The detection of ionospheric trough with GNSS measurements.

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INTRODUCTION
The ionospheric trough represents a large scale depletion of plasma density elongated in longitude, which is typically observed at the boundary between high- and mid-latitude ionosphere. The trough is characterized by a steep density gradient in a poleward direction and gradual on the equatorward side. According to the recent studies, it begins in the late afternoon, moves equatorward during the night-time and rapidly retreats to higher latitudes at a dawn. Due to the dynamic of auroral oval, this ionospheric feature exhibits a temporal variability and drifts equatorward during the geomagnetic activity.

METHODOLOGY OF GNSS-BASED DETECTION OF IONOSPHERIC TROUGH
The recent investigations aimed at characterization of high-latitude ionosphere demonstrated that appropriate processing of GNSS data can provide the very detailed view of polar and auroral disturbances. Furthermore, the conducted analysis involved also mid-latitudes and revealed that the adopted algorithm - relative TEC values - is similar to ionospheric trough as well (Sieradzki and Paziewski, 2010). The example of such signature in the rightside vector of ionosphere at 40° of geomagnetic latitude demonstrates Fig. 1.

A case of depleted ionosphere – March 8, 2012
The second case depicts the conditions just after a long period of northwestward orientated IMF, which was combined with negative recovery phase after the storm which occurred on March 7, 2012. The consequence of the interaction was strong increase of plasma in the auroral oval, related probably to an oval aligned on. On the other the negative phase of the storm triggered the global depletion of the ionosphere. Both these factors lead to a sharp gradient observed at the boundary auroral oval -- ionospheric trough. The position of this boundary was located at higher latitudes and thus, we used GNS data from PBO stations located mostly in Alaska (Fig. 6). Looking at the comparison of the results from different sources (Fig. 7) we can see that GPS map captured the strong gradient at the equatorward boundary of the ridge. On the other hand, the applied interpolation caused its smoothing in latitude direction. The single results provide the real scale of changes in maps of plasma on both sides of boundary, which exceeds at 10 TECU. Furthermore, the results depict that there was extensively long depletion without an increase of TEC up to 45° latitude. Comparing the results for both satellites one can observe a drift in boundary position, which is related to slightly different epochs of trough signature.

A case of geomagnetic storm – March 7, 2012
The first case concerns the situation given in Fig. 1. i.e. the ionospheric trough near the peak of the geomagnetic storm on March 7, 2012. As it was confirmed in our previous investigations, the auroral oval was then extremely expanded and consequently the ionospheric trough was also moved equatorward. The preliminary step of analysis involved the verification what conditions demonstrate the global ionospheric maps (Fig. 3). For this purpose we used the products provided by ESA and UPC (Indiveri 1998 and Hernández-Pajares et al. 1999). As one can observe TEC differs significantly in both these cases. There is no doubt that the map generated by ESA is smoother what is probably related to spherical harmonic expansion applied for VTEC representation. For presentation single-arc VTEC (referenced to UPL map at epoch 12:00 UT), we used 16 GSE stations from Plate Boundary Observatory mission which is acknowledged (Fig. 4). Each linear sub-network of permanent stations allows clear visualization of ionospheric trough for different longitudes.

CONCLUSIONS
• The particular ionospheric maps are based on different algorithms and thus their efficiency in depicting of ionospheric trough varies significantly. This may be also related to different datasets used for maps preparation.
• As demonstrated, the time series of geometry-free observables can be used for detection of ionospheric trough at the northern hemisphere. The variations of slant TEC, derived directly from dual-frequency data, can be aligned to a ionosphere map and consequently converted to VTEC values. The application of the proposed algorithm to linear network of GNS stations provides the detailed spatial view on ionospheric conditions.
• The results for different satellites are basically consistent. The discrepancies seem to be related to different epochs of trough signatures. In the analyzed cases the trough was observed simultaneously only by a few GPS satellites. On the other hand, one can expect that multi-GNSS receivers should improve applicability of the proposed algorithm.
• The comparison of different results indicates that the main advantage of the detection based on single arc data is providing sharp ionospheric signatures, which is not possible for VTEC maps. This is especially true at the edges of the trough. As a consequence we can detect a compressed depletion for the main phase of geomagnetic storms.
• In both analysed cases VTEC depletion exceeded 10 TECU and was extremely rapid (about one degree in longitudinal direction).
• The promising results suggest that the proposed algorithm can be applied for more detailed statistical studies of ionospheric trough.

REFERENCES
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