3 - 7 July
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ROTI Maps: a new IGS's ionospheric product characterizing the ionospheric irregularities occurrence

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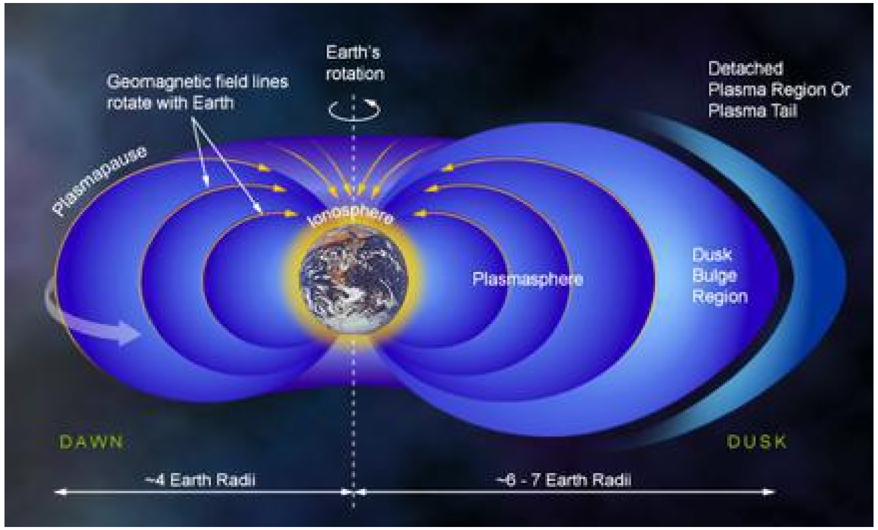
Introduction. Ionosphere

Ionosphere is the part of the Earth's atmosphere, consisting of several ionized layers and extending from about 50 km up to 1,000 km.
Plasma density distribution in the ionosphere varies with:

- altitude
- day/night
- seasons
- latitude/longitude
- solar activity
- geomagnetic conditions



Ionosphere-plasmasphere system
(courtesy of *the Windows to the Universe*)

Equatorial Region: strongest effects; highest; strongest TEC gradients; Irregularities not correlated with magnetic activity

Mid-Latitude Region: normally quiescent but with strong gradients during extreme levels of geomagnetic activity

Auroral Region: aurora and structures. Phase scintillations.

Global ionospheric maps of total electron content (TEC) – IGS GIMs

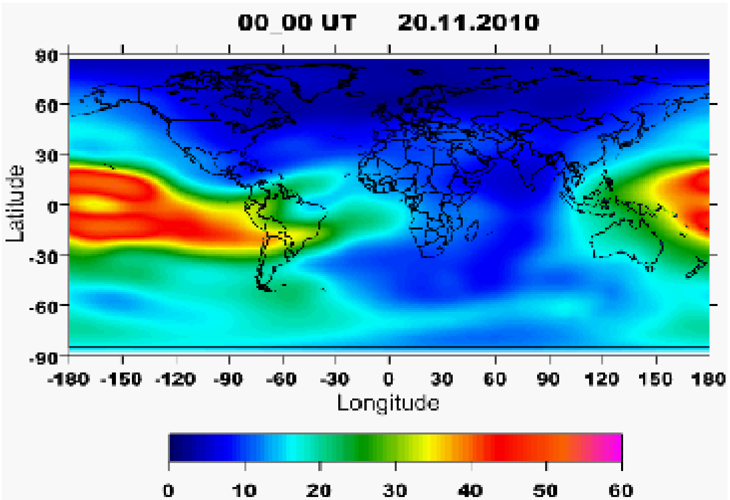
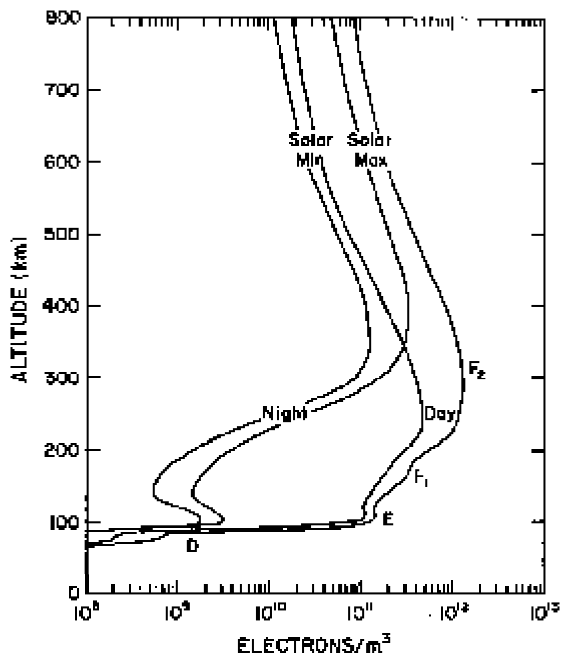


Image credit: UWM

Electron density distribution with altitude



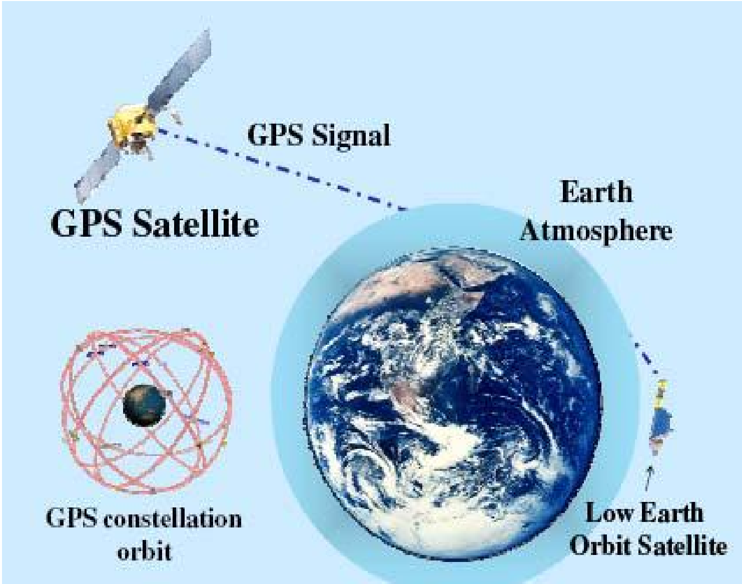
Introduction. GNSS signals propagation

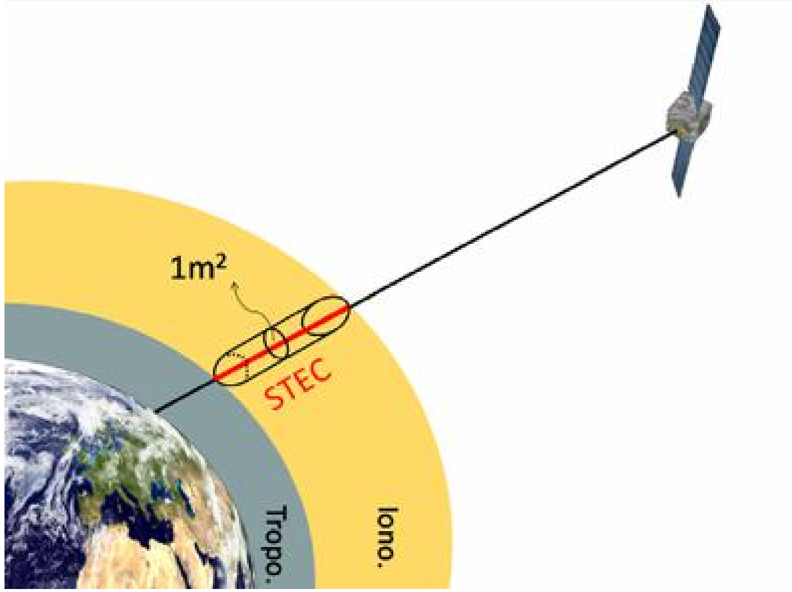
The ionosphere – medium where GNSS signals pass a long distance.

The ionosphere delay is the significant error source for satellite navigation systems, but it can be directly measured and mitigated with using dual frequency GNSS receivers.

Dual frequency GPS measurements can effectively provide integral information on the electron density along the ray path by computing differential phases of code and carrier phase measurements.

The integral of the electron density along the ray path (TEC) between the transmitting GNSS satellite and the receiver.

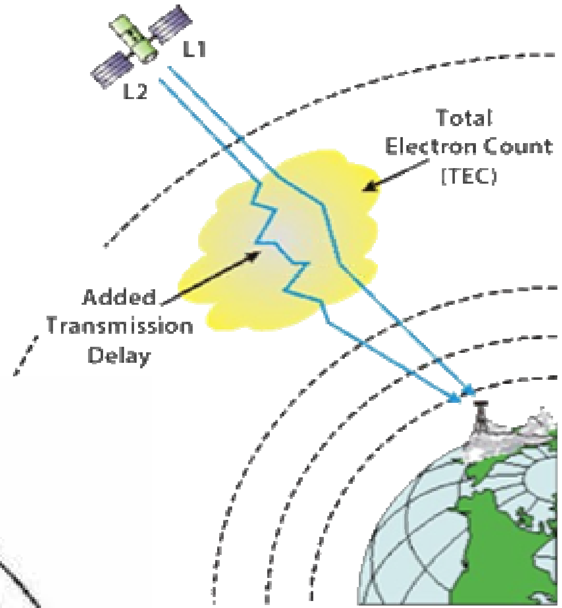


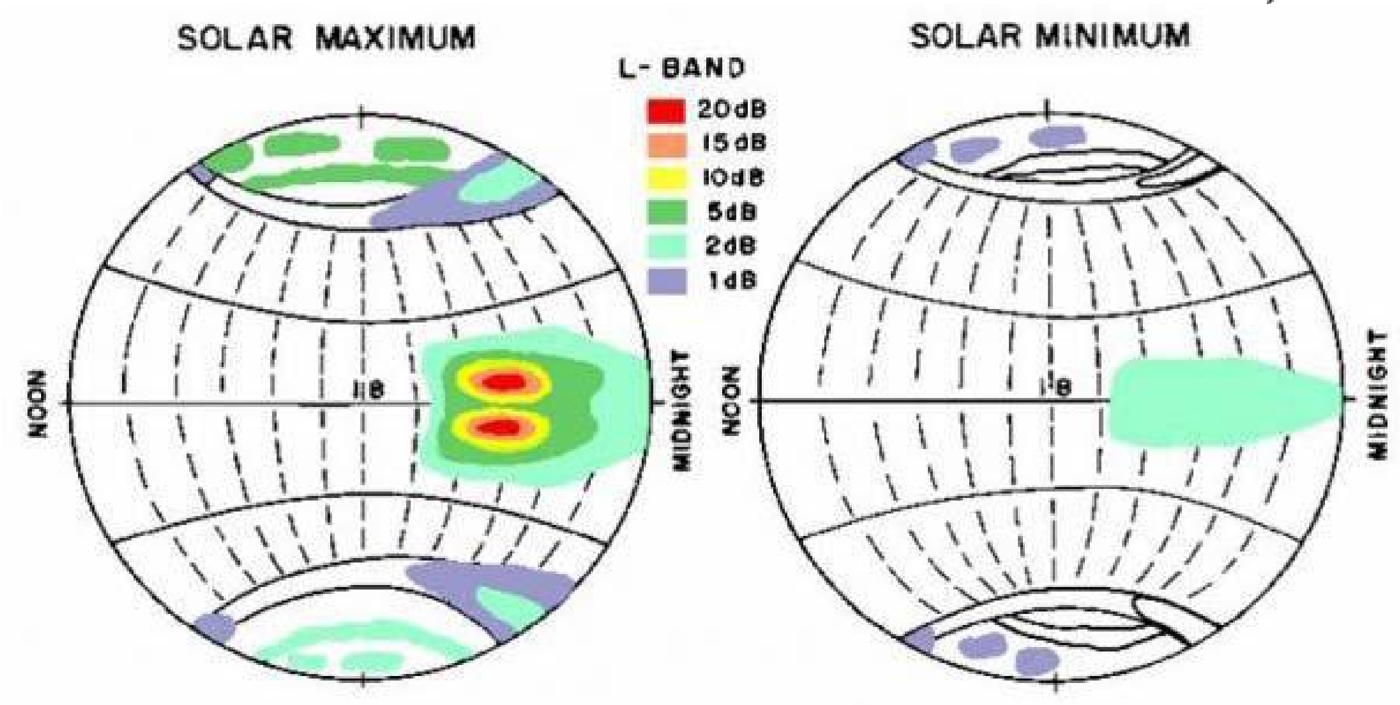


Motivation

Ionospheric irregularities and trans-ionospheric radiowaves propagation

Global distribution of ionospheric scintillation during high and low solar activity





(Basu. et al., J. Atmos. Terr. Phys, 2002)

The open questions:

When and where high-latitude ionospheric plasma irregularities are developed?

Our task:

Monitoring of the ionospheric irregularities over the Northern Hemisphere.

Our approach:

The TEC rapid changes analysis on the base of GPS signal measurements

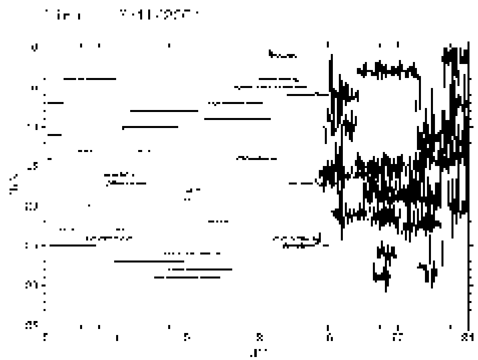
Methodology

Basic approach:

1. The Rate of TEC (dTEC/dt) calculation

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

$\Delta t = t_k - t_{k-1} = 1$ min.

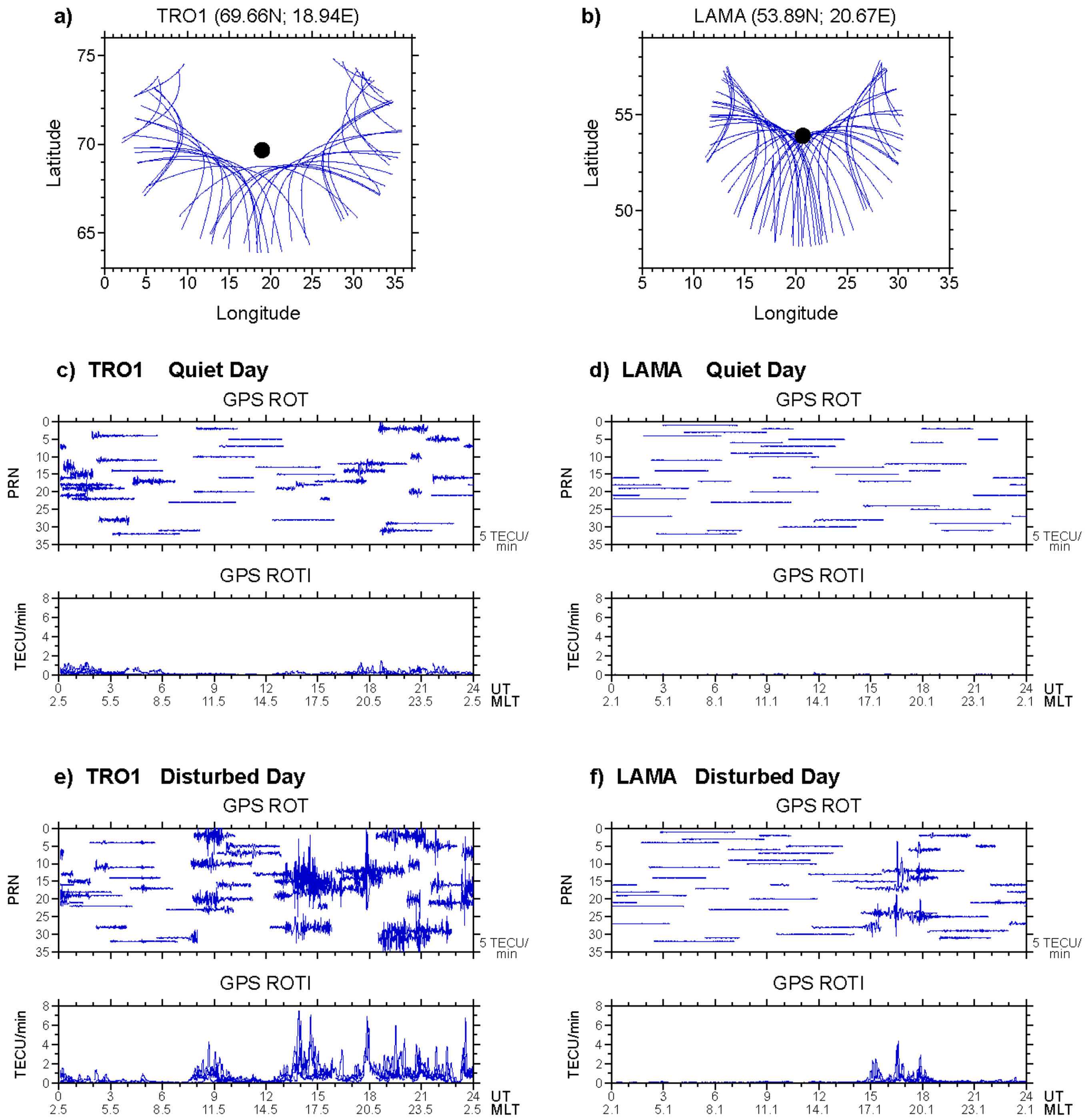


2. The Rate of TEC Index (ROTI) estimation

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

Standard deviation of ROT (on 5 min intervals)

Methodology

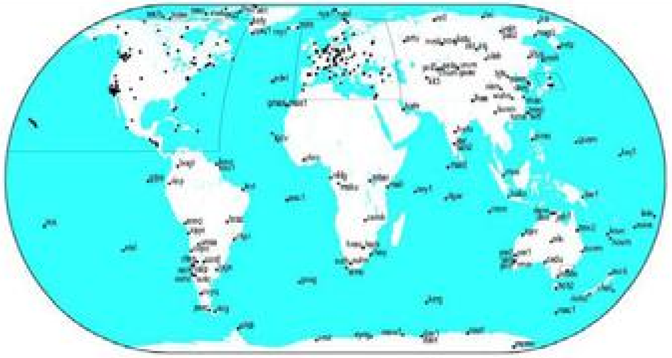


Methodology

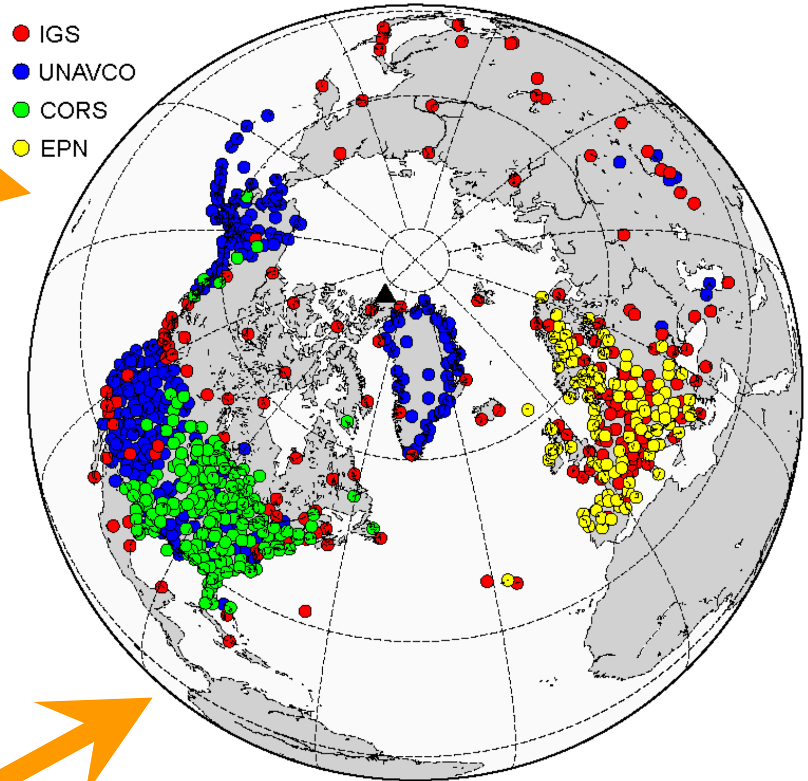
Data sources:

> 700 stations

IGS



UNAVCO



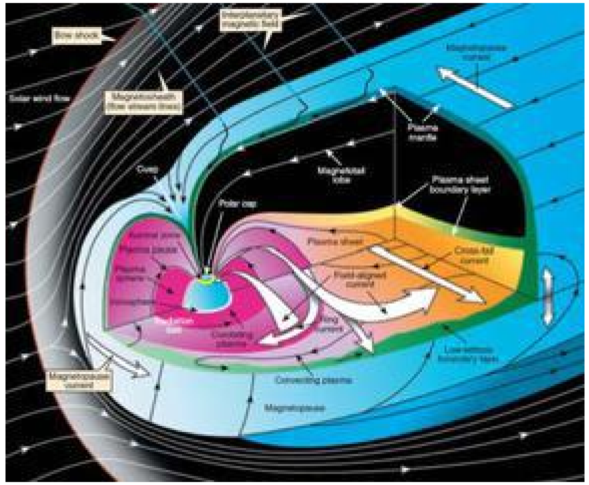
Methodology

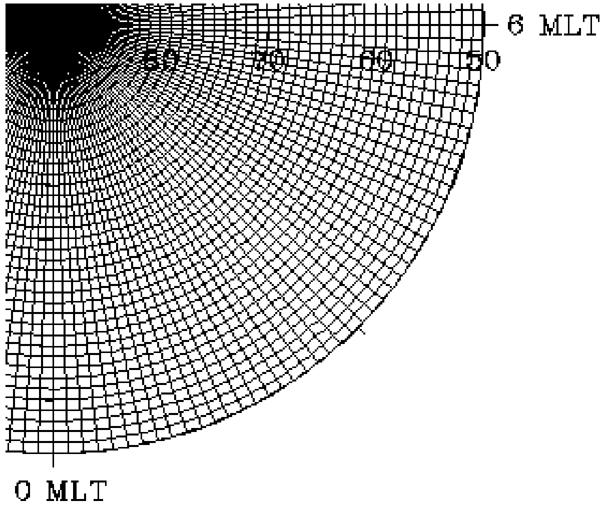
Basic approach:

3. The Rate of TEC Index mapping

Ionospheric plasma variability drivers:

- Solar radiation
- Geomagnetic field





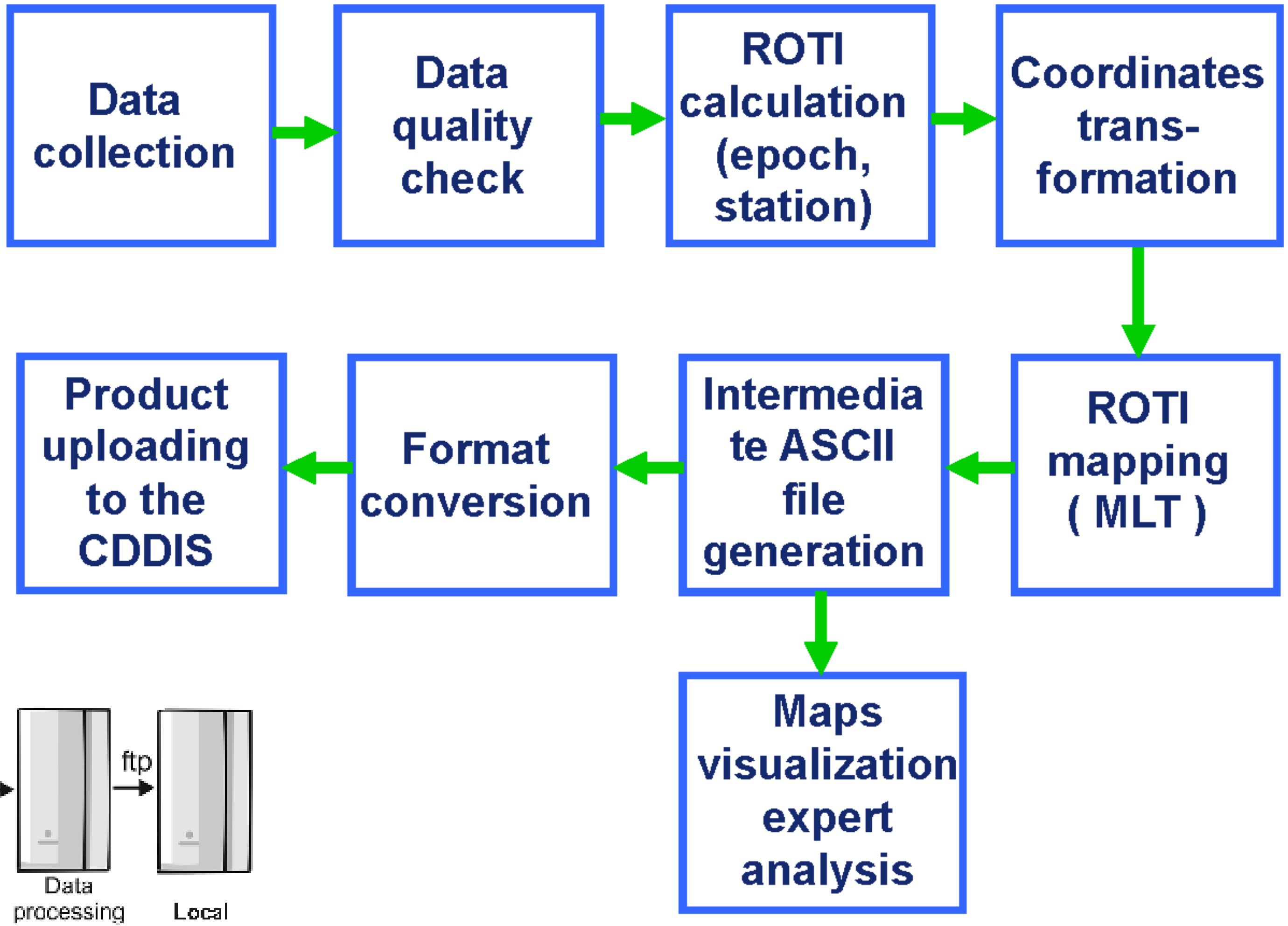
The coordinates system:

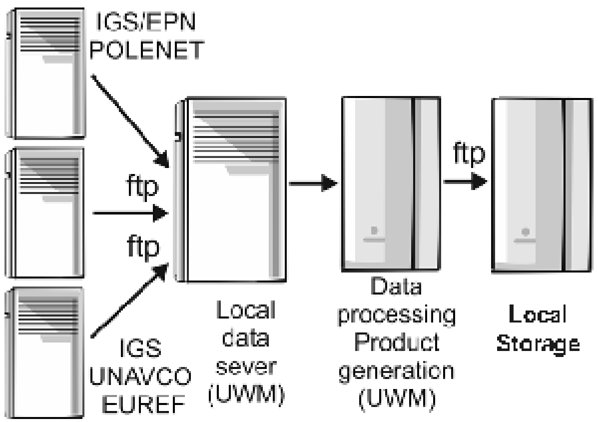
Magnetic local time (MLT) and

corrected magnetic latitude (MLAT)

ROTI Maps Product

Steps of ROTI Maps product generation at UWM:





ROTI Maps Product

Steps of ROTI Maps product generation at UWM:

The ROTI Maps latency

Input data	Latency	Availability
GPS observations ftp://data-out.unavco.org/pub/rinex/obs/ ftp://epncb.oma.be/pub/obs/	6h	30%
	12h	50%
	20h	75%
GPS orbit data ftp://cddis.gsfc.nasa.gov/pub/gps/products/	12h	Non avaliable
	24h	Avaliable

N	Processing phase	Processing time
1	Data collection	2h
2	Quality check	1h
3	Data processing	2,5h
4	Final product generation	5 min
	Total	5h 40 min

The product latency is determined on the input data availability and it takes more 48 h.

ROTI Maps Product

ROTI Maps format

The output maps provided in the ASCII formats.

This data prepared in the IONEX-like format on grid 2 x 2 degree - geomagnetic latitude from 51º to 89º with step 2º and corresponded to magnetic local time (00-24 MLT) polar coordinates from 0 to 359.

```
ROTIPOLARMAP
START OF ROTIPOLARMAP
  2015      1      1
    51.0    1.0 359.0
 0.0344  0.0363  0.0365  0.0372  0.0355  0.0355  0.0359  0.0347  0.0332  0.0324
 0.0333  0.0328  0.0328  0.0327  0.0319  0.0328  0.0343  0.0322  0.0302  0.0293
 0.0306  0.0328  0.0343  0.0358  0.0379  0.0393  0.0388  0.0379  0.0372  0.0380
 0.0382  0.0374  0.0375  0.0360  0.0356  0.0360  0.0350  0.0350  0.0365  0.0390
 0.0409  0.0406  0.0408  0.0410  0.0398  0.0404  0.0408  0.0410  0.0427  0.0445
 0.0412  0.0389  0.0372  0.0369  0.0357  0.0352  0.0350  0.0348  0.0348  0.0350
 0.0343  0.0339  0.0361  0.0371  0.0378  0.0373  0.0360  0.0361  0.0362  0.0355
 0.0353  0.0362  0.0349  0.0355  0.0348  0.0348  0.0351  0.0340  0.0326  0.0324
 0.0331  0.0317  0.0309  0.0298  0.0316  0.0308  0.0306  0.0318  0.0328  0.0329
 0.0334  0.0337  0.0348  0.0353  0.0365  0.0391  0.0422  0.0418  0.0424  0.0441
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 0.0401  0.0406  0.0425  0.0417  0.0414  0.0426  0.0459  0.0466  0.0467  0.0480
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 0.0403  0.0403  0.0388  0.0391  0.0398  0.0411  0.0412  0.0416  0.0397  0.0400
 0.0406  0.0416  0.0434  0.0443  0.0445  0.0448  0.0430  0.0405  0.0410  0.0412
 0.0434  0.0451  0.0421  0.0441  0.0423  0.0434  0.0423  0.0441  0.0406  0.0375
 0.0399  0.0385  0.0371  0.0367  0.0356  0.0342  0.0339  0.0326  0.0316  0.0312
 0.0316  0.0317  0.0320  0.0307  0.0296  0.0304  0.0307  0.0305  0.0323  0.0329
    53.0    1.0 359.0
 0.0322  0.0336  0.0326  0.0336  0.0308  0.0318  0.0368  0.0391  0.0377  0.0382
 0.0342  0.0348  0.0326  0.0332  0.0330  0.0326  0.0340  0.0330  0.0315  0.0323
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 0.0339  0.0311  0.0315  0.0310  0.0347  0.0354  0.0331  0.0320  0.0307  0.0304
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 0.0451  0.0447  0.0447  0.0461  0.0501  0.0490  0.0482  0.0461  0.0435  0.0439
 0.0418  0.0424  0.0439  0.0455  0.0456  0.0446  0.0447  0.0452  0.0453  0.0448
 0.0462  0.0452  0.0443  0.0462  0.0452  0.0429  0.0467  0.0473  0.0470  0.0427
 0.0401  0.0424  0.0442  0.0481  0.0557  0.0497  0.0454  0.0403  0.0373  0.0363
 0.0362  0.0365  0.0384  0.0388  0.0365  0.0348  0.0337  0.0330  0.0327  0.0305
 0.0311  0.0307  0.0297  0.0297  0.0299  0.0305  0.0300  0.0298  0.0304  0.0313
    55.0    1.0 359.0
 0.0356  0.0327  0.0306  0.0374  0.0397  0.0385  0.0406  0.0420  0.0403  0.0371
 0.0370  0.0377  0.0365  0.0361  0.0372  0.0372  0.0376  0.0405  0.0401  0.0390
 0.0378  0.0361  0.0338  0.0333  0.0328  0.0361  0.0419  0.0416  0.0390  0.0377
```
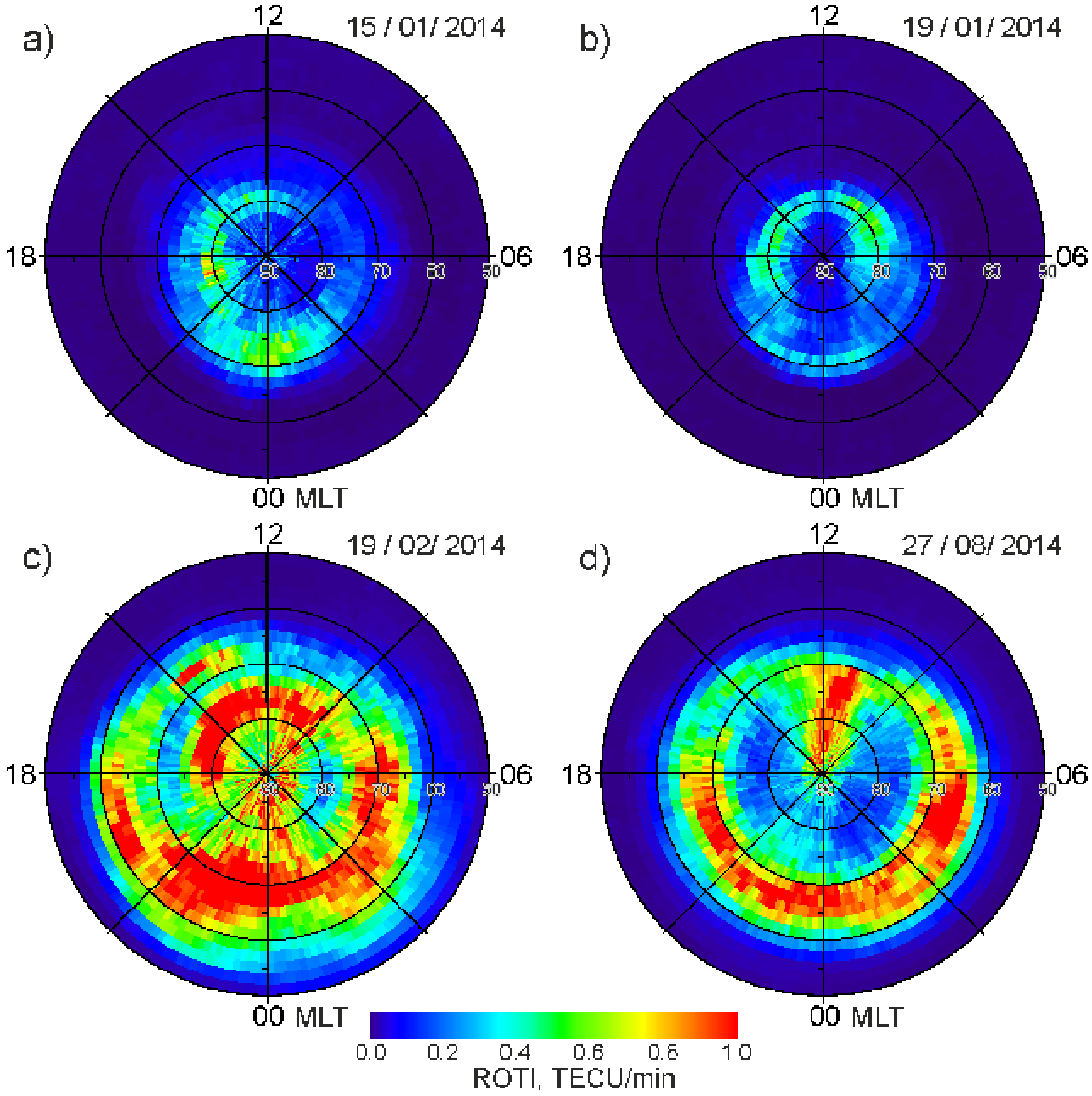

The sample of the ROTI Maps output: ASCII format.

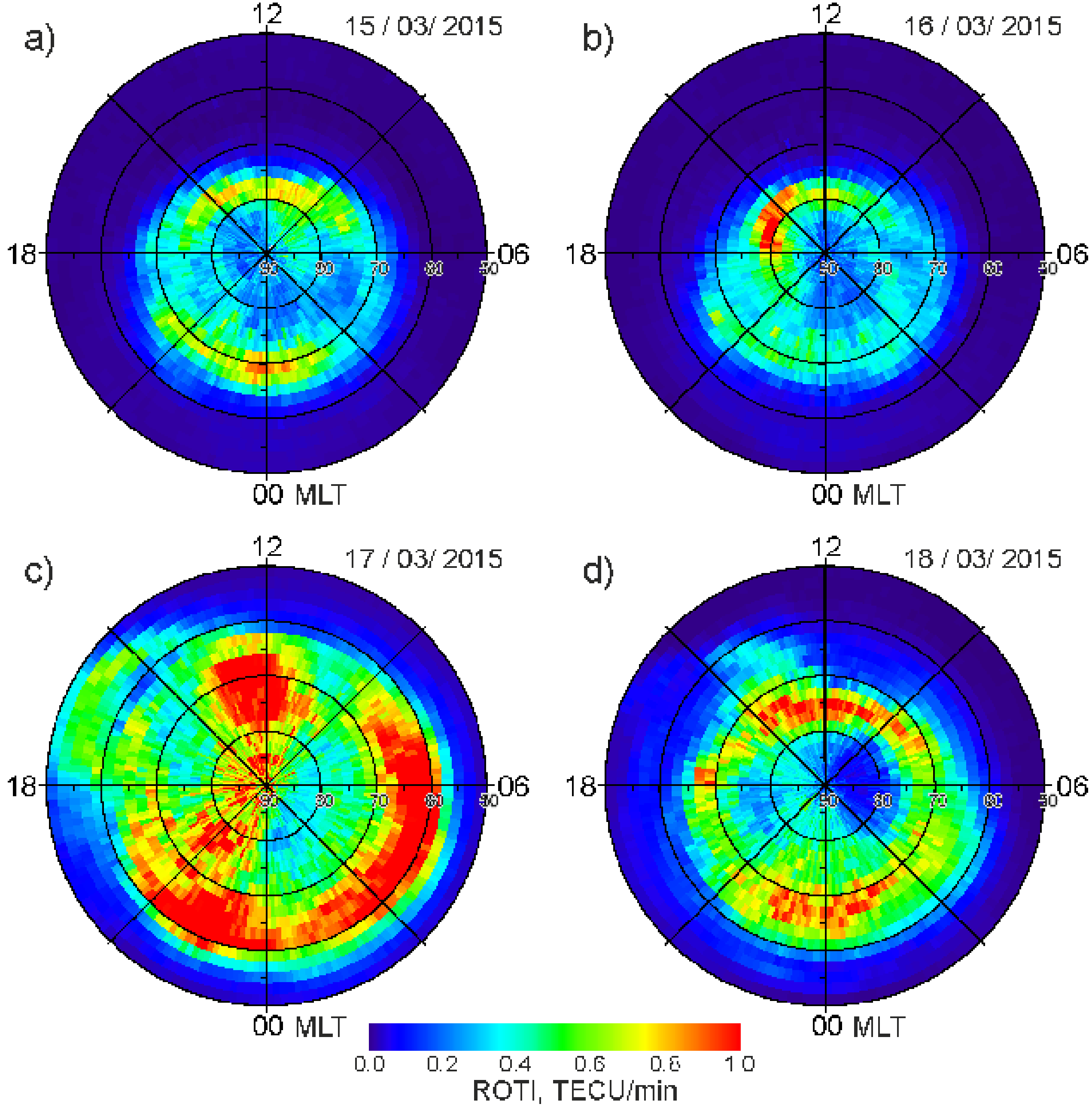
ROTI Maps Product

ROTI Maps visualization



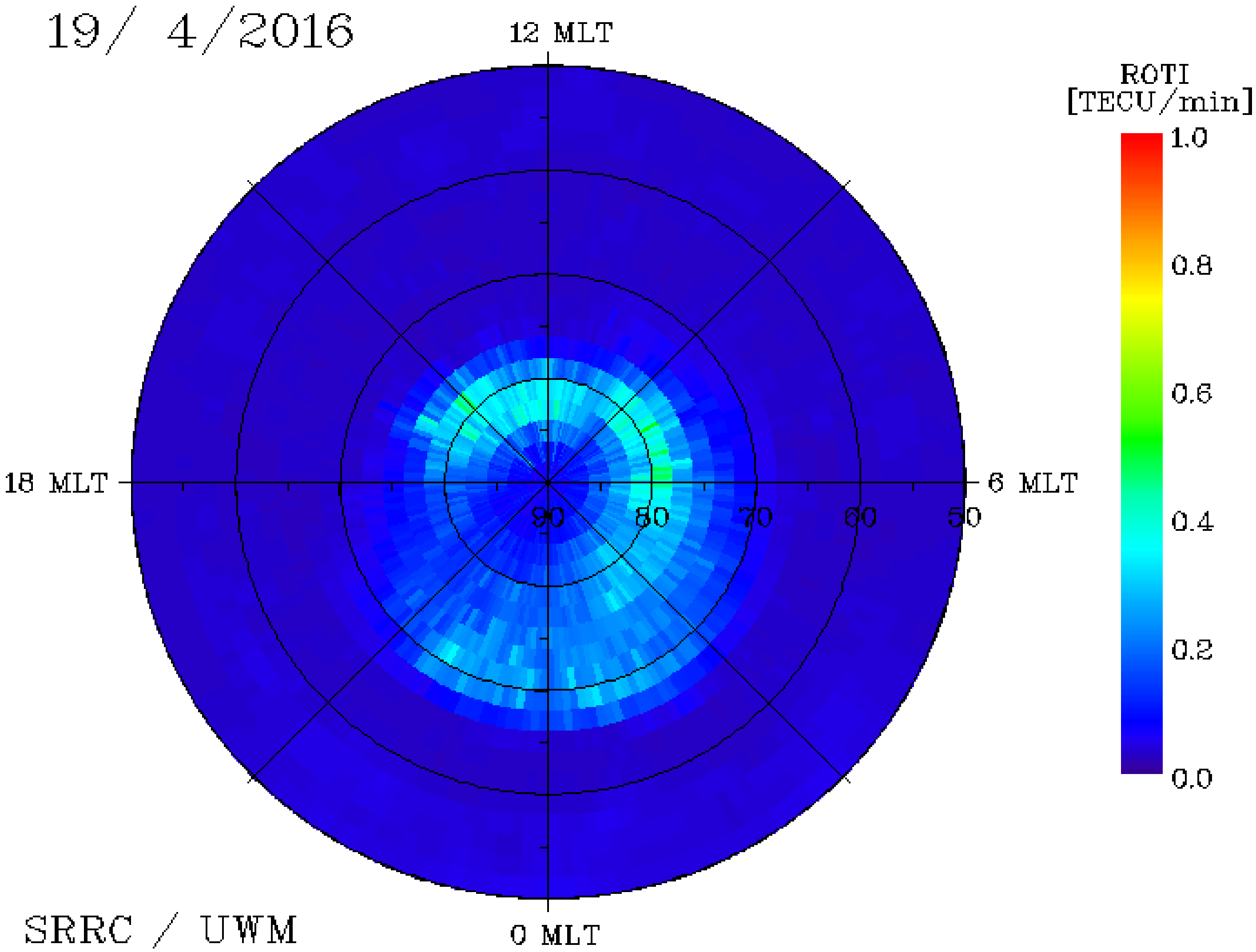
ROTI Maps Product

ROTI Maps visualization



ROTI Maps Product

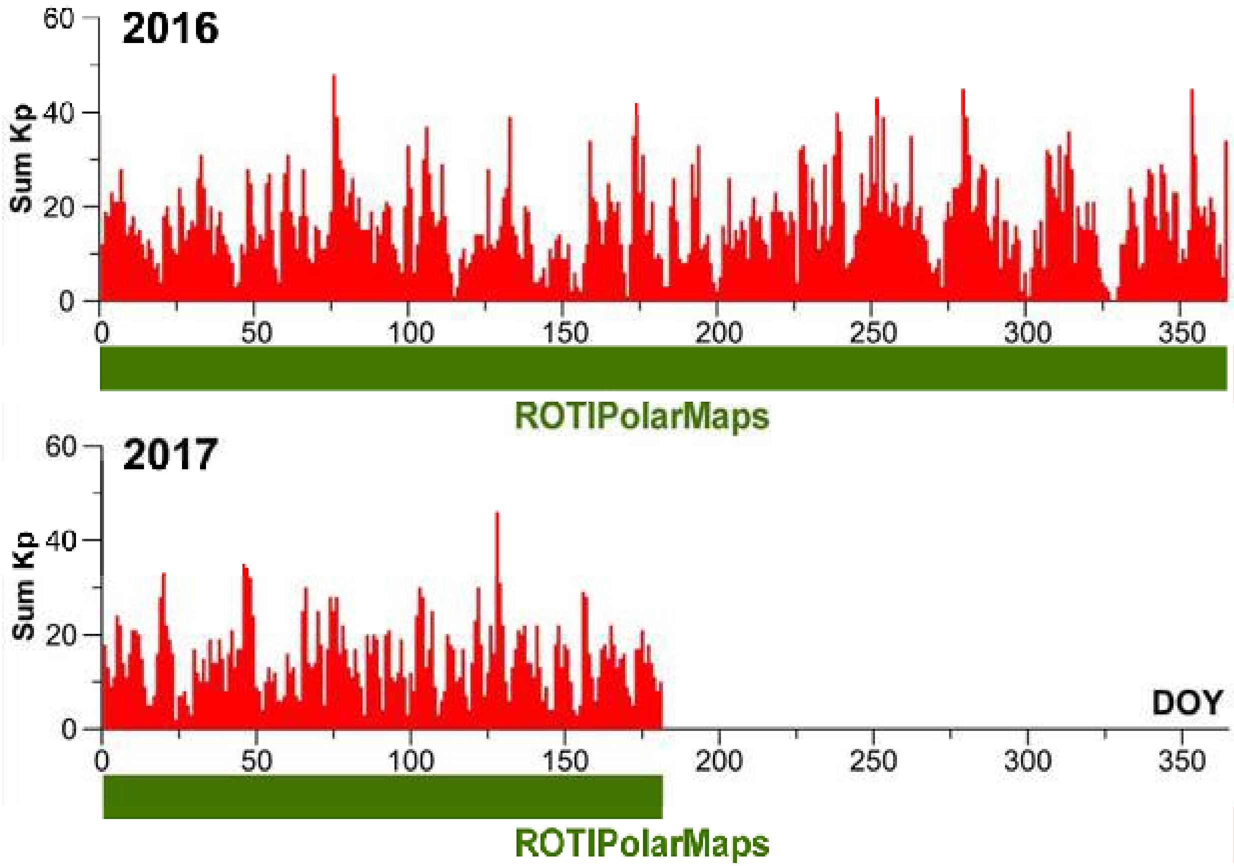
ROTI Maps visualization



ROTI Maps Product

The ROTI Maps product generation at UWM:

The UWM ROTI Maps processor operates routinely since January, 1, 2015.



Cherniak et al., GPS Solution, 2017

It was processed and collected data and resulted product from 2010up to now since the test service established.

There is no gaps in the ROTI Maps product dataset for test period.

The ROTI maps product validation activity on 2015-2016 dataset.

ROTI Maps product for 2016 – 2017 available since March 2017 on CDDIS.

Detailed description of the ROTI Maps Product will be available in paper Cherniak et al., GPS Solution, 2017 (under review).

ROTI Maps Product

MONITOR Content

- Introduction
- Project partners
- Documentation
- Stations map - data
- Stations map - products
- Search input data
- Search products
- Data policy
- Contact

SEARCH OUTPUT PRODUCTS

Day of year 12 (1-366) Year 2016 Hour (0-23)

Product Type roti ☑ search plots, too

Select the provider:

◉ Processor ROTIPolarMaps (UWM)

or

○ Station

Search Reset

PRODUCT AVAILABILITY (ROTI) - DAY: 012, 2016, PROVIDER: ROTIPOLARMAPS (UWM)

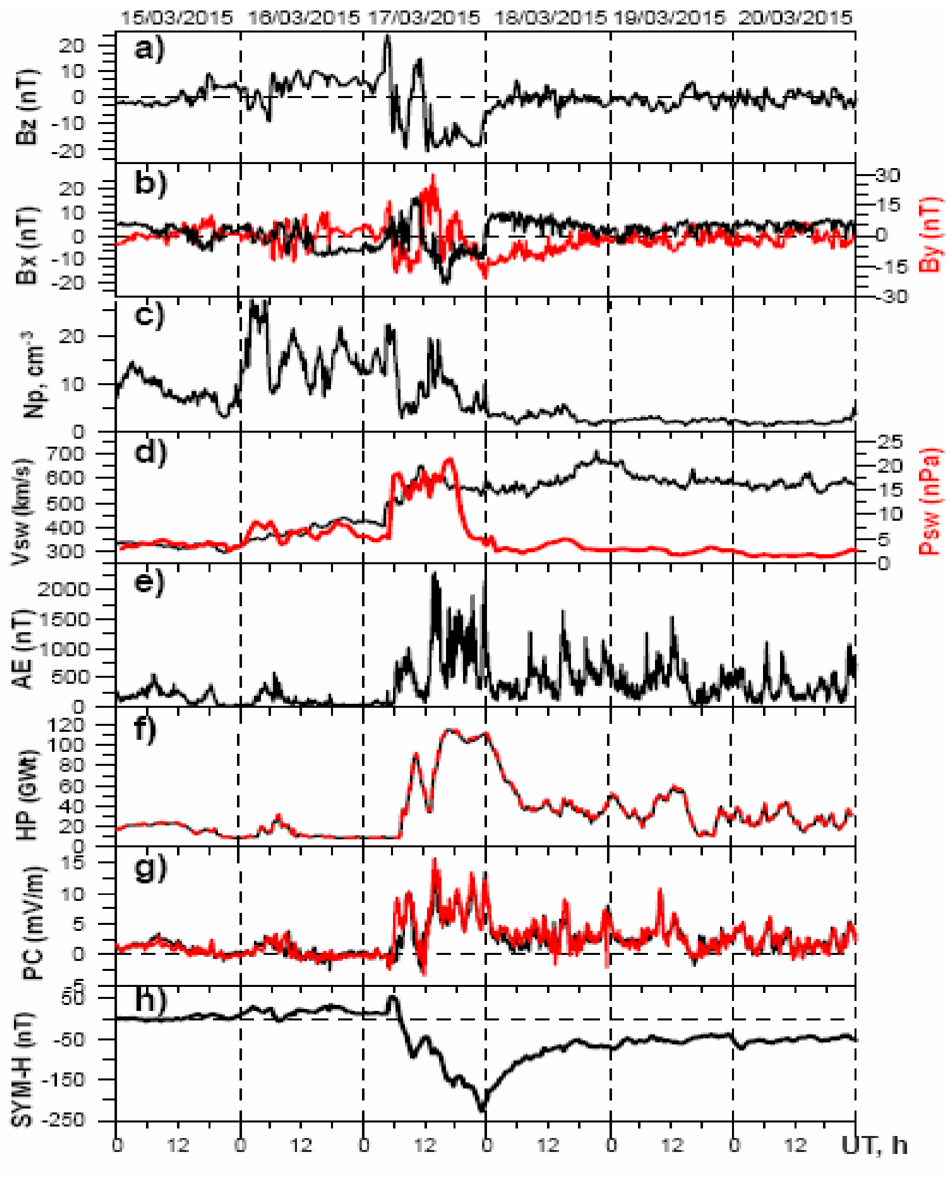
Instructions: left-click on a file name to get its FTP address.

Left-click on a plot thumbnail to display it in original size. Only the authorised users can download product files or non-public plots via FTP.

NAME	ARCHIVED DATE	ACTION
ROTI0120.16f	2016-01-16 02:48:09	
ROTI0120.16f.png	2016-01-16 02:48:09	

The ROTI maps product have been validated within framework of Monitor-2 European Space Agency Project (2015-2016 dataset). Beniguel et al., 2016, AnnGeo.

ROTI Maps Product. Scientific Applications.

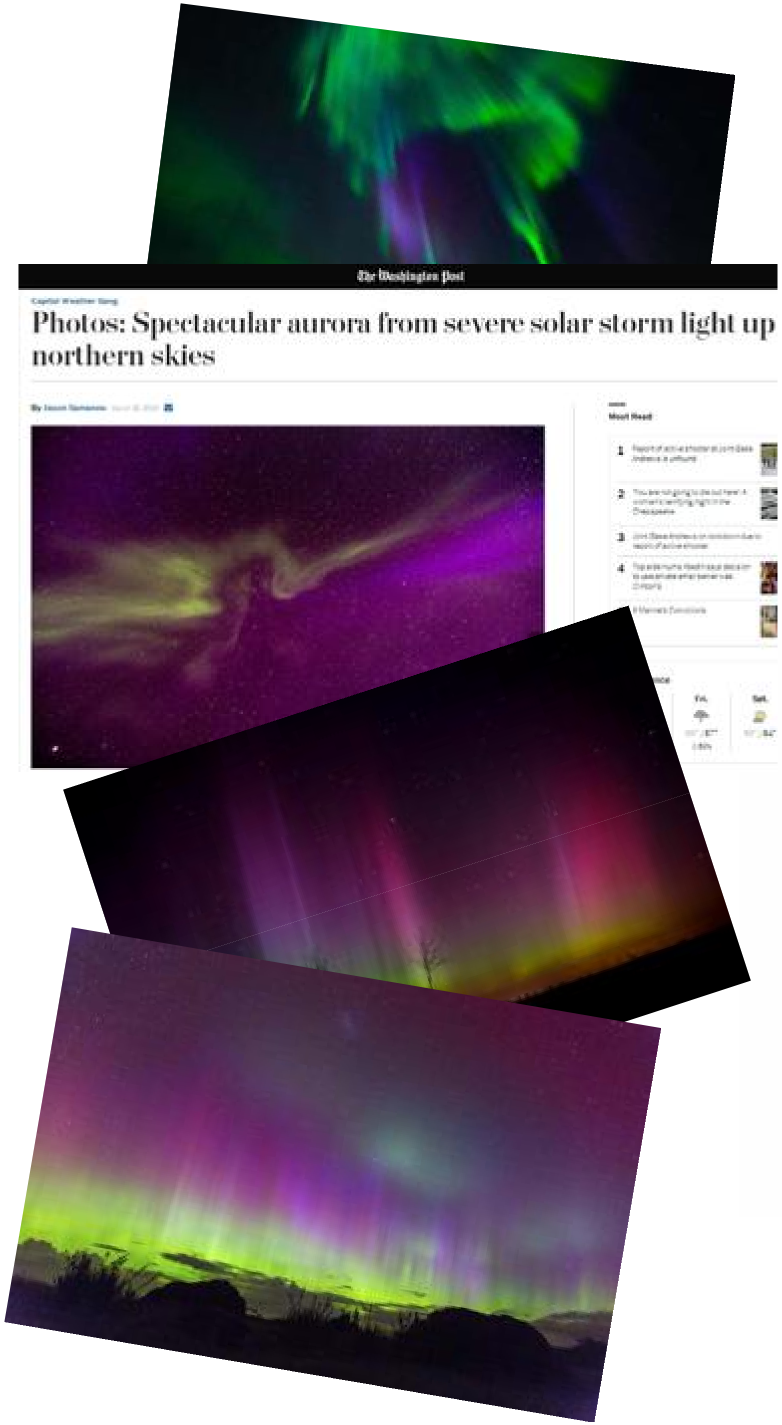


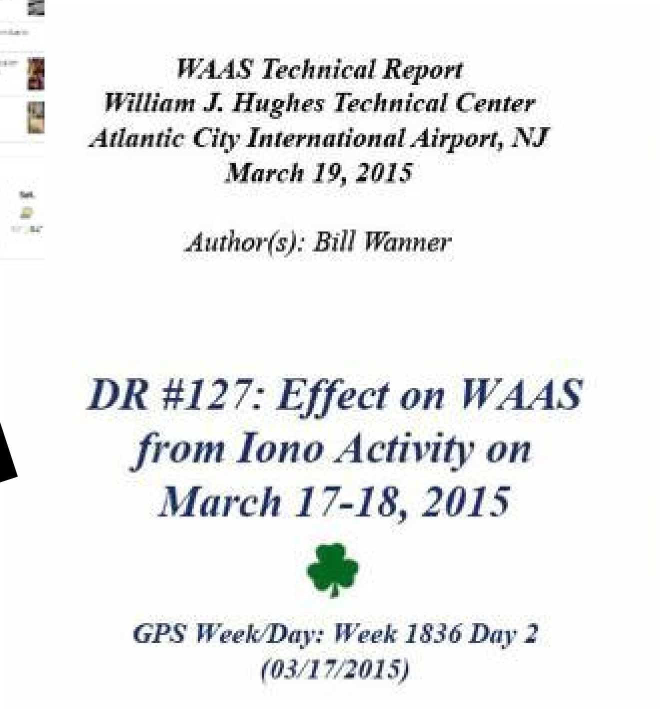
2015 St. Patrick's Day Storm

- Largest storm for last 10 years
- Intense particle precipitation
- Aurora was registered at mid-latitudes

(Cherniak et al,, AGU SW, 2015

B. Wanner, WAAS Technical Report:
“Iono activity affected WAAS performance in Canada, Alaska, and CONUS on March 17 and March 18”



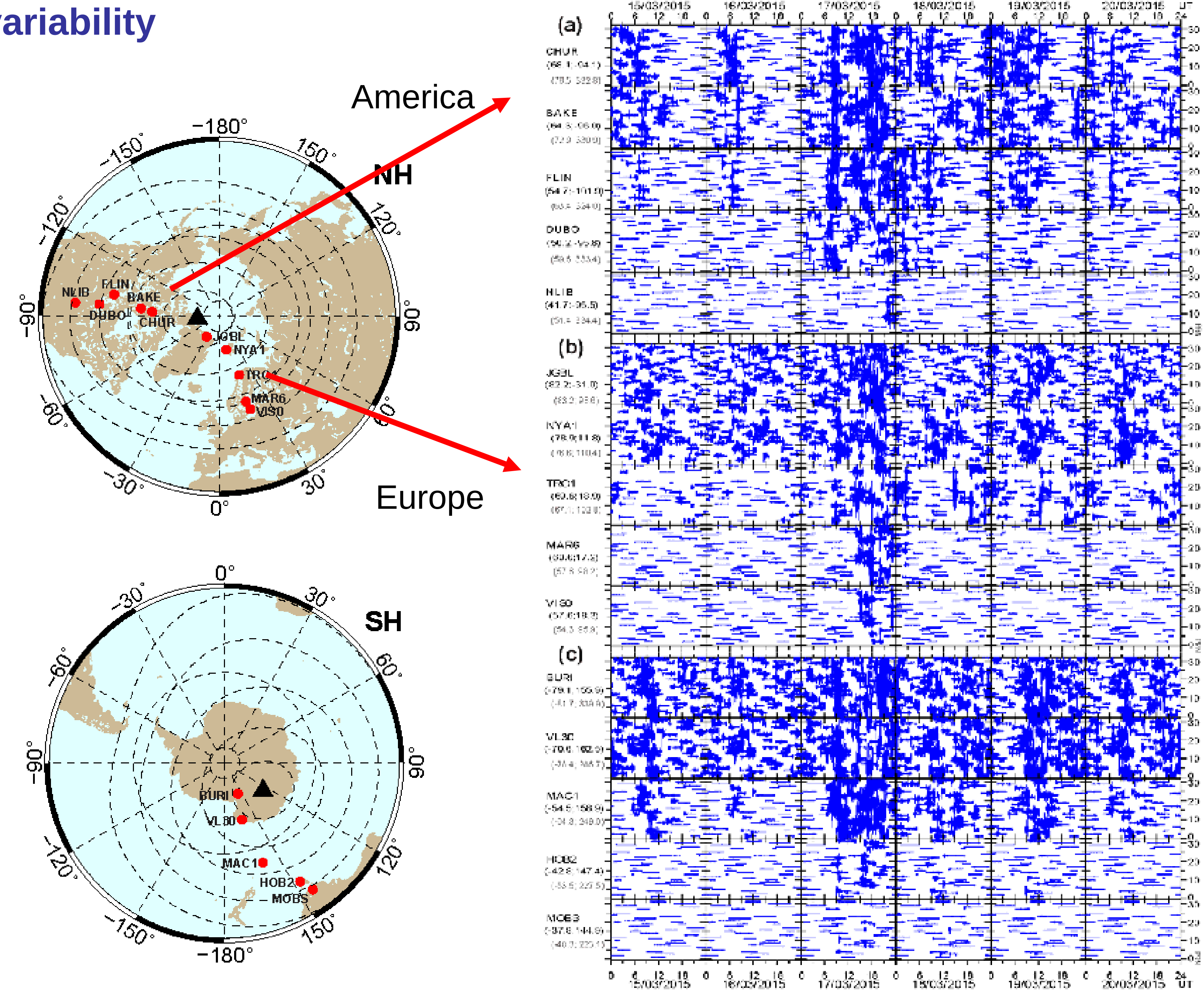

WAAS Technical Report
William J. Hughes Technical Center
Atlantic City International Airport, NJ
March 19, 2015

Author(s): Bill Wanner

DR #127: Effect on WAAS from Iono Activity on March 17-18, 2015

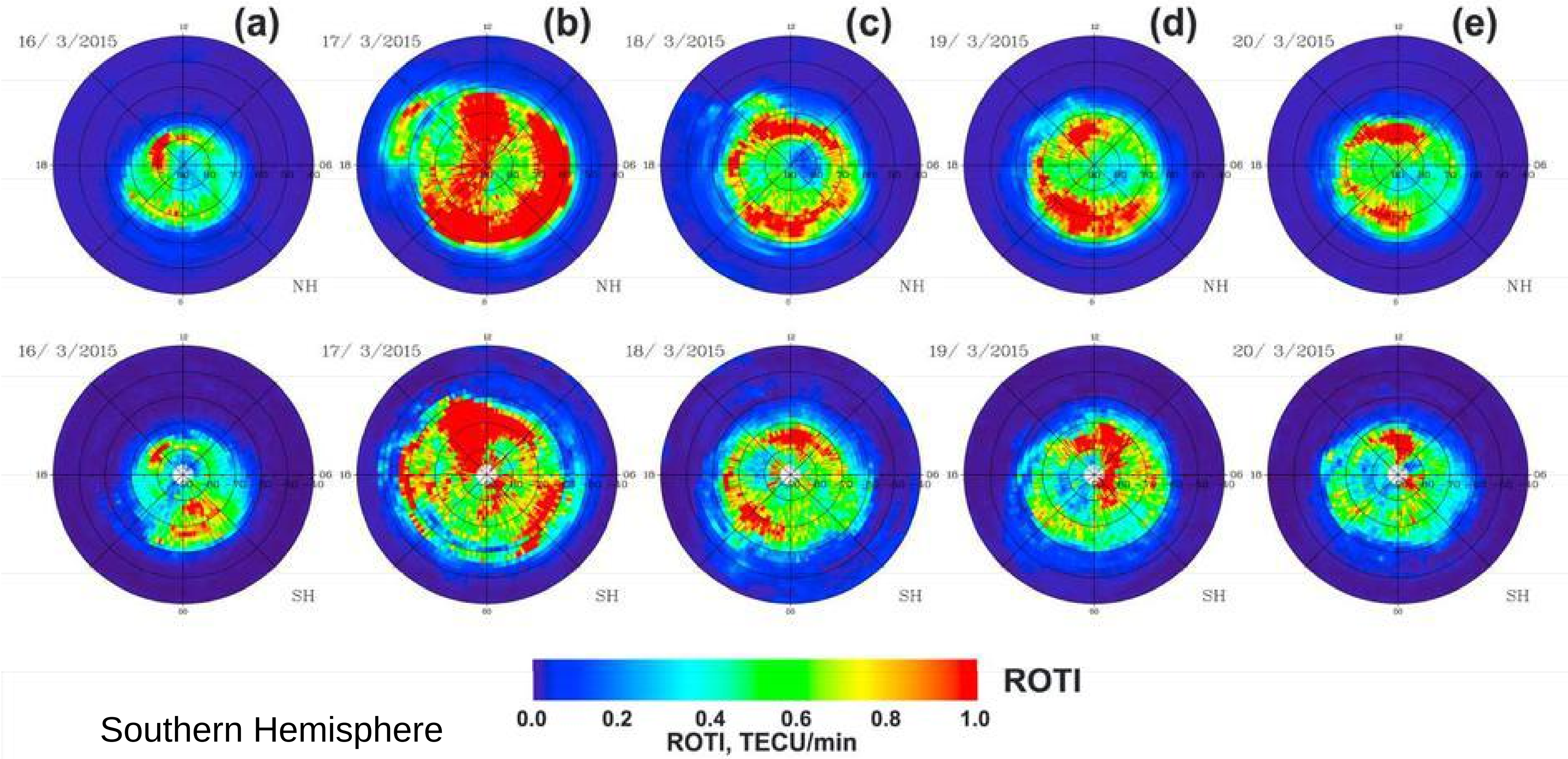
GPS Week/Day: Week 1836 Day 2
(03/17/2015)

ROT variability



Diurnal ROTI maps

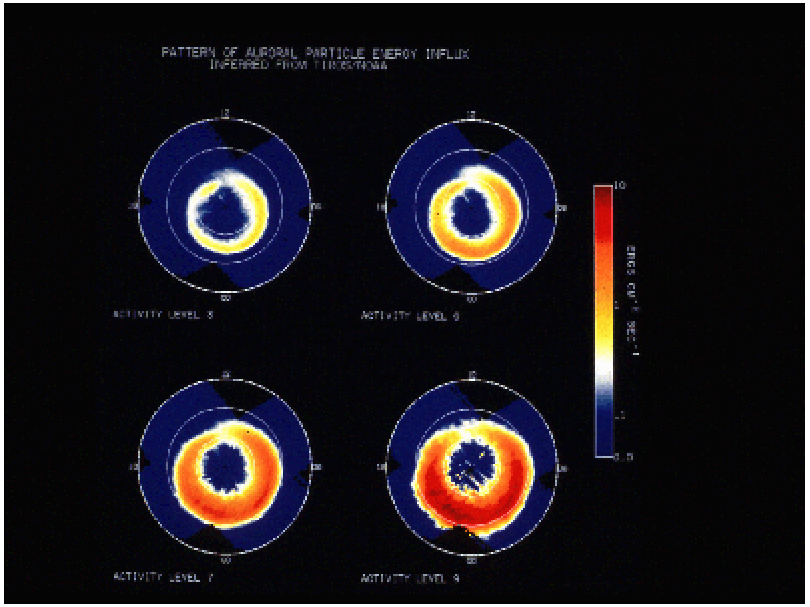
Northern Hemisphere



Southern Hemisphere

Cherniak et al., SW, 2015

Diurnal ROTI maps vs patterns of auroral particle energy flux



TIROS/NOAA Auroral Observations

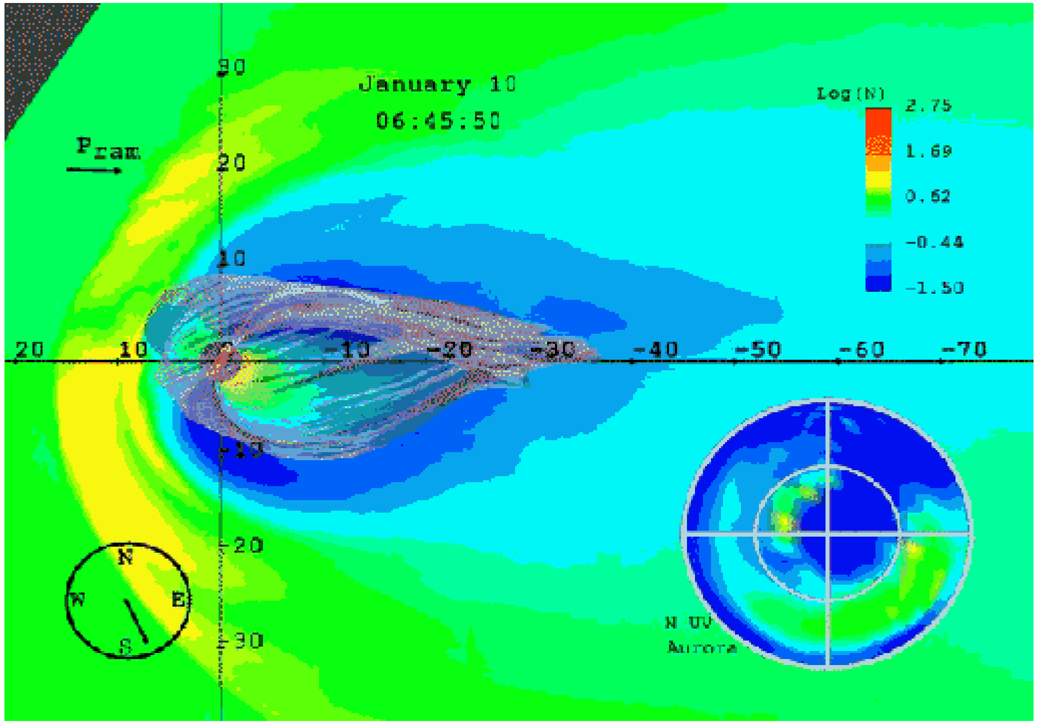
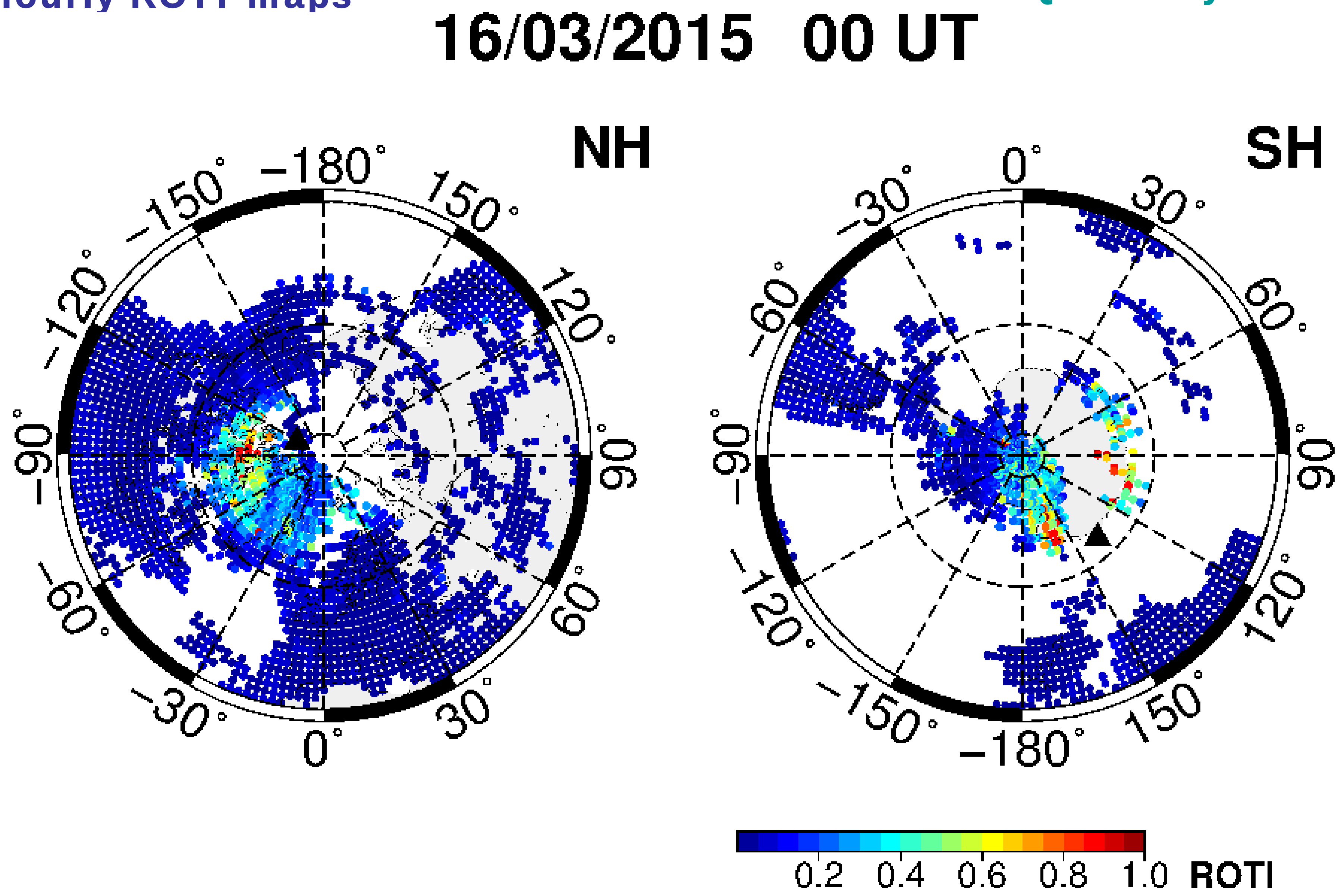


Image credit: SRI International

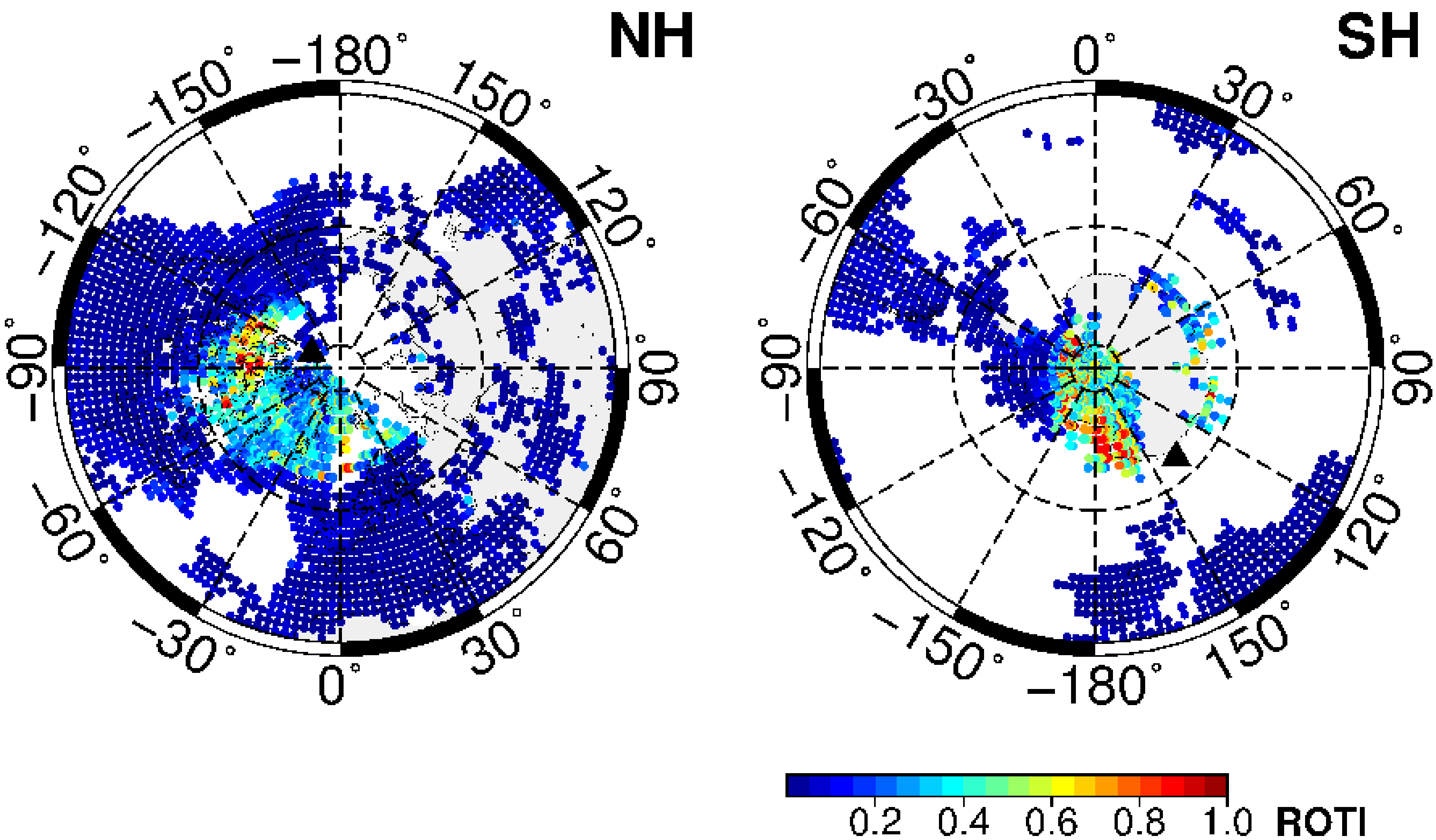
Dynamics of ionospheric irregularities:
Hourly ROTI maps

Quiet Day

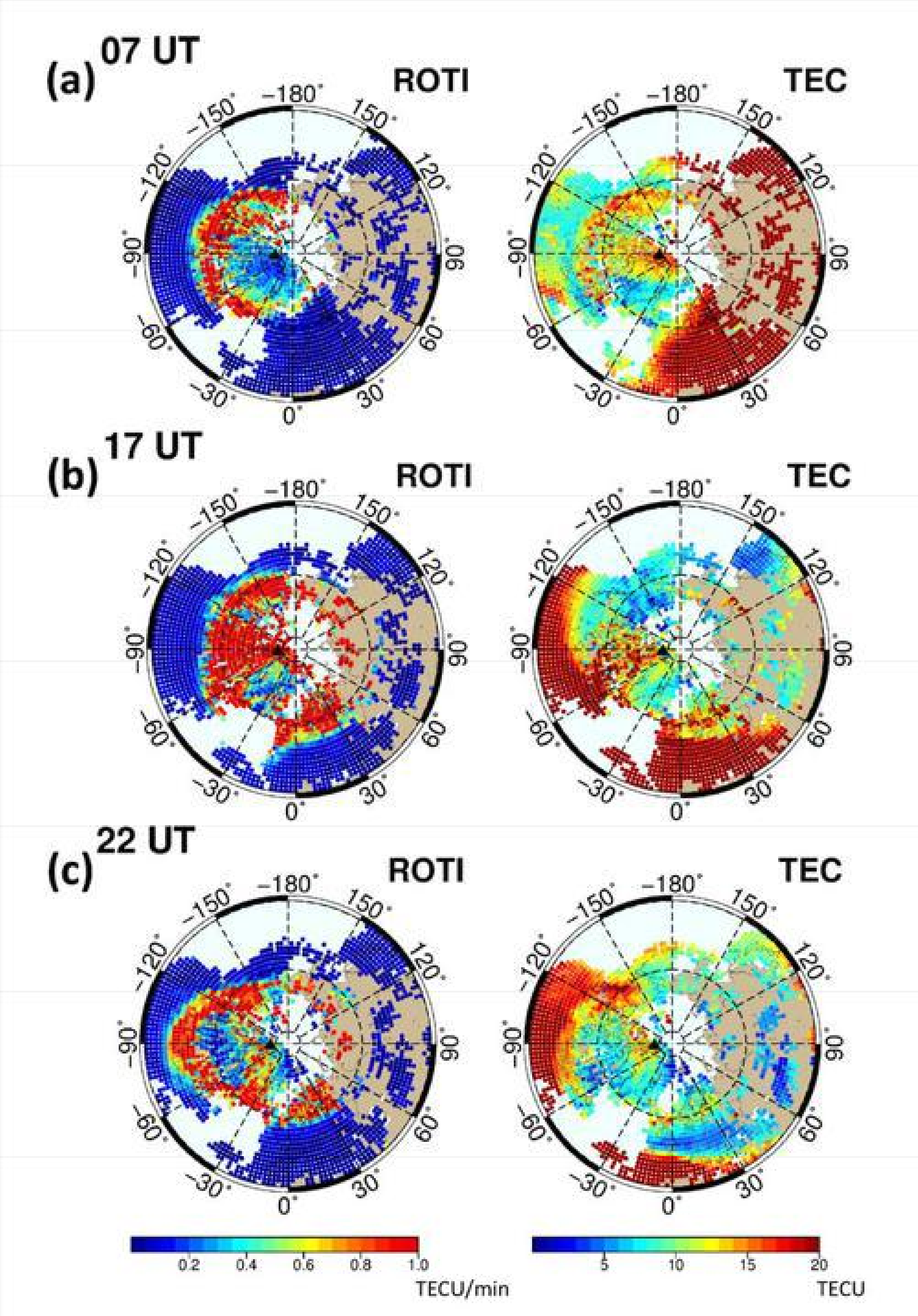


Dynamics of ionospheric irregularities: Storm day

17/03/2015 00 UT



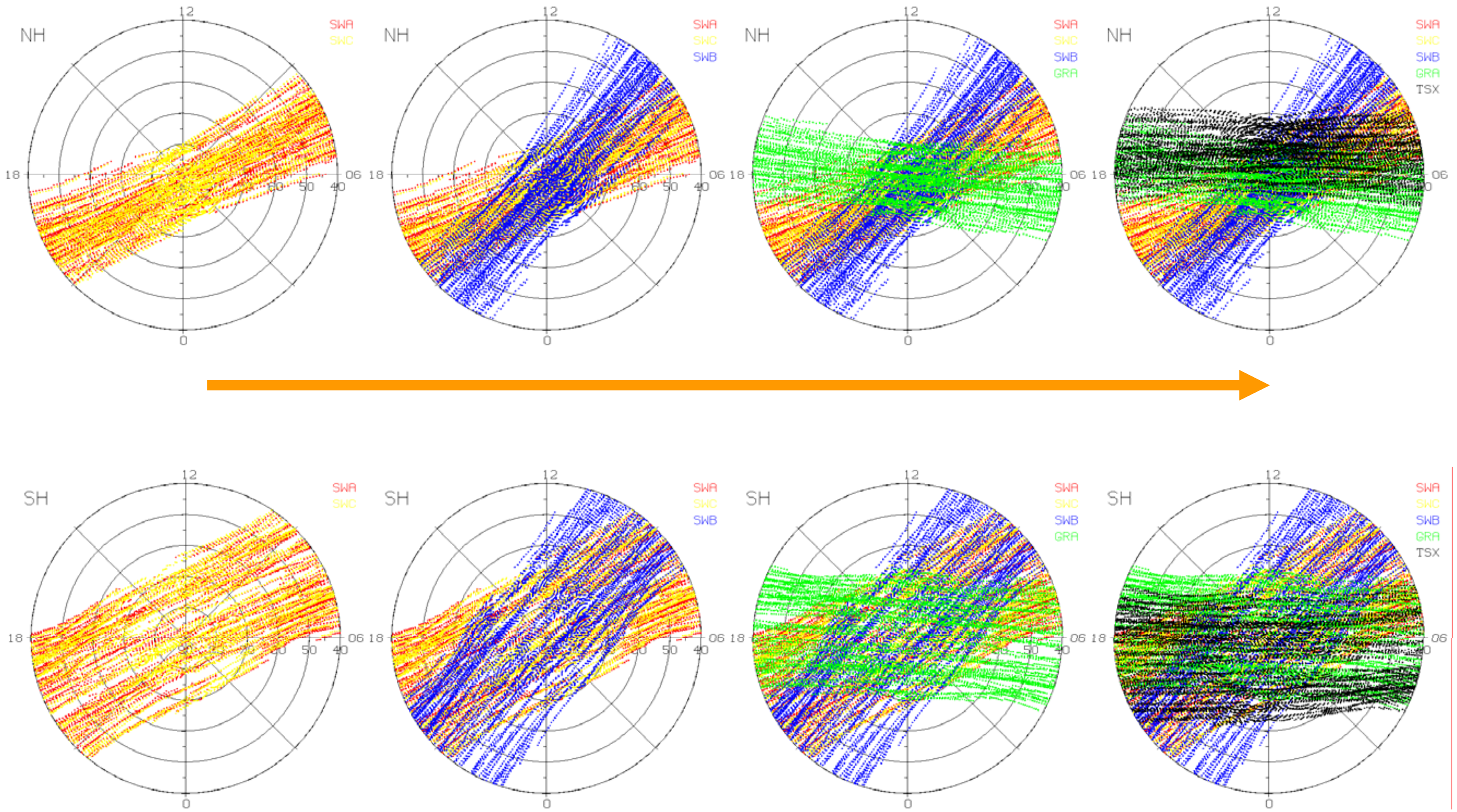
SED / TOI



(a) 07 UT
ROTI
TEC
(b) 17 UT
ROTI
TEC
(c) 22 UT
ROTI
TEC
−180°
150°
120°
90°
60°
30°
0°
−30°
−60°
−90°
−120°
−150°
0.2
0.4
0.6
0.8
1.0
TECU/min
5
10
15
20
TECU

ROTI Maps Product. Scientific Applications.

Expending to LEO

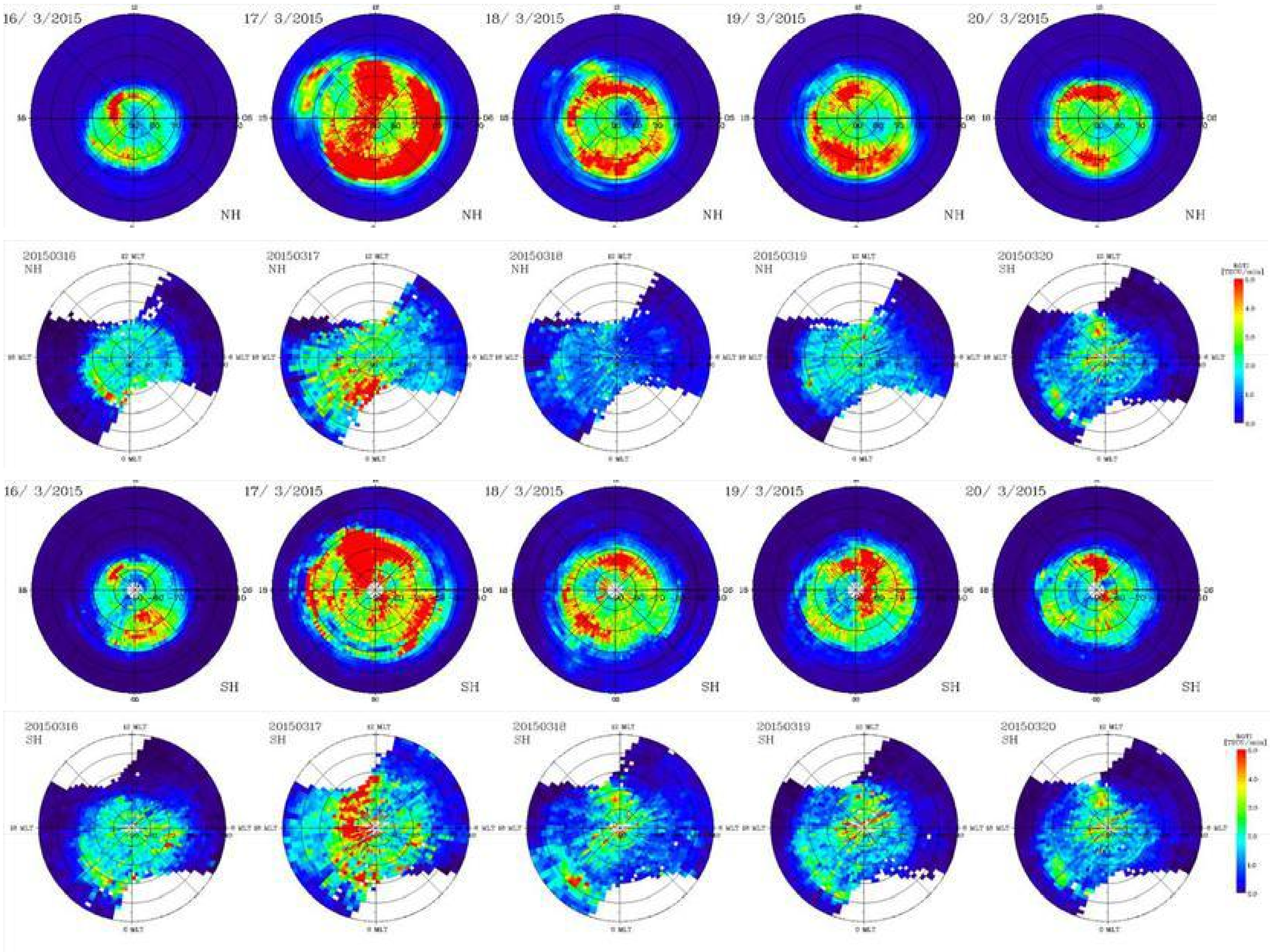


Advantages of multi-satellite observations:

Swarm A, Swarm C, Swarm B, GRACE, TerraSAR-X

Cherniak and Zakharenkova, EPS, 2016

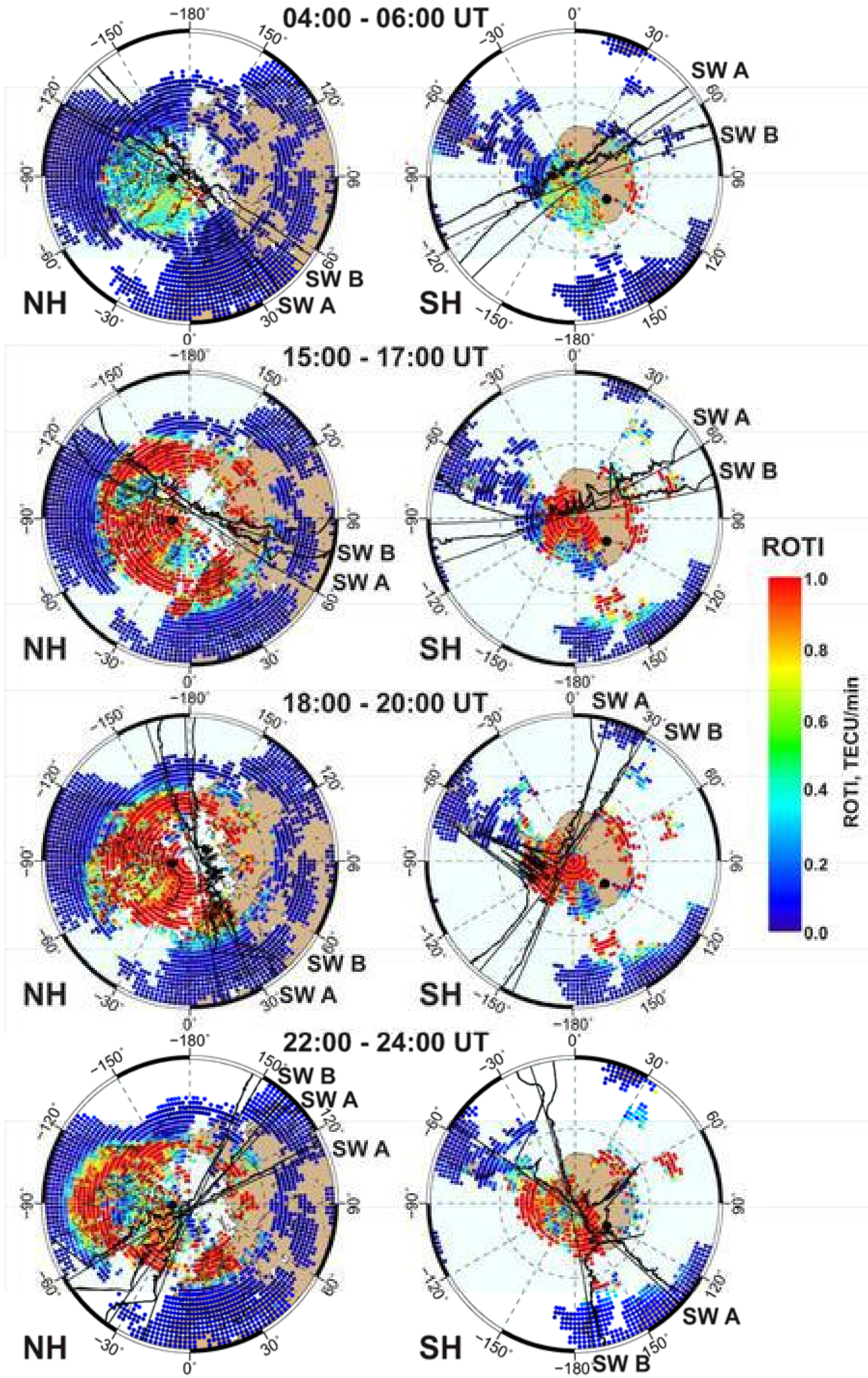
Duirnal ROTI maps: Ground GPS vs LEO GPS



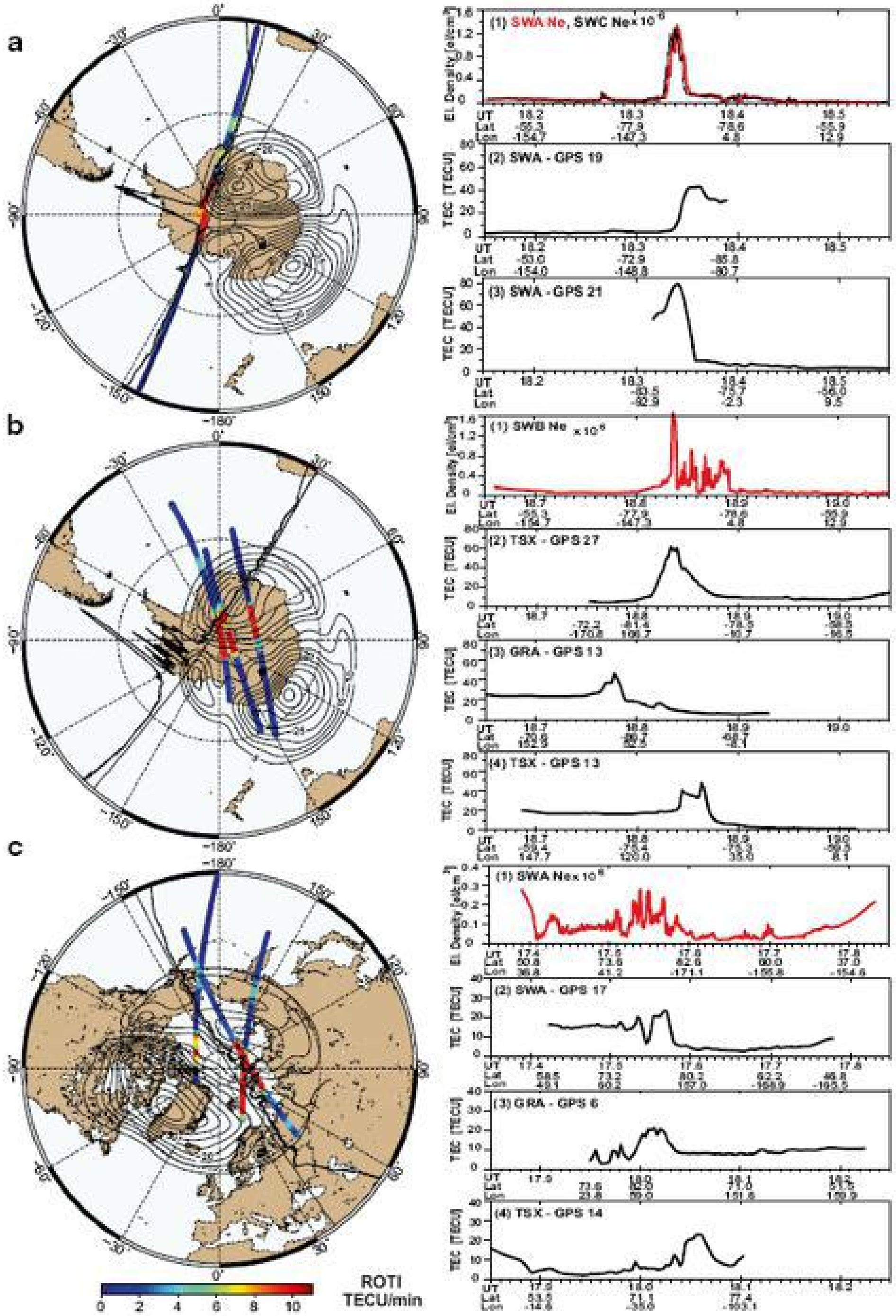
Application of ROTI mapping technique to LEO GPS measurements.

ROTI Maps Product. Scientific Applications.

GPS ROTI and Swarm plasma density probe



Swarm LP data confirm electron density enhancement in SED/TOI and ionospheric irregularities structure.



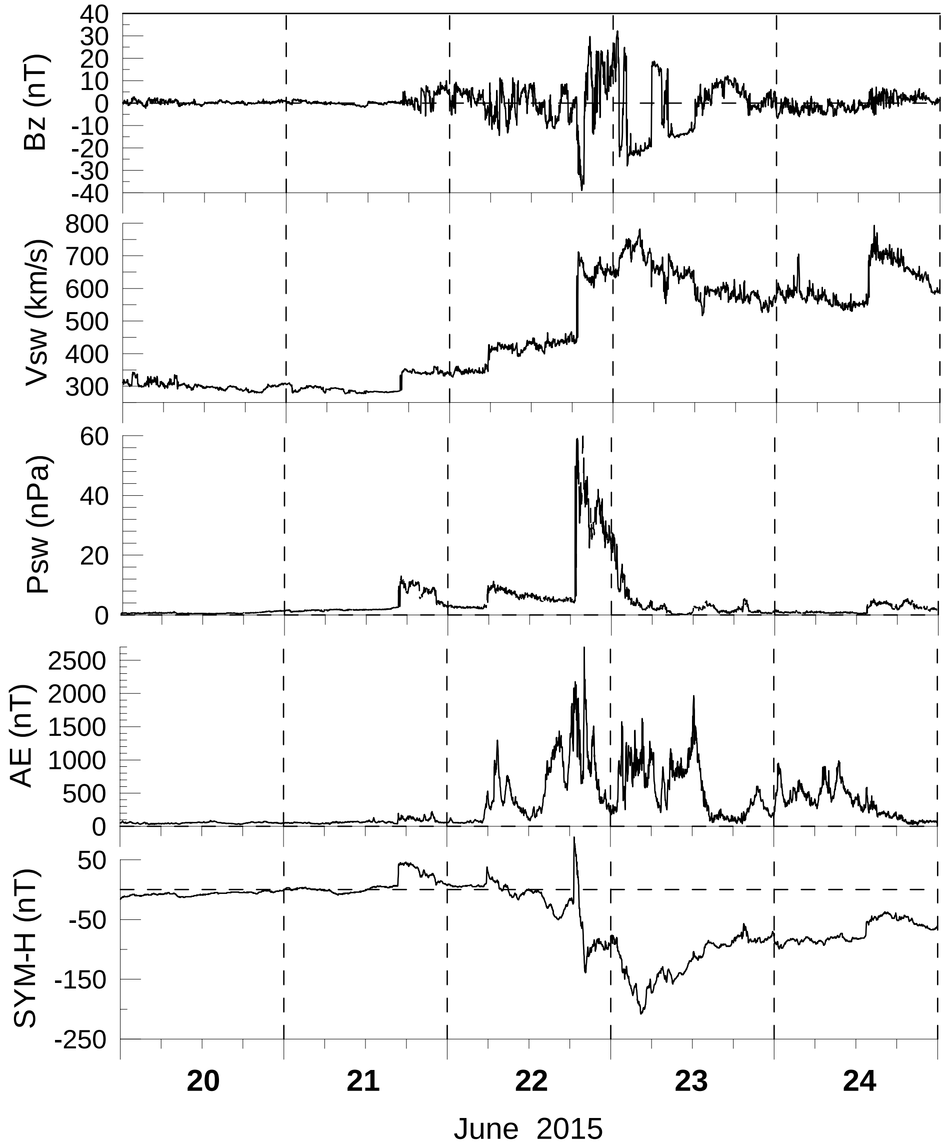
SuperDARN polar potential maps for the Southern Hemisphere at a 18.4 UT and b 18.8 UT, and the Northern Hemisphere at c 18.0 UT with superimposed low earth orbit (LEO) Rate of TEC (ionospheric total electron content) index (ROTI) (*colored lines*) and in situ (*thick black line*) observations.

Black dot indicates the position of the magnetic pole.

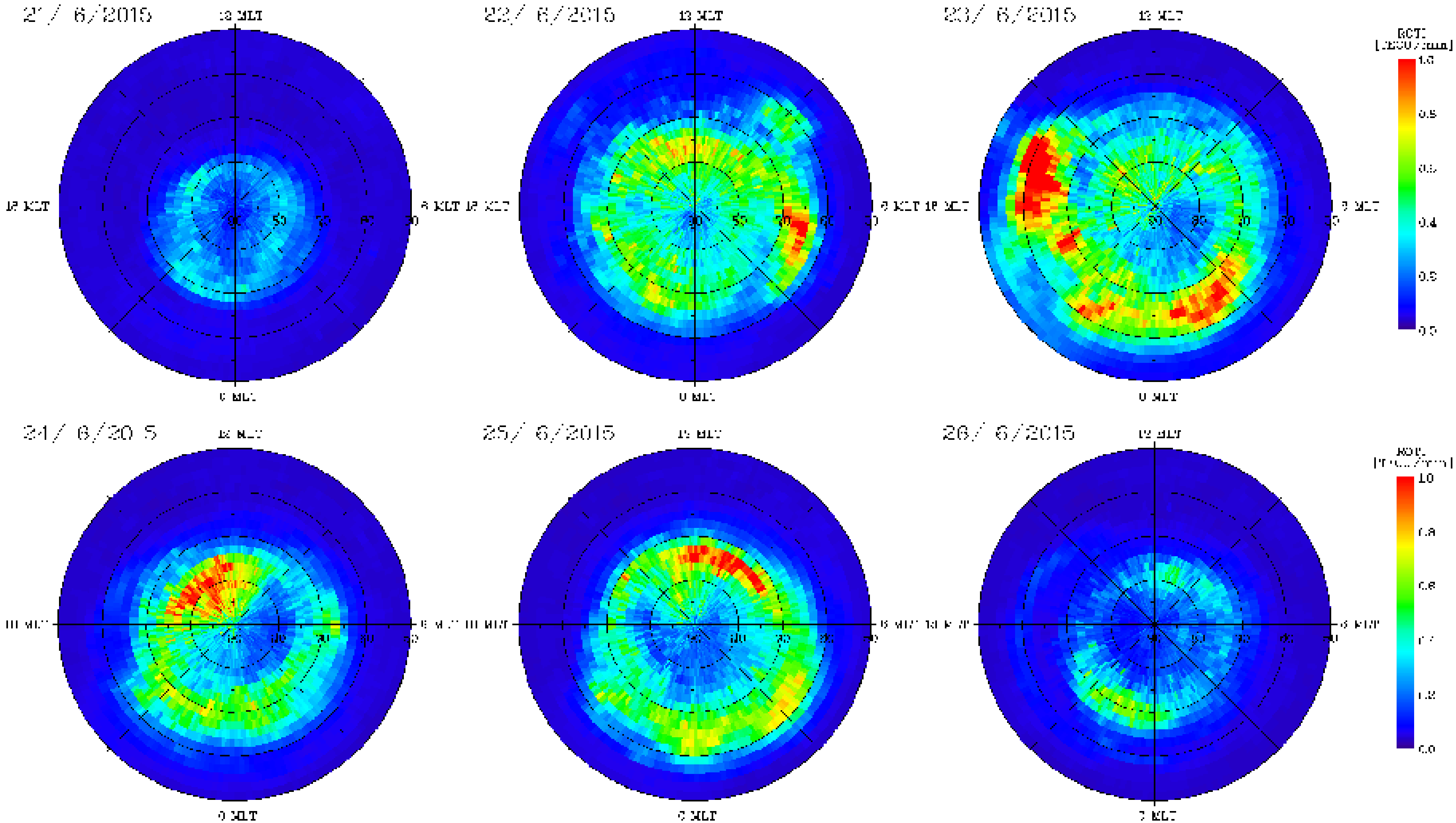
The *right-hand panel* shows Swarm electron density (Ne) and LEO TEC variations for corresponding tracks on the maps. UT and geographic latitude and longitude are noted at the *bottom axes*.

Data tracks are line of sight between two points, e.g., “SWA-GPS 19” denotes the data between SWA and GPS PRN 19. TEC data are the relative slant TEC measurements. ROTI is shown in units of TECU/min. Minutes are indicated in *decimal format*

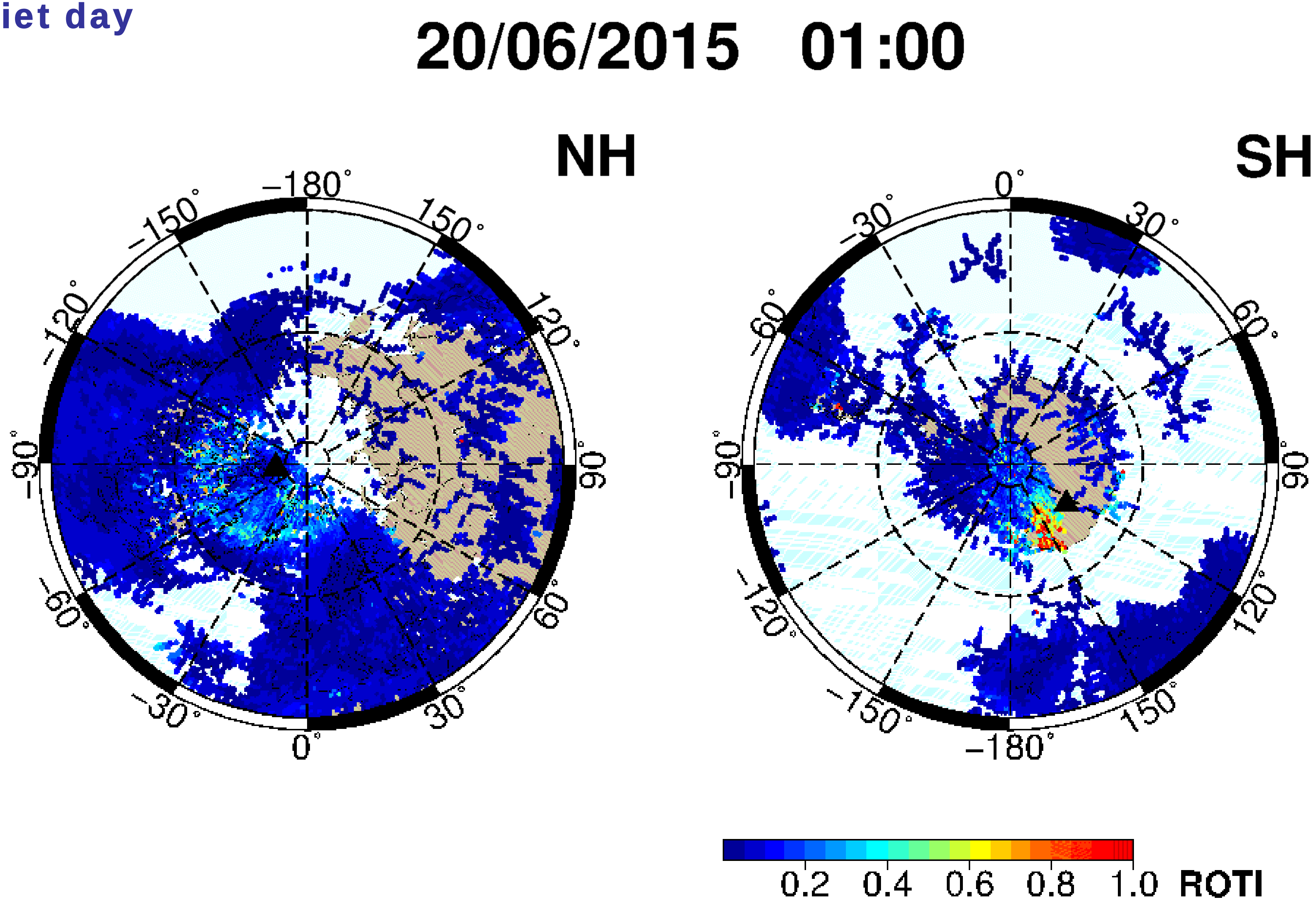
June 2015 Storm



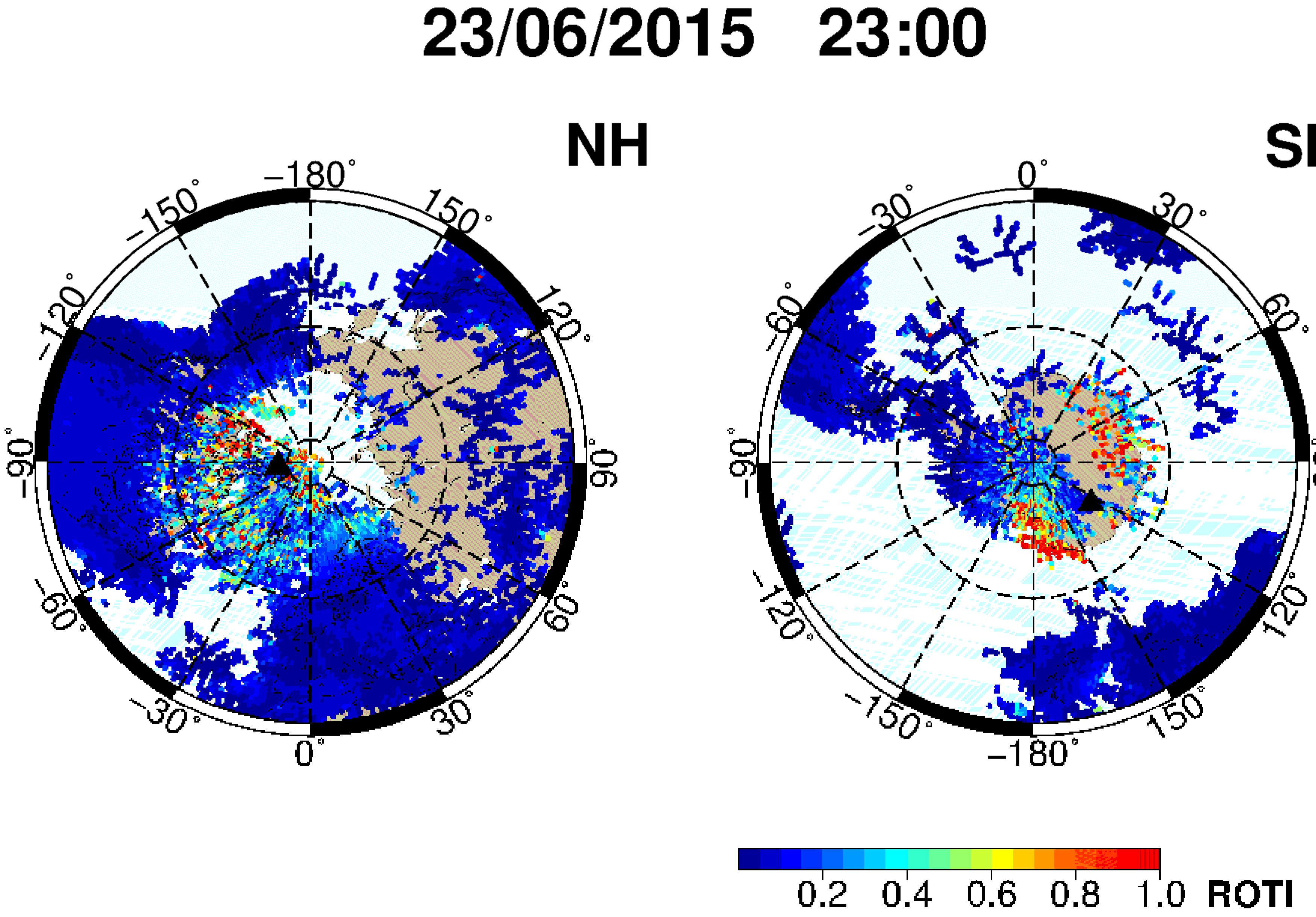
Diurnal ROTI maps

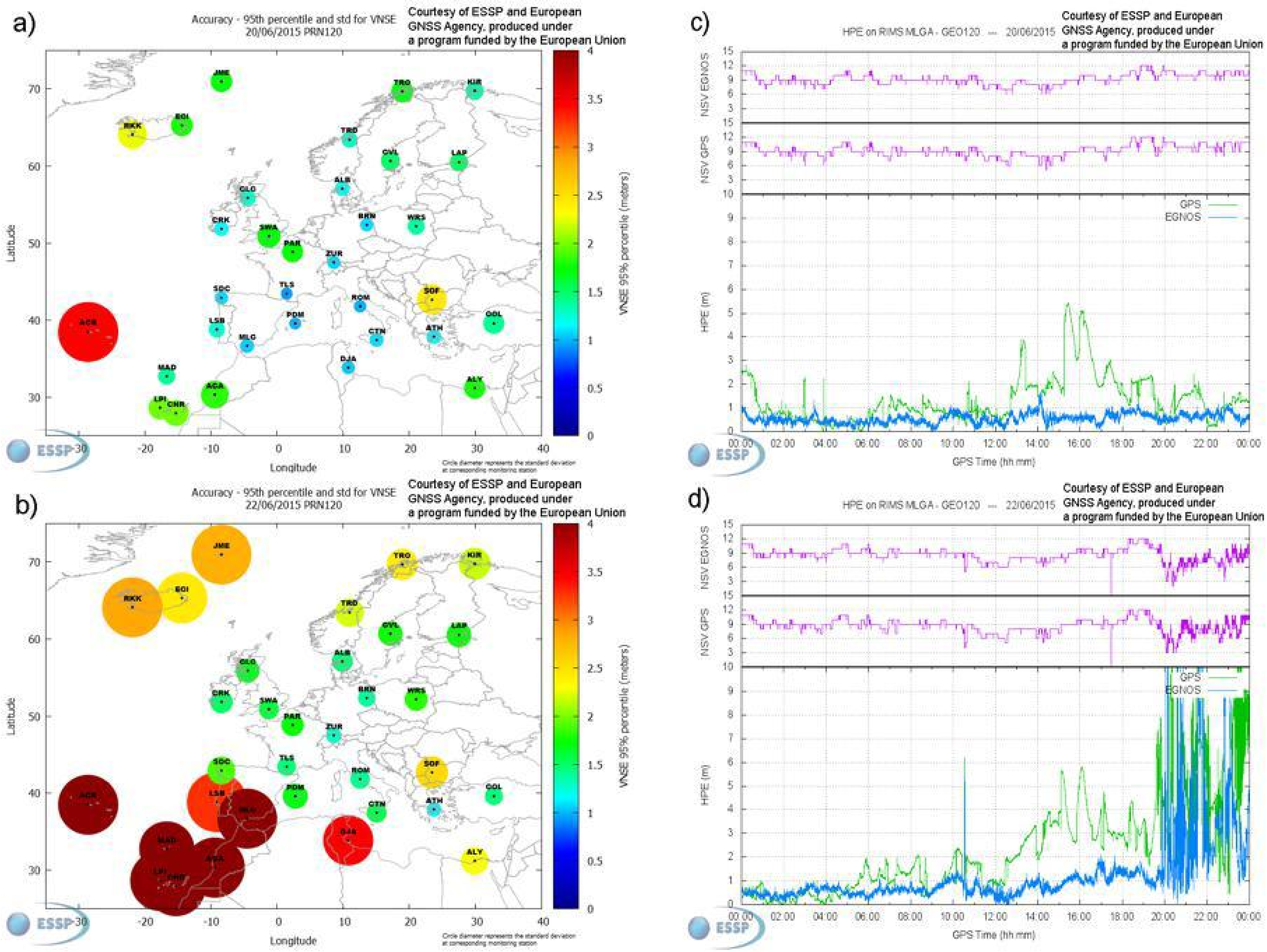


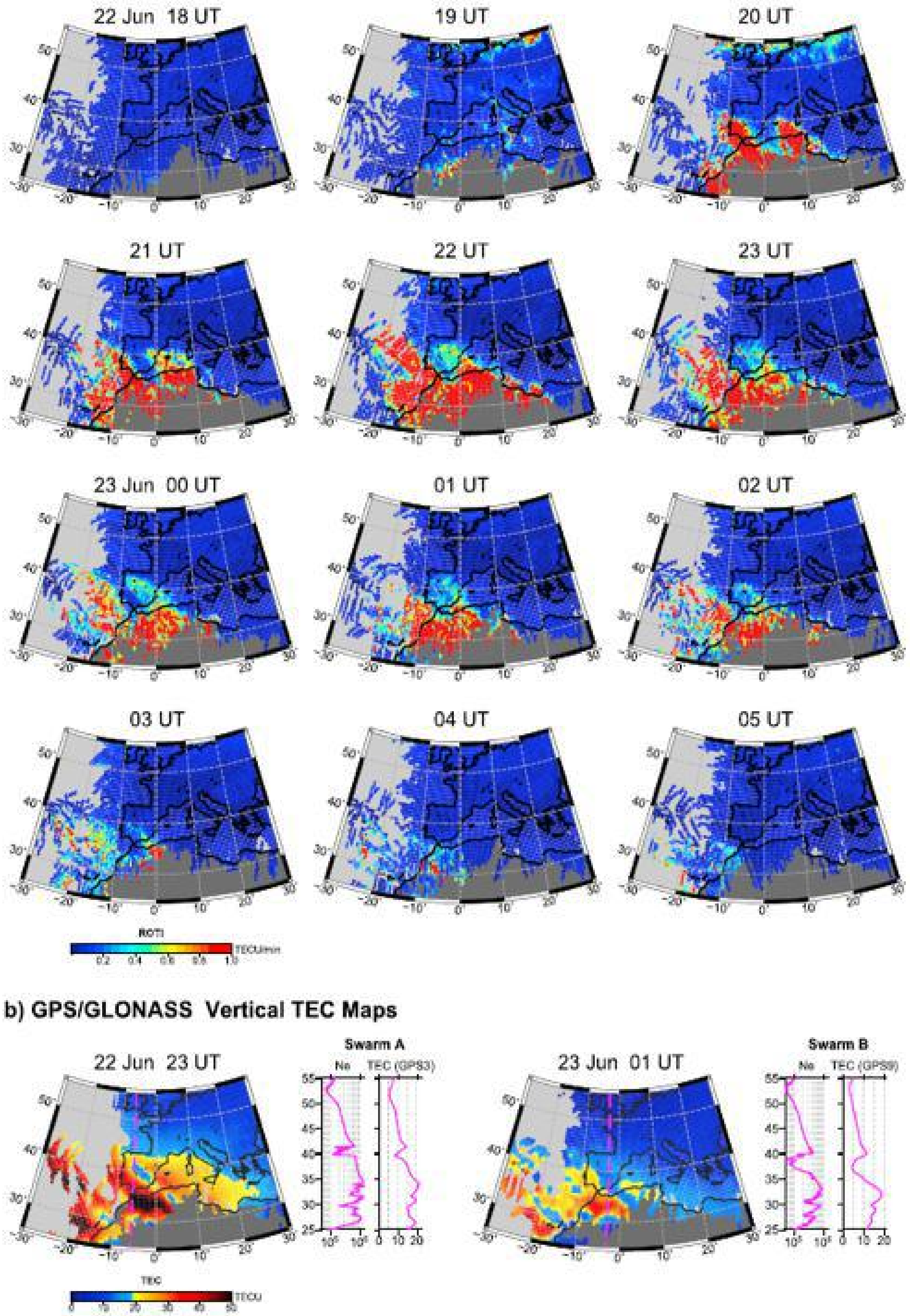
Dynamics of ionospheric irregularities:
Quiet day



Dynamics of ionospheric irregularities: Storm day



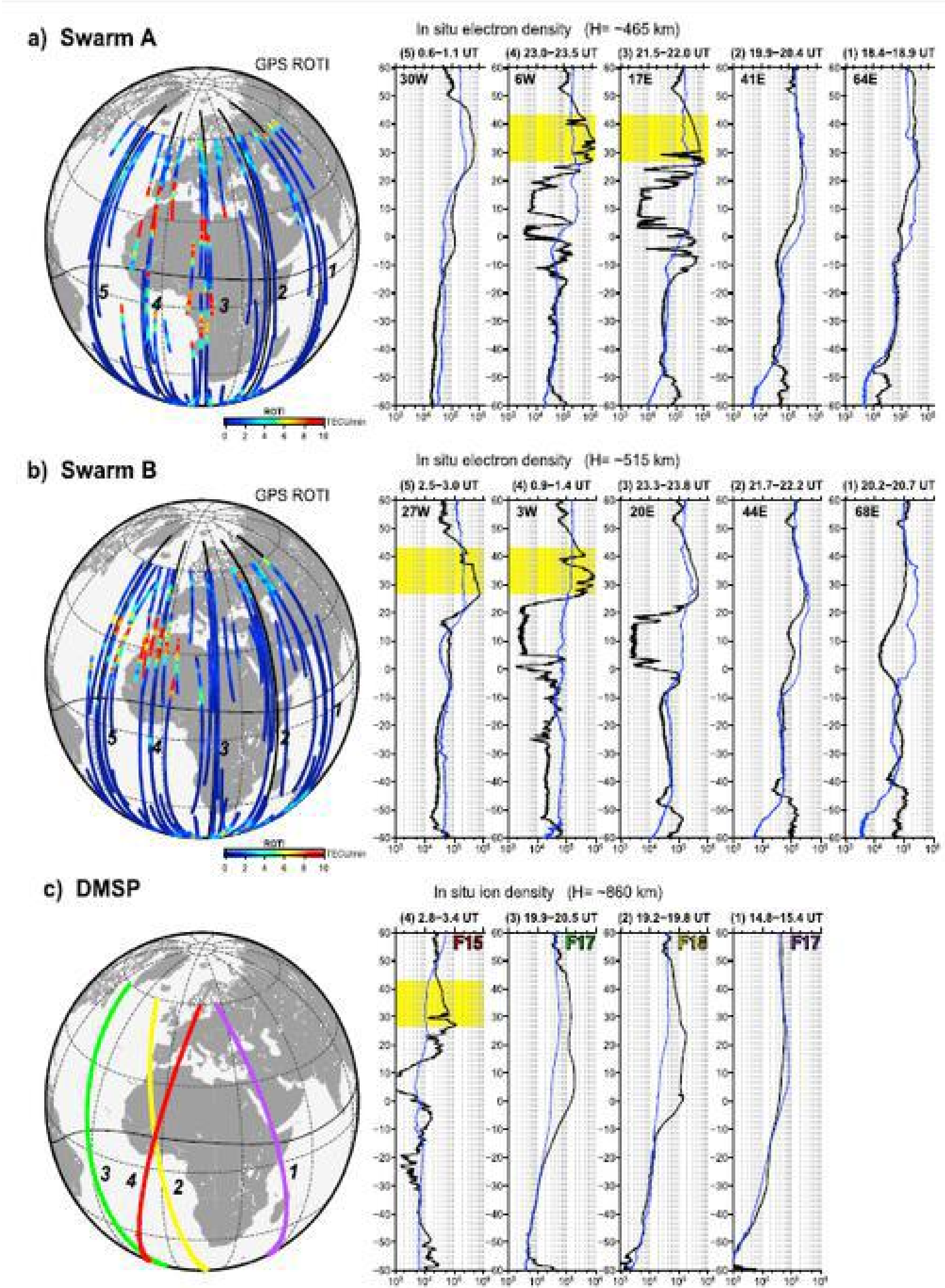

a)
Accuracy - 95th percentile and std for VNSE
20/06/2015 PRN120
Courtesy of ESSP and European GNSS Agency, produced under a program funded by the European Union
Latitude
Longitude
VNSE 95% percentile (meters)
Circle diameter represents the standard deviation at corresponding monitoring station
ESSP
b)
Accuracy - 95th percentile and std for VNSE
22/06/2015 PRN120
Courtesy of ESSP and European GNSS Agency, produced under a program funded by the European Union
Latitude
Longitude
VNSE 95% percentile (meters)
Circle diameter represents the standard deviation at corresponding monitoring station
ESSP
c)
HPE on RIMS MLGA - GEO120 --- 20/06/2015
Courtesy of ESSP and European GNSS Agency, produced under a program funded by the European Union
NSV EGNOS
NSV GPS
HPE (m)
GPS
EGNOS
GPS Time (hh mm)
ESSP
d)
HPE on RIMS MLGA - GEO120 --- 22/06/2015
Courtesy of ESSP and European GNSS Agency, produced under a program funded by the European Union
NSV EGNOS
NSV GPS
HPE (m)
GPS
EGNOS
GPS Time (hh mm)
ESSP



Two-dimensional ROTI maps of ionospheric irregularities in geographic coordinates over Europe with 1 h interval during 18 UT–05 UT on 22–23 June 2015.

Cherniak and Zakharenkova, GRL, 2016

(b) Two-dimensional maps of vertical TEC with superimposed Swarm A and Swarm B passes (magenta lines) for 23 UT and 01 UT, respectively; in situ electron density and topside vertical TEC along these passes are shown at small panels on the right. Numerous plasma depletions are embedded into high TEC plasma within 25°–40°N.



The (left) global view with Swarm A satellite passes and spaceborne GPS ROTI;

(right) variation of in situ electron density Ne as a function of geographical latitude along these passes.

Black lines
on latitudinal profiles present Ne values for 22–23 June; thin blue lines are quiet-time conditions of 20–21 June 2015.

Universal time (UT) and geographic longitude for each satellite pass are given at the top of graphs.

The yellow shaded area
indicates deep plasma depletions in Europe and its close vicinity. (b) The same as Figure 1a but for Swarm B satellite. (c)

The passes of DMSP F15, F17, and F18 satellites (left) and in situ ion density variations along these passes (right). On each geographic map, grid with 30° is shown by thin dashed line; geomagnetic equator is shown by black solid line.

Conclusions

- The indices and maps, based on GPS ROT/ROTI variations, can be effective and very perspective indicator of the presence of phase fluctuations in the high and mid-latitude ionosphere.

- 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

- The applied approach for ROTI map construction does not use any interpolation technique for ROTI mapping, result is real observations, averaged in each cell of 2 x 2 deg. This will allow to avoid errors related with unrealistic interpolation values over areas with data gaps.

- The results demonstrate that it is possible to use current network of GNSS permanent stations to reveal the ionospheric irregularities intensity, and position of the irregularities oval.

- The ROTI maps product have been validated against different types of ground and sattelite based measurements.

-The ROTI Maps product available since March 2017 on CDDIS.

- Detailed description of the ROTI Maps Product will be available in paper “ROTI Maps: a new IGS’s ionospheric product characterizing the ionospheric irregularities occurrence” by Iu. Cherniak, A. Krankowski, I. Zakharenkova:, GPS Solution, 2017 (under review).

Acknowledgments

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