On the real time reconstruction of the ionospheric electron density profile based on concurrent measurements from collocated digital ionosonde and GNSS receiver

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Abstract

This paper is concerned with the open issue of reliably specifying, in real time, the vertical electron density distribution in the upper ionosphere. We share our experience in developing a technique for reconstructing the ionospheric electron profile and the recent implementation of this technique into an operational system based on measurements from the collocated digital ionosonde and GNSS receiver installed at the RMI Geophysical Centre in Dourbes (50.1N, 4.6E). The system, dubbed LIEDR (Local Ionospheric Electron Density profile Reconstruction), acquires and promptly processes the incoming measurements, computes the full-height ionospheric electron density profile, and displays the resulting profilograms. LIEDR is designed to operate in continuous real-time mode for service applications and to provide historical data/plots for research applications and further developments of the system.

Introduction

Real-time ionospheric data provision from modern digital ionosondes offers important input to address the needs of the radio communication services and various ionosphere/space research applications. The digisonde is a powerful tool in ionospheric nowcast because of its improved reliability, its ability to automatically scale and analyse the sounding data, and also to promptly distribute the results through internet connections.

The paper presents an operational system for deducing the vertical distribution of the electron density in the local ionosphere. The system LIEDR (Local Ionospheric Electron Density profile Reconstruction) acquires and processes in real time the concurrent and collocated ground-based total electron content (TEC) and digital ionosonde measurements, and ultimately, deduces a full-height electron density profile based on a reconstruction technique originally proposed by *Stankov and Muhtarov* (2001).

First, the reconstruction method will be outlined, followed by a description of the database and the measurements that are required. Next, results from an assessment of the digisonde's autoscaling performance will be presented and error bounds for the autoscaled characteristics of importance to LIEDR will be obtained. The LIEDR system implementation and some representative results will be presented and discussed in the next section. The paper will conclude with an outlook to further developments and possible applications.

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Method

The vertical electron density profile at a given location is deduced from ground-based measurements of the total electron content, ionospheric vertical soundings, and empirically-obtained values of the upper ion transition level (UTL) – the height at which the O^+ and H^+ ion densities are equal. The retrieval of the corresponding electron density distribution is performed in two main stages: construction of the bottom-side electron profile (below $h_m F_2$) and construction of the top-side profiles (above $h_m F_2$). Here we only outline the technique; more details, including the derivation of all formulae, can be found in *Stankov and Muhtarov* (2001), *Stankov* (2002b), *Stankov* et al. (2003).

High-precision ionosonde measurements are used for directly obtaining the lower part of the electron density profile based on Epstein layer functions utilizing measured values of the critical frequencies, $f_o F_2$ and $f_o E$, the peak heights, $h_m F_2$ and $h_m E$, and the propagation factor, $M_{3000} F_2$. The corresponding bottom-side part of TEC is calculated from this profile and is then subtracted from the entire TEC in order to obtain the unknown portion of TEC in the upper part. The topside TEC (TEC_{top}) is used in the next stage for deducing the top-side ion and electron profiles.

The electron density (N_e), at a given altitude h in the topside ionosphere, is considered as a sum of the constituent major ions (O^+ and H^+) densities, N_{O+} and N_{H+}, i.e.

$$N_e(h) = N_{O+}(h) + N_{H+}(h) \tag{1}$$

Each ion density profile is permitted to take one of several forms, as follows:

(Exponential): $$N_i(h) = N_i(h_m)\exp\left\{-\frac{h-h_m}{H_i}\right\} \tag{2}$$

(Chapman): $$N_i(h) = N_i(h_m)\exp\left\{c\left[1-\frac{h-h_m}{H_i}-\exp\left(-\frac{h-h_m}{H_i}\right)\right]\right\},\ c=\begin{cases}0.5\,, & \alpha-Chapman\\ 1.0\,, & \beta-Chapman\end{cases} \tag{3}$$

(Epstein, sech-squared): $$N_i(h) = N_i(h_m)\,sech^2\left(\frac{h-h_m}{2\,H_i}\right) \tag{4}$$

where N_i and H_i are the corresponding ion's (O^+ or H^+) density and scale height, and h_m is the maximum ion density height which, for both ions, is assumed to be at the height of the electron density peak, $h_m F_2$. Thus, considering the two major ions (O^+ and H^+) in the topside ionosphere, there are four parameters that need to be determined in order to reconstruct the topside electron density profile. These parameters are the oxygen topside scale height (H_{O+}), the oxygen concentration at h_m (N_{mO+}), the hydrogen topside scale height (H_{H+}), and the hydrogen concentration at h_m (N_{mH+}). These unknowns require a system of four equations in order to find a unique solution. For the purpose, the following system is assembled:

$$N_{mO+} + N_{mH+} = N_m \tag{5}$$

$$H_{H+} = (\mu_{O+}/\mu_{H+})\,\xi\, H_{O+} \tag{6}$$

$$TEC_{top} = \aleph_{O+}(H_{O+}, N_{mO+}, h_m) + \aleph_{H+}(H_{H+}, N_{mH+}, h_m) \tag{7}$$

$$N_{O+}(H_{O+}, N_{mO+}, h_m; h_{tr}) = N_{H+}(H_{H+}, N_{mH+}, h_m; h_{tr}) \tag{8}$$

where:

N_m – the F2-layer peak electron density ($N_m F_2$)

μ_{O+} – the O^+ ion mass

μ_{H+} – the H^+ ion mass

ξ – the vertical 'scale height' corrector, $\xi = \sin\left[\arctan\left(2\tan\varphi\right)\right]$, φ - latitude

h_{tr} – the O^+/H^+ ion transition height

TEC_{top} – the measured topside TEC (content above $h_m F_2$)

$\aleph_{O+}$ – the integrated topside O^+ ion concentration

$\aleph_{H+}$ – the integrated topside H^+ ion concentration

The first system equation (5), represents the principle of plasma quasi-neutrality. The next equation (6) represents the relation between the O^+ and H^+ ion scale heights. The third equation (7) is obtained after integrating the proposed 'reconstruction' formula (1) from $h_m F_2$ to infinity. The last equation (8) summarizes the fact that the O^+ and H^+ ion densities are equal at the upper ion transition level.

The system is solved by excluding the unknowns from the first three equations and replacing them in the last equation. The resulting transcendental equation features only one unknown parameter, H_{O+}, provided that the values of TEC_{top} (also denoted with Φ_t), h_m, and h_{tr} are already known – measured/modelled. Thus, the equations corresponding to each of the above-described profilers (2, 3, 4) are:

$$\left(\frac{16\,\xi}{(16\,\xi-1)}N_m - \frac{1}{(16\,\xi-1)\,H_{O+}}\Phi_t\right)\exp\left(-\frac{h_{tr}-h_m}{H_{O+}}\right) - \left(\frac{1}{(16\,\xi-1)\,H_{O+}}\Phi_t - \frac{1}{(16\,\xi-1)}N_m\right)\exp\left(-\frac{h_{tr}-h_m}{16\,\xi\,H_{O+}}\right) = 0 \tag{9}$$

$$\left(\frac{16\,\xi}{(16\,\xi-1)}N_m - \frac{1}{\hat{c}\,(16\,\xi-1)\,H_{O+}}\Phi_t\right)\times\exp\left(1-\frac{h_{tr}-h_m}{H_{O+}}-\exp\left(-\frac{h_{tr}-h_m}{H_{O+}}\right)\right) - \left(\frac{1}{\hat{c}\,(16\,\xi-1)\,H_{O+}}\Phi_t - \frac{1}{(16\,\xi-1)}N_m\right)\times\exp\left(1-\frac{h_{tr}-h_m}{16\,\xi\,H_{O+}}-\exp\left(-\frac{h_{tr}-h_m}{16\,\xi\,H_{O+}}\right)\right) = 0$$

$$\hat{c} = \begin{cases} 2.821\,, \alpha - Chapman \\ 1.718\,, \beta - Chapman \end{cases} \tag{10}$$

$$\left(\frac{16\,\xi}{(16\,\xi-1)}N_m - \frac{1}{2\,(16\,\xi-1)\,H_{O+}}\Phi_t\right)\text{sech}^2\left(\frac{h_{tr}-h_m}{2\,H_{O+}}\right) - \left(\frac{1}{2\,(16\,\xi-1)\,H_{O+}}\Phi_t - \frac{1}{(16\,\xi-1)}N_m\right)\text{sech}^2\left(\frac{h_{tr}-h_m}{32\,\xi\,H_{O+}}\right) = 0 \tag{11}$$

Each of these equations can be solved using dichotomy methods for finding the root (i.e. the unknown). Having the O^+ scale height value H_{O+} calculated, the rest of the unknowns (H_{H+}, N_{mO+}, N_{mH+}) can be obtained from formulae (5) - (7). The topside electron profile is then easy to reconstruct from the main formula (1) and the selected profiler.

Data

Most measurements needed for the LIEDR operation are made at the RMI Geophysical Centre in Dourbes (50.1ºN, 4.6ºE) (*Stankov*, 2002b).

The Dourbes digital ionosonde (URSI code: DB049) carries out regular vertical ionospheric soundings with a Lowell Digisonde-256. All ionograms are automatically scaled and the values of $f_o F_2$, $f_o E$, $M_{3000} F_2$, $h_m F_2$ are deduced with only a short delay. 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. Currently, the sounding rate is set to 1 per every 15 minutes, but it can be increased if necessary.

TEC observations are made with a GPS (Global Positioning System) receiver (co-located with the digisonde) by applying a computational procedure based on a 'geometry-free' combination of GPS code and phase measurements for resolving the ambiguities. Receiver and satellite group delays are estimated via polynomial approximation of the slant TEC, depending on latitude and local time. The conversion to vertical TEC assumes the standard ionospheric thin-shell model at a mean ionospheric height of 350 km. To obtain a TEC value for the ionosphere above a given location, selected and averaged are all values within a latitudinal range of ±1.5° over a 15 minute period.

It is well known that the plasma scale height, and the vertical plasma distribution in general, change substantially during active/storm geomagnetic conditions; therefore, monitoring the geomagnetic activity is considered an important component of the LIEDR system. For determination of the local geomagnetic activity, we use 1-min vector magnetic field (H, D, and Z components) data as obtained directly from the instruments of the Dourbes magnetic observatory; with precision of 1 sec for time and 0.1 nT for the field components. A nowcast system for operational estimation of the geomagnetic index K has already been deployed.

Since the relative abundance of oxygen and hydrogen ions in the upper ionosphere is a significant factor affecting the topside plasma density distribution, the O^+/H^+ transition level is a key reference point in the reconstruction technique. Here, the UTL value is obtained from an empirical model (*Kutiev et al*., 1994; *Stankov*, 2002a) based on satellite and rocket in-situ ion density measurements, parameterised by solar activity, season, local time, latitude and longitude.

Assessment of the digisonde's autoscaling performance

In this section we investigate the reliability of the digisonde's autoscaling algorithm in terms of regularly providing autoscaled values and the quality of the autoscaling itself. For the purpose, we have statistically analysed autoscaled and manually-scaled ionospheric characteristics based on the Dourbes digisonde's data from year 2002 through 2008 (more than 50,000 ionograms).

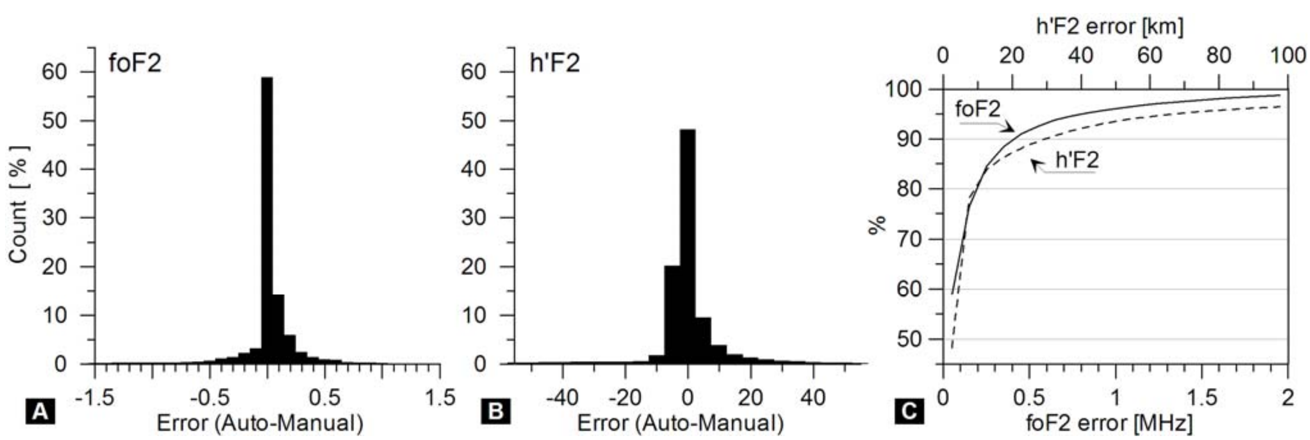

Fig.1. Comparison between automatically and manually-scaled ionospheric characteristics for the Dourbes DGS-256 / ARTIST-4 system during the 2002-2008 period. (A/B): Histograms of the foF2 and h'F2 errors. (C): Relative cumulative foF2 and h'F2 error distributions.

It has been found that the DGS-256/ARTIST-4.0 system was able to provide automatic scaling in 94-98% cases for all characteristics except foF1 (89%). Some results for foF2 and h'F2 are presented in **Fig.1**. Histograms of the residual errors (autoscaled minus manually-scaled values) show (**Fig.1**A/B) that "perfect" matches are achieved in 58% for foF2 (error within ±0.05MHz) and about 50% for h'F2 (±2.5km). The relative cumulative foF2 and h'F2 error distributions (**Fig.1**C) show that about 85% of the foF2 / h'F2 errors are within 0.3 MHz / 15 km accuracy. Based on the above analysis, error bounds have been determined (95% probability) for each of the following characteristics: foF2(-0.75,+0.85MHz), foE(-0.35,+0.40MHz), h’F2(-68,+67km), h’E(-26, +2km), and M3000F2(-0.55,+0.45). For some characteristics (mostly foF2 and M3000F2) the autoscaling accuracy varied noticeably in local time, season and solar activity. Although geomagnetic storms seem to affect the autoscaling, the overall results about the influence of geomagnetic activity remain inconclusive.

System implementation and results

The described nowcast system has been implemented at the RMI Geophysical Centre in Dourbes and proved to be capable of producing density profiles every 15 min, which is a sufficiently good rate for many applications, including ionospheric storm investigations. As an example, a screenshot of the LIEDR system output is presented in **Fig.2** for the recent storm period of 10-13 March 2011.

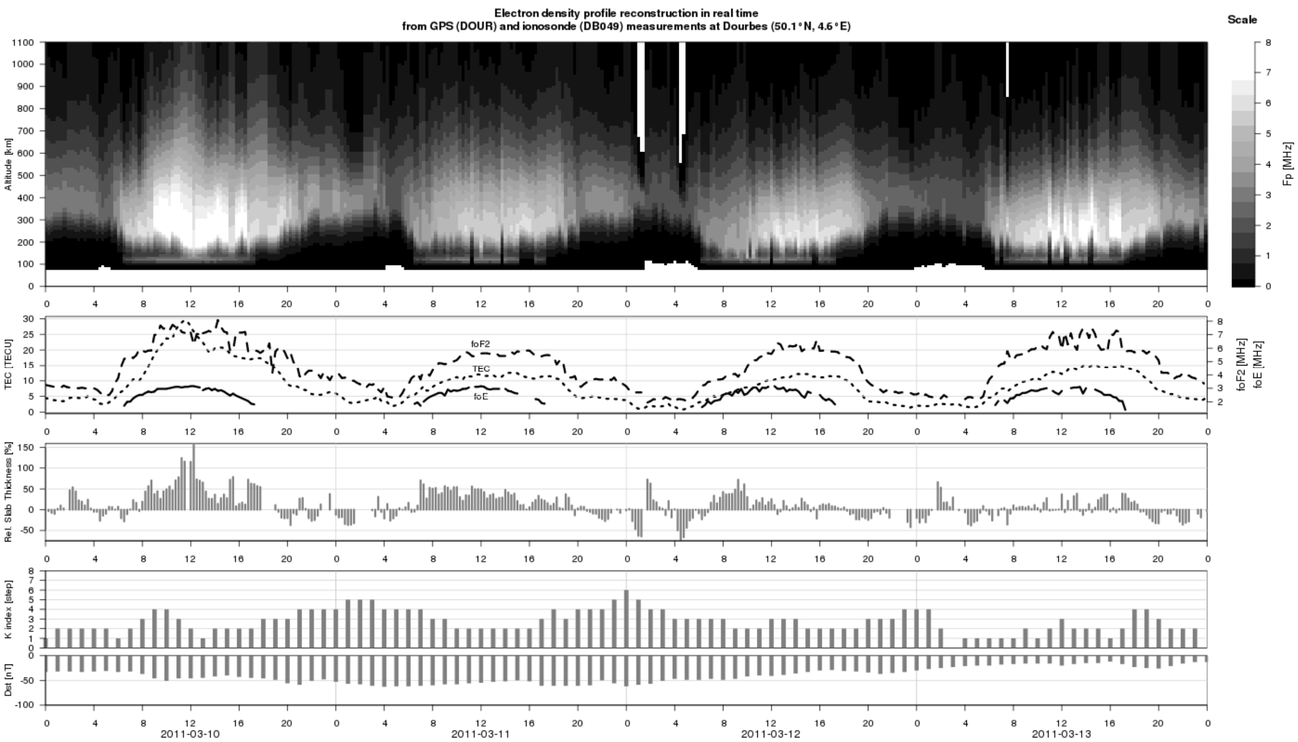

Fig.2. Real-time reconstruction of the electron density profile at Dourbes (4.6°E, 50.1°N) during the storm time period 10-13 March 2011. Top panel: profilograms showing the reconstructed electron density (plasma frequency) profiles as function of height and time. Second panel: GPS TEC and ionosonde measurements of the critical frequencies foF2 and foE. Third panel: Ionospheric slab thickness measurements. Bottom panel: Geomagnetic indices K (Dourbes) and Dst (Lund) estimations in real time.

In the top panel, the reconstructed altitudinal electron density profile is plotted against the universal time as soon as the profile becomes available. Thus, over time, a so-called profilogram is produced, in this case over a period of 96 hours. For better graphic representation, instead of the electron density (N_e), the plasma frequency (f_p) is plotted (colour-coded, scale on the right): $f_p[MHz] = 0.898 \times 10^{-5} \sqrt{N_e[el/m^3]}$. In this case, the Epstein layer is applied for night-time conditions, while the Exponential profiler is used during day-time hours. Note the detailed vertical distribution in the upper ionosphere - it is easy to detect the changes in the calculated scale height and the resulting density distribution as they change during the day. TEC and f_oF_2 (second panel) show similar diurnal behaviour during the first day of the storm (10 March). Both quantities increase sharply in the morning, reach their maximum around noon, maintain relatively high values in the afternoon, and then decrease steadily in the evening hours. The next day (11 March) was characterised with the development of a negative phase, i.e. depleted TEC and f_oF_2, that continued throughout the following day (12 March).

The operational reconstruction of the electron density profile was unproblematic most of the time, with only a few exceptions when the digisonde failed to deliver autoscaled values or the TEC values were too low to produce realistic topside profiles (cf. the white stripes). The plot clearly shows the increased electron density and topside plasma scale height during the positive phase of the storm and the depleted ionosphere during the recovery phase.

Summary and outlook

An operational system for deducing and imaging the vertical distribution of the electron density in the local ionosphere was presented together with results demonstrating the system's operational capabilities. LIEDR offers an easy access to current and historical images and data records concerning the local ionospheric behaviour. The growing availability of GNSS TEC and ionosonde measurements, combined with the demonstrated ability to run the system in real time, gives both the approach and the system much potential. Possible applications include: testing and developing various ionosphere-plasmasphere models, facilitating ionospheric data assimilation and tomography applications, optimising radio system and GNSS positioning operations, investigating ionospheric storms and other space-weather studies. With the help of the other companion developments (geomagnetic activity and slab thickness monitoring), LIEDR offers opportunities for gaining a deeper understanding of the physical processes (and the drivers behind these processes) in the local ionosphere. Both the input data and the reconstruction results can be used for validation purposes in ionospheric models, maps, and services. Distribution and bounds of physically-possible model-driving parameters and solutions can also be investigated. With the new wealth of prompt data, it is imperative that effective (data assimilation and tomography) methods be developed for use in ionospheric modelling and research. The profile reconstruction technique is further being developed to incorporate variable scale height profilers. Also, implementations of a new UTL model from topside sounders data and a short-term ionospheric forecast are under way.

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