IRI 2023 Workshop

Korea Astronomy and Space Science Institute

# GNSS data and ionospheric studies


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UNIVERSITY
OF WARMIA AND MAZURY
IN OLSZTYN

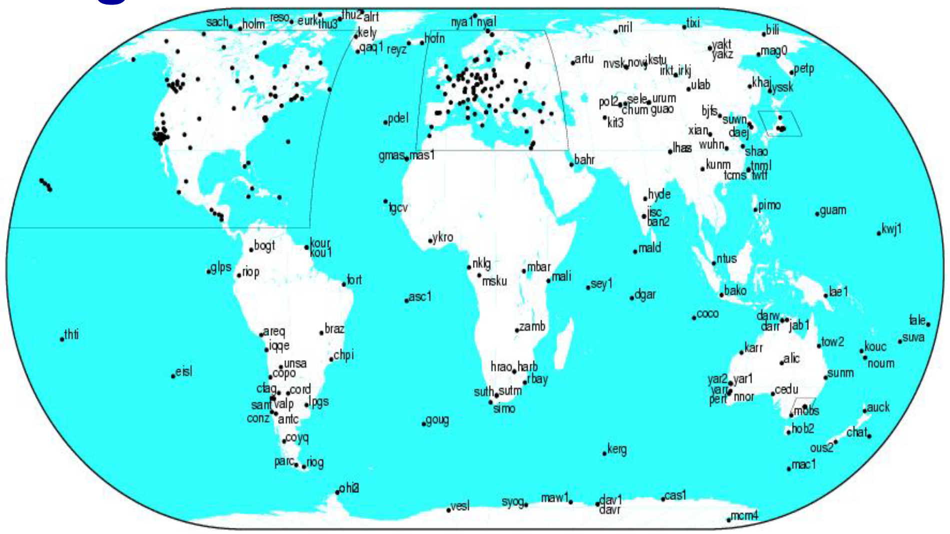

# Agenda

## Outline

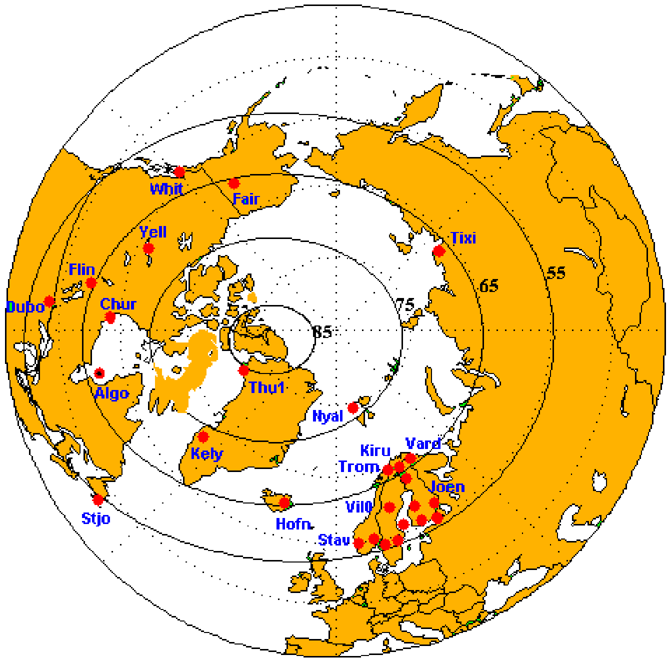
- Introduction. GNSS networks as data for the ionosphere monitoring
- IGS/UWM Ionosphre Combination Centre
    - VTEC maps and the IONEX format
- Monitoring of the TEC fluctuations using GNSS data
- LOFAR
- GNSS monitoring of the ionosphere
- Conclusions

# GNSS networks as data for the ionosphere monitoring

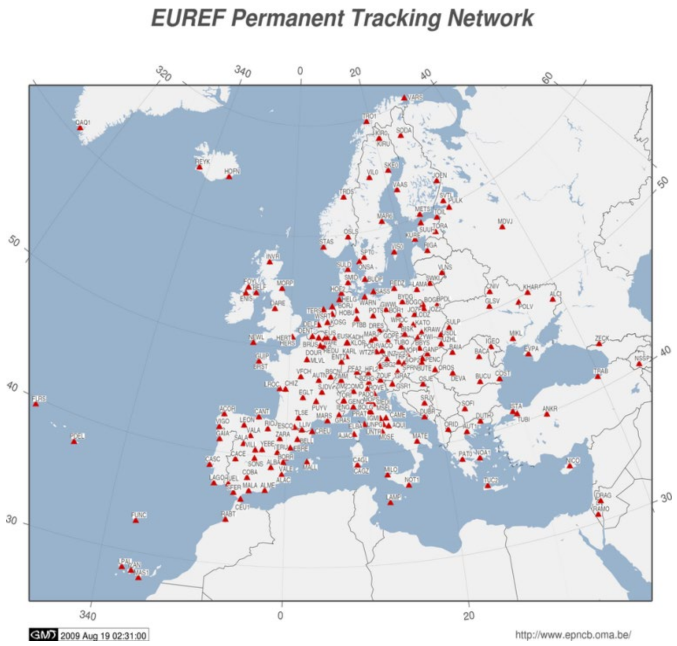
The IGS and other permanent GNSS networks collects, archives, and distributes GPS observation data sets of sufficient accuracy to satisfy the objectives of a wide range of applications and experimentation. The GNSS observations provided by IGS and other permanent station networks, with a 30 s sampling RINEX data.



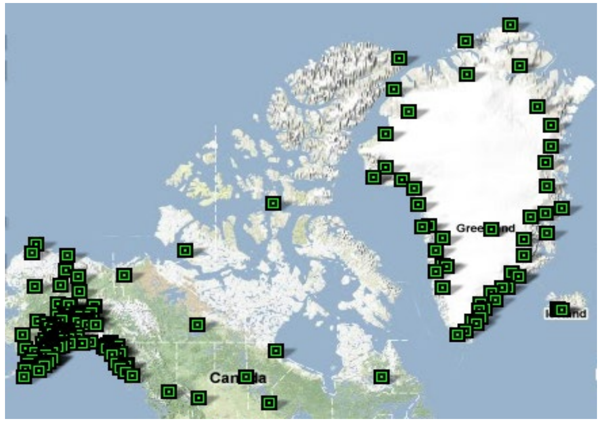
International GNSS Service - IGS




IGS polar stations




IGS/EPN
(EUREF Permanent Tracking Network)



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

# Overview of the IonoWG

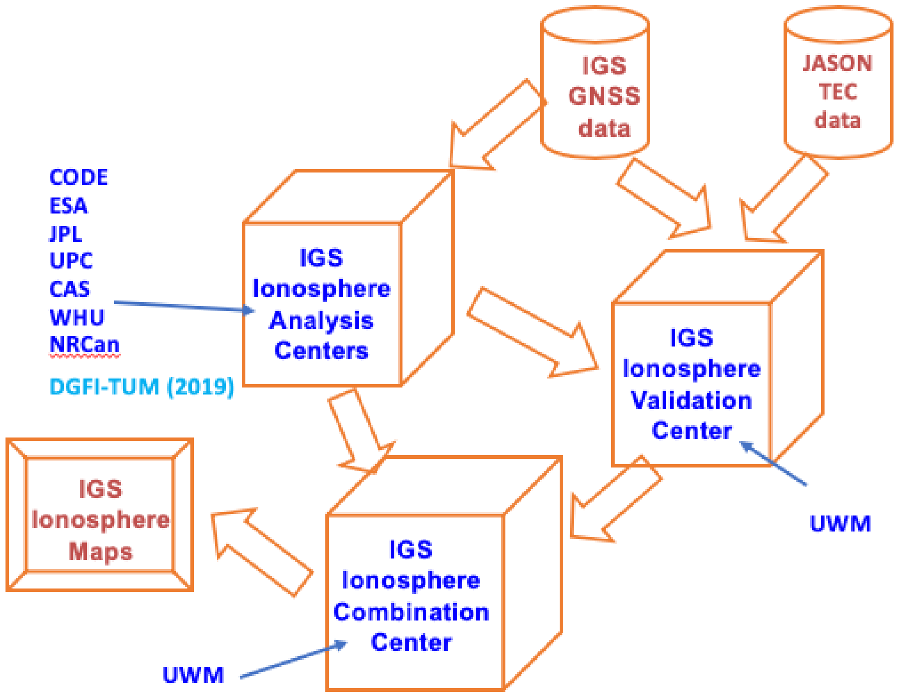
The IGS Ionosphere Working group started its activities in June 1998 with the main goal of a routinely producing IGS Global TEC maps.

This is being done now with a latency of 11 days (final product) and with a latency of less than 24 hours (rapid product).

This has been done under the direct responsibility of the Iono-WG chairmans:

1. Dr Joachim Feltens, ESA 1998–2002,
2. Prof. Manuel Hernández-Pajares, UPC, 2002–2007
3. Prof. Andrzej Krankowski, UWM, 2008-

The IGS ionosphere product is a result of the combination of TEC maps derived by different Analysis Centers by using weights computed by Validation Center, in order to get a more accurate product.



# 2022 IGS Virtual Workshop Recommendations

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

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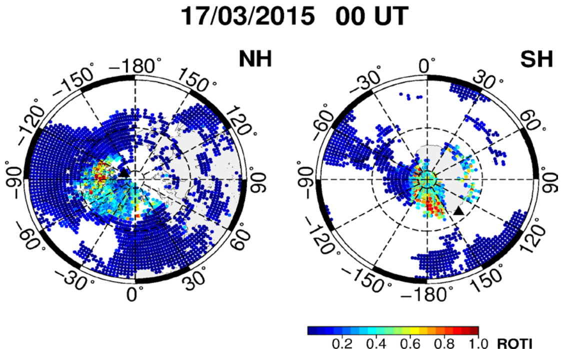
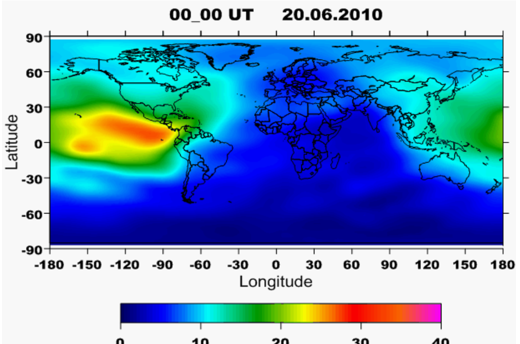
2022 Virtual Workshop
"Science from Earth to Space"

- **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.**

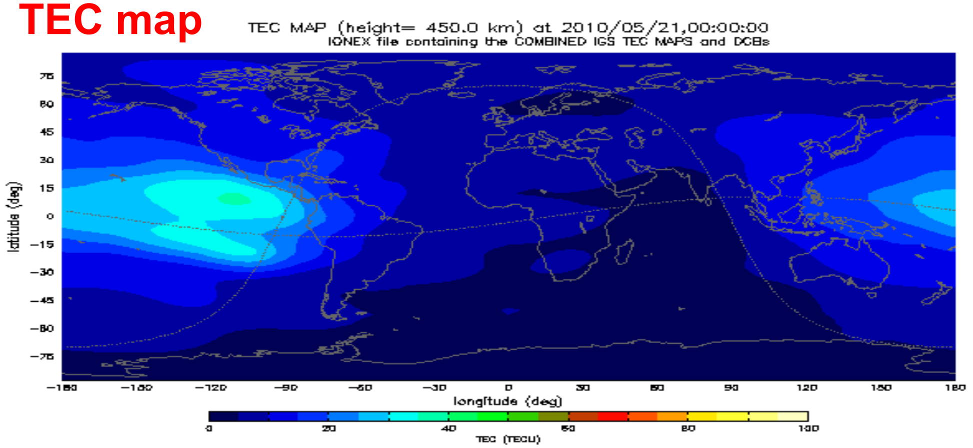


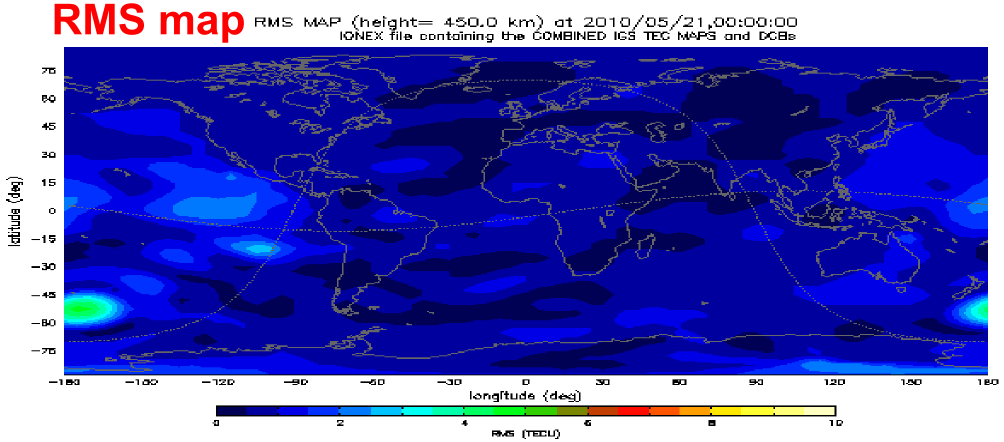

IGS

# Example of IGS Final GIM: 2010-141 DOY

**TEC map**




**RMS map**




**8 Analysis Centers: CODE, ESA, JPL, UPC, WHU, CAS, NRCan, DGFI-TUM (since 2019) and a Validation Center (UWM) have been providing maps (at 2 hours x 5 deg. x 2.5 deg in UT x Lon. x Lat.), weights and external (altimetry-derived) TEC data.**

**From such maps and weights the Combination Center (at first ESA, then UPC, and since 2008 - UWM) has produced the IGS TEC maps in IONEX format.**

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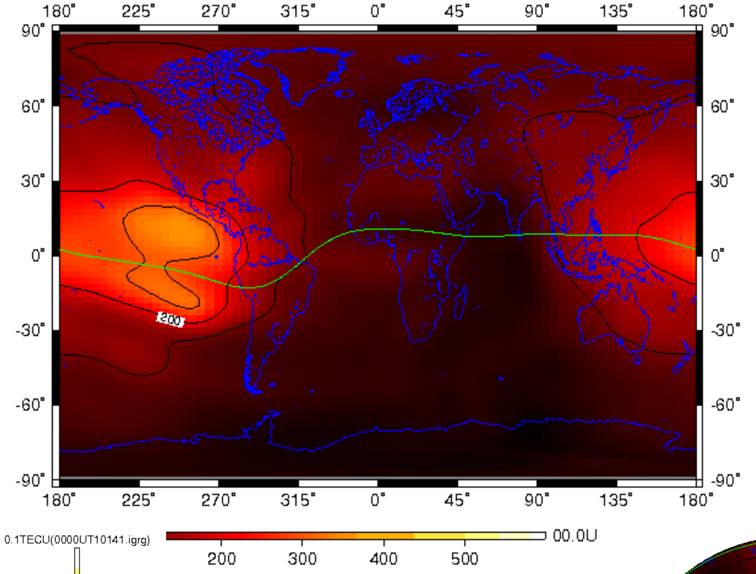
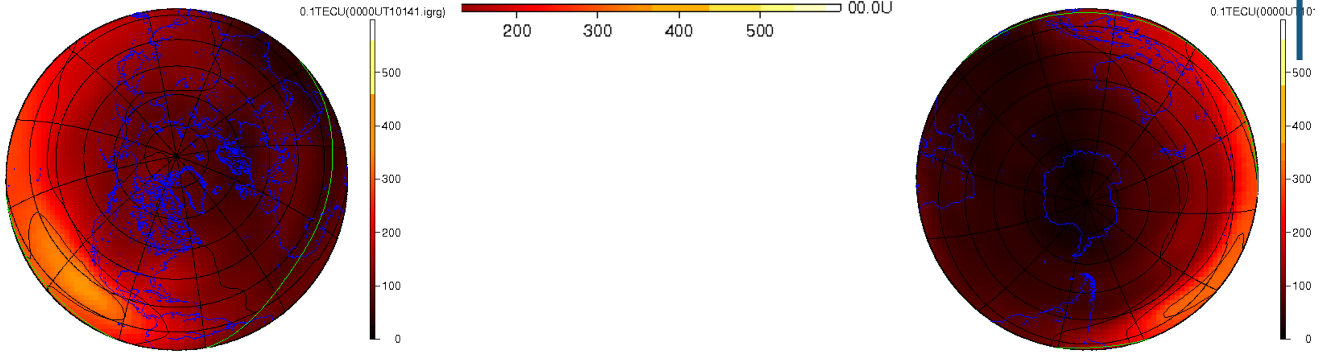
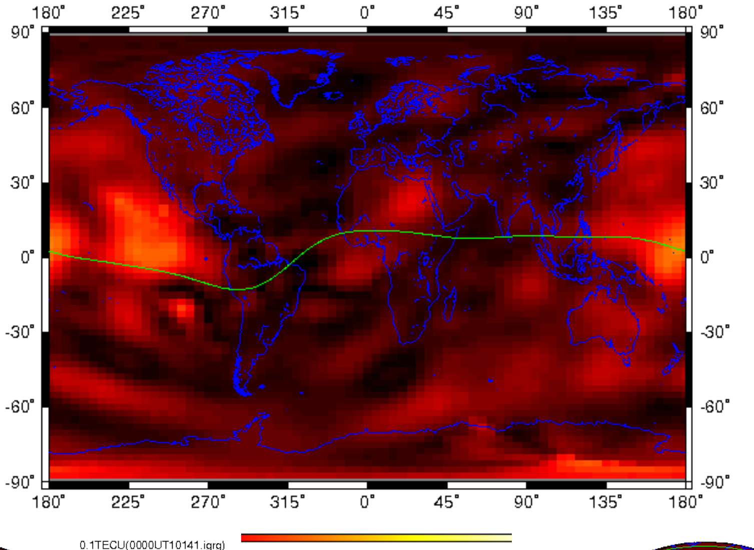
# Example of IGS RAPID GIM: 2010-141 DOY

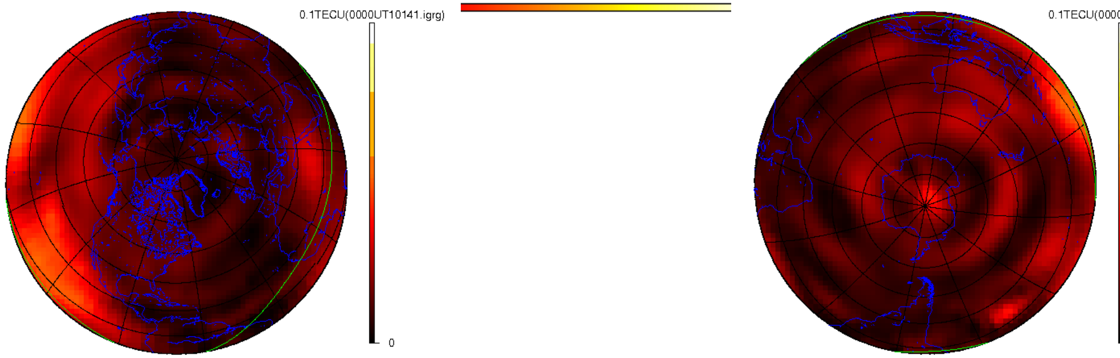
## TEC maps




## RMS maps



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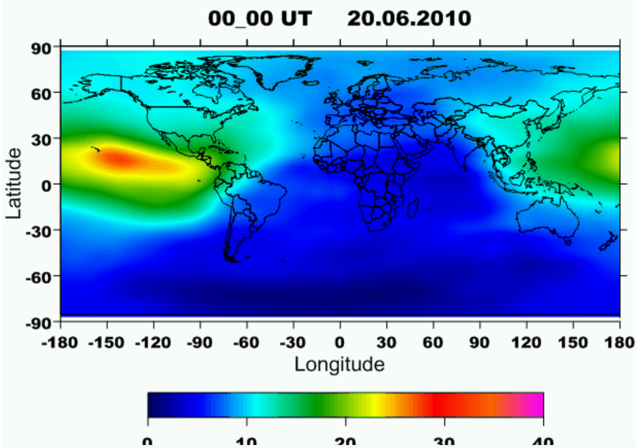
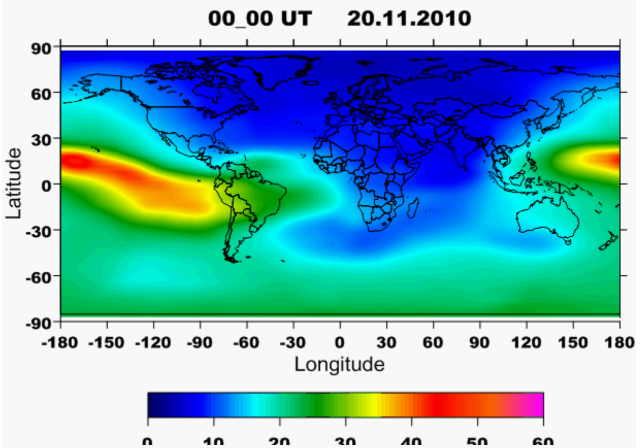
# Example of IGS PREDICTED GIM

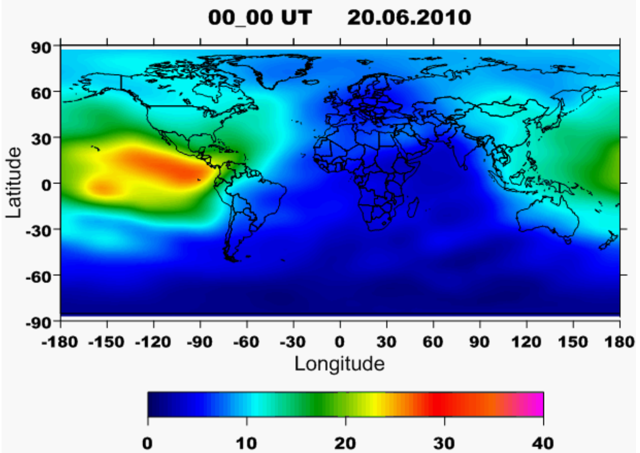
## June 20, 2010

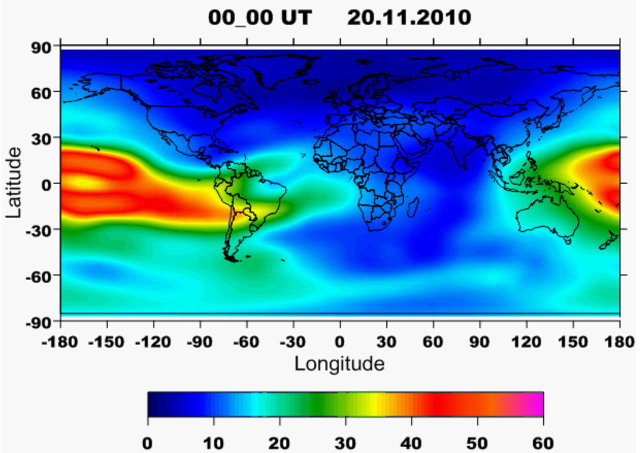
## November 20, 2010




IGS Predicted GIM




IGS Final GIM

# Looking for optimal ways to combine IGS global ionospheric maps in real-time

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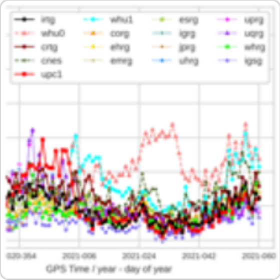
## More details about IGS RT-GIM

Data description paper 23 Sep 2021

### The cooperative IGS RT-GIMs: a reliable estimation of the global ionospheric electron content distribution in real time



Qi Liu[1], Manuel Hernández-Pajares[1,2], Heng Yang[3,1], Enric Monte-Moreno[4], David Roma-Dollase[2], Alberto García-Rigo[1,2], Zishen Li[5], Ningbo Wang[5], Denis Laurichesse[6], Alexis Blot[6], Qile Zhao[7,8], Qiang Zhang[7], André Hauschild[9], Loukis Agrotis[10], Martin Schmitz[11], Gerhard Wübbena[11], Andrea Stürze[12], Andrzej Krankowski[13], Stefan Schaer[14,15], Joachim Feltens[16], Attila Komjathy[17], and Reza Ghoddousi-Fard[18]

**Earth Syst. Sci. Data, 13, 4567–4582, 2021**

https://essd.copernicus.org/articles/13/4567/2021/essd-13-4567-2021.html

Original Article | Published: 18 February 2020

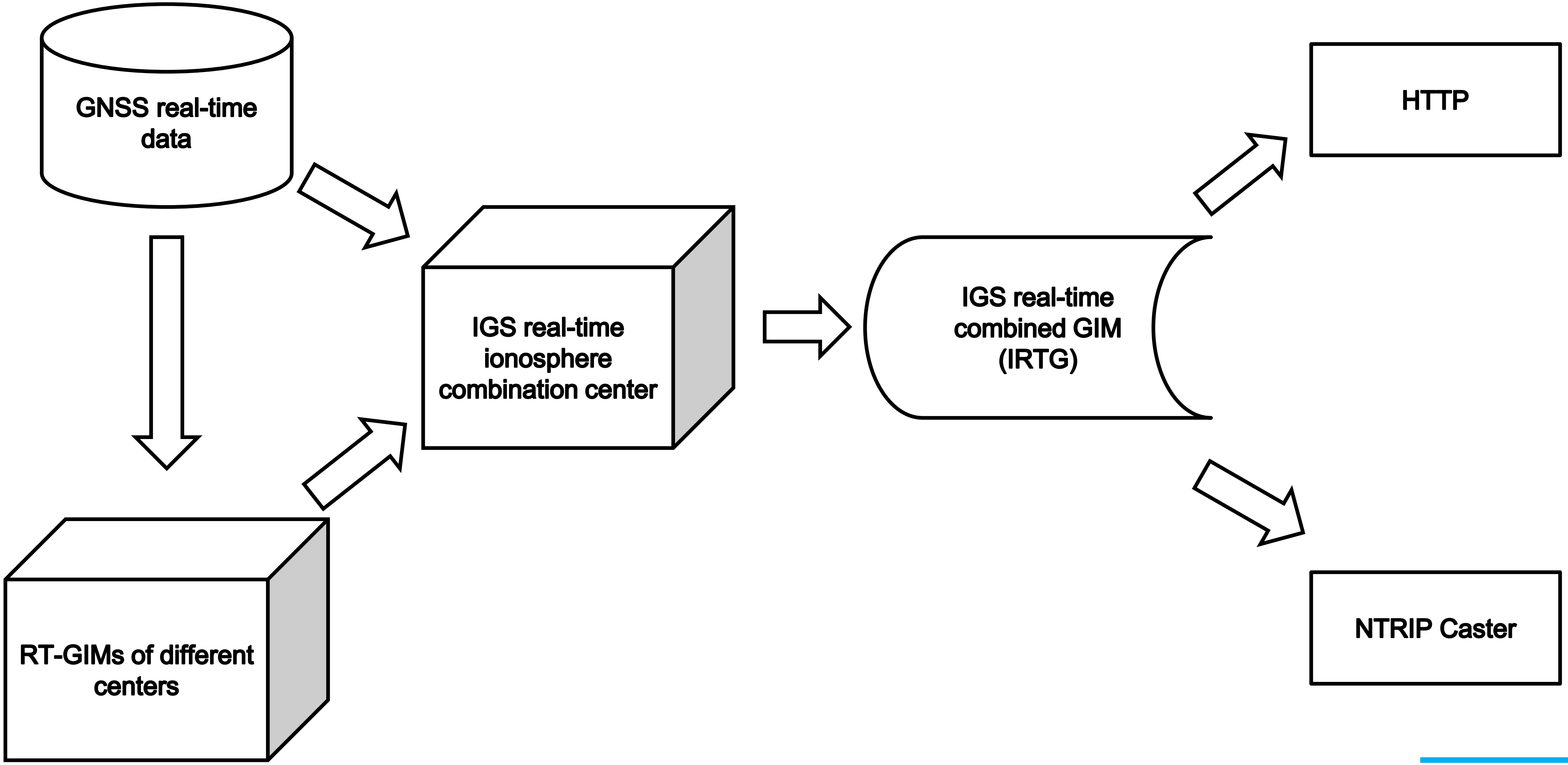
### IGS real-time service for global ionospheric total electron content modeling

Zishen Li, Ningbo Wang, Manuel Hernández-Pajares, Yunbin Yuan, Andrzej Krankowski, Ang Liu, Jiuping Zha, Alberto García-Rigo, David Roma-Dollase, Heng Yang, Denis Laurichesse & Alexis Blot

**Journal of Geodesy 94, 32, 2020**

https://link.springer.com/article/10.1007/s00190-020-01360-0

# Data flow for the IGS real-time combined GIM



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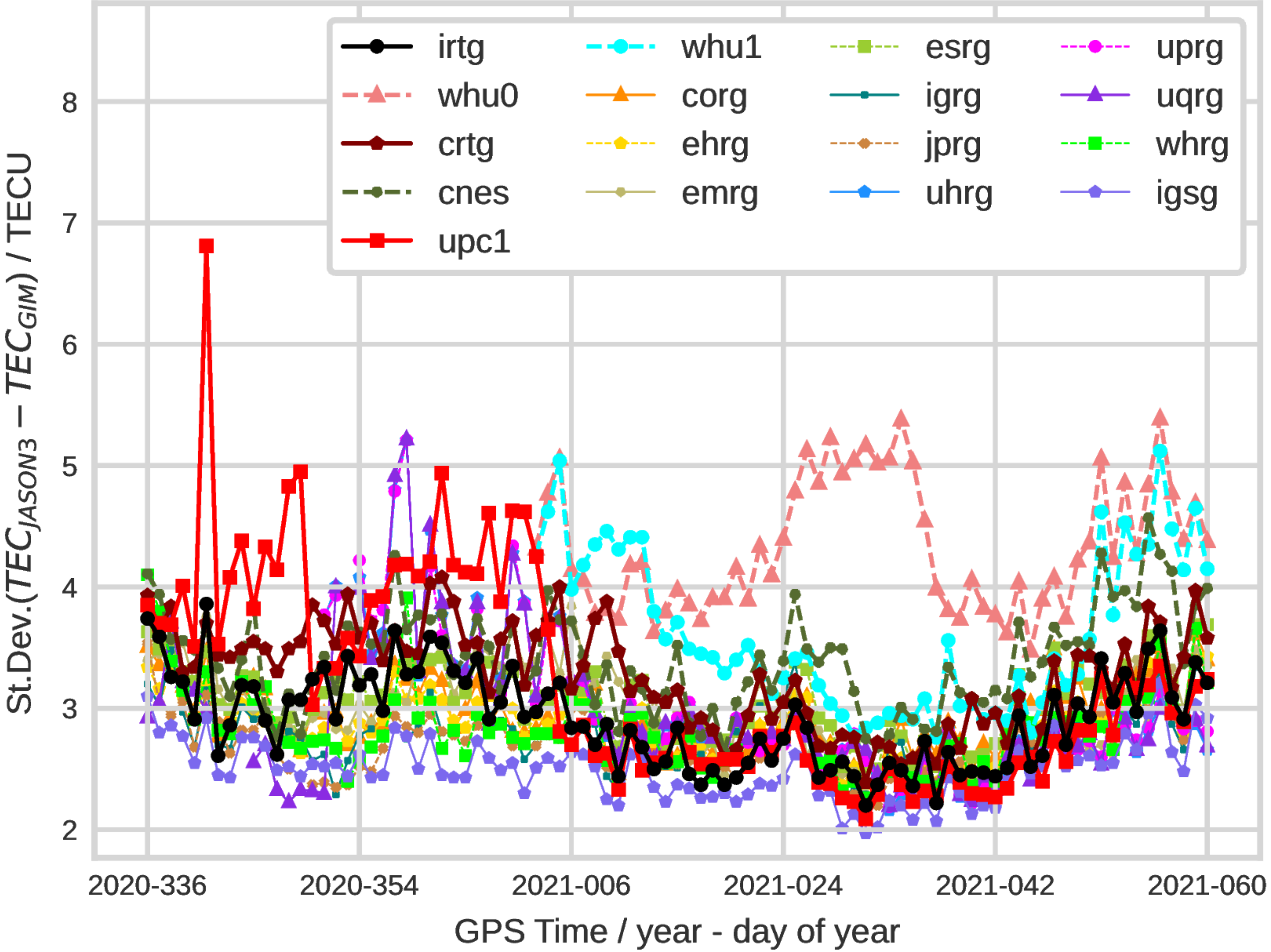
# The performance of GIMs versus Jason3-VTEC



# The current status of broadcasting IGS RT-GIMs

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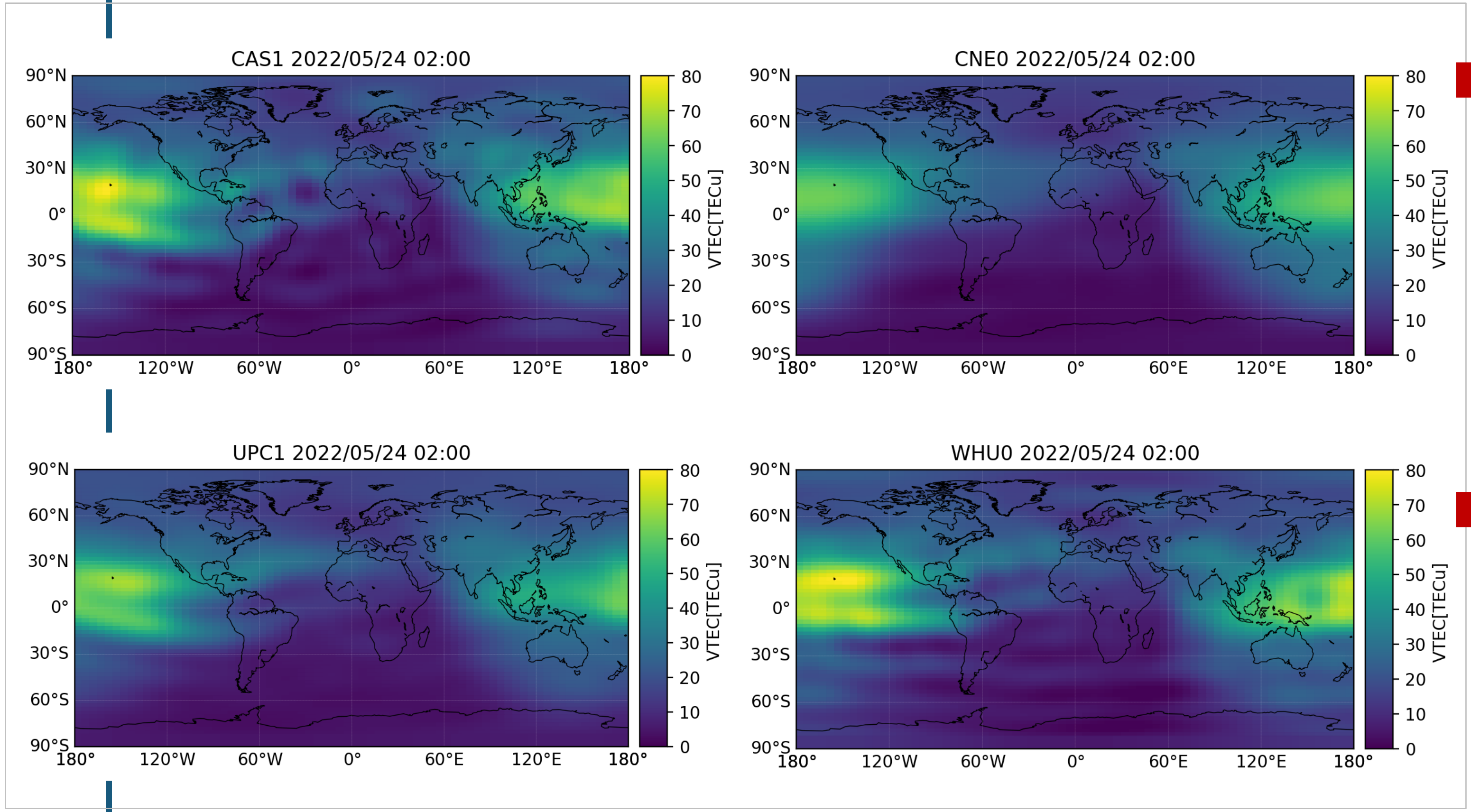
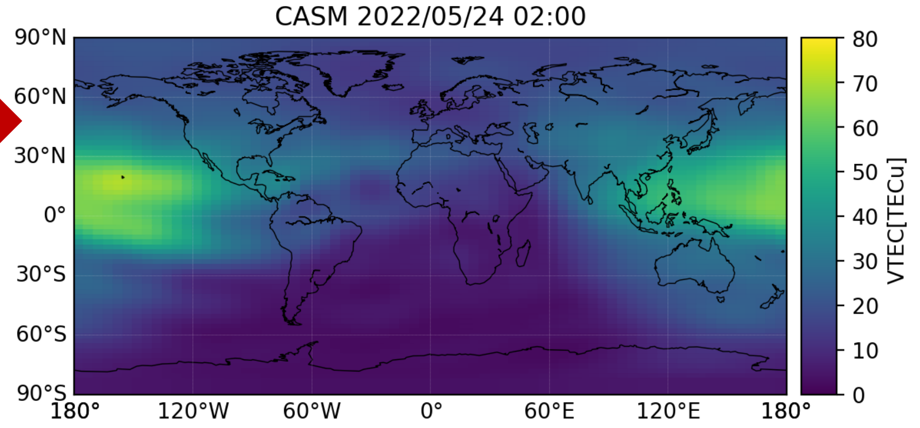
| Agency | Temporal resolution | Broadcast frequency | Spherical harmonic degree | Mountpoints in NTRIP caster (in SSR format) | Real-Time IONEX files saved at FTP/HTTP |
|---|---|---|---|---|---|
| CAS | 5 minutes | 1 minute | 15 | 59.110.42.14:2101/SSRA00CAS1<br>59.110.42.14:2101/SSRA00CAS0<br>59.110.42.14:2101/SSRC00CAS1<br>59.110.42.14:2101/SSRC00CAS0<br>182.92.166.182:2101/IONO00CAS1<br>182.92.166.182:2101/IONO00CAS0 | ftp://ftp.gipp.org.cn/product/ionex/ |
| CNES | 2 minutes | 1 minute | 12 | products.igs-ip.net:2101/SSRA00CNE1<br>products.igs-ip.net:2101/SSRA00CNE0<br>products.igs-ip.net:2101/SSRC00CNE1<br>products.igs-ip.net:2101/SSRC00CNE0 | No |
| UPC-IonSAT | 15 minutes | 15 seconds | 15 | products.igs-ip.net:2101/IONO00UPC1 | http://chapman.upc.es/tomion/real-time/quick/ |
| WHU | 5 minutes | 1 minute | 15 | 58.49.58.150:2106/IONO00WHU0 | ftp://igs.gnsswhu.cn/pub/whu/MGEX/realtime-ionex/ |
| IRTG (IGS) | 20 minutes | 15 seconds | 15 | products.igs-ip.net:2101/IONO00IGS1 | http://chapman.upc.es/irtg/ |

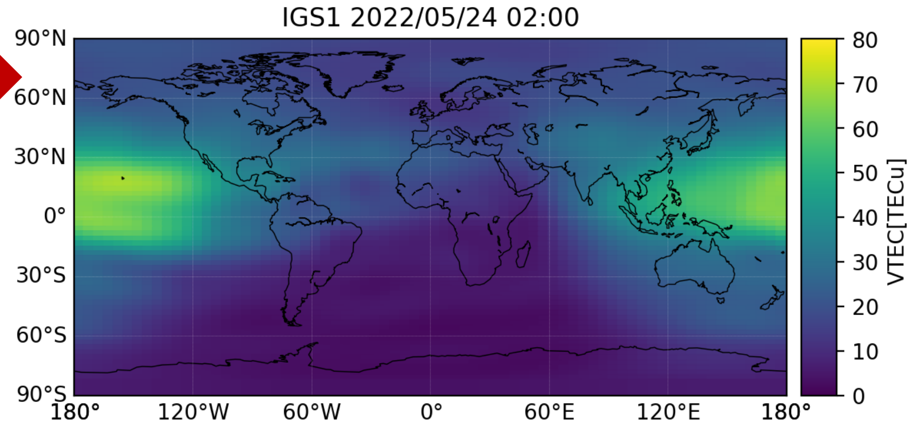
# RT-GIMs provided by different ACs




CAS combined RT-GIM

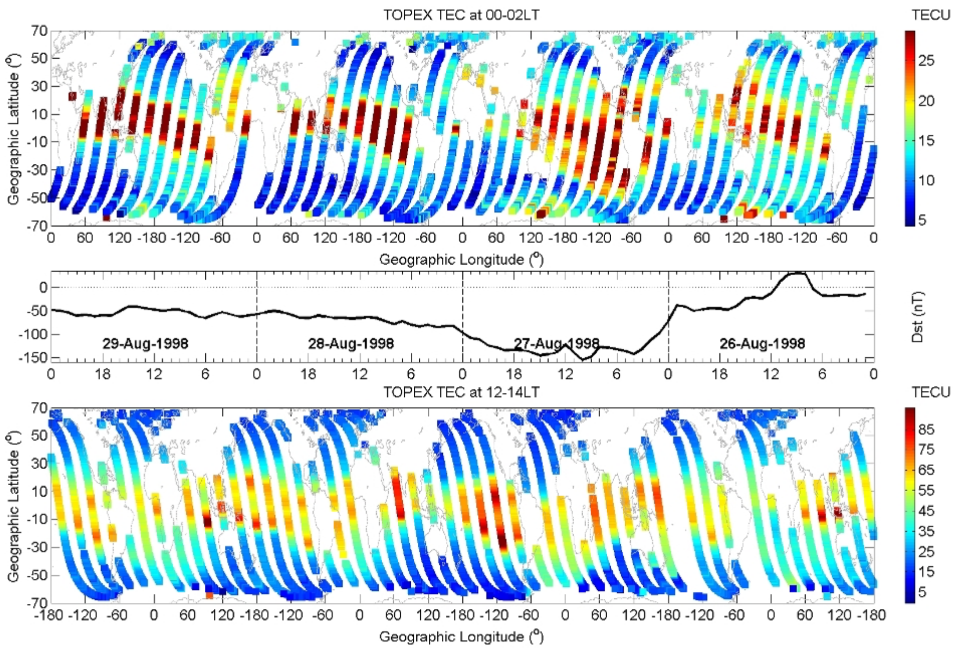


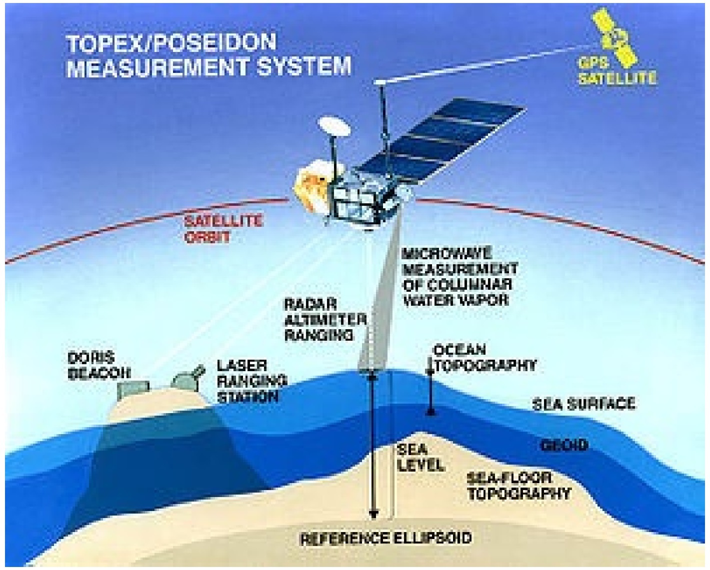

UPC combined RT-GIM



# Vertical Total Electron Content from TOPEX/Jason

TOPEX and Jason satellites provide vertical TEC (up to about 1300 km altitude) over the oceans from 1992 until now.




**Largest errors are associated with biases of the order of 3-5 TECU.**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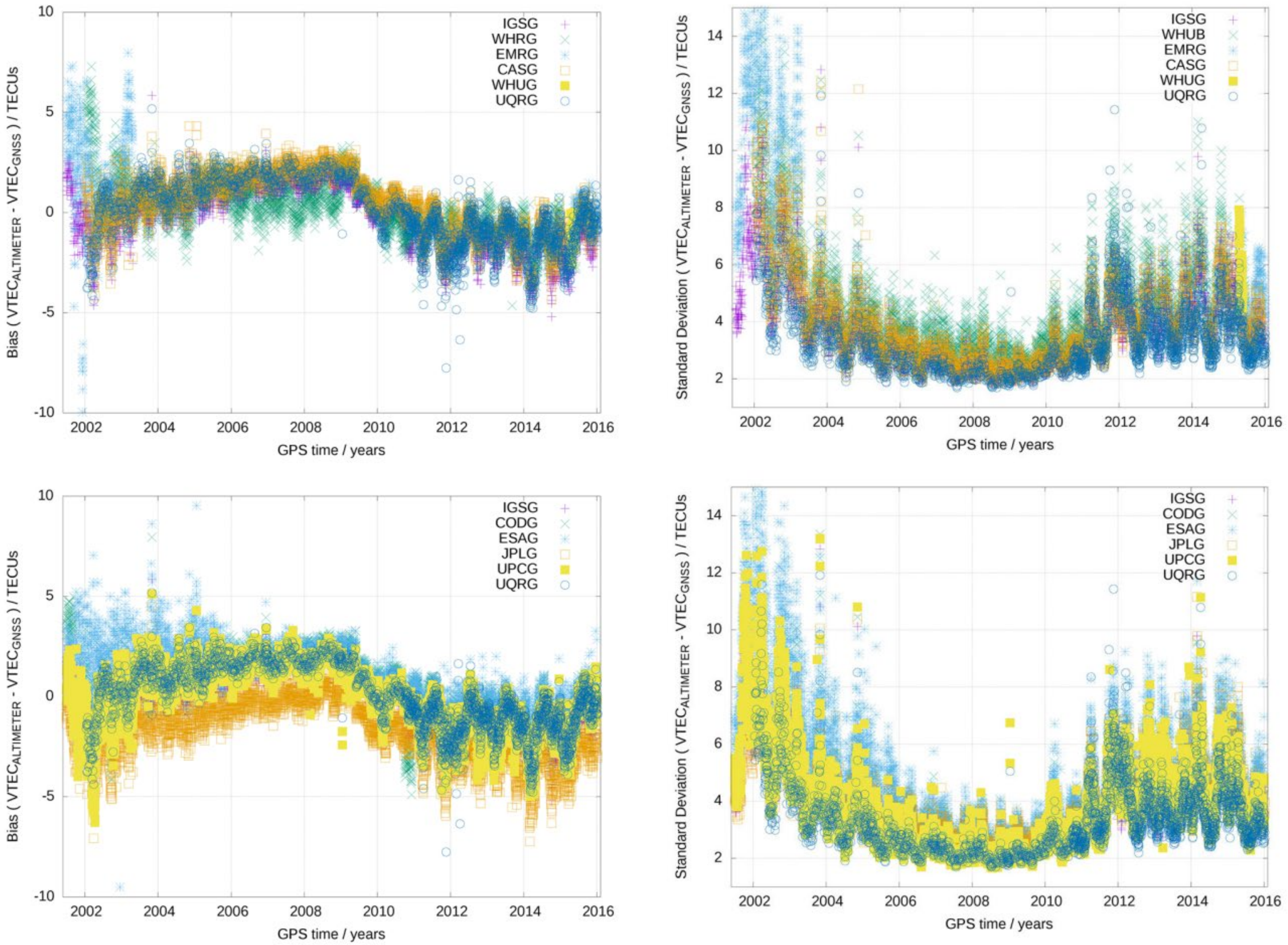
# IGS Validation process

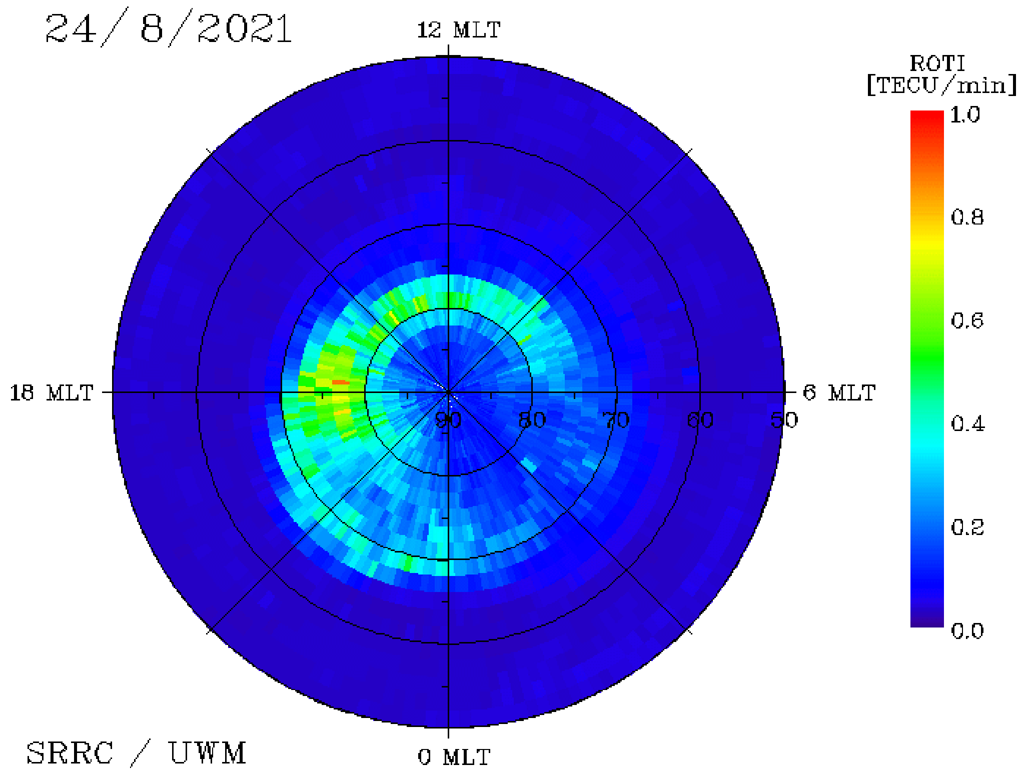



„Consistency of seven different GNSS global ionospheric mapping techniques during one solar cycle", David Roma-Dollase, Manuel Hernández-Pajares, Andrzej Krankowski, Kacper Kotulak, Reza Ghoddousi-Fard, Yunbin Yuan, Zishen Li, Hongping Zhang, Chuang Shi, Cheng Wang, Joachim Feltens, Panagiotis Vergados, Attila Komjathy, Stefan Schaer, Alberto García-Rigo & José M. Gómez-Cama, Journal of Geodesy, vol. 92, 2018, pp. 691–706

# 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 signifficant 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

# Monitoring of the TEC fluctuations using GNSS data

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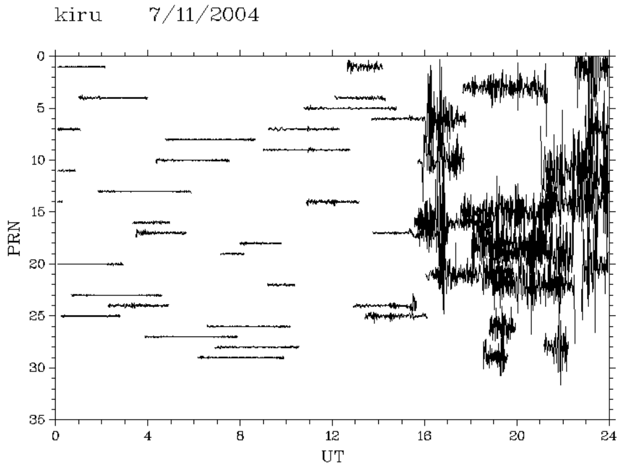
## High latitude TEC fluctuations

**For fast detecting phase fluctuation occurrence the rate of TEC (dTEC/dt) is more preferred (Wanninger, 1993):**

$$ROT = 9.52 \cdot 10^{16}\ el/m \cdot (\Delta\Phi_i - \Delta\Phi_k)$$




$\Delta\Phi_{ki}$ - differential carrier phase sample with 30 sec interval

$$\Delta t = t_k - t_i = 1\ min.$$

**As a measure of ionospheric activity we used also the Rate of TEC Index (ROTI) based on standard deviation of ROT (for 5 minut intervals)(Pi et all, 1997):**

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

# Methodology

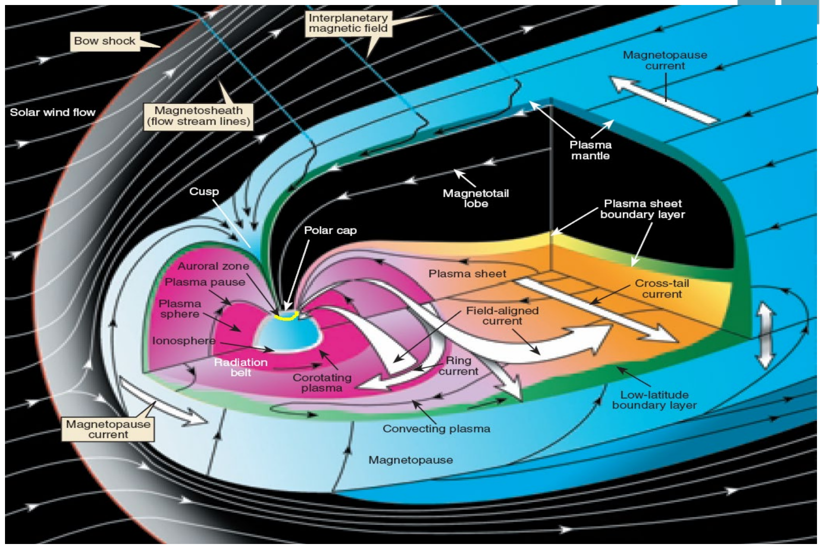
## Basic approach:

## 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 (MI

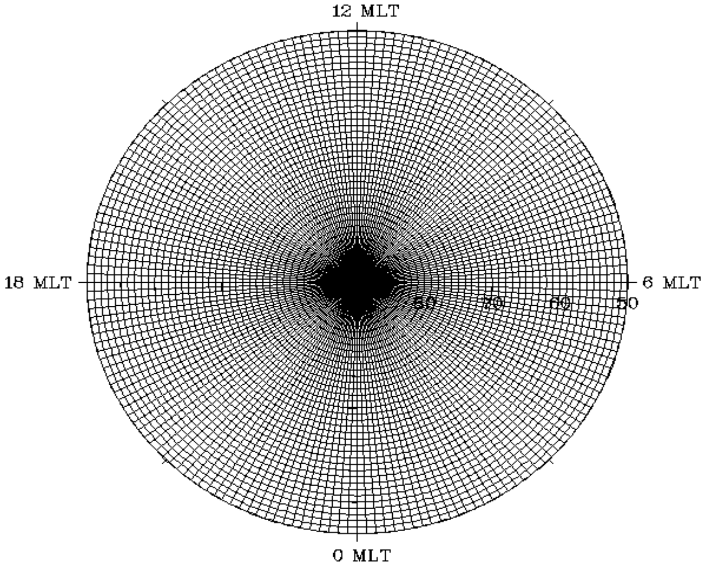



**Fig. The grid of ROTI maps in polar coordinates with grid 2 degree (magnetic local time) and 2 degree (geomagnetic latitude).**

**ROTI data were binned and averaged in cells of 2° magnetic latitude by 8 min MLT**

# Methodology

## Data sources:

**In the updated version, more than 700 permanent stations (available both from UNAVCO and EUREF databases) have been involved into analysis of the ionosphere fluctuation service.**

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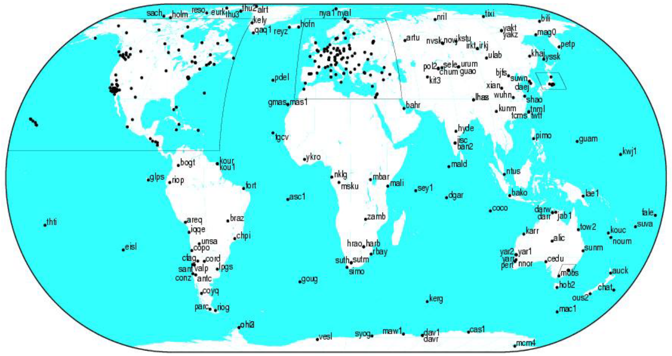
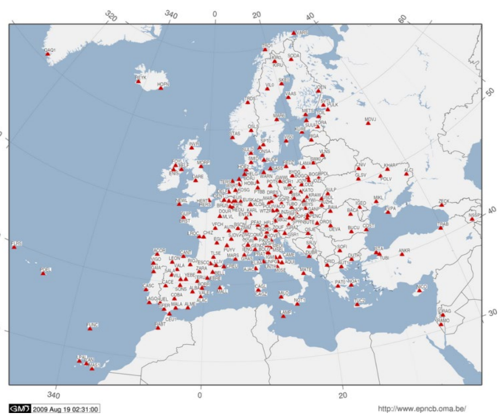
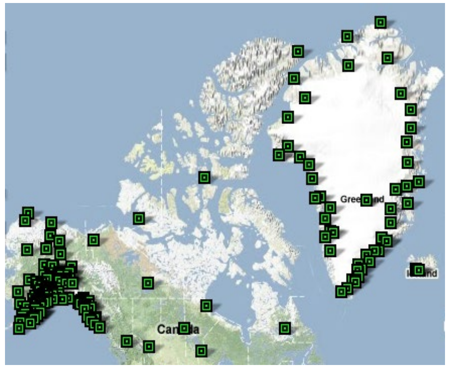


EUREF Permanent Tracking Network



UNAVCO



**> 700 stations**

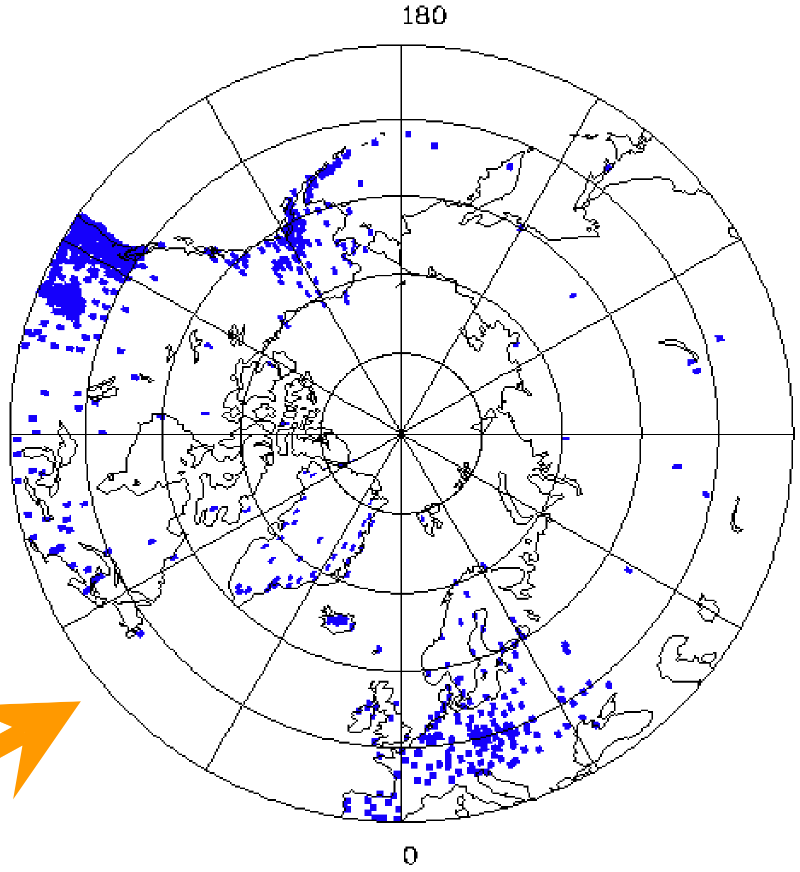



**Fig. The locations of the stations around the North Geomagnetic Pole.**

# ROTI Maps Product

## Steps of ROTI Maps product generation at UWM:

Data collection → Data quality check → ROTI calculation (every stat) → Coordinates trans-formation → ROTI mapping → ASCII fl. generation → Product uploading to UWM Datacenter

ASCII fl. generation → Maps visualization local using

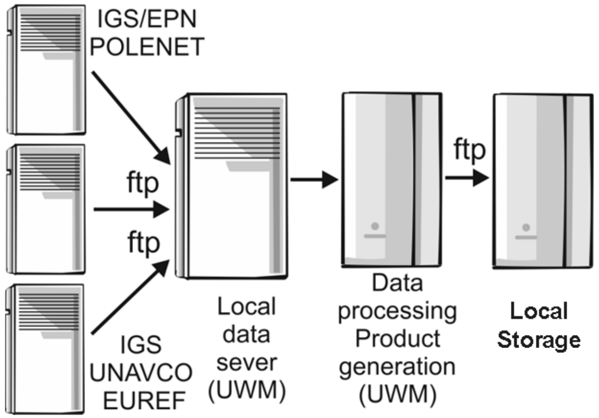
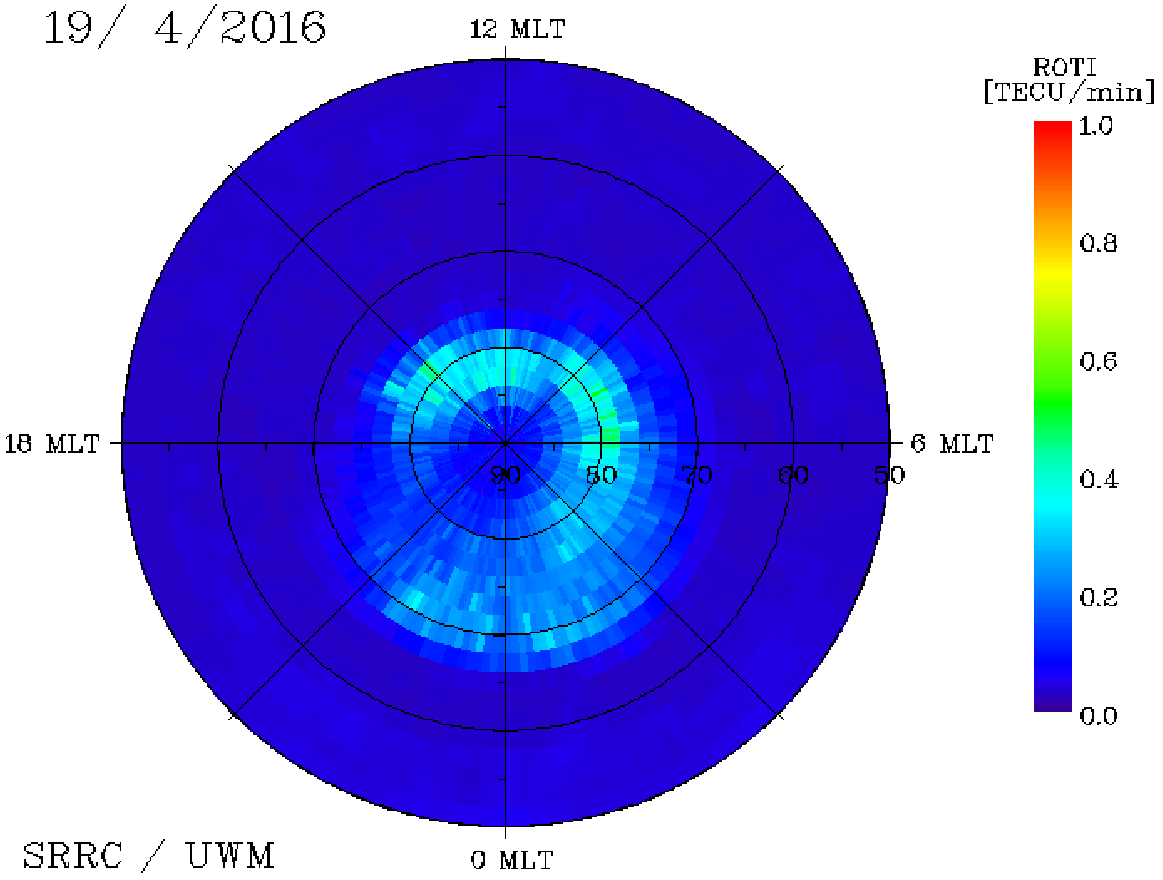



Fig. TEC fluctuation service operation diagram

# ROTI Maps Product

## ROTI Maps visualization




Output ROTI visualized in polar coordinates from 0 to 359

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# IGS ROTI Maps extension toward Southern Hemisphere and low latitudes

## Preliminary results – ROTI maps on validation stage

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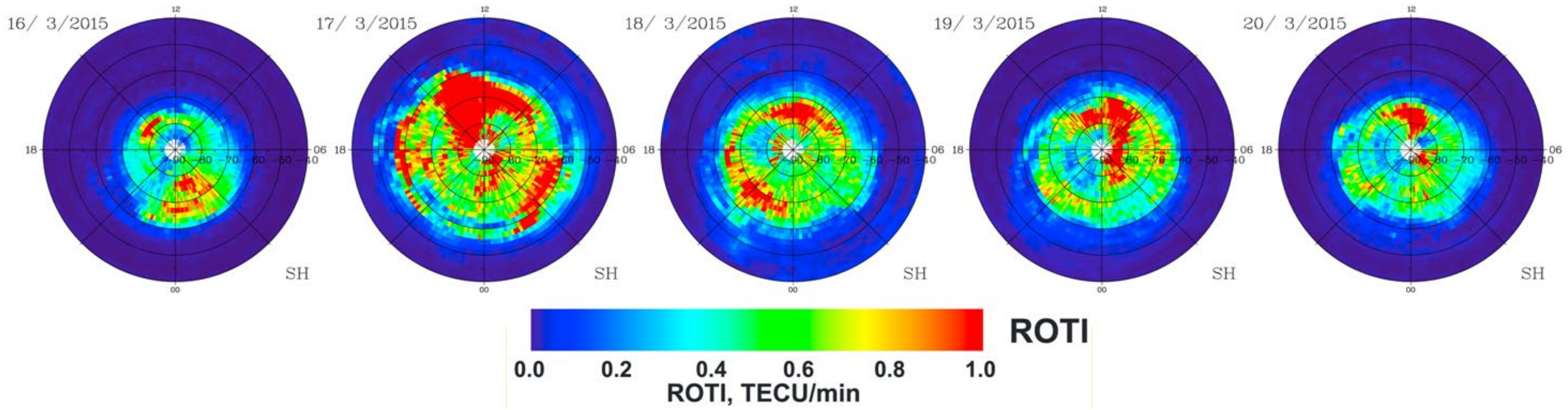
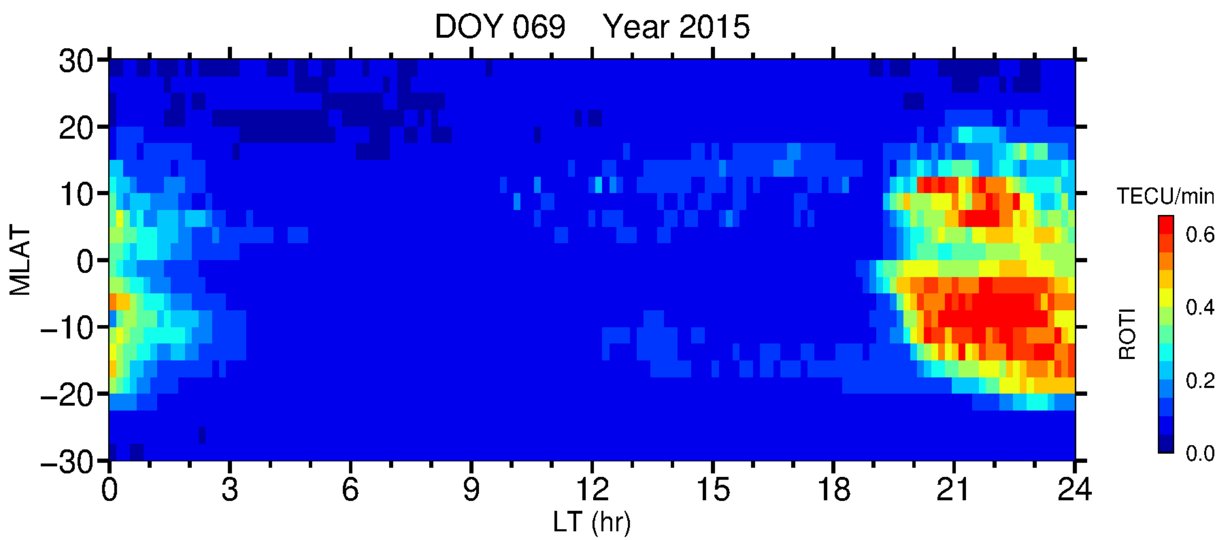
### ROTI Maps for Southern Hemisphere




### 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

```
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

# Towards cooperative global mapping of the ionosphere. Fusion feasibility for IGS and IRI with global climate VTEC maps

- **The climate VTEC maps introduced in 2020** aimed for establishment of an ionosphere mapping service fusing measurements from two independent sensor networks:
  - IGS permanent GNSS receivers providing the vertical total electron content (VTEC) measurements
  - ionosondes of the Global Ionosphere Radio Observatory (GIRO) that compute the bottom-side vertical profiles of the ionospheric plasma density.
- That research established data sources and fusion methodology for the joined purpose of thorough ionosphere mapping. **It has been achieved with inclusion of over 10 years of IGS climate VTEC maps to GAMBIT Database and Explorer**, allowing the fusion with the IRI model and GIRO products.

Adam Froń, Ivan Galkin, Andrzej Krankowski, Dieter Bilitza, Manuel Hernández-Pajares, Bodo Reinisch, Zishen Li, Kacper Kotulak, Irina Zakharenkova, Iurii Cherniak, David Roma Dollase, Ningbo Wang, Paweł Flisek and Alberto García-Rigo, **Towards Cooperative Global Mapping of the Ionosphere: Fusion Feasibility for IGS and IRI with Global Climate VTEC Maps, Remote Sensing. 2020, 12(21), 3531**; doi.: 10.3390/rs12213531

- The **system is now expanded** with inclusion of weather VTEC based on real-time and rapid products of IGS IONO IAACS.

- The real time archive spans back to doy 251/2017. The combined file, aggregating all the real-time data for each day, is published with 1-2 hour latency.

- **At UWM, the real-time IGS VTEC data from IGS/UWM/CAS is gathered every 15 minutes** and then averaged to maintain the conformity with **GAMBIT** 15-minutes temporal resolution and resampled over the 8 deg (LON) x 4 deg (LAT) resolution of NASA WorldWind convention.

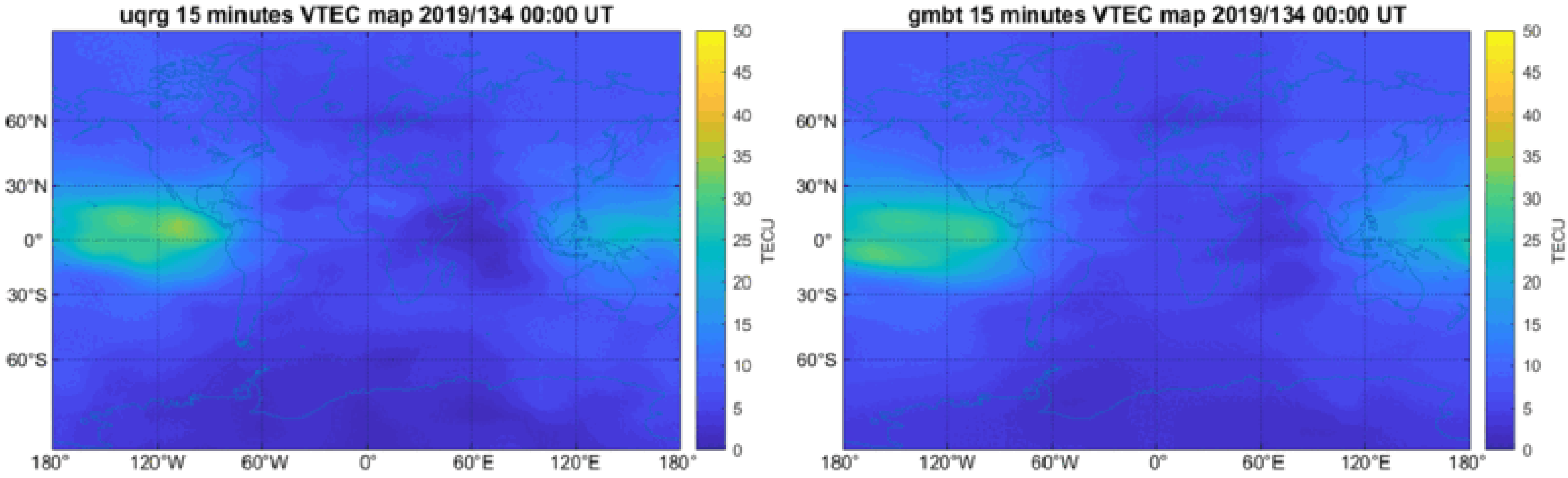
- **Produced maps are stored at the same time in separate one-epoch IONEX files** and appended IONEX file containing all the maps produced since 0:00 UT. The aggregated IONEX file is then valid in the GAMBIT database until IGS rapid file for the selected day is published at CDDIS.

- **The presented data delivery scheme is meant to create an elastic system**, that will allow including additional products in order to improve the GAMBIT VTEC products provided by IGS. The climate and rapid maps are both based on IGS rapid UQRG maps, hence their conformity should be on a satisfying level, well depicting any unforeseen disturbances of the ionosphere.

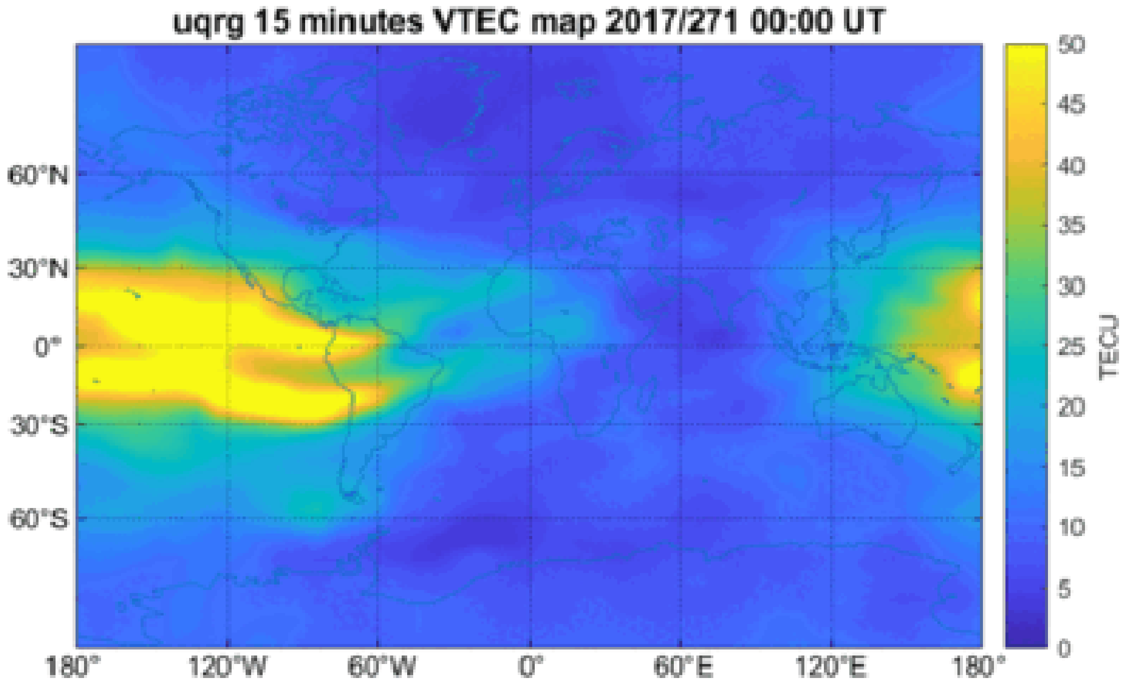
Ivan Galkin, Adam Froń, Bodo Reinisch, Manuel Hernández-Pajares, Andrzej Krankowski, Bruno Nava, Dieter Bilitza, Kacper Kotulak, Paweł Flisek, Zishen Li, Ningbo Wang, David Roma Dollase, Alberto García-Rigo and Inez Batista, Global **Monitoring of Ionospheric Weather by GIRO and GNSS Data Fusion, Atmosphere 2022, 13(3), 371**; doi.: 10.3390/atmos13030371

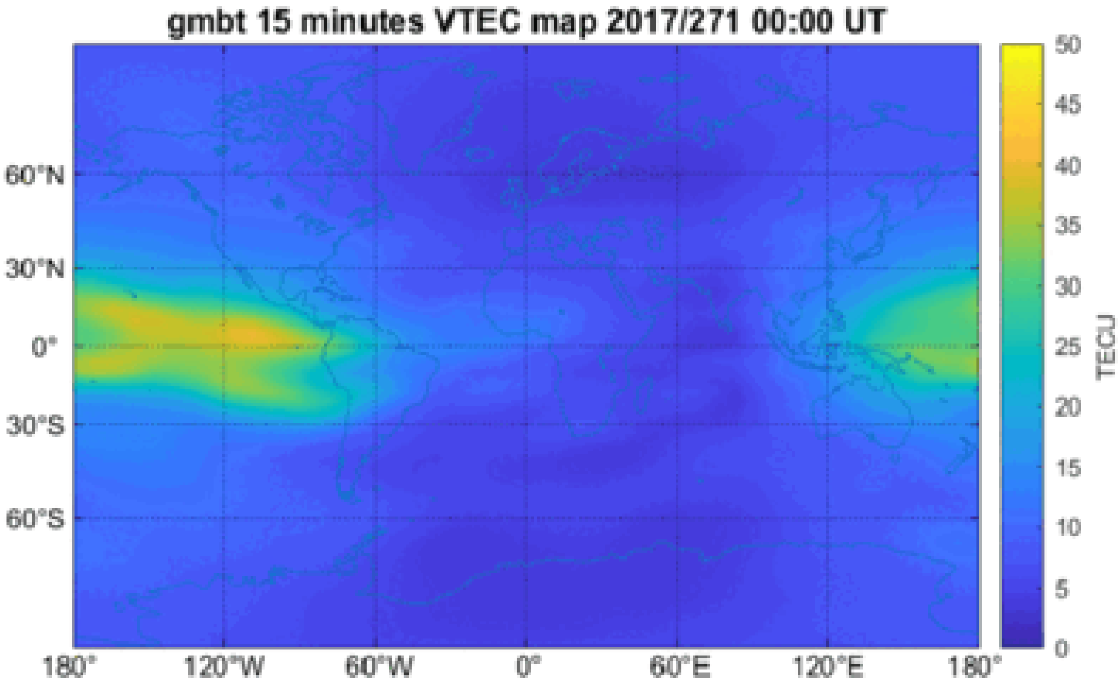
IGS INTERNATIONAL GNSS SERVICE

# Comparison between IGS UQRG-based weather (rapid) and climate VTEC product for GAMBIT system (quiet day):

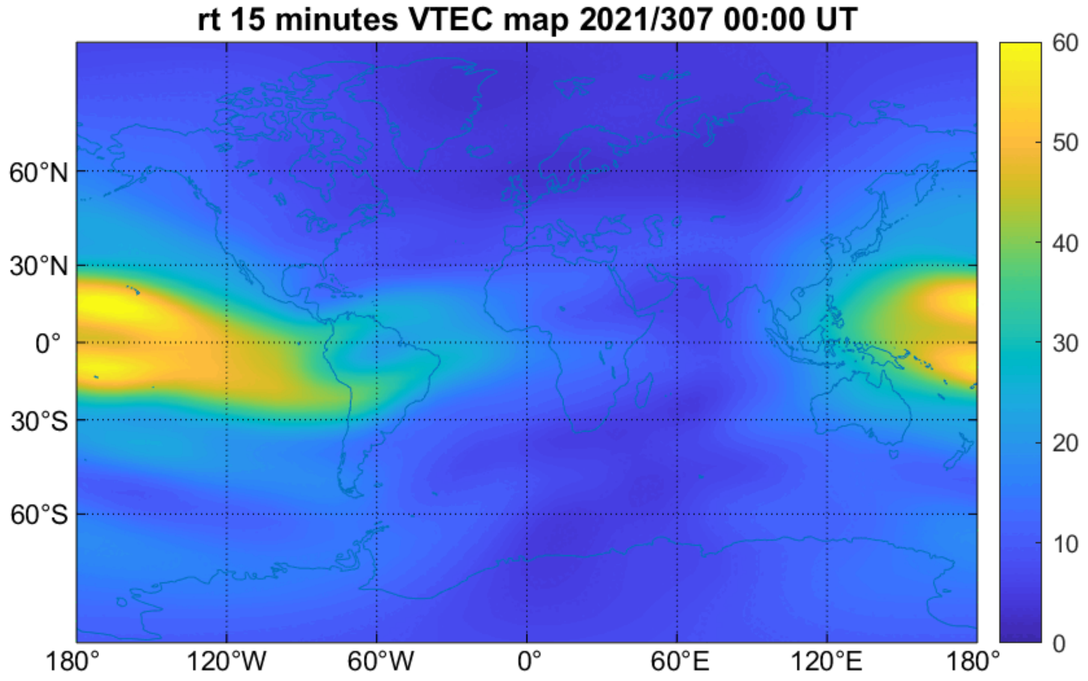


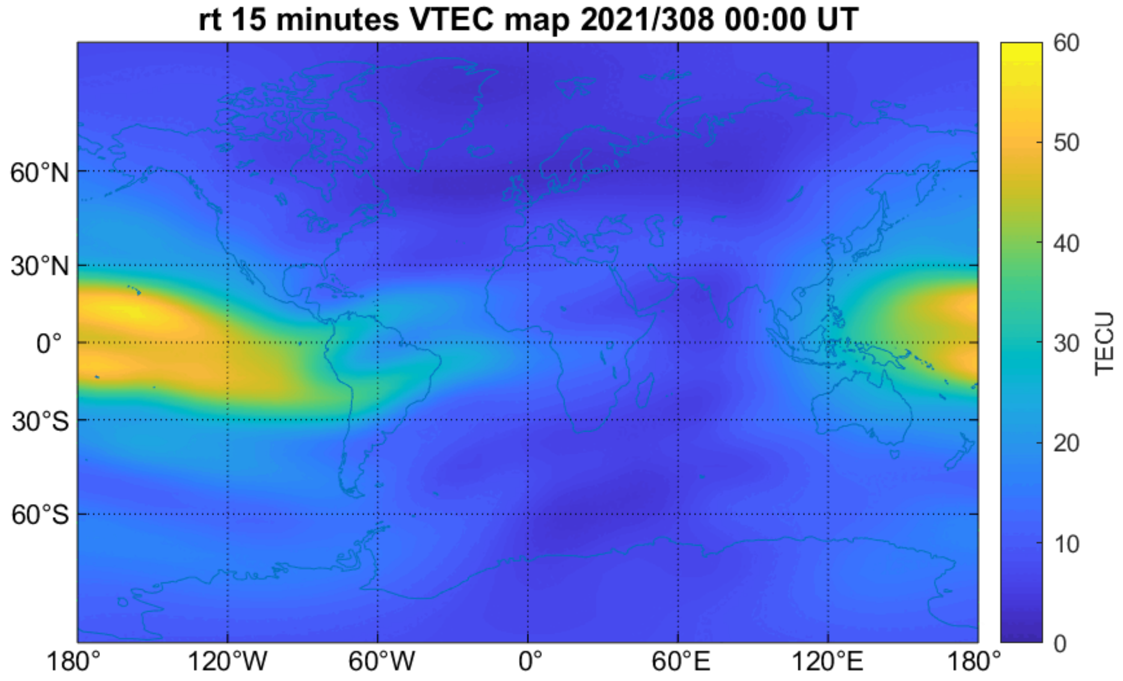
## Comparison between IGS UQRG-based weather (rapid) and climate VTEC product for GAMBIT system (disturbed day):

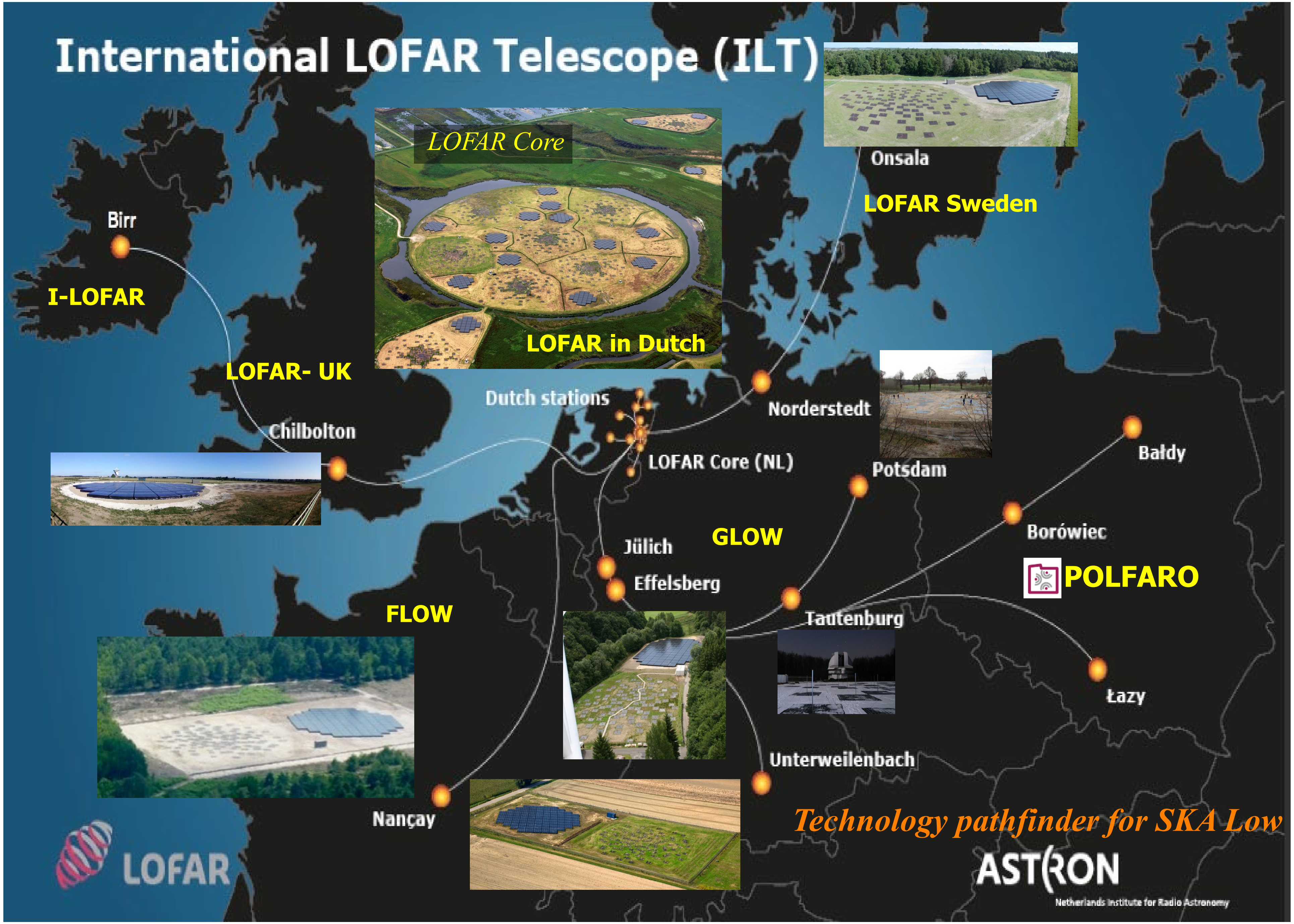


# Examples of IGS UWM/CAS real-time VTEC maps for GAMBIT system:



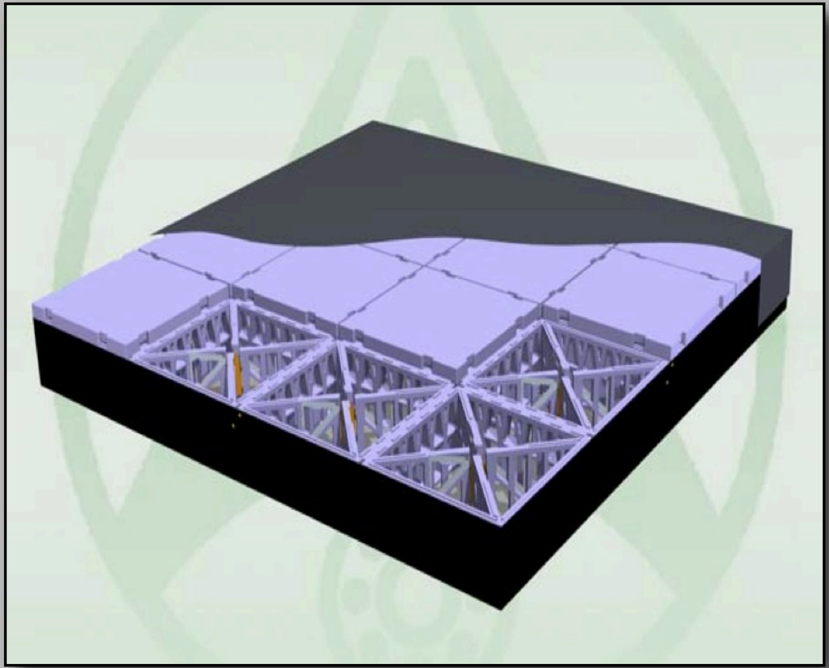




International LOFAR Telescope (ILT)
LOFAR Core
LOFAR in Dutch
Onsala
LOFAR Sweden
Birr
I-LOFAR
LOFAR- UK
Chilbolton
Dutch stations
LOFAR Core (NL)
Norderstedt
Potsdam
Bałdy
Borówiec
POLFARO
GLOW
Jülich
Effelsberg
Tautenburg
Łazy
FLOW
Unterweilenbach
Nançay
Technology pathfinder for SKA Low
LOFAR
ASTRON
Netherlands Institute for Radio Astronomy

# LOFAR Antennas

Low band antenna: 30 – 80 MHz
48/96 antennas per station

High band tiles:120 – 240 MHz
48/96 tiles/station, 4x4 antennas/tile

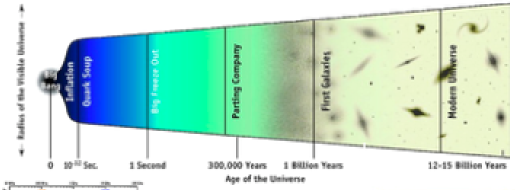


38 NL + 13 EU stations of dipoles
Replace big dishes by many cheap dipoles
No moving parts: electronic beam steering
Flexible digital beam forming

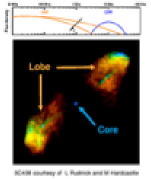
**Technology pathfinder for Square Kilometre Array**

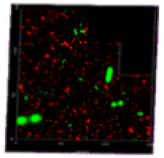
# LOFAR - The Key Science Projects

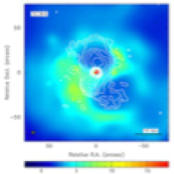
Epoch of Reionisation

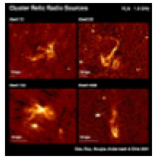



Surveys



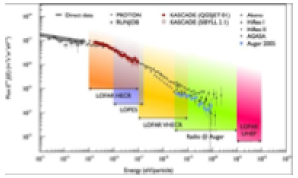



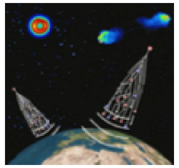




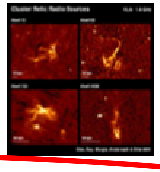
Transients

Cosmic Rays

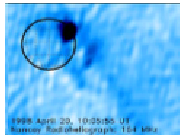


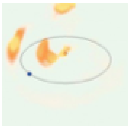


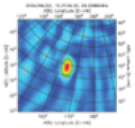
Magnetism



**Sun, Space Weather**





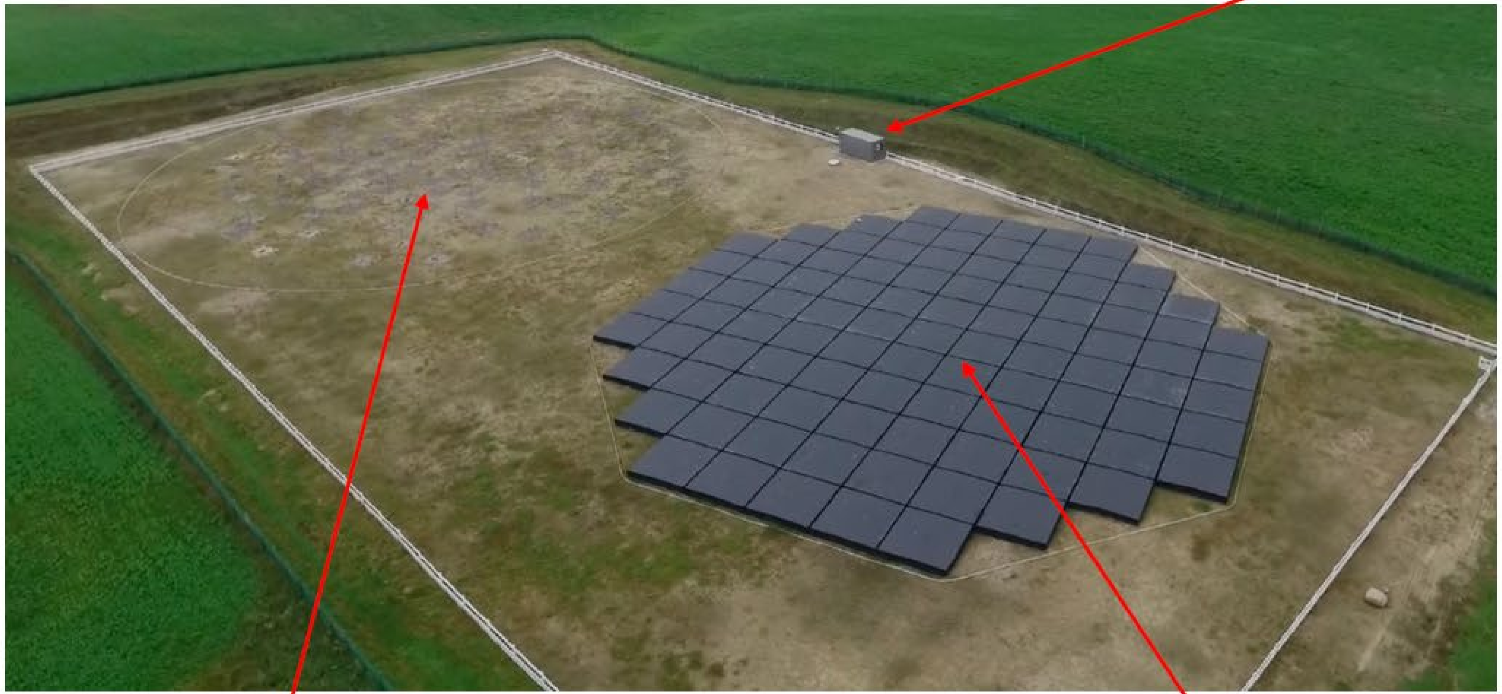


# About LOFAR

## International LOFAR station in Bałdy (PL612)

**How does LOFAR look?**

**Container**



**LBA**

**HBA**

**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

# 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)

# Monitoring of Sun and scintillations

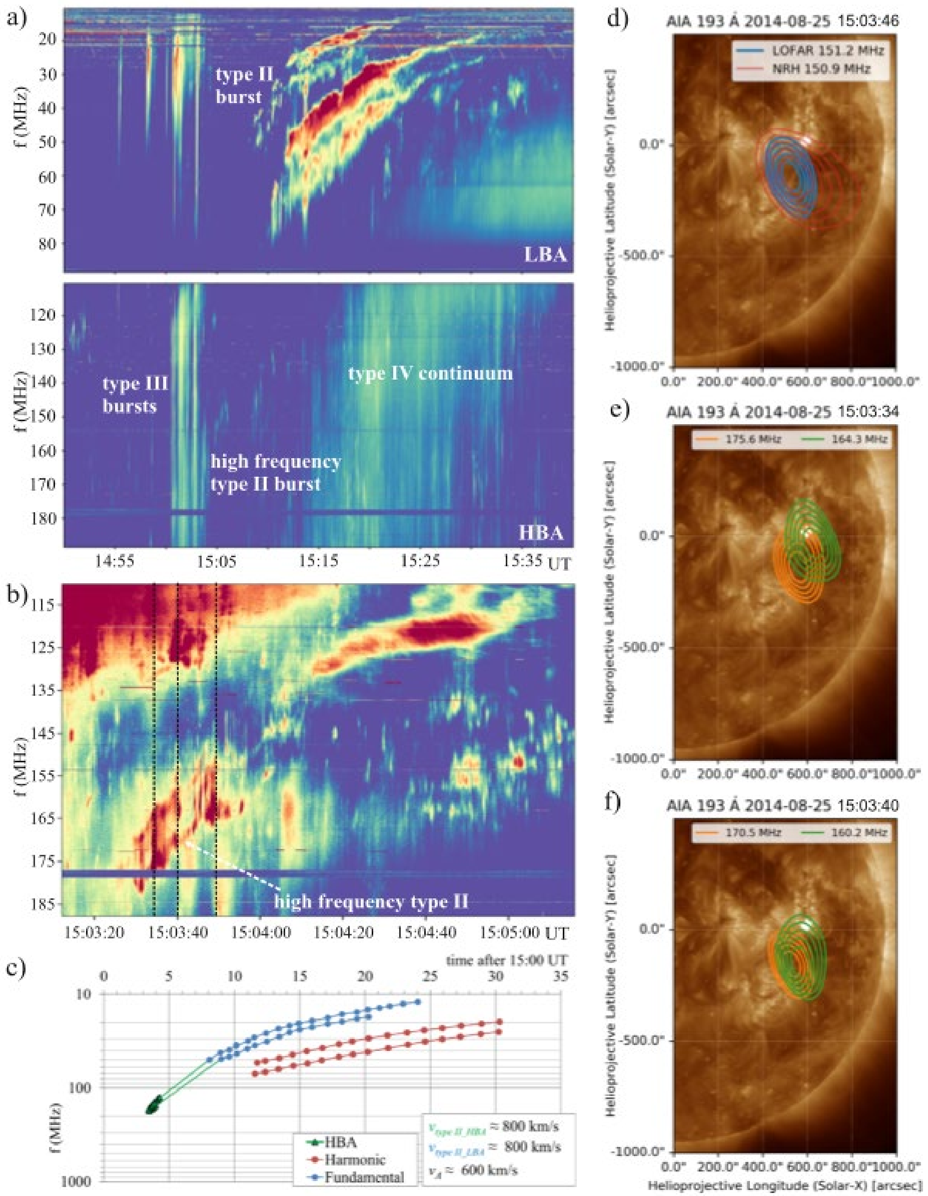


Figure 1. (a) Dynamic spectrum with reduced time/frequency resolutions of the radio event on 2014 August 25. (b) Detail of the high-frequency component of the type II burst in the HBA observation. (c) Kinematics of the type II radio burst. (d) Comparison of LOFAR and NRH images of the high-frequency type II sources. Radio sources are overlaid using images taken the closest together in time 193 Å. (e) and (f) Images of two pairs of simultaneous sources of the high-frequency type II band-split.

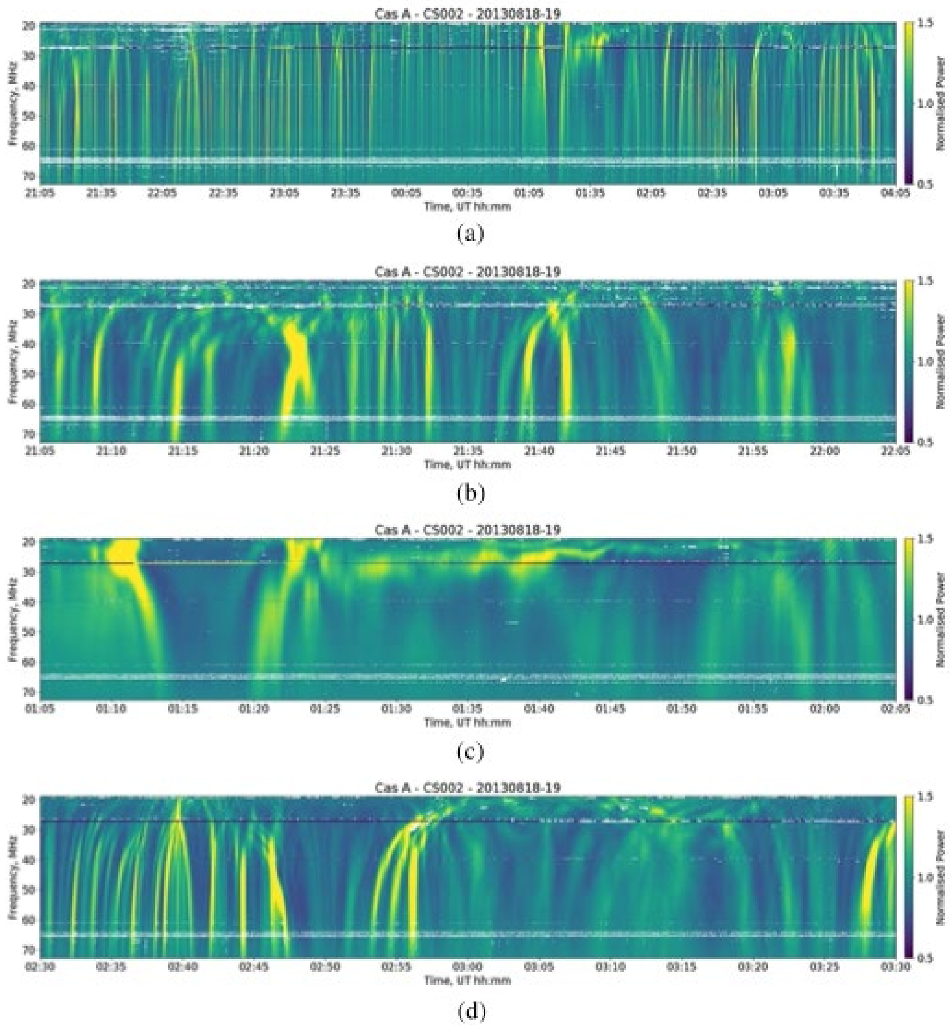
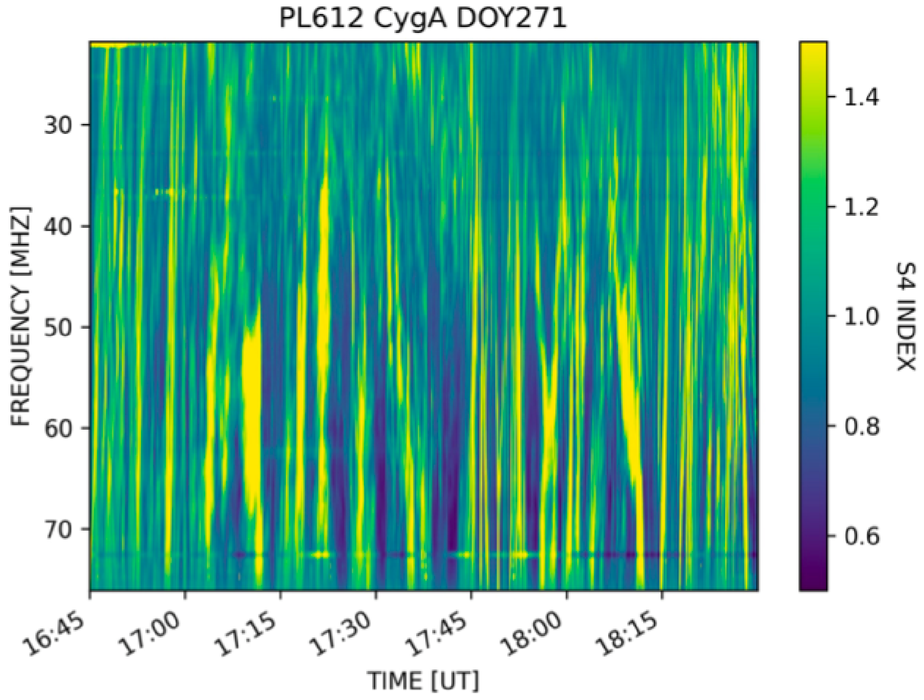


Fig. 2. Dynamic spectra of normalised intensity data taken by LOFAR station CS002 during the observation of Cas A on 18–19 August 2013. The dynamic spectrum of the entire observing period is given at the top, with zooms into three different hours of observation below to illustrate the range of conditions seen. White areas within the plots indicate where RFI was identified.

POLFAR

# 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

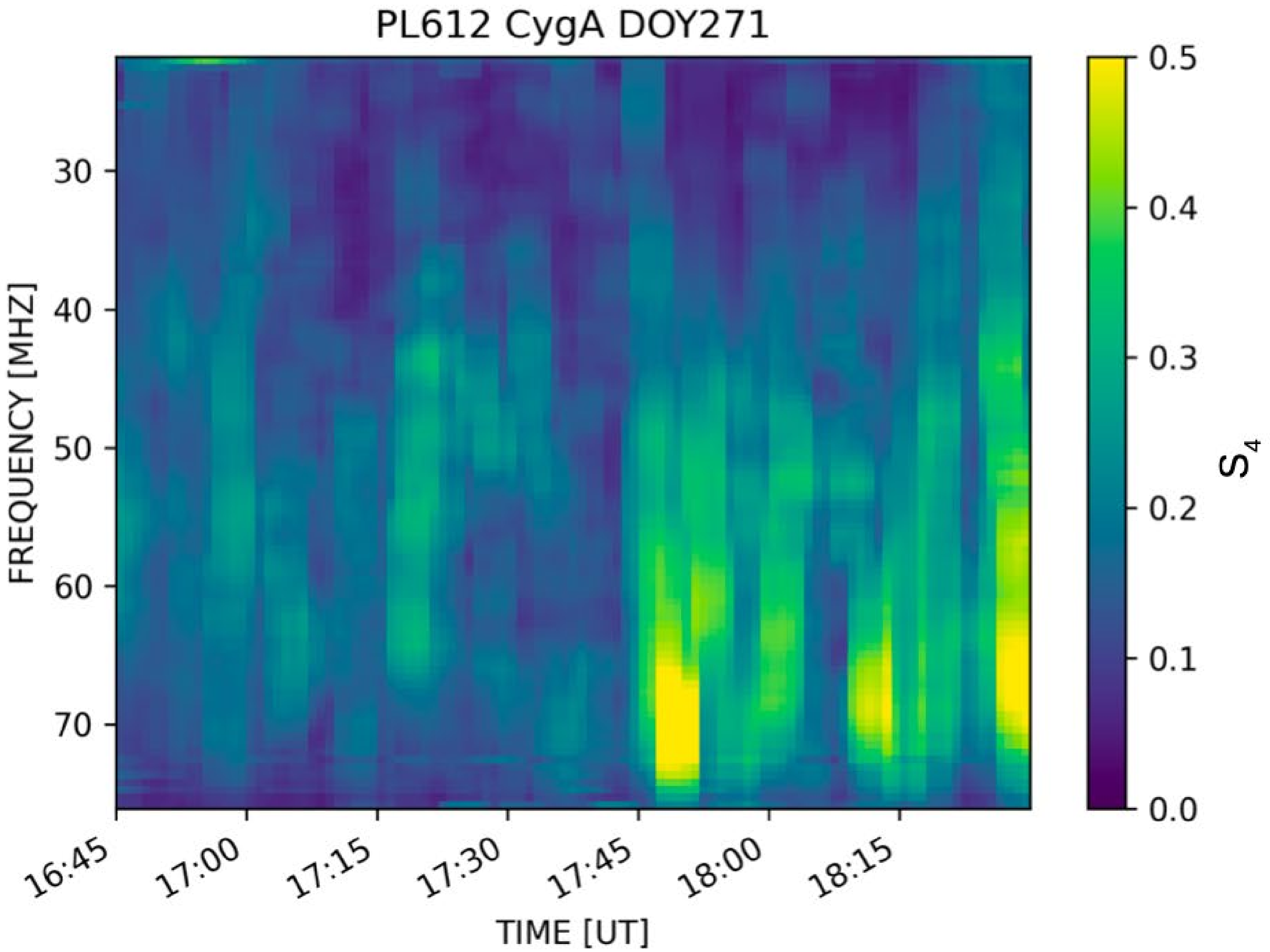
$\langle \; \rangle$ temporal averaging in lieu of ensemble averaging

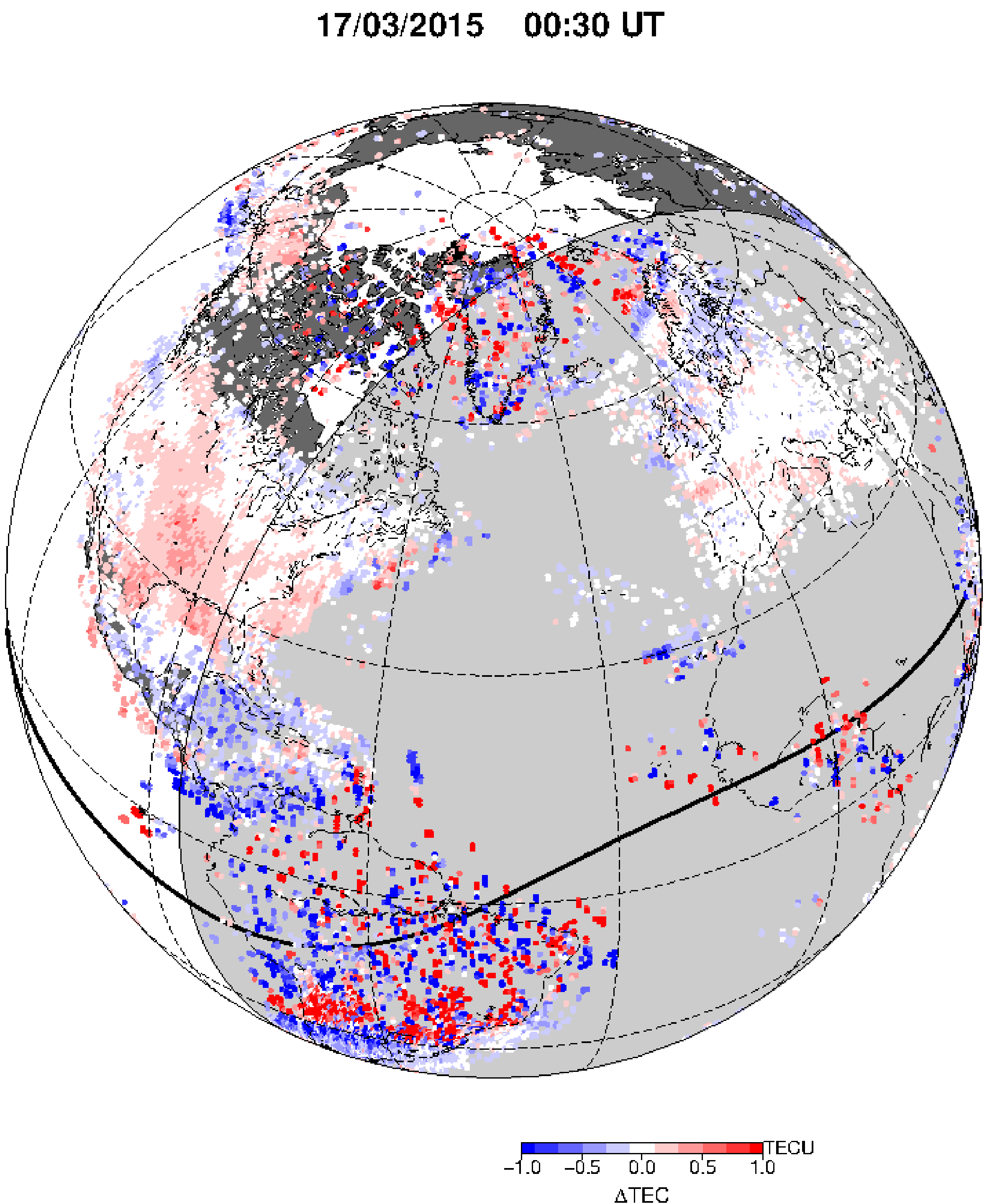
was estimated for GNSS L1 & L2 by means of a GNSS scintillation monitor (over 1 minute intervals)

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

# Example: DOY271 2017

LOFAR scintillation index estimated over various VHF radio-wave frequencies





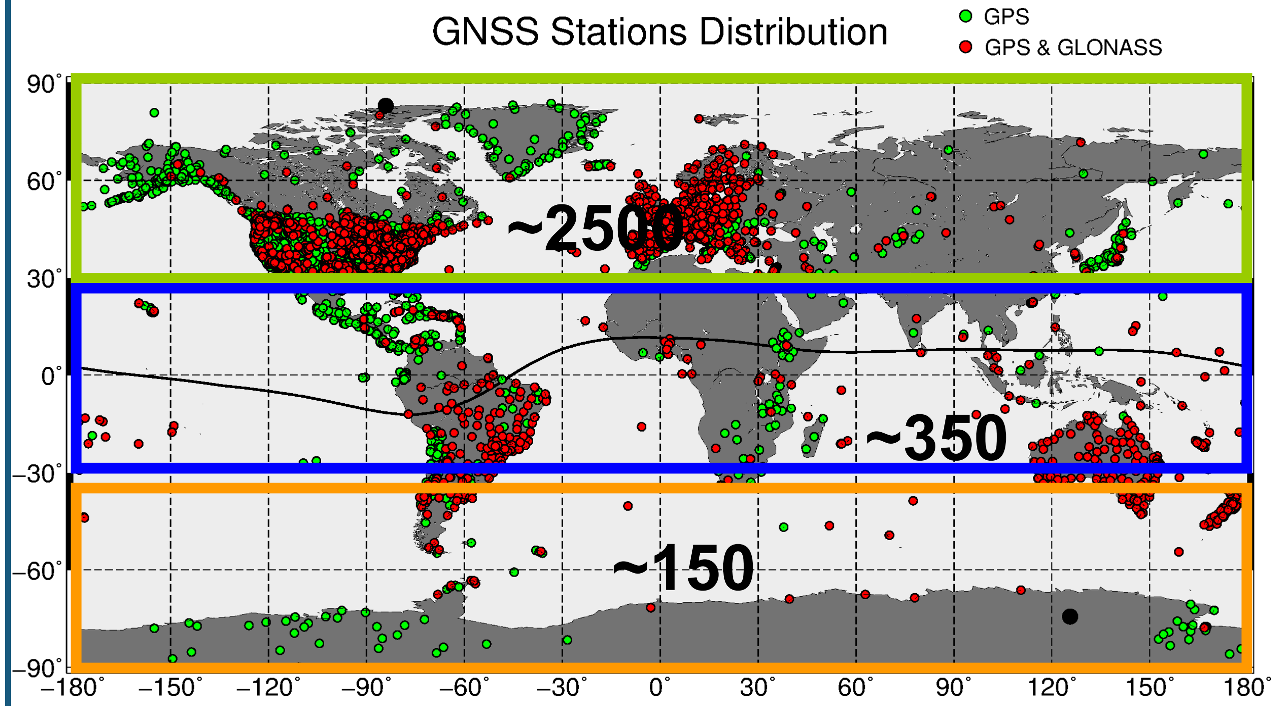

## Case of 2015 St. Patrick's Day storm

- ~ 5300 stations
  ~2000 multi-GNSS stations
  (GPS + GLONASS+GALILEO+BEIDOU)
- TEC maps with
  time resolution 10 min

Zakharenkova et al, JGR, 2016

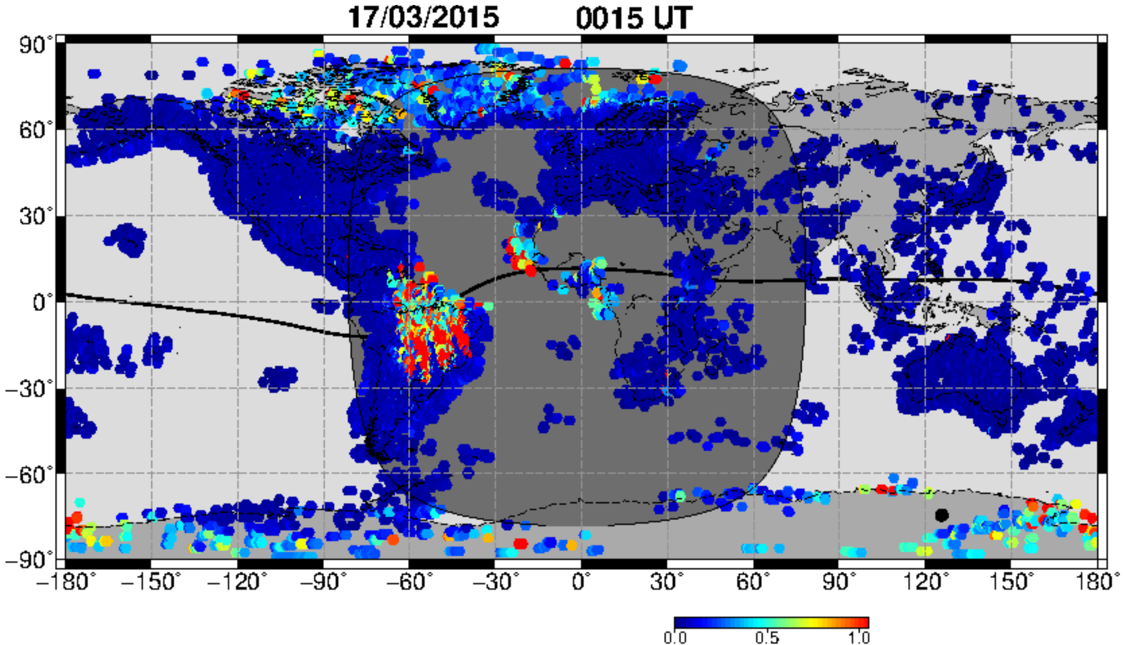
# IGS ROTI Maps extension toward Southern Hemisphere and low latitudes

## Main chalange – non uniform global distribution of permanent GNSS stations

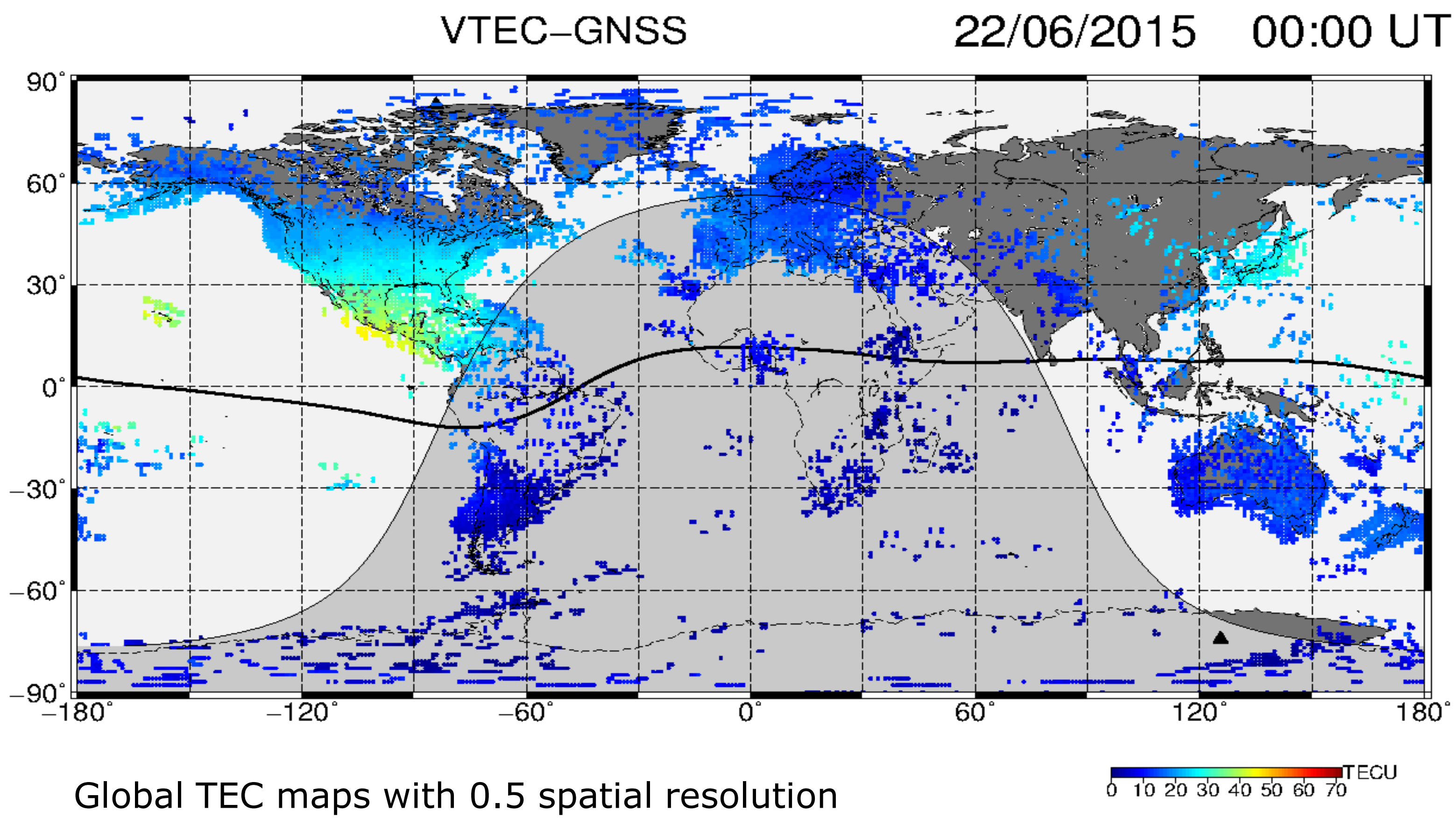



**Case of 2015 St. Patrick's Day storm**

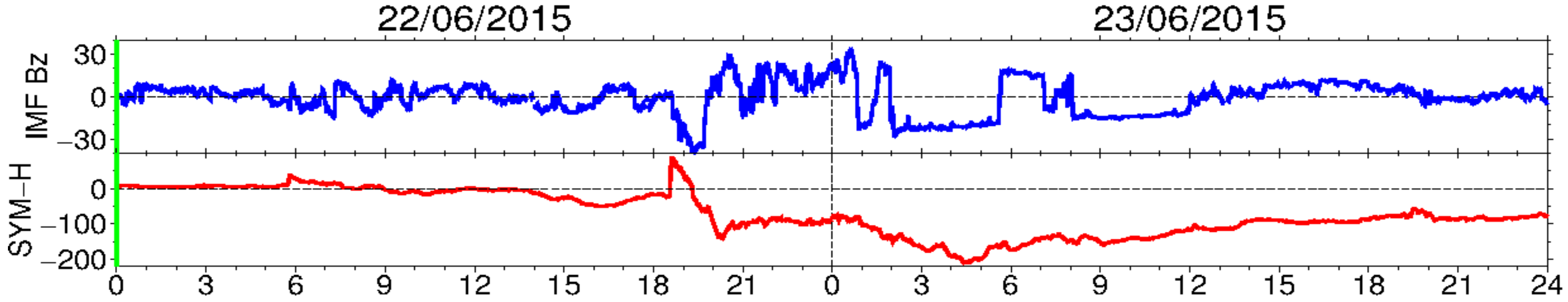
- ~ 5300 stations
  ~2000 multi-GNSS stations
  (GPS + GLONASS+GALILEO+BEIDOU)
- ROTI maps with
  time resolution 15 min
  spatial resolution 2 x 2 degree



# Global GNSS TEC maps - 22-23 June 2015 storm

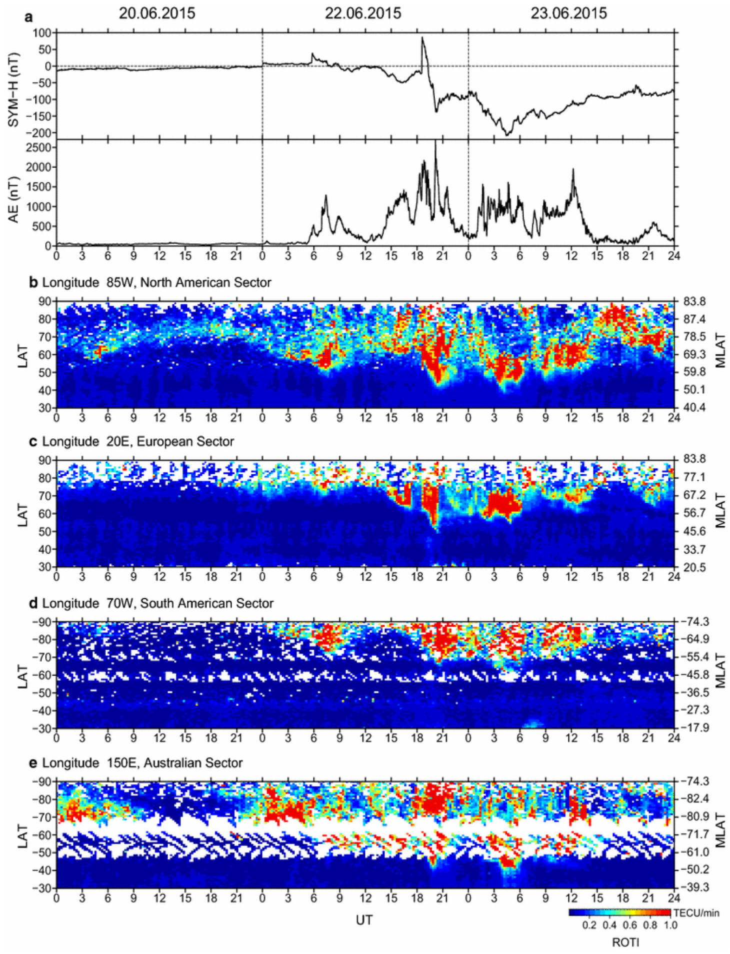



Global TEC maps with 0.5 spatial resolution

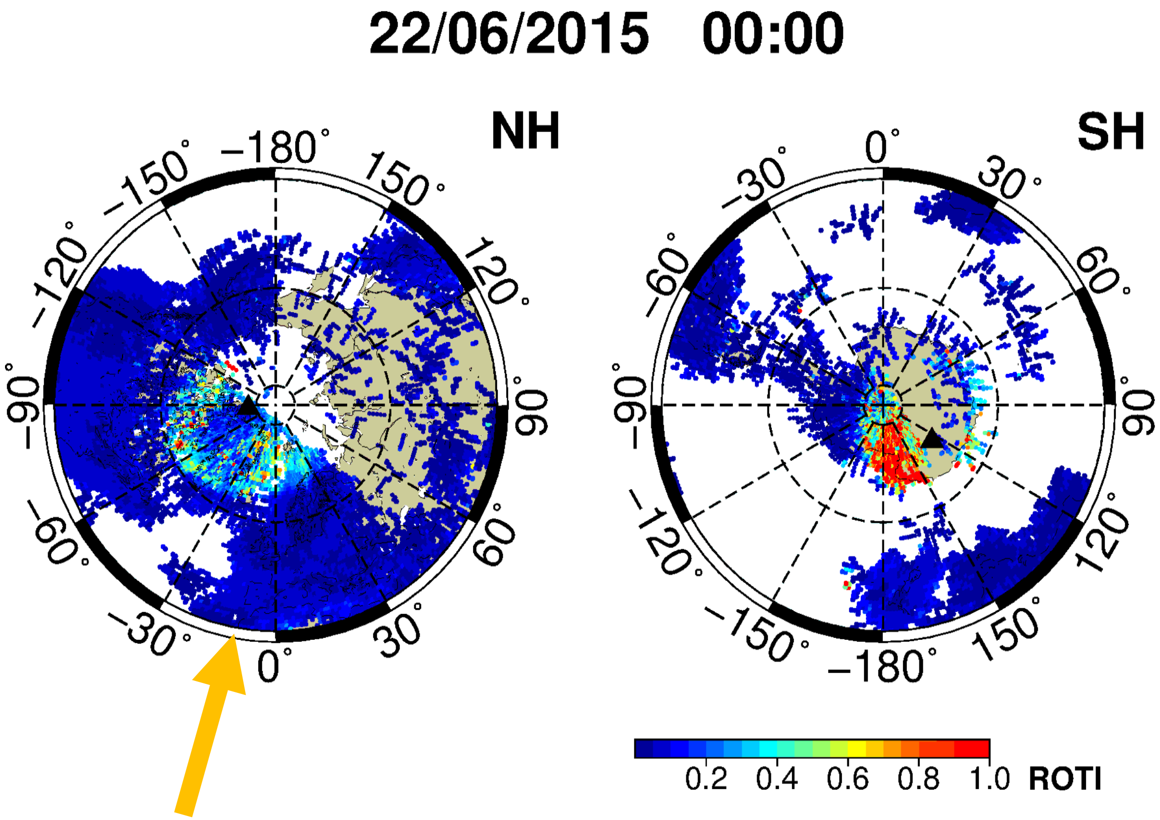



Space Radio-diagnostics Research Centre

# Storm-induced plasma bubbles at midlatitudes



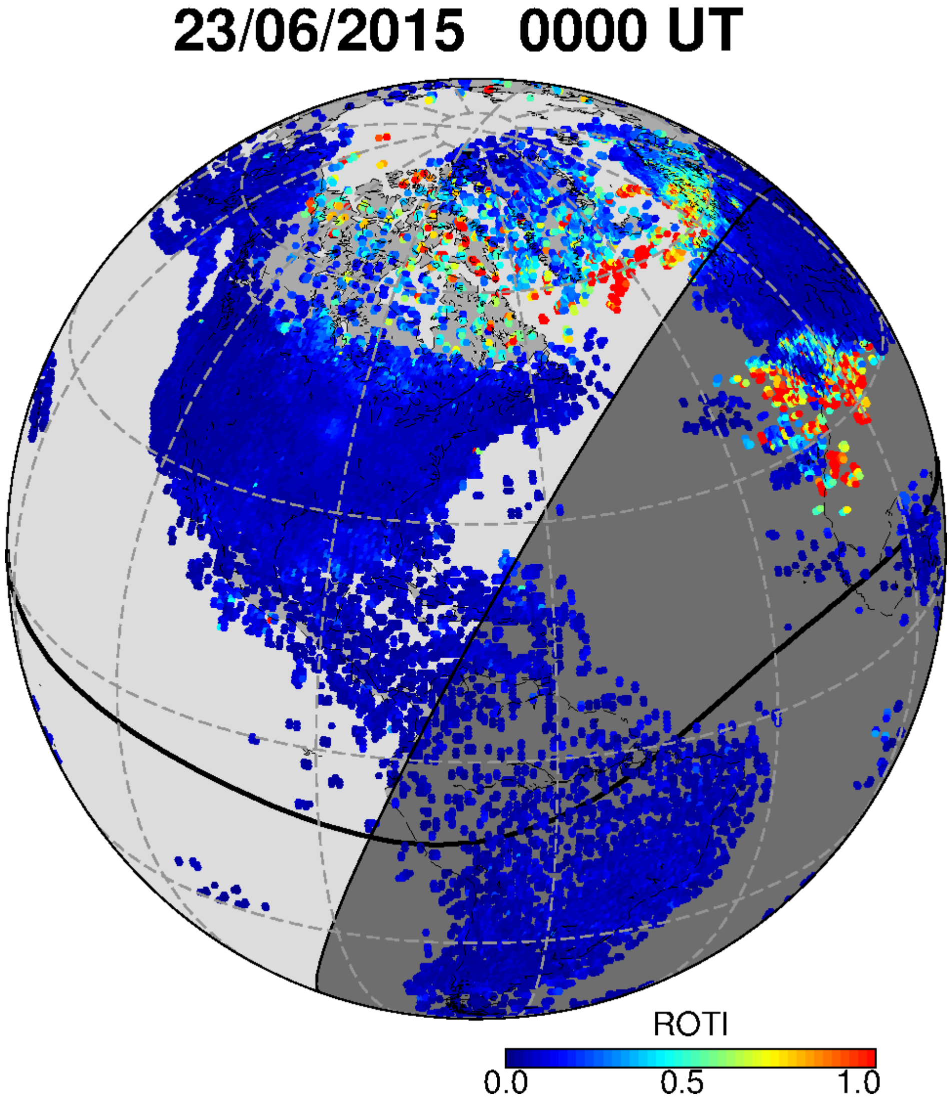
## June 2015 geomagnetic storm

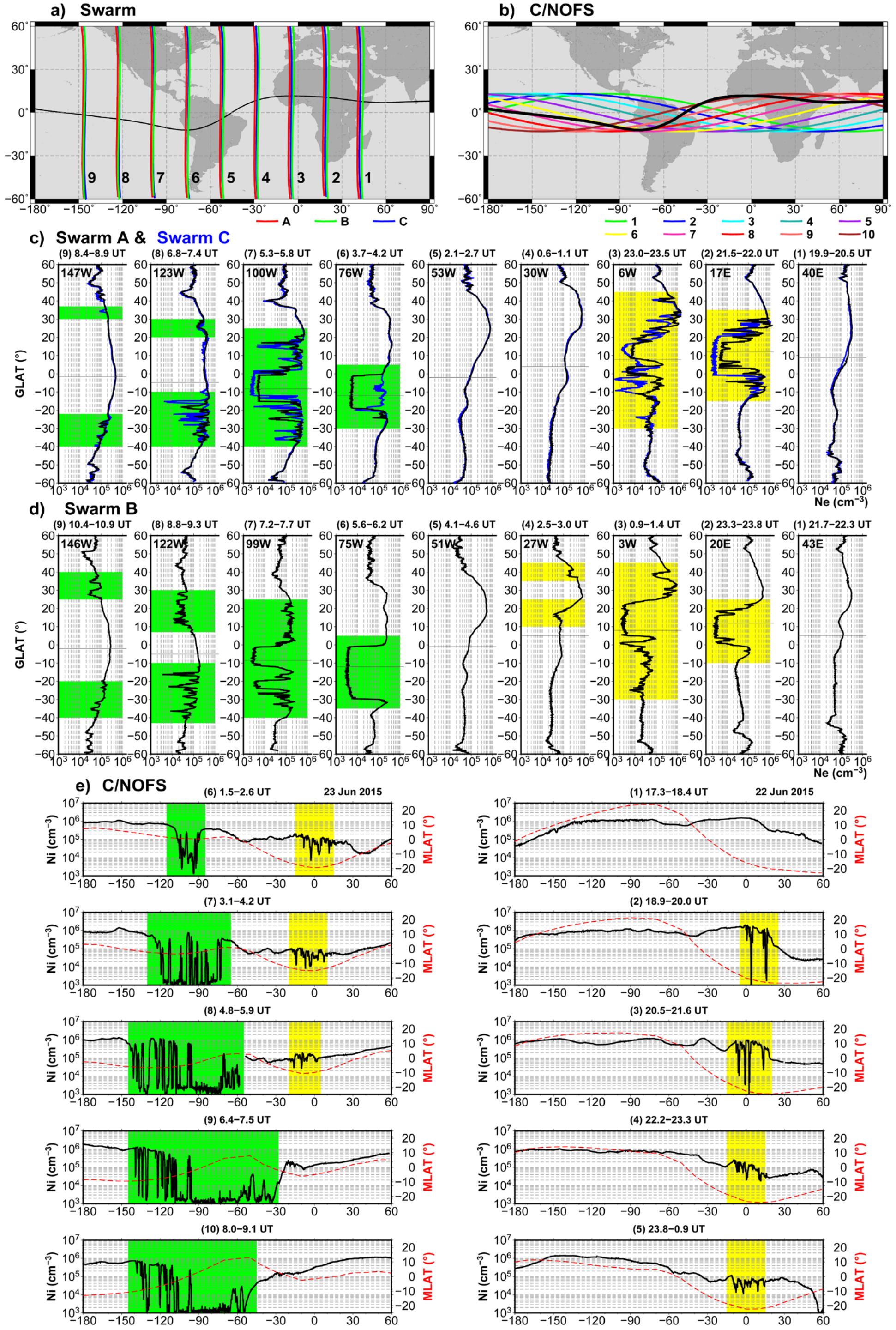



Combined ground based GPS and GLONASS observations

CDRŚK/UWM ionospheric monitoring

## Storm-induced plasma bubbles at midlatitudes




**Multi sensor concept for ionospheric irregularities study**

Cherniak et al, JGR, 2019



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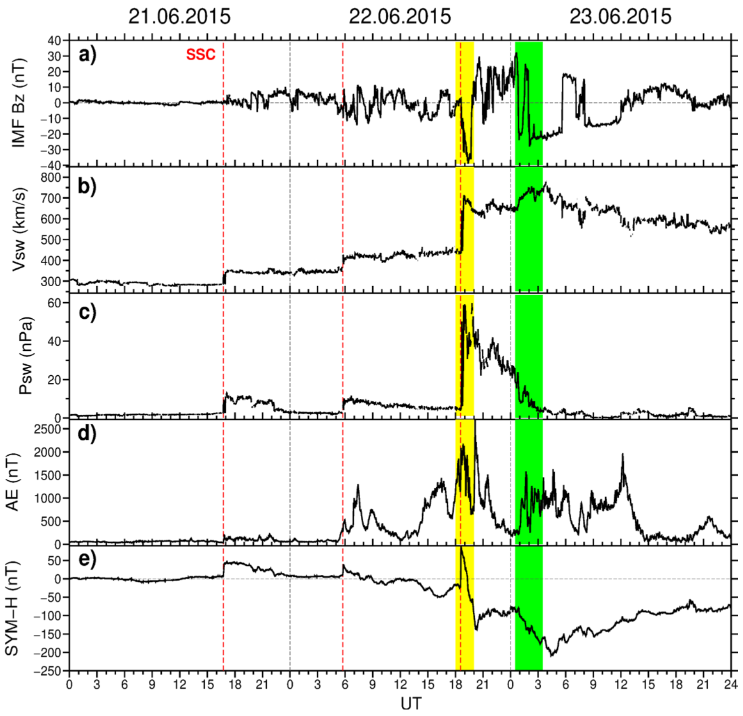
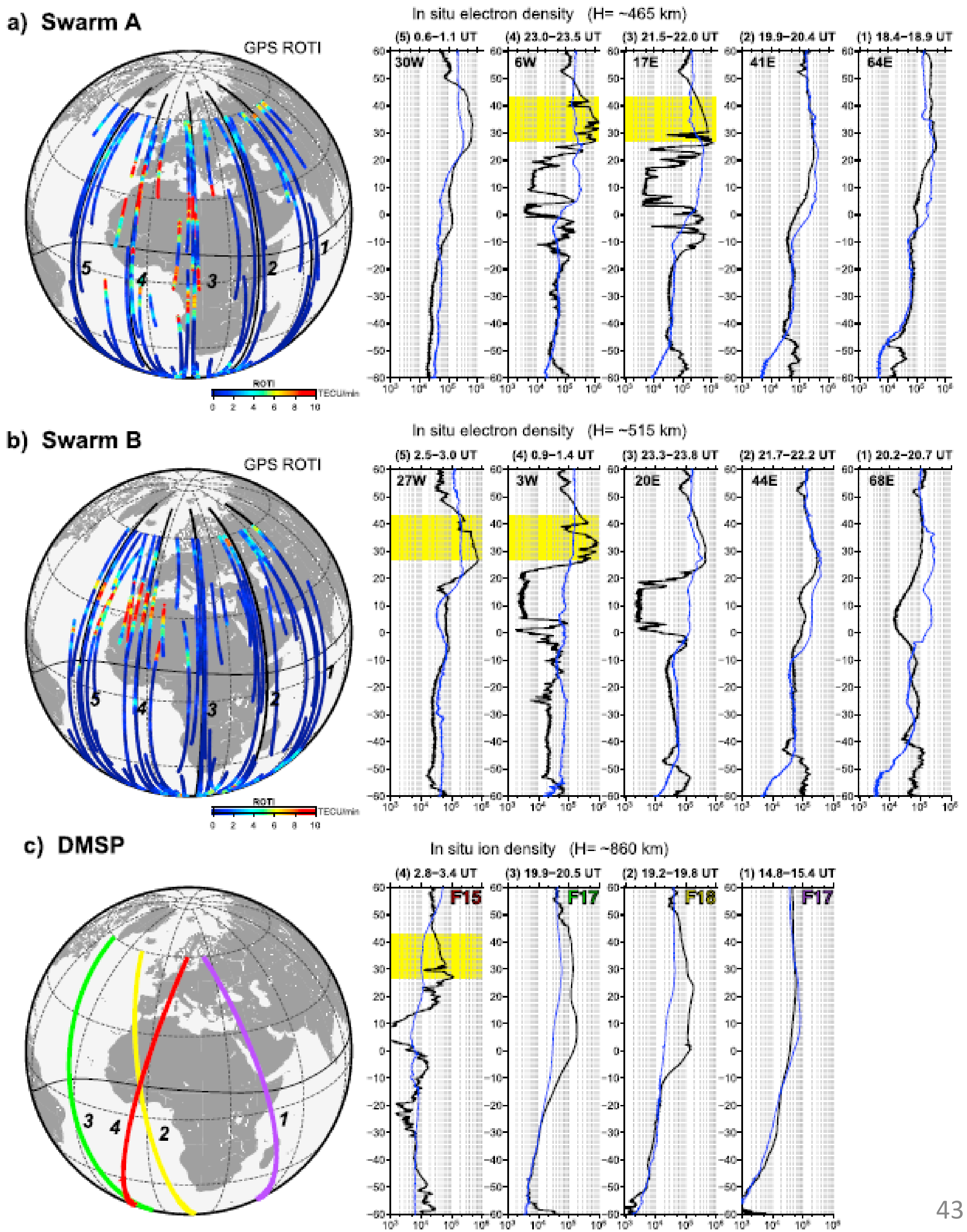
## Storm-induced plasma bubbles at midlatitudes

### June 2015 geomagnetic storm




Plasma bubbles signatures in spaceborne GPS ROTI and Ne from Swarm satellites passes and DMSP in situ ion density.

Cherniak&Zakharenkova, GRL, 2016

SRRC
Space Radio-diagnostics Research Centre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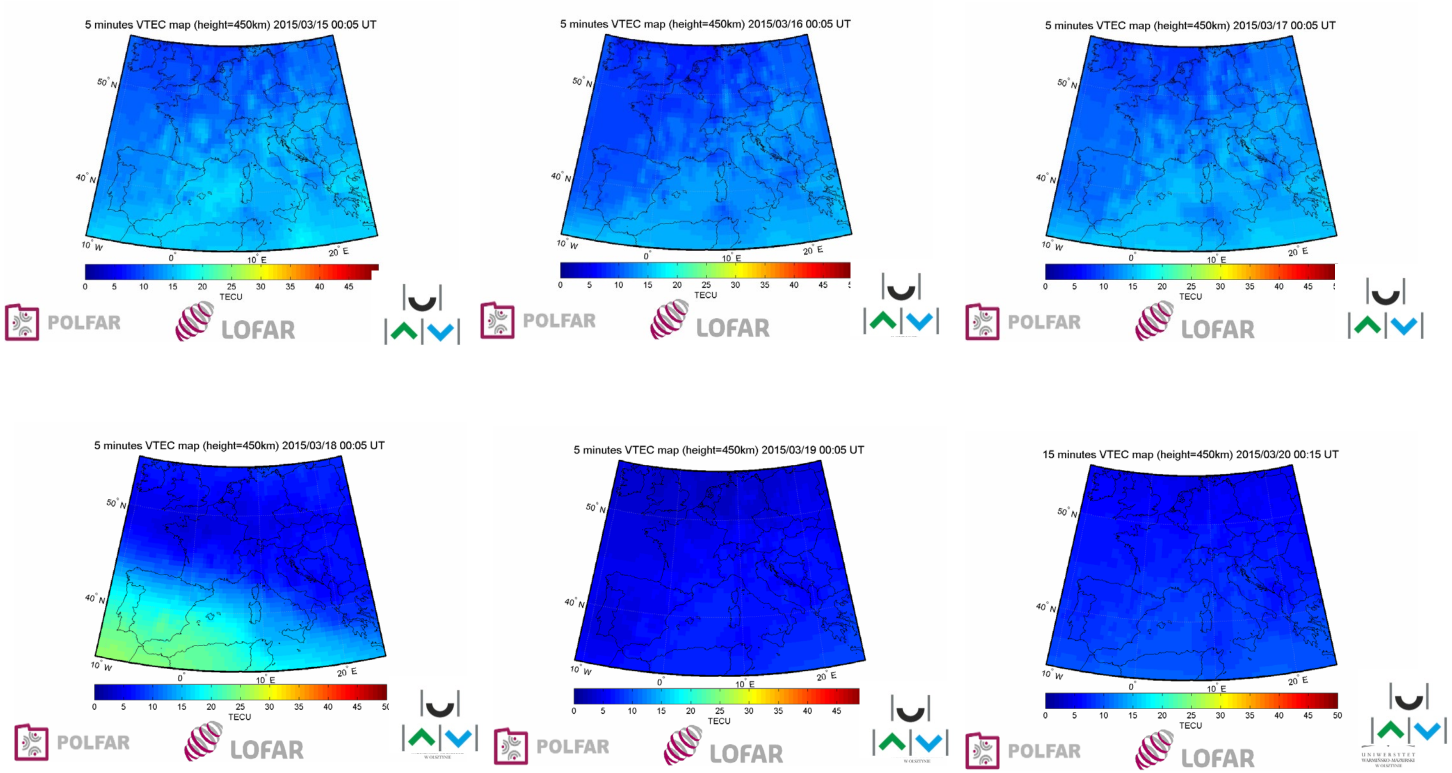
# 5-minute European TEC maps

## 2015-03-15 - 2015-03-20



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# Thank You!

**Contact:**

Andrzej Krankowski

kand@uwm.edu.pl

UNIWERSYTET WARMIŃSKO-MAZURSKI W OLSZTYNIE

INTERNATIONAL REFERENCE IONOSPHERE

U.R.S.I.

COSPAR COMMITTEE ON SPACE RESEARCH