IMPROVED OPERATIONAL MODEL FOR REAL-TIME RECONSTRUCTION OF THE ELECTRON DENSITY PROFILE AT A SINGLE IONOSONDE LOCATION

S. M. Stankov (1) , **R. Warnant** (2) , **J. C. Jodogne** (1)

(1) Royal Meteorological Institute of Belgium, B-1180 Brussels, Belgium
(2) Royal Observatory of Belgium, B-1180 Brussels, Belgium

Abstract

Presented is a new improved operational model for real-time reconstruction of the vertical electron density distribution from concurrent GPS-based total electron content and ionosonde measurements. The model is developed on the basis of a novel approach for deducing the topside ion scale heights assuming Exponential, Epstein, or Chapman type of vertical density distribution. The required input data are submitted on-line to an operational centre where processing is carried out immediately and the electron density profile is derived. The method is suitable for use at middle latitudes at sites where ionosonde measurements are available. Several tests have been carried out and preliminary results have been presented and discussed. Here, further developments in the operational reconstruction model are reported, mainly in the operational procedure.

Keywords: total electron content, electron density, real-time reconstruction

1. Introduction

The advances in the Total Electron Content (TEC) measurement technology, using signals from the Global Positioning System (GPS), provides an excellent opportunity for regular monitoring of the ionosphere-plasmasphere system. Another advantage of using this technology is in the information it provides for the plasma density above the F2 layer peak height – a region which is difficult to access with the available ground ionosonde network. Moreover, the access to this information in a real-time mode allows the solution of various problems of importance, such as the estimation and correction of the propagation delays in the Global Navigation Satellite System (GNSS), verification of empirical and theoretical ionosphere-plasmasphere models, operation of satellite augmentation systems, space weather effects on telecommunications, etc.

This report aims at presenting a new *improved* operational model for reconstruction of the ionosphere-plasmasphere vertical electron density distribution on a real-time basis.

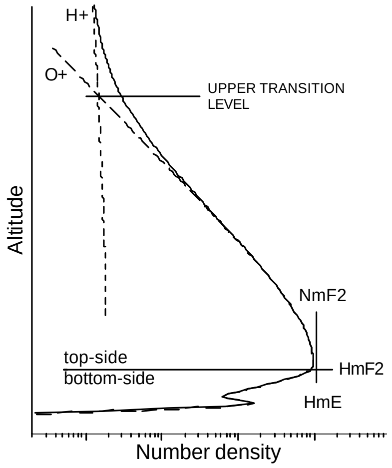

Fig.1 The electron density profile characteristics.

The core of such defined operational model is the novel reconstruction technique (Stankov and Muhtarov, 2001) which uses various types of concurrent observations (GPS TEC, ionosonde, direct satellite) to reliably deduce the most adequate electron density height profile at a given location and for the time of observations. Details of this technique are provided in the next part. The method has been tested using real GPS TEC data (Stankov et al., 2001; Stankov et al., 2002a) and proved to be reliable.

Another important ingredient of the operational model is the procedure for operating the reconstruction (Stankov et al., 2002b). Apart from 'managing' the reconstruction, it also takes care of collecting, transferring and processing the measurement data in a fast and reliable way. Important issues in such 'data assimilation' procedure are data digitalization, network reliability, strict time control, etc. Details are also given further below. Tests have been already executed with actual measurements obtained as a result of the operational system developed jointly by the Royal Meteorological Institute and the Royal Observatory of Belgium. Preliminary results have been also presented and discussed (Stankov et al., 2002c).

The operational reconstruction model has been recently upgraded with new options resulting from the estimation of various analytical ionospheric models (Stankov 2002).

Presented at the EU COST 271 Workshop, 1-5 October 2002, Faro, Portugal

2. Reconstruction technique

The reconstruction technique (Stankov and Muhtarov, 2001; Stankov et al., 2001; Stankov et al., 2002a), on which the operational procedure is based, is essentially a novel approach with great capabilities. Shortly, the vertical electron density profile at a given location can be deduced from ground measurements of the total electron content, ionosphere soundings, and empirically-obtained values of the upper transition level (UTL). The retrieval of the corresponding electron density distribution is performed in two main stages (Fig.**1**): construction of the bottom-side electron profile (below hmF2) and construction of the top-side profiles (above hmF2). The ionosonde measurements are used primarily for obtaining the bottom-side profile; digital ionosondes deduce profiles from about 60 km up to hmF2. Another option (Stankov et al., 2001), used here, is to represent the bottom-side profile as a composition of two (F2 and E) Epstein-type layers by using foF2, foE, M(3000)F2, and hmF2. Once the bottom-side profile is obtained, the corresponding bottom-side electron content, TECb, is calculated. Having TEC and TECb, the top-side part is TECt = TEC-TECb , used in the next stage for deducing the top-side profiles. The following 'reconstruction' formula is proposed for calculation of the top-side (h>hmF2) electron density profile:

$$N_e(h) = N_{O+}(h_m F2)\, sech^2\left(\frac{h - h_m F2}{2.H_{O+}}\right) + N_{H+}(h_m F2)\, sech^2\left(\frac{h - h_m F2}{32.H_{O+}}\right) \qquad \mathbf{(1)}$$

where H_{O+} is the O^+ scale height, sech(h)=2/[exp(h)+exp(-h)]. It is assumed that the height of the O^+ density maximum is equal to the height of the H^+ density maximum. Along a geomagnetic field line, and under isotropic conditions, the H^+ scale height will be 16 times larger than the O^+ scale height, following the scale height definition ($H_i = kT_i / m_i g$). Three are the unknowns in the proposed formula - the O^+ and H^+ densities at hmF2, i.e. $N_{O+}(h_m F2)$ and $N_{H+}(h_m F2)$, and the O^+ scale height, H_{O+}. The following system is assembled to determine the unknowns:

$$N_{O+}(h_m F2) \;+\; N_{H+}(h_m F2) \;=\; N_m F2 \qquad \mathbf{(2)}$$

$$N_{O+}(h_m F2)\, sech^2\big((h_{tr} - h_m F2)/2.H_{O+}\big) = N_{H+}(h_m F2)\, sech^2\big((h_{tr} - h_m F2)/32.H_{O+}\big) \qquad \mathbf{(3)}$$

$$TEC_t \;=\; 2\,.\,H_{O+}\,.\,N_{O+}(h_m F2) \;+\; 32\,.\,H_{O+}\,.\,N_{H+}(h_m F2) \qquad \mathbf{(4)}$$

The first equation represents the principle of plasma quasi-neutrality at the F2 peak height. The second equation denotes the fact that the hydrogen and oxygen ion densities are equal at the O^+-H^+ transition level (h_{tr}); the level is obtained from a model based on satellite and rocket measurements (Kutiev et al., 1994; Stankov et al., 2001). The UTL is approximated by a multi-variable polynomial depending on solar activity, season, local time, longitude and latitude. The third equation is obtained after integrating the proposed $N_e(h)$ 'reconstruction' formula (**1**) from $h_m F2$ to infinity. Equations (**3**) and (**4**) need some correction when vertical density distribution is required (Stankov et al., 2001; Stankov et al., 2002a). The solution of system (**2**)-(**4**) delivers the top-side scale heights; the electron profile is then easy to reconstruct from formula (**1**). To map the profile onto the vertical axis, z , a simple conversion dz = sinI ds is used, where ds is the differential element along the field lines, I is the inclination. If the geomagnetic declination is ignored, the element dz is obtained as dz=sin[arctg(2tgφ)]ds, where φ is the latitude. Denoting V=sin[arctg(2tgφ)], formula (**1**) then acquires its new look:

$$N_e(h) = N_{O+}(h_m)\, sech^2\left(\frac{h - h_m}{2\, H_{O+}}\right) + N_{H+}(h_m)\, sech^2\left(\frac{h - h_m}{32\, V H_{O+}}\right) \;,\quad h > h_m \qquad (5)$$

Equation (**3**) is replaced by Eq.(**5**) in the system (**2**)-(**4**) and the unknowns $N_{O+}(h_m F2)$ and $N_{H+}(h_m F2)$ are excluded. Thus, solving the reconstruction system (**2**)-(**4**) is equivalent to solving the following transcendental equation, (Stankov et al, 2001; Stankov et al., 2002a):

$$\left(\frac{16V}{(16V-1)} N_m - \frac{1}{2\,(16V-1) H_{O+}} TEC_t\right) sech^2\left(\frac{h_{tr} - h_{tr}}{2H_{O+}}\right) - \left(\frac{1}{2\,(16V-1)\, H_{O+}} TEC_t - \frac{1}{(16V-1)} N_m\right) exp\left(-\frac{h_{tr} - h_m}{32\, V H_{O+}}\right) = 0 \qquad \mathbf{(6)}$$

The only unknown variable in the above transcendental equation is the oxygen ion scale height (H_{O+}), obtained after numerically solving the equation.

The reconstruction method has been further improved and the Exponential, α-Chapman, and β-Chapman ionospheric profilers also included in the method by developing their corresponding reconstruction formulae (Stankov, 2002).

The *Exponential* layer is: $N_i(h) = N_i(h_m)\, exp(-(h-h_m)/H_i)$, where $N_i(h)$ is the density at height h , and H_i (positive value) is the ion scale height. The corresponding transcendental equation, based on the Exponential layer, is:

$$\left(\frac{16V}{(16V-1)}N_m - \frac{1}{(16V-1)H_{O+}}TEC_t\right)exp\left(-\frac{h_{tr}-h_m}{H_{O+}}\right) - \\ -\left(\frac{1}{(16V-1)H_{O+}}TEC_t - \frac{1}{(16V-1)}N_m\right)exp\left(-\frac{h_{tr}-h_m}{16VH_{O+}}\right)=0 \qquad \textbf{(7)}$$

The general form of the *Chapman* layer is $N(h)=N(h_m)\exp\{c[1-(h-h_m)/H-\exp(-(h-h_m)/H)]\}$, where h_m is the F2-layer peak density height, H is the scale height, and c is the layer-type coefficient: α-Chapman (c = 0.5) or β-Chapman (c = 1).

The transcendental equation, based on the α-Chapman layer, is:

$$\left(\frac{16V}{(16V-1)}N_m - \frac{1}{2.821(16V-1)H_{O+}}TEC_t\right)exp\frac{1}{2}\left(1-\frac{h_{tr}-h_m}{H_{O+}} - \exp\left(-\frac{h_{tr}-h_m}{H_{O+}}\right)\right) - \\ -\left(\frac{1}{2.821\ (16V-1)H_{O+}}TEC_t - \frac{1}{(16V-1)}N_m\right)exp\frac{1}{2}\left(1-\frac{h_{tr}-h_m}{16\,VH_{O+}} - \exp\left(-\frac{h_{tr}-h_m}{16VH_{O+}}\right)\right)=0 \qquad \textbf{(8)}$$

The transcendental equation, based on the β-Chapman layer, is:

$$\left(\frac{16V}{(16V-1)}N_m - \frac{1}{1.718\,(16V-1)H_{O+}}TEC_t\right)exp\left(1-\frac{h_{tr}-h_m}{H_{O+}} - \exp\left(-\frac{h_{tr}-h_m}{H_{O+}}\right)\right) - \\ -\left(\frac{1}{1.718\ (16V-1)H_{O+}}TEC_t - \frac{1}{(16V-1)}N_m\right)exp\left(1-\frac{h_{tr}-h_m}{16\,VH_{O+}} - \exp\left(-\frac{h_{tr}-h_m}{16VH_{O+}}\right)\right)=0 \qquad \textbf{(9)}$$

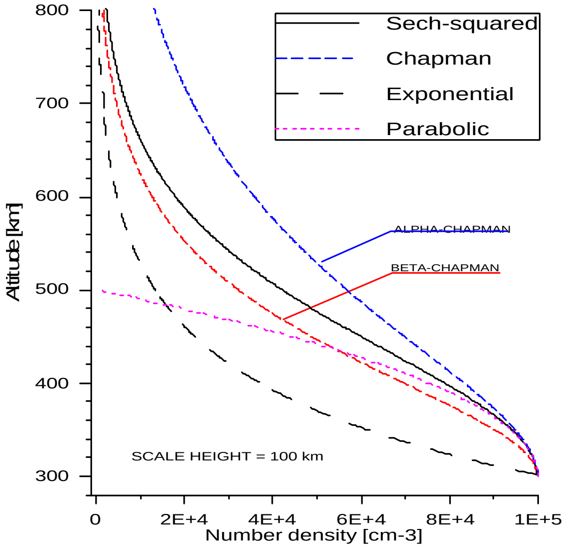

Fig.2 Comparison between vertical electron profiles obtained with several analytical models and a scale height of 100 km.

Recently, in addition to the original Sech-squared ionospheric profiler, the above-mentioned Exponential, α-Chapman, and β-Chapman profilers have been also incorporated in the operational reconstruction model.

However, because different topside density distributions are produced by the different profilers using a same scale height (Fig.**2**), each profiler was thoroughly evaluated as a possible reconstruction tool (Stankov, 2002; Jodogne and Stankov, 2002). It was found that for day-time conditions the Exponential layer is more suitable than the other profilers. Oppositely, for night-time conditions, the Sech-squared and Chapman models guarantee better reconstruction results. The Parabolic layer is not suitable for reconstruction except near the F2 density peak height.

The evaluation results have been implemented in the improved version of the operational procedure.

3. Operational procedure

The operational procedure (Fig.**3**) is one of the important ingredients of the operational reconstruction model. In general, this operational procedure ensures the collecting, transferring and processing of measurement data, manages the reconstruction using the presented reconstruction technique, and finally disseminates the results in a real-time mode. It is a stand-by procedure: its execution is triggered by either a time control system or the arrival of a new measurement data block. Currently, the key control parameters are the date, time, and level of solar activity. Implicitly, the level of geomagnetic activity is also included.

Several distinct stages are observed in this operational reconstruction procedure: retrieval/transmission of measurement data and determination of all input parameters, construction of the bottom-side electron profiles, solution of the reconstruction system, construction of the top-side electron profile, backup and display of results. The improved version of the procedure includes a new on-line evaluation of the most suitable profiler for the reconstruction.

Most of the required data are transmitted immediately using the File Transfer Protocol. The necessary UTL value is provided by an empirical model which is a part of the reconstruction software. If some observations are not available in time, there are opportunities for substitution of these observations (e.g. GPS-TEC, HmF2) with model values. For example, if the GPS-TEC value is not available, it is possible to use the ionosonde-based TEC value; the mean and standard deviations for low solar activity (LSA) are estimated at approximately 0.46 and 1.72 TECU (Warnant and Jodogne, 1998). Analytical expressions are also available for hmF2.

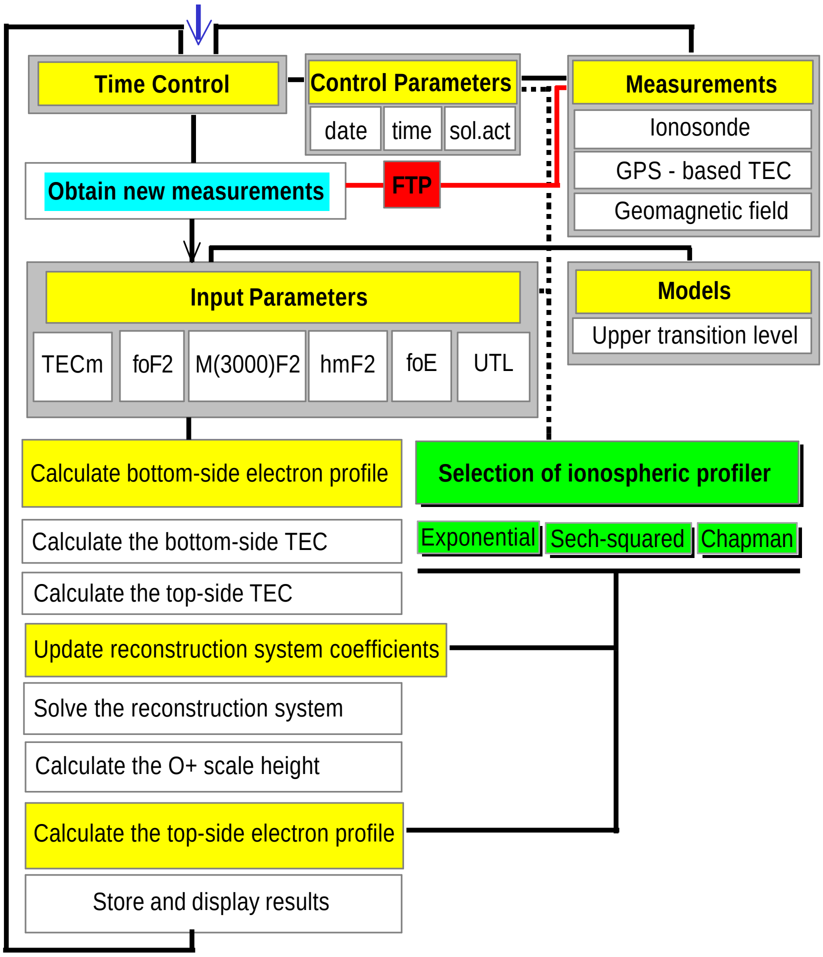

Fig.3 The improved operational procedure for real-time reconstruction of the electron density profile.

For the retrieval of the top-side electron profile, it is necessary to adopt the most adequate ionospheric profiler for the topside oxygen and hydrogen ion densities. In the final stage of the procedure all results are stored and displayed. The next round of calculations can be initiated by either the time control or the arrival of new measurements.

The procedure relies heavily on the regular influx of digital data - ionosonde, local geomagnetic and GPS TEC measurements. All types of observations should be synchronized and processed quickly (in real-time mode), so representative results would be obtained for a given location at a given moment. Highest flexibility, in terms of time resolution, is offered by the digital ionosonde – a new block of measurement data can be expected with a maximum delay of 5 minutes. A longer delay is expected when receiving the GPS TEC value, because the TEC derivation procedure (Warnant, 1997; Warnant, 1998) requires time and sufficient number of measurements. In practice, a TEC value can be obtained every 15 minutes, which is sufficient for most applications.

4. Measurements

The Royal Meteorological Institute (RMI) Geophysics Centre at Dourbes (4.6°E, 50.1°N) is a complex observational site consisting of several modern observatories – meteorological, ionosphere sounding, geomagnetic, cosmic ray, GPS TEC, etc. (Jodogne and Stankov, 2002a). All observatories are connected via a local area network based on optical-fibre connections. A fast link with the Institute at Brussels and with the WWW allows immediate access to the observations.

The Dourbes digital ionosonde (DB049) carries out regular vertical ionospheric soundings with a Digisonde 256 sounder, developed by the University of Massachusetts - Lowell. All ionograms are automatically scaled and the values of foF2, foE, M3000F2, hmF2 are deduced with short delay of 4-5 minutes. Some ionogram settings are as follows: frequency range 1-16 MHz, frequency scale – linear, frequency step - 100 kHz, amplitude resolution - 0.25 dB, phase resolution – 1.4°, Doppler resolution – 4 Hz, range resolution - 5 km, range start – 60 km, ionogram duration – 4 min, etc. The sounding rate is set to 1 per hour, but it can be increased if required.

The GPS TEC observations are performed with a GPS receiver collocated with the ionospheric sounder. Using the GPS signals on two coherent carrier frequencies (L1/L2 = 1575.42/1227.6[MHz]), the TEC computation procedure (Warnant, 1997; Warnant, 1998) is based on the 'geometry-free' combinations of GPS code ($P^i_{p,GF}$) and phase ($F^i_{p,GF}$) measurements

$$P^i_{p,GF} = P^i_{p,L1} - P^i_{p,L2} \quad , \quad F^i_{p,GF} = F^i_{p,L1} - (f_{L1} / f_{L2}) F^i_{p,L2} \tag{10}$$

where P^i_p is the code measurement made by receiver p on i $^{-\text{th}}$ satellite, F^i_p is the carrier phase measurement made by receiver p on the $i^{-\text{th}}$ satellite, and f_{L1}, f_{L2} – the frequencies on the L1,L2 carriers respectively. Rewritten as functions of TEC, the above equations read:

$$P^i_{p,GF} = -1.05 \times 10^{-17} TEC^i_p + (D_p - D^i) \tag{11}$$

$$F^i_{p,GF} = -5.52 \times 10^{-17} TEC^i_p + N^i_{p,GF} \tag{12}$$

where N^i_p is the phase ambiguity, TEC^i_p is the slant electron content (along the $i^{-\text{th}}$ satellite raypath) in TECU, D^i, D_p are the $i^{-\text{th}}$ satellite and receiver p differential group delays. The ambiguity is eliminated by the following combination of 'geometry-free' code and phase measurements:

$$P^i_{p,GF} - \lambda_{L1} F^i_{p,GF} = (D_p - D^i) - \lambda_{L1} N^i_{p,GF} \tag{13}$$

where λ_{L1} is the L1 carrier wavelength. The formula requires the estimation of receiver and satellite group delays, which estimation is obtained from Eq.**11** after modelling the TEC value by means of a simple polynomial depending on latitude and local time. The conversion to vertical TEC is performed by assuming that the ionosphere is a layer of infinitesimal thickness located at a 'mean ionospheric' height of 350 km and using simple cosine function of the zenith angle at the 'ionospheric point' (raypath's point at mean ionospheric height). Finally, the TEC value is calculated from Eq.**12**. To obtain a TEC value, representative for the ionosphere above a given observing station, the following method is applied: (i) selected are all TEC values within a latitude difference of 1.5° from the latitude of the observing station, and (ii) computed is the mean of these TEC values on 15 min periods.

The Dourbes geomagnetic observatory provides the geomagnetic field components. Most important (for operational profile reconstruction) is the horizontal component (H) of the geomagnetic field. Initially used only as a local indicator of geomagnetic activity, the component is now being recorded for the purpose of quickly detecting/confirming storm conditions and adequate modification of the reconstruction. The observed strong correlation between the H component and the Dst index (Fig.**4**), suggests the use of H as a local instrument for detecting sudden storm commencements and as a substitute of the Dst index. However, the task is not easy and requires further investigation.

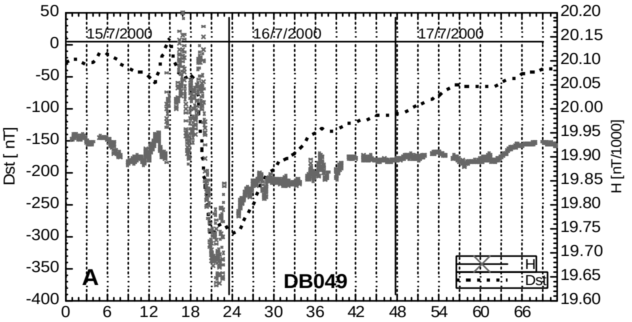

Fig.4 Comparison between observations of the H component (Dourbes) and Dst; 15-17 July 2002.

5. Results and discussion

The new operational model, based on the presented procedure and reconstruction method, has been tested extensively with actual hourly values of GPS TEC and ionosonde measurements acquired in real-time mode at the RMI Geophysics Centre.

A trial run started at 00:00LT on 11 March 2002 and finished at 24:00 on 17 March 2002. During this period, the solar activity was relatively high (176<F10.7<185) and geomagnetic activity conditions–quiet (Ap<12). Reconstructed electron profiles were ready for display well before the planed 15 minute time delay limit. Thus, the model proved to be capable of producing density profiles every 15 minutes using new observations, which is a sufficiently good rate for most of the envisaged applications (storm investigation included). Post-processed graphics of the reconstructed vertical electron density, together with the used input parameters, can be seen in Fig.**5**.

Recent development of the reconstruction technique proved (Stankov, 2002) that the day-time topside ionosphere is better represented by the Exponential profiler than by the Sech-squared profiler. Therefore, we used the original Sech-squared profiler reconstruction (Fig.**5**, top panels) for the night-time conditions (19:00-07:00LT) and the Exponential profiler reconstruction for the day-time hours (07:00-19:00LT) only. As a result, the reconstructed diurnal behaviour of the electron concentration (Fig.**5**, middle panels) represents much better the diurnal behaviour of the topside ionosphere characteristics.

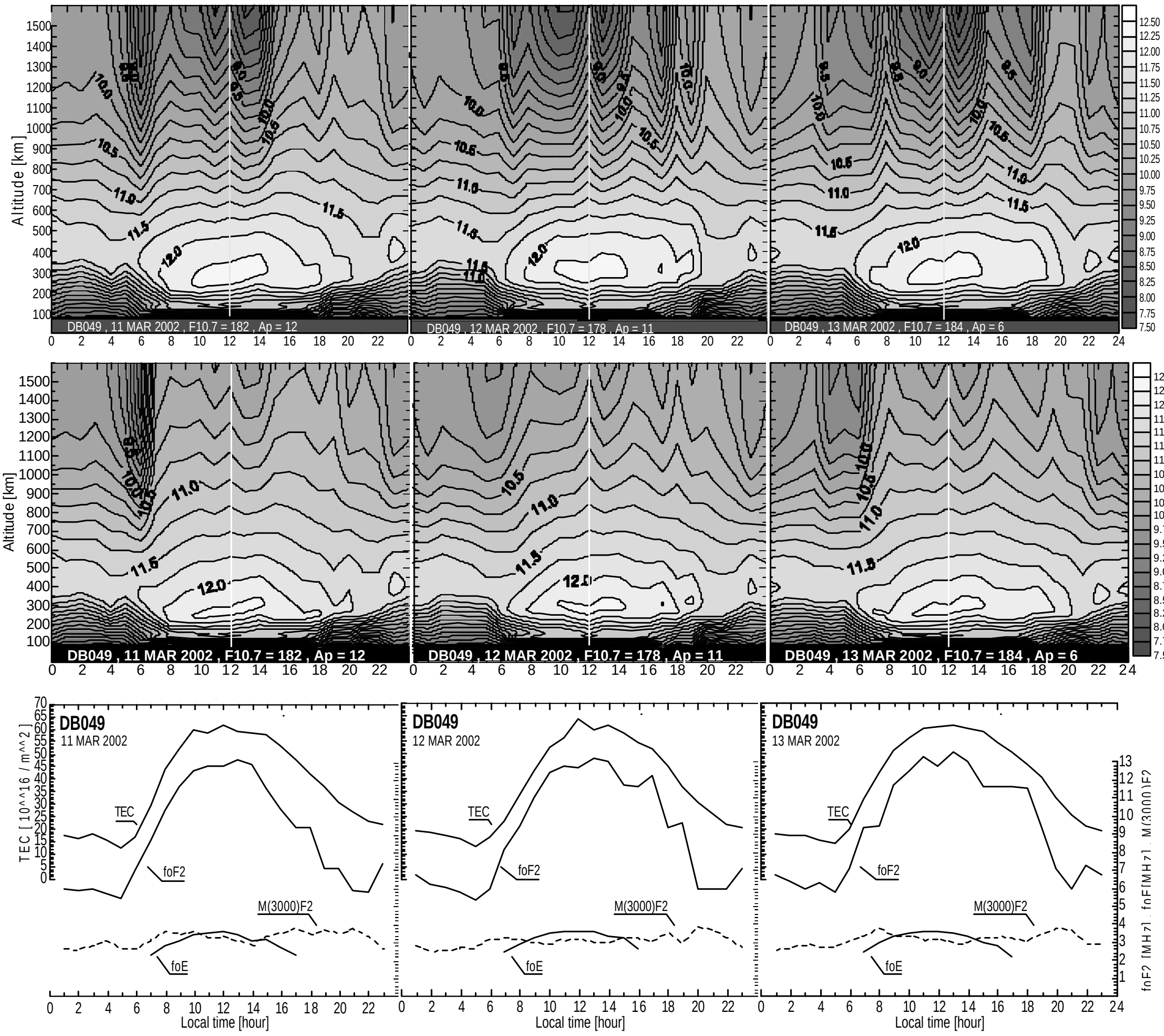

Fig.5 Real-time reconstruction of the electron density profiles, 11-13 March 2002, Dourbes (4.6°E, 50.1°N). *Top panels*: reconstruction using the Sech-squared profiler. *Middle panels*: reconstruction using the Sech-squared profiler for night-time conditions and the Exponential profiler for the day-time conditions. *Bottom panels*: ionosonde and GPS TEC measurements used as input parameters for the reconstruction.

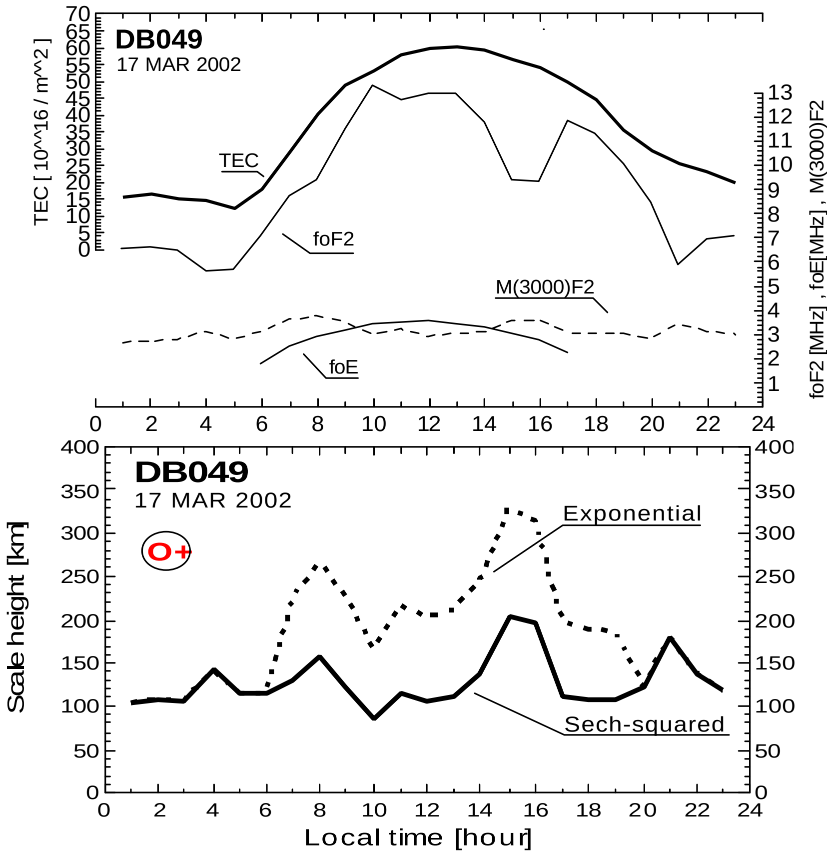

Fig.6 The O^+ ion scale heights as obtained from the profile reconstruction using Sech-squared (solid line) and Exponential (dashed line) profilers; 17 March 2002, Dourbes (4.6°E, 50.1°N).

The improvement can be demonstrated on the calculated O^+ scale height for the test on 17 March 2002 (Fig.**6**). The diurnal behaviour of the ionosonde and TEC input parameters are plotted in the top panel. Given in the bottom panel is the deduced O^+ scale height using the Sech-squared (solid line) and Exponential (dashed line) profilers.

Considering the quiet geomagnetic conditions, it is natural to expect that the scale height will increase during the day. However, it is obvious from the plots that, if only the Sech-squared profiler was applied for the whole 24-hour period, the deduced scale height would not notably increase during day-time. If the Exponential profiler is used for the day-time hours, the expected increase of the scale height is delivered.

6. Summary

Presented was a new improved operational model for real-time reconstruction of the electron density profile from concurrent GPS TEC and digital ionosonde measurements. The following main conclusions can be summarized as follows:

- The developed electron density reconstruction technique proved to be very useful for deducing the topside electron density distribution in a real-time mode.
- The recent evaluation of different ionospheric profilers as reconstruction tools improved the quality of the reconstruction technique.
- The operational procedure is reliable, easy to maintain and upgrade. It is important that new measurements can be obtained and processed up to four times per hour, which in turn can provide higher resolution in the results.
- The model is suitable for investigating local storm-time ionosphere development. However, for better identifying and observing a storm, it is necessary to include geomagnetic field measurements – the horizontal component (H) of the field in particular. Preliminary tests have been performed which encourage the use of H as a local instrument for detecting sudden storm commencements and as a substitute of the Dst index.
- A crucial advantage of the proposed model is its applicability on a global scale through the ever-growing GPS TEC and ionosonde measurements network. Data, collected at Brussels (50.8°N, 4.4°E), allow the TEC computation from about 35°N to 60°N in latitude and from 20°W to 25°E in longitude.

Important applications of the operational reconstruction model are envisaged: test and development of ionosphere-plasmasphere models, optimisation of HF radio systems operation, ionospheric storms and other space-weather studies.

Acknowledgements

This research was supported by the Belgian Federal Office for Scientific, Technical and Cultural Affairs and by the Royal Meteorological Institute of Belgium.

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