Characteristics of large scale travelling ionospheric disturbances exploiting ground-based ionograms, GPS-TEC and 3D electron density distribution maps

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ABSTRACT

The ionosphere is a region in the near-Earth space where a number of operations take place. These operations are important for the daily life and the safety of the citizens: telecommunication systems, navigation and surveillance systems, aircraft safety systems, all rely on signals propagating in the ionosphere and through the ionosphere. Therefore it is important to continuously monitor the state of the ionosphere and be able to predict irregularities and disturbances, that may affect the operation of these critical systems. Large scale travelling ionospheric disturbances (LSTIDs) are associated with auroral and geomagnetic activity and propagate with wavelengths of 1000 - 3000 km, velocity of 300 – 1000 m/s and amplitude greater than 5-10 TECU. Current identification techniques of LSTIDs rely on the analysis of slant estimates of the Total Electron Content (sTEC) from the ground-based GNSS receiver network. In this contribution we explore additional techniques for the identification and tracking of LSTIDs over Europe benefiting from the dense network of DPS4D ionosondes and of IGS receivers. This is a combined analysis based (a) on ionogram traces and their corresponding scaling parameters (foF2, hmF2, FF, HmF2), (b) on sTEC residuals calculated from the signals transmitted from GNSS satellites seen by receivers co-located with the ionosondes and (c) on the reconstructed Electron Density Distribution using the Topside Sounders Model Profiler (TaD) over the specific DPS4D ionosondes. The results indicate that LSTID and their propagation over Europe can be captured by the ionograms and their corresponding scaled parameters, however a cadence of 5 min would improve the capacity of the TID identification system. Another very important result is that the TaD model is sensitive in LSTID propagation over a specific station and relevant electron density disturbances can be reproduced by the model predictions at heights between 200 and 400 km. Finally the analysis of 2 sec resolution sTEC residuals provide an additional indication of LSTID propagation over the area, although at the moment this can be only explored for post-processing purposes.

1. INTRODUCTION

It is generally accepted that large-scale traveling ionospheric disturbances (LSTID) represent the manifestation of atmospheric-gravity waves whose generating regions lie in the auroral zones of the northern or southern hemisphere. LSTIDs have typical periods of 30 min to 3 hours and 1000–2000 km wavelengths causing TEC fluctuations with maximum amplitude 3TECU, and therefore producing disturbances on systems relying on HF and transionospheric propagation. However, the basic properties and parameters of LSTIDs are as yet imperfectly understood:

- What is the physical mechanism that triggers the generation of these waves? Is their source in the thermosphere, the mesosphere or the troposphere (Afraimovich et al., 2001; Vadas and Crowley, 2010; Komjathy et al., 2012; Galvan et al., 2012)?

- Are they a periodic process or a solitary wave propagating to large distances from the source of generation? Some recent studies (Bowman and Mortimer, 2010; 2011) report on a significant number of large-scale travelling ionospheric disturbances which originate at conjugate locations in auroral zones, cross the equator and sometimes encircle the earth within 30 hours.

- How significant is the vertical redistribution of the plasma. The wave(s) of thermospheric air and ionospheric plasma originated from the auroral zone redistribute the plasma in plasmasphere and ionosphere at midlatitudes, due to the effect of ion drag by the winds and corresponding fast diffusion flow along magnetic field lines. The changes in the vertical plasma structure cannot be detected neither by ground based ionosondes nor by GNSS-TEC. Our understanding on the plasma redistribution can be advanced analyzing the distribution of the electron density in the ionosphere-plasmasphere system that only a topside profiler model can provide.

Detailed investigation of characteristics of LSTIDs during various geophysical conditions may provide some answers to the above questions and may also lead to the specification of the requirements for setting up a system to identify and track these irregularities in the whole volume of ionosphere and plasmasphere.

LSTID monitoring is based recently on ground-based GPS networks and on the analysis of the resulted two dimensional maps of the total electron content (TEC). Given that LSTIDs cause a major disturbance at the bottomside part of the ionosphere with a redistribution of the ionization at the higher layers, knowledge of the whole electron density distribution (EDD) with the appropriate spatial-temporal resolution, from the E region up to the plasmasphere, and not just of its height integral (i.e. TEC), is required to reach some advances on this topic.

The purpose of this contribution is to demonstrate the potential of the Topside Sounders Model Profiler – assisted by Digisonde (TaD) which is an advanced electron density reconstruction technique (Kutiev et al., 2012; Belehaki et al., 2012), to identify Travelling Ionospheric Disturbances and to examine ways to exploit this result in order to set a tracking system for LSTIDs over a region such as Europe.

2. METHODOLOGY

The analysis applied here is based on the following methodology:

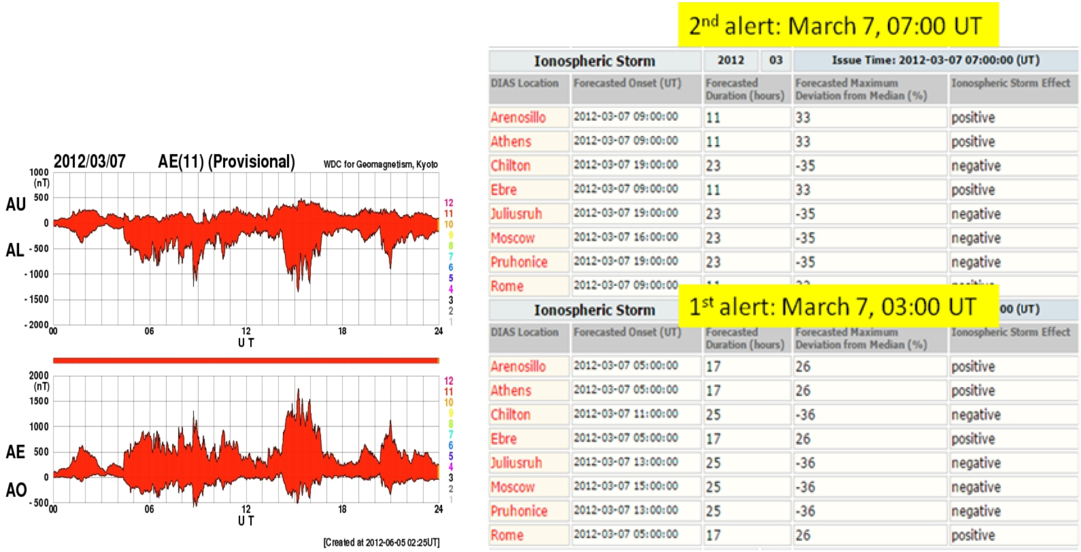
- Identification of the onset time: Early studies by Bowman (1978) demonstrated that large scale travelling ionospheric disturbances originate in auroral-zone regions at the times of onset of polar magnetic substorms. Therefore it is important to identify the local time of the first expansion of the westward electroject, in order to focus on the specific meridian chain for the identification of LSTIDs. For the purpose of this study we analyze ground-based magnetograms from the Canadian and Scandinavian chains.
- Consideration of predictions from the Proelss phenomenological model: Based on the selected local time, the Proelss phenomenological model (Proelss, 1993) can provide a comprehensive scenario for the ionospheric storm evolution and qualitatively predict its effects at different local times.
- Indications from ionograms: the ionograms, especially those recorded from DPS4Ds can give a confirmation about LSTIDs over the specific station location.
- Analysis of ionospheric parameters: the comparative analysis of critical ionospheric parameters such as: the minimum virtual height of the ordinary wave trace for the highest stable stratification in the F region (h'F2), the minimum virtual height of the ordinary wave trace taken

as a whole (h'F), the frequency spread between the extraordinary wave critical frequency and the top frequency of spread F traces (FF) and the effective scale height at hmF2 Titheridge method (H) can provide important information about the equatorward propagation of LSTIDs and the vertical redistribution of the ionospheric layers.

- Indications from the slant TEC (STEC) variation: slant TEC variations can be estimated from the residuals of the background STEC from the total STEC. It is expected that a satellite with elevation greater than 40° can identify variations of the order of few TECU. In this analysis we focus on data recorded by GNSS receivers located near the DPS4D locations in order to be able to cross compare and validate slant TEC variations due to TIDs (STECtid) with ionogram recordings.
- Analysis of the TaD output: The TaD model is a topside profiler based on empirical equations derived from the analysis of the topside sounding data from the Alouette/ISIS database and ingests the Digisonde observations at the height of the maximum electron density to adjust the profiler with the real-time conditions of the ionosphere. The model is implemented in the DIAS system (Belehaki et al., 2006; 2007) and in the ESA SSA Space Weather Portal (Belehaki et al., 2015) to provide maps of electron density at various heights and maps of TEC and partial TEC. If the TaD model is capable in identifying the effects of LSTIDs then the set up of a real-time system is possible.

3. FIRST RESULTS

The present analysis is focused on the geomagnetic storm occurred on 7 March 2012. This is a CAWSES II event, that is triggered by a geoeffective CME recorded by ACE spacecraft at L1. Ionospheric disturbances resulted from the specific storm have been successfully forecasted by the SWIF model (Tsagouri et al., 2009; Tsagouri and Belehaki; 2015) and two successive alerts have been issued by the DIAS system at http://dias.space.noa.gr (see Figure 1).



2nd alert: March 7, 07:00 UT

Ionospheric Storm		2012 03	Issue Time: 2012-03-07 07:00:00 (UT)	
DIAS Location	Forecasted Onset (UT)	Forecasted Duration (hours)	Forecasted Maximum Deviation from Median (%)	Ionospheric Storm Effect
Arenosillo	2012-03-07 09:00:00	11	33	positive
Athens	2012-03-07 09:00:00	11	33	positive
Chilton	2012-03-07 19:00:00	23	-35	negative
Ebre	2012-03-07 09:00:00	11	33	positive
Juliusruh	2012-03-07 19:00:00	23	-35	negative
Moscow	2012-03-07 16:00:00	23	-35	negative
Pruhonice	2012-03-07 19:00:00	23	-35	negative
Rome	2012-03-07 09:00:00	[illegible]	[illegible]	[illegible]

1st alert: March 7, 03:00 UT

Ionospheric Storm			00 (UT)	
DIAS Location	Forecasted Onset (UT)	Forecasted Duration (hours)	Forecasted Maximum Deviation from Median (%)	Ionospheric Storm Effect
Arenosillo	2012-03-07 05:00:00	17	26	positive
Athens	2012-03-07 05:00:00	17	26	positive
Chilton	2012-03-07 11:00:00	25	-36	negative
Ebre	2012-03-07 05:00:00	17	26	positive
Juliusruh	2012-03-07 13:00:00	25	-36	negative
Moscow	2012-03-07 15:00:00	25	-36	negative
Pruhonice	2012-03-07 13:00:00	25	-36	negative
Rome	2012-03-07 05:00:00	17	26	positive

Figure 1. Left: The AE-index from WDC for Geomagnetism, Kyoto for 7 March 2012 and the DIAS alerts issued with the SWIF model.

SWIF is triggered by the Alert Algorithm Detection that analyses in real-time the IMF data at L1 and in case of geoeffective CME, the model forecasts the ionospheric effects at two latitudinal zones (mid latitude and mid to high latitudes) based on the Proelss phenomenological scenario for the local time effects.

The inspection of ground based magnetometers from the Canadian Magnetic Observatory System (CANMOS) and the Scandinavian chains of the IMAGE network indicates that there is a first main onset recorded at 0105 at the IMAGE chain and at 0200 at CANMOS. The second main onset was recorded at 0410 UT at IMAGE and at 0430 at CANMOS. This led us to the conclusion that Europe was closer to the LT when the first intensification of the westward electroject was recorded and therefore it is more reasonable to search for the effects of TID in this sector.

To analyse the ionospheric response recorded from the European Digisondes, we present in Figure 2 the main ionospheric characteristics scaled from the Pruhonice and Ebro DPS4D ionograms recorded on 7 March 2012 (black line) together with the monthly median values (red line) for reference. A small increase in the FF index in Pruhonice at 0100UT and at 0415UT can be associated with the two auroral electroject intensifications. In Ebro the FF index shows an abrupt increase at 0600UT and can be associated with the effect of LSTID generated in the second energization of the westward current and propagated equatorward. However this is only an indication. Simultaneous increase of h'F and hmF2 being more pronounced in Pruhonice than Ebro, indicates uplifting of the F layer during daytime. At the same time foF2 increases, due to increase ionization production rate at higher altitudes. These results are indicative of a spread-F during nighttime and redistribution of ionization during daytime. The source of these disturbances might be Travelling Ionospheric Disturbances. However to confirm this, further analysis is required.

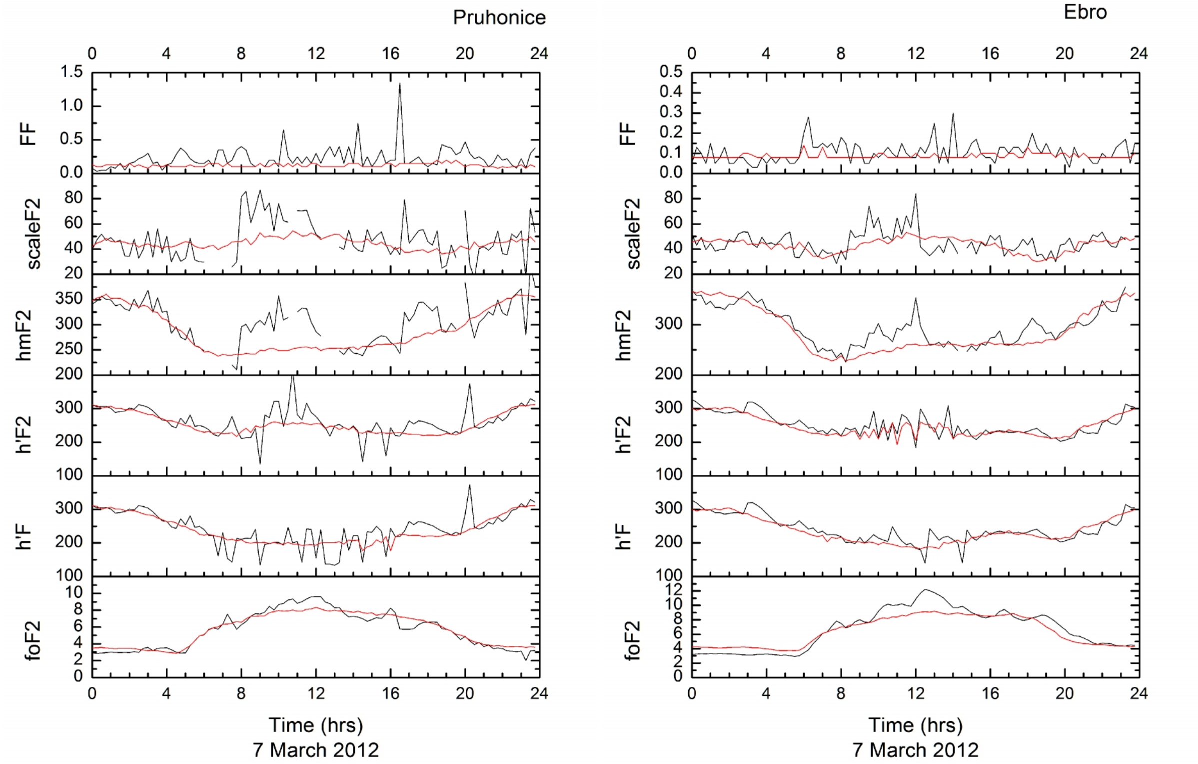


Figure 2. Main ionospheric characteristics auto-scaled from Pruhonice Ebro DPS4D ionograms recorded on 7 March 2012 (black line) together with the monthly median values (red line) for reference.

The ionograms recorded by the two stations in Pruhonice and Ebro gives solid evidence of LSTIDs propagated over the area and confirm the indications provided by the analysis of the ionospheric parameters. In Figure 3 we present some sample ionograms recorded on 7 March 2012 by the two DPS4D with typical LSTID signatures seen in both sites.

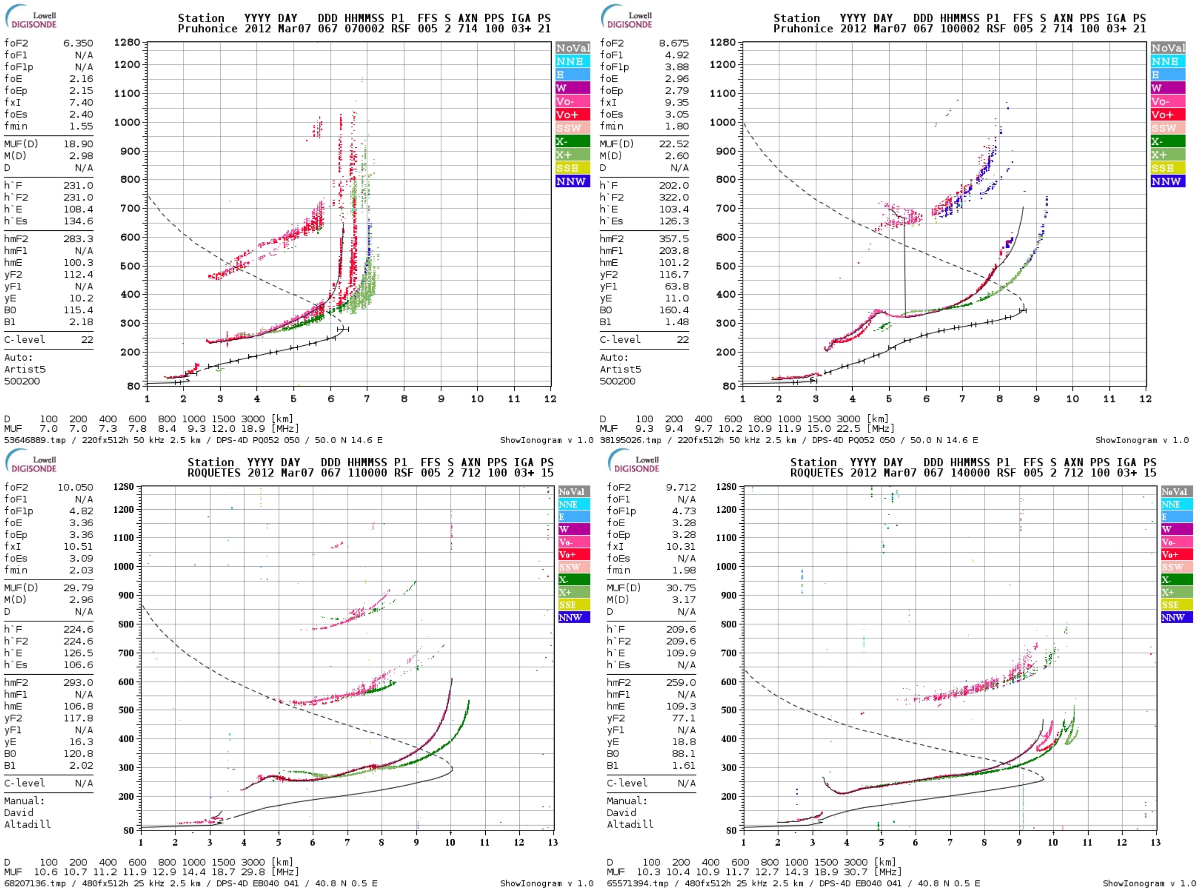


Figure 3. LSTID signatures seen in ionograms recorded in Pruhonice and Ebro DPS4Ds on 7 March 2012.

LSTID signatures have been also identified in the residuals of STEC (STECtid) after subtracting the background following the Ding et al. (2007) method. In Figure 4 we present the STECtid (blue color) together with the STEC values (SLANTEC) in red color and the subtracted background (STECb) in green. Two examples are given for the passage of GPS satellite G013 over SASS ground-based receiver and for the passage of GPS satellite G019 over SFER ground-based receiver. SASS is located north of Pruhonice while SFER is located close to Ebro. The elevation of the satellites is also shown in black and for the selected intervals it is higher than 40° for most of the time, which is an indication that the STEC calculated parameters are accurate. The STECtid in both cases show a wave-like behavior with amplitudes ranging from 1 to 3 TECU. This is an additional indication of TIDs propagating over the two stations.

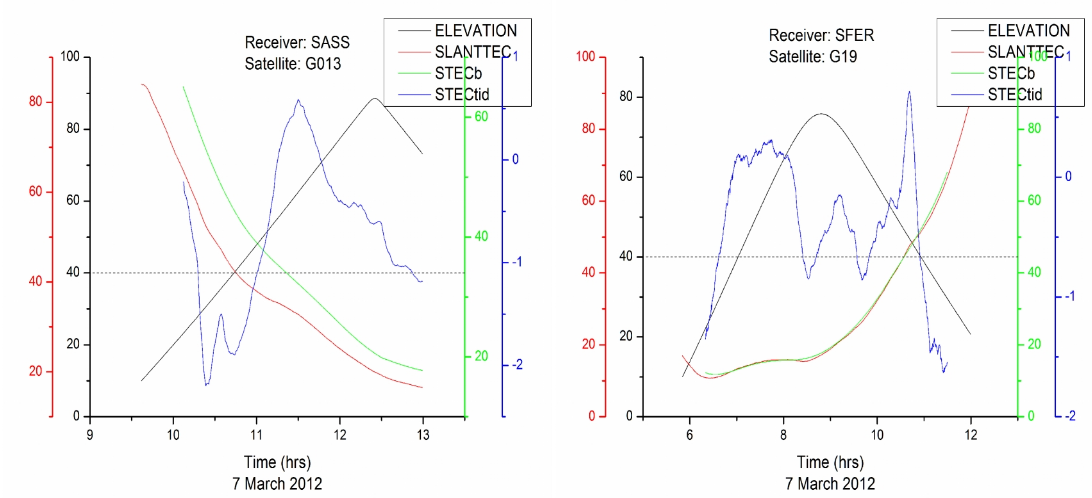


Figure 4. The residuals of STECtid (blue color) together with the STEC values (SLANTEC) in red color and the subtracted background (STECb) in green for two GPS satellite passages over SASS and SFER receiving stations on 7 March 2012. Wave like signatures in STEC are observed.

Finally we analyze the results obtained from the TaD model using as input data from Pruhonice and Ebro Digisondes. The electron density modeled by TaD for heights ranging from 200 to 1000 km are presented in Figures 5 (a) and (b) for Prunonice and Ebre correspondingly. Vertical lines correspond to ionograms presented in Figure 3. The redistribution of the ionization caused by LSTIDs recorded in the ionograms presented in Figure 3, is correctly predicted by the TaD model. The vertical lines in Figure 5 correspond to the time of ionograms shown in Figure 3. A decrease in the ionization is predicted at these times especially in lower ionospheric layers from 200 to 400 km.

4. CONCLUSIONS

- Signatures of LSTIDs propagating towards the equator are seen using multi-point measurement analysis of data from ground-based magnetometers and Digisondes.
- Digisondes are a powerful tool to perform TID scientific investigation. The analysis of Digisonde data confirm that the first indication at night-time is spread-F and at daytime we have observe distortions at the F2 layer and the at the F1 layer. The collection of ionograms with a cadence of 5 min would improve the capacity of the TID identification system
- The analysis of STEC parameters provide an additional indication of TID propagation over the area, although more systematic analysis is required. The amplitude of TIDs decreases towards the lower latitudes in the dayside because of the higher electron density which causes dispersion of the wave energy.
- The TaD is able to predict LSTIDs during the evolution of a storm and provide a realistic representation of the ionization redistribution.

ACKNOWLEDGEMENTS

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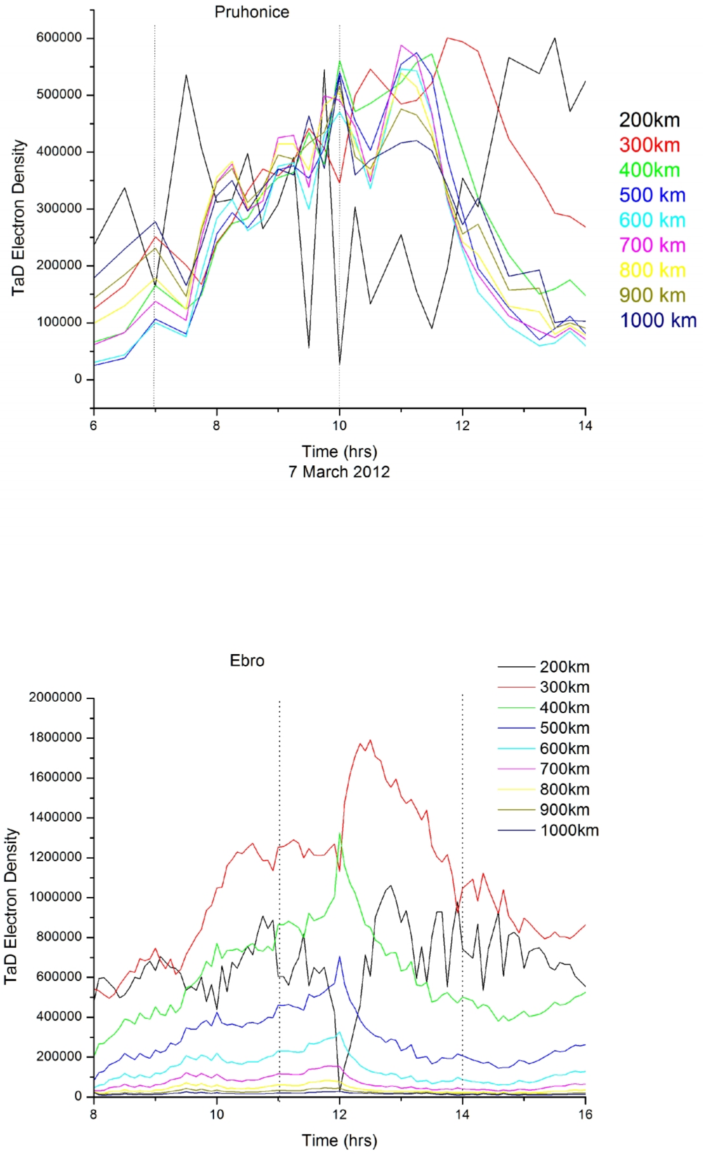

Figure 5. The TaD model results using as input ionospheric data from Pruhonice (top) and Ebro (bottom) Digisondes. The calculated electron density is given for heights ranging from 200 to 1000 km.

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