“Physics of Auroral Phenomena”, Proc. XLVI Annual Seminar, Apatity, pp. 15-18, 2023

Polar Geophysical Institute

DOI: 10.51981/2588-0039.2023.46.003

TEC FLUCTUATIONS AND GPS POSITIONING ERRORS IN POLAR AND AURORAL IONOSPHERE DURING NOVEMBER 4, 2021 STORM

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Abstract. In this report the occurrence of TEC fluctuations and their impact on the Precise Point Positioning (PPP) errors at high latitudes for November 4, 2021 geomagnetic storm is presented. We used GPS observations of polar Ny-Ålesund (MLAT, 76.6°) and auroral Tromsø (MLAT, 66.9°) stations. The fluctuation activity and intensity of fluctuations was evaluated by ROT/ROTI indexes. At both stations the periods of the most intense fluctuations occurrences in GPS data coincided with strong increases in AE index. There is good agreement in dependence of fluctuation intensity (ROTI) and positioning errors. At Ny-Ålesund the errors were reached 4 m against 16 cm at during quiet conditions. At TRO1 strong intensification fluctuations led to a dramatic increase PPP errors.

Introduction

Total electron fluctuations at high latitudes are caused presence in the ionosphere of different scale irregularities. The TEC fluctuations are occurred as phase fluctuations GPS/GLONASS signals. The most intense ionospheric irregularities have been observed during ionospheric storms and depend on latitude, solar geomagnetic activity and local time [*Jin et al.*, 2018]. Irregularities are classified according with subauroral, auroral cusp and polar cap regions [*Franceshi et al.*, 2019]. Phase fluctuations are often observed on the dayside of the cusp at magnetic latitudes 73.5°–80° in the interval 09–15 MLT (Magnetic Local Time; 06–12 UT); the polar cap at latitudes above 75º, except for the cusp; and in the region of the auroral oval at latitudes 65º–75º in the interval 19–02 MLT [*Prikryl et al.*, 2015]. In the auroral region, phase fluctuations are usually observed during periods of auroral disturbances near the local magnetic midnight and are closely associated with the dynamics of the auroral oval [*Shagimuratov et al.*, 2021]. The ionospheric irregularities also exist a subauroral region equatorward of the main ionospheric trough (MIT). Strong TEC fluctuations can complicate phase ambiguity resolution and to increase the number of undetected and uncorrected cycle slips and loss of signal lock in GPS navigation and positioning errors [*Luo et al.*, 2022; *Shagimuratov et al.*, 2022]. Early analysis of TEC fluctuations was done mainly for strong magnetic storms. In this work we present features of the TEC fluctuations occurrence and positioning errors for the moderate geomagnetic storm of 4 November 2021.

Data and method

Standard 30-second dual-frequency GPS measurements served as our initial data. GPS observations were from the Ny-Ålesund polar station (NYA1) and the Tromsø auroral station (TRO1) were used. Time-derivative of TEC change (ROT, rate of TEC) used to measure of GPS signal phase fluctuation activity. Intensity TEC fluctuations was evaluated by ROTI [*Pi et al.*, 2017]. The ROTI index main advantage over other scintillation indices is that it is calculated based on measurements from standard dual frequency GNSS receivers sampling at 30 s interval [*Zhao et al.*, 2022; *Kotulak et al.*, 2019]. The index was calculated for a 5 min interval for all satellites visible by the station with satellite elevation angles above 20°. We used additional processing of the data in order to identify and correct phase slips (cycle slips, phase loss, phase jump), and to eliminate possible outliers. Index ROTI is very effective to detect the presence of ionospheric irregularities.

We analyzed positioning errors using PPP algorithm on the base of the GIPSY software of the NASA Jet Propulsion Laboratory in kinematic mode (*http://apps.gdgps.net*). The GIPSY takes corrected GPS satellite orbit and clock data as well as user's dual-frequency GNSS phase and pseudorange data to determine the user position. Under normal conditions, the accuracy of post-processed positioning using GIPSY is at a few centimeter level (standard deviation). The 3D position errors were computed with 5 min interval. The 3D position error (P_{3D}) was defined as the offset of the detrended coordinate from its median value and calculated for each epoch.

Geomagnetic conditions

The sudden storm commencement was registered at 20:50 UT on November 3, 2021, SYM/H increase to ~47 nT. Then it dropped to the value of −105 nT at 14 UT on 4 November 2021. During the main phase of storm, the auroral electrojet AE reached value 1000 nT on 02 UT and do value 2000 nT at 06-13 UT.

Effects over NYA1 station

In Fig. 1 (from top to bottom) geomagnetic field variations (X-component), AE index, ROT/ROTI indexes and positioning errors at NYA1 station are presented. Diurnal variations ROT along all visible GPS satellites on different latitudes are shown. The ROT variations are shown separately for all satellites — the vertical axis indicates the satellite number (PRN), the horizontal axis displays time in UT. ROT computed from the detrended raw TEC using 10-min running average.

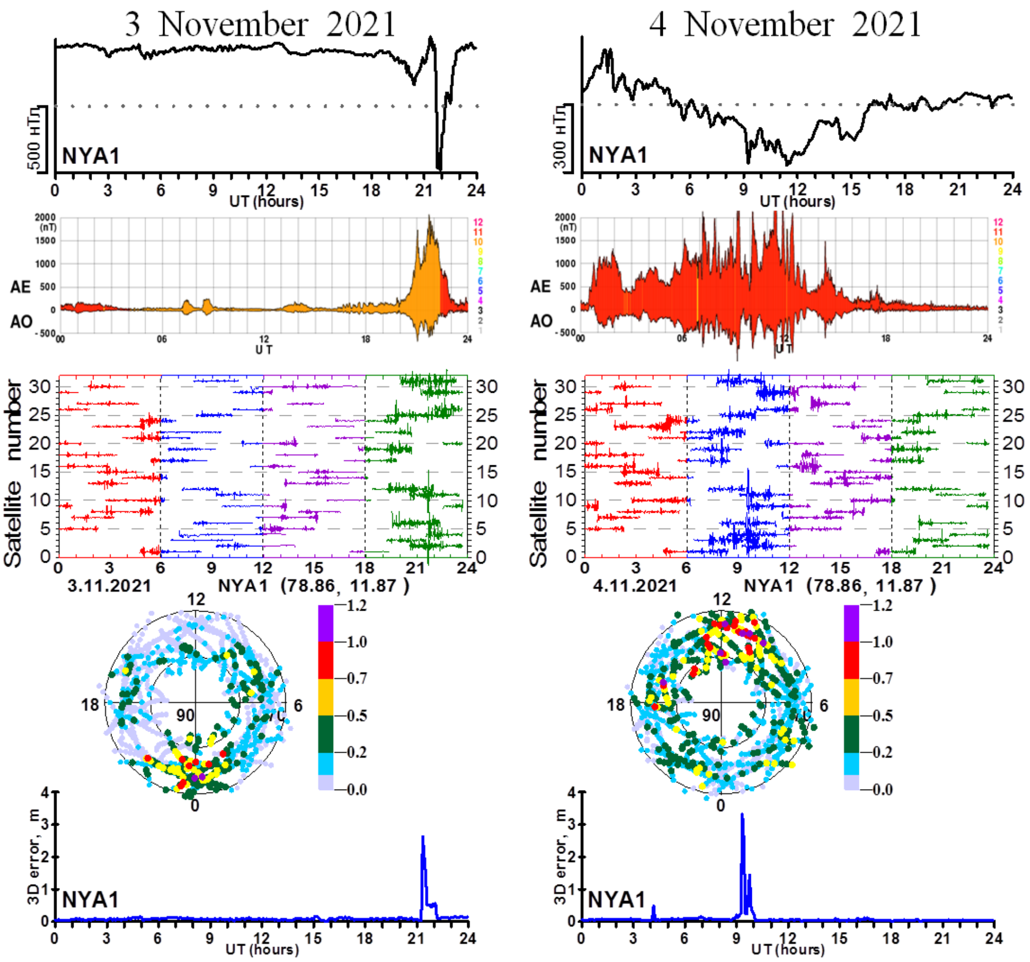

Figure 1. Variations of the geomagnetic, fluctuation activity (ROT/ROTI) and positioning errors during 3 and 4 November 2021.

During quiet day at station of NYAL TEC fluctuations occur all day. Station Ny-Ålesund monitors the ionosphere within the range of 78º–82º magnetic latitude. Fluctuations observed at this station are associated with the cusp, polar cap and auroral oval. In this regions can observed different kinds perturbations such as dayside/cusp precipitation, substorm precipitation, daytime and nighttime polar cap patches [*Belakhovsky et al.*, 2021]. Intense fluctuations are often are associated with polar patches. It is known that sharp, intensive gradients at edge of patches, lead a significantly higher GPS phase scintillation.

Fig. 1 shows that at during 3 November substorm occurred night time 21 UT. Amplitude of geomagnetic field variations (X-component) was more than 1000 nT. In this time the sharp increase of AE was observed, amplitude was about 2000 nT. At the time intervals 19–23 UT the fluctuation activity (ROT) strong increased. The intensity of fluctuations is reproduced in the coordinates: magnetic latitude/magnetic local time (MLT). Polar view map covers 00–24 MLT and 60°–90° MLAT. In each map, magnetic noon/midnight is at the top/bottom. Maximal intensity of fluctuations occurred at near local midnight. We consider that the fluctuations are caused with polar night precipitations.

During storm day of 4 November the geomagnetic field disturbance (X-component) started after 04 UT. Maximal values occurred near 12 UT after than one recovered to initial value at 21 UT. Auroral disturbance is observed at the time interval 01-15 UT. Amplitude of AE reached more than 2000 nT, maximal intensity occurred around 06-13 UT. The fluctuation activity was, in whole, higher during storm than quiet day of 3 November. The intensity of fluctuations was observed around magnetic noon. At NYAL have been increased on interval 06-12 UT; 09-15 MLT.

Effects over TRO1 station

At TRO1 very strong the fluctuations activity is essentially increased during storm. Fluctuations in this region are associated with auroral disturbances, the precipitation of energetic particles, and auroras. They are closely related to the dynamics of the auroral oval. During 3 November strong geomagnetic field variations (X-component) as well NYA1 as occurred at near 22 UT (Fig. 2). At this time, the sharp increasing fluctuations activity was registered. The fluctuations at all satellite passes were observed. It should be noted that the time interval of occurrence of fluctuations was longer at NYA1 than at TRO1. At both stations maximal intensity of fluctuations occurred near 00 MLT.

During storm at TRO1 the geomagnetic field variations were some differed from NYA1, but the maximal amplitudes occurred at the same time at booth stations. The intensity of fluctuations was essentially higher at TRO1 than NYA1. The intensity of fluctuations was observed in day time on interval 03-14 UT; 06-17 MLT.

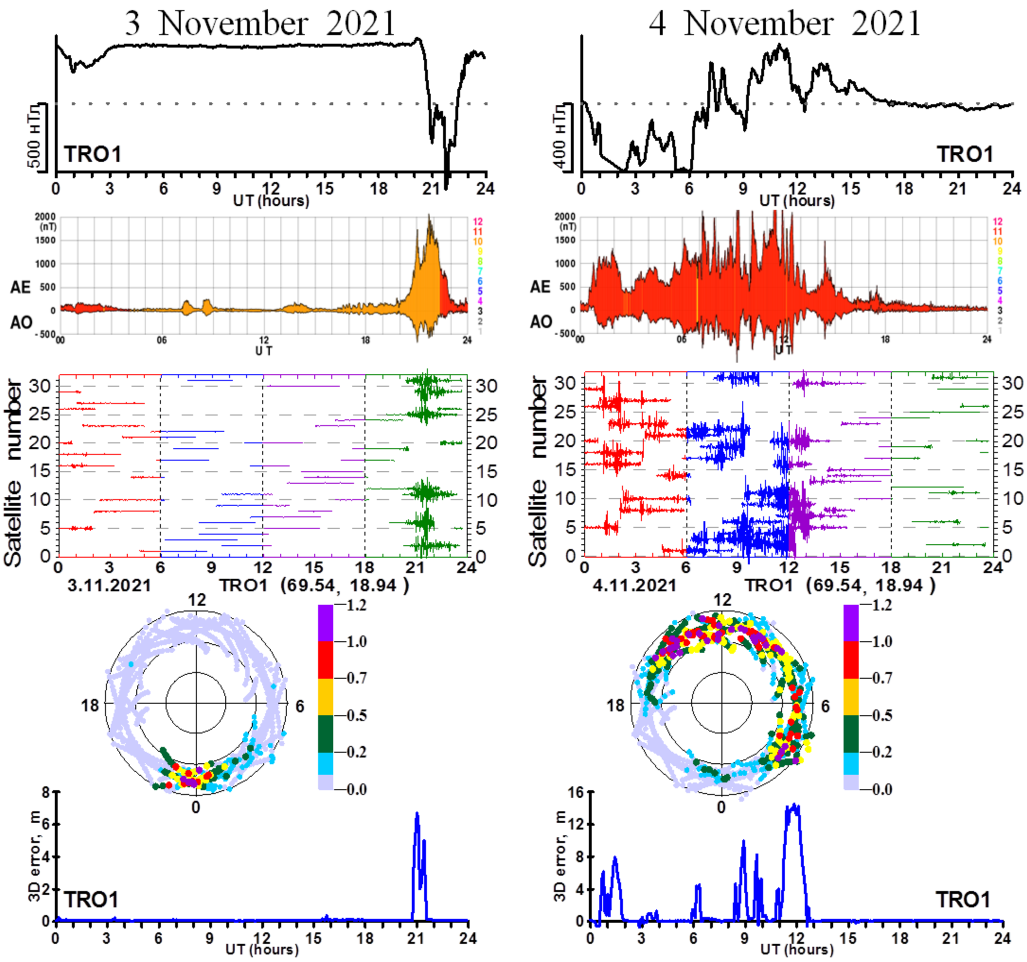

Figure 2. Variations of the geomagnetic, fluctuation activity (ROT/ROTI) and positioning errors during 3 and 4 November 2021.

Positioning errors

The 3D position error (P_{3D}) was defined as the offset of the detrended coordinate from its median value and calculated for each epoch. A median value we used coordinate calculated on 24 hour interval for previous day of the storm. There is good agreement in dependence of fluctuation intensity (ROTI) and positioning errors. A non-linear correlation between ROTI statistic and PPP errors was revealed. The coefficients of correlation were 0.39 for station NYAL and 0.67 for TRO1 [*Jacobsen and Dähnn*, 2012, 2014].

In Fig. 1, 2 positioning errors for 3 November and 4 November days at NYAL and TRO1 stations are presented. In quiet day maximal errors do not exceed 15 cm for NYAL and 30 cm TRO1 respectively. During storm that essentially increase at both stations. Largest positioning errors were registered during when intensity of fluctuations increase. At TRO1 large errors occurred within the time interval of 02–14 UT when auroral activity have been increased.

The large short-term 3D errors in the form of bursts were registered during a storm. It is known that positioning accuracy is deteriorated as the number of satellites subjected to fluctuations increases. Fluctuations are irregular, so the number of satellite subjected to fluctuations, at one time, can vary greatly, that is reflected in values of positioning errors. So, if simultaneous 4 or more subjected to fluctuations errors can reach to 15 m.

Summary

We analyzed of occurrence TEC fluctuations and positioning errors associated with disturbances of 4 November 2021 over polar and auroral ionosphere. The fluctuations activity and their intensity fluctuations were evaluated by index ROTI. At both regions occurrence phase fluctuations shows strong relation with auroral activity. At polar NYAL station the maximal intensity of TEC fluctuations was occurred on 12-15 MLT. Positioning errors increased rapidly with ROTI. At NYA1 positioning errors were reached 4 m against 16 cm during quiet conditions. At auroral TRO1 station very strong fluctuations took place at 09-17 UT when developed auroral activity. At TRO1 strong intensification fluctuations led to a dramatic increase PPP errors.

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