Observation of the ionospheric irregularities over the Northern Hemisphere: Methodology and Service

Iurii Cherniak, Andrzej Krankowski,
Irina Zakharenkova

University of Warmia and Mazury in Olsztyn,
Space Radio-Diagnostics Research Centre (SRRC/UWM)

UWM
UNIWERSYTET WARMIŃSKO-MAZURSKI W OLSZTYNIE

IGS INTERNATIONAL GNSS SERVICE

Introduction

The ionosphere plays an important role in GNSS applications because it influences radio wave propagation through. The ionosphere delay is the biggest error source for satellite navigation systems, but it can be directly measured and mitigated with using dual frequency GNSS receivers. However GNSS signal fading due to electron density gradients and irregularities in the ionosphere raise a concern about the operational availability of navigation system. It is known that GNSS radio signals passing through the ionosphere suffer varying degrees of rapid variations of their amplitude and phase - signal fluctuations, referred as scintillations, are created by random fluctuations of the medium's refractive index, which are caused by inhomogeneities inside the ionosphere. These effects are caused by the presence of a wide range of scale size irregularities in the ionosphere.

The spatial and temporary dynamics of ionosphere fluctuations depends on geophysical conditions, and detailed study of these effects is very important, especially during space weather events. For this reason several types of analysis of the ionospheric total electron content (TEC) fluctuations effects on GNSS signals have been carried out and still actual currently. If electron density irregularities cover a big area above receiver, there is a high probability that a receiver can lose more than one satellite signal simultaneously. Simultaneous loss of a significant number of satellites signal discontinues GNSS navigation or degrades the navigation accuracy.

Therefore, strong ionosphere TEC gradients and resulted fluctuations and signal scintillations could be hazardous in terms of continuity and availability for GNSS navigation.

Recommendations after 2012 IGS Workshop

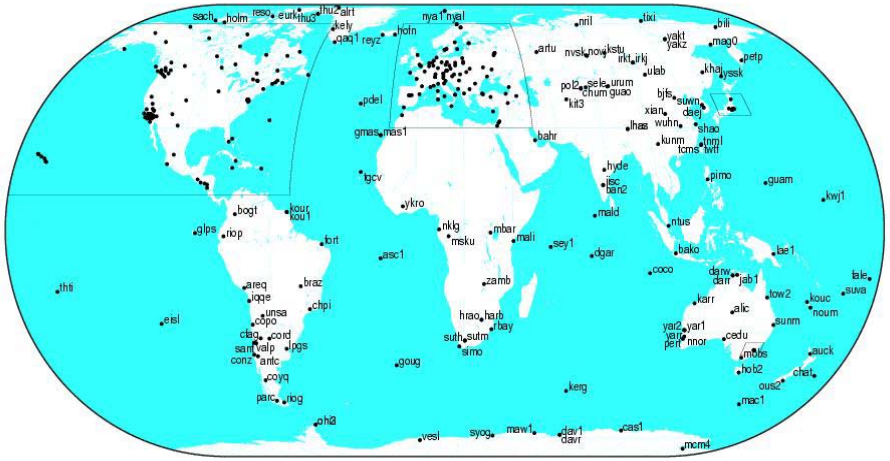
Ionosphere Working Group

Starting a new official/operational product – TEC fluctuation changes over North Pole to study the dynamic of oval irregularities (carried out by UWM to be started as official/routine product after performance evaluation period)

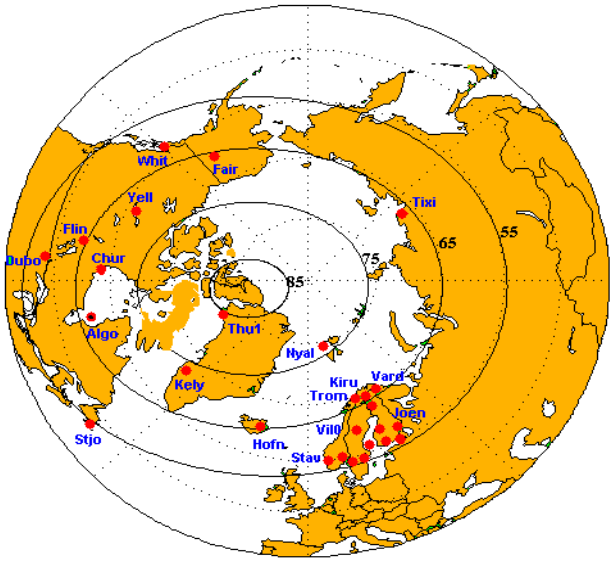
According with the recommendation of the Ionosphere Working Group of IGS at the IGS 2012 Workshop "Starting a new official/operational product – TEC fluctuation changes over the North Pole to study the dynamic of oval irregularities", we propose version of the product that can represent the ionospheric fluctuations in a map format. Such maps can be useful for space weather monitoring and navigation by combining them with currently produced IGS global ionospheric maps (GIMs) or regional ionospheric TEC maps.

GNSS networks as data for ionospheric irregularities observations

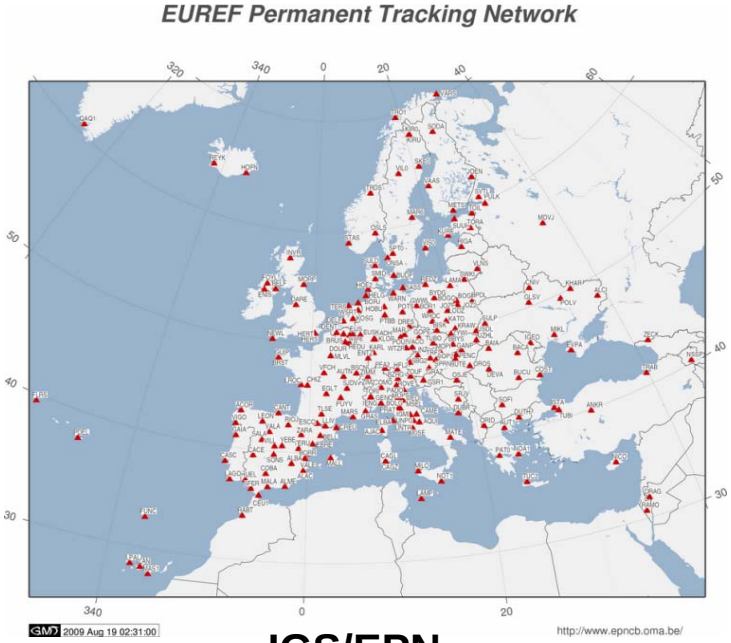
The IGS collects, archives, and distributes GPS observation data sets of sufficient accuracy to satisfy the objectives of a wide range of applications and experimentation. The GNSS observations provided by IGS and other permanent station networks, with a 30 s sampling, allow to detect the ionospheric irregularities with a scale size of about tents km.



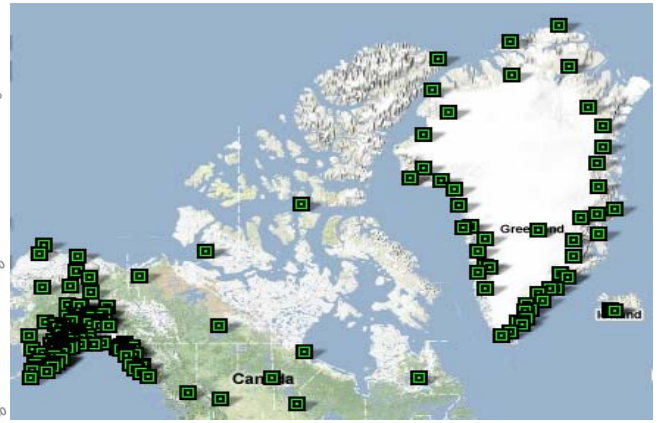
International GNSS Service - IGS



IGS polar stations



IGS/EPN
(EUREF Permanent Tracking Network)



PBO Network –
Plate Boundary Observatory
POLENET - The Polar Earth Observing Network

Monitoring of the TEC fluctuations using GNSS data

In order to analyze TEC fluctuation activity there were considered the Northern hemisphere polar, subauroral and midlatitude regions geographically located from 45°N geomagnetic latitude to the North Pole.

Monitoring the time-derivative of TEC (ROT, rate of TEC change) is useful for tracing the presence of the ionospheric irregularities. ROT, as a measure of phase fluctuation activity, is calculated using the algorithm, that was proposed by *Pi et al.* [1997]:

$$ROT = \frac{TEC_k^i - TEC_{k-1}^i}{(t_k - t_{k-1})}$$

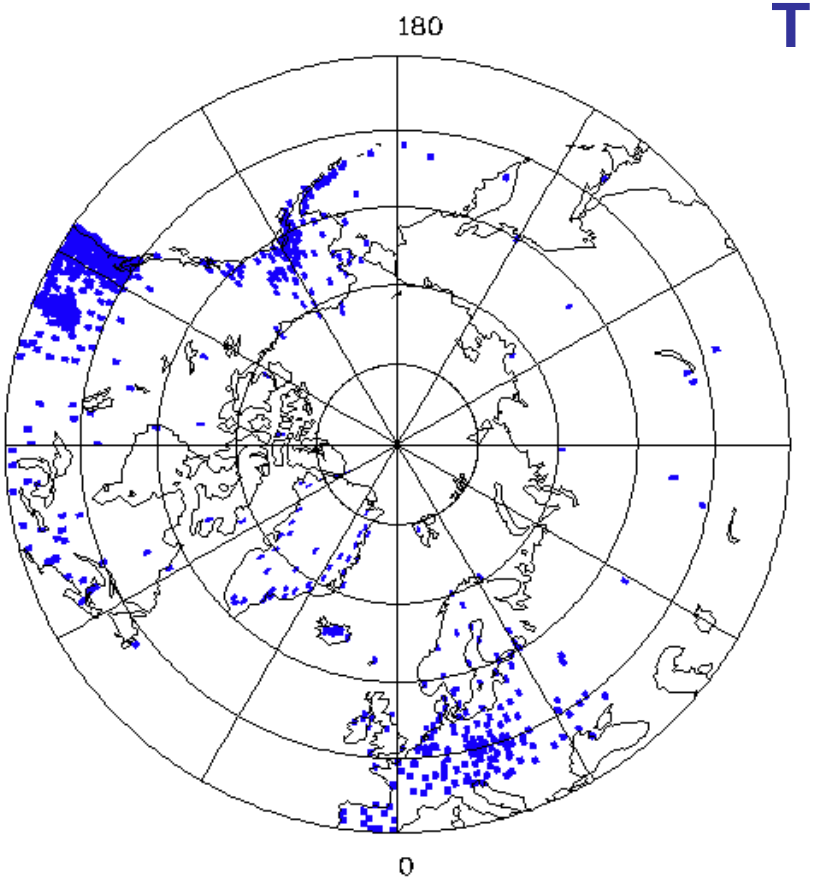
where ***i*** is the visible satellite and ***k*** is the time of epoch. In standard RINEX files raw data sampled every 30 seconds. ROT is calculated in units of TECU/min for each visible satellite over GNSS station. The ROT values are calculated and then detrended for all individual satellite tracks for elevation angles over 20 degrees.

ROTI is defined as the standard deviation (taken over 5 minutes) of the detrended rate of change of TEC (ROT) [*Pi et al.*, 1997]. Based on the retrieved values of ROT, the ROTI values are calculated over 5-minute periods with running window for each station:

$$ROTI = \sqrt{\langle ROT^2 \rangle - \langle ROT \rangle^2}$$

To observe the spatial behavior of the ionospheric fluctuations over the North Pole, we process ROTI data from considered multi-site database and visualize result in the form of ROTI map.

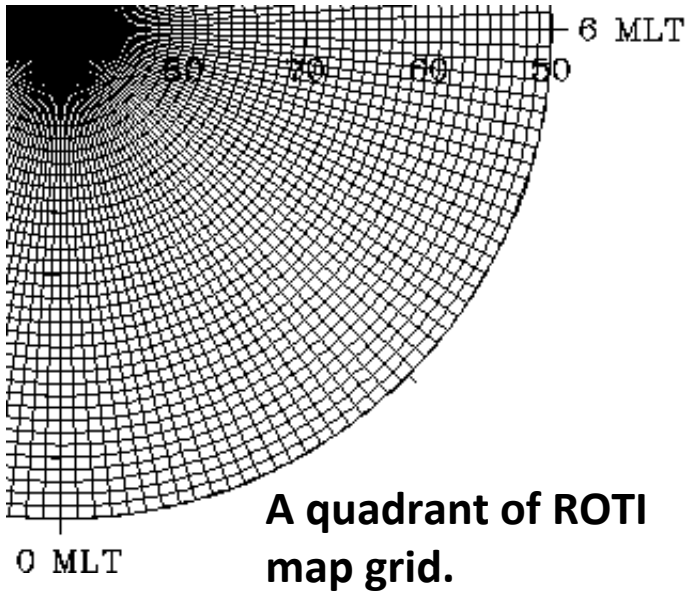
The ROTI maps



There are more than 700 permanent stations (from IGS, UNAVCO and EUREF databases) have been involved into processing for the ionosphere fluctuation service. Such number of stations provides enough data for representation a detailed structure of the ionospheric irregularities pattern.

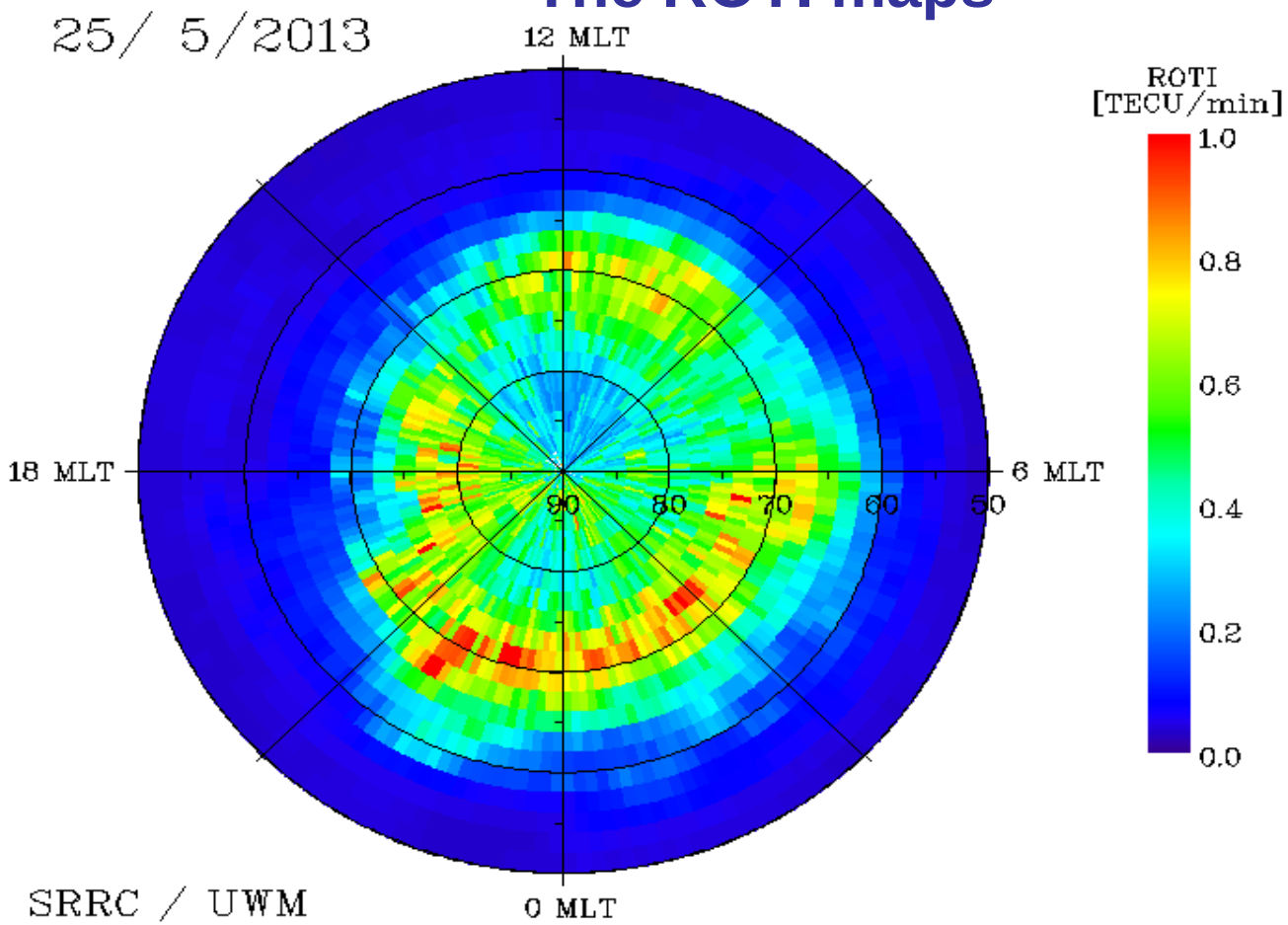
The locations of the stations in the North Hemisphere used for ROTI map construction

Due to strong connections between the Earth's magnetic field and the ionosphere, the behavior of the fluctuation occurrence is represented as a function of the magnetic local time (MLT) and of the corrected magnetic latitude. The grid of ROTI maps in polar coordinates with cell size 2 degree (magnetic local time) and 2 degree (geomagnetic latitude).



A quadrant of ROTI map grid.

The ROTI maps



Each map, as a daily map, demonstrates ROTI variation with geomagnetic local time (00-24 MLT). The value in every cell is calculated by averaging of all ROTI values cover by this cell area and it is proportional to the fluctuation event probability in the current sector. If in the cell there are only few ROTI values (less than 30), this grid cell is marked as a blank. This approach will allow to avoid frequent errors of interpolation techniques, related with unrealistic interpolation values over areas with data gaps.

The proposed format to store of the ROTI values

For ROTI data storing it is proposed simple ASCII format based on grid 2 x 2 degree - geomagnetic latitude from 89o to 51o with step 2 and corresponded to magnetic local time (00-24 MLT) polar coordinates from 0 to 360.

	89	87	85	83	81	79	77	75	73	71	69	67	65	63	61	59	57	55	53	51
1	0.2959	0.4422	0.465	0.311	0.3678	0.4486	0.3578	0.3835	0.4148	0.3314	0.3425	0.126	0.0913	0.032	0.0351	0.0331	0.036	0.0372	0.0382	0.0336
3	0.2927	0.4224	0.3924	0.3731	0.4034	0.4608	0.3389	0.4352	0.4048	0.2986	0.248	0.1268	0.1171	0.0378	0.0352	0.0335	0.0346	0.0343	0.0396	0.0335
5	0.2792	0.394	0.3942	0.4697	0.3284	0.4379	0.3944	0.465	0.3843	0.2807	0.2481	0.1496	0.1099	0.0438	0.0323	0.0327	0.0355	0.0367	0.0374	0.0336
7	0.2609	0.4365	0.3266	0.3829	0.4267	0.5317	0.4661	0.4689	0.3635	0.3103	0.2117	0.1402	0.0725	0.0444	0.0335	0.0344	0.0363	0.0382	0.0357	0.034
9	0.4455	0.4226	0.3477	0.4237	0.4313	0.5694	0.5135	0.3641	0.4155	0.2923	0.2217	0.1319	0.0794	0.0449	0.0369	0.0335	0.0385	0.0396	0.0383	0.0358
11	0.5008	0.4245	0.4262	0.3578	0.3814	0.5214	0.5073	0.3896	0.3925	0.3136	0.2374	0.1492	0.08	0.0393	0.0322	0.033	0.0367	0.0411	0.0384	0.0389
13	0.3294	0.3593	0.4965	0.3778	0.4072	0.7487	0.5215	0.3219	0.3607	0.3442	0.2959	0.1609	0.0808	0.0463	0.0344	0.0292	0.0343	0.0422	0.0377	0.038
15	0.3004	0.3847	0.4443	0.3325	0.3606	0.6081	0.3513	0.3715	0.368	0.307	0.2705	0.1739	0.068	0.0364	0.0365	0.0293	0.0342	0.0416	0.0397	0.0401
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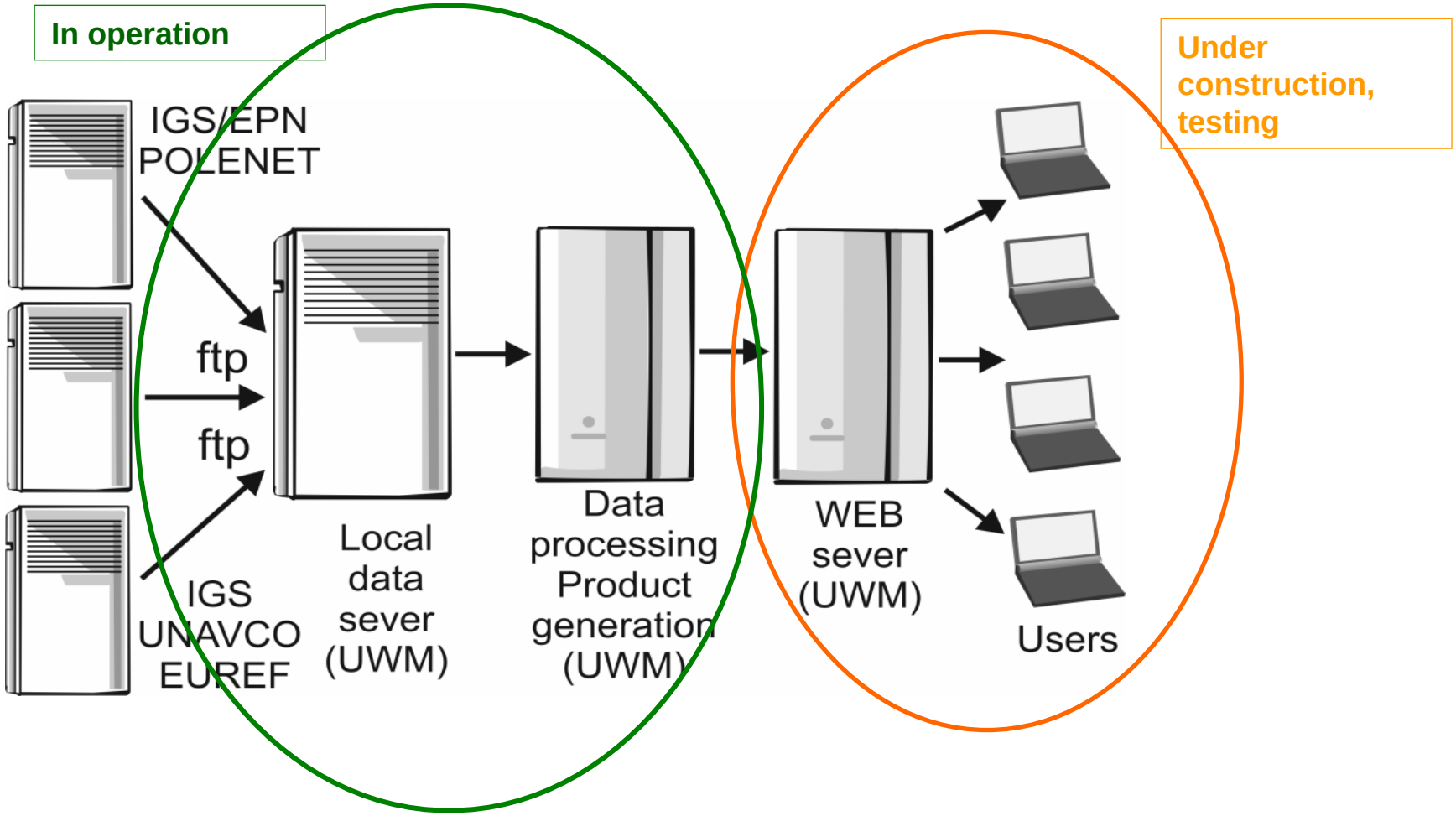
345	0.3648	0.6725	0.3646	0.4227	0.4633	0.4701	0.568	0.433	0.3694	0.3681	0.2091	0.1214	0.0726	0.0373	0.0385	0.0391	0.0347	0.0342	0.0352	0.0336
347	0.3667	0.4735	0.3784	0.3845	0.5204	0.5891	0.5423	0.434	0.4858	0.3508	0.2132	0.1101	0.0882	0.0437	0.0373	0.0412	0.0361	0.0345	0.0343	0.0345
349	0.3688	0.5449	0.4021	0.3499	0.5294	0.6081	0.578	0.4124	0.4193	0.3378	0.2235	0.1295	0.0939	0.0418	0.0367	0.0369	0.0379	0.0346	0.0334	0.036
351	0.4049	0.5729	0.4159	0.3901	0.4119	0.5135	0.4602	0.4285	0.4767	0.3112	0.2217	0.1312	0.0837	0.0399	0.0355	0.034	0.0536	0.035	0.0328	0.0325
353	0.3524	0.389	0.4495	0.3115	0.5101	0.5135	0.4072	0.4766	0.5348	0.282	0.2186	0.1162	0.0782	0.0412	0.0342	0.0314	0.0545	0.0372	0.0326	0.0339
355	0.297	0.3992	0.3368	0.3606	0.5323	0.4776	0.367	0.4452	0.5001	0.336	0.282	0.1088	0.0834	0.0404	0.0327	0.0321	0.0391	0.0441	0.0323	0.0352
357	0.2614	0.4348	0.31	0.4465	0.3972	0.4235	0.3796	0.3958	0.44	0.3829	0.3155	0.1115	0.0709	0.0361	0.033	0.0318	0.0408	0.0397	0.0382	0.0367
359	0.2838	0.3851	0.3392	0.4338	0.4432	0.3893	0.323	0.3949	0.4581	0.3688	0.3274	0.147	0.0744	0.0332	0.0331	0.0338	0.0365	0.0378	0.0377	0.0364

The sample of ROTI-ex format body

The service for creating ROTI maps

In the Space Radio-Diagnostics Research Centre (SRRC/UWM) is developing and testing service for automatically download RINEX observational and navigational files, unzip and process data and generate ionospheric products.



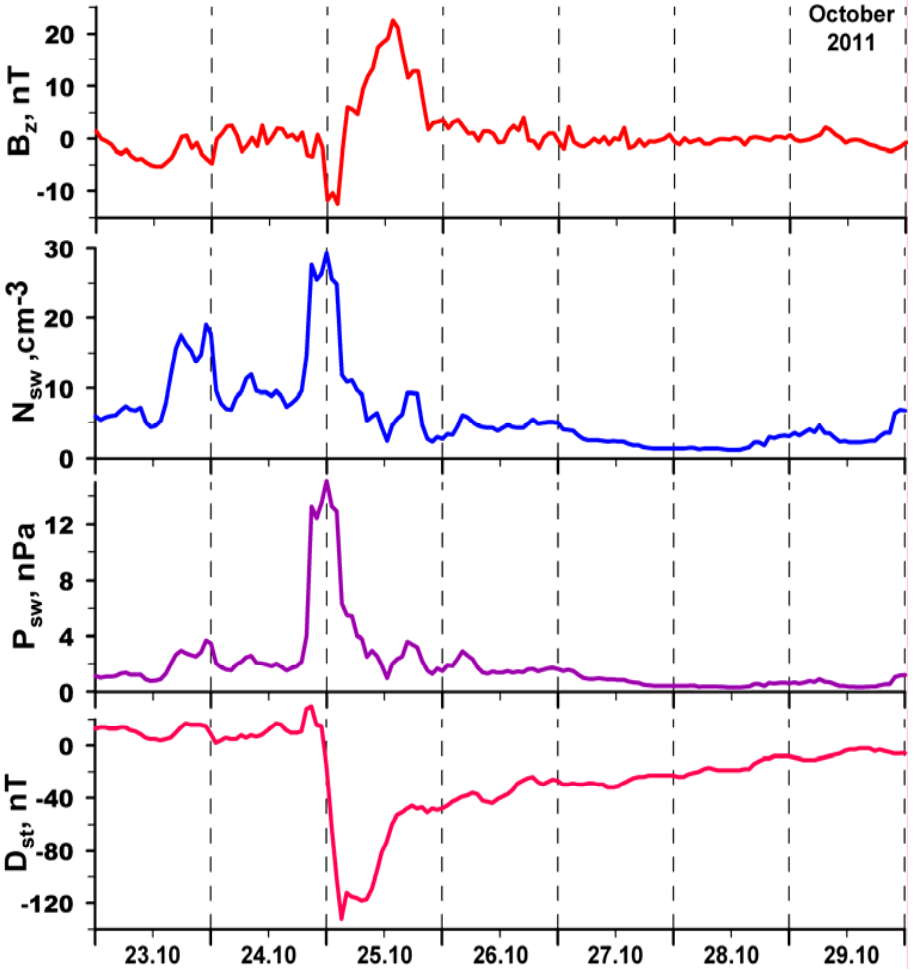
The TEC fluctuation service operation diagram and status

Ionospheric irregularities observed using GNSS networks: case study

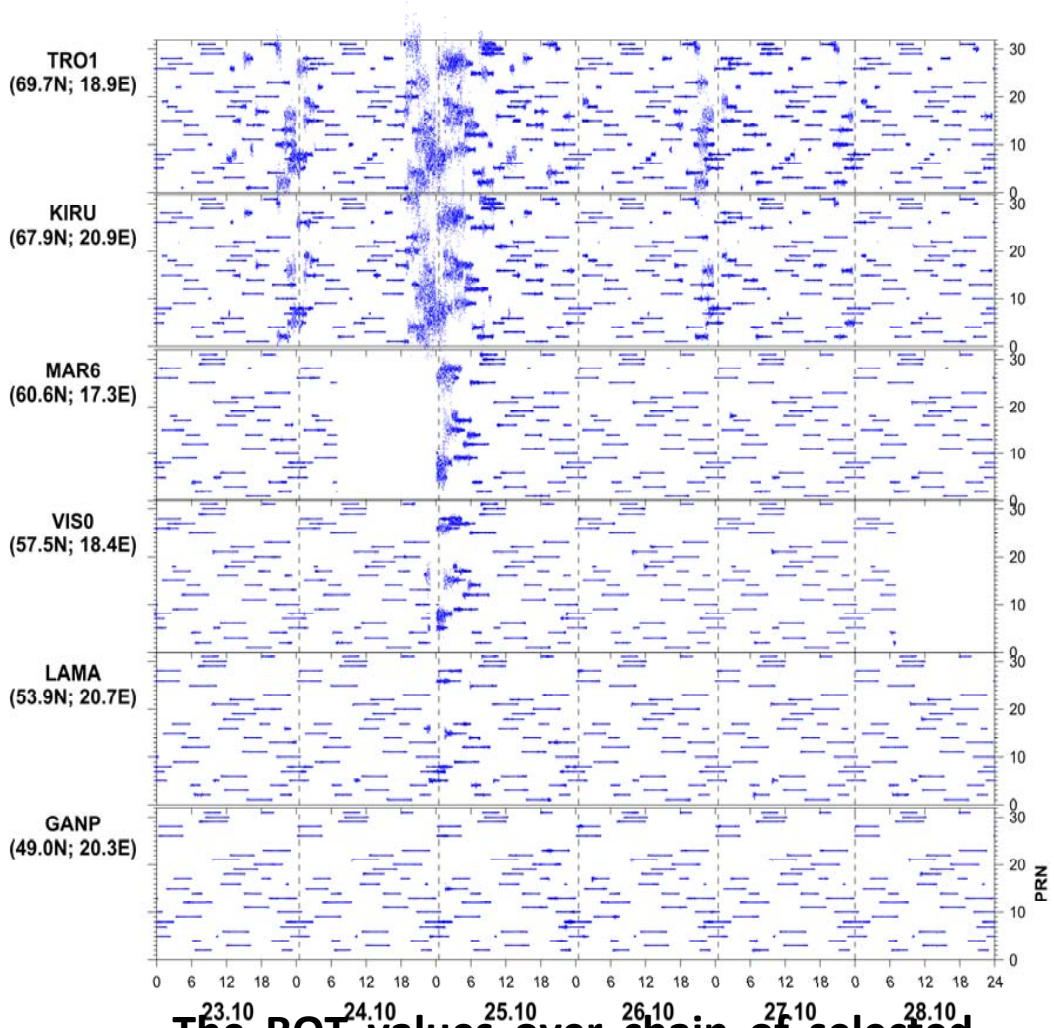
It is known that structure and dynamics of the ionosphere are highly sensitive to the geomagnetic disturbance activity that occurs regularly within the Earth's magnetosphere. Occurrence of ionospheric irregularities is difficult to predict and to model, because of the temporal and spatial variability of the ionosphere and solar activities that are driving forces of space weather phenomena. The constructed ROTI maps allow to estimate the overall fluctuation activity and auroral oval evolutions. For case study analysis we selected two geomagnetic storms of the new 24th solar cycle with similar intensity described by Dst index but different initial and recovery conditions. The data about space weather conditions obtained were obtained from NASA OMNIWEB service located on ftp://spdf.gsfc.nasa.gov/pub/data/omni.

The first case - the geomagnetic storm which initiated by sharp increasing of proton flux and and pressure with the maximum before the 23:00 UT on 24 October, 2011, sharp changing of magnitude and sighn of IMF Bz component (Fig. 4). The Dst index reach minimum value -118 nT at 05:00 UT on 25 October 2011. Additionaly, before the main storm phase there was remarkable increasing of the solar wind density and pressure, as well as remarkable variations of IMF Bz component on 23 October, 2011. The duration of the main phase of geomagnetic storm was about 4h and then the recovery phase started with duration about 48 h.

Geomagnetic storm 23 -29 October 2011.

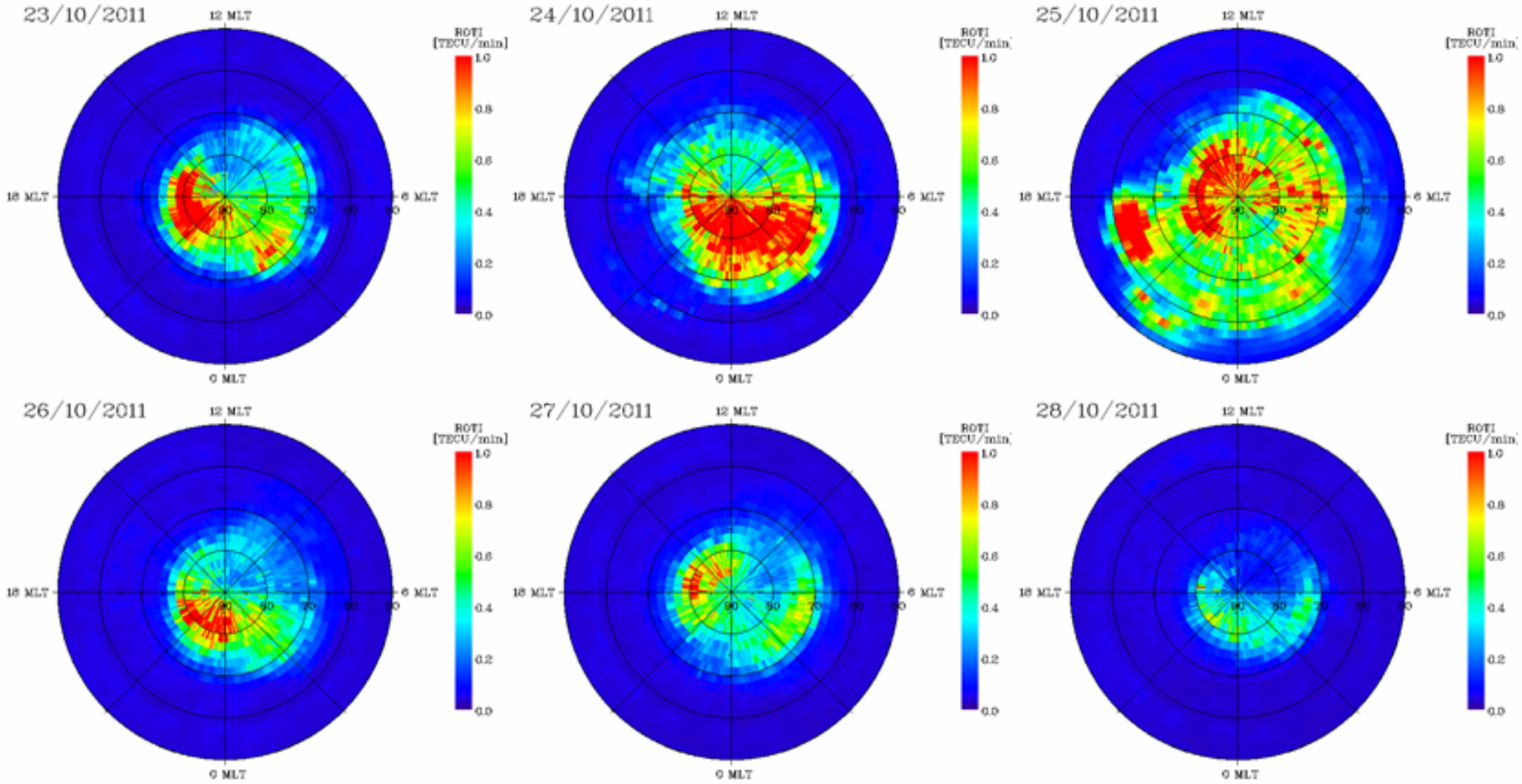


The interplanetary geomagnetic field (IMF) Bz component, density and pressure of solar wind (SW) and Dst index variations for 23 - 29 October 2011.



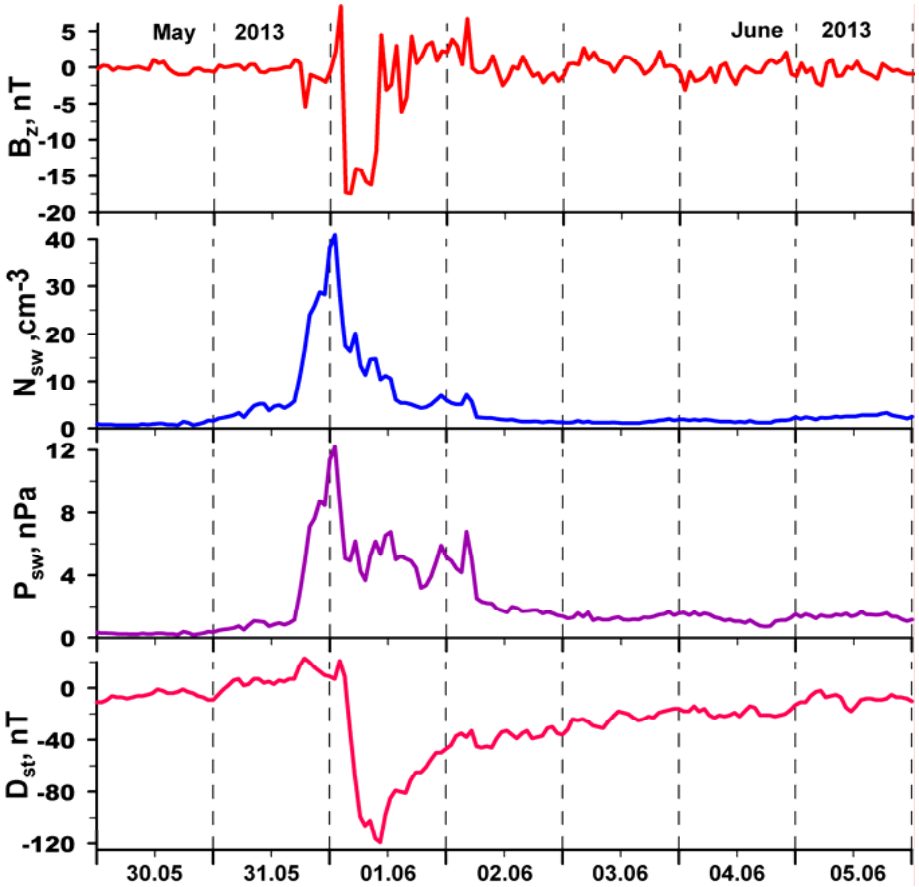
The ROT values over chain of selected European GNSS stations (23-28 October 2011).

Geomagnetic storm 23 -29 October 2011.

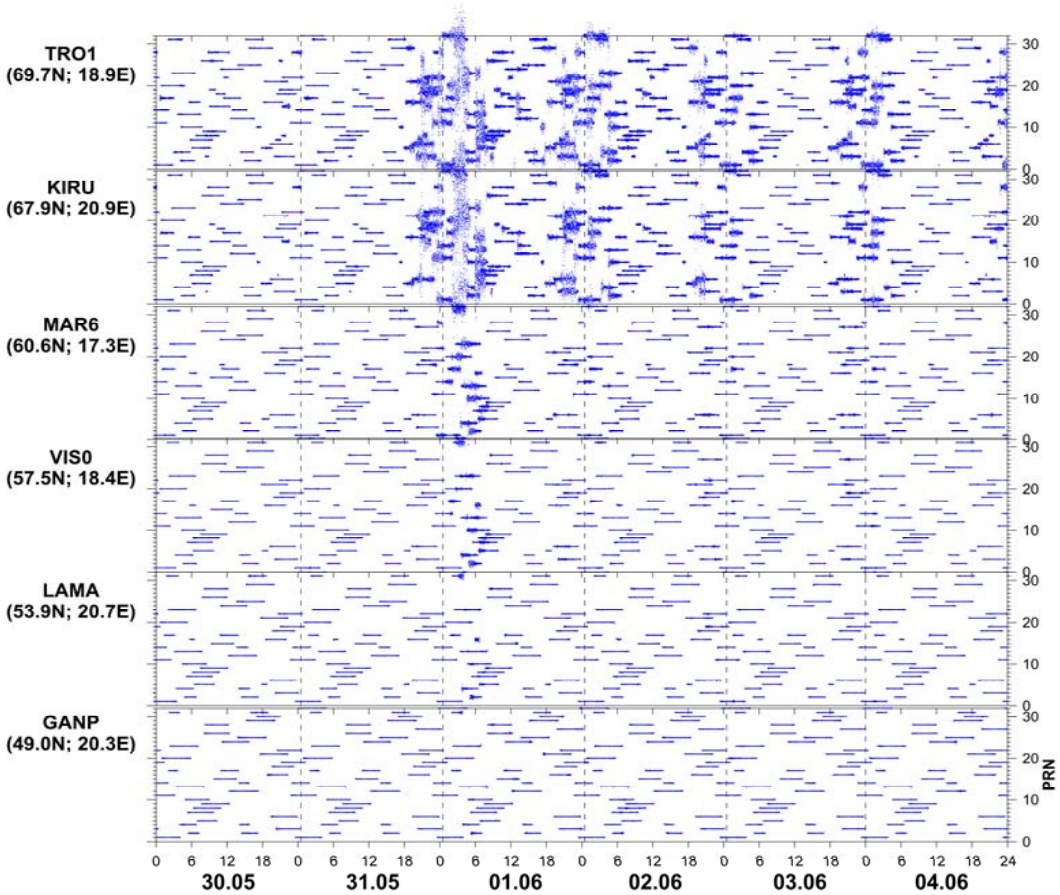


The structure and intensity of the ionospheric irregularities for the period from 23 to 28 October, 2011. The sequence of graphs shows the day to day evolution of ionospheric fluctuation pattern before the main phase of storm and during main and recovery phase of geomagnetic disturbance.

The ionospheric storm occurred on June 2013 was the result of the strong geomagnetic disturbances occurred after midnight on 1 June 2013. Before the storm parameters, characterized solar wind density and pressure, had low values and there was not observed remarkable variations of IMF Bz. Geomagnetic storms were initiated by increasing of proton flux and pressure with the maximum before the midnight between 31 May – 1 June 2013, and turn of sign to negative of interplanetary magnetic field Bz component.

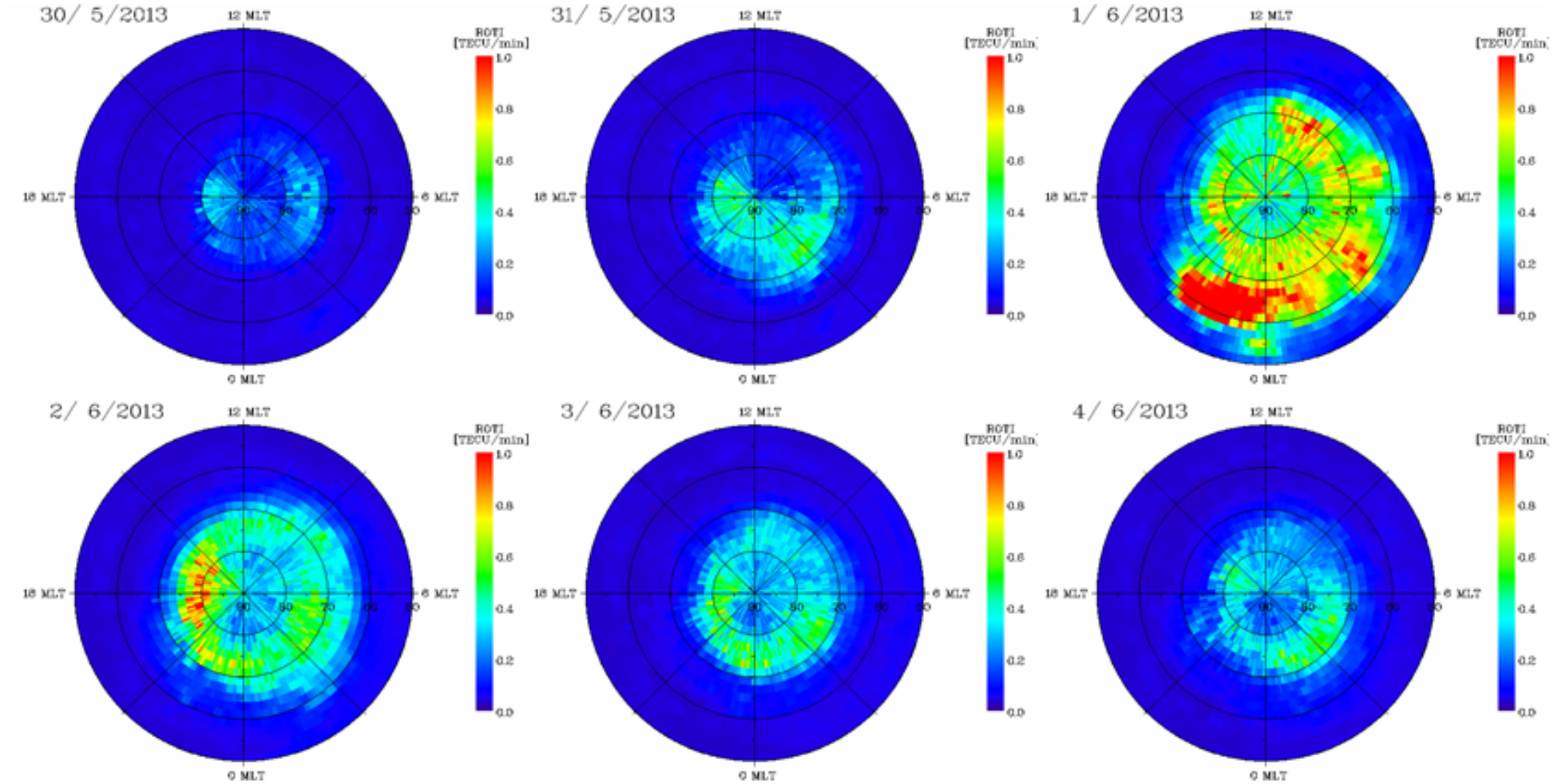


The IMF Bz, SW density and pressure and Dst index variations for 30 May – 5 June 2013.



The ROT values over selected European GNSS stations (30 May – 4 June 2013).

Geomagnetic storm 30 May – 5 June 2013.



The ROTI map on 30 June 2013 demonstrates very weak overall fluctuation intensity when rather low ROTI values appeared within 68 degree circle. For 1 June 2013, corresponded to the main phase of storm, the ROTI map shows very high fluctuation activity in the sector corresponded to the local night conditions, the remarkable fluctuations were registered up to 55 degree MLat. The maps for next day show also high fluctuation activity level, fluctuation oval southern border situated on 75º - 78º.

Conclusions

Although the physics of the ionosphere irregularities has been studied for several decades the characteristics of these effects on GPS signals are still not well explained, and the current navigation system is still vulnerable to strong irregularities events. Large-scale irregularities and associated TEC fluctuations can complicate phase ambiguity resolution, increase the number of undetected and uncorrected cycle slips and losses of signal lock in GNSS So the knowledge about morphology and spatial and temporary dynamics of ionospheric fluctuation, dependences on geophysical factors is very important.

The ionospheric fluctuation maps can be usable for retrospective estimation of space weather impact on positioning and potentially for the future development of forecasting algorithms as well as for testing irregularities models.

For calculation of fluctuation indices there are used measurements of more than 700 stations, that belong to international permanent GNSS networks.

One of the advantages of ROTI maps construction with our technique is that there is not applied any interpolation technique for ROTI mapping, result is real observations, averaged in each cell of 2 deg x 2 deg. This will allow to avoid errors related with unrealistic interpolation values over areas with data gaps.

Conclusions

The ROTI maps allow to estimate the overall fluctuation activity and auroral oval evolutions, the values of ROTI index corresponded to probability of GPS signals phase fluctuations as well as the local intensity of ionospheric irregularities (by ROT index) over every processed GNSS stations.

Occurrence of ionospheric irregularities is driven by forces of space weather phenomena and considered case-studies demonstrate the ability to retrieve information about ionospheric irregularities structure, position and duration. Obtained results show clear dependence of ionospheric fluctuation activity, described by ROT and ROTI, on solar wind and IMF parameters variations.

The occurrence and magnitude of TEC fluctuations increase dramatically during space weather events. The irregularities oval expands considerably equator-ward with simultaneous increase of the fluctuation intensity. We found that during quiet ionospheric conditions the fluctuation events are mainly observed during geographic or magnetic local nighttime within circle of 70º MLat and practically are not registered in dayside sector.

The indices and maps, based on TEC changes, can be effective and very perspective indicator of the presence of phase fluctuations in the high and mid-latitude ionosphere. We expect the high potential of the proposed service and its products, however it is only tool and great work should be done on data processing, statistical analysis, comparative or/and joint investigations with other ionospheric measurements

Acknowledgments

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