

The circumpolar ionosphere is recognized as one of the most disturbed region of the ionized part of the atmosphere. The reasons for that are mainly dynamic conditions in the coupled system of the magnetosphere and the ionosphere as well as feeding of the polar plasma from the mid-latitude reservoir. One of the consequences of these phenomenon is the occurrence of large-scale ionospheric structures called polar patches.

The work presents a new algorithm of ionospheric patch detection with ground-based GNSS data and its application to preliminary statistical investigations of polar activity in the northern hemisphere. We detect the patches with relative STEC values derived directly from time series of geometry-free combination. The temporal variation of this combination corresponds exactly to a change of ionospheric delay along the signal path and thus, it can be converted to the relative STEC value. In order to extract the information on plasma enhancement associated with ionospheric structures we propose a two-step algorithm.

The first part of the applied procedure aims at phase measurement cleaning. Its starting point is the generation of L_4 time series for each satellite arc assuming elevation mask equal to 15° . Subsequently, a cycle-slip detection using temporal difference of geometry-free combination is performed. This examination, performed with a threshold limit set to 10 TECu/min, provides time series of L_4 data divided into clean subarcs. The data with no cycle-slips longer than 15 minutes are shifted in compliance with the equation:

$$\tilde{L}_{4(k)} = L_{4(k)} - \text{median}(L_{4(i,j)} + P_{4(i,j)})_{\text{arc}} = I_{4(k)} - \text{DCB} \approx -P_{4(k)}$$

The terms $\tilde{L}_{4(k)}$, $L_{4(k)}$, $P_{4(k)}$ represent shifted phase, phase and code data at epoch k , whereas $L_{4(i,j)}$ and $P_{4(i,j)}$ are time series of GNSS phase and code data for particular subarc. For sparse short periods (< 15 minutes) of low quality data, $\tilde{L}_{4(k)}$ values are simply computed as 5-epoch moving average of $-P_{4(k)}$.

The second part of the algorithm extracts the information on relative STEC enhancement observed for ionospheric structures. For this purpose we use an iterative polynomial fitting of the 4th order. The first fitting provides an initial information on the occurrence of ionospheric disturbances. If the difference between $\tilde{L}_{4(k)}$ and a corresponding value of polynomial does not exceed 3 TECu for any epoch, we assume that there are no disturbances and the process of background STEC estimation terminates. Otherwise, the process of fitting is repeated twice, excluding the epochs with the above difference higher than 1.5 TECu. This reduction of data with positive enhancement enables a faster convergence of results to the background STEC level. Finally, we compute the relative STEC values as a difference between $\tilde{L}_{4(k)}$ and the fitted polynomial.

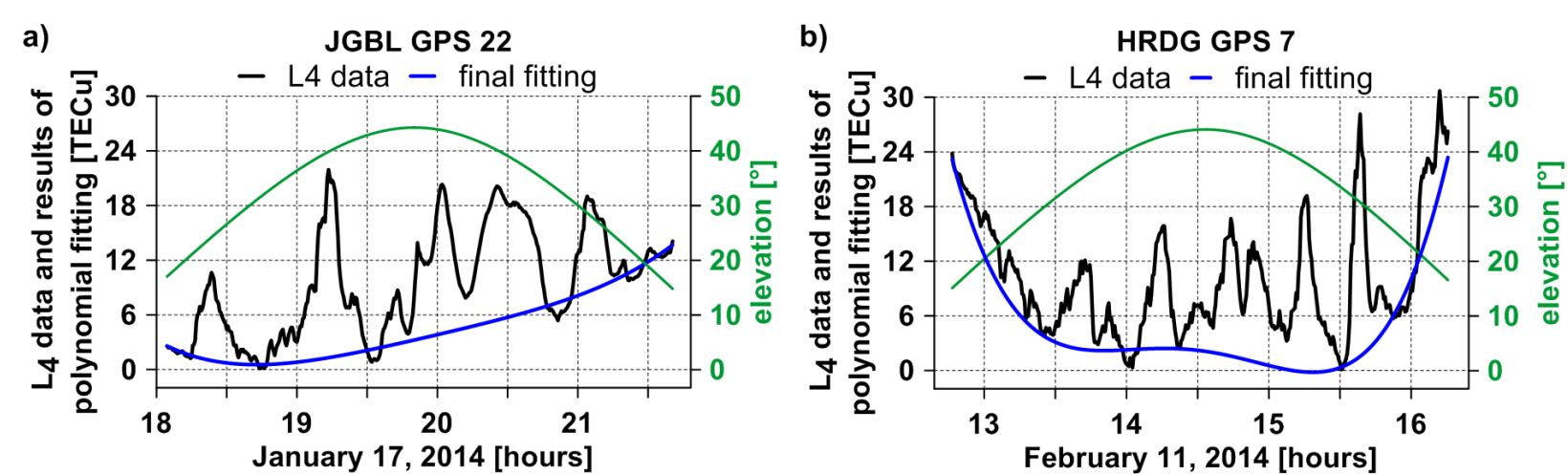


Fig.1 The results of background STEC estimation with an iterative polynomial fitting.

Since the single-arc results are limited applicability for statistical investigations, we apply the above algorithm to 30-seconds data provided by 48 stations of International GNSS Service (IGS), EUREF Permanent Network (EPN) and Plate Boundary Observatory (PBO) mission (Fig. 2).

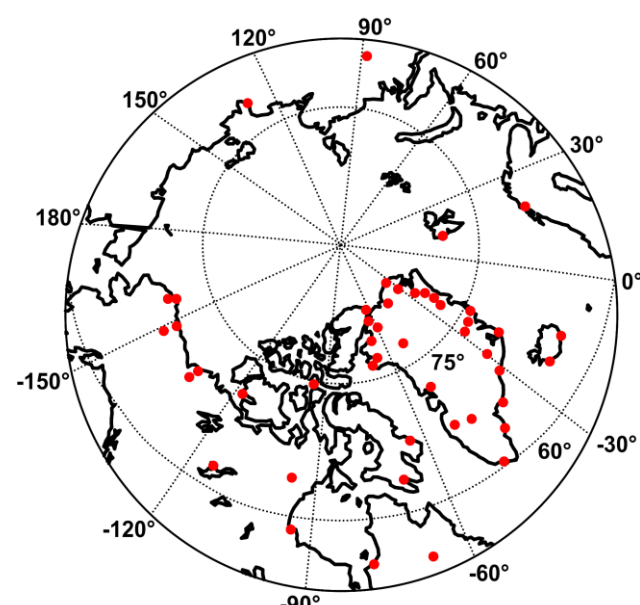


Fig.2 Localization of GNSS stations used in experiment.

We decided to monitor the ionosphere within the sector marked in Figure 3a. This is warranted by continuous time series of observations and the unification of the detection point providing a homogenous dataset. The narrow range in the direction of the patch propagation of 3° allows us to avoid merging structures that follow one after another as well as their multiple counting.

Considering the patch definition we cannot apply the common criterium that is double amount of plasma. Thus, we use an equivalent ratio for GNSS data involving our results and VTEC derived from global ionospheric maps

$$\frac{\text{relative STEC} + \text{VTEC}}{\text{VTEC}} > 1.5$$

In this equation the relative STEC represents the maximal epoch-wise value in the chosen sector, whereas VTEC corresponds to the state of the ionosphere at the north geomagnetic pole (the centre of area used for detection). The latter value is linearly interpolated for each epoch from the hourly GIM. The mixing of slant and vertical TEC in the applied ratio is correct if we assume an approximately spherical shape of patches and, consequently, low dependence of their enhancement on the elevation angle. Since the slant signal may penetrate the auroral oval as well, the above definition is insufficient for GNSS data and has to be constrained with an absolute lower limit, which in our case is set to 6 TECu.

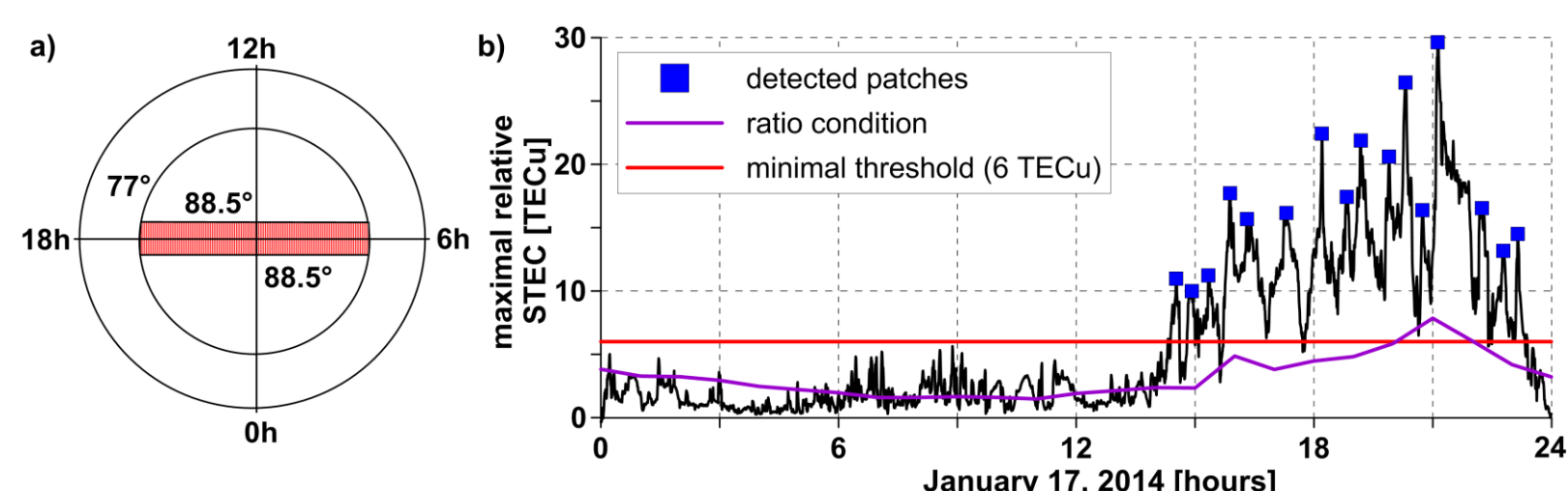


Fig.3 The area of patch detection (a) and functioning of algorithm aimed at identification of polar structures from multi-station solution (b)

RESULTS

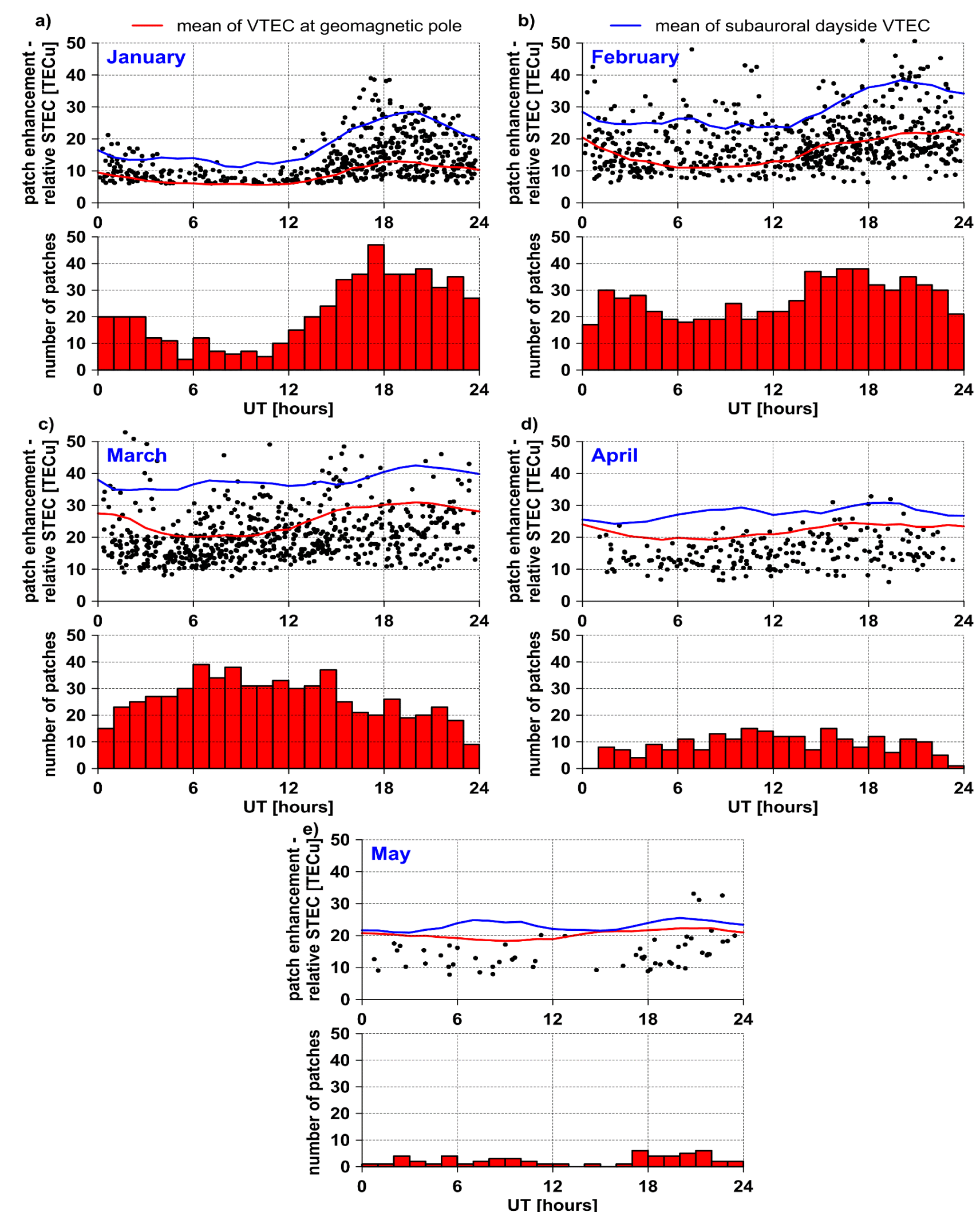


Fig. 4 Monthly statistics of patch occurrence. The top panels - STEC enhancements for particular structures, the bottom panels - the cumulative number of patches within a 1 hour long time span.

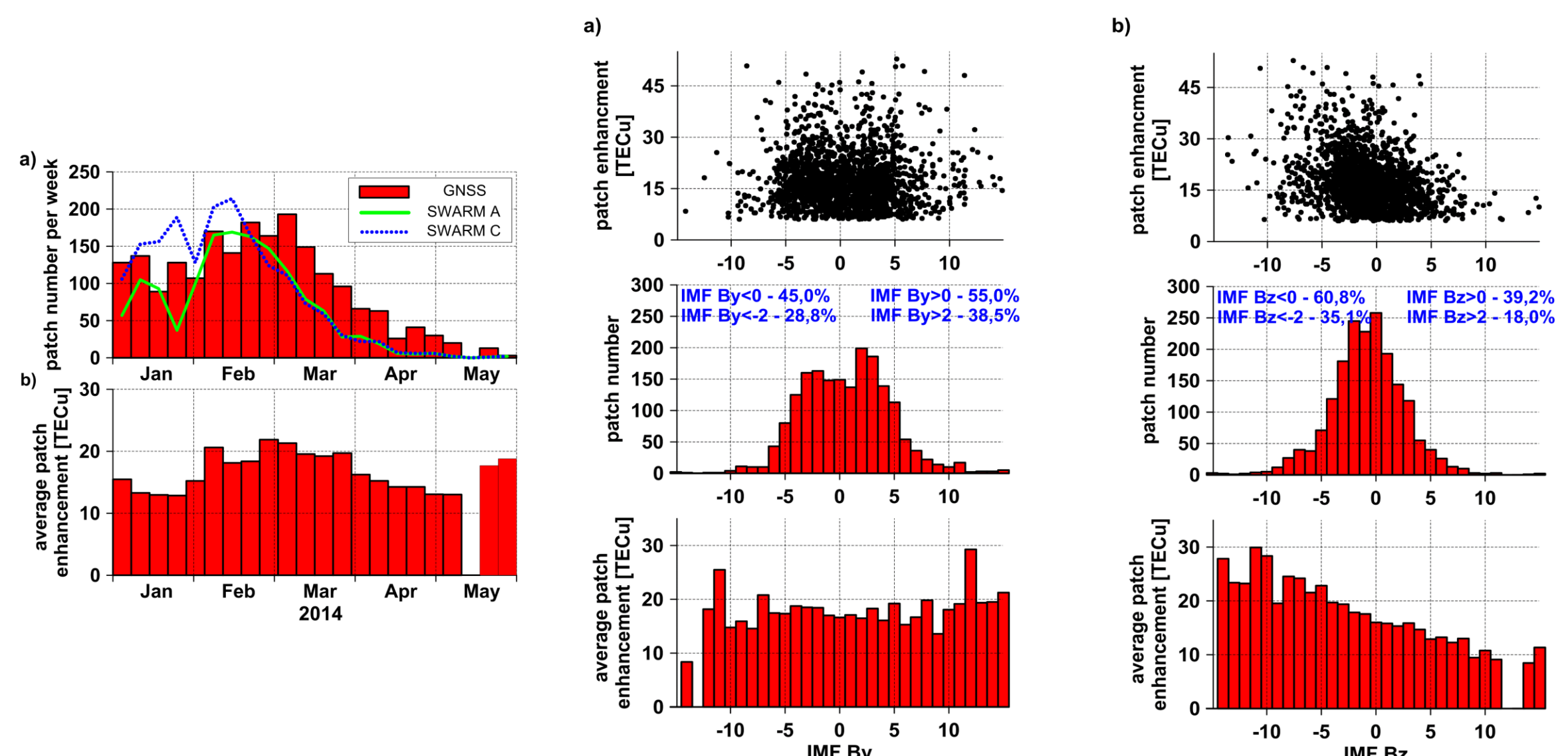


Fig. 5 The weekly patch number from GNSS and SWARM datasets (a) and GNSS-based average patch enhancement measured in a slant direction (b)

Fig.6 IMF dependence of polar patches on IMF. From top to bottom the distribution of structures as a function of IMF components, the corresponding numbers of patches and their average enhancement.

CONCLUSIONS

The main advantage of the relative STEC is its independence from any spatio-temporal filtering, which allows the separation of particular ionospheric structures and, consequently, their comprehensive statistical studies as well. The proposed methodology can be simply adopted to datasets derived from a permanent GNSS network. In such cases it ensures the continuous monitoring of ionosphere at the north geomagnetic pole and spatially unified time series of polar activity.

The effectiveness of the GNSS-based approach for statistical purposes is confirmed by its cross-validation with results derived from in-situ SWARM measurements. This comparison depicts the same seasonal pattern with the equinoctial peak and a good coincidence with regard to the number of detected structures. The minor discrepancies between both methods of ionosphere sounding seem to be a result of different definitions of the patch, which for GNSS data has to be supported with an additional lower limit. This distinct classification is particularly problematic for winter months with strongly depleted ionosphere, where overestimation of in-situ outcome is expected.

The benefits of GNSS data use, resulting from permanent ionosphere sounding, are clearly evident upon the investigation of the daily patterns of polar patches. In this regard we report a transformation of the UT dependence following a variation of the ionospheric gradient between subauroral and polar areas. Specifically, the maximum of patches near winter solstice correspond to the post-noon UT period, whereas the March pattern is opposite, with the more frequent structures at early morning hours. Furthermore, the introduction of the ionospheric gradient as an additional parameter clearly explains the seasonality of patch incidence resulting from the varying impact of solar EUV radiation. This factor also drives the plasma enhancement of polar structures, the most severe of which occur near spring equinox. Finally, the presented analysis confirms that the patches are stronger and more frequent for southwardly oriented IMF Bz.