The IGS Ionosphere working group: Computing, assessing and combining Global Ionospheric Maps during more than 25 years

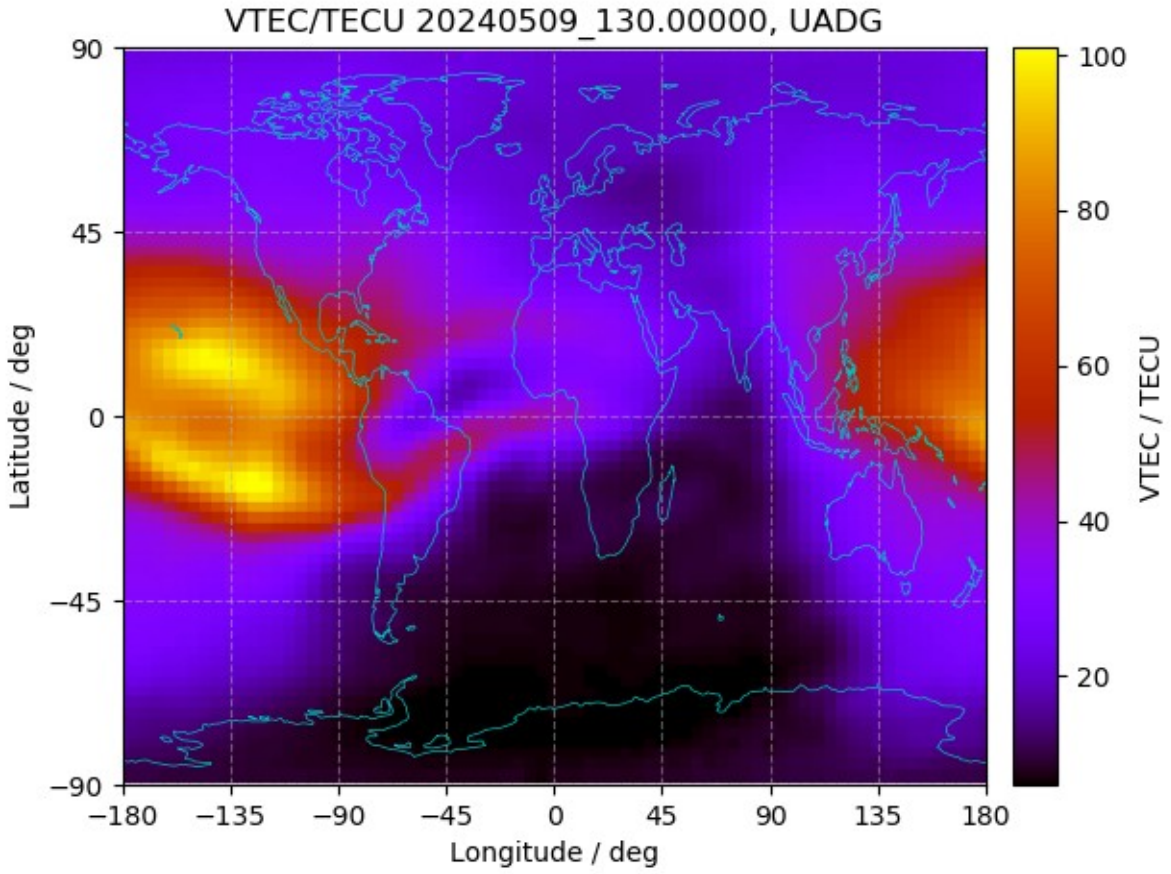
Manuel Hernández-Pajares(1), Andrzej Krankowski(2), Joachim Feltens(3), Stefan Schaer(4), Attila Komjathy(5), Zishen Li(6), Reza Ghoddousi-Fard(7), Adam Fron(2), Alberto García-Rigo(3), & so many IGS Ionosphere WG colleagues & collaborators (see references)

(1) UPC-IonSAT, IEEC-UPC, Barcelona, Spain; (2) University of Warmia and Mazury in Olsztyn, Poland; (3) ESA/ESOC, Darmstadt, Germany; (4) Swisstopo, Univ. Bern and CODE, Switzerland; (5) JPL, Pasadena, CA, USA; (6) Chinese Academy of Science (CAS), Beijing, China, (7) NRCan, Ottawa, Canada

IGS Symposium and Workshop 2024: 30 years of IGS
Bern, Switzerland, 01-05 July 2024

IGS INTERNATIONAL GNSS SERVICE

What is this?


VTEC/TECU 20240509_130.00000, UADG
Latitude / deg
Longitude / deg
VTEC / TECU
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−180
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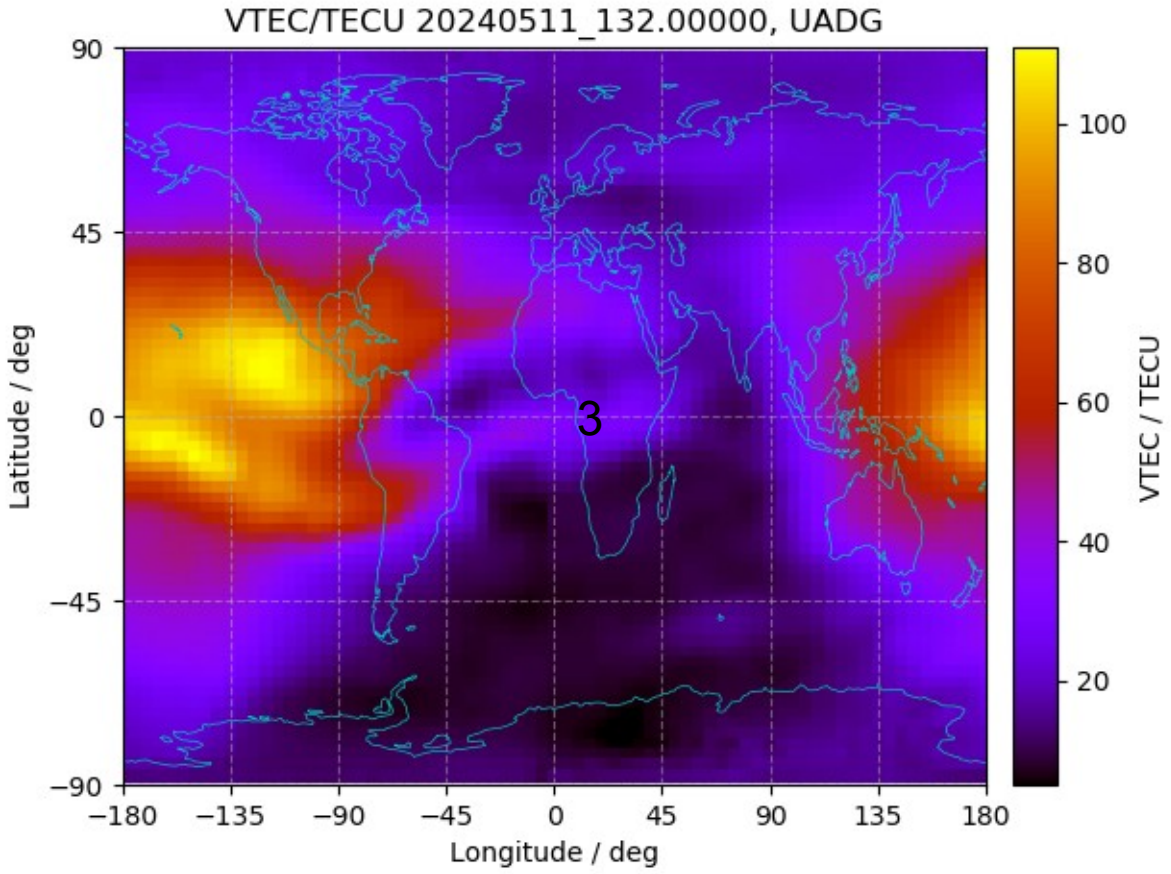
VTEC/TECU 20240511_132.00000, UADG
Latitude / deg
Longitude / deg
VTEC / TECU
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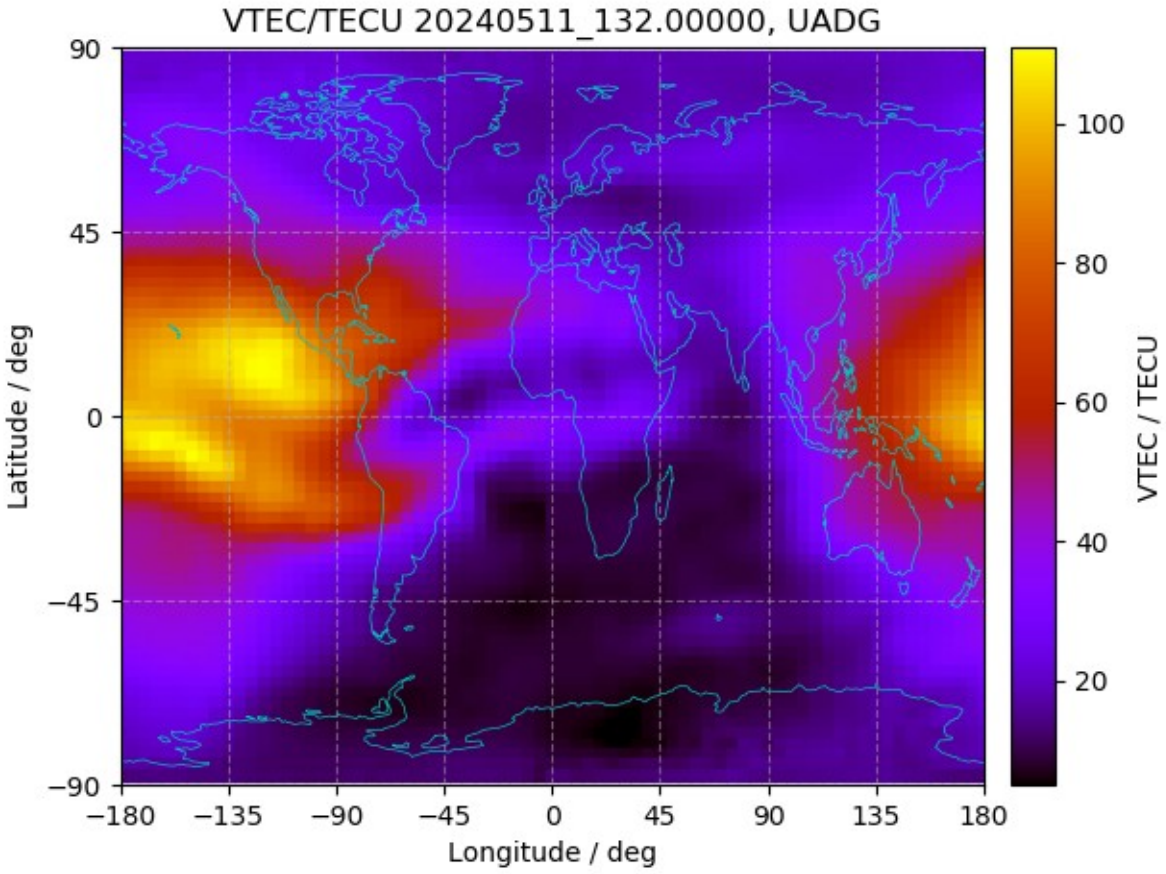
What is this?

Two Global Ionospheric Maps (UQRG) of vertically integrated electron number density (AKA Vertical Total Electron Content, VTEC) of the partially ionized part of the Earth atmosphere (ionosphere) computed from worldwide Global Navigation Satellite System (GNSS) multifrequency measurements by one IGS Ionosphere Associate Analysis Center, and provided in IONEX format.

It corresponds to days 09 May 2024, 00h (left figure in previous slide) and 11 May 2024, 00h (right figure), one day before and during the larger ionospheric storm happened so far in 21 years, respectively.

Do you wish to check the VTEC GIM in RT?

It is also possible from IGS centers! For example:



http://chapman.upc.es/tomion/real-time/quick/last_results.uadg/RT-DAILY-VTEC-MOVIE.gif

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Some hints during +25 years of IGS Ionosphere WG

t0(day 56, 1998): Definition of a robust format for VTEC GIMs

t1(day 152, 1998): The common IGS VTEC GIM started

t2(2009): External validation of IGS VTEC GIMs and beyond

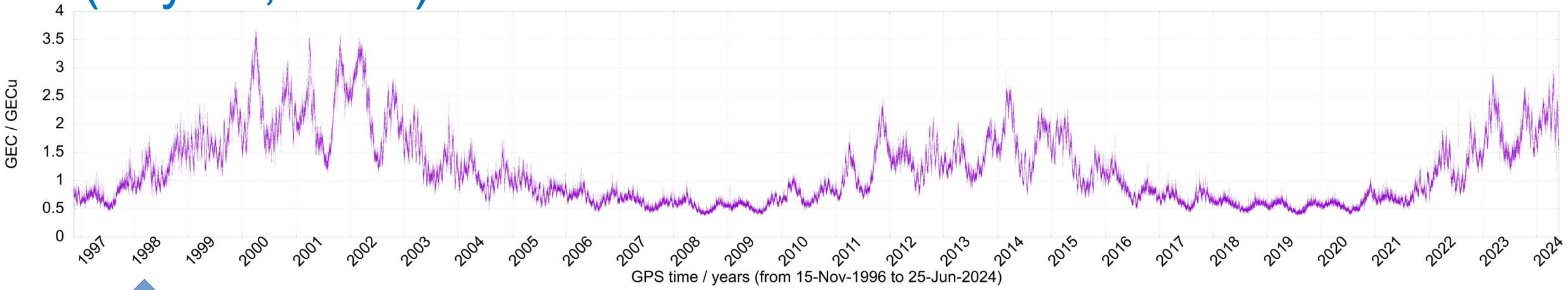
t3(2012): The International GNSS RT Service started

t4(2018): A new campaign of IGS VTEC GIMs external validation

t5(2020): The external validation for RT-GIMs started

t6(2021): The external validation of RT-GIMs is extended

t0(day 56, 1998): Definition of a robust format for VTEC GIMs



t0

IONEX: The IONosphere Map EXchange Format Version 1

Stefan Schaer, Werner Gurtner
Astronomical Institute, University of Berne, Switzerland
stefan.schaer@aiub.unibe.ch

Joachim Feltens
ESA/ESOC, Darmstadt, Germany

February 25, 1998

Proceedings of the IGS AC Workshop, Darmstadt, Germany, February 9–11, 1998

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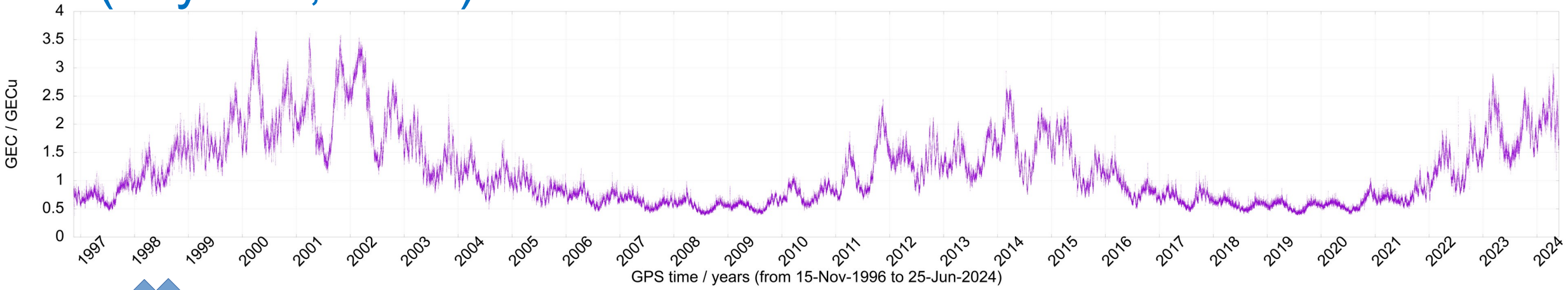
t1 (day 152, 1998): The common IGS VTEC GIM started



t0 t1

Abstract This article is based on a position paper presented at the IGS Network, Data and Analysis Center Workshop 2002 in Ottawa, Canada, 8–11 April 2002, and introduces the IGS Ionosphere Working Group (Iono_WG). Detailed information about the IGS in general can be found on the IGS Central Bureau Web page: http://igscb.jpl.nasa.gov. The Iono_WG commenced working in June 1998. The working group's main activity currently is the routine production of ionosphere Total Electron Content (TEC) maps with a 2-h time resolution and daily sets of GPS satellite and receiver hardware differential code bias (DCB) values. The TEC maps and DCB sets are derived from GPS dual-frequency tracking data recorded with the global IGS tracking network.

Review article

The activities of the Ionosphere Working Group of the International GPS Service (IGS)

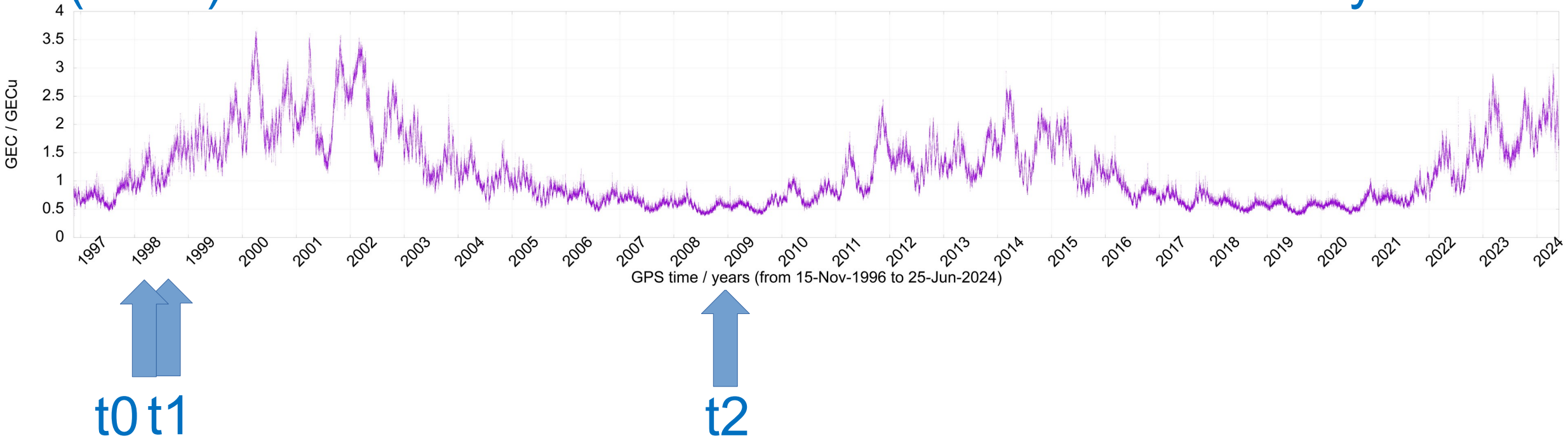
Joachim Feltens

In the medium- and long-term, the working group intends to refine algorithms for the mapping of ionospheric parameters from GPS measurements and to realize near–real–time availability of IGS ionosphere products. The paper will give an overview of the Iono_WG activities that include a summary of activities since its establishment, achievements and future plans.

IGS INTERNATIONAL GNSS SERVICE

*Feltens, Joachim. "The activities of the ionosphere working group of the International GPS Service (IGS)." GPS solutions 7 (**2003**): 41-46.*

t2(2009): External validation of IGS VTEC GIMs and beyond



J Geod (2009) 83:263–275
DOI 10.1007/s00190-008-0266-1

ORIGINAL ARTICLE

The IGS VTEC maps: a reliable source of ionospheric information since 1998

M. Hernández-Pajares · J. M. Juan · J. Sanz ·
R. Orus · A. Garcia-Rigo · J. Feltens · A. Komjathy ·
S. C. Schaer · A. Krankowski

IGS INTERNATIONAL GNSS SERVICE

t2(2009): External validation of IGS VTEC GIMs and beyond

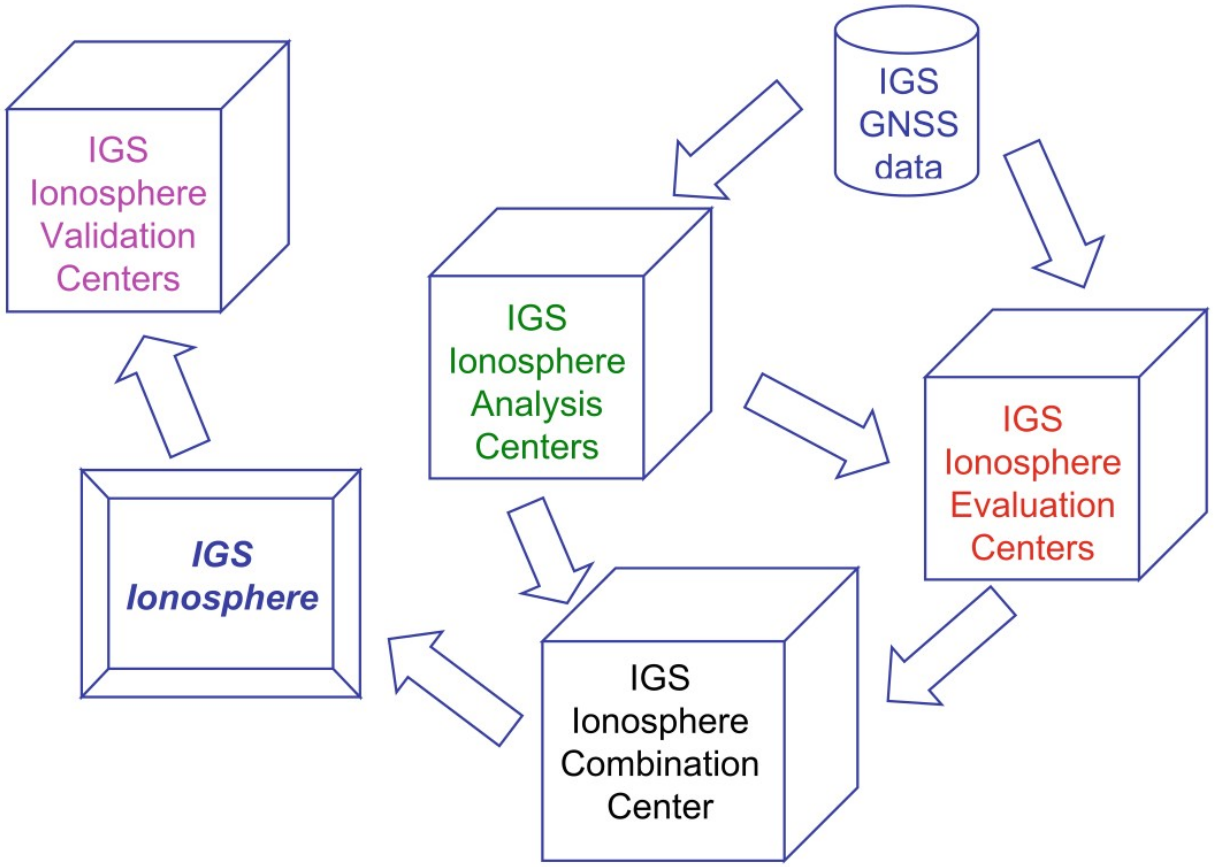


Fig. 1 Diagram showing the data flow required to generate the IGS VTEC maps

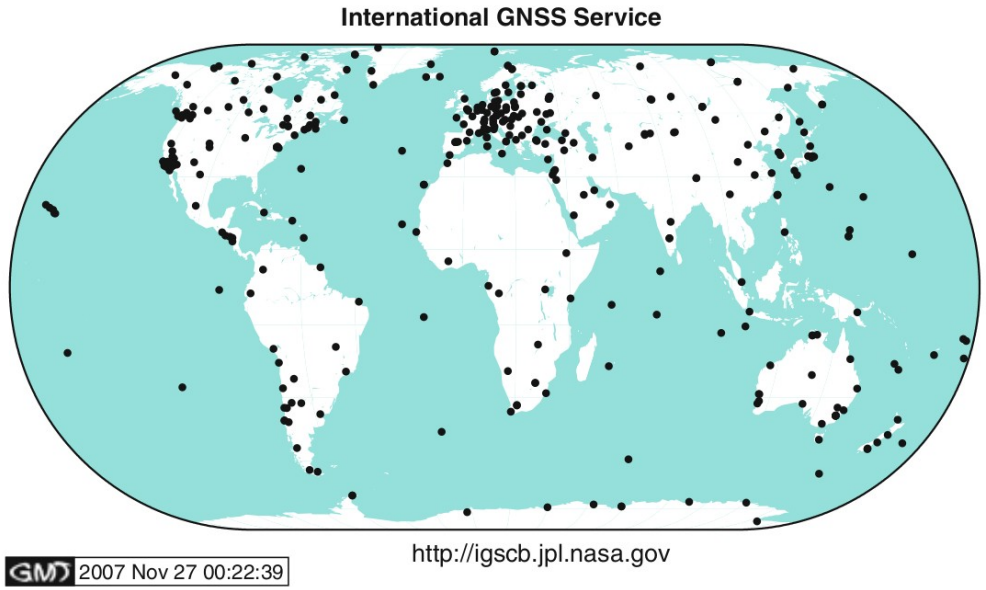
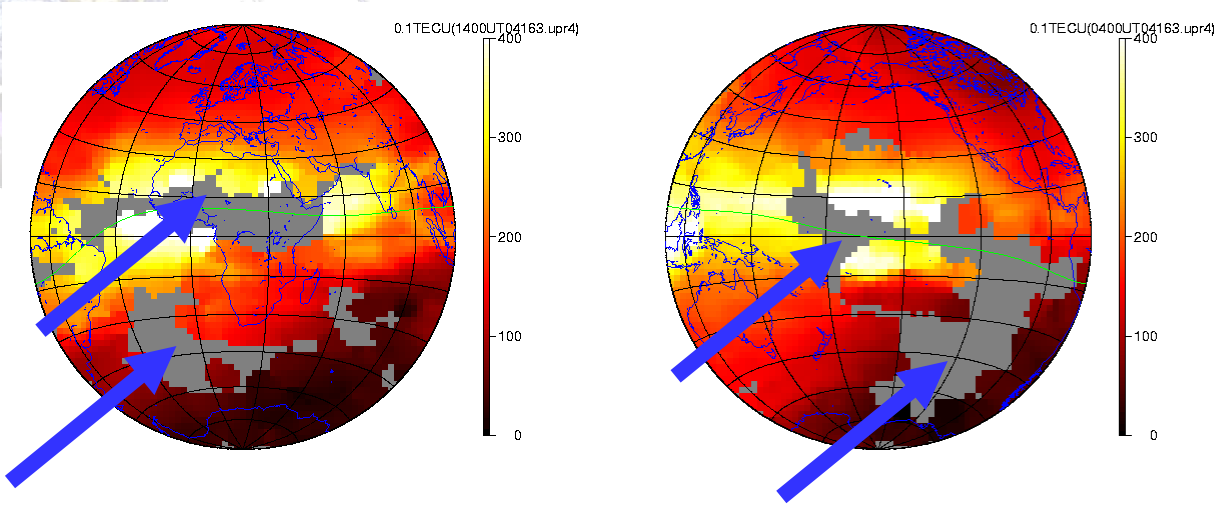


Fig. 2 Map showing the distribution of IGS receivers (as of 26 November 2007)

t2(2009): External validation of IGS VTEC GIMs and beyond



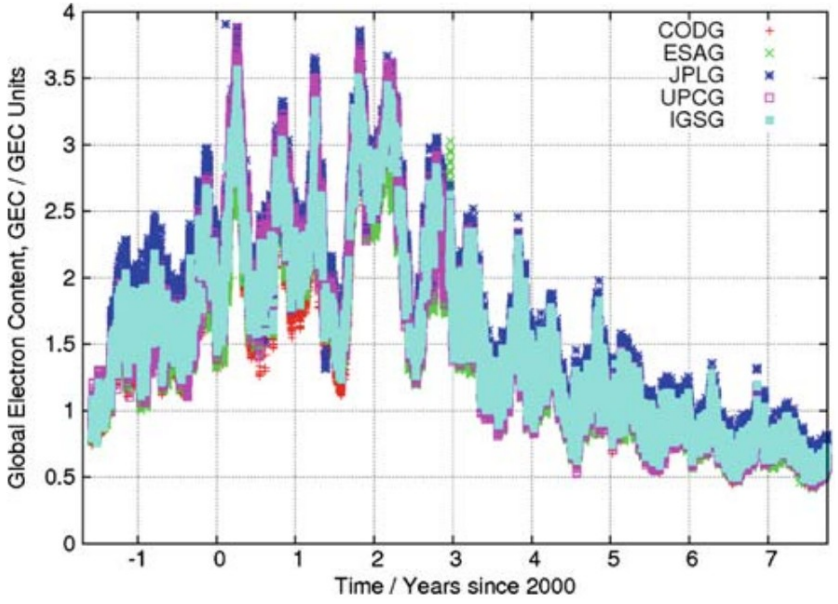
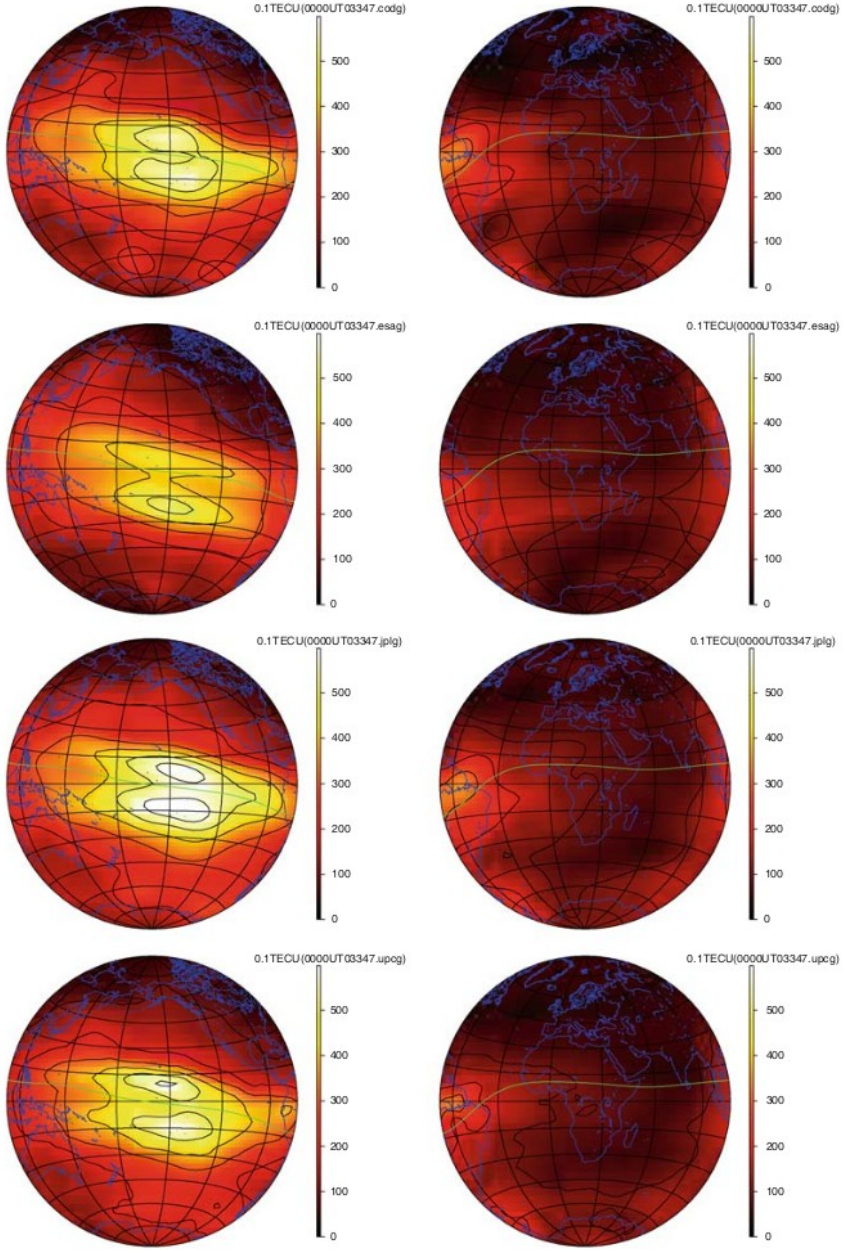


Fig. 18 Global electron content evolution during the availability of IGS Ionospheric products, since 1 June 1998 (source: Final IGS VTEC maps)

Fig. 4 Example of IAAC VTEC maps snapshots, for day 347 (13 Dec) of 2003, at 00UT. Every *row*, from *top* to *bottom*, corresponds to CODE, ESA, JPL and UPC. The units for all maps are tenths of a TECU



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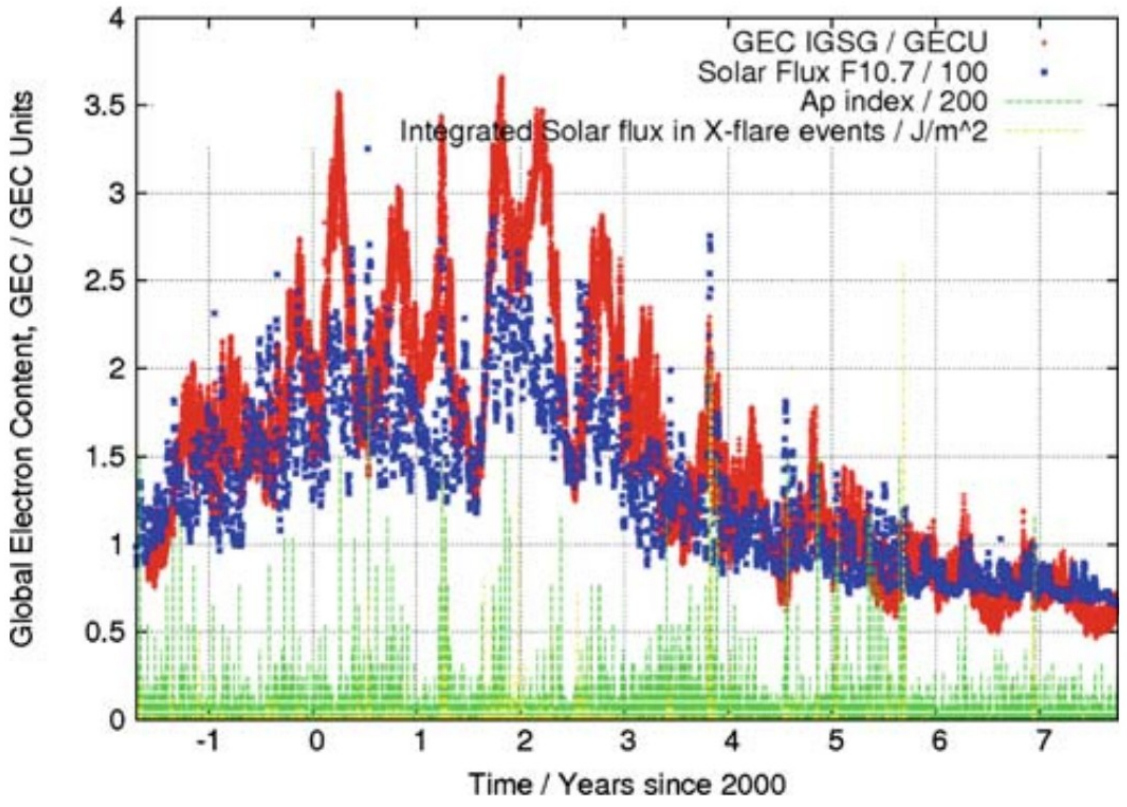
t2(2009): External validation of IGS VTEC GIMs and beyond



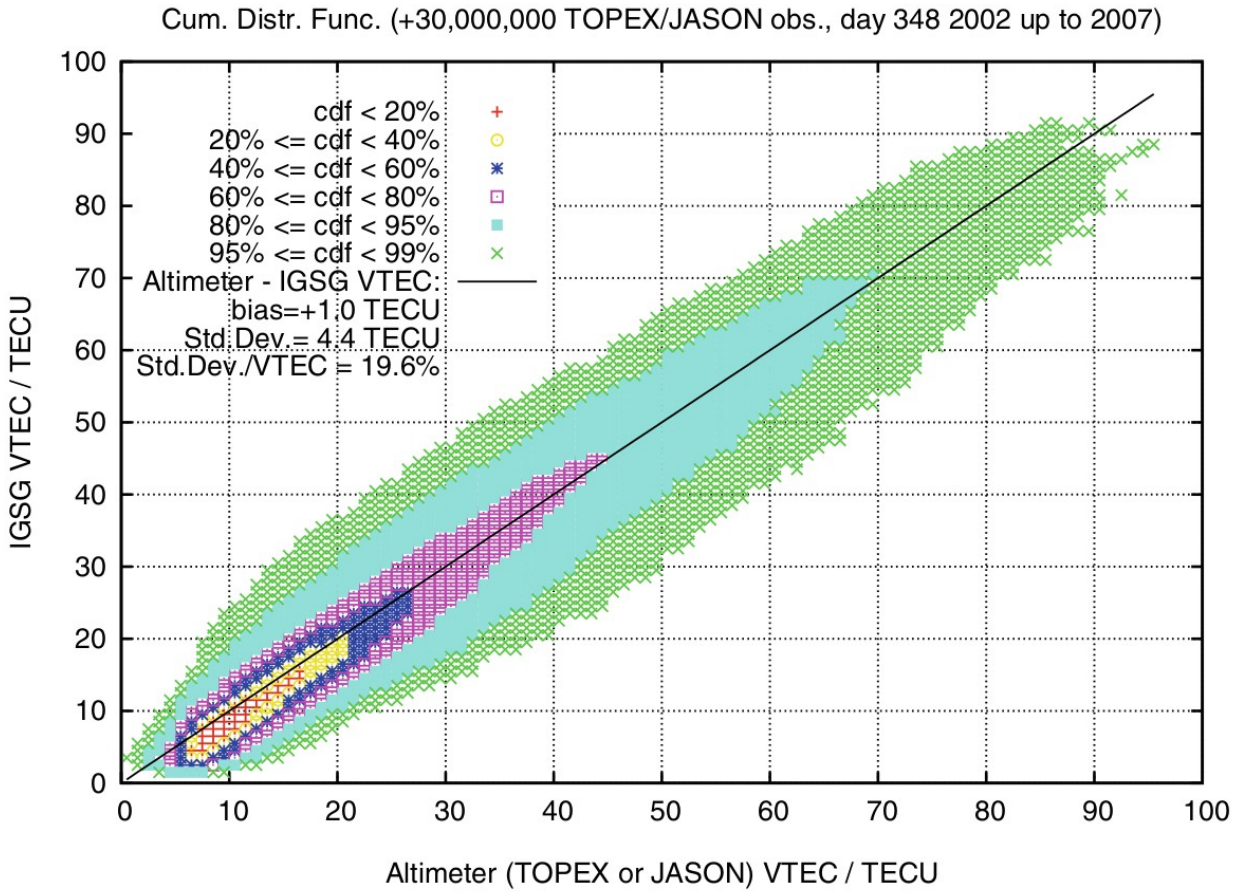
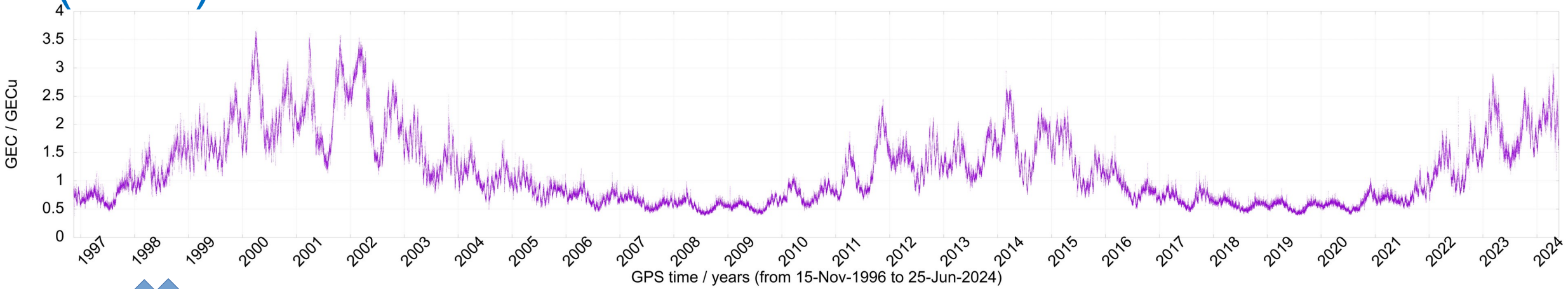


Fig. 20 Global electron content evolution during the availability of IGS Ionospheric products, versus Solar Flux, Ap index and Xray flux, since 1 June 1998 (source: Final IGS VTEC maps)

t3(2012): The International GNSS RT Service started



t0 t1 t2 t3

INNOVATION | Augmentation & Assistance

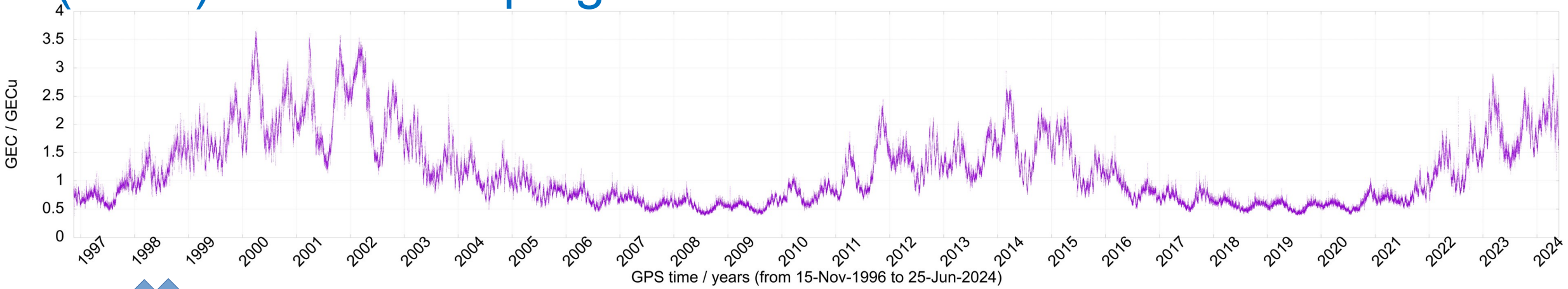
Coming Soon

The International GNSS Real-Time Service

Mark Caissy, Loukis Agrotis, Georg Weber, Manuel Hernandez-Pajares, and Urs Hugentobler

IGS INTERNATIONAL GNSS SERVICE

t4(2018): A new campaign of IGS VTEC GIMs external validation



t0 t1 t2 t3 t4

Journal of Geodesy
https://doi.org/10.1007/s00190-017-1088-9

ORIGINAL ARTICLE

Consistency of seven different GNSS global ionospheric mapping techniques during one solar cycle

David Roma-Dollase[1,2] · Manuel Hernández-Pajares[1] · Andrzej Krankowski[3] · Kacper Kotulak[3] · Reza Ghoddousi-Fard[4] · Yunbin Yuan[5] · Zishen Li[6] · Hongping Zhang[7] · Chuang Shi[7] · Cheng Wang[7] Joachim Feltens[8] · Panagiotis Vergados[9] · Attila Komjathy[9] · Stefan Schaer[10] · Alberto García-Rigo[1] · José M. Gómez-Cama[2]

IGS INTERNATIONAL GNSS SERVICE

t4(2018): A new campaign of IGS VTEC GIMs external validation

Table 1 Summary of the different GIMs assessed in this work

GIM ID	Method	DCB computation	Shell model	Start date	References
IGSG	Weighted mean	Combined	Combined	1998.4	Hernández-Pajares et al. (2009)
CODG	Spherical harmonics	Same time as VTEC	Modified 2-D	1998.4	Schaer (1999)
ESAG[a]	Spherical harmonics	Same time as VTEC	2-D	1998.4	Feltens (2007)
JPLG	Three-shell model	Same time as VTEC	3-D	1998.4	Mannucci et al. (1998)
UPCG	Tomographic with splines	From VTEC	3-D	1998.4	Hernández-Pajares et al. (1999)
UQRG[b,c]	Tomographic with kriging	From VTEC	3-D	2011	Orús et al. (2005)
CASG	Spherical harmonics and generalized trigonometric series	Same time as VTEC	2-D	2016	Li et al. (2015)
EMRG[c]	Spherical harmonics	Same time as VTEC	2-D	1998.4, 2015.3	Ghoddousi-Fard (2014)
WHRG[c]	Spherical harmonics and inequality-constrained least squares	Same time as VTEC	2-D	2016	Zhang et al. (2013)
WHUG	Spherical harmonics and inequality-constrained least squares	Same time as VTEC	2-D	2016	Zhang et al. (2013)

[a]A 3D multilayer assimilation model is currently under development by ESA. [b]The time interval of UQRG is 15 min, in contrast with the other GIMs which have a time interval of 2 h. [c]UQRG, EMRG and WHRG are rapid GIMs with a latency of less than two days, in contrast with the other final GIMs which have a latency about 1 week

t4(2018): A new campaign of IGS VTEC GIMs external validation

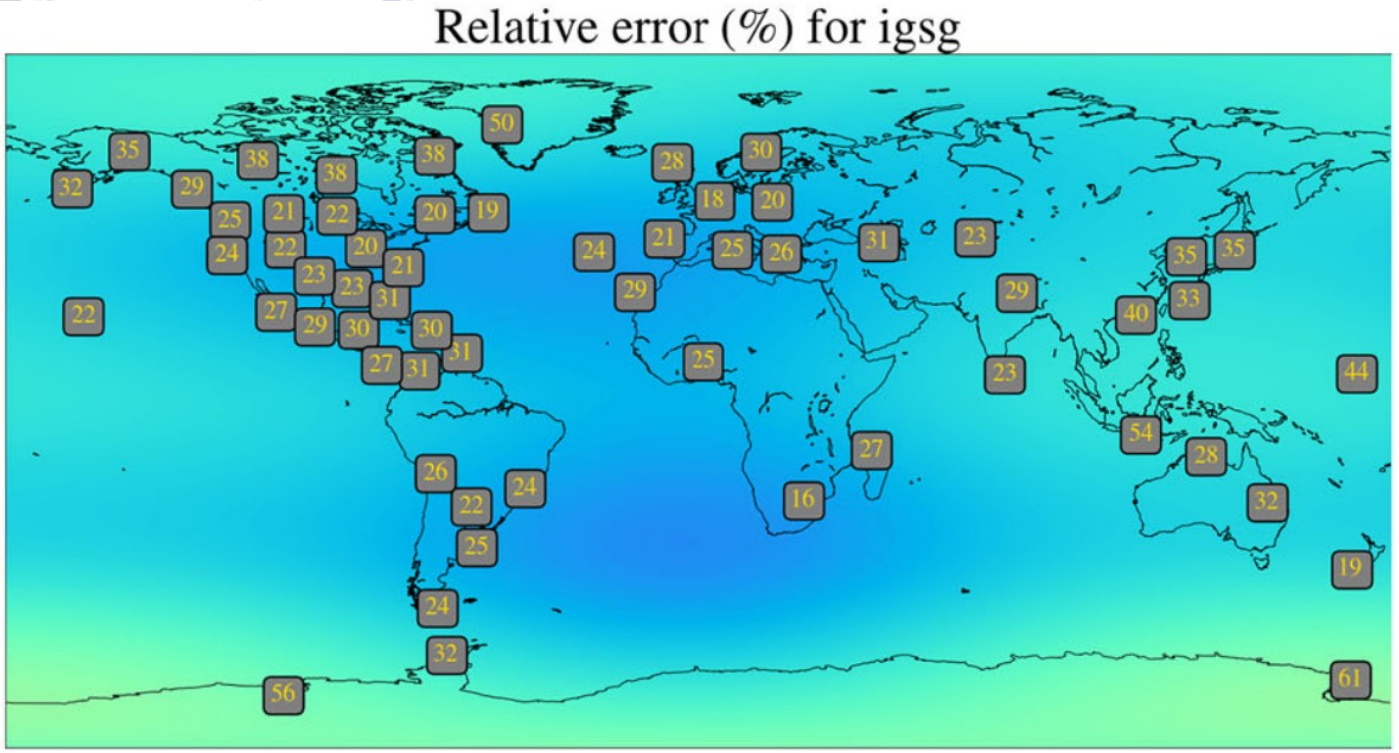


Fig. 8 Map approximating the spatial distribution of dSTEC relative error for classical IGS GIMs (left hand column, for IGSG,

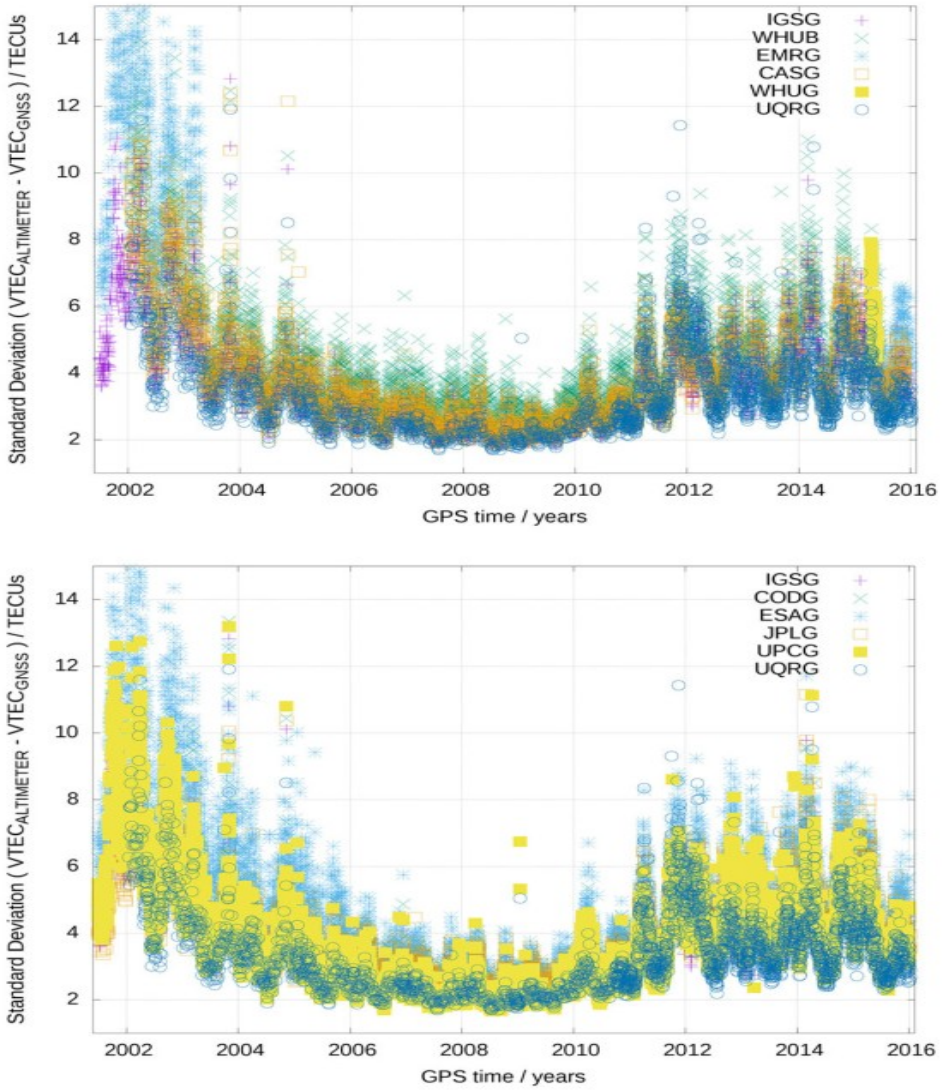
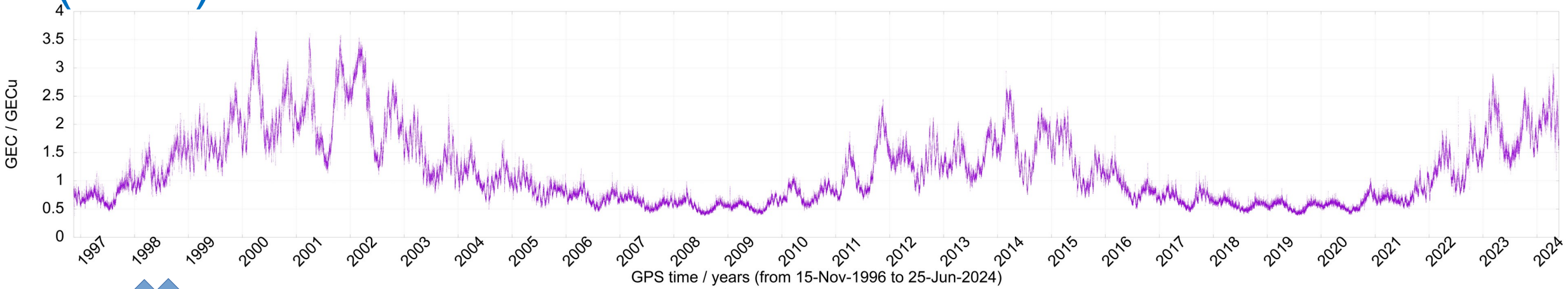


Fig. 3 Daily standard deviation of the VTEC difference regarding altimeter VTEC measurements, involving new GIMs (top plot) and classical GIMs (bottom plot). The comparison has been performed over the same dataset referenced in Fig. 1

IGS INTERNATIONAL GNSS SERVICE

t5(2020): The external validation for RT-GIMs started



t0 t1 t2 t3 t4 t5

Journal of Geodesy (2020) 94:32
https://doi.org/10.1007/s00190-020-01360-0

ORIGINAL ARTICLE

Check for updates

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

Zishen Li[1,2] · Ningbo Wang[1,3] · Manuel Hernández-Pajares[4] · Yunbin Yuan[2] · Andrzej Krankowski[5] · Ang Liu[1,6] · Jiuping Zha[2,6] · Alberto García-Rigo[4] · David Roma-Dollase[4] · Heng Yang[4] · Denis Laurichesse[7] · Alexis Blot[7]

Received: 8 July 2019 / Accepted: 3 February 2020

IGS INTERNATIONAL GNSS SERVICE

t5(2020): The external validation for RT-GIMs started

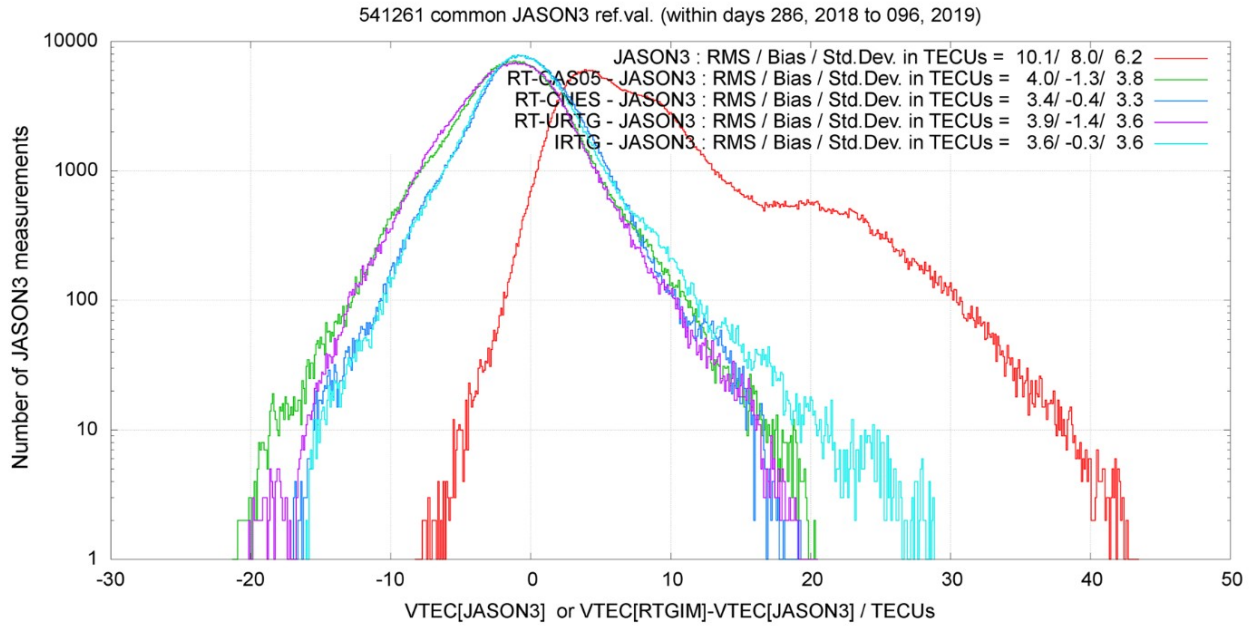


Fig. 9 Histogram, in log-scale for the number of counts, of the VTEC difference of Jason-3 measurement minus RT-GIM value during days 286 in 2018 to 096 in 2019 for RT-GIMs of CAS (green), CNES (dark blue), UPC (magenta) and IGS combined one (light blue). The histogram of the reference values of Jason-3 is represented in red

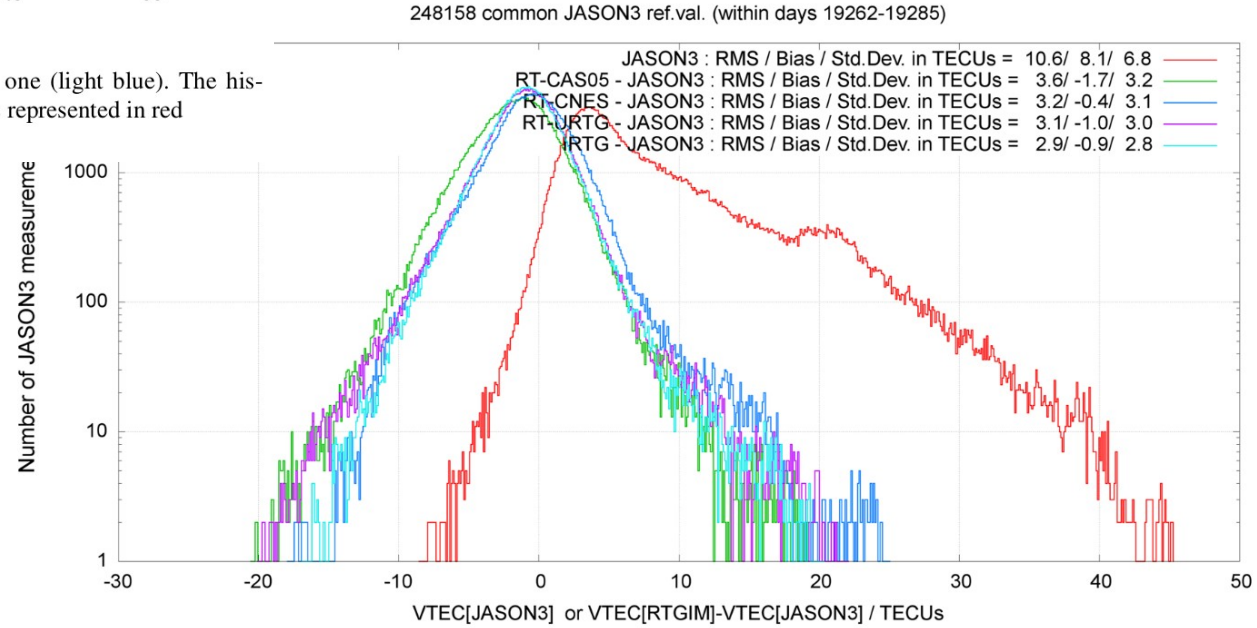
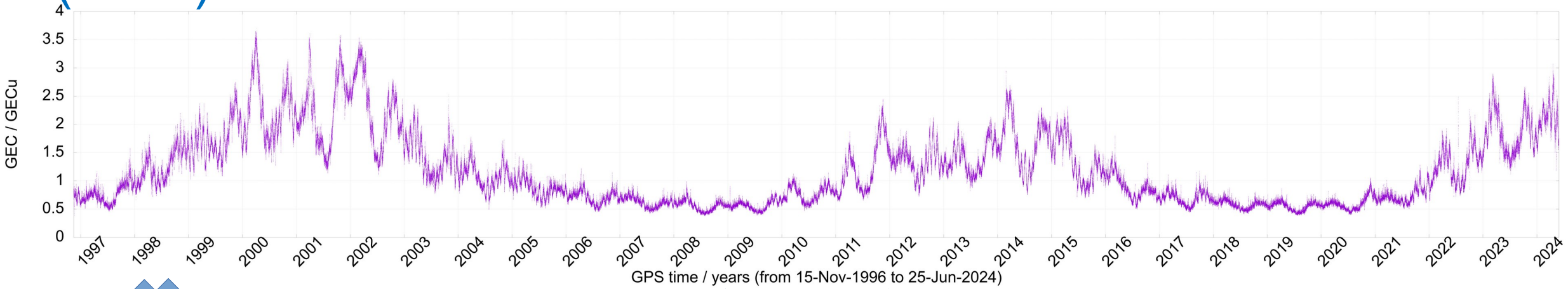


Fig. 11 Same as Fig. 9 but presenting the result after the recent update of UPC RT-GIM interpolation strategy during days 262 and 285 in 2019

t6(2021): The external validation of RT-GIMs is extended



t0 t1 t2 t3 t4 t5 t6

Earth Syst. Sci. Data, 13, 4567–4582, 2021
https://doi.org/10.5194/essd-13-4567-2021

Open Access Earth System Science Data

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]

IGS INTERNATIONAL GNSS SERVICE

t6(2021): The external validation of RT-GIMs is extended

Table 2. The current status of broadcasting IGS RT-GIMs.

Agency	Temporal resolution	Broadcast frequency	Spherical harmonic degree	Mount points in NTRIP caster	Real-time IONEX saved at FTP/HTTP
CAS	5 min	1 min	15	123.56.176.228:2101/CAS05[a] 59.110.42.14:2101/SSRA00CAS1[b] 59.110.42.14:2101/SSRA00CAS0[a] 59.110.42.14:2101/SSRC00CAS1[b] 59.110.42.14:2101/SSRC00CAS0[a] 182.92.166.182:2101/IONO00CAS1[b] 182.92.166.182:2101/IONO00CAS0[a]	ftp://ftp.gipp.org.cn/product/ionex/ (last access: 10 September 2021) (update at the end of day)
CNES	2 min	1 min	12	products.igs-ip.net:2101/CLK91[a] products.igs-ip.net:2101/SSRA00CNE1[b] products.igs-ip.net:2101/SSRA00CNE0[a] products.igs-ip.net:2101/SSRC00CNE1[b] products.igs-ip.net:2101/SSRC00CNE0[a]	No
UPC (only UADG)	15 min	15 s	15	products.igs-ip.net:2101/IONO00UPC1[b]	http://chapman.upc.es/tomion/real-time/quick/ (last access: 10 September 2021) (UADG and USRG, update every 15 min)
WHU	5 min	1 min	15	58.49.58.150:2106/IONO00WHU0[a]	No
IGS	20 min	15 s	15	products.igs-ip.net:2101/IONO00IGS1[b]	http://chapman.upc.es/irtg/ (last access: 10 September 2021) (update every 20 min)

[a] RTCM-SSR format.
[b] IGS-SSR format.

t6(2021): The external validation of RT-GIMs is extended

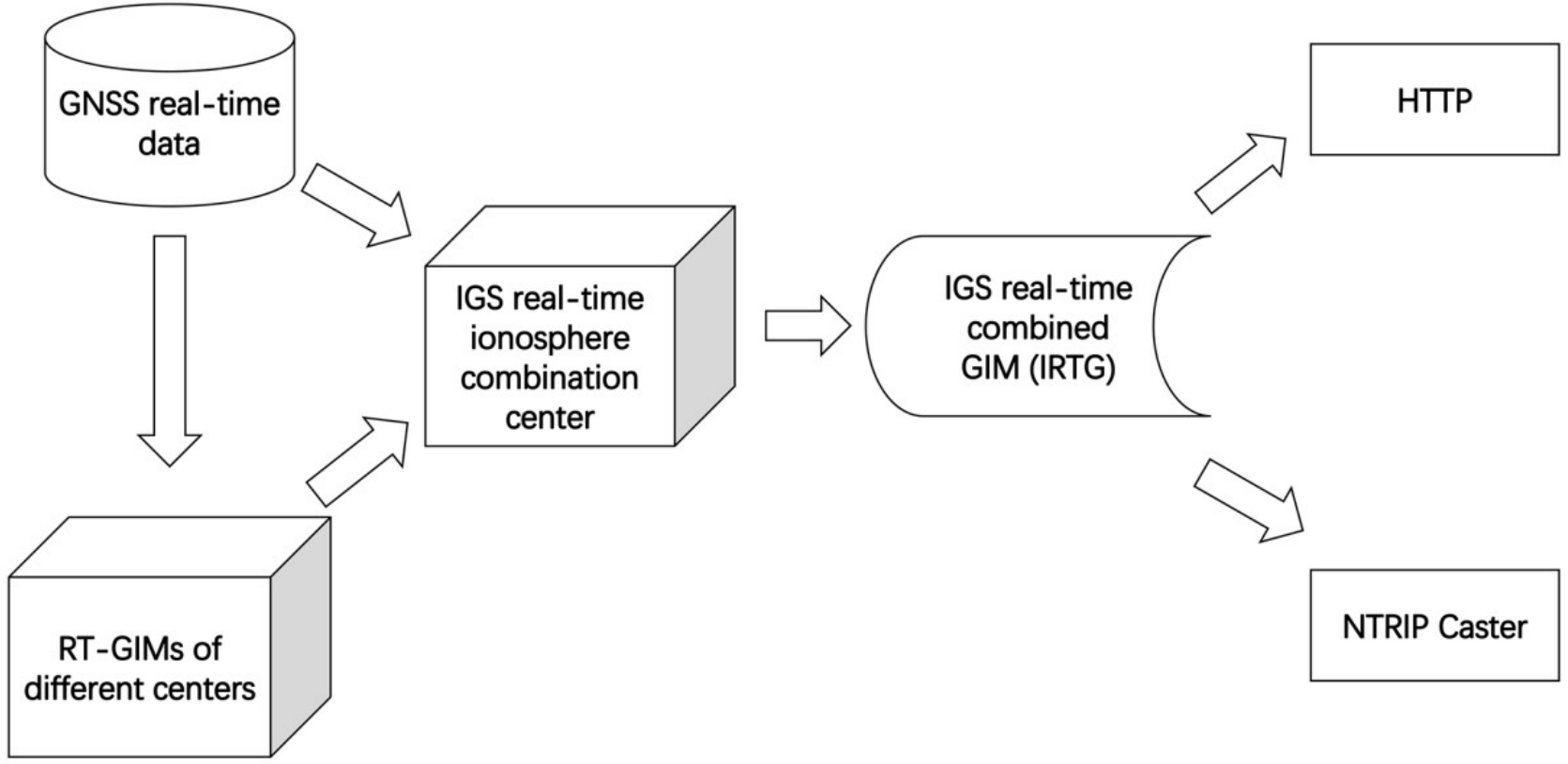


Figure 2. Data flow for the IGS real-time combined GIM.

t6(2021): The external validation of RT-GIMs is extended

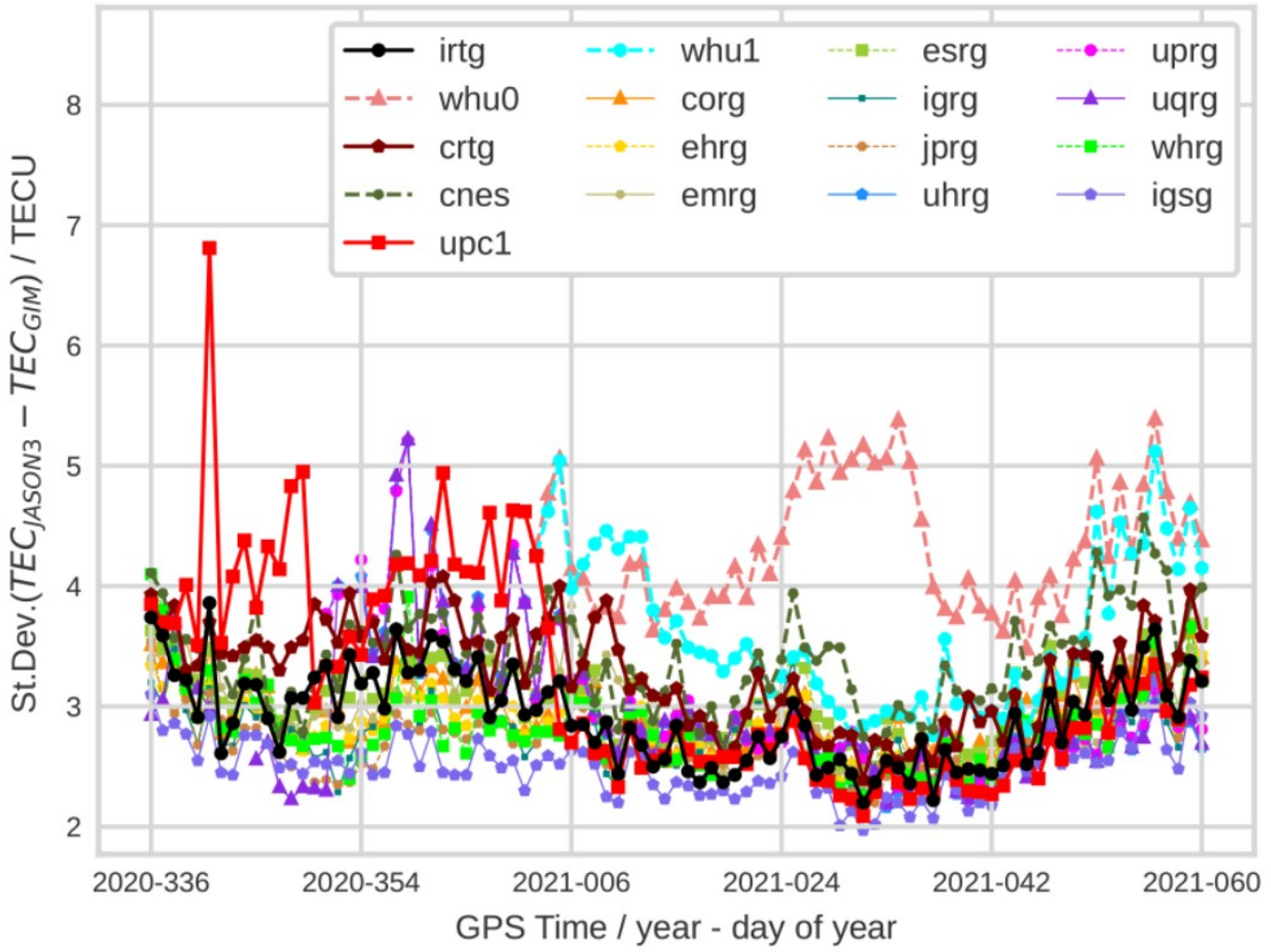


Figure 3. Daily standard deviation of GIM VTEC versus measured Jason-3 VTEC (in TECU), from 1 December 2020 to 1 March 2021.

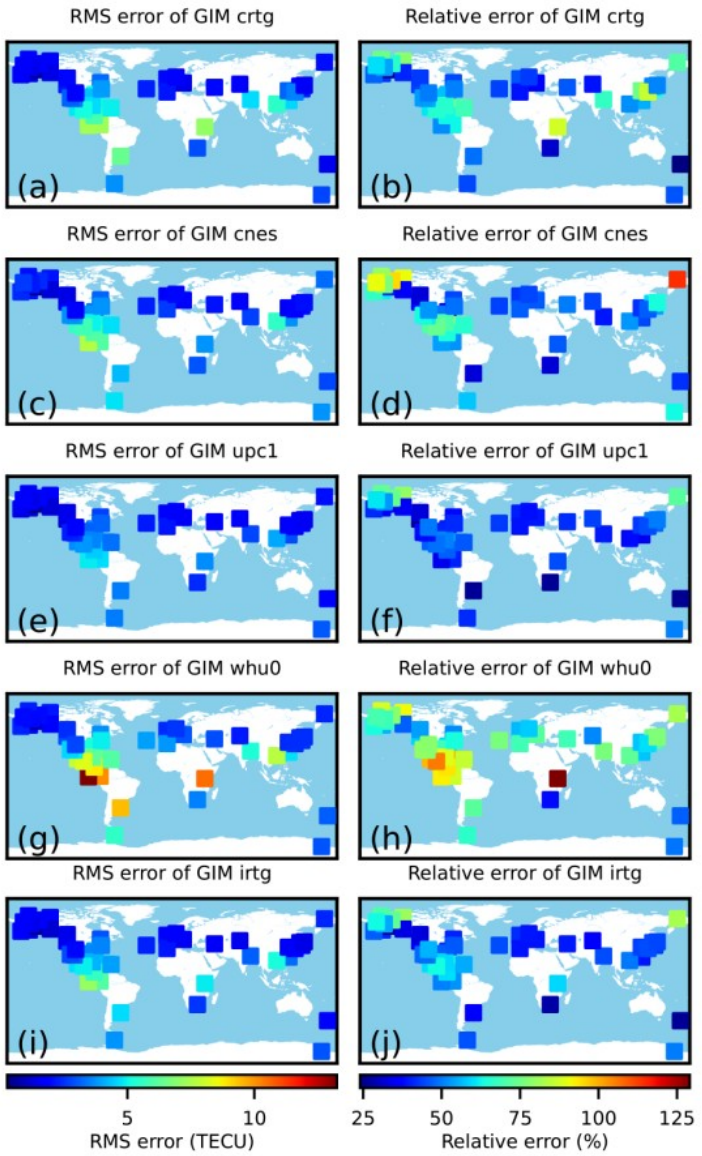


Figure 4. The distribution of dSTEC-GPS results on 5 January 2021 (after the improvement of the UPC interpolation technique).

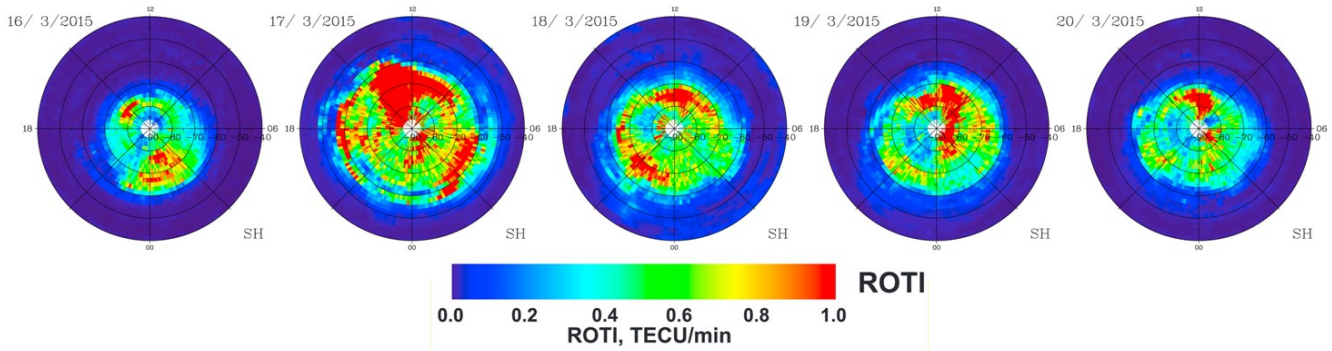
IGS INTERNATIONAL GNSS SERVICE

& products beyond GIMs borned below IGS Iono. WG umbrella...

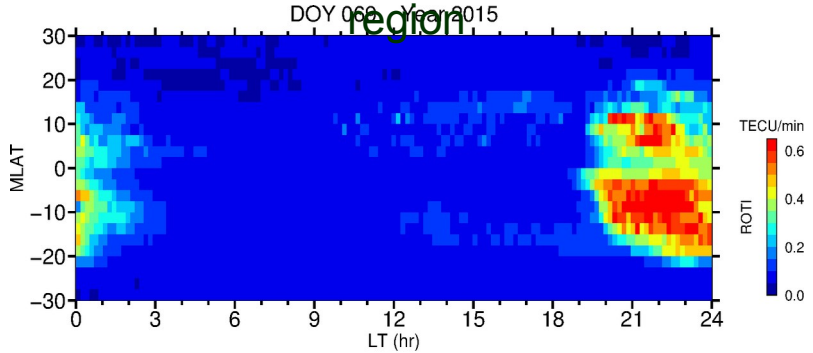
IGS ROTI Maps Product (since 2015)

- **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**

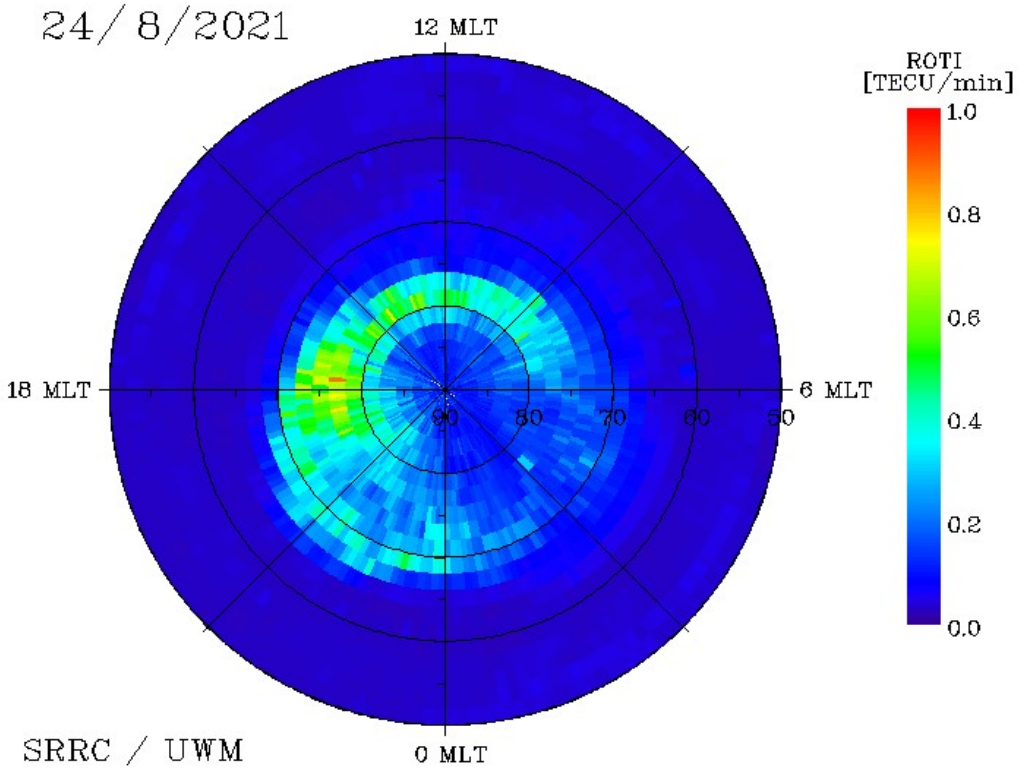
ROTI Maps for Southern Hemisphere



ROTI Maps for Low Latitudional region



ROTI Maps for Northen Hemisphere



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

Cherniak et al., GPS Solution, 2018

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& products beyond GIMs borned below IGS Iono. WG umbrella...

Advances in Space Research
Available online 9 December 2023
In Press, Corrected Proof ⓘ What's this?

GNSS Solar Astronomy in real-time during more than one solar cycle

Manuel Hernández-Pajares [a b], Alberto García-Rigo [b a], Enric Monte-Moreno [c], Qi Liu [d a], David Roma-Dollase [b a], Heng Yang [e a], Yannick Béniguel [f], David Moreno-Borràs [a], Octavi Fors [g], Haixia Lyu [h a], Raul Orus-Perez [i], Javier Ventura-Traveset [j]

Space Weather
RESEARCH ARTICLE
10.1029/2020SW002441

Key Points:
- The simultaneous determination of stellar EUV flares in time and location with the existing GNSS infrastructure is presented
- It is based on the modeling of the Earth ionosphere electron content increase, from dual-frequency GNSS data, due to the stellar flare

Real-Time Detection, Location, and Measurement of Geoeffective Stellar Flares From Global Navigation Satellite System Data: New Technique and Case Studies

Manuel Hernández-Pajares[1] and David Moreno-Borràs[1]

[1] Department of Mathematics, Universitat Politècnica de Catalunya, UPC-IonSAT and IEEC-UPC res. groups, Barcelona, Spain

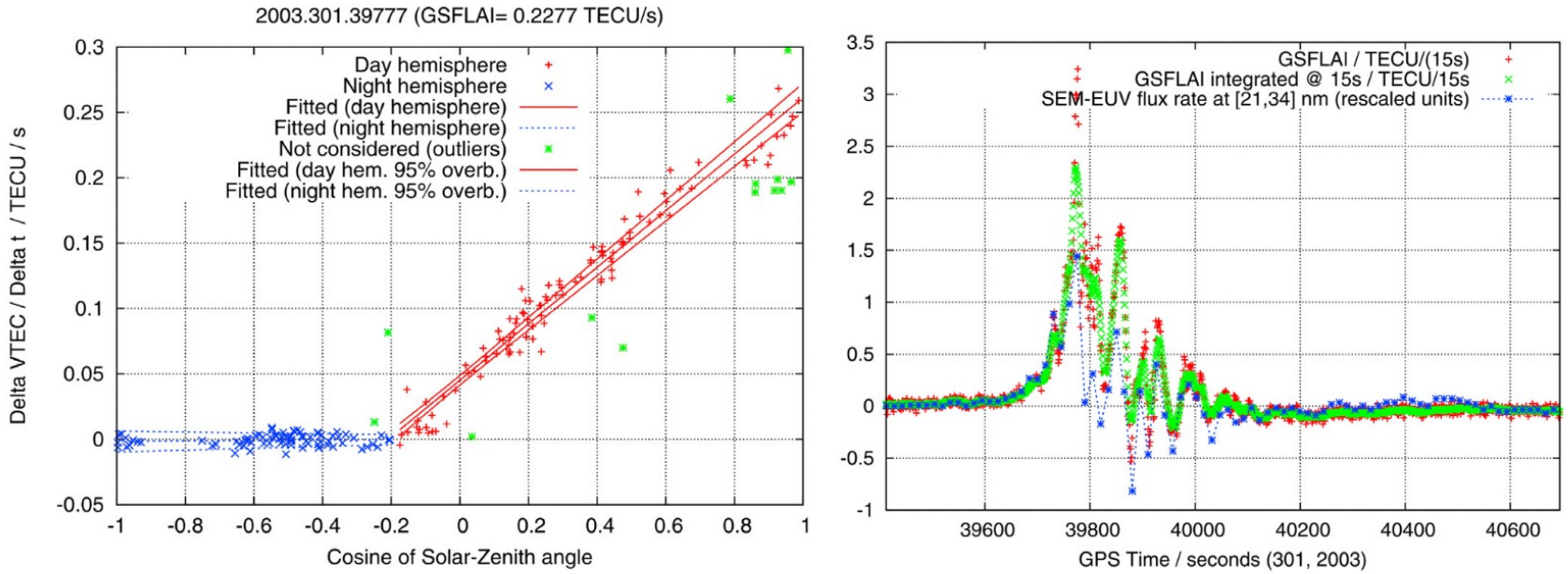

Fig. 2. Left-hand plot: Detrended VTEC rate, $\dot{V}$, vs cosine of solar-zenithal angle, cos χ, for a major solar flare and the associated ionospheric super-storm during October 28th, 2003, precursor flare of Halloween storm (X17.2 flare, day 301, 2003, 39777s of GPS time). Right-hand plot: GSFLAI results compared with SEM EUV flux rate at [21,34]nm band, $\dot{E}$, provided by SOHO during representative X-class solar flares, and rescaled as $0.502 \times \dot{E}/1.5 \times 10^8$/photons/cm^2/s (extracted from Hernández-Pajares et al. (2012)).

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Conclusions and potential evolution considering recent results

-The **International GNSS Service Ionosphere Working Group** has been **improving the generation, assessment and consistent combination, providing millions of VTEC GIMs** (i.e. tens of thousands millions of VTEC value and VTEC error RMS estimations) since it started in June 1st, 1998.

-This successful experience of **friendly collaboration, motivation and learning in common** between worldwide research teams has been **extended to 24/7 real-time service** with a similar success.

-**New operative ionospheric products** for the community were created **under the IGS Ionosphere WG unmbrella**: **ROTI maps** (distributed through CDDIS) and **RT GNSS Solar EUV flux rate proxy.**

-Recent results suggest potential ways of extending the ionospheric products, for instance, towards:
i) **The generation of GIMs of electron density**. One motivation is its high sensitivity as potential tracers to natural hazards, e.g. **to detect tsunami signatures** from the tomographic model used to run some of IGS GIMs (Alfonsi et al. 2024), and also from GNSS LEO POD data (Yang et al. 2022).
ii) **The generation of GIMs of VTEC gradient:** it has been recently demonstrated (Liu et al. 2022) that the VTEC GIMs are able to provide realistic VTEC gradients, **important e.g. for civil aviation**.
iii) **The generation of GIMs of Space Weather activity semaphors**, once it has been recently demonstrated that they can be realistically generated from the VTEC GIMs (Liu et al. 2021) and that which forecasting might **facilitate precise warnings of SW activity affecting GNSS users**.

And the comprehensive Tsunami Early-Warning Cubesat mission looking for international support

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Tsunami Early-Warning CubeSat Design Reference Mission (DRM)

Global constellation for near real-time detection, characterization, and warning of dangerous tsunami; detection and evaluation of large earthquakes and volcanic eruptions; and study and continuous monitoring of the ionosphere and climate change.

https://ntrs.nasa.gov/api/citations/20230003987/downloads/NASA%20TM%2020230003987.pdf

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THANK YOU Prof. Oscar Lucas Colombo (July 16, 1942 — June 1, 2024). Rest in peace

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