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Current performance of IGS ionospheric products and future improvements

Andrzej Krankowski [1], Manuel Hernandez-Pajares [2], Zishen Li [3], Ningbo Wang [3], Kacper Kotulak [1], Irina Zakharenkova [1], Iurii Cherniak [1], Adam Froń [1], Paweł Flisek [1], Alberto Garcia-Rigo [2]

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UNIWERSYTET WARMIŃSKO-MAZURSKI W OLSZTYNIE

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

AIR

UNITED NATIONS Office for Outer Space Affairs

ICG International Committee on Global Navigation Satellite Systems

United Nations/Azerbaijan Workshop on the International Space Weather Initiative:
The Sun, Space Weather and Geosphere

Organised jointly by The United Nations Office for Outer Space Affairs and The Baku State University on behalf of the Government of Azerbaijan; Co-organized and co-sponsored by The International Committee on Global Navigation Satellite Systems and The National Aeronautics and Space Administration, United States of America

The Baku State University 31 October – 4 November 2022 Baku, Azerbaijan

Outline

1. Overview of the IonoWG

- Examples of IGS Ionospheric products
- A list of key technical items to be discussed by IonoWG
- 2022 IGS Virtual Workshop IonoWG Recommendations

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

3. IGS IGS ROTI maps. Current Status and its extension towards equatorial region and southern hemisphere

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

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

6. Summary

Overview of the IonoWG

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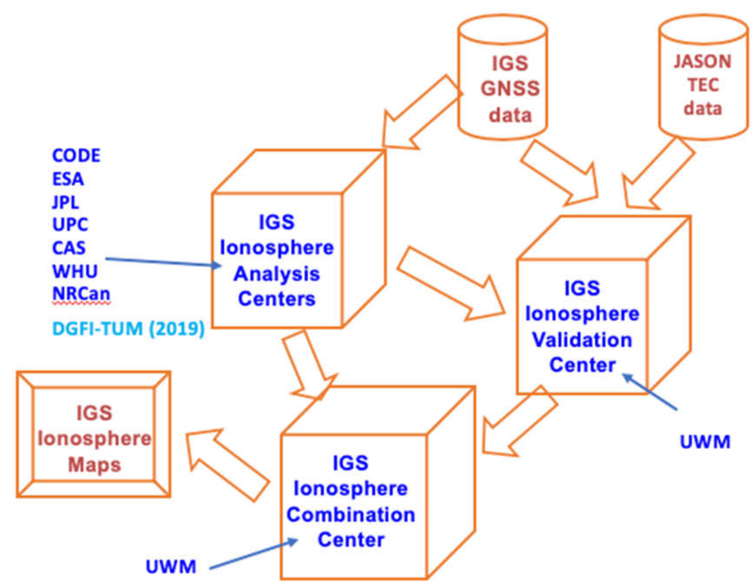
The IGS Ionosphere Working group started its activities in June 1998 with the main goal of a routinely producing IGS Global TEC maps.

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:

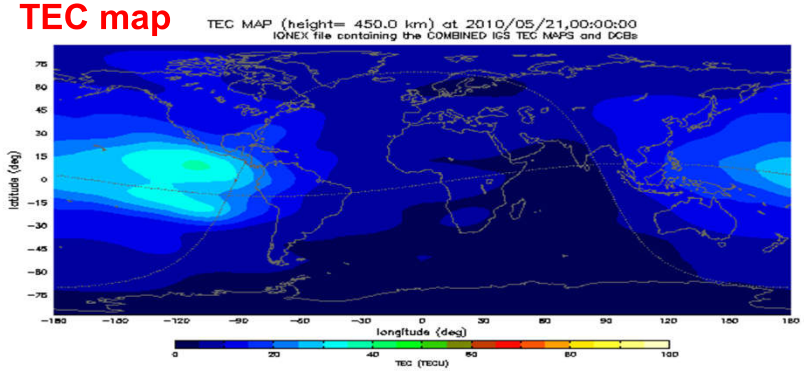
1. Dr Joachim Feltens, ESA 1998–2002,
2. Prof. Manuel Hernández-Pajares, UPC, 2002–2007
3. Prof. Andrzej Krankowski, UWM, 2008-

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.

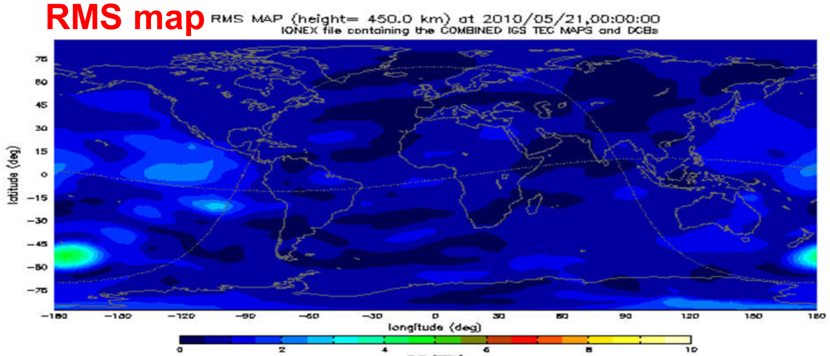


Example of IGS Final GIM: 2010-141 DOY

TEC map



RMS map

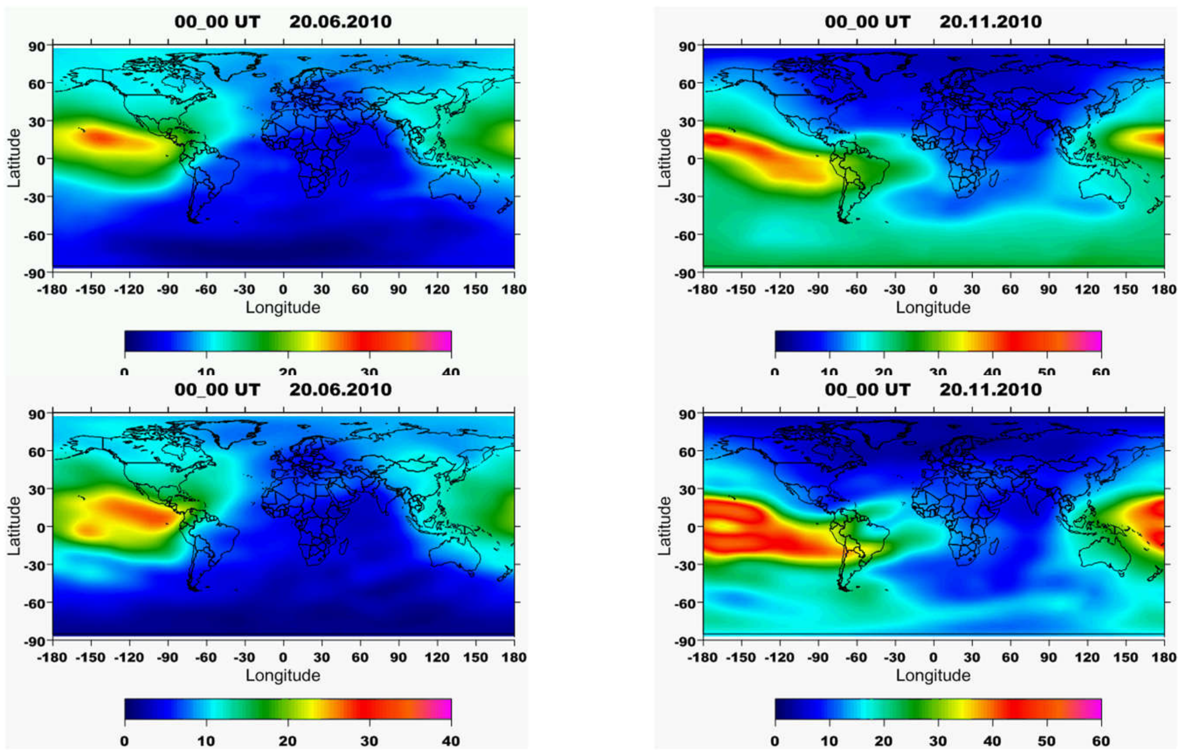


8 Analysis Centers: CODE, ESA, JPL, UPC, WHU, CAS, NRCan, DGFI-TUM (since 2019) and a Validation Center (UWM) have been providing maps (at 2 hours x 5 deg. x 2.5 deg in UT x Lon. x Lat.), weights and external (altimetry-derived) TEC data.

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.

Example of IGS PREDICTED GIM

June 20, 2010 | November 20, 2010

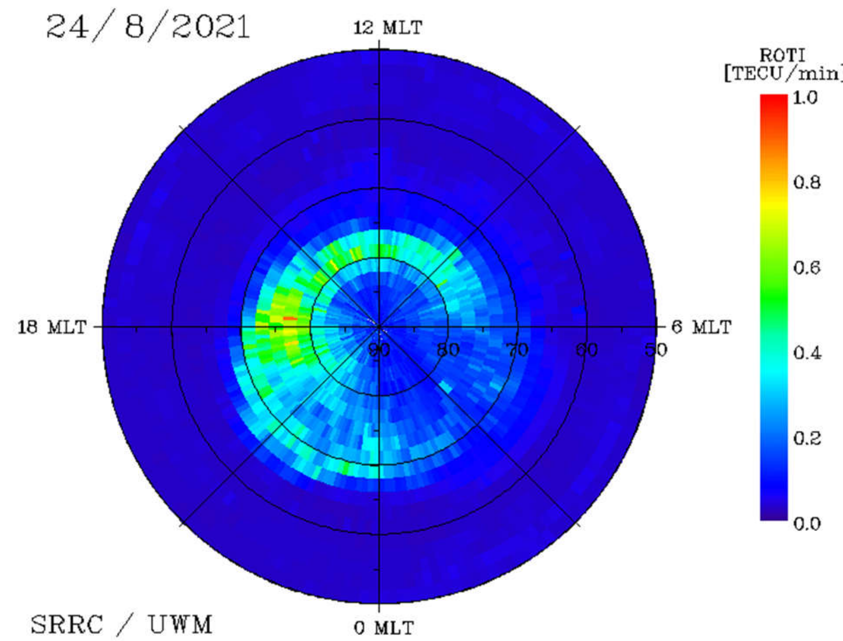


IGS Predicted GIM

IGS Final GIM

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
- 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



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

The activity has signifficant group of geophyical users interrested in.

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**

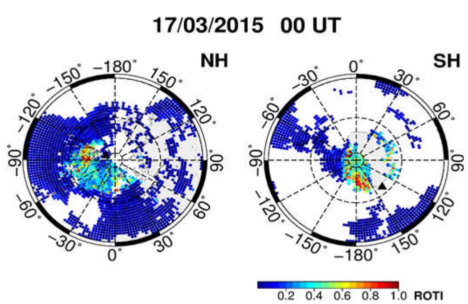
Iurii Cherniak, Andrzej Krankowski, Irina Zakharenkova, ROTI Maps: a new IGS ionospheric product characterizing the ionospheric irregularities occurrence, **GPS Solutions**, 22, 69, **2018**, doi.: 10.1007/s10291-018-0730-1

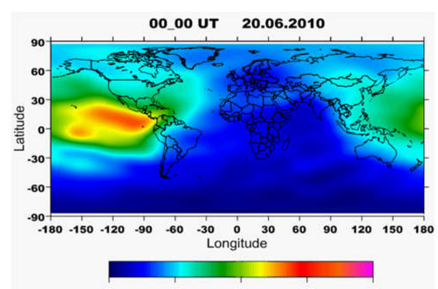
2022 IGS Virtual Workshop Recommendations

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

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.**





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

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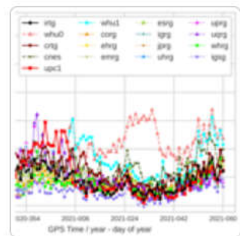
More details about IGS RT-GIM

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

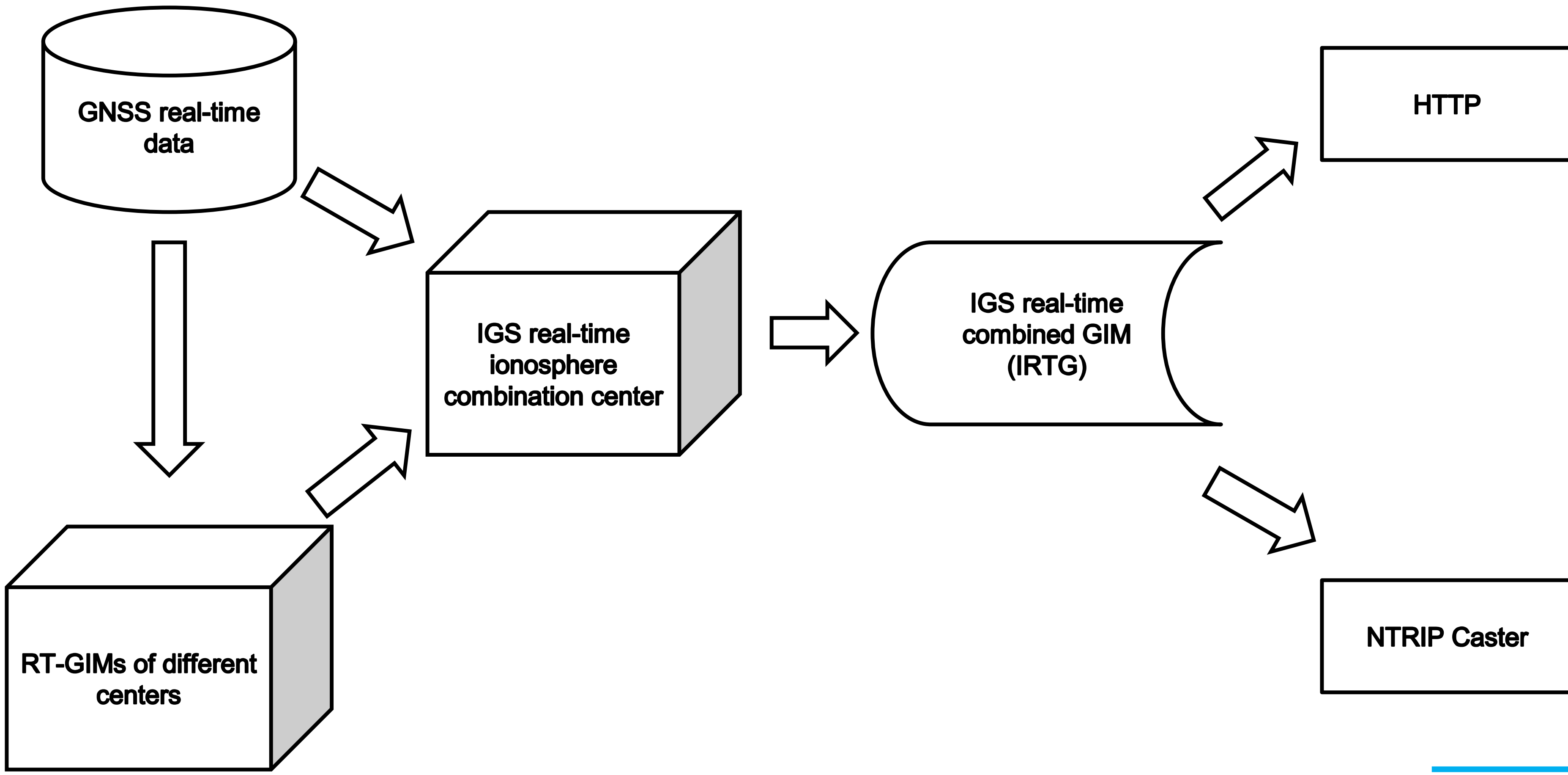
IGS real-time service for global ionospheric total electron content modeling

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



The current status of broadcasting IGS RT-GIMs

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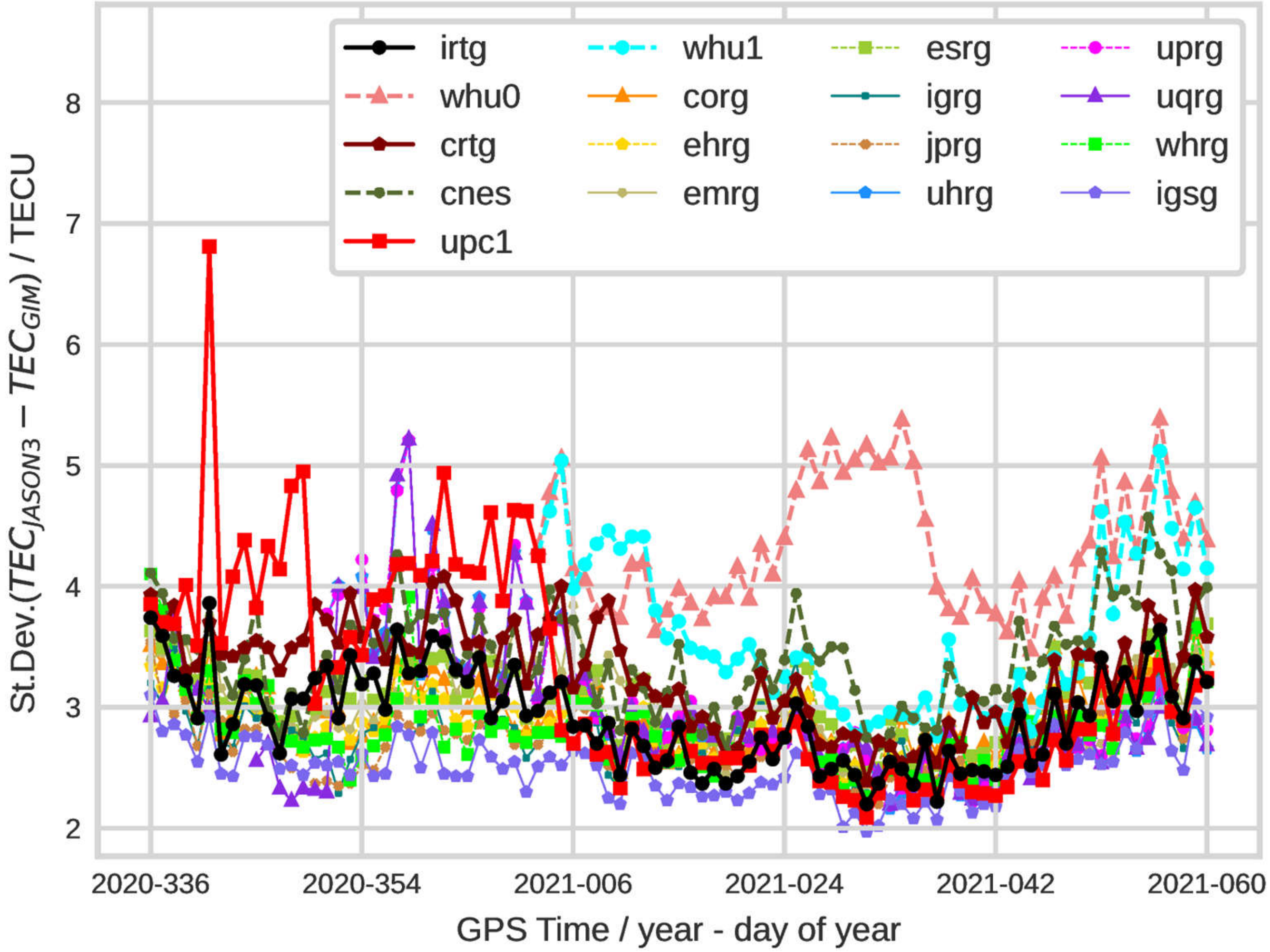
Agency	Temporal resolution	Broadcast frequency	Spherical harmonic degree	Mountpoints in NTRIP caster (in SSR format)	Real-Time IONEX files saved at FTP/HTTP
CAS	5 minutes	1 minute	15	59.110.42.14:2101/SSRA00CAS1 59.110.42.14:2101/SSRA00CAS0 59.110.42.14:2101/SSRC00CAS1 59.110.42.14:2101/SSRC00CAS0 182.92.166.182:2101/IONO00CAS1 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 products.igs-ip.net:2101/SSRA00CNE0 products.igs-ip.net:2101/SSRC00CNE1 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/

The performance of GIMs versus Jason3-VTEC



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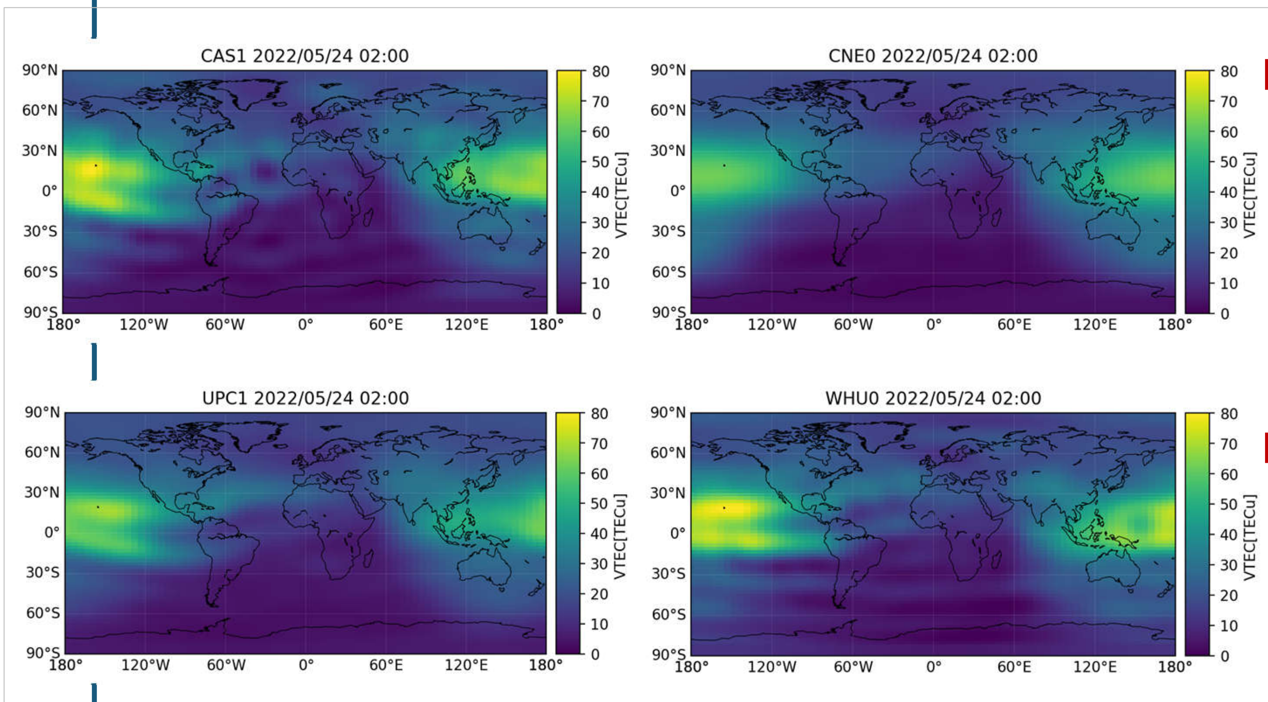
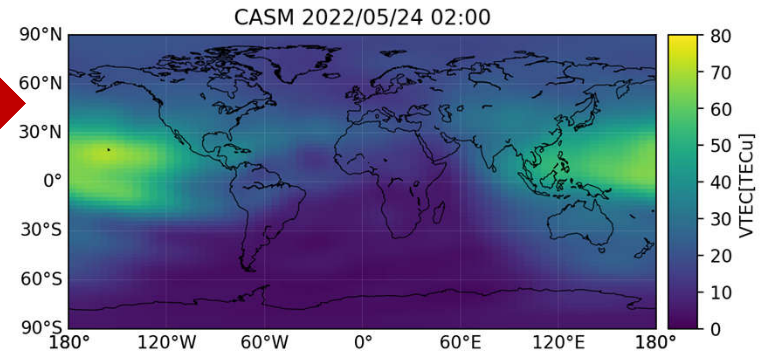
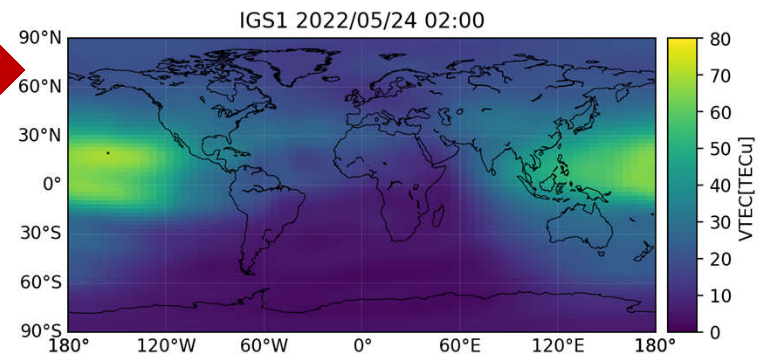
RT-GIMs provided by different ACs



CAS combined RT-GIM



UPC combined RT-GIM



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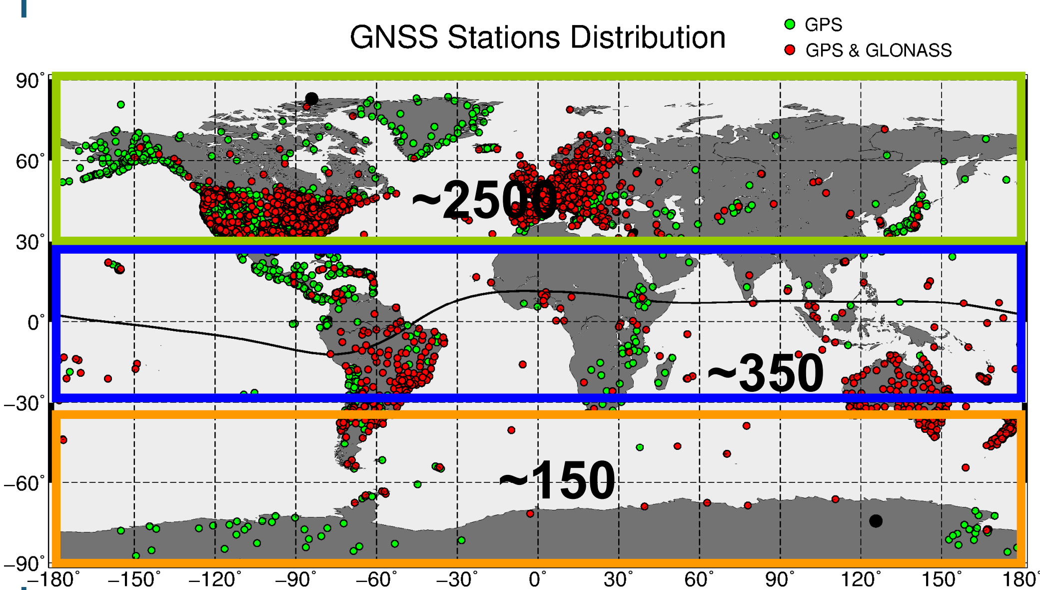
IGS ROTI Maps extension toward Southern Hemisphere and low latitudes

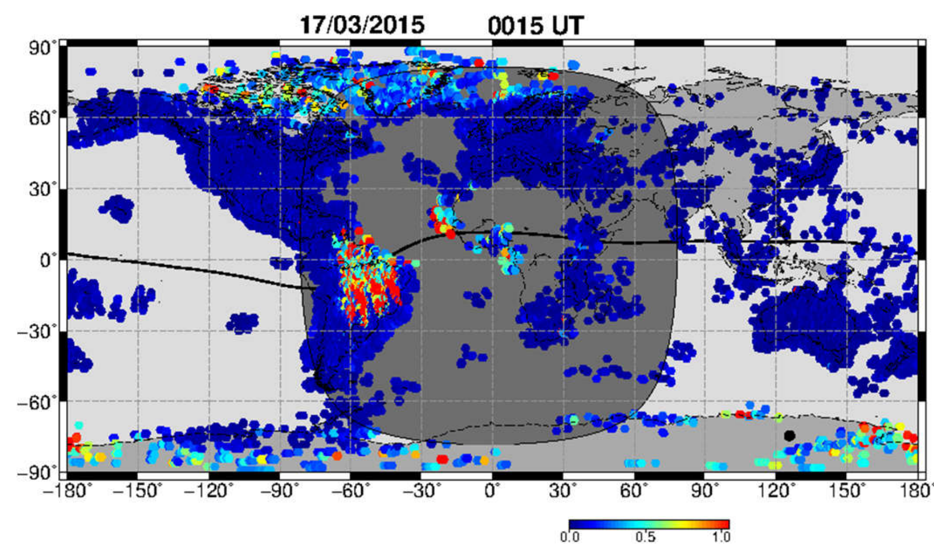
Main chalange – non uniform global distribution of permanent GNSS stations



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

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



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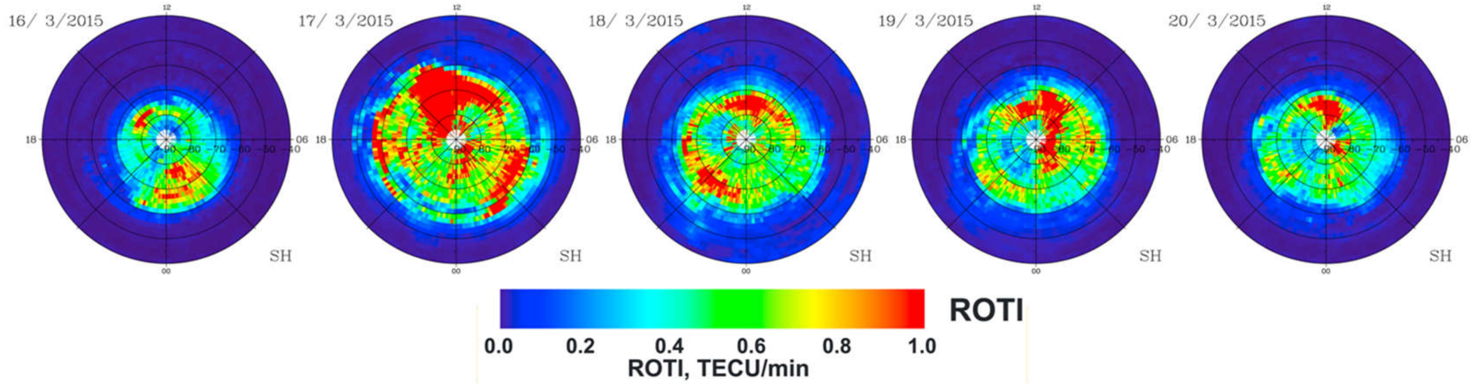
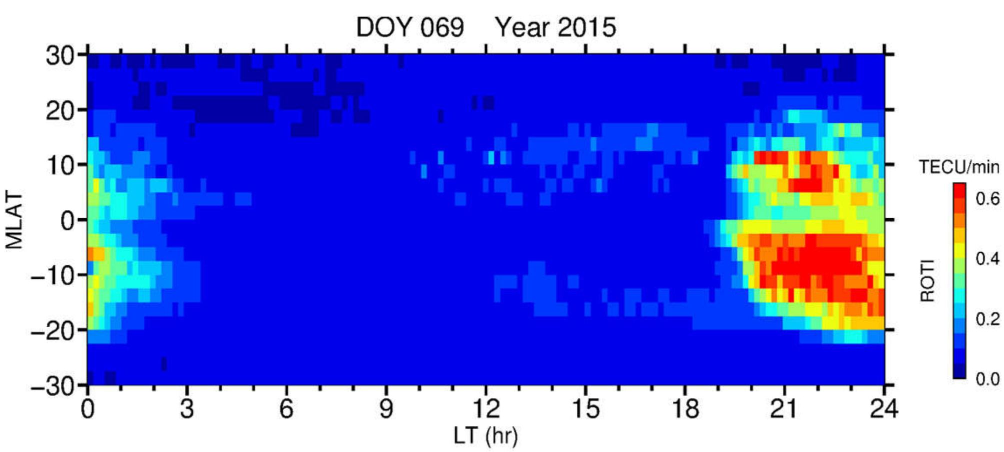
IGS ROTI Maps extension toward Southern Hemisphere and low latitudes

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

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```
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

LOFAR

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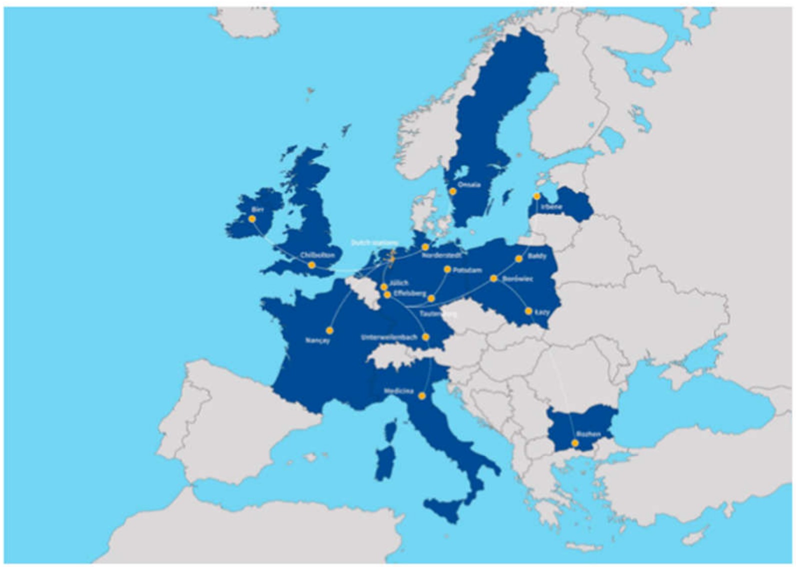
52 LOFAR stations across Europe



LOFAR Superterb (6 stations):

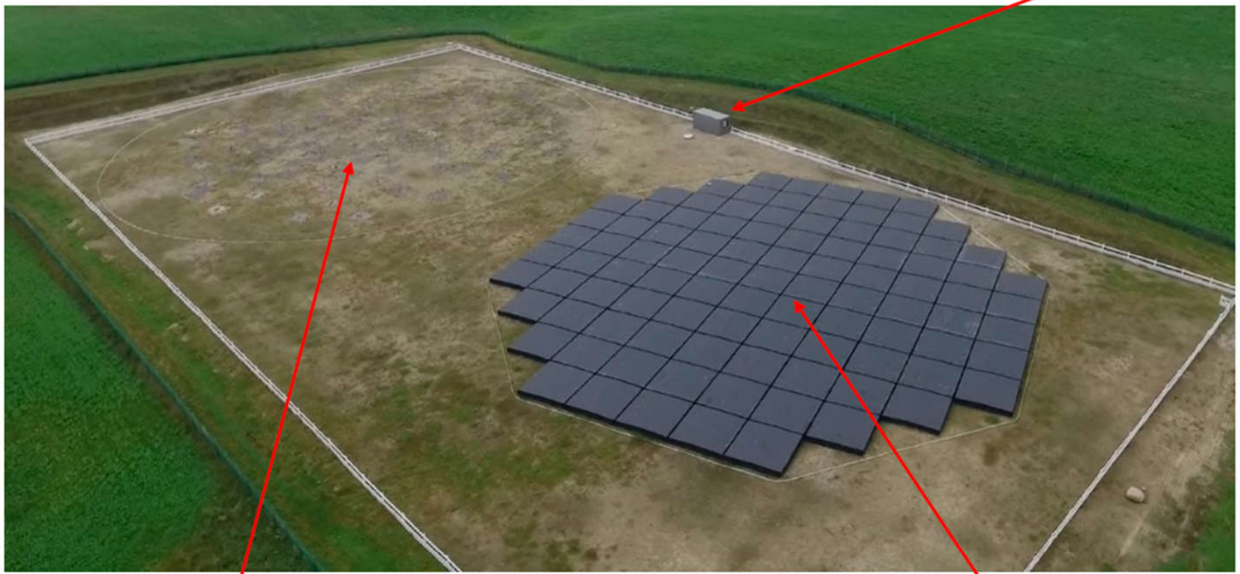
Classification of LOFAR stations:

- 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?



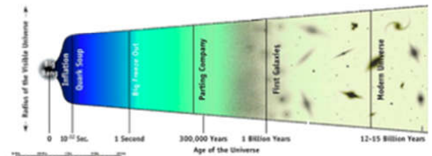
What data do we get?

- 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.

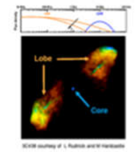
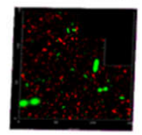
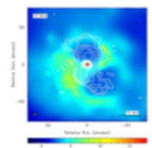
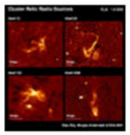
LOFAR POLFAR POLFARO

LOFAR - The Key Science Projects

Epoch of Reionisation

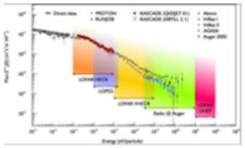
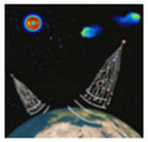


Surveys

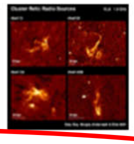





Transients

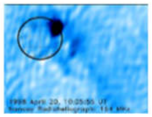
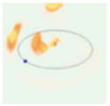
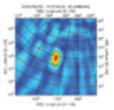
Cosmic Rays

Magnetism

Sun, Space Weather

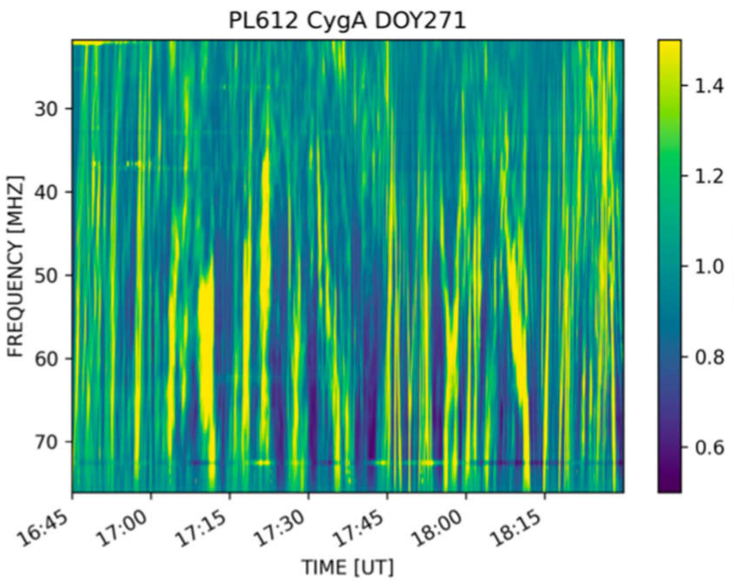




Ionospheric indices

- 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

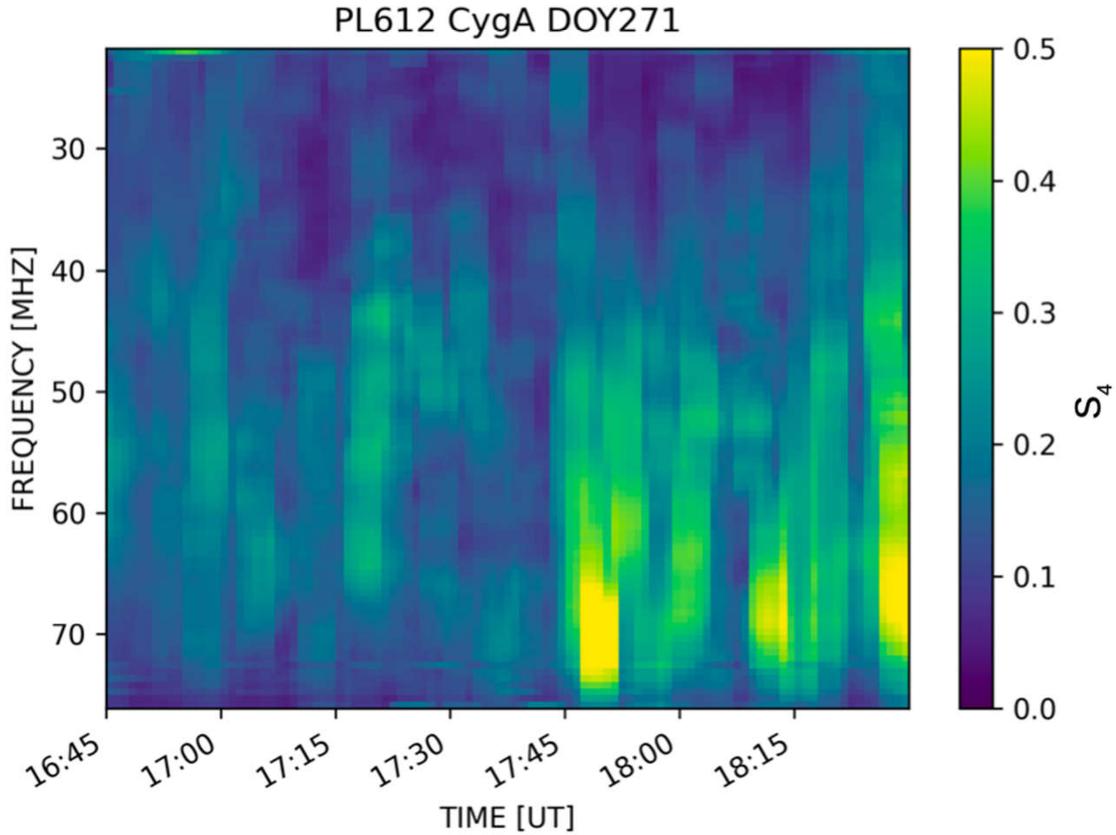
$\langle \; \rangle$ temporal averaging in lieu of ensemble averaging

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

LOFAR scintillation index estimated over various VHF radio-wave frequencies



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

Global Assimilative Model of Bottomside Ionosphere Timeline

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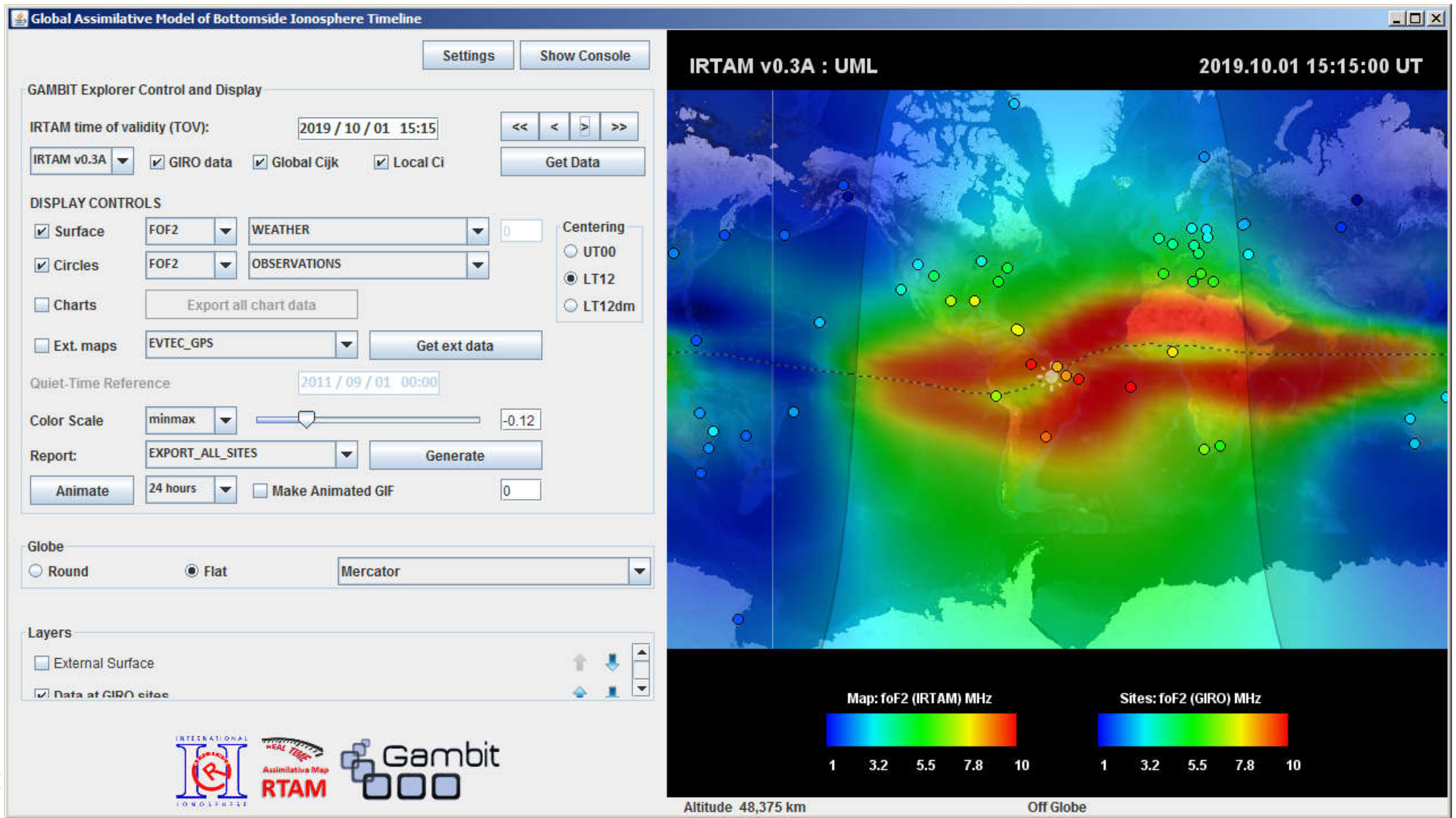
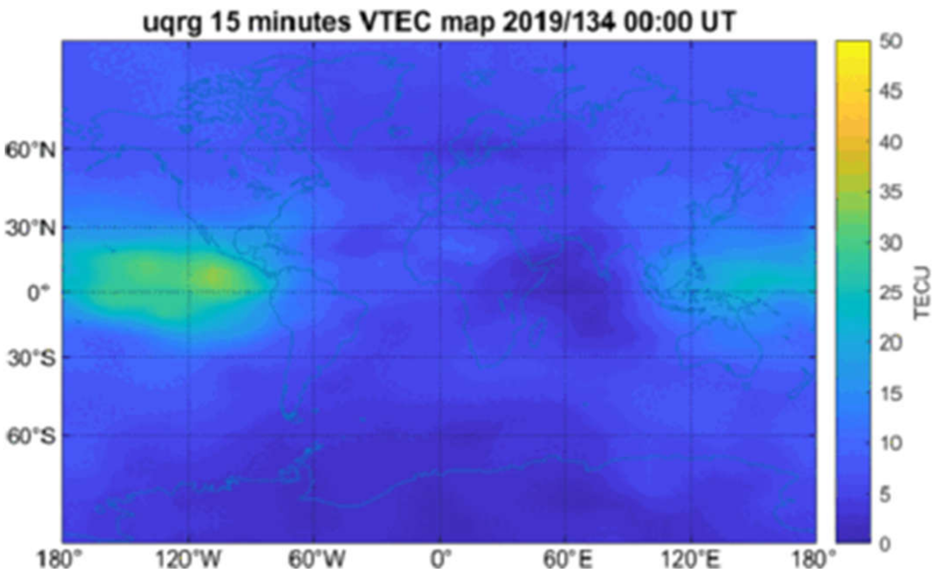
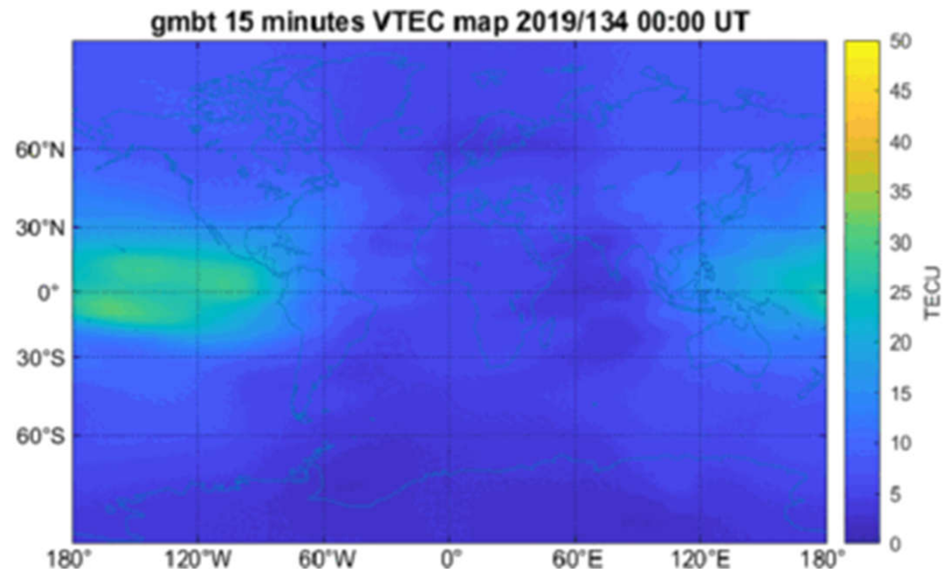
GAMBIT Explorer is a single frame application with all controls available on its main panel



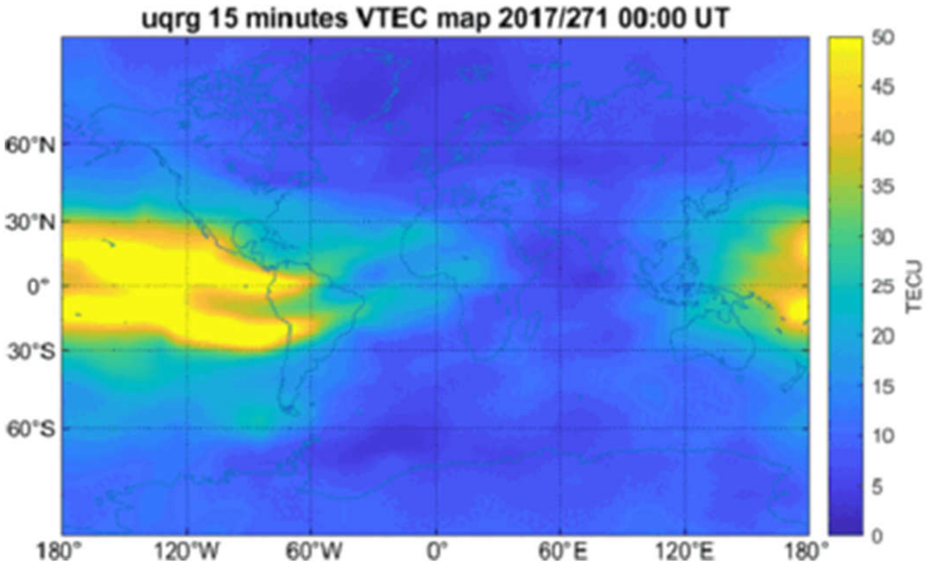
Gambit

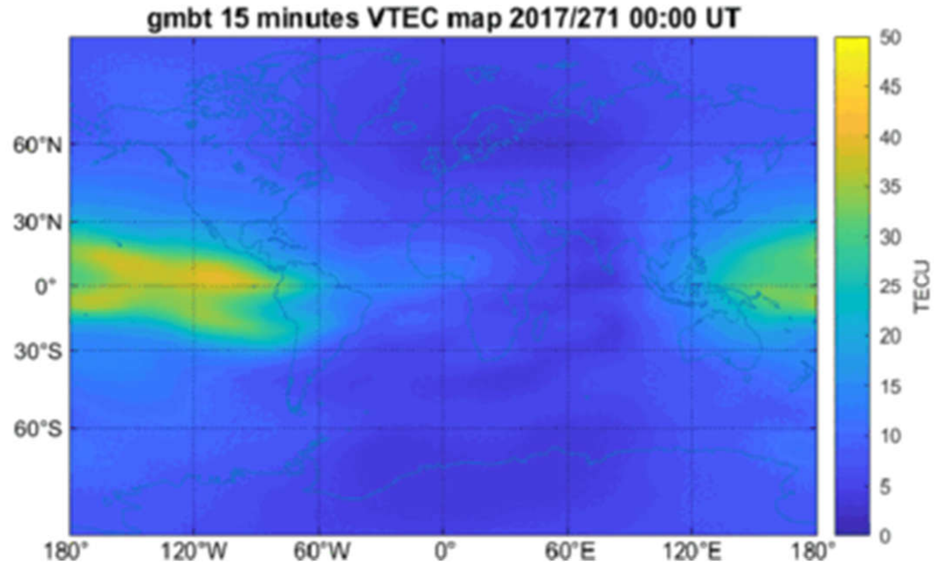
Comparison between IGS UQRG-based weather (rapid) and climate VTEC product for GAMBIT system (quiet day):



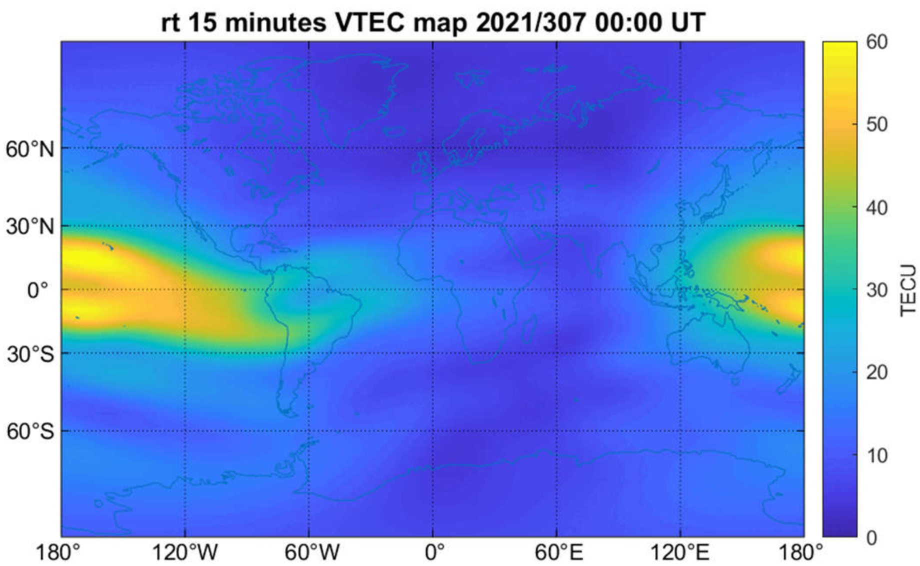


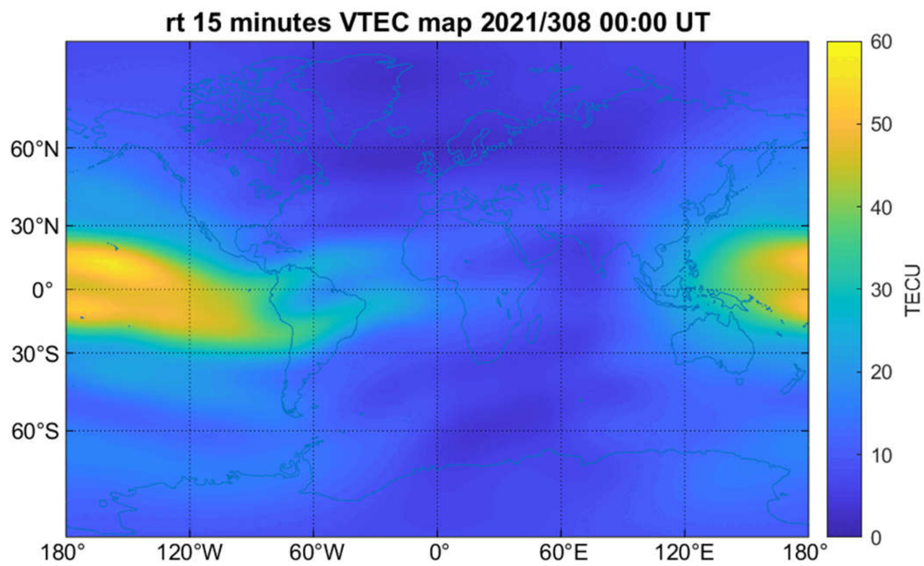
Comparison between IGS UQRG-based weather (rapid) and climate VTEC product for GAMBIT system (disturbed day):





Examples of IGS real-time VTEC maps for GAMBIT system:





Summary

- 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.

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Thank You!

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