Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 55 (2015) 2058–2069

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Ionospheric specification with analytical profilers: Evidences of non-Chapman electron density distribution in the upper ionosphere

T. Verhulst *, S.M. Stankov

Royal Meteorological Institute (RMI), Ringlaan 3, B-1180 Brussels, Belgium

Received 24 March 2014; received in revised form 8 October 2014; accepted 16 October 2014
Available online 23 October 2014

Abstract

In relation to the development of an operational ionospheric monitoring and imaging system, the most frequently used analytical ionospheric profilers (Chapman, Epstein, Exponential) were investigated in terms of suitability for topside ionosphere modelling. For the purpose, topside sounder measurements onboard Alouette and ISIS satellites have been analysed. We have come to the conclusion that the use of the Chapman profiler should be exercised with precaution as there are evidences that there are conditions when other profilers are better fit for modelling purposes. This is highlighted during ionospheric disturbances (e.g. during geomagnetic storms), when the shape of the topside electron density distribution might be better described by an Epstein profiler rather than a Chapman profiler.

Keywords: Ionospheric profiler; Total electron content; Slab thickness; Geomagnetic storm

1. Introduction

Ionospheric modelling is essential in the overall space weather monitoring and mitigation of the related influences. Modelling the topside ionosphere, the region above the height (h_mF_2) of the peak of ionosphere density (N_mF_2), poses particular difficulties. While the bottomside ionosphere is easily accessible for ground-based observation, e.g. by the traditionally-used vertical incidence sounder (ionosonde), such ionosonde measurements alone are not able to deliver information about the topside ionosphere and thus to provide data for empirical modelling. There are other means (rather expensive) to collect such information, mostly via rocket and satellite in-situ measurements, coherent and incoherent scatter radar probing, topside sounding using ionosondes onboard satellites, and more recently, the ionospheric radio occultations.

Over the years, theoretical modelling efforts led to the development of various ionospheric models, from relatively simple ones to complex, global multi-dimensional models. Some of the most frequently used simple models of the vertical electron density distribution are the Exponential, Chapman and Epstein profile models, also called profilers (Appendix A). Of them, the Chapman profiler is particularly popular (e.g. Reinisch and Huang, 2001; Bilitza, 2004; Feltens, 2007; Tulasi Ram et al., 2009). A nice feature of the Chapman profiler is that it needs only the ionospheric peak density (N_mF_2), peak height (h_mF_2), and an estimate of the scale height to calculate the distribution (profile) of electron density in the topside ionosphere. However, since the constructed profile is not tied to any additional measurements, its (indiscriminate) use is vulnerable to over-simplification of the plasma distribution, especially in a region known for its dynamic nature. One proposed improvement is to use a combination of multiple profiles, with different scale heights (Fonda et al., 2005; Kutiev et al., 2006a), or with scale heights varying with height (Reinisch et al., 2007; Nsumei et al., 2012).

* Corresponding author. Tel.: +32 (0)60/395472; fax: +32 (0)60/395423.
E-mail addresses: tobias.verhulst@meteo.be (T. Verhulst), s.stankov@meteo.be (S.M. Stankov).

http://dx.doi.org/10.1016/j.asr.2014.10.017
0273-1177/

However, these more sophisticated models still rely on the assumption that the shape of the topside profile is essentially a Chapman curve.

An operational local ionosphere monitoring system, based on ionosonde and GNSS measurements for deducing and imaging the vertical distribution of electron density, has been developed and installed at the RMI Geophysical Centre in Dourbes (50.1N, 4.6E) (Stankov et al., 2011, more details in Appendix B). As part of the evaluation process and further improving the system, we used topside sounder measurements (onboard Alouette and ISIS satellites) to find out which of the abovementioned profilers yield better results and under what circumstances (Verhulst and Stankov, 2013; 2014). The electron density profiles measured by the topside sounders have been fitted with each of the theoretical ionospheric profilers and the corresponding approximation errors were calculated. The approximation results were analysed with respect to "external" factors (local time, geomagnetic latitude, season, and solar activity), as well as to the key characteristics of the topside ionosphere (N_mF_2, h_mF_2, and the upper transition level, *UTL*). One important finding is that, although there is an influence of these external factors on the shape of the density profile, the indices representing these factors (such as K_p or *Dst*) are unsuitable for selecting the "best" profile. Better selection criteria are offered by the key ionospheric characteristics, a possible explanation being that these characteristics react to the external factors thus intrinsically contain the necessary information for the selection process.

The aim of the here-presented study is to provide evidences of the diversity of plasma distribution (non-Chapman in particular) in the upper ionosphere and to analyse the conditions leading to this variety. In doing so, additional key ionospheric characteristics, such as the total electron content (TEC) and ionospheric slab thickness, are utilised.

The paper outline is as follows. First, the measurements used for this work are presented. The next section provides some evidences of profiles best fitted by non-Chapman profilers. This is followed by analysis of the TEC and slab thickness relations to the shape of the topside electron density profile (EDP). After that, we focus on the ionospheric storm-time behaviour of the TEC and slab thickness. The paper concludes with a discussion of the results in view of the possibilities they offer for improving the profiler selection for the LIEDR (Local Ionospheric Electron Density profile Reconstruction) procedure.

2. Data

2.1. Space-based measurements (topside sounders)

For this work, we use the data from the topside ionosondes that flew on the Alouette-1 and -2 and ISIS-1 and -2 satellites (Jackson, 1969; Jackson and Warren, 1969; Jackson et al., 1980; Jackson, 1988). These data are available from NASA/GSFC's Space Physics Data Facility (SPDF) and include electron density profiles that had been obtained from manually scaled ionograms in the 1970s (Bilitza et al., 2003) and more recently with the Topside Ionogram Scaler With True Height Algorithm (TOPIST) software (Bilitza et al., 2004; Benson, 2010). This collection contains more than 170,000 electron density profiles. The first of the four satellites, Alouette 1, started its soundings in 1962, while the final measurements in this dataset (ISIS-1) date back to 1981. Data is therefore available covering more than one complete solar cycle. Unfortunately, the data distribution, both temporal and spatial, is very irregular which gives rise to systematic biases and data selection problems that have to be corrected for (Verhulst and Stankov, 2013; 2014). Also, not all available profiles are useful for our study, because we can only use those that cover the entire region between the F_2 peak and the upper transition height (Verhulst and Stankov, 2013).

For the purpose of this study, it is important that the data also cover all magnetic conditions. From Table 1 it can be seen that 7.88% of the profiles were measured when *Dst* was below -50, an indication of a geomagnetic storm; or 6.15% when $K_p \geqslant 5$, if the *K* index is used to indicate storm conditions. Additionally, 25.28% of the measurements were taken when the *K* index was 3 or 4, signifying minor geomagnetic disturbances. This gives an opportunity to study the influences on the topside shape during disturbances of different severity (Warren, 1969).

2.2. Ground-based measurements (ionosonde and GNSS)

For many years, the Dourbes ionosonde (URSI code: DB049) has been carrying out regular vertical ionospheric soundings with Lowell digital ionospheric sounders, previously DGS-128, DGS-256, and since April 2011, Digisonde-4D® (Reinisch et al., 2009). All ionograms are automatically scaled and the values of f_oF_2, f_oE, $M_{3000}F_2$, and h_mF_2 are deduced with only a short delay. Some of the current ionosonde settings are: frequency range 1.0–16.0 MHz (daytime) and 0.5–12.0 MHz (nighttime), frequency scale – linear, coarse frequency step – 25 kHz, fine frequency step – 5 kHz, range 80–1500 km, range resolution – 2.5 km, integrated repeats – 4, ionogram duration – 150 s. Currently, the sounding rate (cadence) is set to one every 5 min, but it can be further increased if necessary. The automatic scaling of ionograms has been evaluated (Stankov et al., 2012) and error bounds have been

Table 1
Availability of topside sounder measurements under different geomagnetic activity conditions as represented by the K_p (left) and Dst (right) indices.

K_p index		*Dst* index	
0–2	68.57%	$\geqslant 0$	29.93%
3	16.28%	−50 to 0	62.19%
4	9.00%	−100 to −50	6.34%
$\geqslant 5$	6.15%	<−100	1.54%