

# **Effect of auroral substorm on GPS slips in the polar ionosphere**

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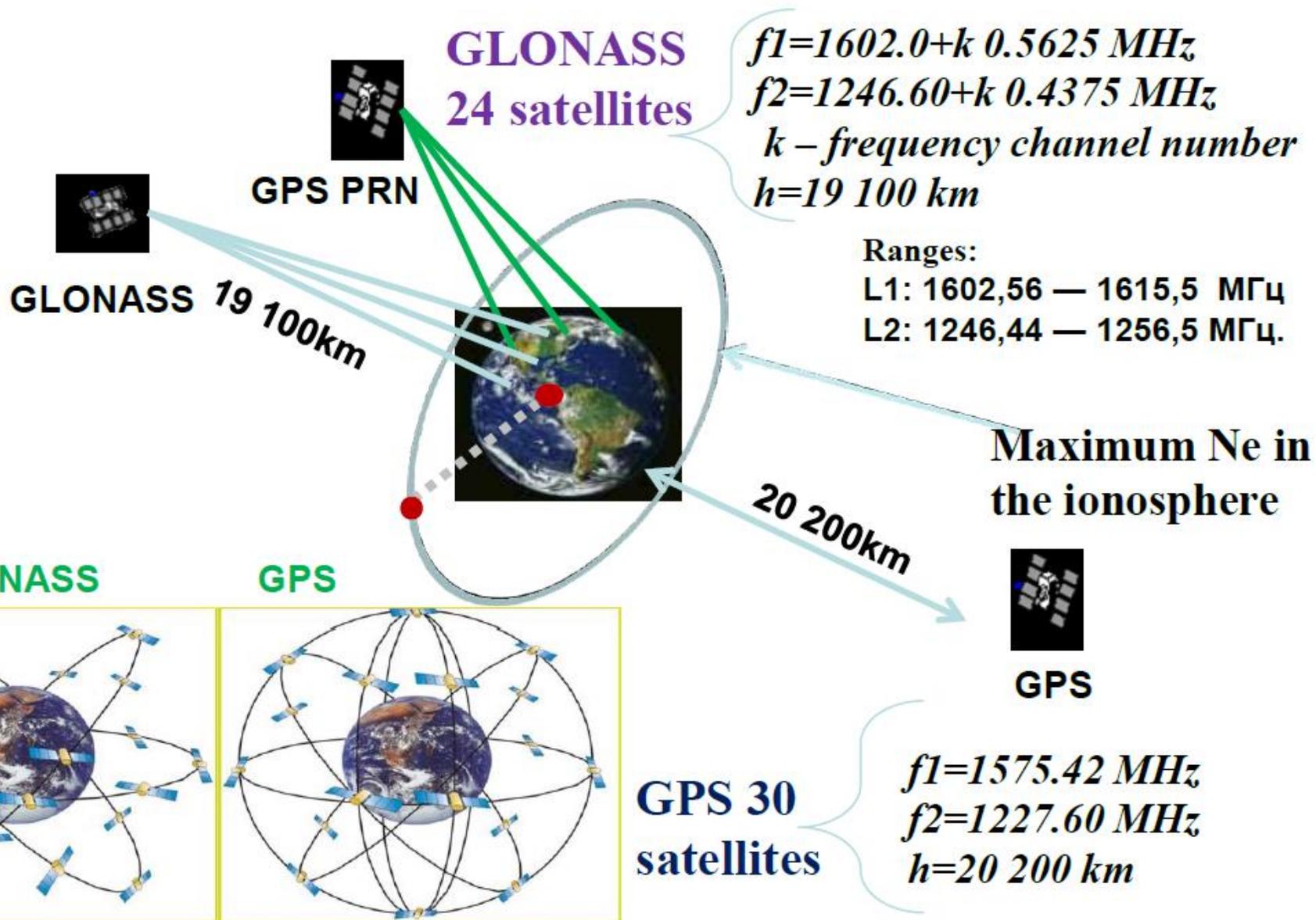
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# Navigation satellites



# Ionosphere

EM waves transmitted by the GNSS satellites, whose wavelengths are of the order of decimeters, travel through the ionosphere, which is the ionized part of the atmosphere, before reaching a ground-based receiver. Thus, free electrons in the ionosphere can have a large impact on the group, phase and amplitude characteristics of such waves. ***The ionosphere leads to the group delay and phase advance of GNSS signals.***

**The main sources of ionospheric irregularities are of helio- and geophysical disturbances of the near-earth space. The state of the near-earth environment in relation to the solar activity gives the context of "space weather". This is more pronounced in high latitudes, i.e., in the polar regions.**

# Goals

- **Study in detail the effects of a geomagnetic substorm on the slips in phases L1 and L2 as well as TEC jumps, determined by the GPS navigation signals, at high latitudes.**
- **The use of the optical data from the all-sky imager and magnetometers to monitor the evolution of the substorm to complete the analysis.**
- **Get quantitative estimates of the effect of geomagnetic substorm on slips of the main parameters of the navigation signal**

# Terminology

Two types of operational slips are considered:

**(i) instrumental slips including losses in the measured phase of the GPS signal**

These slips are of a technical character, reflecting the quality of the electronic components of the radio transmission unit, and can virtually affect the accuracy of navigational positioning

**(i) sharp TEC variations (jumps or slips) lacking physical explanation.**

The determination of TEC is affected by both additional phase uncertainties and regular properties of the disturbed ionosphere.

**For example:** *The GPS signal phase slips or jumps, resulting in TEC jumps (more 1 TECU/min), occur predominantly inside the auroral oval and in the vicinity of its equatorward boundary.*

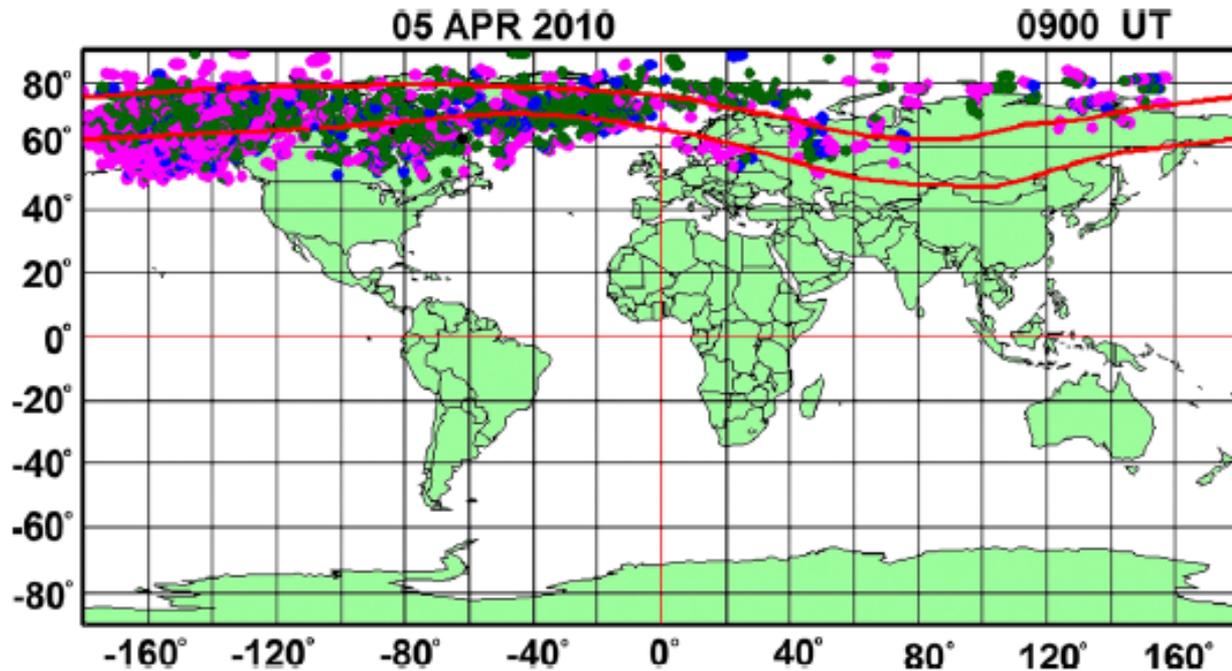


Fig. 8 Pierce points corresponding to moments of non-physical TEC level jumps during the period 08-11 UT, with superposed boundaries of the OVATION auroral oval (corresponding to 09 UT). Color codes denote magnitudes of jumps  $dVTEC/dt > 1-5$  TECu/min (dark green colors correspond to 1-3, blue to 3-5, and pink  $>5$ )

*Kozyreva et al, GPS Solutions (2017)* states that during the substorm TECU/min value is usually 1-5.

# Instrumentation

We use in total 4 GPS receivers in the Scandinavian sector, in Tromsø (TRO1), Skibotn (SKBN), Kiruna (KIRU) and Sondankyla (SODA)

We use the all-sky imager (ASI) located at Skibotn as well as the OMNI IMF data and the data from the ground-based magnetometer at Tromsø. ASI at Skibotn is collocated with the GPS scintillation receiver.

Data from three GPS receivers are taken from the IGS in the RINEX format while the data from Skibotn is taken directly from the receiver with resolution of 1 sec.



# GPS TEC slips (jumps)

$$TEC = \frac{1}{40.308} \cdot \frac{f_1^2 \cdot f_2^2}{(f_1^2 - f_2^2)} \cdot [(L_1 \lambda_1 - L_2 \lambda_2) + K + nL] \quad \text{- TEC calculation from the two-frequency phase measurements}$$

**Calculation distributions of slips in time for each observed satellite (GPS PRN):**

$$P_{T,i,GPS} = \frac{N_{i,GPS}(T)}{S_{i,GPS}} \cdot 100\%$$

$N_i(T)$  is the total number of slips of the studied signal "i" recorded for a given GPS satellite *within the observation time T*

$S_i$  is the total number of daily observations of signal  $i$ .

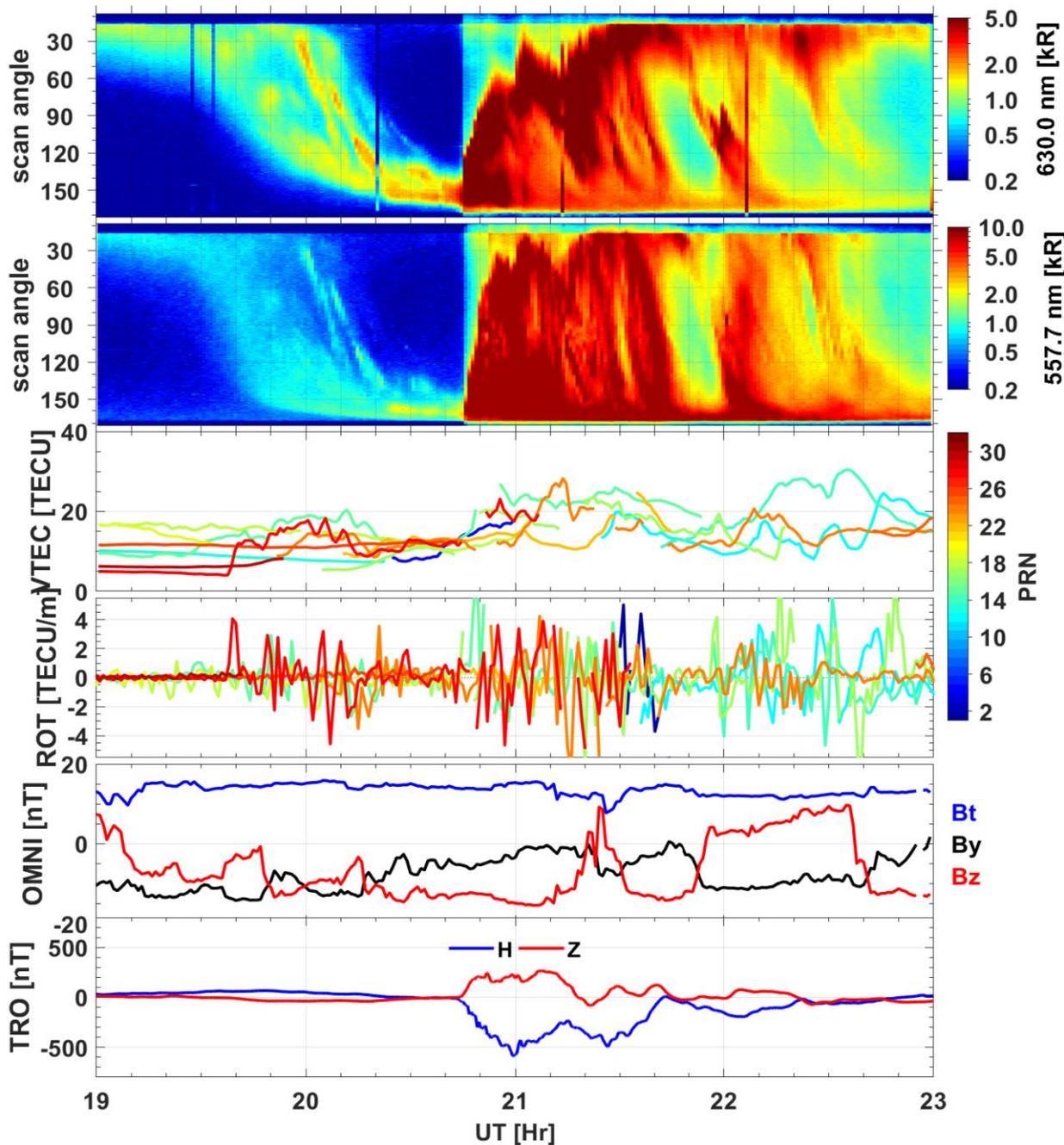
"i" means L2, L1, TEC, P1 and P2)

The use of the number of observations per day, rather than 1 hour period, as a normalization, makes it possible to avoid an overestimation in nonstationary processes of the jumps probability for observations in incomplete hours of satellite visibility during rising or setting.

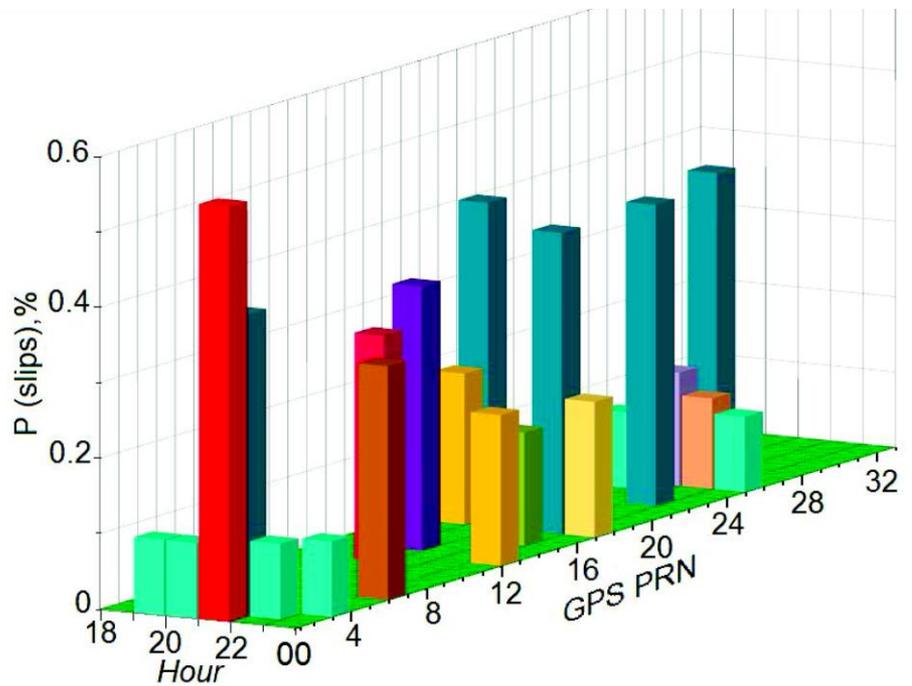
**Estimation the probability of slips in the parameter "i" measured at each receiving station for all visible navigation satellites  $N_{GPS}$  :**

$$P_{T,i} = \frac{\sum_{j=1}^{N_{GPS}} (N_{i,GPS}(T))_j}{\sum_{j=1}^{N_{GPS}} (S_{i,GPS})_j} \cdot 100\%$$

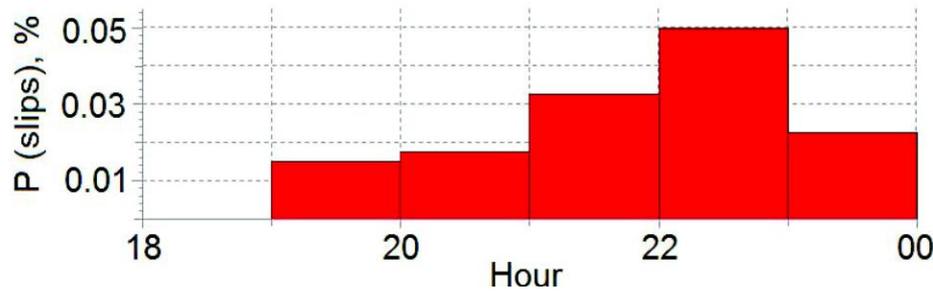
# A geomagnetic substorm that occurred on December 23, 2014, between 19:00 and 23:59UT

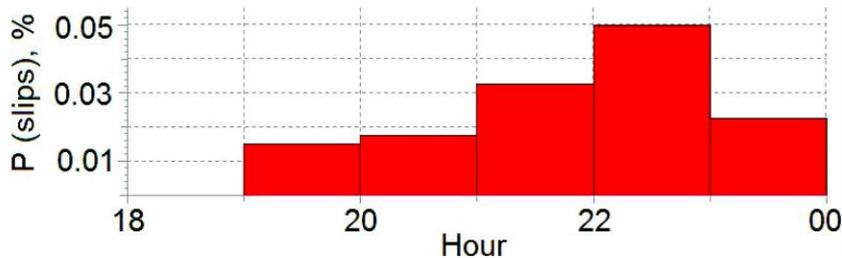
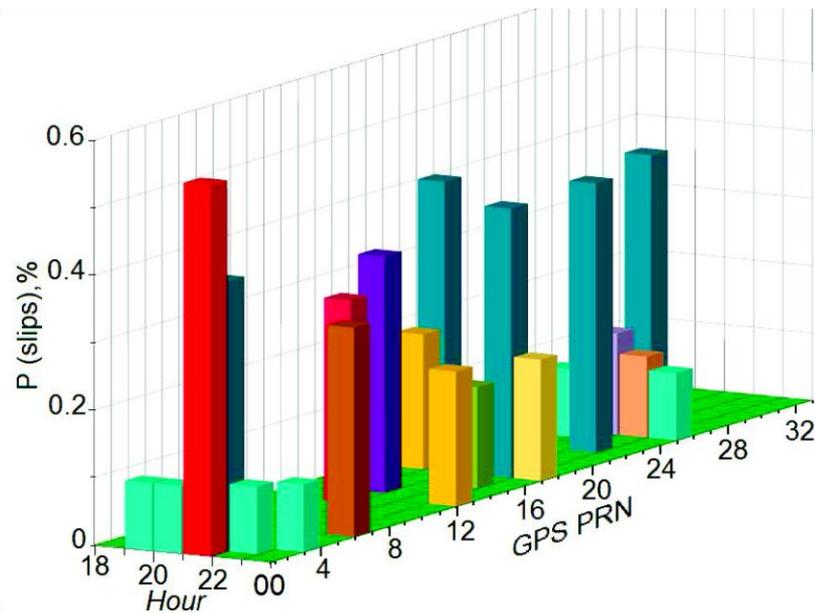


From top to bottom: the optical data in a keogram format from the all-sky imager at 630.0 nm and 557.7 nm, respectively, GPS TEC from the collocated GPS receiver at Skibotn (the color shows data from different GPS satellites as indicating by the PRN code in the color bar), the rate of change of TEC, the OMNI IMF data, and the H and Z components of the magnetic field from the ground-based magnetometer in Tromsø.

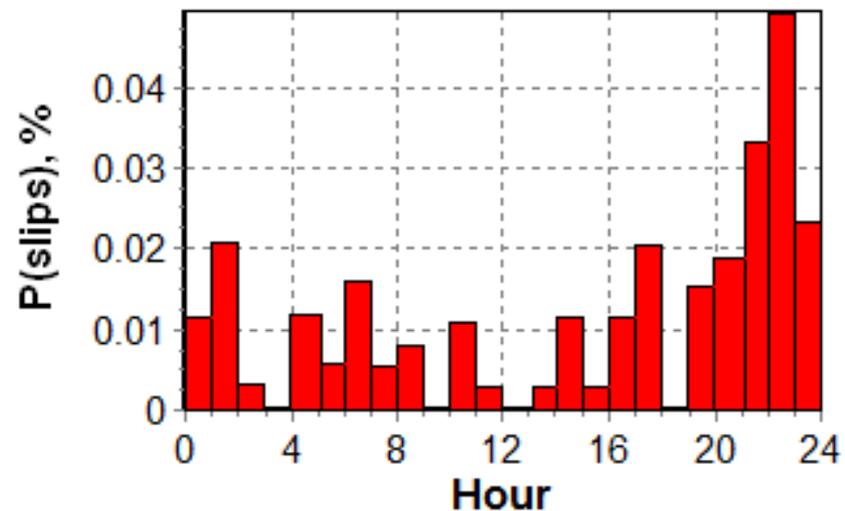


Temporal distribution of phase slips at the frequency L1 (top panel) and averaged probability of phase slips at the frequency L1 (bottom panel) on December 23, 2014 for all visible GPS satellites at station *SKBN*.

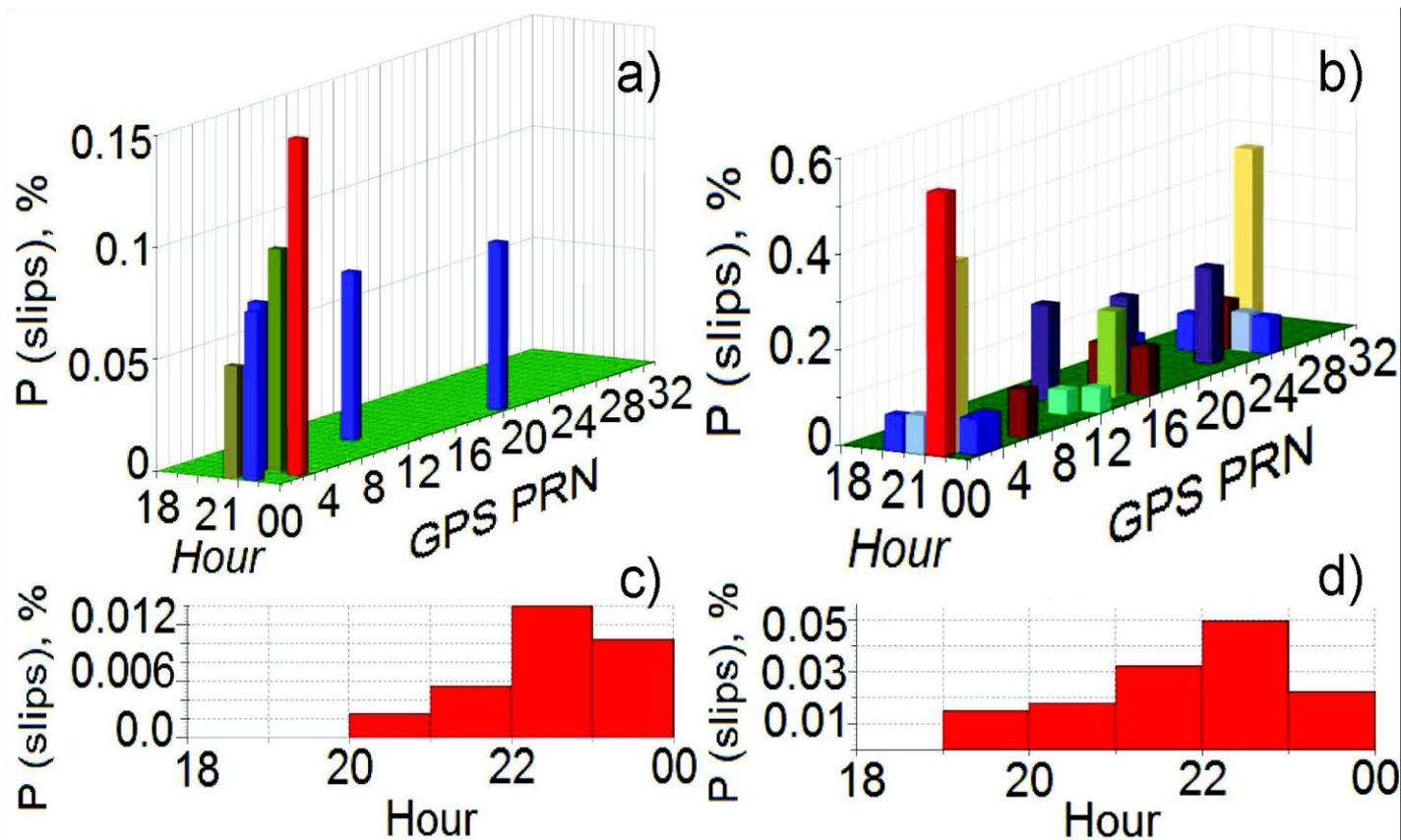




Temporal distribution of phase slips at the frequency L1 (top panel) and averaged probability of phase slips at the frequency L1 (bottom panel) on December 23, 2014 for all visible GPS satellites at station *SKBN*.

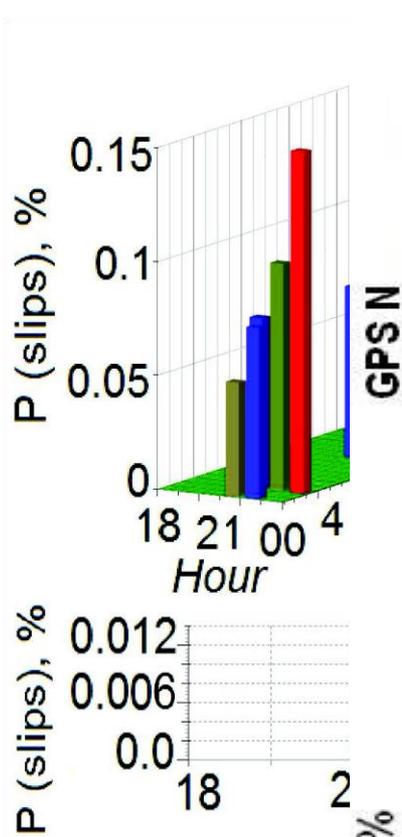


Any slips or phase jumps in the partial hour at the beginning or end of the observation session would have more weight than similar phenomena in a full hour. The fact is that the number of observation points for different navigation satellites varies at different hours, and our normalization is devoid of the indicated complexity. An example for the whole day:

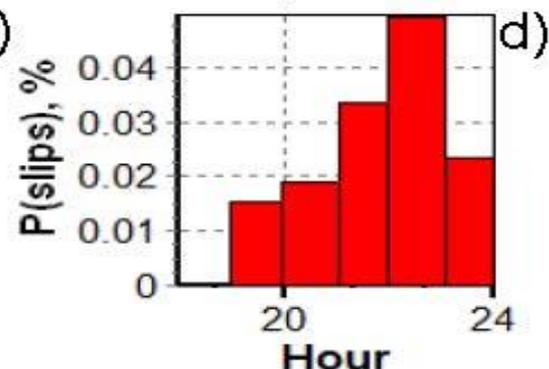
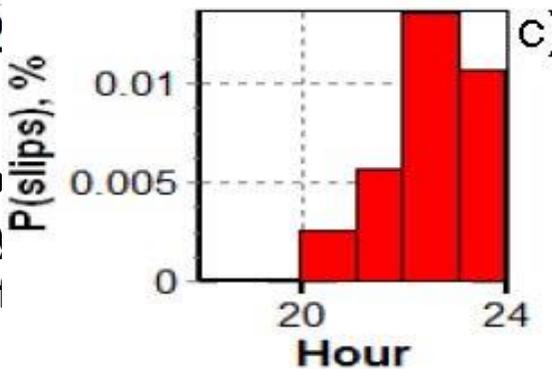
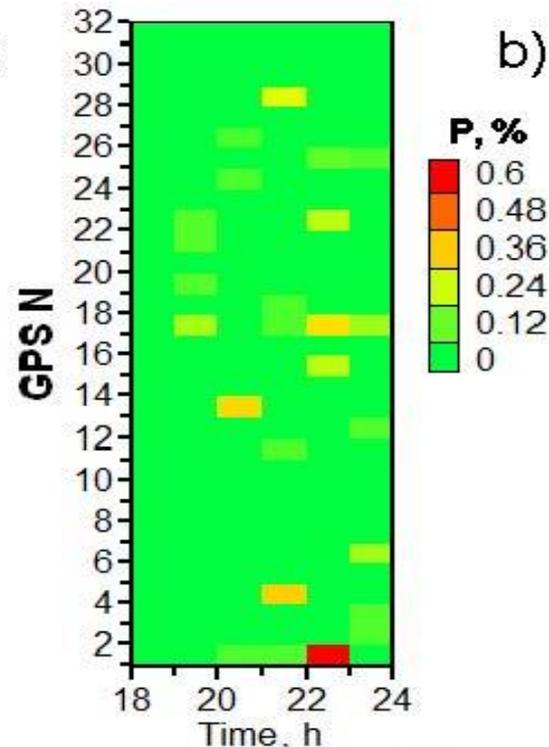
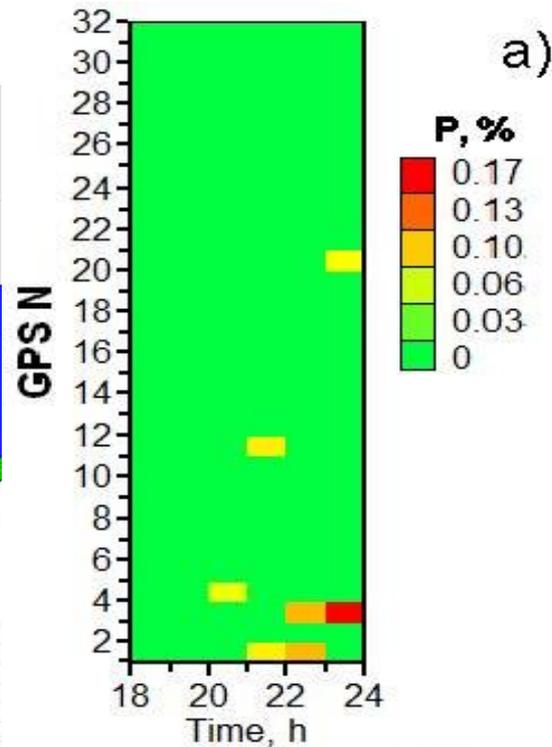


**Temporal distribution of phase slips at the frequency L2 at stations *a) SODA* and *b) SKBN*. Averaged probability of phase slips at the frequency L2 at stations *c) SODA* and *d) SKBN* on December 23, 2014 for all visible GPS satellites at stations.**

*Note that the substorm leads to increase in cycle slips L2 at stations SODA and SKBN with a delay of several hours which is probably associated with the specific features of plasma turbulence originating from magnetic disturbances.*

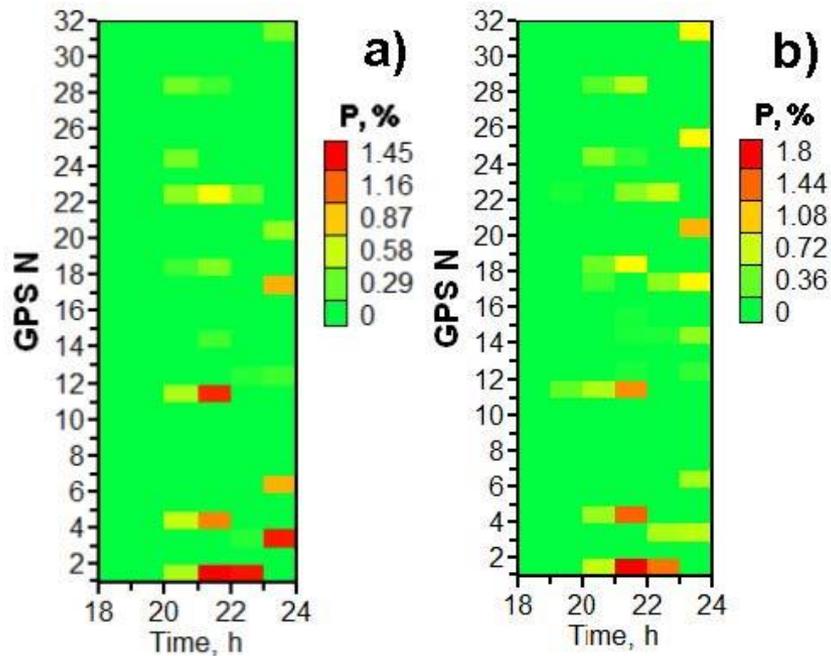


Temporal distribution of averaged probability of cycle slips for stations 18, 21, 00, and 4 on December 23, 2014.

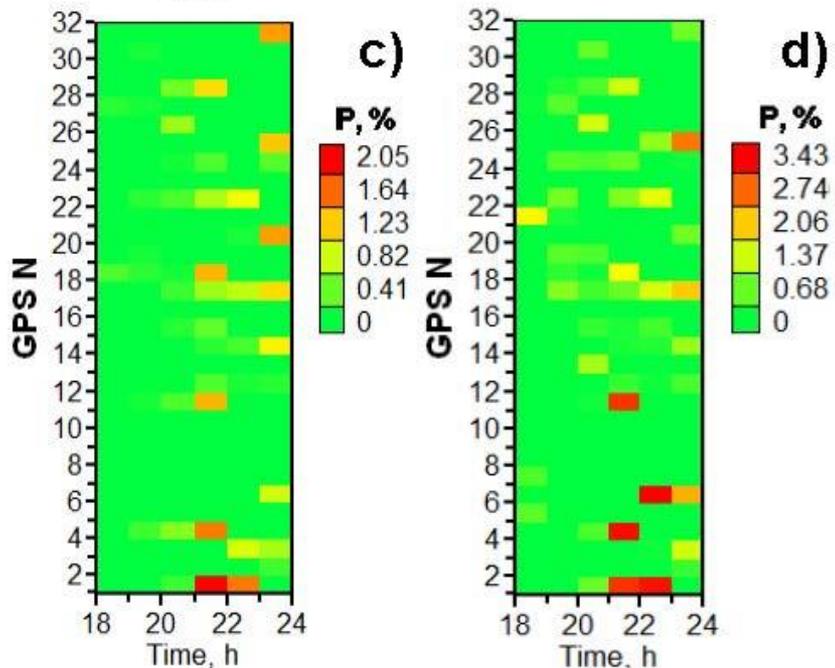


) SKBN.  
SKBN on

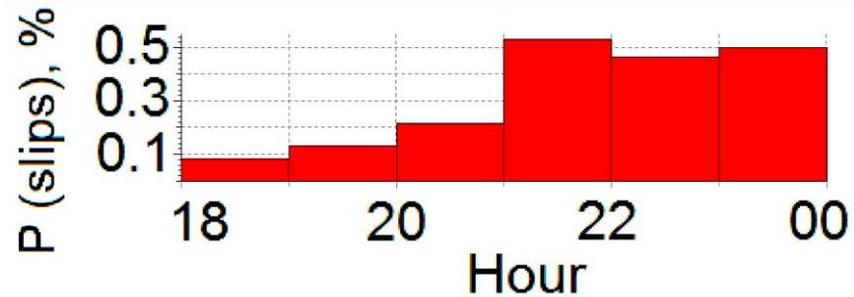
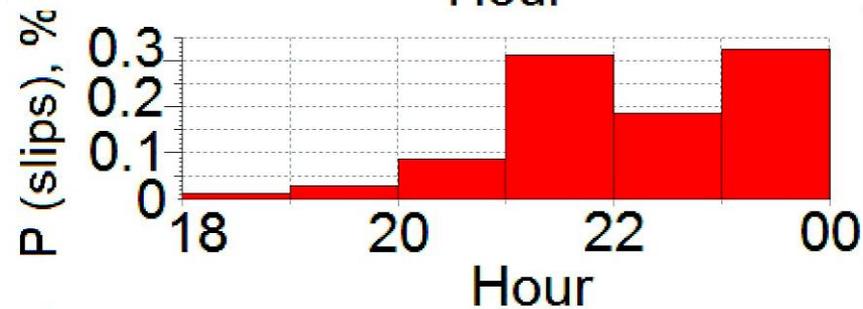
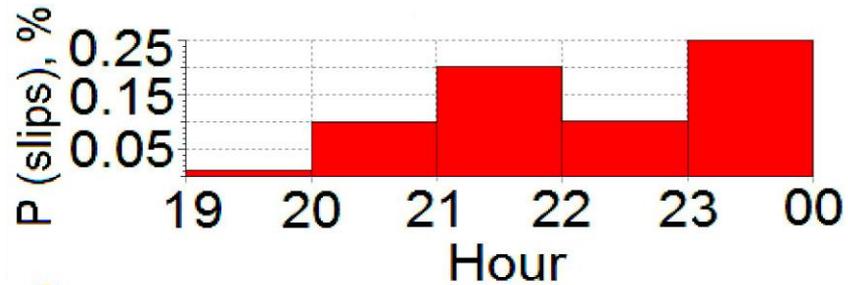
Note that the substorm leads to increase in cycle slips L2 at stations SODA and SKBN with a delay of several hours which is probably associated with the specific features of plasma turbulence originating from magnetic disturbances.



**Temporal distribution of TEC jumps on December 23, 2014 for all visible GPS satellites at stations: a) *SODA*; b) *KIRU*; c) *TRO1* and d) *SKBN***



It is clear that TEC slips probability increases with the substorm onset (about 20 UT) and peaks during the recovery and growth phases.

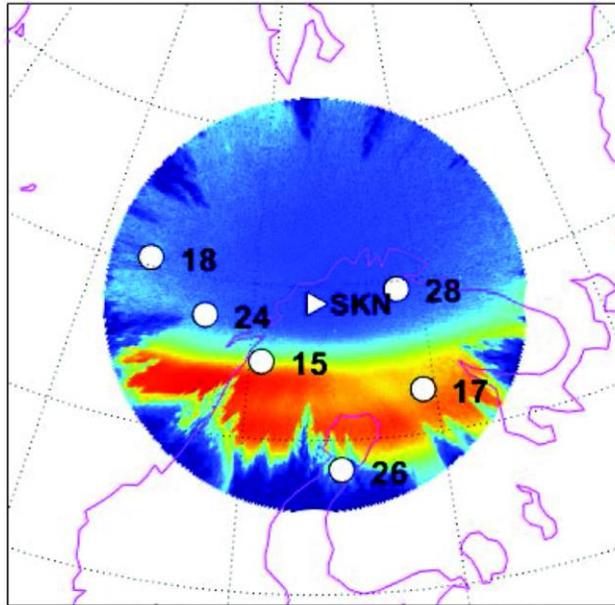


**Averaged probability of TEC jumps at stations *KIRU* (top panel); *TRO1* (middle panel); and *SKBN* (bottom panel); for all visible GPS satellites on December 23, 2014.**

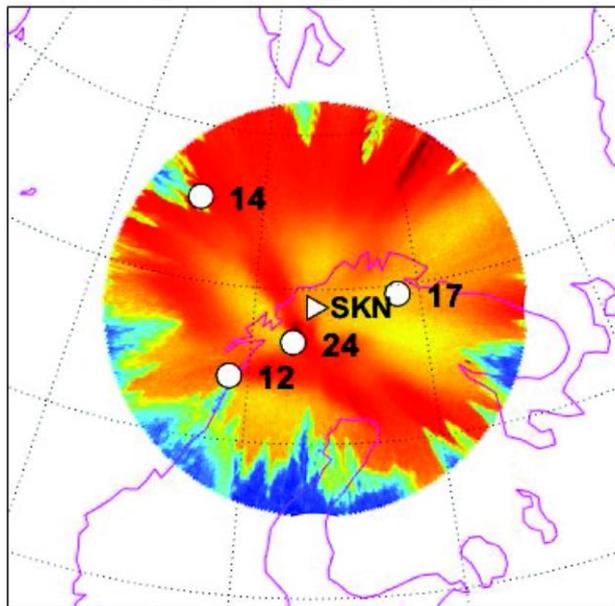
As a criterion of jumps, we take a level of TEC change of more than 1 TECU/min

*TEC jumps increase 5-10 times during a substorm as compared to a quiet period. Note that TEC jump means in general additional turbulence in the electron concentration on the trace of navigation signal. **Therefore, TEC jumps have some diagnostic character.***

SKN4\_20141223\_20:37.00\_6300



SKN4\_20141223\_22:07.00\_6300



**Locations of navigation satellites over the studied region and the optical manifestations of auroral phenomena for two different times, namely, 20:37 UT upper panel 20:37, which is just before the substorm onset, and 22:07 corresponding to the maximum in the geomagnetic substorm when the aurora covered the whole field-of-view over station *SKBN*.**

This relates the high number of observed TEC slips for the selected satellites to the auroral phenomena.

# Summary

- TEC jumps and cycle slips in navigation signals can be related to auroral particle precipitations in the high-latitude ionosphere;
- For the first time, we correlate the GPS TEC jumps with the optical data for auroral emissions in the polar ionosphere during a geomagnetic substorm;
- The TEC slips probability is several times higher than the probability of cycle slips in phase at the frequencies L1 and L2, Frequency L2 has more cycle slips than L1 both in quiet conditions and during geomagnetic activity in the polar regions;
- The auroral substorm leads to a growth in cycle slips L2 at the stations in Sondankyla and Skibotn with a delay of several hours, which is probably associated with specific features of plasma turbulence originating from magnetic disturbances;
- The maximum of GPS TEC slips occurrence is during the recovery phase of a geomagnetic substorm. This fact reflects the dynamics of the substorm influence on the ionosphere and, most likely, it is associated with the evolution of plasma inhomogeneities and instabilities in the high-latitude ionosphere excited during the geomagnetic activity.

**Thanks for attention!**

