from the necessity of a special quality control of the data when dealing with historical data sets stressed by many authors and especially in the work by McNamara (2008), we want here to emphasize the importance of considering the effect of geomagnetic field secular variations on an ionospheric characteristic such as M(3000)F2 which is widely used to detect ionospheric trends.

This factor is obtained manually using a transmission-curve based on the propagation of radio signals in the ionosphere neglecting Earth's magnetic field. Current studies assume that the error associated with this approximation is insignificant compared to other error sources such as the assumption of geographic uniformity of the ionosphere over the transmission path. Assuming a constant geomagnetic field this assumption would not lead to an error in hmF2 trend estimation. It consists at most in a constant systematic error for not taking into account a factor in M(3000)F2 estimation that affects absolute values but do not affect slope assessments in linear trend analysis. However, the terrestrial magnetic field varies, with the most drastic change being a polarity reversal that takes place on average every ~200 000 years (Glassmeier et al., 2009). This means that the error introduced in hmF2 estimation using M(3000)F2, varies accordingly. Since the expected hmF2 trends as a consequence of greenhouse effect are less than 1%/year, the “trending” error associated with ignoring the magnetic field effects could completely screen it.

There is in addition the error associated with the hmF2 calculation. A thorough and deep analysis of the accuracy of hmF2 formulas using M(3000)F2 has been performed in the work by McNamara (2008). Considering that the uncertainty in scaled values of M(3000)F2 is ± 0.05 MHz plus a random component raising it to 0.1, a ~15 km error in hmF2 results using the Shimazaki formula, for example. As stated in the work by McNamara (2008), if errors are random, they should be overcome using hmF2 monthly medians derived using the corresponding formula.

In the present work the terrestrial magnetic field effects on M(3000)F2 and the error introduced in hmF2 obtained through formulas in terms of M(3000)F2 are analyzed. Possible hmF2 trends induced by geomagnetic field secular variations on M(3000)F2 are compared to trend values expected from the long-term thermosphere cooling linked presumably to increasing greenhouse gases concentration.

Section 2 describes how M(3000)F2 is obtained through ionograms manual scaling. In Section 3 the effect of considering Earth's magnetic field is analyzed together with the consequences of secular variations, followed by Section 4 where Bilitza's formula is analyzed for a varying magnetic field. Finally, discussion and conclusions are presented in Section 5.

2. M(3000)F2 estimated from ionograms

The propagation factor M(3000)F2 is routinely scaled from ionograms by a standard graphical method (Piggott and Rawer, 1978). This method employs what is called a transmission curve (Smith, 1939),