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REAL-TIME RECONSTRUCTION OF THE VERTICAL ELECTRON DENSITY DISTRIBUTION FROM GPS TEC MEASUREMENTS

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Presented is a new 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 and high latitude locations where ionosonde measurements are available. Several tests have been carried out and preliminary results have been presented and discussed.

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

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 (h_mF2), the top-side ionosphere region which is difficult to access with the existing 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, etc.

This paper presents a new operational model for reconstruction of the ionosphere-plasmasphere vertical electron density distribution on a real-time basis. 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 the 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, 2002a) and proved to be reliable. Another important ingredient of the operational model is the procedure for operating

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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 complex procedure are the precise time control, database management, network speed and reliability, etc. More details are provided below. Several tests have been already executed utilizing actual measurements obtained from the operational system developed jointly by the Royal Meteorological Institute (RMI) and the Royal Observatory of Belgium (ROB). Preliminary results have been also presented and discussed (Stankov et al. 2002c). The operational reconstruction model has been recently upgraded with new options available after the analysis of various analytical ionospheric models (Stankov 2002).

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, constitutes a novel approach with diverse capabilities. Briefly, 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 O^+–H^+ transition level (also called Upper Transition Level, or UTL). The retrieval of the corresponding electron density distribution is performed in two main stages (ref. Fig. 1): first, construction of the bottom-side electron profile (below h_mF2) and second, construction of the top-side profiles (above h_mF2). The ionosonde measurements are used primarily for deducing the bottom-side profile; digital ionosondes deliver automatically-scaled electron profiles from about 60 km up to h_mF2. Another option is to represent the bottom-side profile as a composition of Epstein-type F2- and E-layers by using the corresponding critical frequencies f_oF2 and f_oE, the propagation factor (M(3000)F2), and the F2-layer peak height (h_mF2). Once the bottom-side profile is obtained, the corresponding bottom-side electron content (TEC_b) is easily calculated. Having both TEC and TEC_b values, the top-side electron content is then TEC_t = TEC-TEC_b, used in the next stage for deducing the top-side density profiles. The following 'reconstruction' formula is proposed for calculation of the top-side ($h > h_m$F2) electron density profile:

$$N_e(h) = N_{\mathrm{O}^+}(h_mF2)sech^2\left(\frac{h-h_m}{2H_{\mathrm{O}^+}}\right) + N_{H^+}(h_m)sech^2\left(\frac{h-h_m}{2H_{\mathrm{H}^+}}\right) \qquad (1)$$

where N_e is the electron density, $\mathrm{H}_{\mathrm{O}^+}$ is the O^+ scale height, $\mathrm{H}_{\mathrm{H}^+}$ is the H^+ scale height, h_m is the height h_mF2, and by definition $sech(h) = 2/[\exp(h) + \exp(-h)]$. Along a geomagnetic field line, and under assumed isotropic conditions, the H^+ scale height will be approximately 16 times larger than the O^+ scale height ($H_{\mathrm{H}^+} \approx 16 \cdot H_{\mathrm{O}^+}$), following the scale height definition ($H_i = kT_i/m_ig$, k – Boltzmann constant, T_i – ion temperature, m_i – ion mass, g – gravity). Three are the unknowns in the proposed formula — the O^+ and H^+ densities at h_mF2, i.e. $\mathrm{N}_{\mathrm{O}^+}(h_m)$ and $\mathrm{N}_{\mathrm{H}^+}(h_m)$, and the O^+ scale height, $\mathrm{H}_{\mathrm{O}^+}$. The following system is assembled to

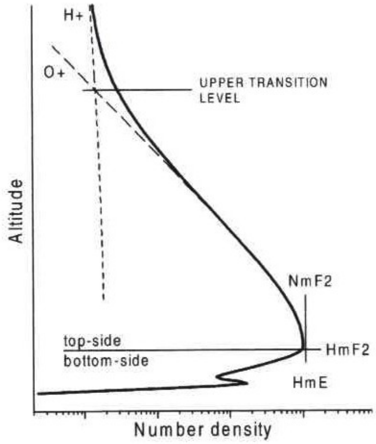

Fig. 1. Schematic view of the vertical ion and electron density profiles and their characteristics

determine them:

$$N_{\mathrm{O}^+}(h_m) + N_{\mathrm{H}^+}(h_m) = N_m\mathrm{F2} \tag{2}$$

$$\mathrm{TEC}_t = 2H_{\mathrm{O}^+} \cdot N_{\mathrm{O}^+}(h_m) + 32H_{\mathrm{O}^+} \cdot N_{\mathrm{H}^+}(h_m) \tag{3}$$

$$N_{\mathrm{O}^+}(h_m)sech^2\left(\frac{h_{tr}-h_m}{2H_{\mathrm{O}^+}}\right) = N_{\mathrm{H}^+}(h_m)sech^2\left(\frac{h_{tr}-h_m}{32H_{\mathrm{O}^+}}\right). \tag{4}$$

The first equation in this system represents the principle of plasma quasineutrality at the F2-layer peak height and it is implicitly assumed that the height of the H^+ density maximum is equal to the height of the O^+ density maximum. The second equation is obtained after integrating $N_e(h)$ in the proposed 'reconstruction' formula (Eq. 1) from $h_m\mathrm{F2}$ to infinity. The third equation denotes the fact that the hydrogen and oxygen ion densities are equal at the O^+–H^+ transition height. Equations (3) and (4) need correction when vertical density distribution is required (Stankov et al. 2001, Stankov et al. 2002a). To map the profile onto the vertical axis, h, a simple conversion $dh = sinI\ ds$ is used, where ds is the differential element along the field lines, I is the inclination. If the geomagnetic declination is ignored, the element dh is obtained as $dh = \sin[\mathrm{atan}(2\tan\varphi)]ds$, where φ is the latitude. Denoting $\xi = \sin[\mathrm{atan}(2\tan\varphi)]$, Eq. (1) will read:

$$N_e(h) = N_{\mathrm{O}^+}(h_m)sech^2\left(\frac{h-h_m}{2H_{\mathrm{O}^+}}\right) + N_{\mathrm{H}^+}(h_m)sech^2\left(\frac{h-h_m}{32\xi H_{\mathrm{O}^+}}\right), \quad h > h_m\,. \tag{5}$$

The unknowns $N_{\mathrm{O}^+}(h_m\mathrm{F2})$ and $N_{\mathrm{H}^+}(h_m\mathrm{F2})$ are are expressed from Eqs (2) and (3), and then substituted in Eq. (4). Thus, solving the reconstruction system Eqs (2)–(4) is equivalent to solving the following transcendental equation:

$$\begin{aligned}&\left(\frac{16\xi}{(16\xi-1)}N_m - \frac{1}{2(16\xi-1)H_{\mathrm{O}^+}}\mathrm{TEC}_t\right)sech^2\left(\frac{h_{tr}-h_m}{2H_{\mathrm{O}^+}}\right) - \\ &-\left(\frac{1}{2(16\xi-1)H_{\mathrm{O}^+}}\mathrm{TEC}_t - \frac{1}{(16\xi-1)}N_m\right)sech^2\left(-\frac{h_{tr}-h_m}{32\xi H_{\mathrm{O}^+}}\right) = 0.\end{aligned} \tag{6}$$

The value of the ion transition height (h_{tr}) is delivered by an empirical model (Kutiev et al. 1994) based on satellite and rocket measurements with respect to solar activity, season, local time, longitude and latitude. Hence, the only unknown variable in the above transcendental equation is the oxygen ion scale height (H_{O^+}), obtained after numerically solving the equation. Having both ion scale heights calculated, the top-side electron density profile is then easy to obtain from the 'reconstruction' formula, i.e. Eq. (1) or Eq. (5).

The reconstruction method has been further improved and the exponential α-Chapman, 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 profiler, is

$$\begin{aligned}&\left(\frac{16\xi}{(16\xi-1)}N_m - \frac{1}{(16\xi-1)H_{O^+}}\mathrm{TEC}_t\right)\exp\left(-\frac{h_{tr}-h_m}{H_{O^+}}\right) - \\ &-\left(\frac{1}{(16\xi-1)H_{O^+}}\mathrm{TEC}_t - \frac{1}{(16\xi-1)}N_m\right)\exp\left(-\frac{h_{tr}-h_m}{16\xi H_{O^+}}\right) = 0.\end{aligned} \tag{7}$$

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:

$$\begin{aligned}&\left(\frac{16\xi}{(16\xi-1)}N_m - \frac{1}{2.821(16\xi-1)H_{O^+}}\mathrm{TEC}_t\right)\cdot \\ &\cdot\exp\frac{1}{2}\left(1-\frac{h_{tr}-h_m}{H_{O^+}} - \exp\left(-\frac{h_{tr}-h_m}{H_{O^+}}\right)\right) - \\ &-\left(\frac{1}{2.821(16\xi-1)H_{O^+}}\mathrm{TEC}_t - \frac{1}{(16\xi-1)}N_m\right)\cdot \\ &\cdot\exp\frac{1}{2}\left(1-\frac{h_{tr}-h_m}{16\xi H_{O^+}} - \exp\left(-\frac{h_{tr}-h_m}{16\xi H_{O^+}}\right)\right) = 0\end{aligned} \tag{8}$$

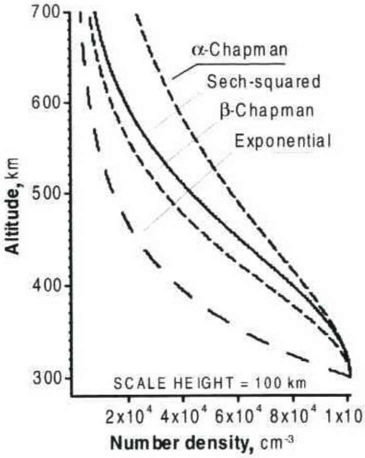

Fig. 2. Comparison between vertical electron profiles obtained with several analytical models and a scale height of 100 km

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

$$\begin{aligned}&\left(\frac{16\xi}{(16\xi-1)}N_m-\frac{1}{1.718(16\xi-1)H_{\mathrm{O}^+}}\mathrm{TEC}_t\right)\cdot\\&\cdot\exp\left(1-\frac{h_{tr}-h_m}{H_{\mathrm{O}^+}}-\exp\left(-\frac{h_{tr}-h_m}{H_{\mathrm{O}^+}}\right)\right)-\\&-\left(\frac{1}{1.718(16\xi-1)H_{\mathrm{O}^+}}\mathrm{TEC}_t-\frac{1}{(16\xi-1)}N_m\right)\cdot\\&\cdot\exp\left(1-\frac{h_{tr}-h_m}{16\xi H_{\mathrm{O}^+}}-\exp\left(-\frac{h_{tr}-h_m}{16\xi H_{\mathrm{O}^+}}\right)\right)=0\,.\end{aligned}\tag{9}$$

As already said, 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 profilers produce different topside density distributions (Fig. 2), all profilers have been additionally evaluated as potential reconstruction tools (Stankov 2002, Jodogne and Stankov 2002b). It has been 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. Thus, the evaluation results have been used when implementing the new module deciding on which profiler to be used in a particular situation.

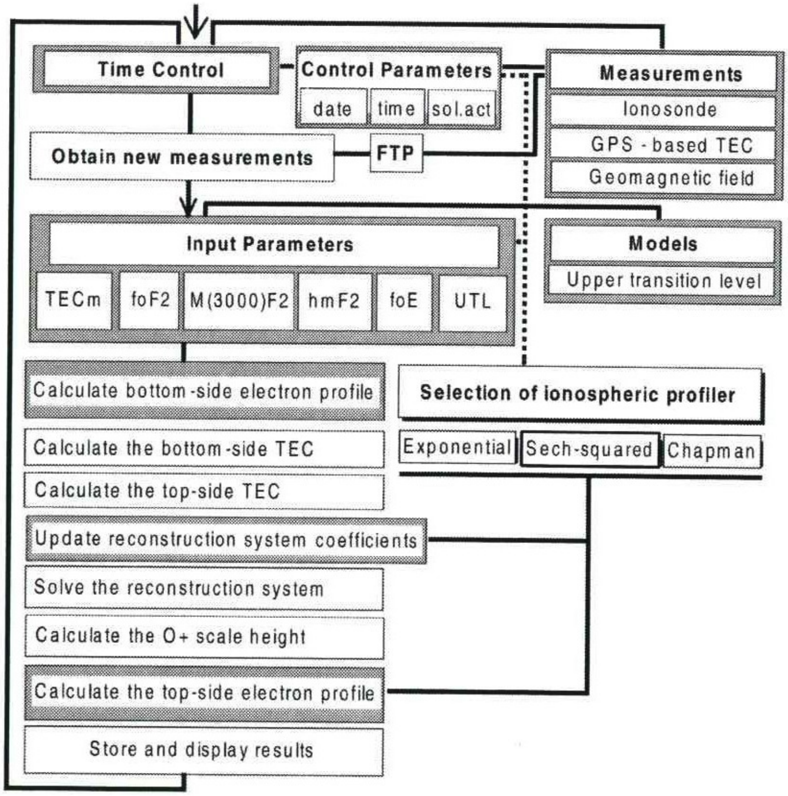

Fig. 3. The operational procedure for real-time reconstruction of the electron density profile

3. Operational procedure

The operational procedure (Fig. 3) is one of the important ingredients in 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 either by the time control system or the arrival of a new measurement data block. Currently, the key control parameters are the date, local time, and level of solar activity. Implicitly, the level of geomagnetic activity is also included via the ionosonde measurements.

Several distinct stages are observed in this operational 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. A new improved version of the procedure includes on-line evaluation of the most suitable profiler for the reconstruction. The majority of the required observations are immediately transmitted using the File Transfer Protocol. The necessary UTL value is provided by the above-mentioned empirical model which is now a part of the reconstruction software. If some observations are unavailable on time, there are opportunities for substitution of these observations (e.g. GPS TEC, h_mF2) with modelled 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 (Warnant and Jodogne 1998) at approximately 0.46 and 1.72 TECU, 1 TECU = $1 \times 10^{16}\mathrm{m}^{-2}$. Analytical expressions are also available for h_mF2. For the retrieval of the top-side electron profile, it is necessary to adopt the most adequate ionospheric profiler(s) for the topside oxygen and hydrogen ion densities. In the final stage of the procedure all results are conveniently stored and displayed. The next round of calculations can be initiated again by the time control module or the new set of 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, 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 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. Fast links with the RMI and ROB premises in Brussels allow immediate access to the most recent 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 f_oF2, f_oE, M(3000)F2, h_mF2 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, 1998) is based on the 'geometry-free' combinations of GPS code ($P^i_{p,GF}$) and phase

$(F^i_{p,GF})$ measurements

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

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:

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

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

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 and 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 D_{st} index (Fig. 4), suggests the use of H as a local instrument for detecting sudden storm commencements and as a substitute of the D_{st} index. However, the task is not easy and requires further investigation.

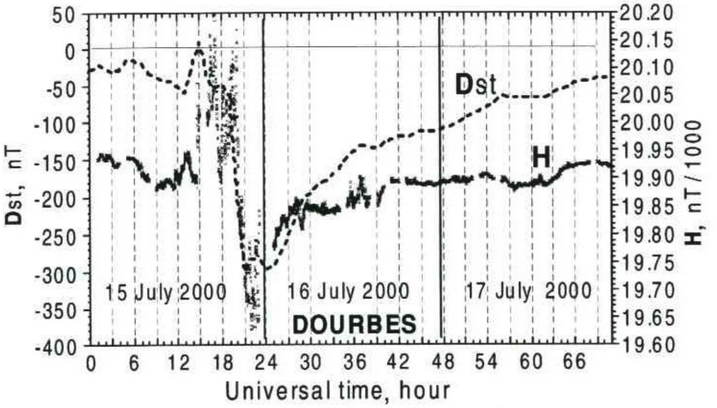

Fig. 4. Comparison between measurements of the geomagnetic field's horizontal component H recorded at Dourbes (4.6°E, 50.1°N) and the D_{st} index during the 15–17 July 2000 geomagnetic storm

5. Results and discussions

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 ($176 < \mathrm{F}10.7 < 185$) and geomagnetic activity conditions – quiet ($A_p < 12$). Reconstructed electron profiles were ready for display well before the planned time-delay limit of 15 minutes. Thus, the model proved to be capable of producing density profiles every 15 minutes, which is a sufficiently good rate for most of the envisaged applications (ionospheric storm studies included). Post-processed plots of the reconstructed vertical electron density and some 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 (1900–0700 LT) and the Exponential profiler reconstruction for the day-time hours (0700–1900 LT) only. As a result, the reconstructed diurnal behaviour of the electron concentration (Fig. 5, middle panels) represents the diurnal behaviour of the topside ionosphere characteristics much better. The improvement can be demonstrated on the O^+ scale height deduced from the test results 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

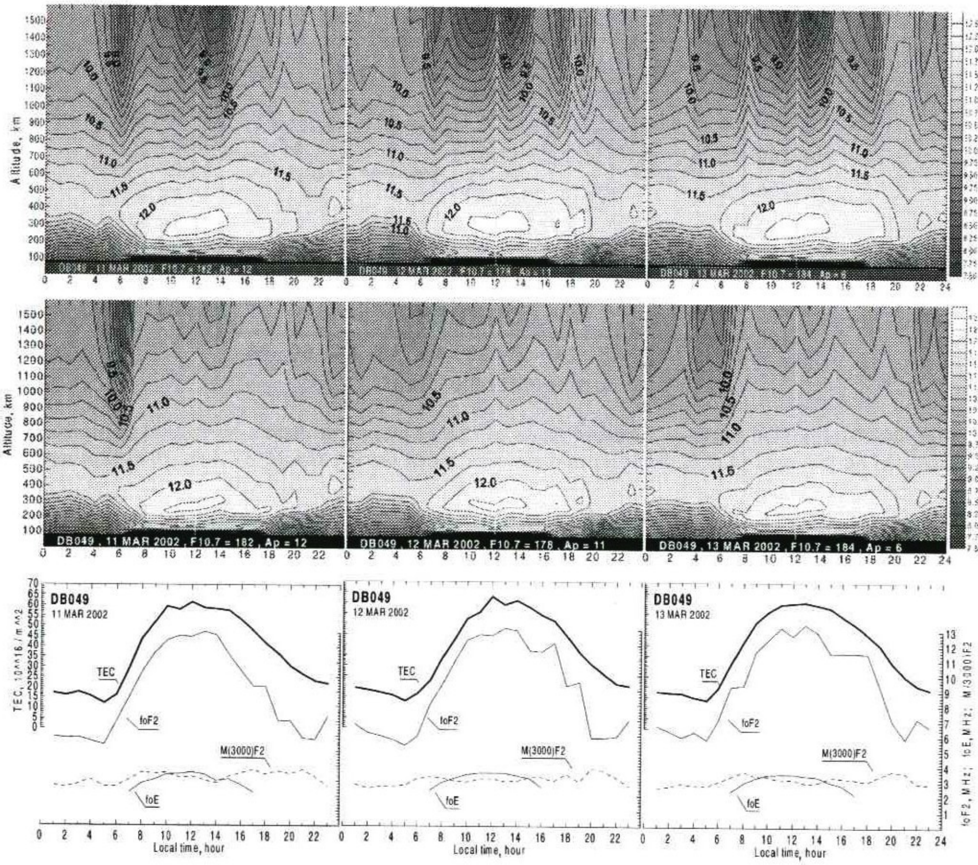

Fig. 5. Real-time reconstruction of the electron density profiles, 11–13 March 2002, Dourbes (4.6°E, 50.1°N). Top panels: reconstruction using the Sech-squared profiler. Middle panels: reconstruction using the Sech-squared profiler for night-time conditions and the Exponential profiler for the day-time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

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 successfully delivered.

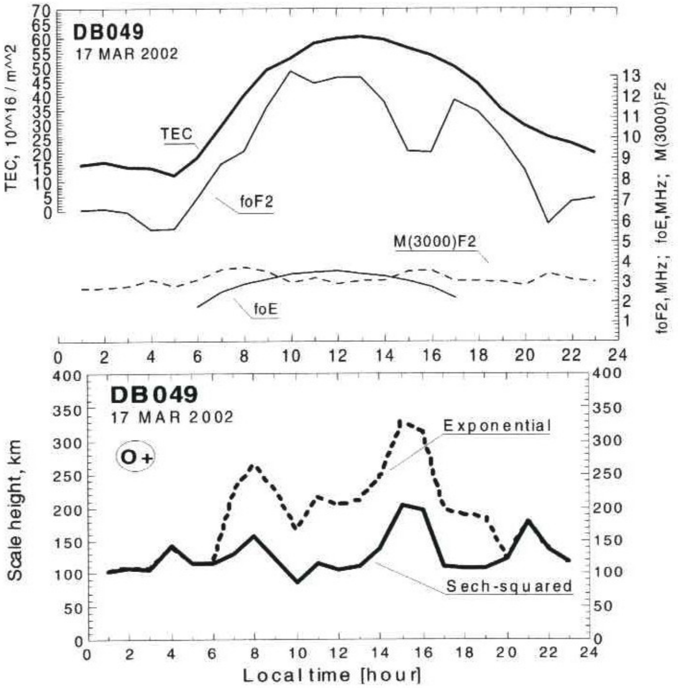

Fig. 6. The O$^+$ ion scale heights as obtained from the profile reconstruction using Sech-squared (solid line) and Exponential (dashed line) profilers; 17 March 2002, Dourbes (4.6° E, 50.1° N)

6. Summary and conclusions

Presented was a new operational model for real-time reconstruction of the electron density profile from concurrent GPS TEC and digital ionosonde measurements. The following conclusions have been made:

- 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 encouraging the use of H as a local instrument for detecting sudden storm commencements and as a substitute of the D_{st} 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. For example, the 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.

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