COMPARISON OF TRUE-HEIGHT ELECTRON DENSITY PROFILES DERIVED BY POLAN AND NHPC METHODS

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ABSTRACT

The changing state of the ionosphere is generally monitored by networks of vertical ionosondes that provide us with regular ionospheric sounding. Many ionospheric applications require determination of the true-height electron density profiles. Therefore, ionograms must be further inverted into real-height electron density profiles. The paper presents the comparison study of the true-height electron density profiles inverted from ionograms using two different methods POLAN (Titheridge, 1985) and NHPC (Huang and Reinish, 1996; Reinish et al., 2005), widely used by the ionospheric research community. Our results show significant systematic differences between electron density profiles calculated by these two inversion methods.

Key words: ionosphere, vertical ionospheric sounding, electron concentration profiles, inversion methods

1. INTRODUCTION

Ionosphere, the ionised part of the Earth's neutral atmosphere, is stratified into several layers that are referred to as D, E, and F (F1 and F2). Borders between layers are characterised by the electron concentration decrease. Maximum electron concentration usually occurs in the highest layer F or F2, if the layer is splitted into F1 and F2. The ground-based vertical ionospheric sounding using ionosondes provides information about part of the ionosphere above 90 km up to maximum of F layer, thus E and F ionospheric layers. Regions with decrease of electron concentration represent problematic regions invisible for ground-based ionosondes. Propagation of electromagnetic waves is affected by the properties of a medium. The ionospheric plasma consists of free electrons and ions. The basic parameter of ionised medium is plasma frequency, which is key parameter in the theory of radio wave propagation. The relation between electron concentration and electron plasma frequency ω_p is given by:

$$\omega_p = \sqrt{\frac{Ne^2}{\varepsilon_0 m}} , \tag{1}$$

where N is electron concentration, e is electron charge, m electron mass and ε_0 is permitivity of free space. Electromagnetic waves with frequencies exceeding plasma frequency enter and propagate through medium. Vertical wave reflection occurs when the plasma frequency is lower or equals to the wave frequency. Details can be found in *Davies (1990)*, *Hargreaves (1979)*, *Chen (1984)* among others.

During vertical ionospheric sounding measurement, the electromagnetic wave is transmitted vertically above ionosonde. Receiving antennas co-located with the transmitter detect the reflected wave from the ionosphere. The registered time-of-flight of the radio signal at a particular frequency indicates the virtual height (h') of the reflecting layer, assuming the wave speed to be equal to that on free space. The 2D-plot of h' as function of the transmitted radio frequency is called ionogram. The h' is always higher than the real height (h) because of the group and phase delays of radio waves travelling throughout an ionised medium. Fig. 1 shows typical day-time and night-time ionograms obtained by ionosonde IPS42 Kel Aerospace. Determination of the real reflection height h is the main goal of all inversion techniques, i.e. to obtain true height electron density profiles $h(N)$ from ionograms.

A large family of ionospheric models exists to study variability of the ionosphere. The models differ by their degree of complexity, calculation time and their primary purpose (*Bilitza, 2001*; *Nava et al., 2005*; *Hochegger et al., 2000*; *Leitinger et al., 2001, 2005*; *Titheridge, 1985*; *Huang and Reinish, 1996*, among others). All are based on ionogram parameters or whole profiles. Paper by *Hochegger et al. (2000)* descibes models that are mainly used for satellite applications and reports their particular uses. For ionospheric studies, dealing with short term electron density variability, two inversion techniques POLAN and NHPC are mainly used by ionospheric community. POLynomial ANalysis POLAN has been developed by *Titheridge (1985)* and it is often used for inversion of ionograms obtained by classical ionosondes (e.g. KEL). NHPC algorithm (*Huang and Reinish, 1996*) is applied routinely by UMLCAR DGS and DPS digisondes to ionogram

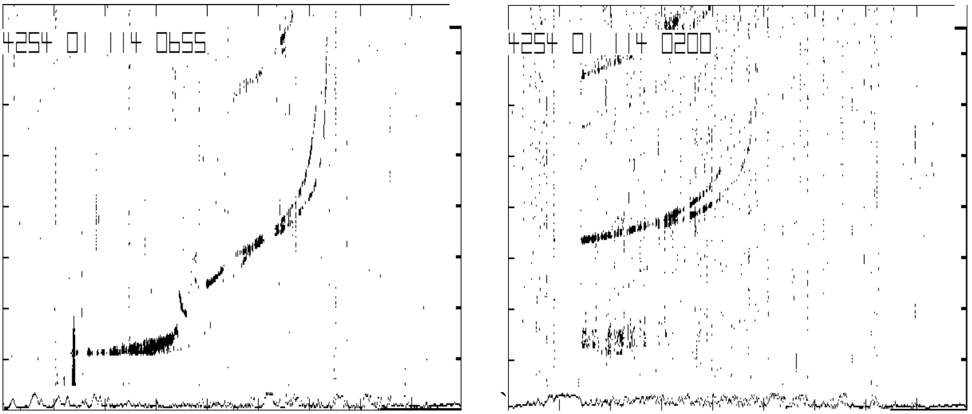

Fig. 1. Representative day-time and night-time ionograms measured by IPS41 KEL Aerospace, 24 April, 2001 at the observatory Průhonice. Left panel represents ionogram recorded at 6 h 55 min UT, right panel at 2 h UT.

inversion, NHPC inversion is also part of the ARTIST software used for automatic ionogram scaling.

Resulting true height electron density profile differs according to model used between layers and uderlaying ionisation. The purpose of our paper is to analyse that and show possible problems that might arise from analyses based on data inverted by different techniques. There is very little chance for user to change parameters of the model involved in the inversion technique. In general, each station has its preferred inversion method for true-height profile computation, that may lead to systematic differences between stations.

In the work of *Šauli et al. (2006)* we found significant differences in the diurnal courses of electron concentration curves at fixed heights at two midlatitude ionospheric station data. Electron concentration lines at fixed height were remarkably smoother when they were derived from NHPC inverted ionograms. These finding was a motivation for our further work. The question was, which part of the wave-like oscillation is related to ionospheric variability and to the inversion technique. *Miró et al. (2005)* found important differences in radio path range and reflection height, when the ray-tracing code uses electron density profiles obtained from the same ionograms by the POLAN and NHPC inversion techniques.

2. DATA

In our analysis, we use ionograms from two midlatiude ionospheric stations Ebro (Spain, 40.8°N, 0.5°E) and Průhonice (Czech Republic, 49.9°N, 14.5°E). Průhonice ionograms were measured by ionosonde IPS 42 KEL Aerospace and Ebro ionograms by digisonde DGS256. Total amount of 10361 ionograms was manually scaled and then recomputed into true height $N(h)$ profiles using the above mentioned methods. Our data set represents ionospheric measurements under low and high geomagnetic activity during periods of high and low solar activity. Průhonice data set covers years 1992–2001. Analysed profiles are representative for all the period as they are regularly distributed over period. Measurements from campaign HIRAC/SolarMax, 23 – 29 April 2001 (*Feltens et al., 2001*) provide us with high quality data and for this period two station data are involved into study. During this campaign ionograms were measured each 5 minutes. As an input to the ionogram inversion we use whole trace. Fig. 2 shows typical geomagnetic quiet time electron density profiles obtained by both techniques. It is evident that on the profiles, there are parts that differ significantly and may lead to miss-interpretation of the further analysis. The following Figs. 3 and 4 show the diurnal courses of electron concentration at fixed heights 150 – 250 km with 5 km step for two stations. Fig. 3 represents electron concentration variability under geomagnetic quiet conditions (high solar activity) and two inversion techniques. The same situation, but for geomagnetically disturbed period, is demonstrated by following Fig. 4. It can be clearly seen that curves of electron concentration are more smooth in case of NHPC inversion technique for both station data.

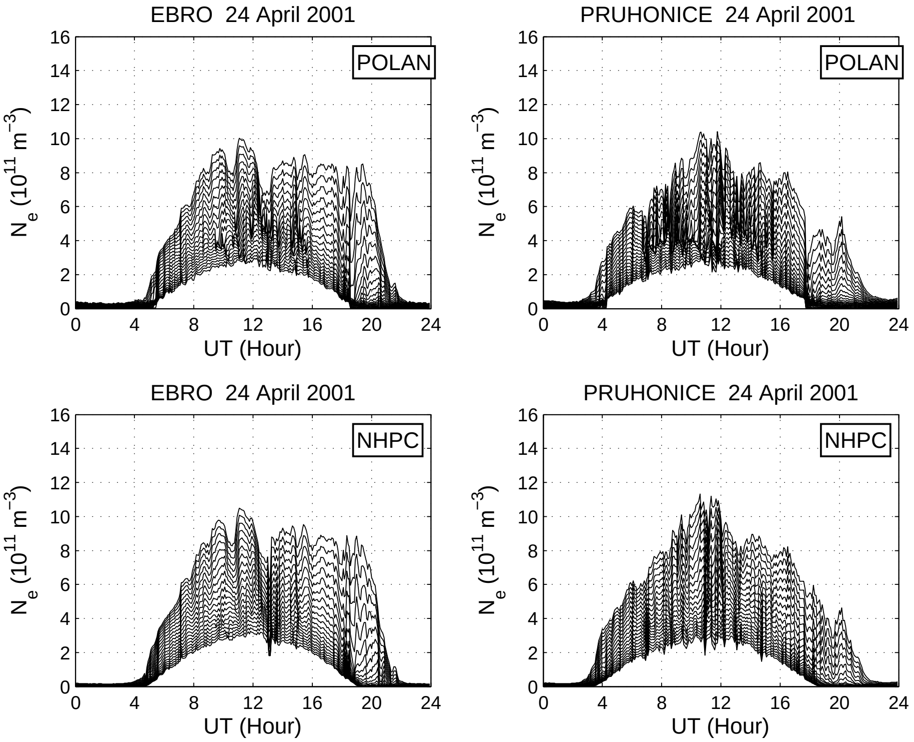

Fig. 2. Typical recomputation difference of the electron density profiles obtained byNHPC and POLAN. Ionograms were recorded at the observatory Průhonice.

3. METHOD

Two and three layer profiles computed using both methods (POLAN, NHPC) are splitted into two or three parts with respect to the critical frequencies *foE*, *foF*1 and *foF*2. Since both algorithms use Valley-model (different for POLAN and NHPC) in a certain frequency interval we have more than one height-value for one frequency, we cut off such frequency interval in order to get monotonous (increasing) height dependence of plasma frequency only. Similarly, the top part of each profile higher above *foF*2 was neglected.

Profile points $\left[h, f_p\right]$, pairs of height h and plasma frequency f_p, are not always equidistant. In order to compare two profiles we use frequency and height sets derived from original profile using linear interpolation. Frequency set consists of values at fixed frequencies beginning 1.5 MHz with 0.1 MHz resolution. Height set contain values at fixed heights from 90 km up to height of the F-layer peak. Thus we get one, two or three parts corresponding to each layer for each profile. After that, we analyse the height and frequency differences (POLAN – NHPC) for frequency and height interpolated profiles, respectively, via classical statistical method:

$$\Delta_{X_i} = X_{i_{\mathrm{POLAN}}} - X_{i_{\mathrm{NHPC}}} \,. \tag{2}$$

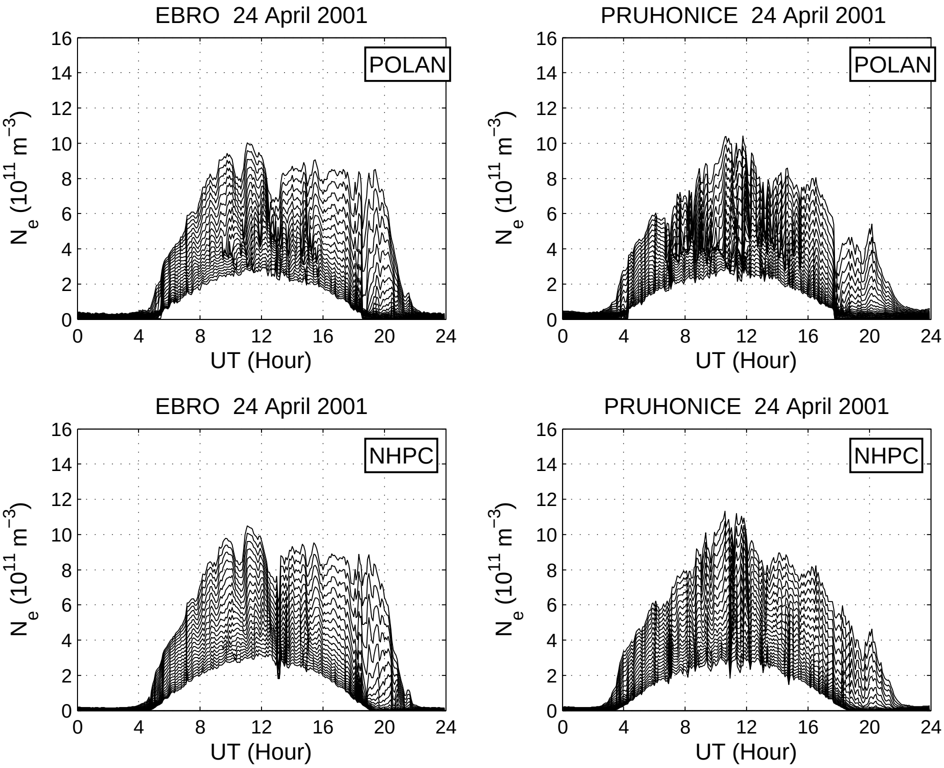

Fig. 3. Electron density variation obtained by NHPC and POLAN from Ebro and Průhonice observatories - 24 April 2001. Upper panels refer to POLAN recomputation technique, while the lower panels to NHPC.

Values X_i stand for heights h_i and frequency f_i, respectively. Each data set is represented by mean and standard deviation (*Weisstein, 2006*; *Anděl, 1998*) for each frequency and height

$$\langle X_i \rangle = \frac{1}{N} \sum_{j=1}^{N} X_j \ , \tag{3}$$

$$\sigma_{X_i} = \sqrt{\langle X_i^2 \rangle - \langle X_i \rangle^2} \ . \tag{4}$$

With increasing frequency (or height) the number of measurements N in the group decreases due to the variability of critical frequencies. Though sets with 100 or less values were neglected. However, the criterion of minimal number of values does not have large influence on the results. Each group of one-layer, twolayer and three-layer profiles is further divided into two subsets with respect to the geomagnetic situation. We consider geomagnetic quiet conditions described by index $Kp < 4$.

4. RESULTS

Results of statistical analysis are divided into two main parts discussing separately height differences and frequency differences between electron density profiles obtained by POLAN and NHPC methods. For all groups of profiles (characterised by number of layers and specified geomagnetic conditions) we demonstrate mean value and its standard deviation computed according to Eqs.(2)–(4). All the following plots in Figs. 5–7 represent statistical means and standard deviations of each analysed group; each group consists of minimum 730 profiles. Height and frequency dependence of the difference between mean values of each particular group of profiles are further discussed in details.

4.1. Height difference

Figs. 5 and 6 show mean difference of the reflection height at fixed frequencies and its corresponding standard deviation. Fig. 5 represents geomagnetically quiet conditions analysis. In the upper panels (night profiles, only F layer present), it is evident that POLAN systematically underestimates true height compared to NHPC at lower frequencies and overestimates at frequencies close to critical frequency *foF*2. However,

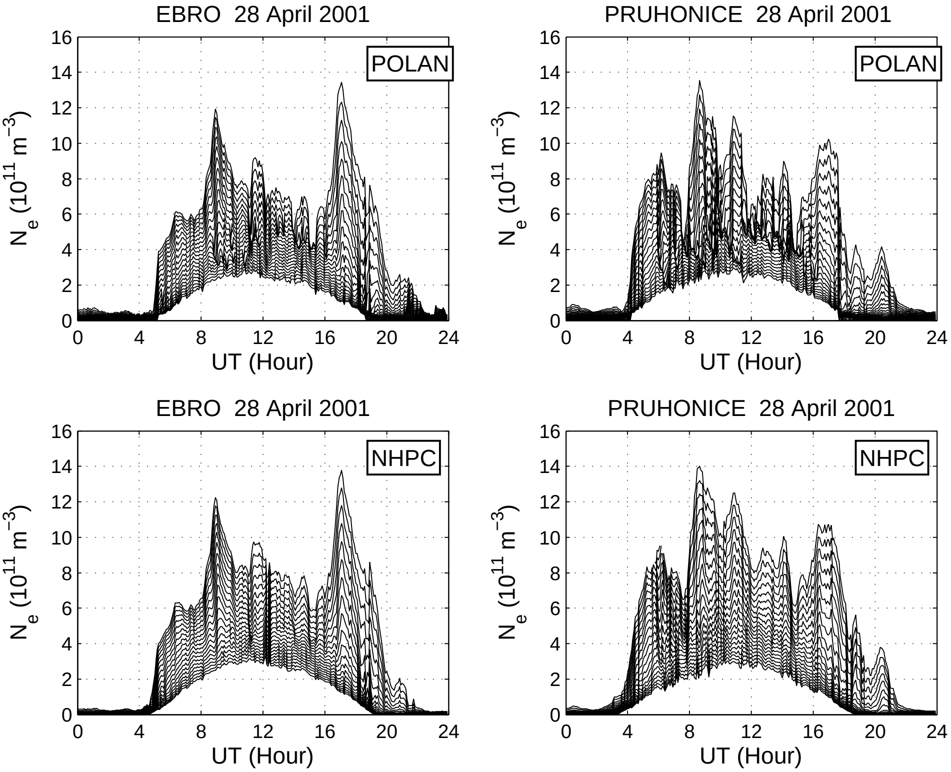

Fig. 4. The same as in Fig. 3, but for the day of geomagnetic minor storm 28 April 2001.

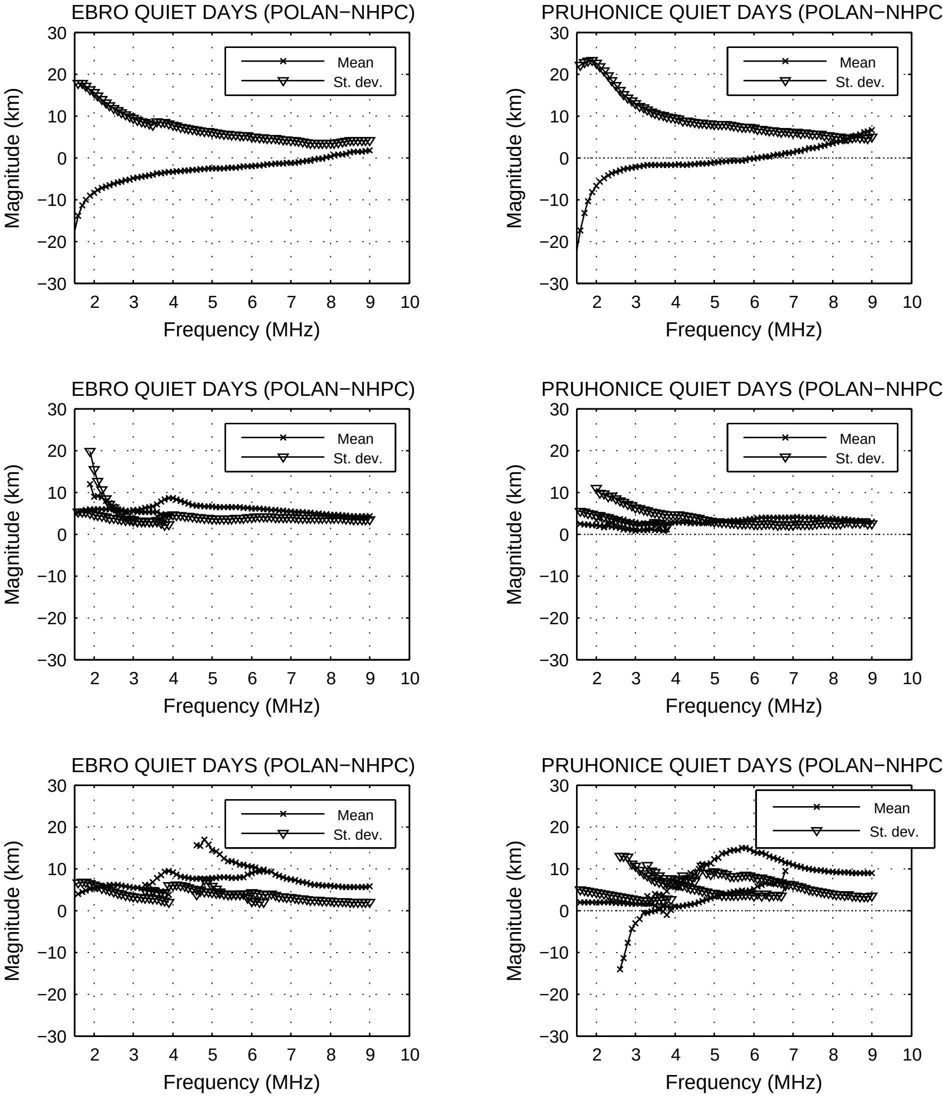

Fig. 5. Results of statistical analysis of the height difference between POLAN and NHPC inverted profiles at particular frequencies during geomagnetically quiet time. Each plot shows frequency dependence of the mean and standard deviation values. On the plots mean values are marked with “×”, symbol “∇” stands for standard deviation. The top plots show the results for nighttime profiles, when only F layer is present. The middle plots represent the results for daytime profiles, when only E and F layer are present. The bottom plots show the results for daytime profiles, when E, F1 and F2 layers are formed.

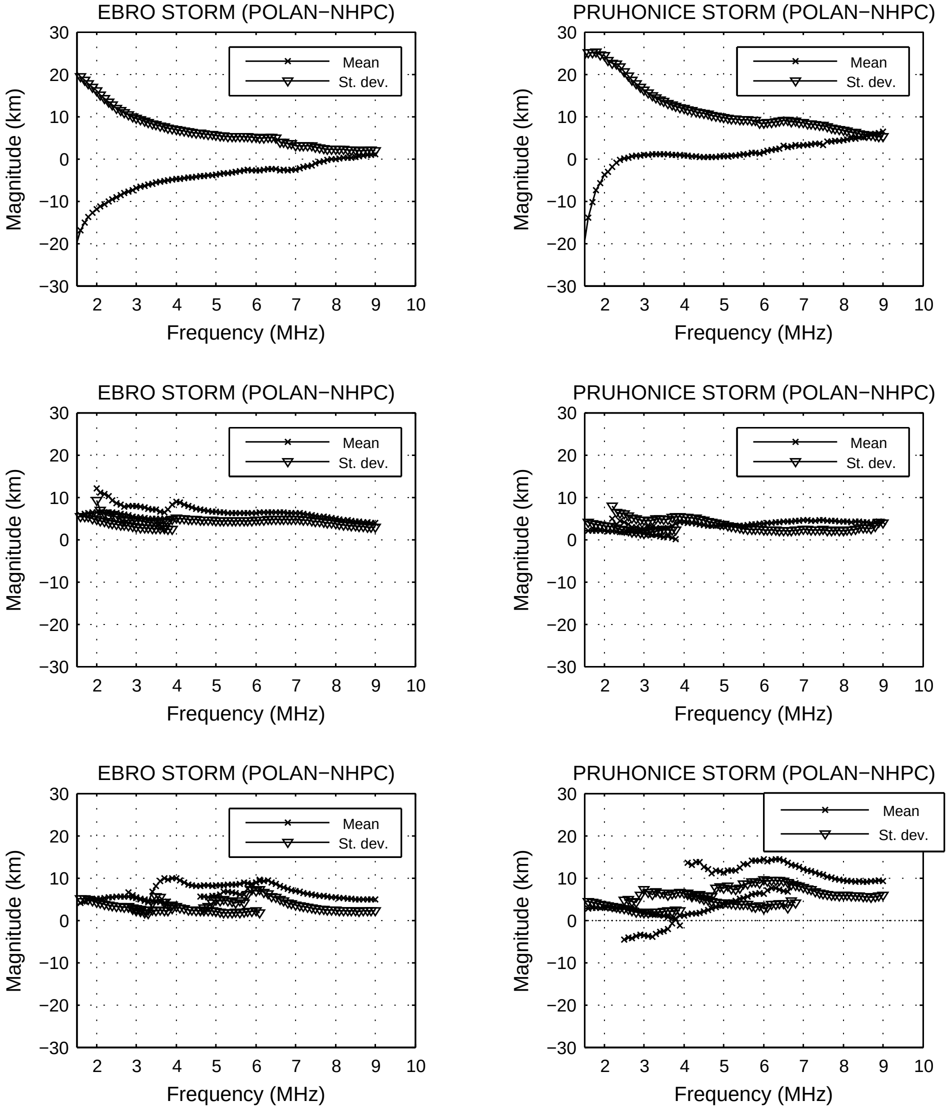

Fig. 6. Results of statistical analysis of the height difference between POLAN and NHPC inverted profiles at particular frequencies during geomagnetic storm. Each plot shows frequency dependence of the mean and standard deviation values. On the plots, mean values are marked with "×", symbol "∇" stands for standard deviation. The top plots show the results for nighttime profiles, when only F layer is present. The middle plots represent the results for daytime profiles, when only E and F layer are present. The bottom plots show the results for daytime profiles, when E, F1 and F2 layers are formed.

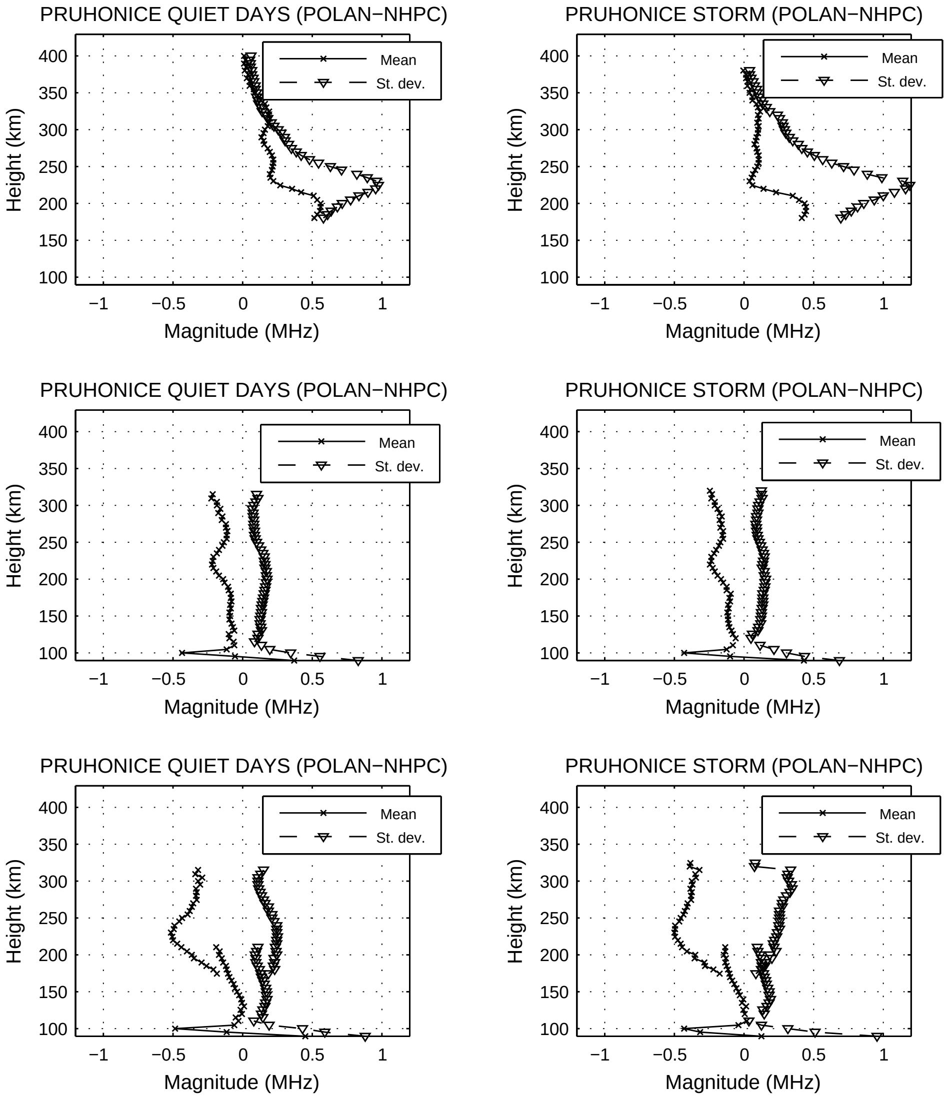

Fig. 7. Results of statistical analysis of the frequency difference between POLAN and NHPC inverted profiles at particular heights. Each plot shows height dependence of the mean and standard deviation values. On the plots mean values are marked with “×”, symbol “∇” stands for standard deviation. Left panels refer to geomagnetically quiet time, right panels to geomagnetic storm time. The top plots show the results for nighttime profiles, when only F layer is present. The middle plots represent the results for daytime profiles, when only E and F layer are present. The bottom plots show the results for daytime profiles, when E, F1 and F2 layers are formed.

the standard deviation reaches large values in the whole studied frequency range, especially at low frequencies. When two or three layers are present, true height derived by NHPC is systematically lower than that computed by POLAN. Maximum differences are located around 5–6 MHz (Fig. 5, bottom panel) and exceed values of 10 km in case of three-layers profiles. Results for two stations are in agreement. During high geomagnetic activity (Fig. 6) the character of the result remains the same except for Průhonice night-profiles, where the difference is positive and very close to zero. Standard deviation significantly increases in case of one-layer profiles (Fig. 6, upper panel). Maximum difference at two-layer and three-layer profiles occurs close to 5–6 MHz (Fig. 6, middle and bottom panels). Maximum difference is larger in Průhonice data. Larger differences at nighttime occur on the base of the F region, and at the transition regions between layers during daytime. This is probably caused by different connection techniques between layers in both inversion algorithms POLAN and NHPC.

4.2. Frequency difference

Fig. 7 demonstrates height dependence of frequency difference of profiles for Pr°uhonice data. It is evident that the largest difference in one-layer profiles occurs slightly below 200 km. The difference has positive values, that means at fixed height, POLAN computes larger frequency than NHPC. In all other cases (presence of two or three layers), we see that maximum difference is systematically shifted about 30 km upward and reaches negative values. Under presence of more than one layer, POLAN computes lower frequency than NHPC at a given height. In general, mean standard deviation is larger in stormy data sets compare to quiet days except two-layers profiles. During night-time, when only F-layer is present, mean standard deviation reaches maximum values up to 1 MHz (during storm-time exceeds 1 MHz), such values exceed mean values. That means, we cannot simply conclude that POLAN systematically computes higher frequency at a given height. Bottom and middle panels in Fig. 7 reveal location of the maximum difference close to 200 km independently on the geomagnetic condition. Large differences in the profile bottom parts are caused by model application as described in the previous part.

Results of two observatories are in good agreement and POLAN - NHPC comparisons demonstrate the importance of careful interpretation of the ionospheric true-height profiles derived by these techniques. Study of the entire period covering periods of low and high solar activity confirm our finding discussed for HIRAC profiles.

5. CONCLUSIONS

The reflection true height for a given frequency computed by NHPC is systematically higher at nighttime profiles. On the contrary, the reflection true height for a given frequency computed by POLAN at day-time profiles is higher, and the standard mean deviation representing the significance of the result is smaller especially in two-layers profiles. Similarly, best agreement of both inversion techniques is seen on two-layers profiles. Location of the largest difference between profiles corresponds to F1-layer and transition region between F1 and F2 regions. We emphasise that results at two distant observatories are consistent and that results remain the same through changing solar and geomagnetic activity. One possibility how to try to find which method might be better, POLAN or NHPC, is to use simultaneous common volume measurements of digisonde and a Doppler-type system at 3.5 MHz and compare phase paths from Doppler measurements and POLAN-based and NHPC-based ionogram inversions, as suggested by *Burešová D. et al. (personal communication, 2006)*.

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