OPERATIONAL MODEL FOR REAL-TIME RECONSTRUCTION OF THE ELECTRON DENSITY PROFILE USING GPS TEC MEASUREMENTS

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ABSTRACT

Presented is an 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 Epstein-type of vertical 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 sites where ionosonde measurements are available. Several tests have been carried out and here some preliminary results are presented and discussed.

INTRODUCTION

Recent developments of the Total Electron Content (TEC) measurement technology, using signals from the Global Positioning System (GPS), provides opportunity for a 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 – region difficult to access with the ground ionosonde network. Moreover, the access to this information in real time opens the door to attacking many (old and new) 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 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 [1,2,3], 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. Another important ingredient of the operational model is the procedure for operating the reconstruction. 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 at the Belgian Royal Meteorological Institute's Geophysics Centre. Preliminary results are presented and discussed. The presented model can be upgraded for use on a global scale.

RECONSTRUCTION TECHNIQUE

The reconstruction technique [1,2,3], 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 [2], 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:

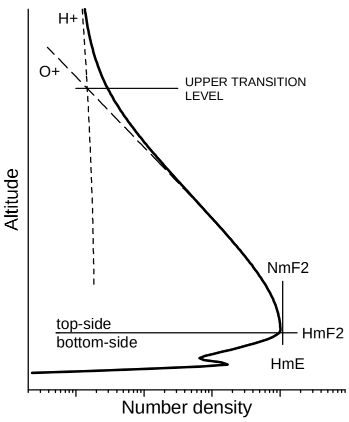

Fig.1 Profile characteristics.

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

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 ($H_i=kT_i/m_ig$). Three are the unknowns in the proposed formula - the O^+ and H^+ densities at hmF2, i.e. $N_{O+}(h_mF2)$ and $N_{H+}(h_mF2)$, and the O^+ scale height, H_{O+}. The following system is assembled to determine the unknowns:

$$N_{O+}(h_mF2) \;+\; N_{H+}(h_mF2) \;=\; N_mF2 \qquad (2)$$

$$N_{O+}(h_mF2)\, sech^2\left((h_{tr}-h_mF2)/2.H_{O+}\right) = N_{H+}(h_mF2)\, sech^2\left((h_{tr}-h_mF2)/32.H_{O+}\right) \qquad (3)$$

$$TEC_t \;=\; 2\,.\,H_{O+}\,.\,N_{O+}(h_mF2) \;+\; 32\,.\,H_{O+}\,.\,N_{H+}(h_mF2) \qquad (4)$$

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, [1,2]. 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_mF2 to infinity. Equations (**3**) and (**4**) need some correction when vertical density distribution is required, [2]. 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 geomagnetic declination is ignored, then dz=sin[arctg(2tgφ)]ds, where φ is the latitude. Denoting V=sin[arctg(2tgφ)], the formula (**1**) then acquires its new look:

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

Equation (**3**) is replaced by Eq.(**5**) in the system (**2**)-(**4**) and the unknowns $N_{O+}(h_mF2)$ and $N_{H+}(h_mF2)$ are excluded. Thus, solving system (**2**)-(**4**) is equivalent to solving the following transcendental equation, [2]:

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

The only unknown variable in the above transcendental equation is the oxygen ion scale height (H_{O+}), which is obtained after numerically solving the equation. The reconstruction method has been further expanded and Exponential α-Chapman, β-Chapman, Parabolic ionospheric profilers also incorporated, [3]. The *Exponential* layer is: $N_i(h) = N_i(h_m)\, exp\left(-(h-h_m)/H_i\right)$, 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 [3]:

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

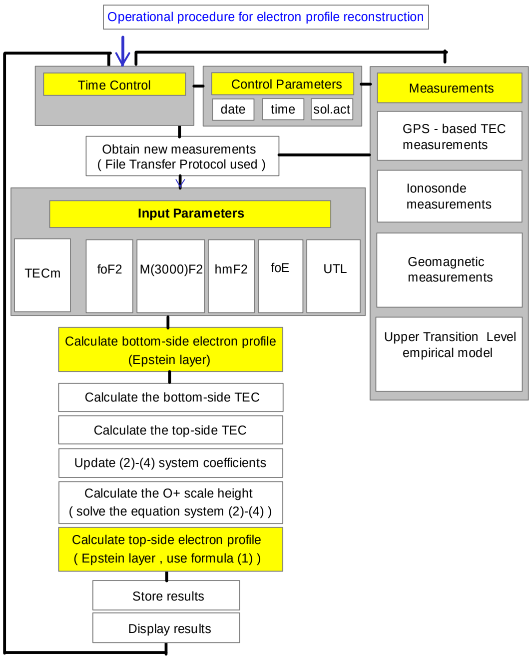

Fig.2 Operational procedure for real-time reconstruction of the electron density distribution.

OPERATIONAL PROCEDURE

In general, it is a stand-by procedure (Fig.2): its execution is triggered by either a time control system or the arrival of new measurements. Thus, it relies heavily on regular influx of ionosonde, geomagnetic and TEC discrete measurement data. All types of observations should be synchronized and processed quickly, so representative results be obtained for a given location and a time. Highest flexibility, in terms of time resolution, is offered by the digital ionosonde – a new measurement data are available within a delay of about 5 minutes. Longer delay is expected for receiving the GPS TEC value, because the TEC derivation procedure [4,5] requires time and sufficient number of measurements. In practice, a TEC value can be obtained every 15 minutes, which is sufficient for most applications.

Several distinct stages are observed in the operational reconstruction procedure (Fig.2): transmission of measurement data and retrieval of input parameters, construction of the bottom- and top- side electron profile, backup and display of results. The data are transmitted using the File Transfer Protocol; the UTL values are provided by an empirical model incorporated into the reconstruction software. If the TEC value is not available on time, 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 [6]. Analytical expressions are also available for hmF2. For the retrieval of the top-side electron profile, it is necessary to adopt a theoretical 'profiler' for the topside oxygen and hydrogen ion densities; in our case the Sech-squared layer is chosen. In the final stage of the procedure all results are stored and displayed. The next round of calculations can be triggered by either time control or arrival of new measurements.

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. 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.

A GPS receiver is 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 [4,5] is based on the 'geometry-free' combinations of GPS code ($P^i_{p,GF}$) and phase ($F^i_{p,GF}$) measurements

$$P^i_{p,GF} = P^i_{p,L1} - P^i_{p,L2} \quad , \quad F^i_{p,GF} = F^i_{p,L1} - (f_{L1}/f_{L2})F^i_{p,L2} \qquad \textbf{(8)}$$

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:

$$P^i_{p,GF} = -1.05\times10^{-17} TEC^i_p + (D_p - D^i) \qquad \textbf{(9)}$$

$$F^i_{p,GF} = -5.52\times10^{-17} TEC^i_p + N^i_{p,GF} \qquad \textbf{(10)}$$

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:

$$P^i_{p,GF} - \lambda_{L1} F^i_{p,GF} = (D_p - D^i) - \lambda_{L1} N^i_{p,GF} \qquad \textbf{(11)}$$

where λ_{L1} is the L1 carrier wavelength. The formula requires the estimation of the receiver and satellite group delays, which estimation is obtained from (**9**) after modelling TEC 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 350km and using simple cosine function of the zenith angle at the 'ionospheric point' (the raypath's point at the mean ionospheric height). Finally, the TEC value is calculated from (**10**). To obtain a TEC value, representative of the ionosphere above a given observing station, the following is applied: first, selected are all TEC values within a latitude difference of 1.5° from the latitude of the observing station, and second, computed is the mean of these TEC values on 15 min periods.

RESULTS AND DISCUSSION

The new operational model, based on the presented procedure and reconstruction method, has been tested 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 15 minute time delay limit. Therefore, the model is capable of producing profiles every 15 minutes using new observations, which is a sufficiently good rate for most of the envisaged applications (storm investigation included). Recent development of the reconstruction technique proved [3] that the day-time topside ionosphere is better represented by the Exponential than the Sech-squared profiler. Therefore, we used the Exponential profiler for the day-time hours (07:00-19:00LT). The reconstructed topside electron concentration (Fig.3) is highly sensitive to the changes in the input parameters. For example, the sharp increase in the foF2 value near 06:00 LT on 11/03/2002 results in a sharp decrease in the slab thickness and depleted electron density above hmF2. The horizontal component (H) of the geomagnetic field is recorded in view of detecting storm conditions.

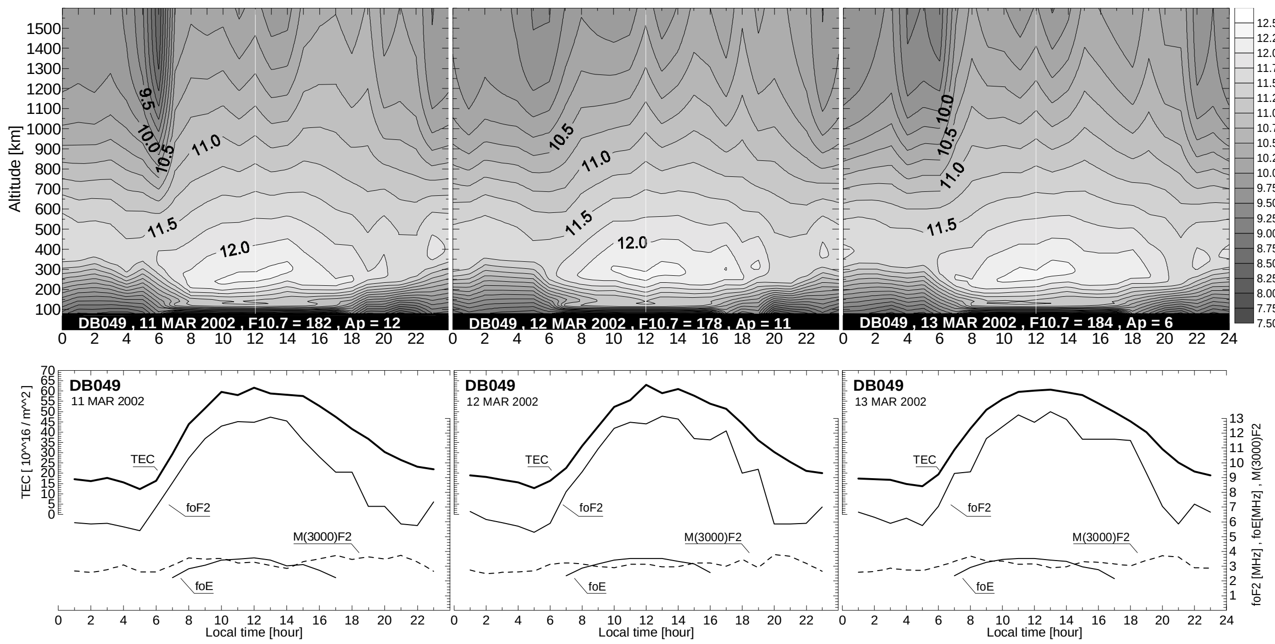

Fig.3 Real-time reconstruction of the electron density profile, 11-13 March 2002, Dourbes (4.6°E, 50.1°N).

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 main conclusions have been made:
* A recently-developed electron density reconstruction technique proved to be very useful in developing a new procedure that will allow obtaining more information on the topside electron density distribution in a real-time mode.
* The developed operational procedure is reliable, easy to maintain and upgrade. It is important that new measurements can be obtained and processed 4 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, in particular.
* 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) alone, 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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