IGS Ionosphere Working Group cooperation with IRI – provision of GNSS TEC products to GAMBIT database

Andrzej Krankowski [1], Adam Froń [1], Ivan Galkin[2], Dieter Bilitza[3], Kacper Kotulak [1], Pawel Flisek[1], Manuel Hernande Pajares [4], Zishen Li [5], Ningbo Wang5[3]

[1)] University of Warmia and Mazury in Olsztyn, Olsztyn, Poland, [2)] University of Massachusetts Lowell, Lowell, Massachusetts, United States, [3)] George Mason University, Fairfax, Virginia, United States, [4)] UPC-IonSAT, Barcelona, Spain, [5)] Aerospace Information Research Institute, CAS, Beijing, China,

United Nations/Finland Workshop on the Applications ofGlobal Navigation Satellite Systems

Jointly organized by The United Nations Office for Outer Space Affairs and the National Land Survey of Finland
Co-organized and co-sponsored by the International Committee on Global Navigation Satellite Systems,
the Finnish Meteorological Institute, the University of Vaasa, the Nordic Institute of Navigation and U-blox

Helsinki, Finland, 23 – 26 October 2023

OUTLINE

1. Overview of the IonoWG

- Examples of IGS Ionospheric products
- 2022 IGS Virtual Workshop IonoWG Recommendations

2. IRI and IGS IONO cooperation

- GIRO and GAMBIT Explorer

3. IGS Data aquisition and methodology

- IGS Rapid VTEC maps
- IGS RT VTEC maps

4. Results

5. GNSS ROT and ROTI monitoring using low-cost Septentrio-mosaic receiver

6. Summary

Overview of the IonoWG

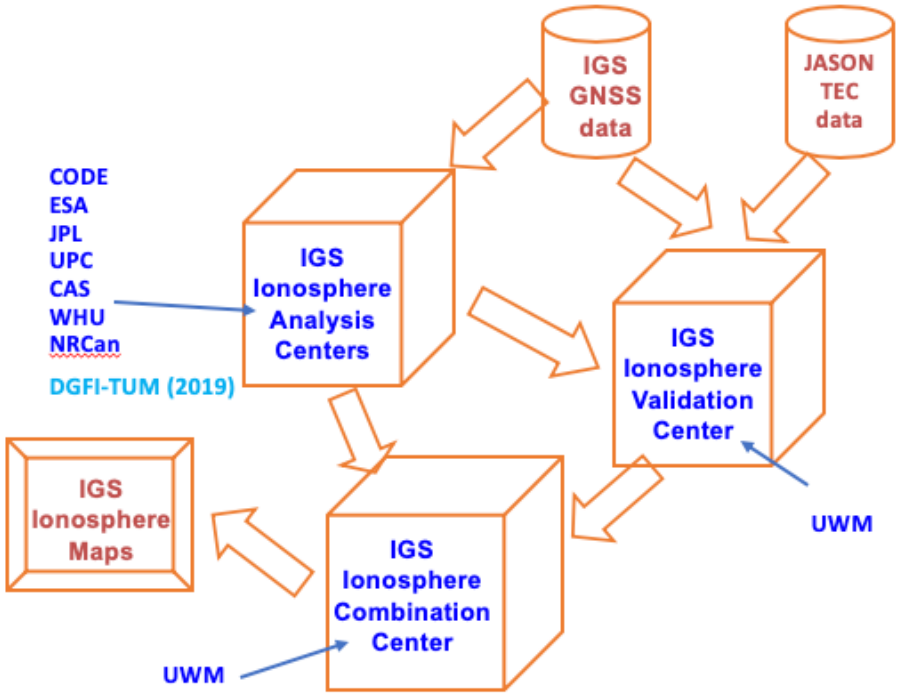
The IGS Ionosphere Working group started its activities in June 1998 with the main goal of a routinely producing IGS Global TEC maps.

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-

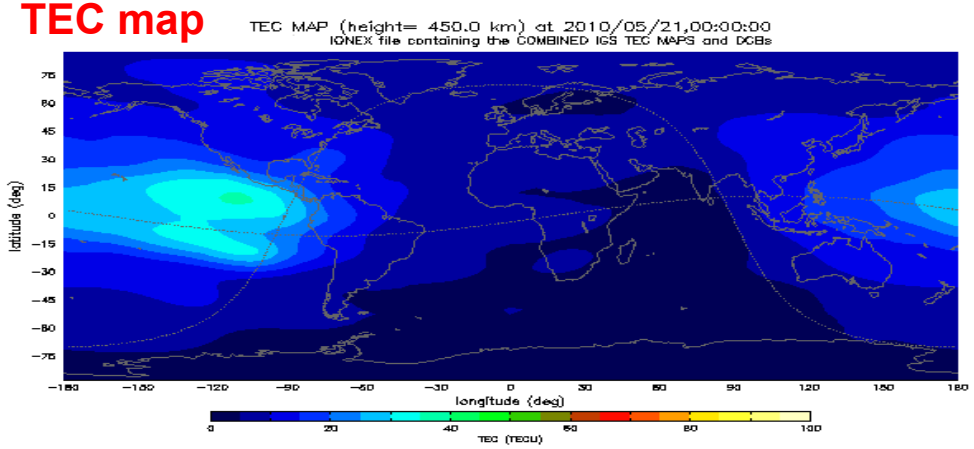
The IGS ionosphere product is a result of the combination of TEC maps derived by different Analysis Centers by using weights computed by Validation Center, in order to get a more accurate product.



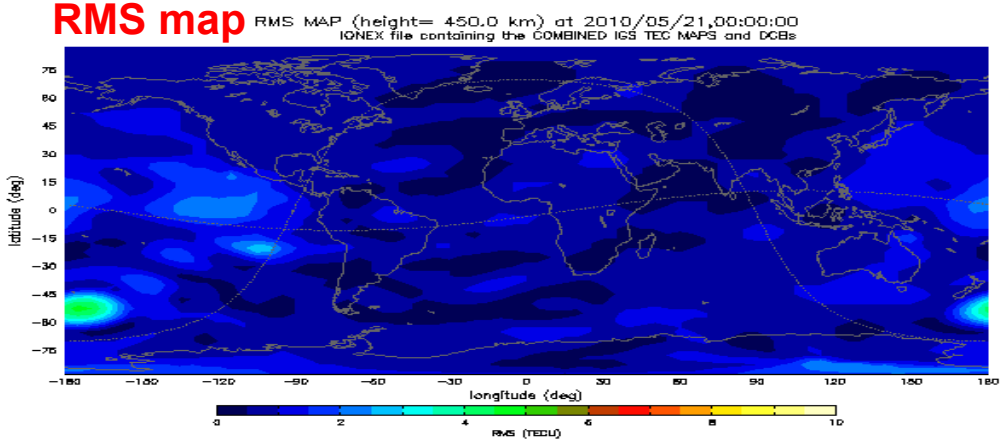
Example of IGS Final GIM: 2010-141 DOY

IGS INTERNATIONAL GNSS SERVICE

TEC map



RMS map



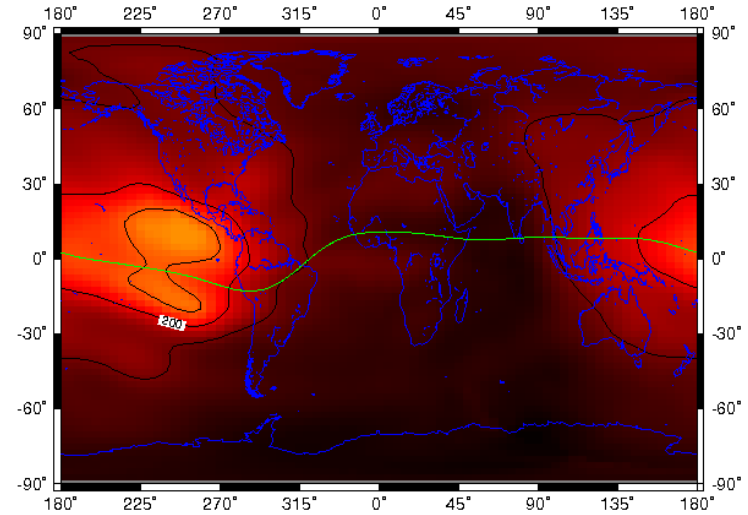
8 Analysis Centers: CODE, ESA, JPL, UPC, WHU, CAS, NRCan, DGFI-TUM (since 2019) and a Validation Center (UWM) have been providing maps (at 2 hours x 5 deg. x 2.5 deg in UT x Lon. x Lat.), weights and external (altimetry-derived) TEC data.

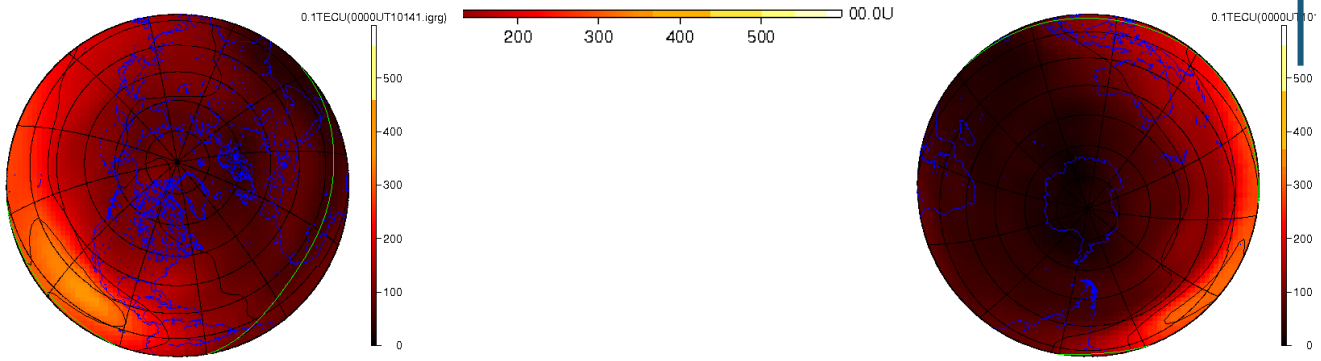
From such maps and weights the Combination Center (at first ESA, then UPC, and since 2008 - UWM) has produced the IGS TEC maps in IONEX format.

Example of IGS RAPID GIM: 2010-141 DOY

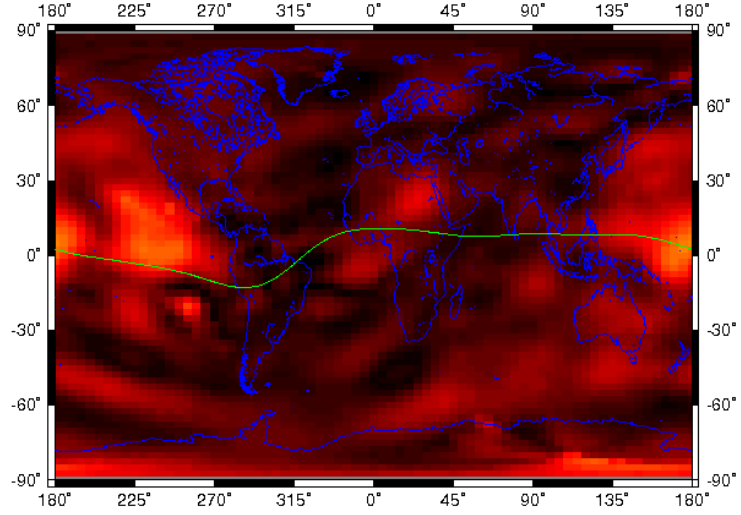
IGS INTERNATIONAL GNSS SERVICE

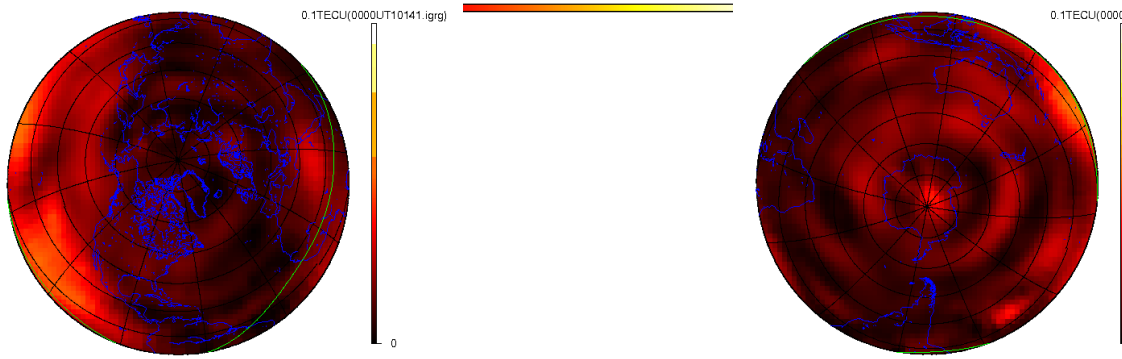
TEC maps





RMS maps





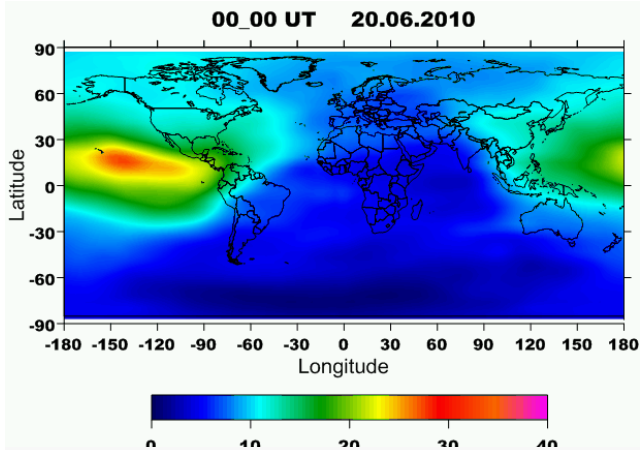
CHARTER

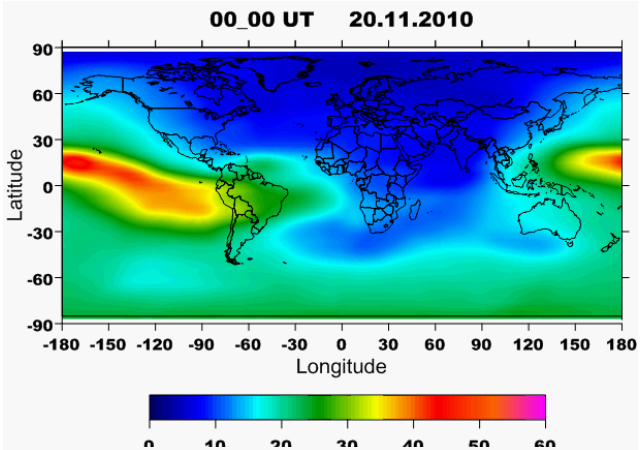
IGS INTERNATIONAL GNSS SERVICE

Example of IGS PREDICTED GIM

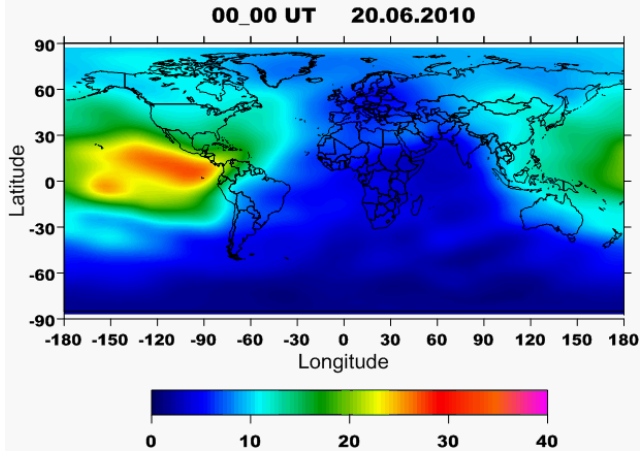
June 20, 2010

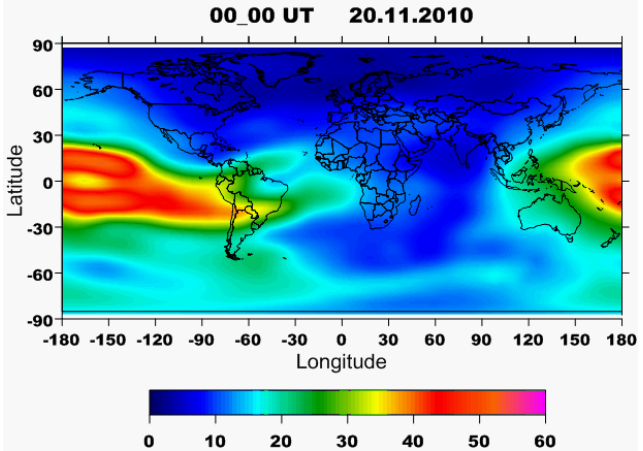
November 20, 2010





IGS Predicted GIM





IGS Final GIM

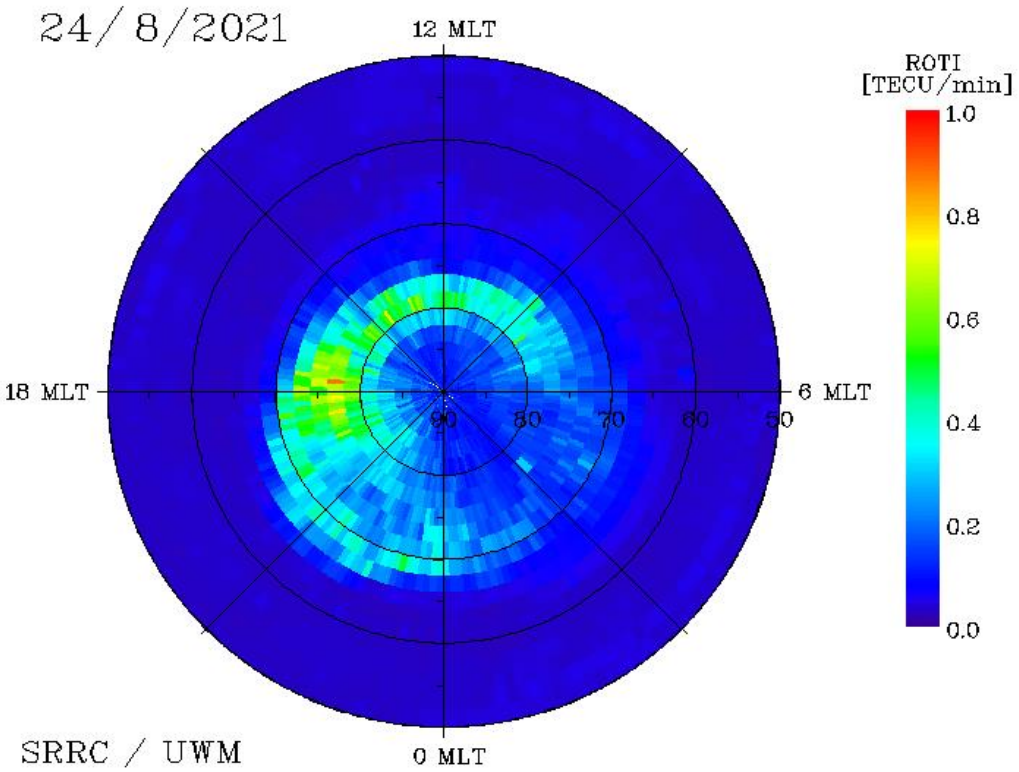
CHARTER

Example of IGS ROTI Maps Product

IGS INTERNATIONAL GNSS SERVICE

- 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

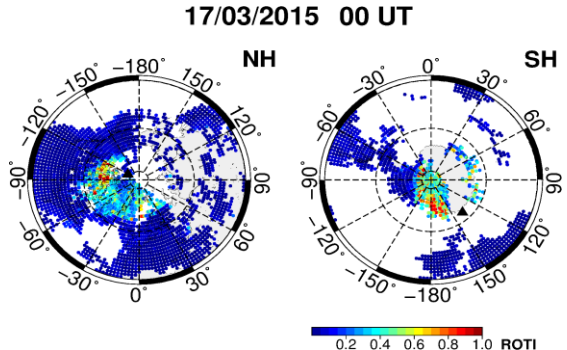
2022 IGS Virtual Workshop Recommendations

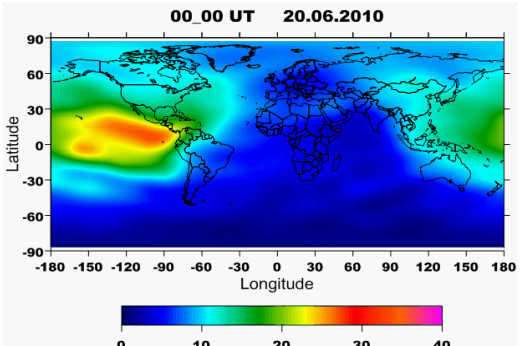
Name of Working Group and Chair: Ionosphere Working Group, Andrzej Krankowski

IGS INTERNATIONAL GNSS SERVICE

IGS INTERNATIONAL GNSS SERVICE
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

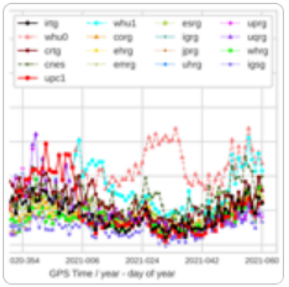
Looking for optimal ways to combine IGS global ionospheric maps in real-time

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

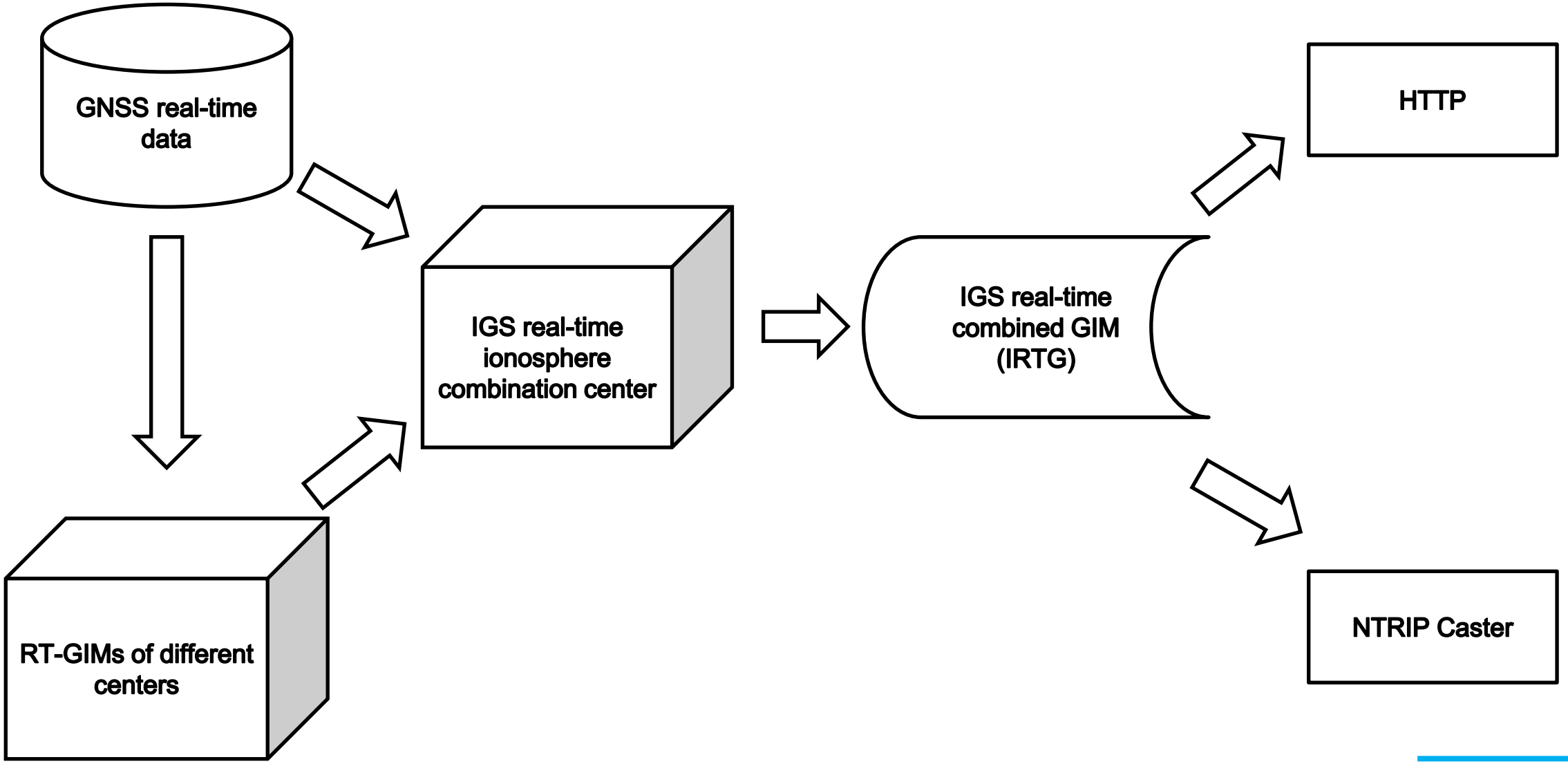
IGS real-time service for global ionospheric total electron content modeling

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

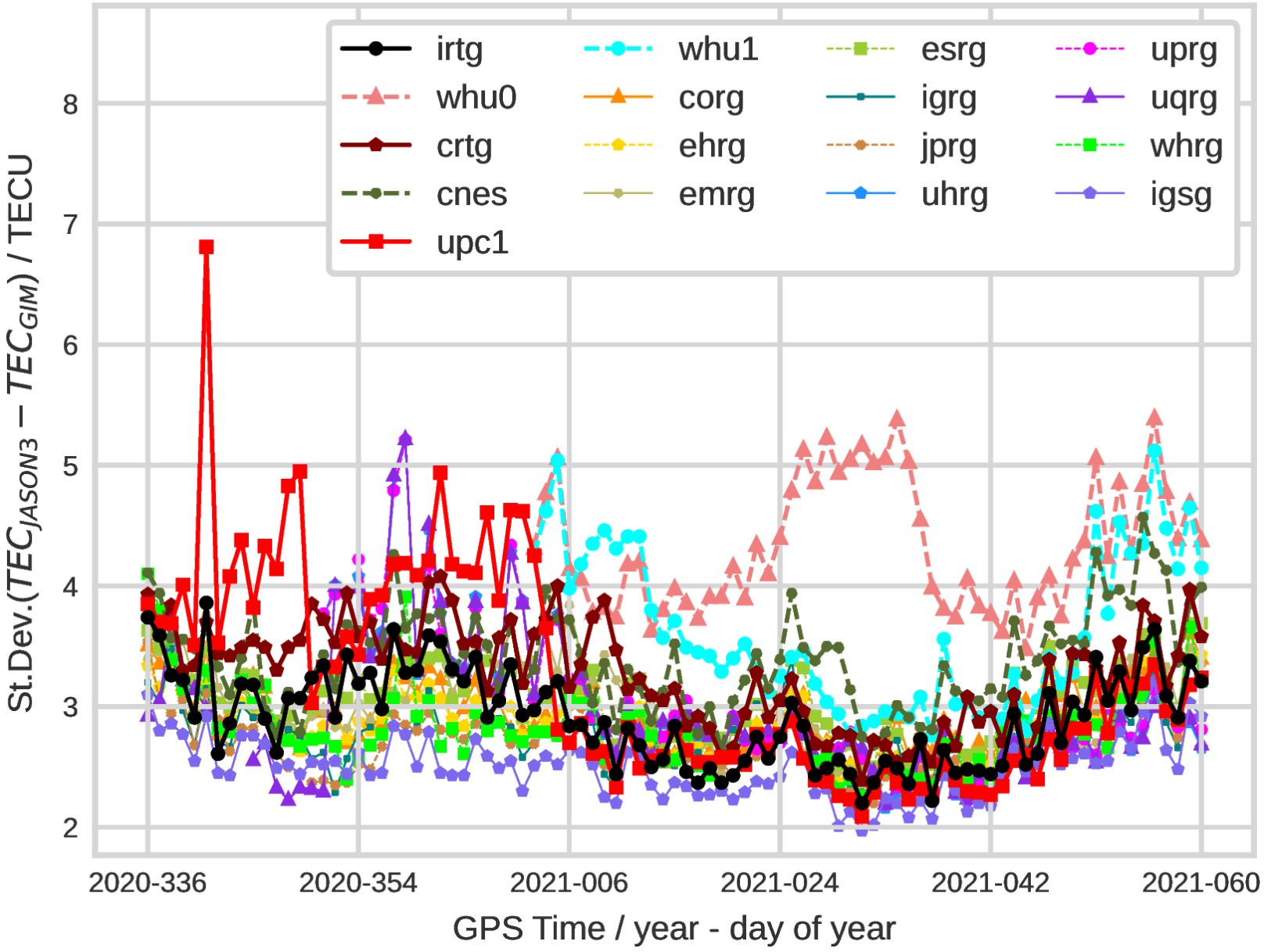
Journal of Geodesy 94, 32, 2020

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

Data flow for the IGS real-time combined GIM



The performance of GIMs versus Jason3-VTEC



The current status of broadcasting IGS RT-GIMs

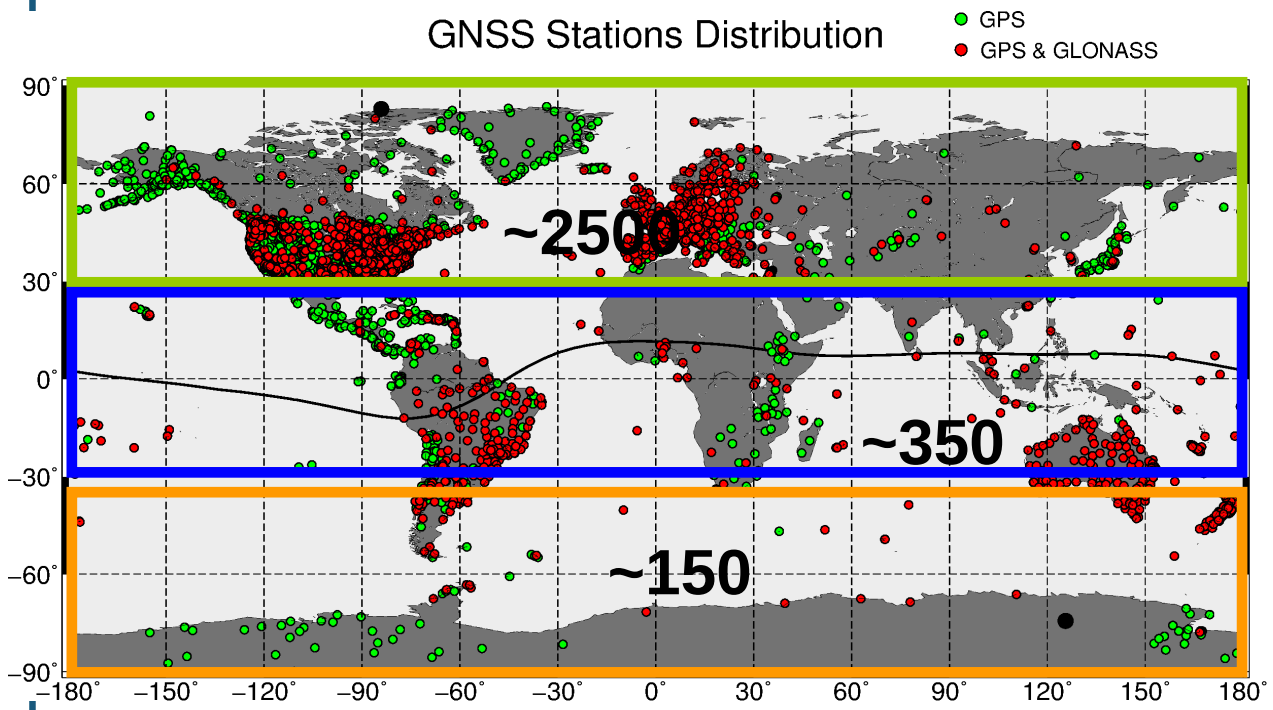
Agency	Temporal resolution	Broadcast frequency	Spherical harmonic degree	Mountpoints in NTRIP caster (in SSR format)	Real-Time IONEX files saved at FTP/HTTP
CAS	5 minutes	1 minute	15	59.110.42.14:2101/SSRA00CAS1 59.110.42.14:2101/SSRA00CAS0 59.110.42.14:2101/SSRC00CAS1 59.110.42.14:2101/SSRC00CAS0 182.92.166.182:2101/IONO00CAS1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

UNIWERSYTET WARMIŃSKO-MAZURSKI W OLSZTYNIE

IGS INTERNATIONAL GNSS SERVICE

IGS ROTI Maps extension toward Southern Hemisphere and low latitudes

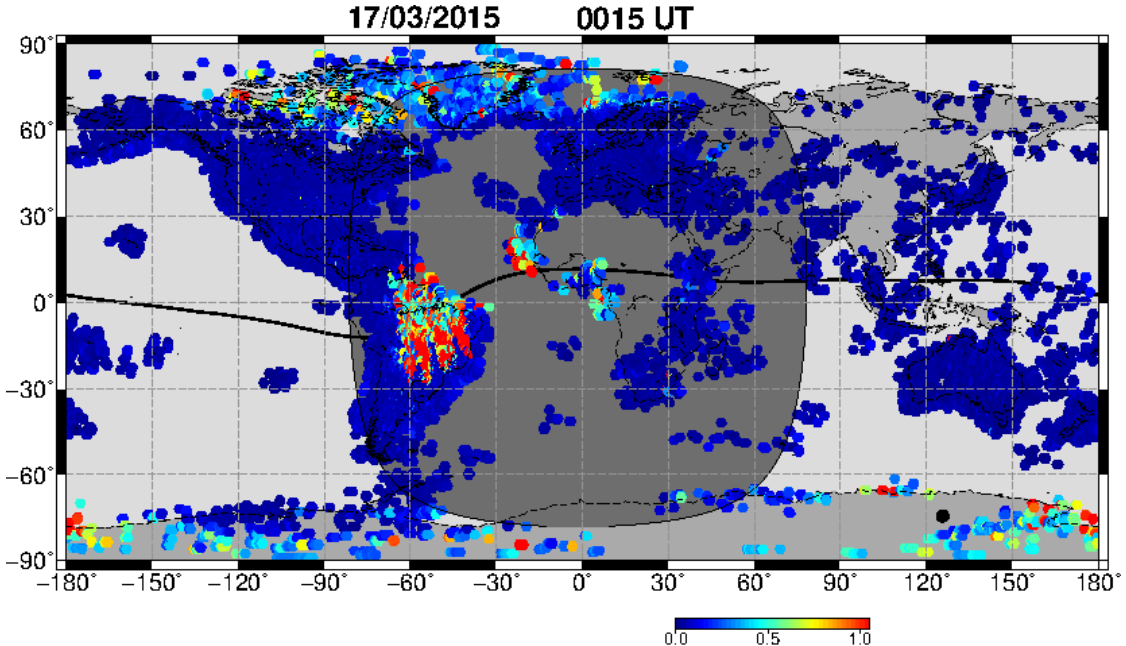
Main chalange – non uniform global distribution of permanent GNSS stations



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

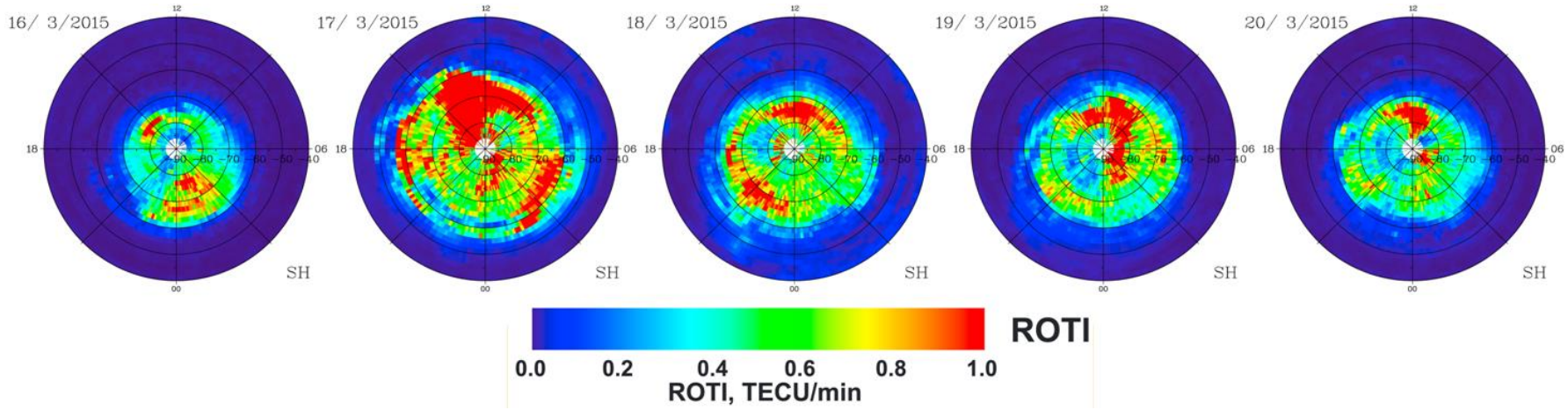
UNIWERSYTET WARMIŃSKO-MAZURSKI W OLSZTYNIE

IGS ROTI Maps extension toward Southern Hemisphere and low latitudes

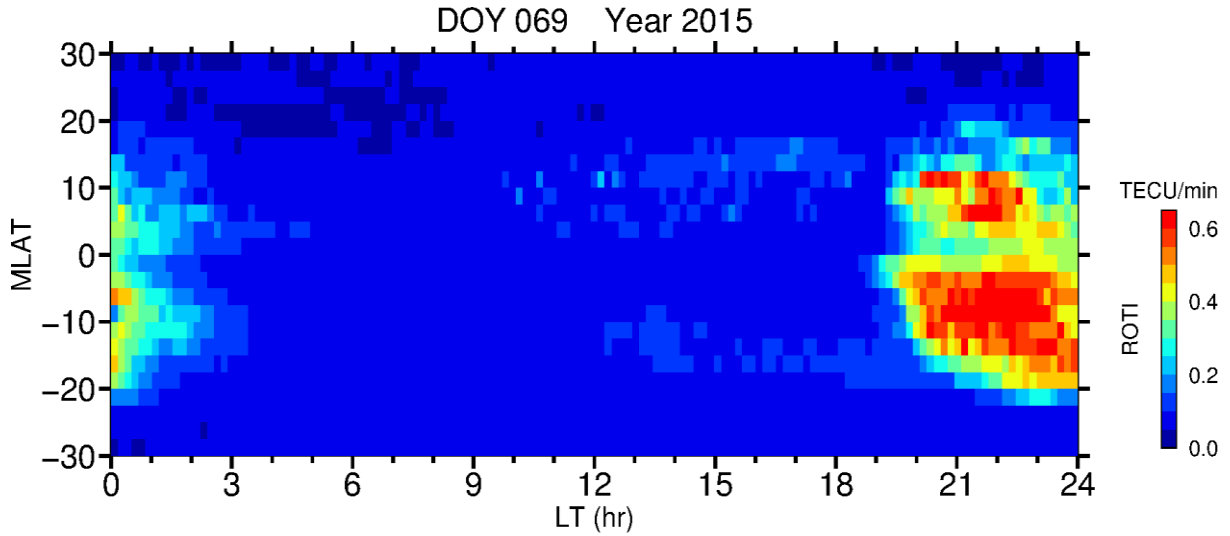
Preliminary results – ROTI maps on validation stage

IGS INTERNATIONAL GNSS SERVICE

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

- **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

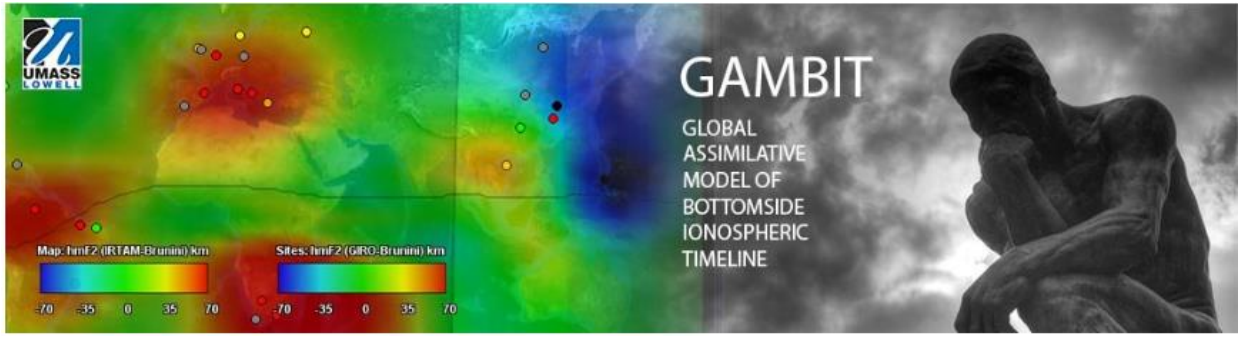
- The **system is now expanded** with inclusion of weather VTEC based on real-time and rapid products of IGS IONO IAACS.
- The real time archive spans back to doy 251/2017. The combined file, aggregating all the real-time data for each day, is published with 1-2 hour latency.
- **At UWM, the real-time IGS VTEC data from CAS and UPC 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 UQRG 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

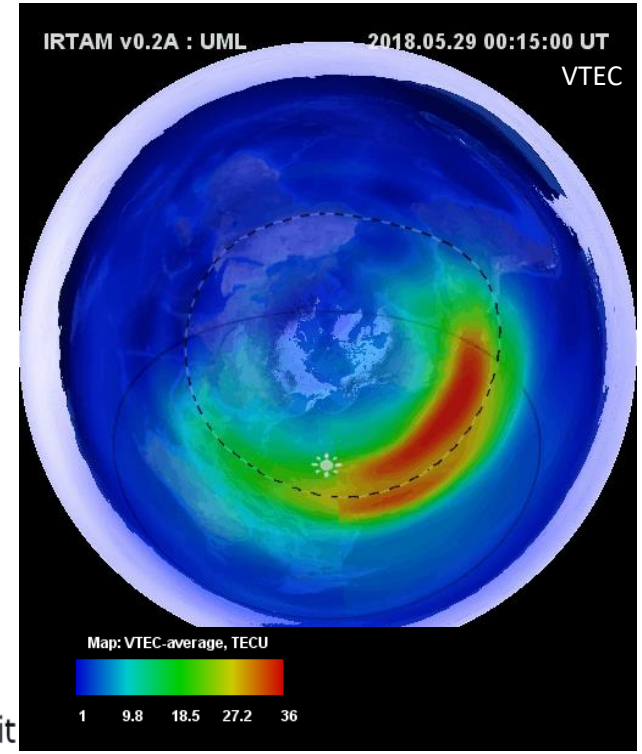
Global Assimilative Model of Bottomside Ionosphere Timeline

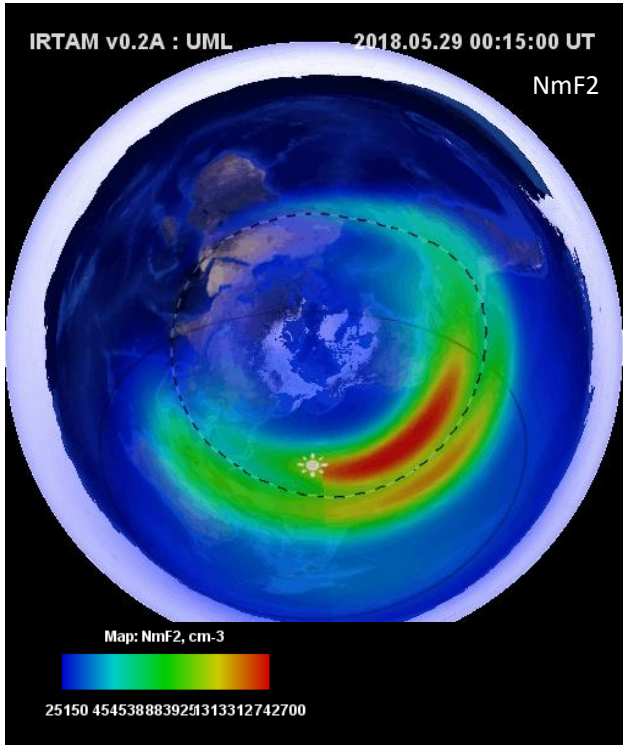
IGS INTERNATIONAL GNSS SERVICE

Online repository of real-time and retrospective global IRTAM 3D ionospheric weather nowcast generated using the Global Ionosphere Radio Observatory (GIRO) sensor measurements



Data acquisition, quality control, processing, modeling, analysis, visualization, and data and facility management resources are designed, developed, and operated by the University of Massachusetts Lowell personnel for the GAMBIT project.



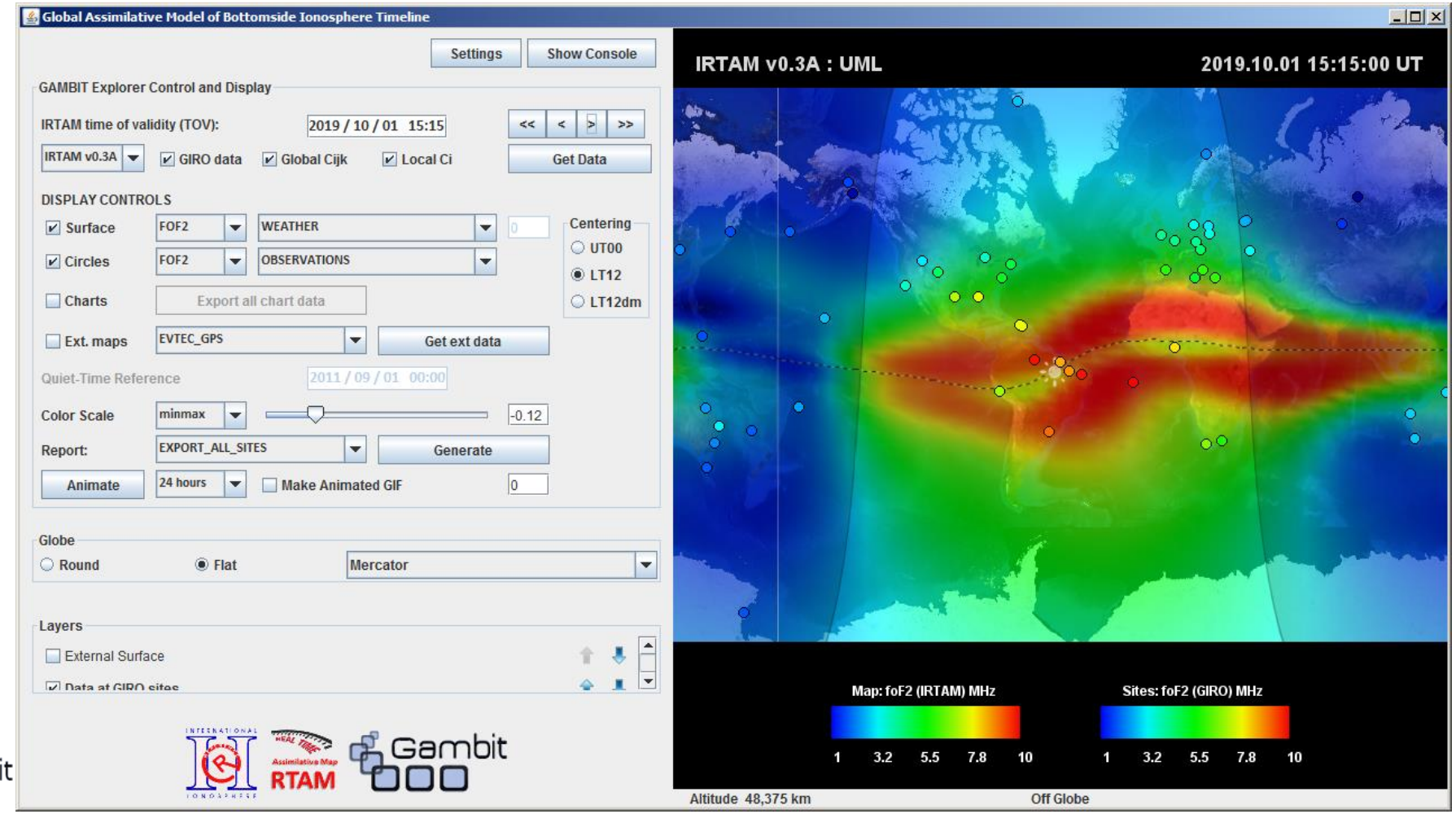


Open Academic-Use Access to retrospective ionospheric weather data in display and numerical formats is provided with GAMBIT Explorer UserApp

Global Assimilative Model of Bottomside Ionosphere Timeline

IGS INTERNATIONAL GNSS SERVICE

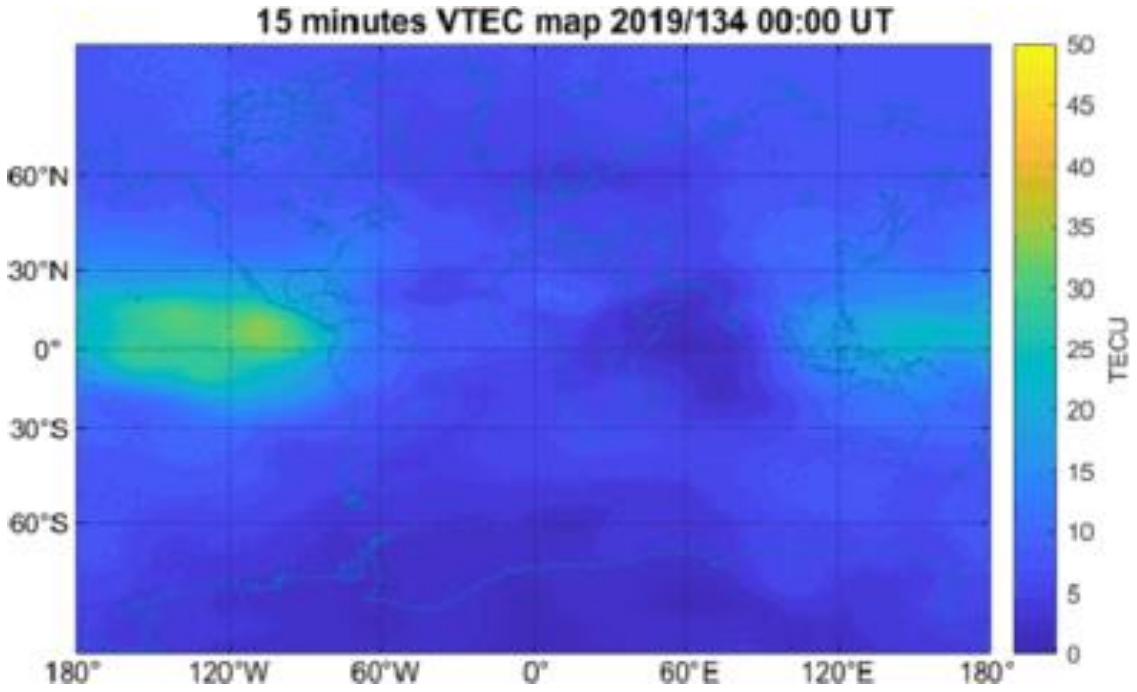
GAMBIT Explorer is a single frame application with all controls available on its main panel



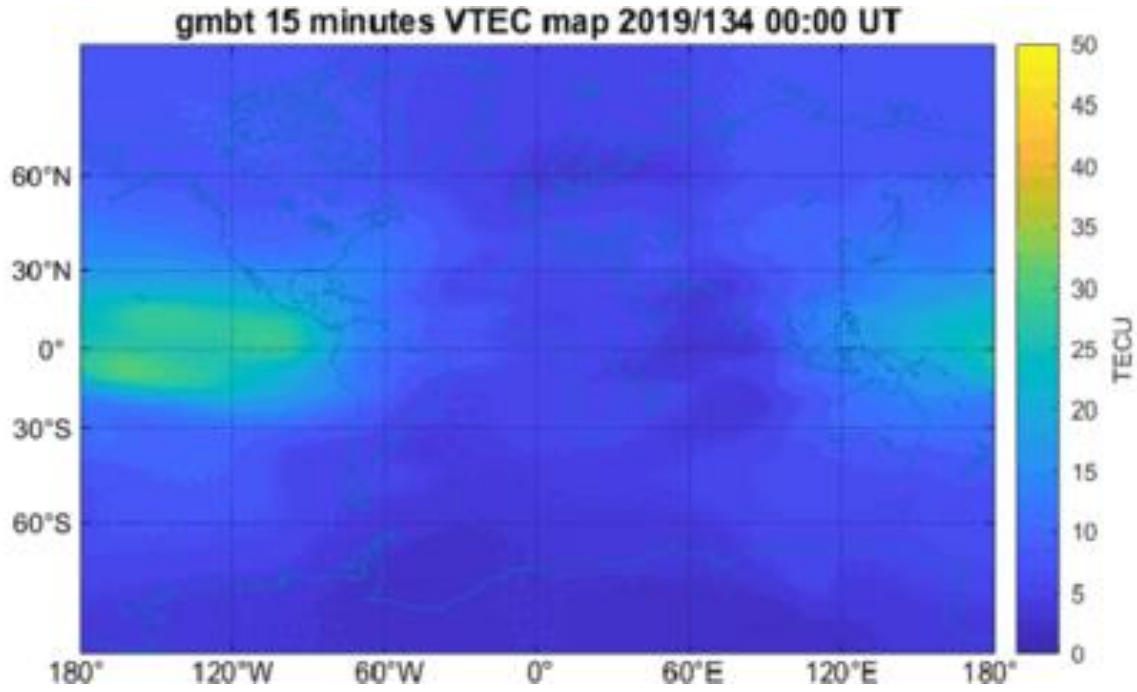
Comparison between IGS rapid and climate VTEC product for GAMBIT system (quiet day):

IGS INTERNATIONAL GNSS SERVICE

IGS rapid



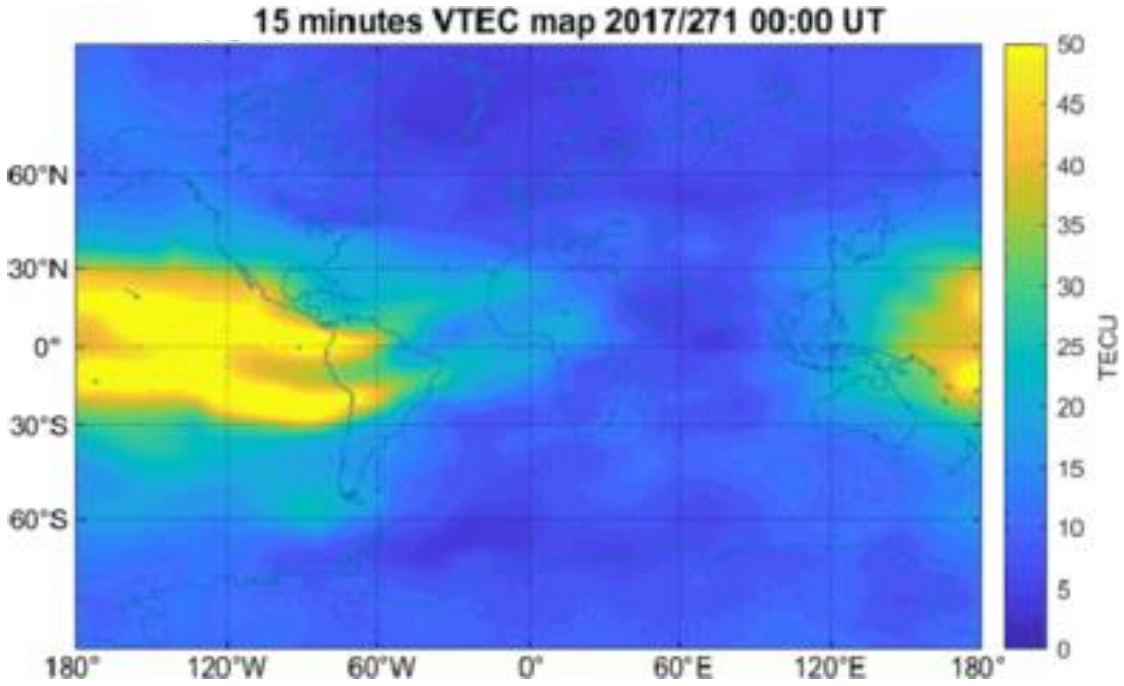
GAMBIT (gmbt)



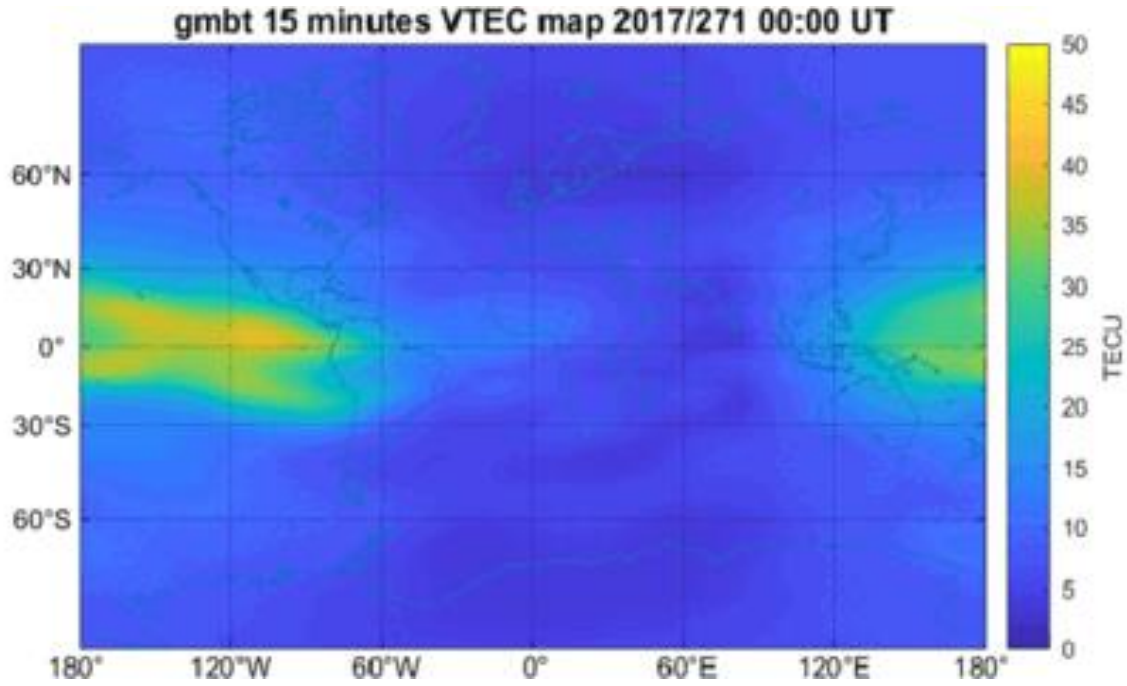
Comparison between IGS rapid and climate VTEC product for GAMBIT system (disturbed day):

IGS INTERNATIONAL GNSS SERVICE

IGS rapid

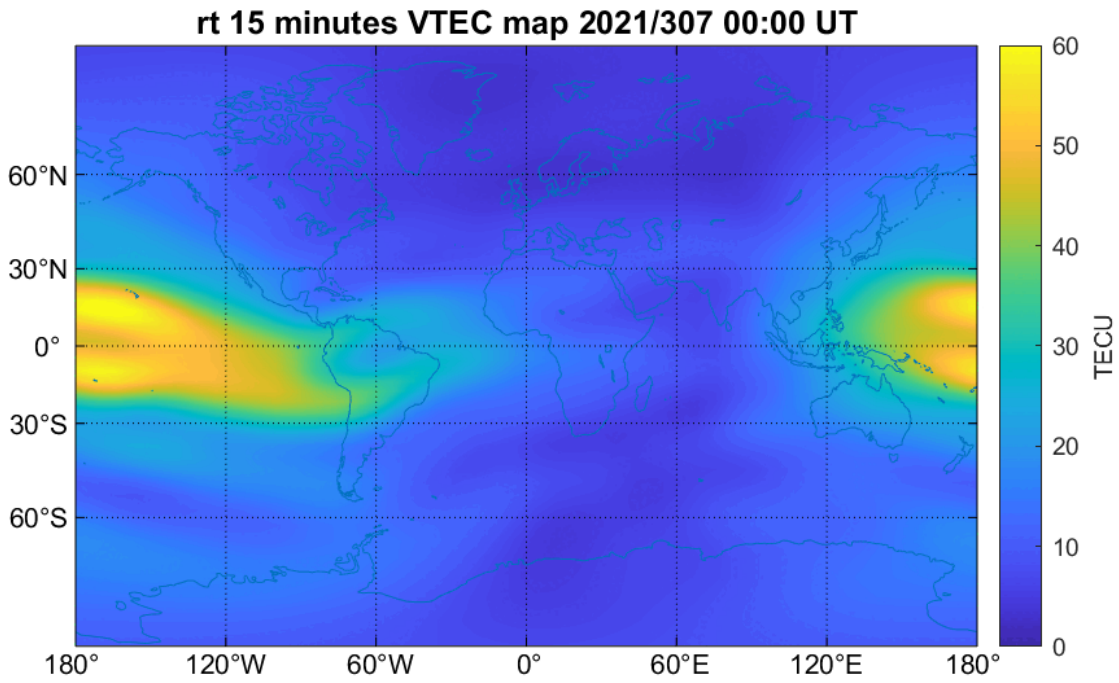


GAMBIT (gmbt)

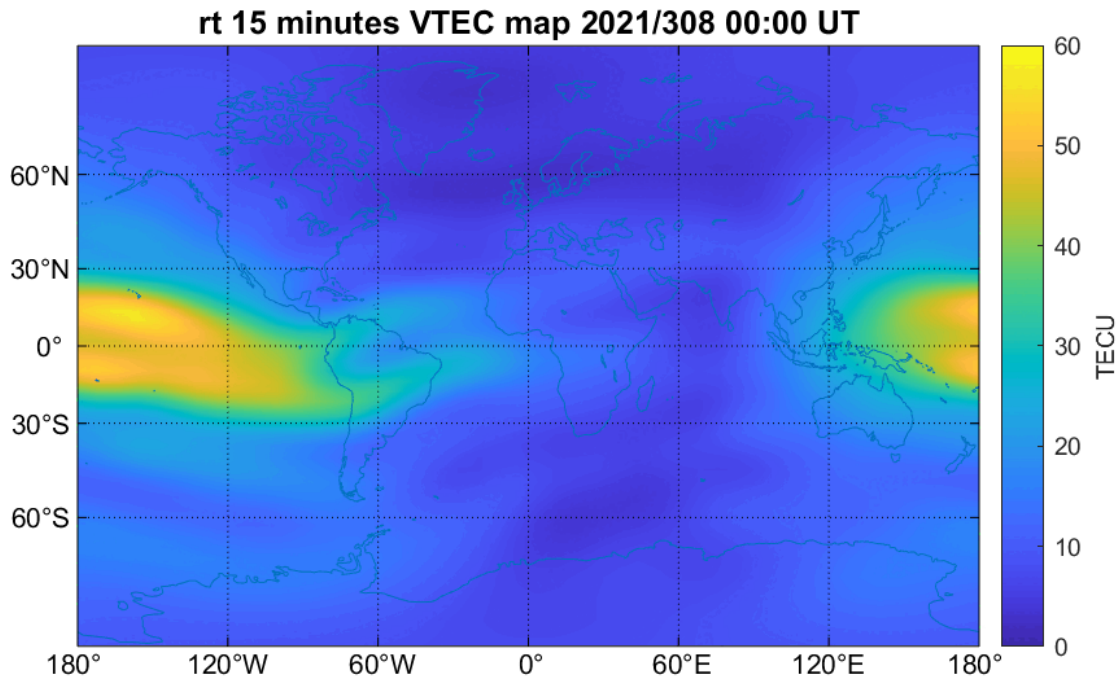


Examples of IGS real-time VTEC maps for GAMBIT system:

Real-Time GAMBIT (gmrt)

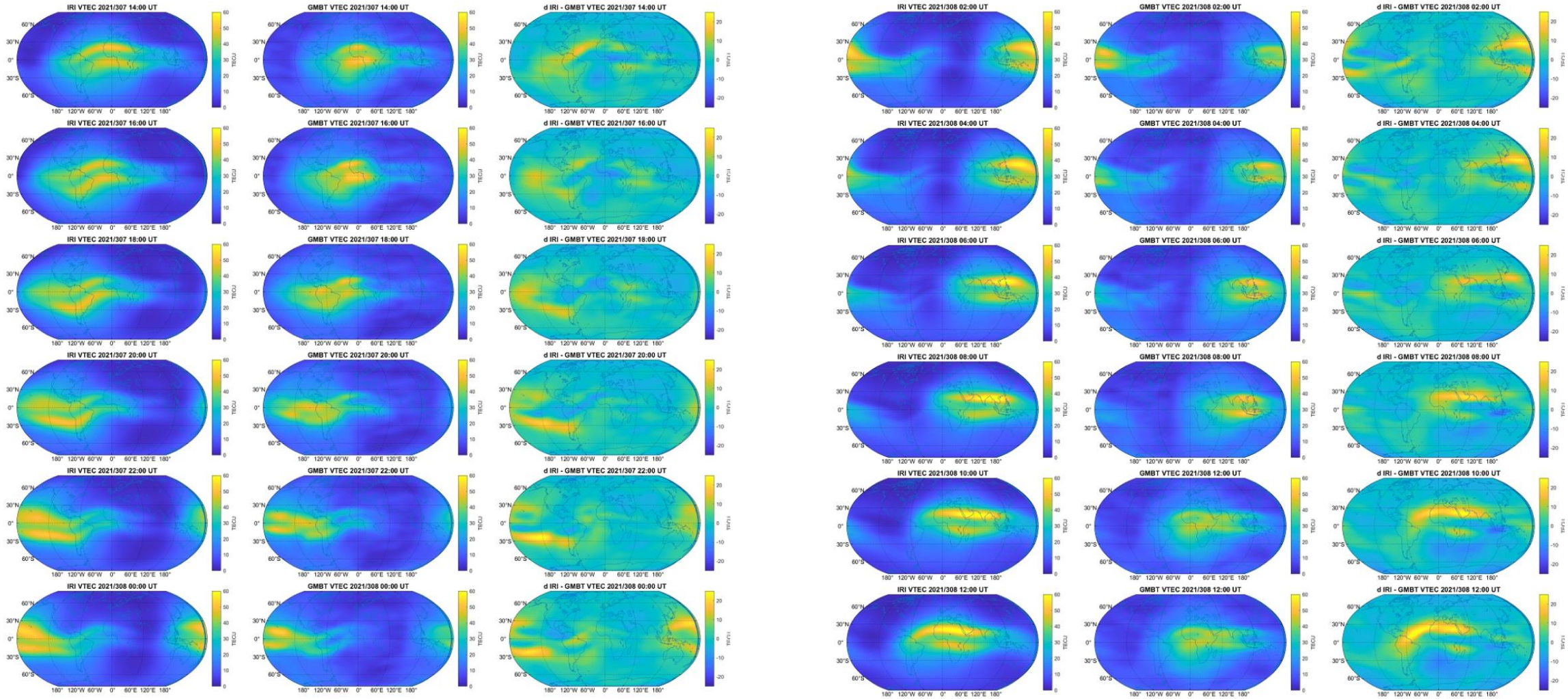


Real-Time GAMBIT (gmrt)



IGS INTERNATIONAL GNSS SERVICE

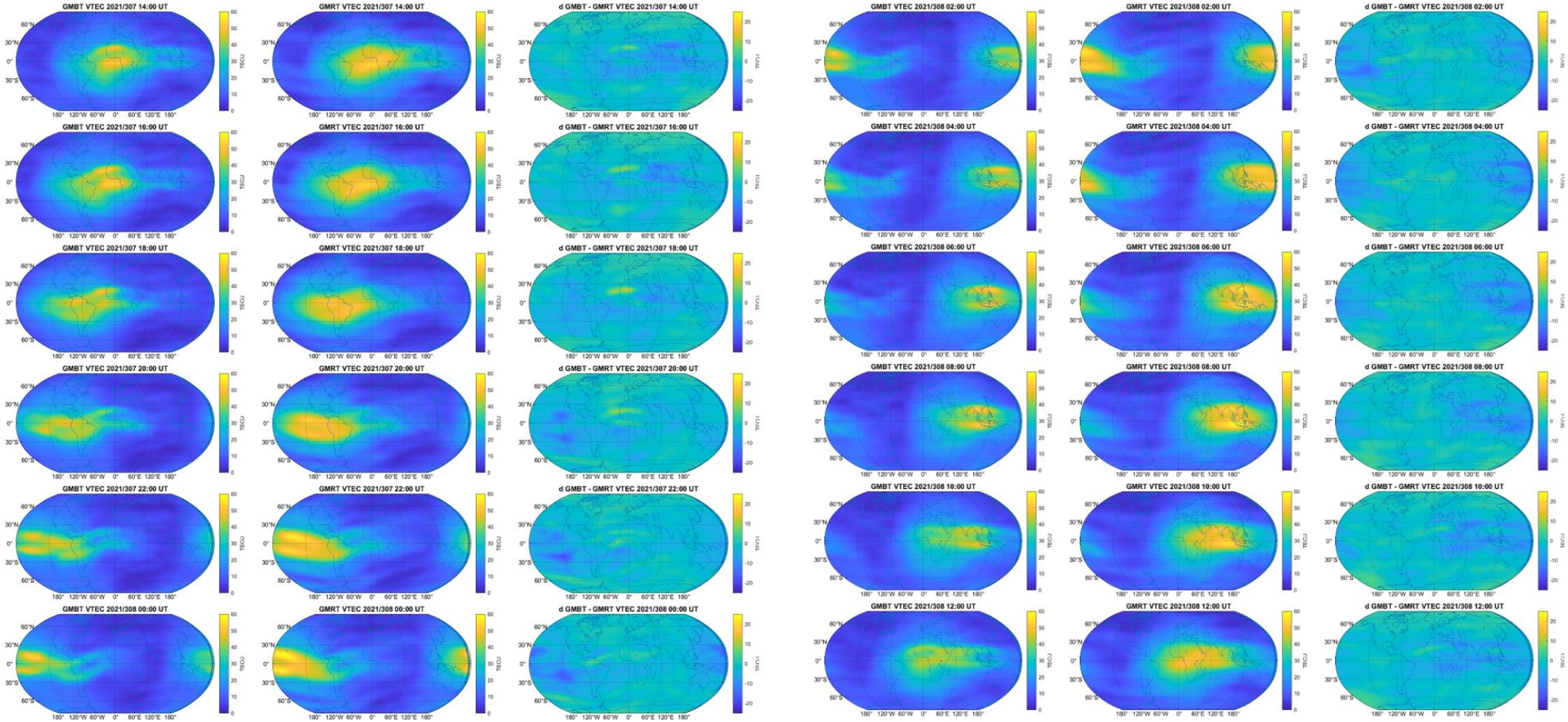
IRI VTEC – GMBT VTEC, 307 and 308, 2021



IRI climate VTEC maps (first column), GAMBIT climate VTEC maps - GMBT (second column) and differential VTEC maps (third column)

IGS INTERNATIONAL GNSS SERVICE

GMBT VTEC – GMRT VTEC, 307 and 308 2021

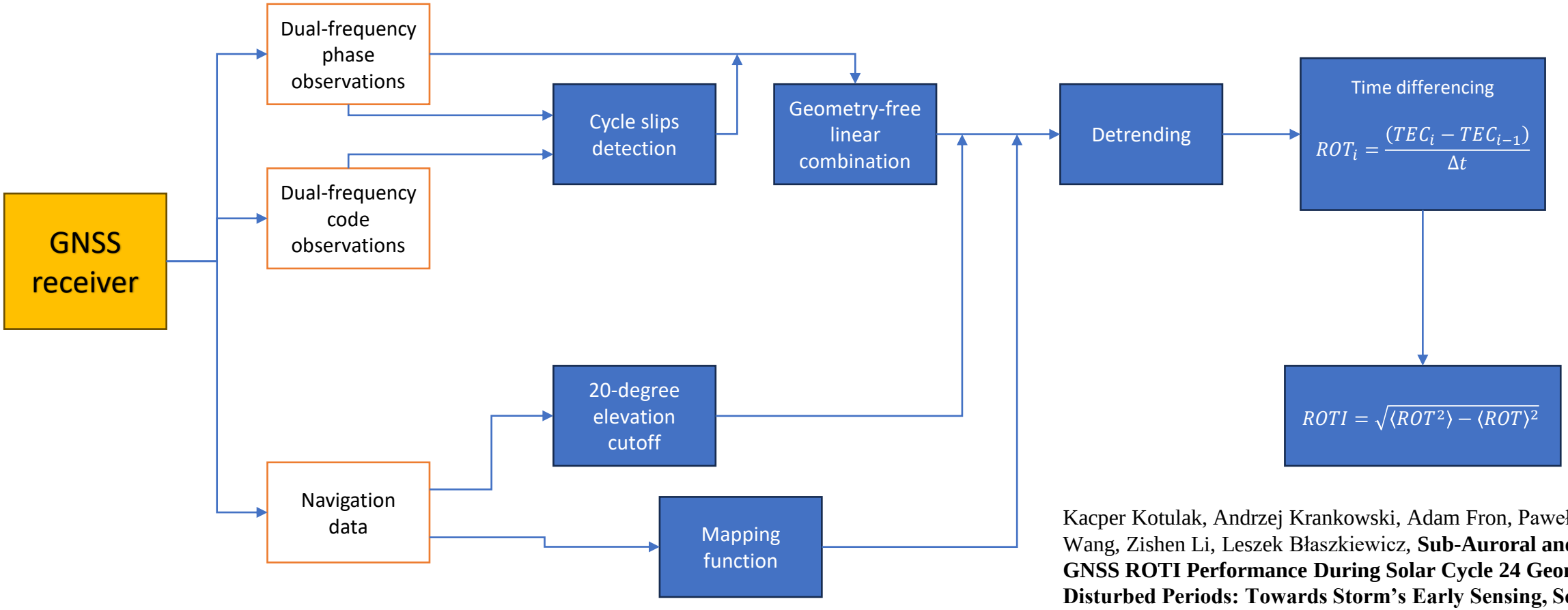


GAMBIT climate VTEC maps – GMBT (first column), GAMBIT real time VTEC maps – GMRT (second column) and differential VTEC maps (third column)

Rate Of TEC (ROT) and Rate Of TEC Index (ROTI) monitorig capabilities of low-cost Septentrio-mosaic receiver

software and comparison with Septentrio PolarX S Pro developed and performed by

Paweł Flisek and Kacper Kotulak



Kacper Kotulak, Andrzej Krankowski, Adam Fron, Paweł Flisek, Ningbo Wang, Zishen Li, Leszek Błaszkiewicz, **Sub-Auroral and Mid-Latitude GNSS ROTI Performance During Solar Cycle 24 Geomagnetic Disturbed Periods: Towards Storm's Early Sensing, Sensors 2021, 21, 4325; doi.: 10.3390/s21134325**

antenna

Septentrio mosaic-X5

Sampling frequency:

up to 100 Hz

Observed systems:

GPS, GLONASS, Galileo, BeiDou, SBAS, QZSS, NAVIC

I/Q corr observable (S4 calculation possibility):

Not available

SIGNAL SPLITTER

Septentrio PolarX S Pro

Sampling frequency:

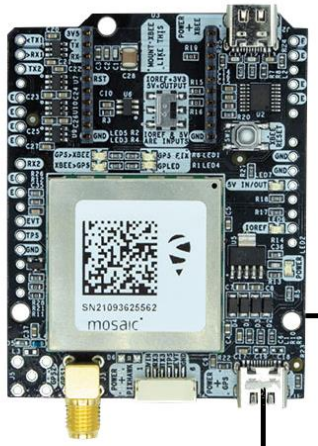
up to 100 Hz

Observed systems:

GPS, GLONASS, Galileo, SBAS

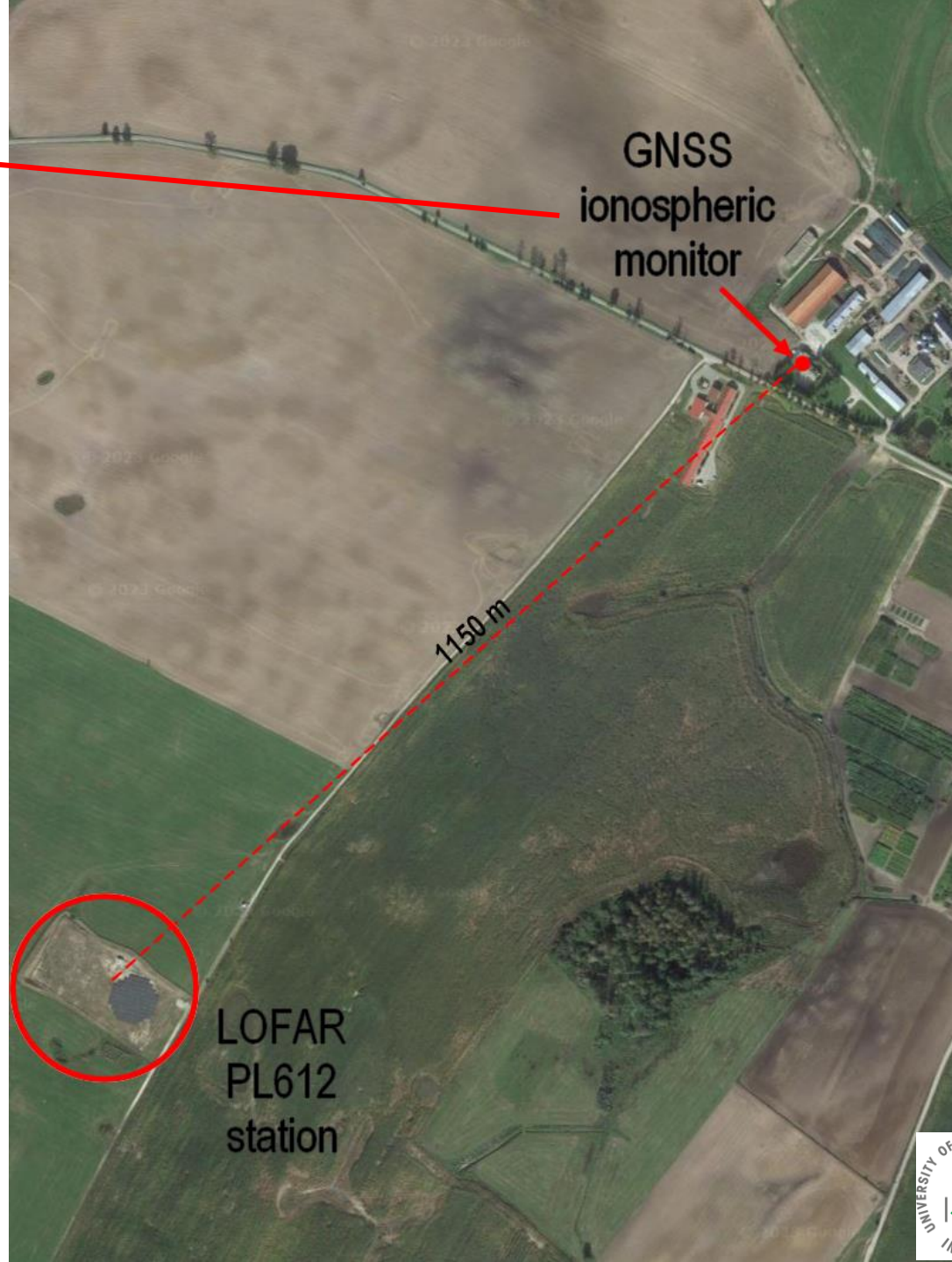
I/Q corr observable (S4 calculation possibility):

Available



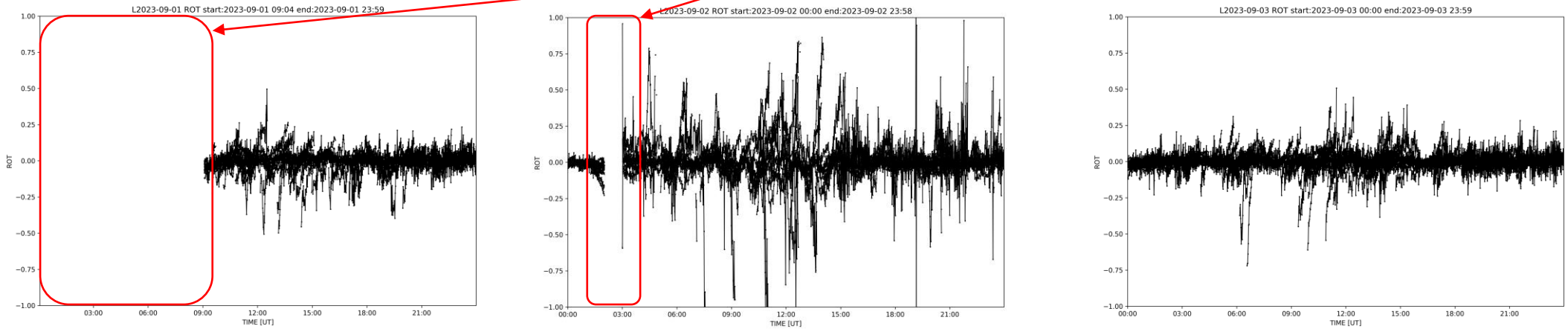
software control section

software control section

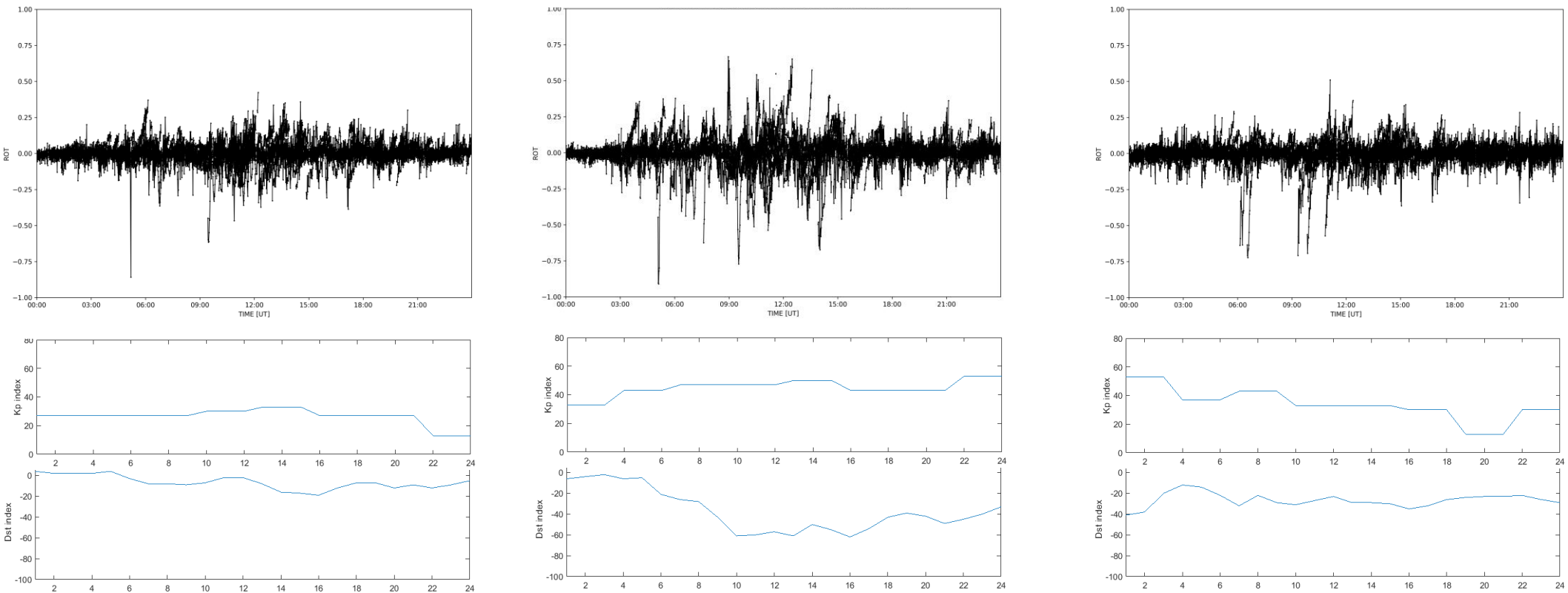


NOTE: occasional data gaps in mosaic series are caused by the external software control unit, not the receiver itself!

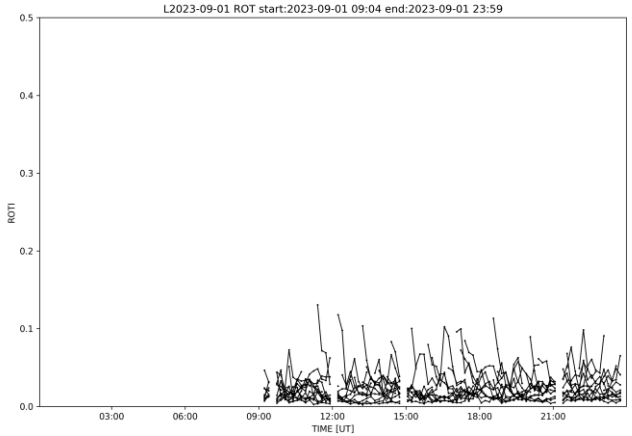
ROT Septentrio Mosaic-X5

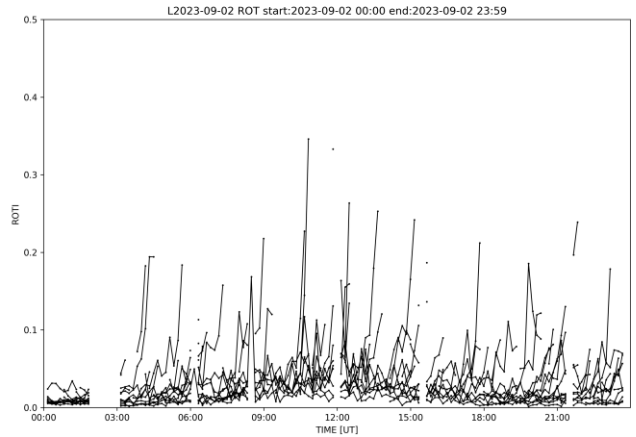


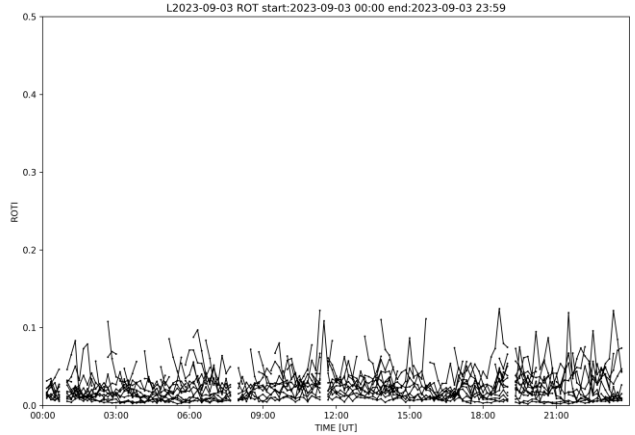
ROT Septentrio PolarX S Pro



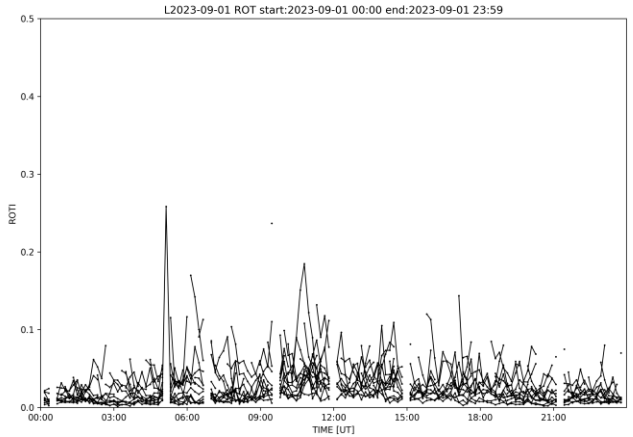
ROTI
(for each satellite)
Septentrio
Mosaic-X5

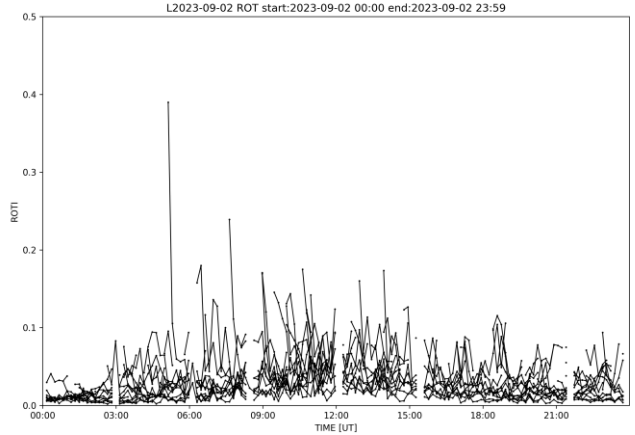


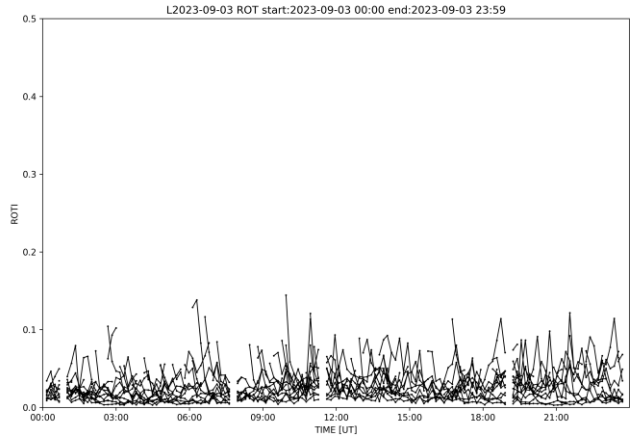


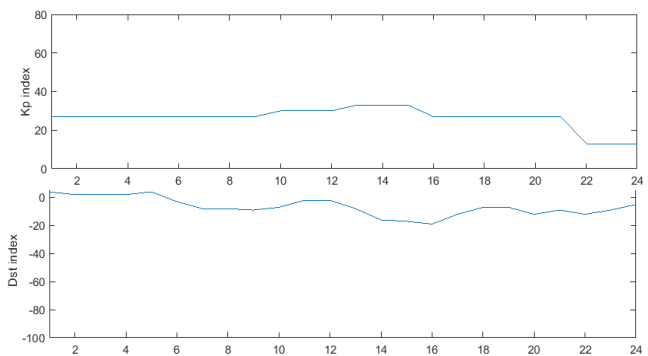


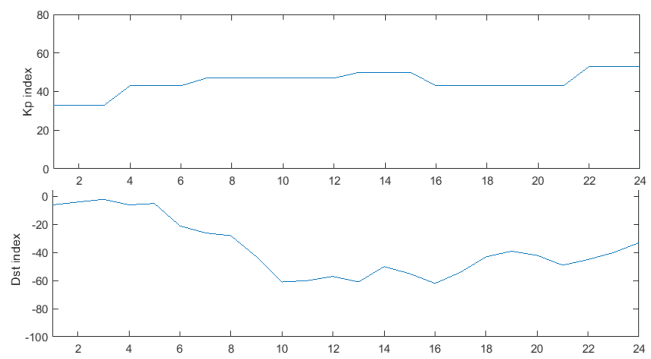
ROTI
(for each satellite)
Septentrio
PolarX S Pro

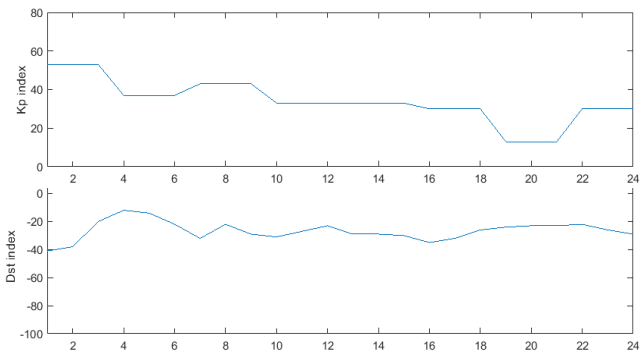












Summary

- Comparison of the „weather” VTEC maps with “climate” counterpart allows rapid evaluation of the anomalous near-space plasma dynamics as it responses to effects in the Sun-Earth system.

- We previously introduced global 30-day average empirical TEC maps into GAMBIT Explorer software used to build deviation maps for ionosonde-derived global maps of the bottomside ionospheric plasma and now suplement them with rapid and RT products based on IGS UPC and IGS CAS contributions as IAACs.

- Combination of IGS and GIRO capabilities brings a possibility of evaluating dynamics of the ionosphere and plasmasphere which real-time performance can be engineered to eventually accomplish below one minute latency of nowcast

- Future work will be mainly concentrated on improving data acquisition and product delivery in order to lower latencies as much as possible.

IGS INTERNATIONAL GNSS SERVICE

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