Current Development of the new IGS ionospheric product - ROTI maps and its synergies with the International LOFAR Telescopes

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United Nations International Meeting on the Applications of Global Navigation Satellite Systems

Organised Hosted bythe United Nations Office for Outer Space Affairs
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Vienna, Austria, 5 – 9 December 2022

Outline

1. Overview of the IonoWG

- 2022 IGS Virtual Workshop IonoWG Recommendations

2. IGS ROTI Maps

- Methodology
- Data processing enviroment
- Application
- Current status, Northern Hemisphere
- Extension towards Equatorial region and Southern Hemisphere
- Results, New IGS ROTI Fluctuations product

4. Cooperation with International LOFAR Telescope (ILT) for potential synergies

5. Summary

2022 IGS Virtual Workshop Recommendations

Name of Working Group and Chair: Ionosphere Working Group, Andrzej Krankowski

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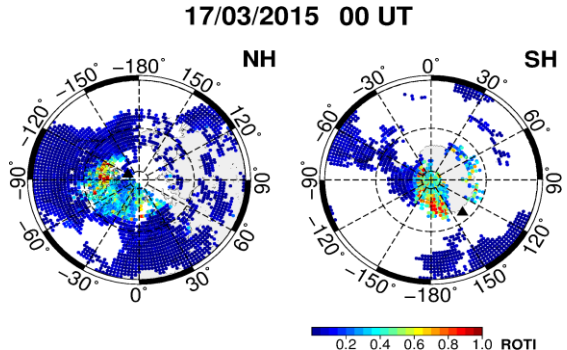
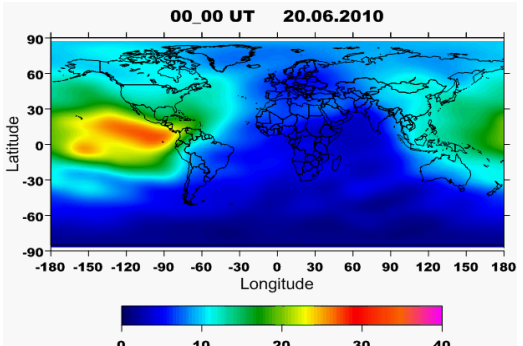
2022 Virtual Workshop
"Science from Earth to Space"

- **Continuation of work on IGS real-time service for global ionospheric total electron content modeling.**
- **Preparation of final version of IGS ROTI maps extension towards low latitudes and Southern Hemisphere.**
- **Continuation of cooperation with IRI and ILT communities.**
- **Close cooperation with the Real-Time Working Group in order to elaborate full real-time VTEC and ROTI products.**





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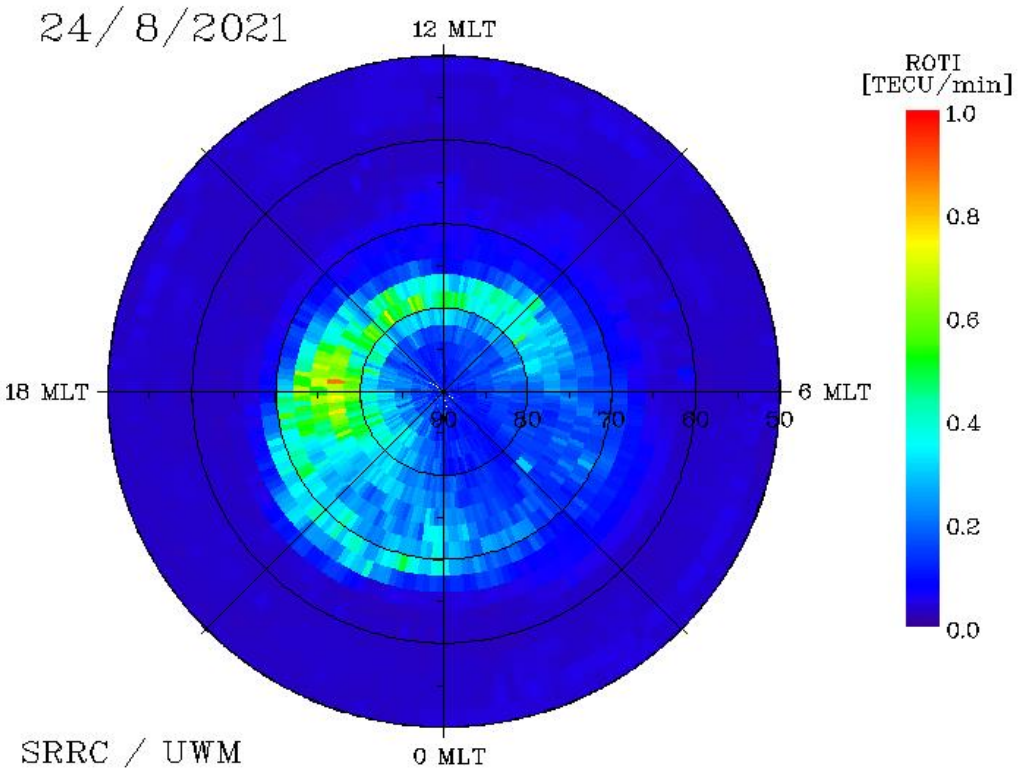
Example of IGS ROTI Maps Product

- The ROTI Maps processor operates routinely since January, 1, 2015
- It was processed and collected data and resulted product from 2010 up to now since the test service established
- ROTI Maps product available on NASA CDDIS
- Representative stations database have been actualised for 2020-2022 on base data avaliability and latancy
- Finished reprocessing of ROTI Maps for 2020-2022 on base updated stations database

The activity has significant group of geophyical users interrested in.



Ionospheric irregularities intensification and extension captured by IGS ROTI Maps. Moderate geomagnetic storm, August 2021

Detailed description of the ROTI Maps Product available in the papers:

Iurii Cherniak, Andrzej Krankowski, Irina Zakharenkova, **Observation of the ionospheric irregularities over the Northern Hemisphere: Methodology and service, Radio Science 49, 8 pp. 653-662, 2014, doi.: 10.1002/2014RS005433**

Iurii Cherniak, Andrzej Krankowski, Irina Zakharenkova, ROTI Maps: a new IGS ionospheric product characterizing the ionospheric irregularities occurrence, **GPS Solutions**, 22, 69, **2018**, doi.: 10.1007/s10291-018-0730-1

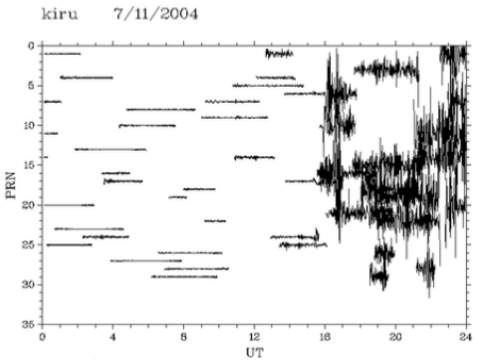
IGS ROTI Maps: Methodology

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.



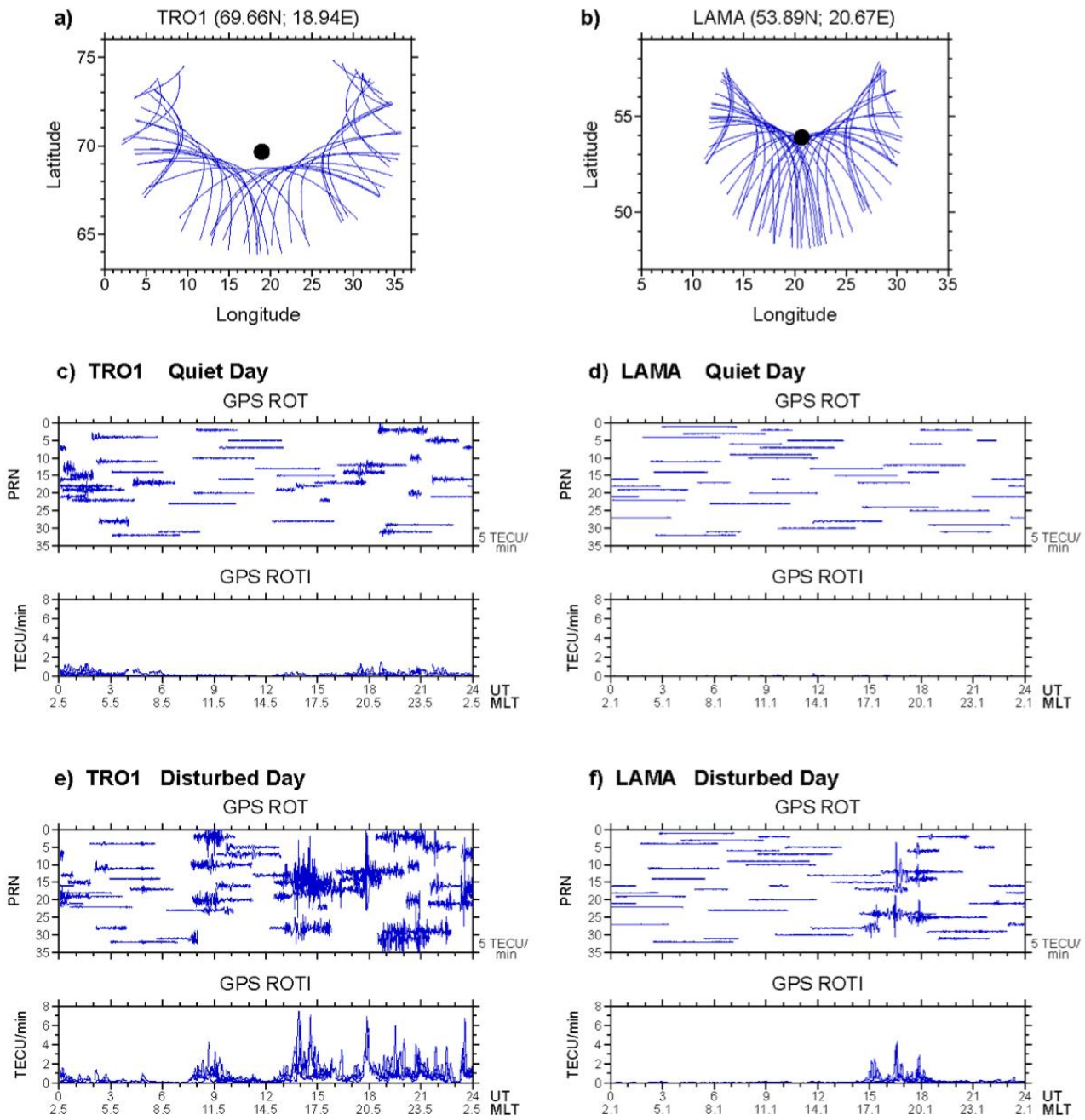
2. The Rate of TEC Index (ROTI) estimation

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

Standard deviation of ROT (on 5 min interwal)

ROT/ROTI techniques was deweloper by NASA JPL team (Pi et al., 1997)

IGS ROTI Maps: Methodology

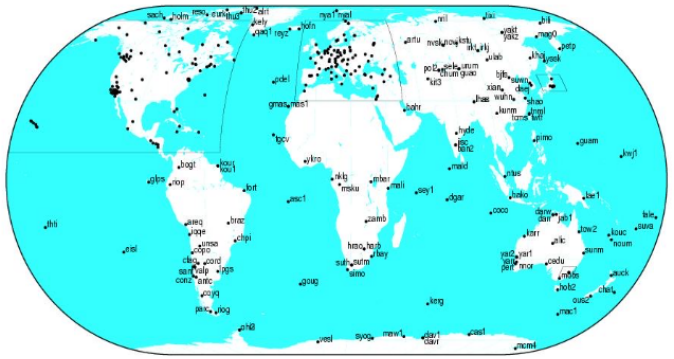


Iurii Cherniak, Andrzej Krankowski, Irina Zakharenkova, **Observation of the ionospheric irregularities over the Northern Hemisphere: Methodology and service, Radio Science 49, 8 pp. 653-662, 2014, doi.: 10.1002/2014RS005433**

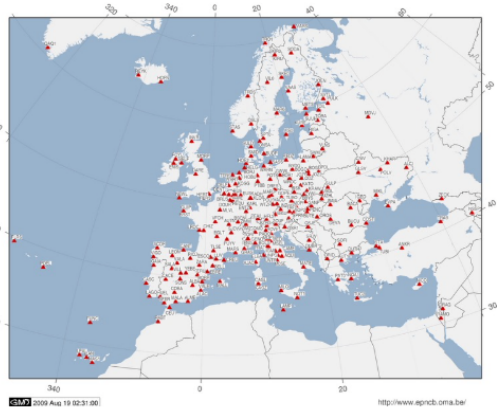
IGS ROTI Maps: Methodology

Data sources:

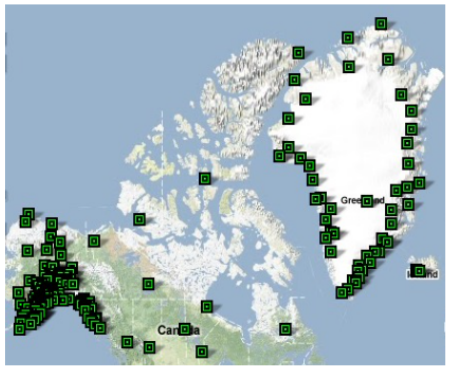
IGS



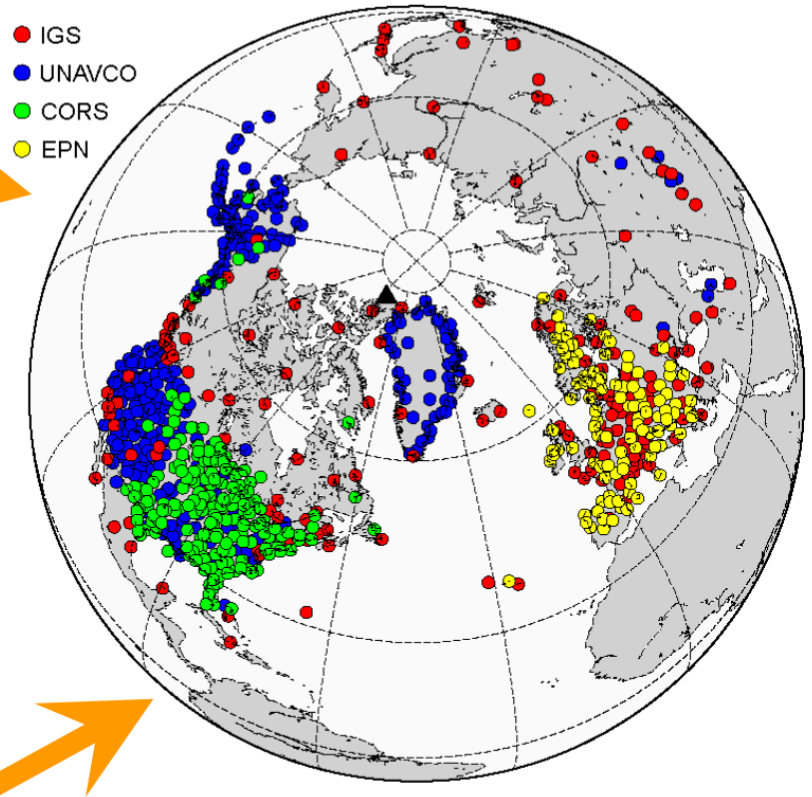
EUREF Permanent Tracking Network



UNAVCO



700 representative stations selected

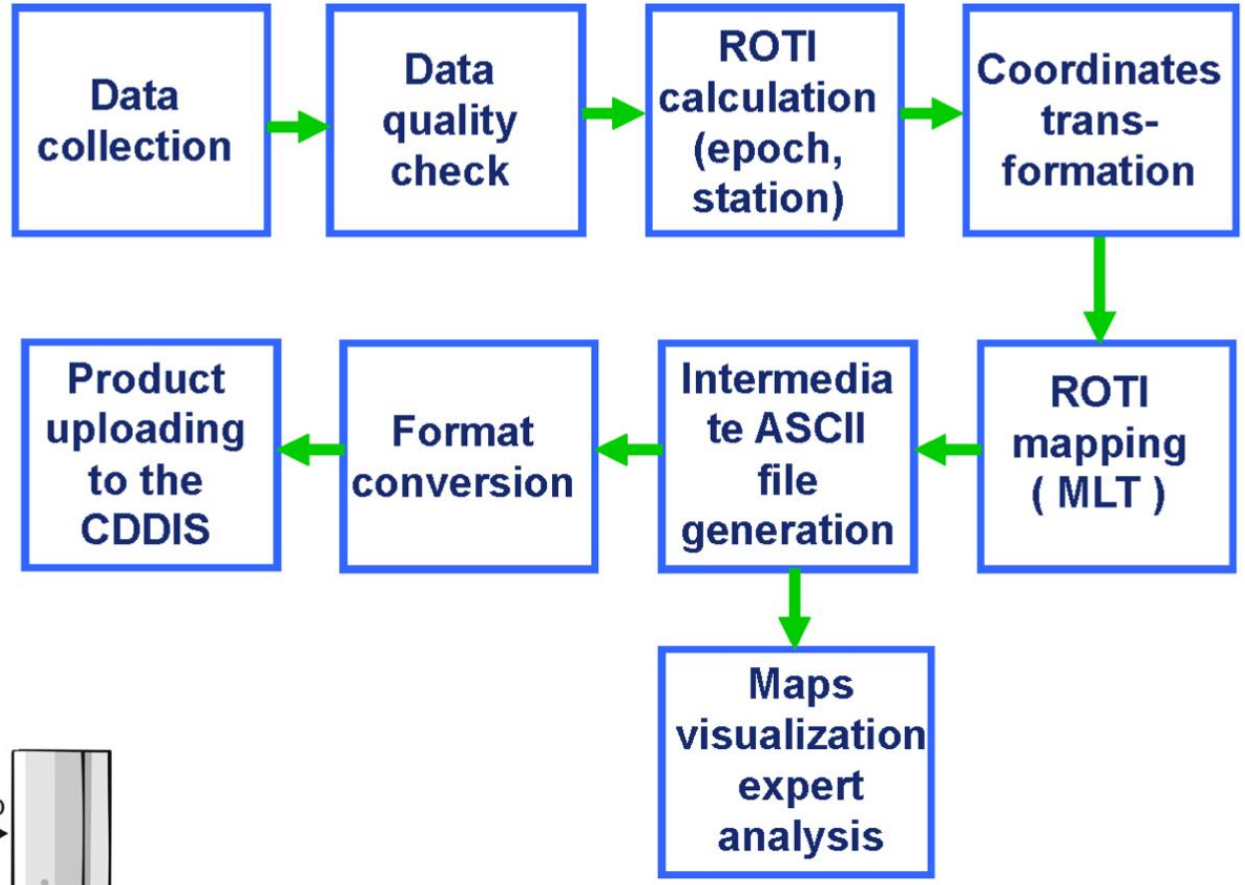


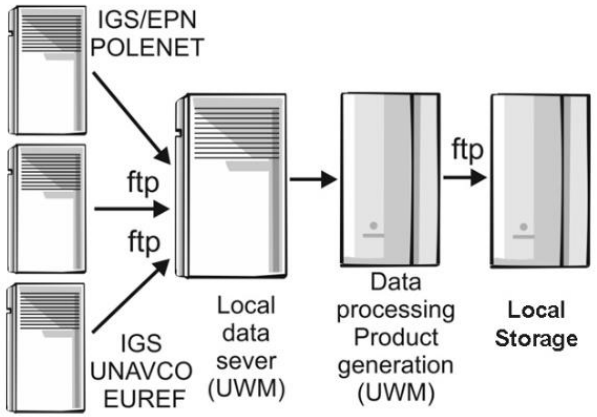
Selected representative stations of core observations from the permanent GPS networks

Iurii Cherniak, Andrzej Krankowski, Irina Zakharenkova, **Observation of the ionospheric irregularities over the Northern Hemisphere: Methodology and service, Radio Science 49, 8 pp. 653-662, 2014, doi.: 10.1002/2014RS005433**

IGS ROTI Maps: Data processing enviroment

Steps of ROTI Maps product generation at UWM:





Iurii Cherniak, Andrzej Krankowski, Irina Zakharenkova, **Observation of the ionospheric irregularities over the Northern Hemisphere: Methodology and service, Radio Science 49, 8 pp. 653-662, 2014, doi.: 10.1002/2014RS005433**

IGS ROTI Maps: Data product format

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ROTI Maps format

The output maps are provided in the ASCII formats.

This data prepared in the IONEX-like format on grid 2 x 2 degree - geomagnetic latitude from 51° to 89° with step 2° 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
 0.0421  0.0412  0.0401  0.0392  0.0380  0.0379  0.0390  0.0382  0.0373  0.0382
 0.0401  0.0406  0.0425  0.0417  0.0414  0.0426  0.0459  0.0466  0.0467  0.0480
 0.0485  0.0460  0.0426  0.0426  0.0460  0.0449  0.0434  0.0425  0.0409  0.0408
 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
 0.0335  0.0359  0.0354  0.0337  0.0352  0.0357  0.0354  0.0346  0.0342  0.0334
 0.0332  0.0347  0.0373  0.0383  0.0366  0.0377  0.0372  0.0357  0.0364  0.0369
 0.0358  0.0363  0.0377  0.0368  0.0368  0.0355  0.0353  0.0349  0.0331  0.0347
 0.0347  0.0346  0.0348  0.0353  0.0351  0.0337  0.0339  0.0329  0.0335  0.0348
 0.0339  0.0311  0.0315  0.0310  0.0347  0.0354  0.0331  0.0320  0.0307  0.0304
 0.0311  0.0318  0.0321  0.0316  0.0328  0.0329  0.0332  0.0320  0.0317  0.0309
 0.0308  0.0313  0.0313  0.0312  0.0289  0.0287  0.0304  0.0319  0.0320  0.0336
 0.0354  0.0366  0.0358  0.0356  0.0347  0.0373  0.0431  0.0445  0.0459  0.0487
 0.0481  0.0465  0.0438  0.0403  0.0415  0.0431  0.0437  0.0435  0.0432  0.0420
 0.0424  0.0425  0.0437  0.0430  0.0428  0.0439  0.0418  0.0418  0.0426  0.0439
 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
```

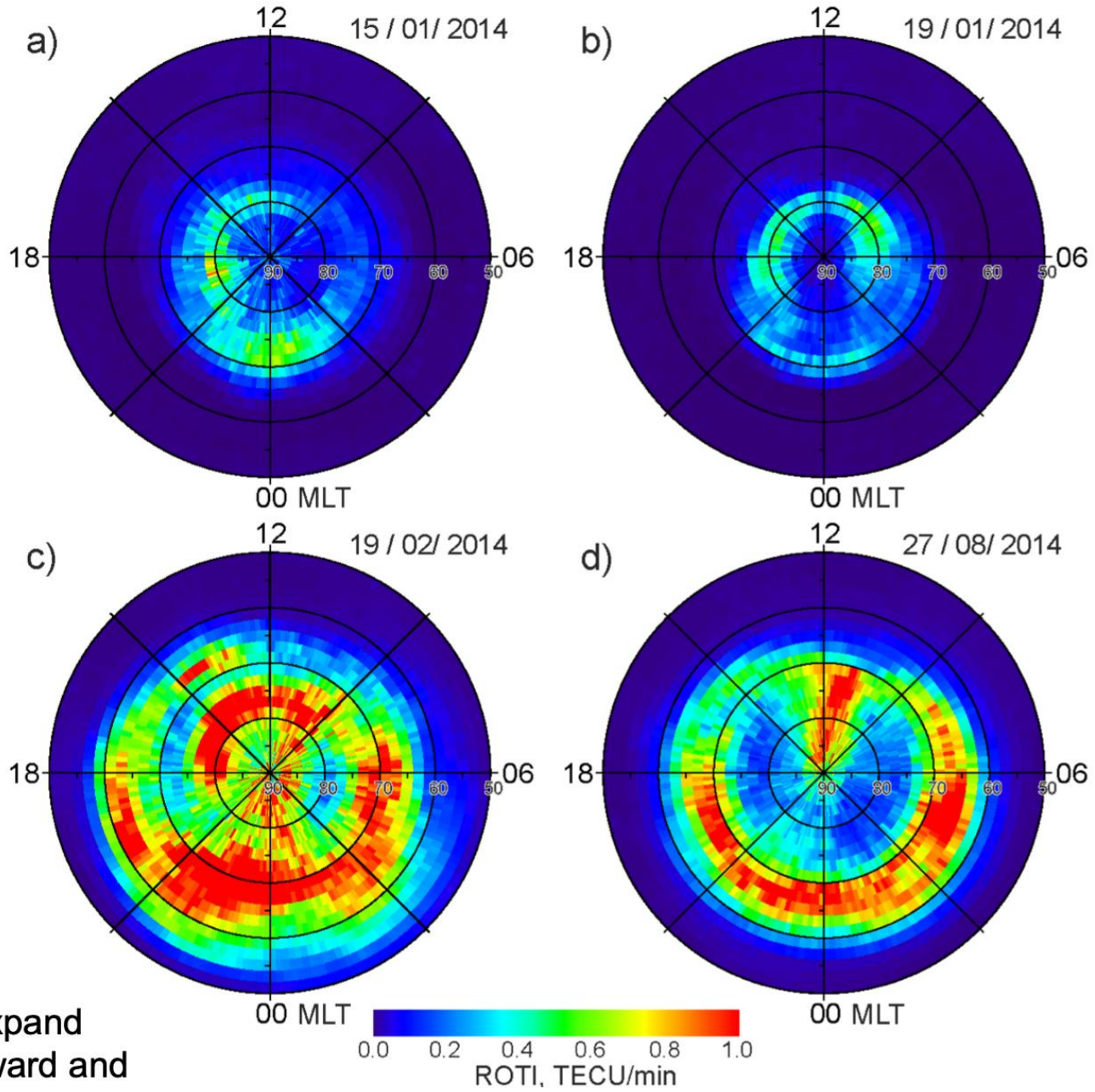
The sample of the ROTI Maps output: ASCII format.

Iurii Cherniak, Andrzej Krankowski, Irina Zakharenkova, **Observation of the ionospheric irregularities over the Northern Hemisphere: Methodology and service, Radio Science 49, 8 pp. 653-662, 2014, doi.: 10.1002/2014RS005433**

ROTI maps product is accessible at the CDDIS data portal in the same folder “IONEX” such as IONEX TEC GIMs for a particular day

IGS ROTI Maps: application

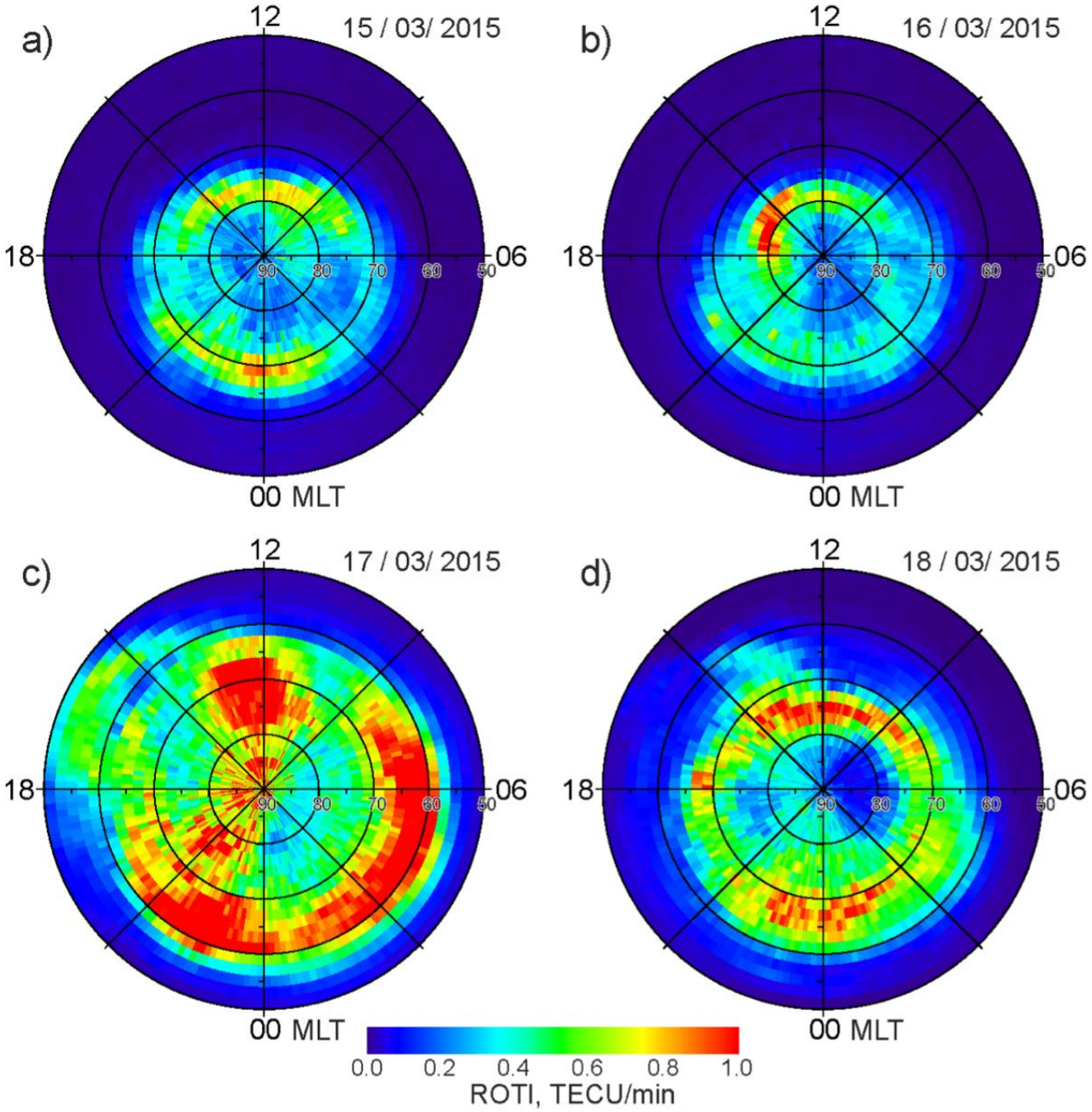
Ionospheric irregularities evolution during strong geomagnetic storm



Oval-like structure that can expand substantially in both the poleward and equatorward directions

IGS ROTI Maps: application

Ionospheric irregularities evolution during strong geomagnetic storm



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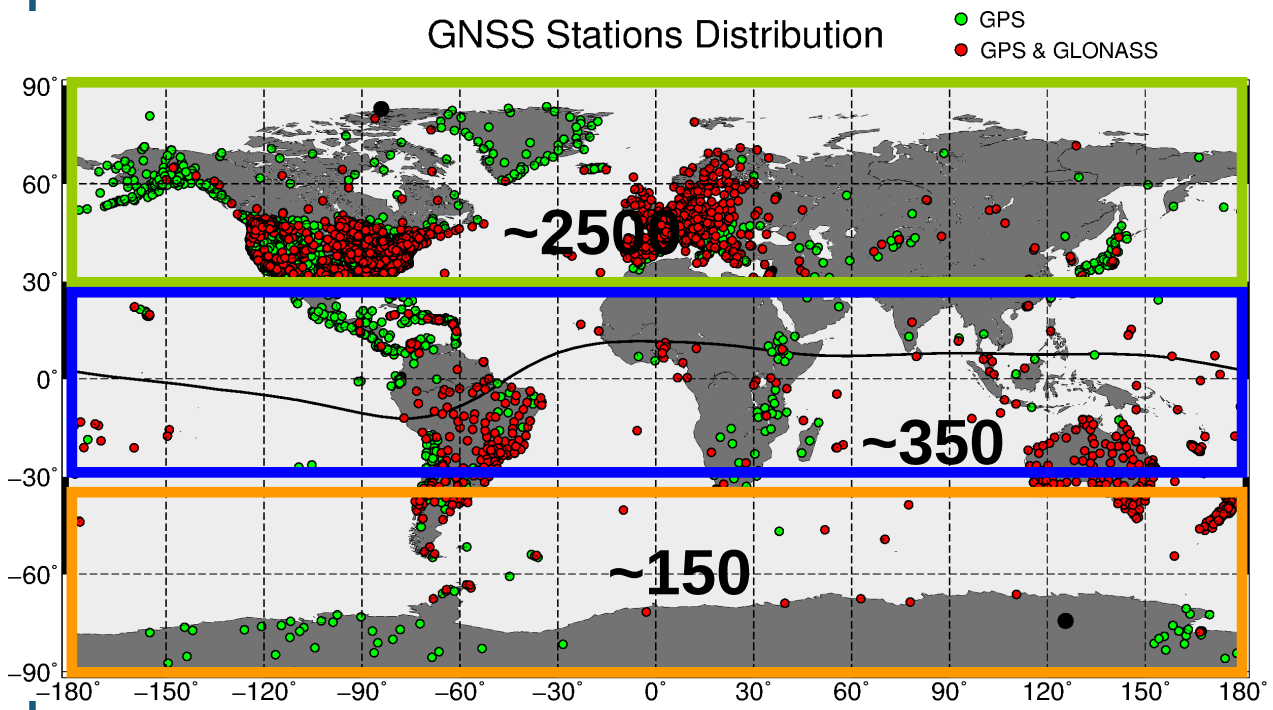
IGS ROTI Maps extension toward Southern Hemisphere and low latitudes

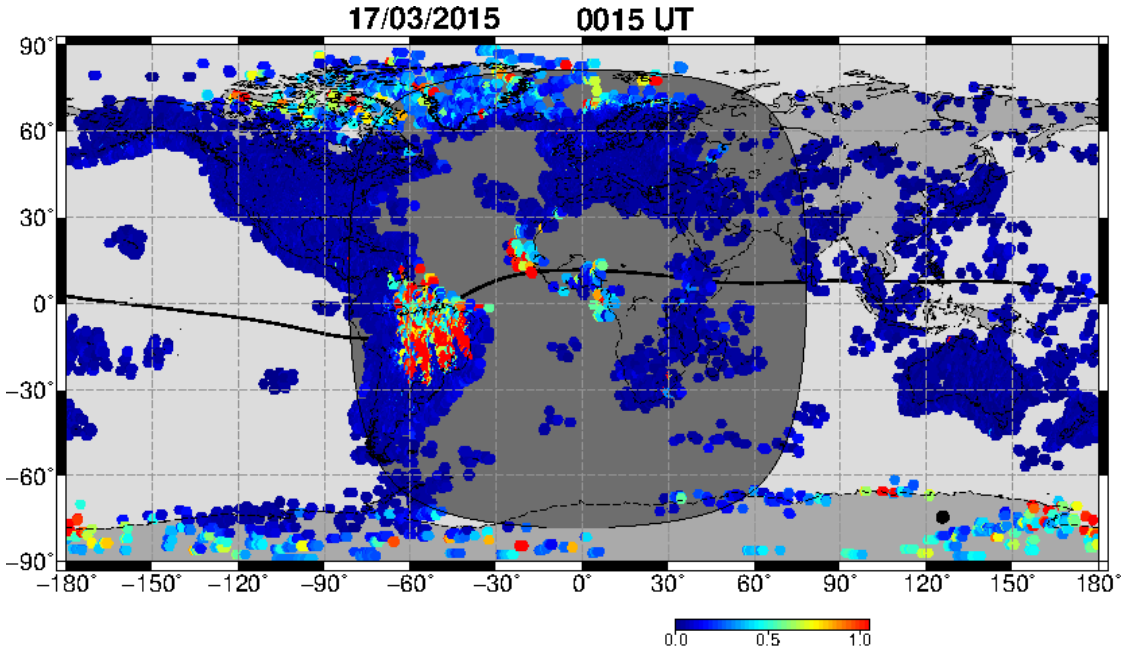
Main chalange – non uniform global distribution of permanent GNSS stations



Case of 2015 St. Patrick's Day storm

- ~ 5300 stations
  ~2000 multi-GNSS stations
  (GPS + GLONASS+GALILEO+BEIDOU)

- ROTI maps with
  time resolution 15 min
  spatial resolution 2 x 2 degree



Iurii Cherniak, Irina Zakharenkova, Andrzej Krankowski, ROTI Maps: **Current Status and Its Extension towards Equatorial Region and Southern Hemisphere, Sensors 2022, 22(10)**, 3748; doi.: 10.3390/s22103748

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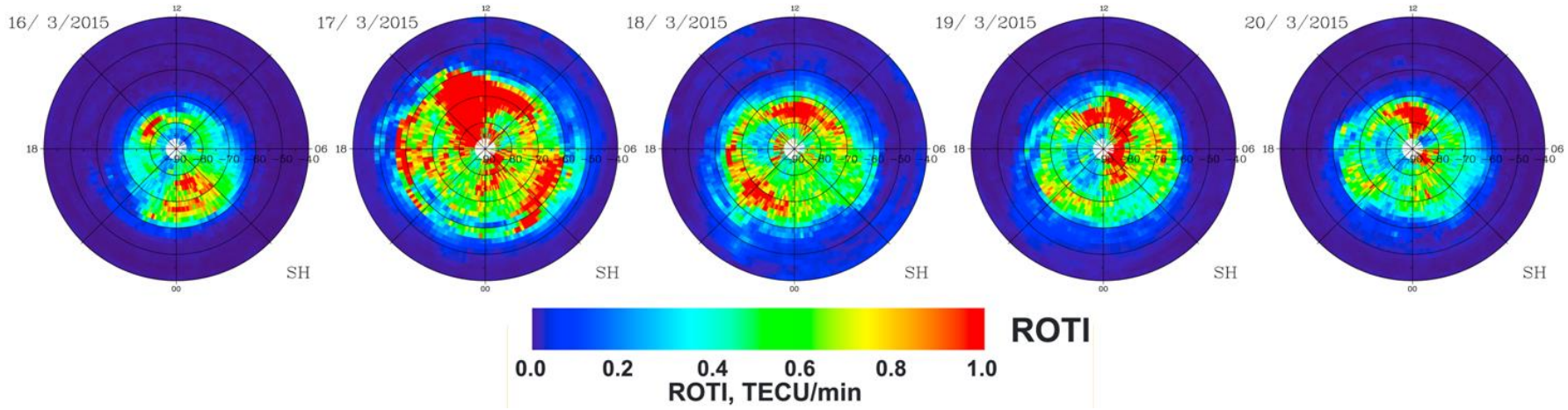
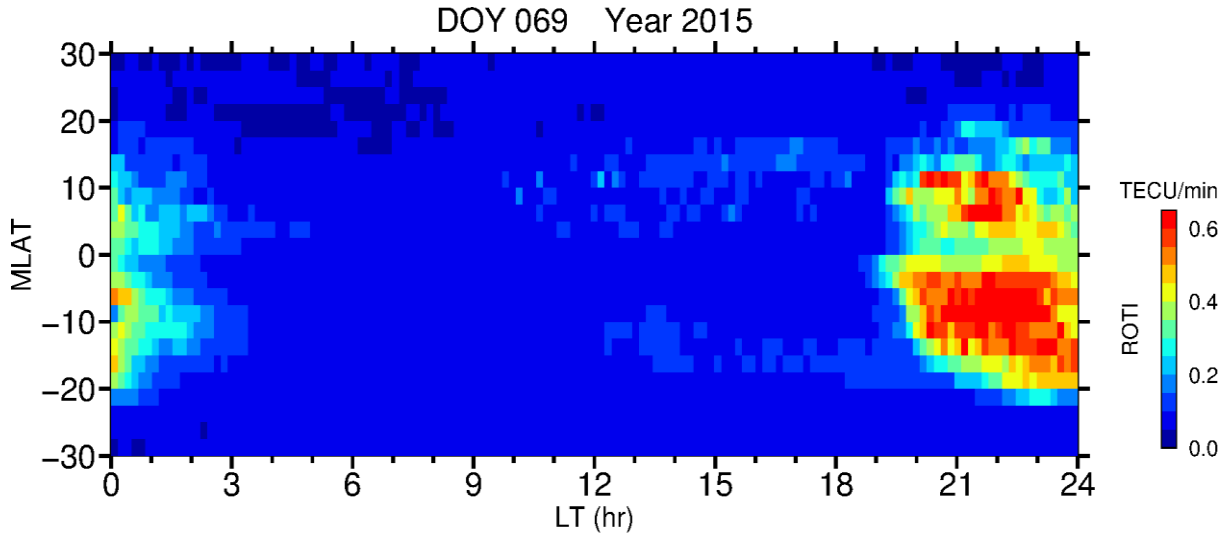
IGS ROTI Maps extension toward Southern Hemisphere and low latitudes

Preliminary results – ROTI maps on validation stage

ROTI Maps for Southern Hemisphere



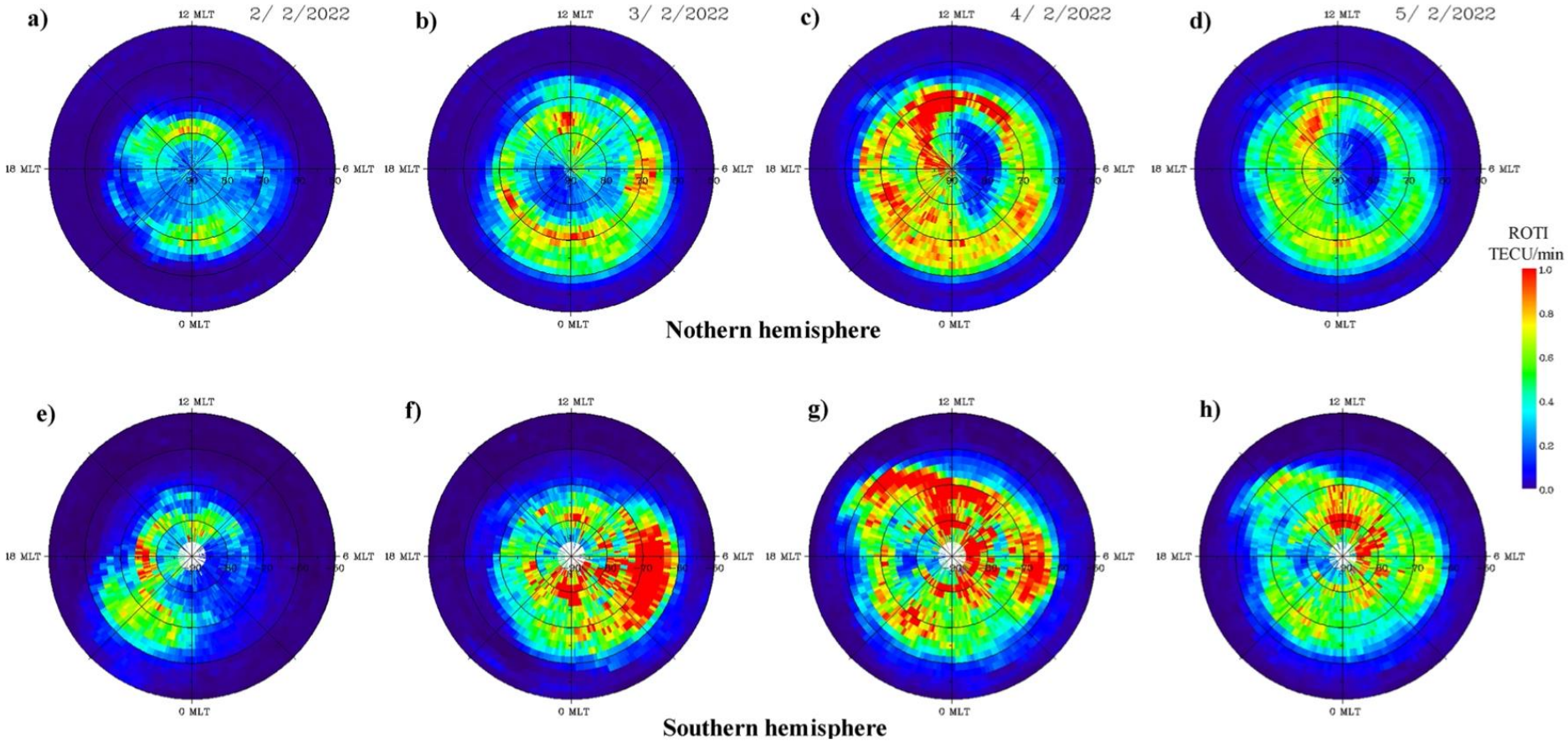
ROTI Maps for Low Latitudional region



Iurii Cherniak, Irina Zakharenkova, Andrzej Krankowski, ROTI Maps: **Current Status and Its Extension towards Equatorial Region and Southern Hemisphere, Sensors 2022, 22(10)**, 3748; doi.: 10.3390/s22103748

IGS ROTI Maps: extension towards Equatorial region and Southern Hemisphere

February 3, 2022 geomagnetic storm



ROTI maps for main phase of storm (03.02.2022) demonstrate a significant intensification of ionospheric irregularities occurrence with ROTI values exceeding 0.9–1.0 TECU/min over both hemispheres, as well as a simultaneous expansion of the irregularities oval area in the poleward and equatorward directions

Iurii Cherniak, Irina Zakharenkova, Andrzej Krankowski, ROTI Maps: **Current Status and Its Extension towards Equatorial Region and Southern Hemisphere, Sensors 2022, 22(10)**, 3748; doi.: 10.3390/s22103748

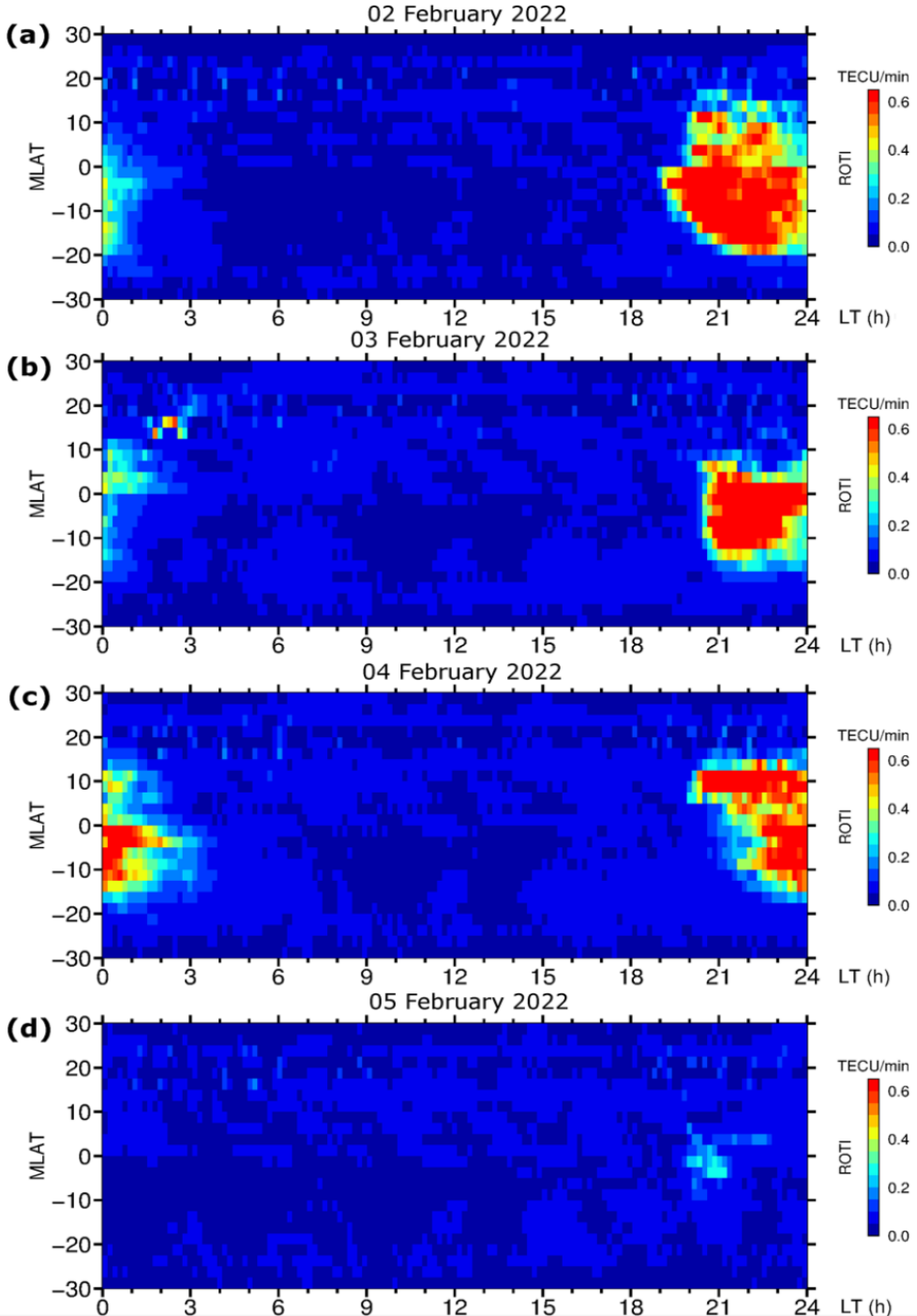
IGS ROTI Maps: extension towards Equatorial region and Southern Hemisphere

Day-by-day sequence of the ROTI maps for the equatorial region for case of February 2022 geomagnetic storm.

- Occurrence of intense equatorial ionospheric irregularities in the local postsunset period after ~19 LT before storm

- Nighttime irregularities development during the main phase of storm

- Suppression of the postsunset equatorial ionospheric irregularities during the recovery phase



Iurii Cherniak, Irina Zakharenkova, Andrzej Krankowski, ROTI Maps: **Current Status and Its Extension towards Equatorial Region and Southern Hemisphere, Sensors 2022, 22(10)**, 3748; doi.: 10.3390/s22103748

IGS ROTI Maps: extension towards Equatorial region and Southern Hemisphere

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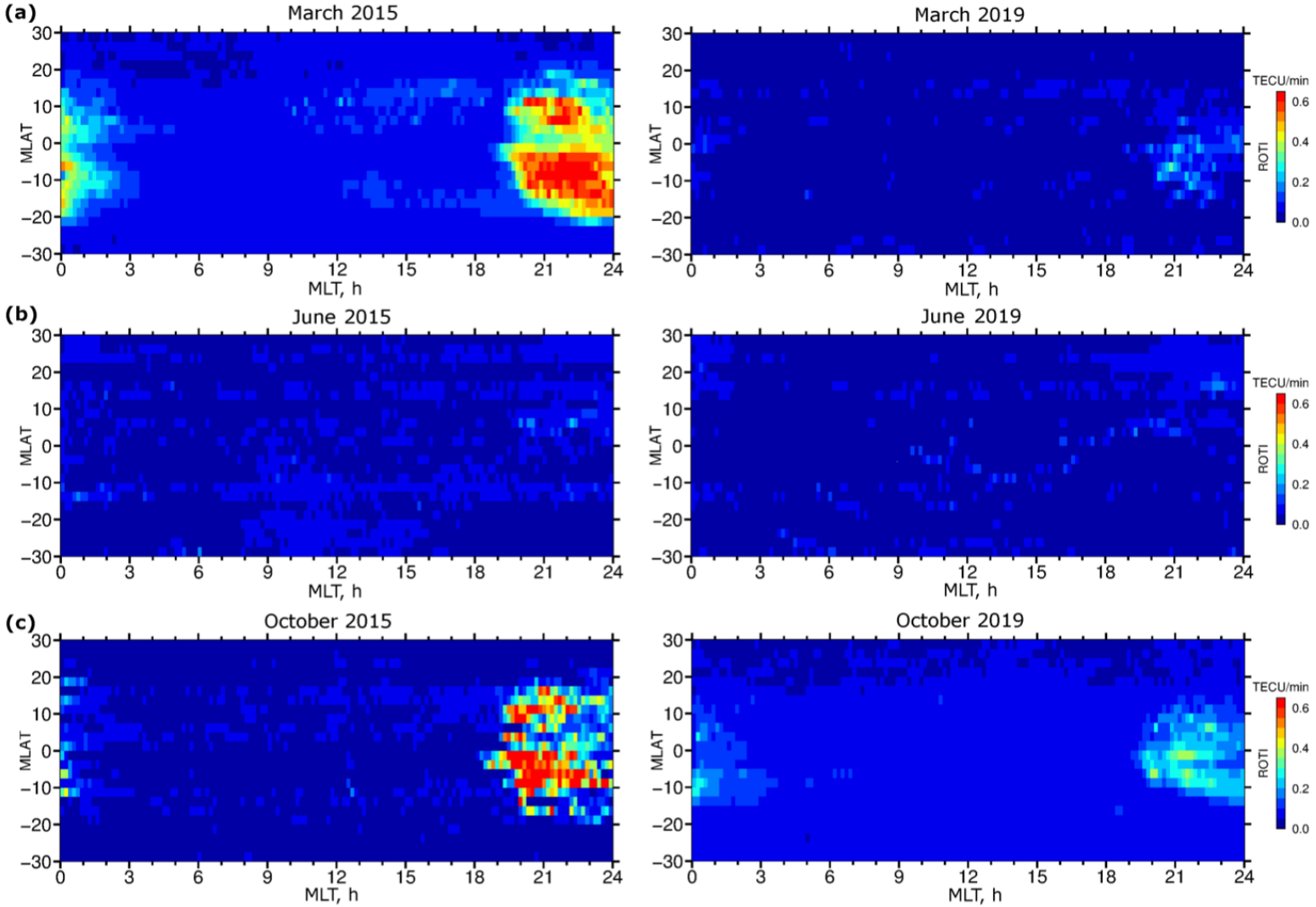
Climatology of ionospheric irregularities driven by plasma bubbles development



ROTI maps constructed for the equatorial region for March, June, and October at high (2015,) and low (2019,) levels of solar activity. ROTI maps allow to recognize plasma irregularities related to plasma bubble during local postsunset hours and climatological their behavior.

Iurii Cherniak, Irina Zakharenkova, Andrzej Krankowski, ROTI Maps: **Current Status and Its Extension towards Equatorial Region and Southern Hemisphere, Sensors 2022, 22(10)**, 3748; doi.: 10.3390/s22103748

IGS ROTI Maps: extension towards Equatorial region and Southern Hemisphere


```
START OF ROTIMAPNH
  2022     2     2
    89.0   1.0 359.0
 0.1554  0.1369  0.2199  0.2078  0.1856  0.1696  0.1808  0.1448  0.1517  0.3349
 0.1926  0.1956  0.2260  0.1824  0.1539  0.2112  0.2243  0.1729  0.2084  0.1959
 ------------------------------------------------------------------------------
                                DATA BODY
 ------------------------------------------------------------------------------
 0.0424  0.0431  0.0405  0.0421  0.0413  0.0417  0.0445  0.0444  0.0467  0.0516
 0.0720  0.0502  0.0480  0.0497  0.0514  0.0525  0.0501  0.0561  0.0600  0.0430
END OF ROTIMAPNH

START OF ROTIMAPSH
  2022     2     2
  -89.0   1.0 359.0
 0.3291  0.5783  0.3803  0.7124  0.6214  0.5290  0.4734  0.4188  0.3309  0.7778
 0.7406  0.6408  0.5258  0.2880  0.5949  0.3570  0.4312  0.9443  0.3914  0.6383
 ------------------------------------------------------------------------------
                                DATA BODY
 ------------------------------------------------------------------------------
 0.8987  0.3856  0.3857  0.2378  0.5682  0.5277  0.3823  0.2237  0.1719  0.2157
 0.2306  0.3553  0.1972  0.2064  0.1809  0.2381  0.1336  0.1976  0.1278  0.1913
END OF ROTIMAPSH

START OF ROTIMAPEQ
  2022     2     2
    30.0   1.0 359.0
 0.0000  1.1358  0.5843  1.1218  1.0786  0.8937  0.7156  0.6557  0.4342  1.2170
 1.0998  1.1241  0.7876  0.4973  0.9472  0.5555  0.6395  1.7643  0.7220  1.1368
 ------------------------------------------------------------------------------
                                DATA BODY
 ------------------------------------------------------------------------------
 1.5253  0.7748  0.5331  0.0000  1.1766  0.8116  0.6269  0.4027  0.2281  0.3921
 0.3123  0.6409  0.3089  0.3500  0.2261  0.3673  0.1671  0.2592  0.1565  0.2664
END OF ROTIMAPEQ
END OF FILE
```

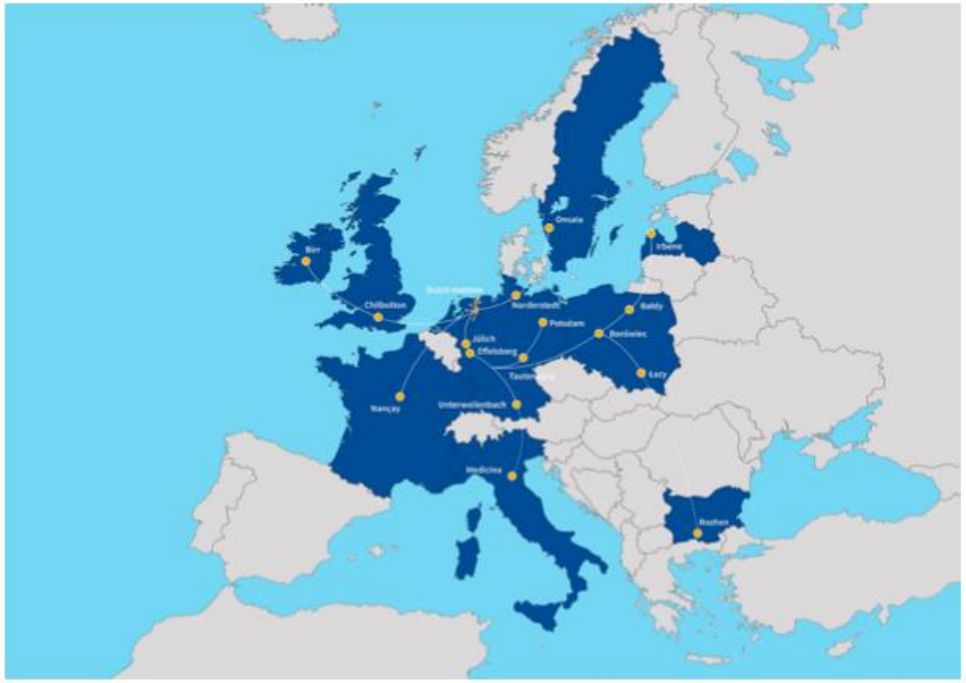
Proposed format of the extended version of the IGS ROTI map product:

- three sections (NH, SH, EQ)
- no changes for Northern hemisphere map
- section separation keywords
- rotiexDDD0.YYf filename

Iurii Cherniak, Irina Zakharenkova, Andrzej Krankowski, ROTI Maps: Current Status and Its Extension towards Equatorial Region and Southern Hemisphere**, Sensors 2022, 22(10)**, 3748; doi.: 10.3390/s22103748

About LOFAR

52 LOFAR stations across Europe



LOFAR Superterb (6 stations):

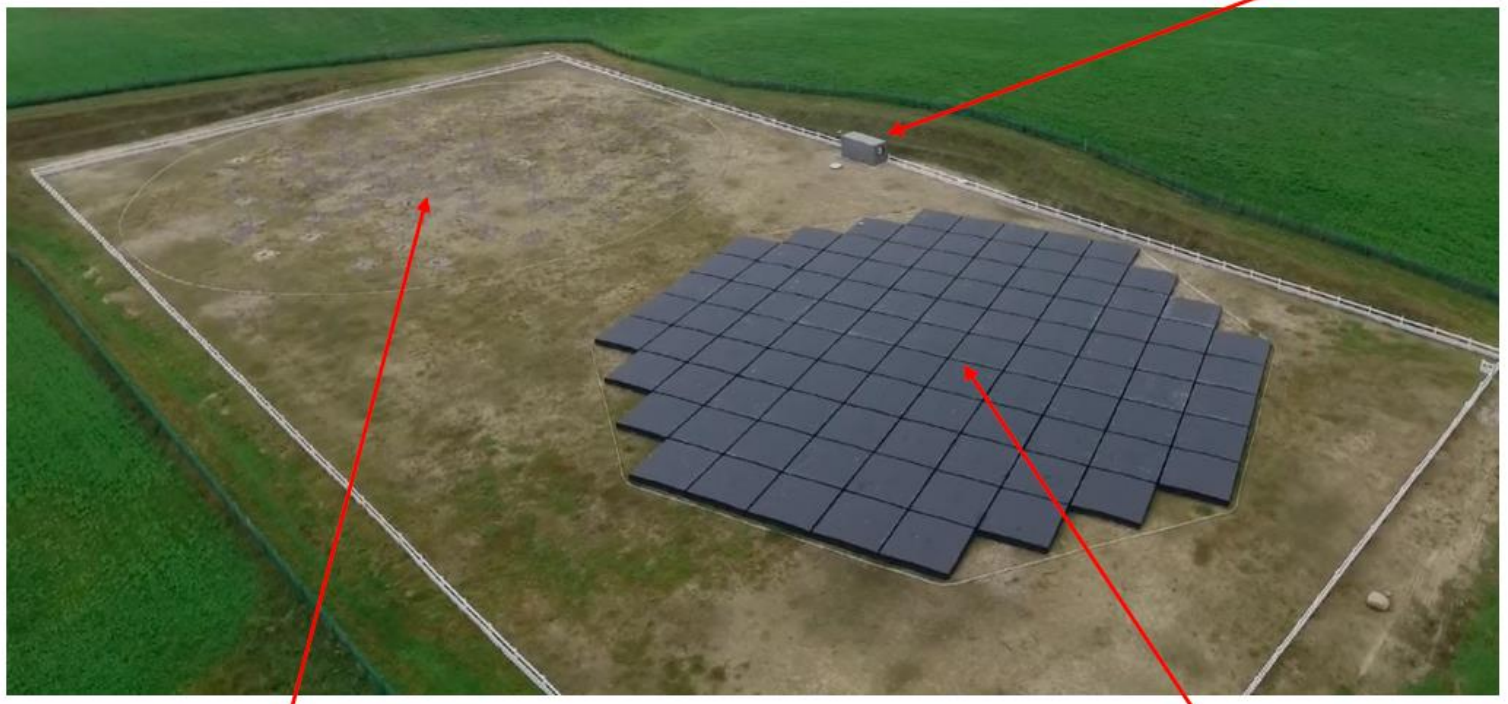
Classification of LOFAR stations:

- Core stations (24 statations);
- Remote stations (14 stations(;
- International (ILT) stations (16 stations).

About LOFAR

International LOFAR station in Bałdy (PL612)

How does LOFAR look?



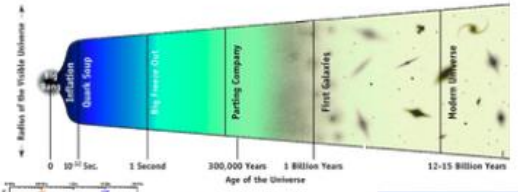
What data do we get?

- 20 ms time interval;
- 0.2 Mhz frequency interval;
- Bandwidth from 30 to 240 Mhz with gap between 90 to 110 Mhz
- Simultaneous observations from three targets: Cassiopeia, Cygnus and Taurus/Perseus.

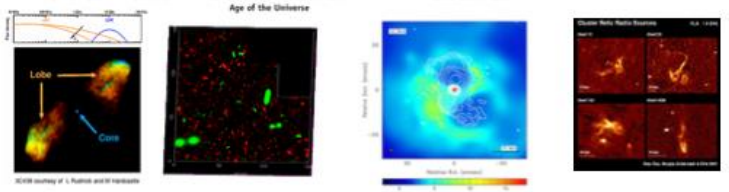
LOFAR POLFAR POLFARO

LOFAR - The Key Science Projects

Epoch of Reionisation

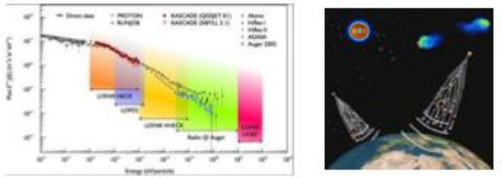


Surveys

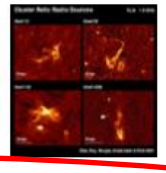


Transients

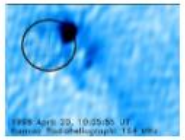
Cosmic Rays

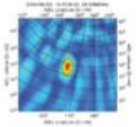


Magnetism



Sun, Space Weather



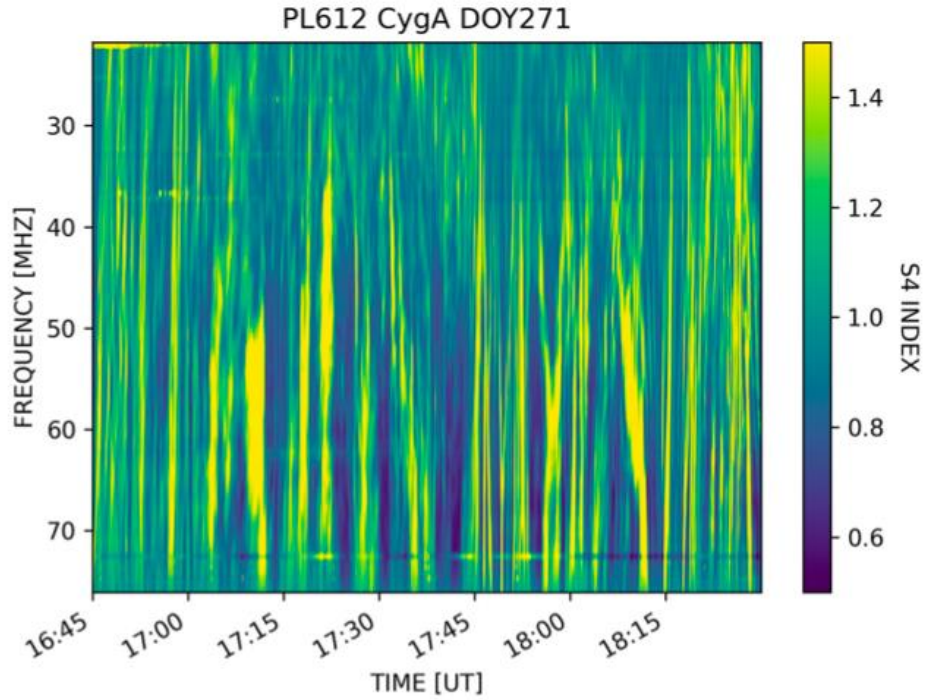


Ionospheric indices

- From GNSS stations (L1, L2 and L5):
  - Rate of change of TEC estimated over 20 ms, 1 s, 60 s
  - scintillation index (based on 20 ms samples, directly output from GNSS scintillation monitor)
- From LOFAR station (VHF):
  - scintillation index (based on 20 ms samples)

Observations and data processing

Raw scintillation data for PL612 (Bałdy) LOFAR station



How do we process data?

- Cleaning – removing RFI with use of standard deviation, removing of spikes;
- Detranding – using the moving average mathod;
- Calculating S_4.

Scintillation index

scintillation index:

$$S_4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}}$$

Where:

I radio-wave intensity

$\langle\ \rangle$ temporal averaging in lieu of ensemble averaging

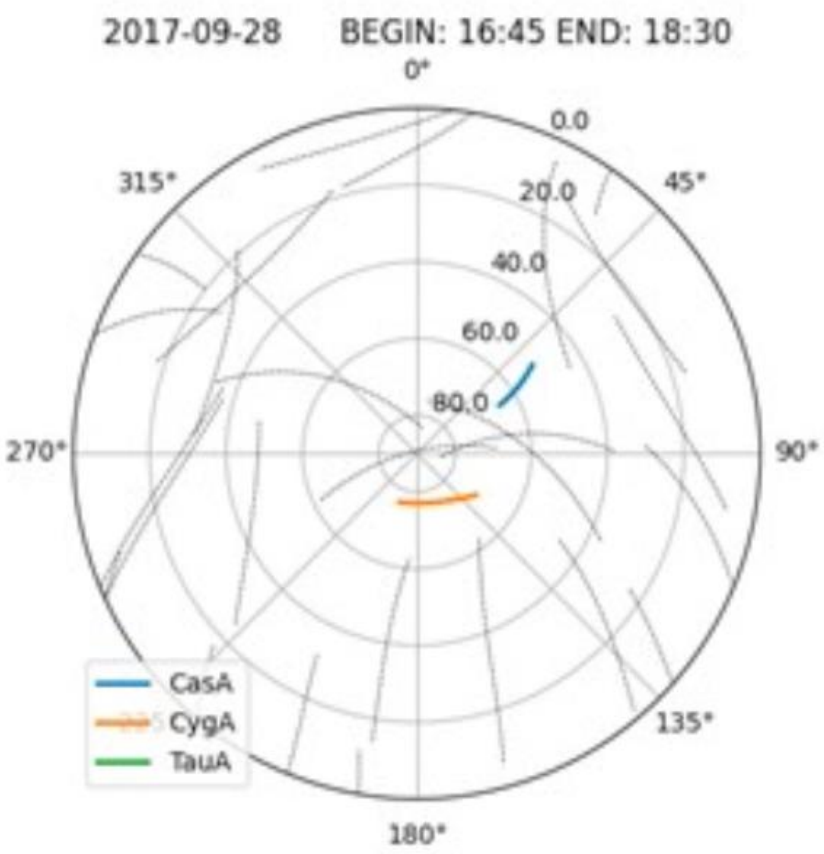
was estimated for GNSS L1 & L2 by means of a GNSS scintillation monitor (over 1 minute intervals)

was estimated for LOFAR VHF radio-wave frequencies (over 3 minute intervals, output every 1 minute by using a sliding window).

Example: DOY271 2017

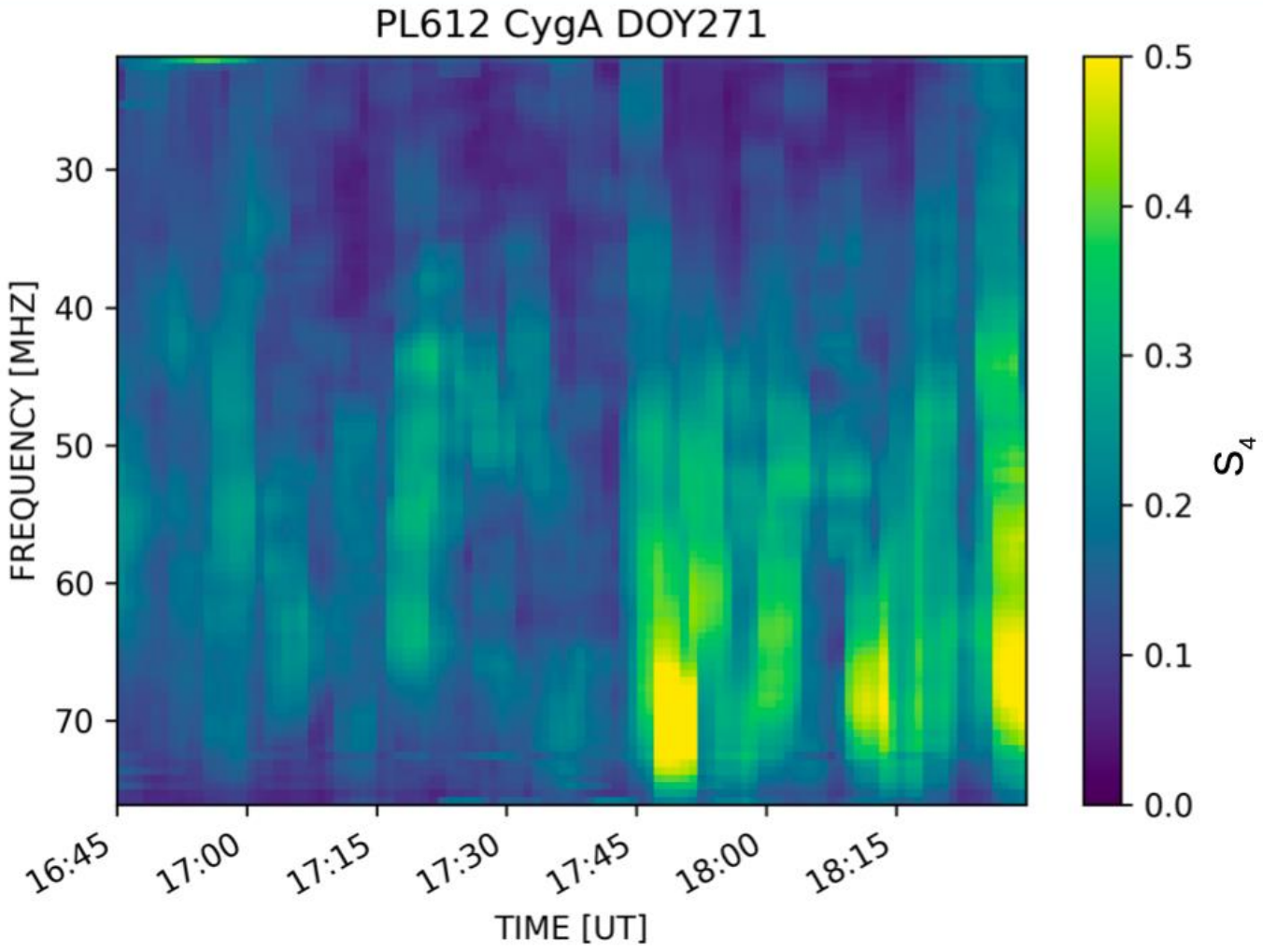
Legend:

- GNSS satellites
- LOFAR:
  - Cassiopeia A
  - Cygnus A
  - Taurus A



Example: DOY271 2017

LOFAR scintillation index estimated over various VHF radio-wave frequencies



Summary

- Being introduced in 2013, ROTI maps is currently official IGS product for ionospheric irregularities specification

- IGS ROTI maps allow to estimate the large scale irregularities activity patterns and auroral oval evolutions. The values of ROTI index corresponded to probability of GPS signals phase fluctuations.

- ROTI maps database hosted by NASA CDDIS covers twelve-year period from 2010.

- Besides the continuous support of the actual ROTI maps product, we are working on the tasks of extension of ROTI maps to cover area of the Southern hemisphere, as well as equatorial and low latitude region .

- The evaluation phase of extended ROTI maps performance assessment is now in progress. After that, the pilot phase of extended ROTI maps implementation will start.

IGS INTERNATIONAL GNSS SERVICE

Thank You!

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