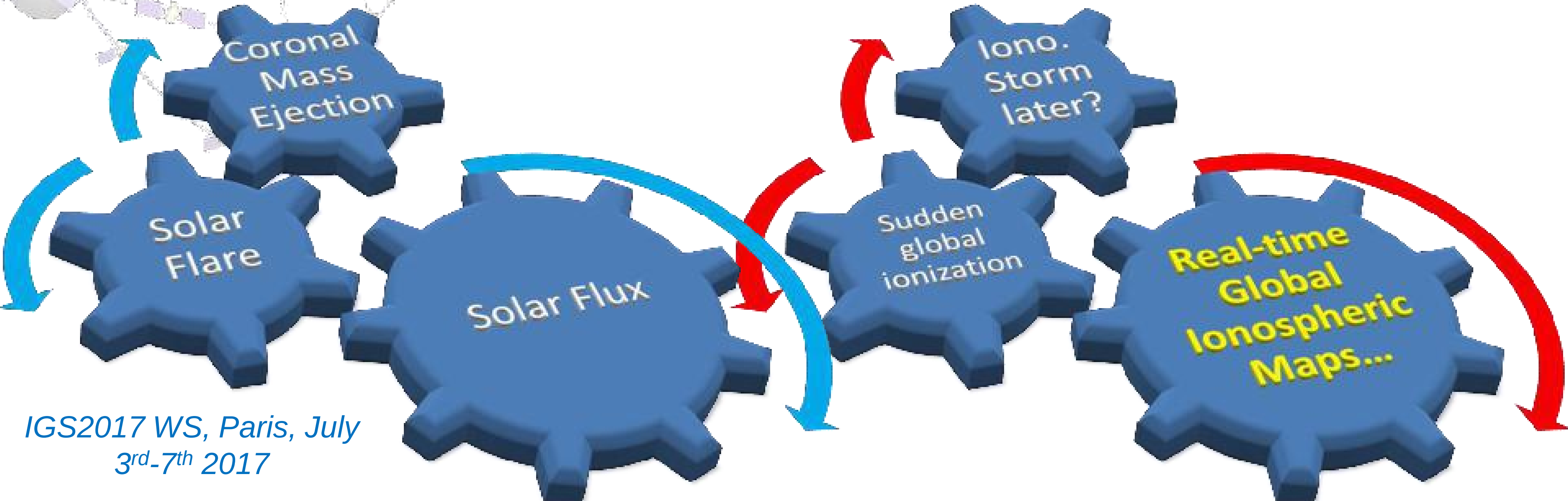
Examples of IGS real-time Ionospheric information benefits: Space Weather monitoring, precise farming and RT-GIMs



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Presented by Manuel Hernández-Pajares(1,2) and David Roma-Dollase (3,1)
(1) UPC-IonSAT, *Technical University of Catalonia (UPC), E08034-Barcelona, Spain*
[contact e-mail : manuel.hernandez@upc.edu]

With different contributions as well from Alberto García-Rigo(1), Denis Laurichesse(4), Michael Schmidt(5), Eren Erdogan(5), Yunbin Yuan(6) , Zishen Li(7), José Ma. Gómez-Cama(3), Andrzej Krankowski(8), Haixia Lyu(9,1), Fabricio S. Prol(10) and many others
(2) CRAE-IEEC, Spain, (3) Department of Engineering Electronics, UB, Spain, (4) CNES, France, (5) DGF TUM, Germany, (6) Institute of Geodesy and Geophysics, CAS, China, (7) Academy of Opto-Electronics, CAS, China, (8) Geodynamics Research Laboratory, UWM, Poland, (9) Wuhan University, China, (10) Universidade Estadual Paulista, Brazil

Outline

Three on-going applications of the dual-frequency GNSS measurements available in real-time from hundreds of IGS permanent receivers will be presented: in the fields of Space Weather, Precise Farming and Real-Time Global Ionospheric Maps, focusing in the last one.

On-going applications of RT-IGS datastreams @ UPC-IonSAT

A) Space Weather: RT detection and estimation of the solar EUV flux rate, during solar flares with SISTED and GSFLAI GNSS indices. Maps of ionospheric scintillation (ROTI) and Medium Scale Travelling Ionospheric Disturbances (MSTID) activity proxies are also produced (started under MONITOR ESA project –see oral presentation of Alberto García-Rigo in ionospheric subsession-).

B) Precise farming: Improvement of precise RT positioning with Wide Area RTK technique and open-source software user receivers for the agriculture improvement in South Europe, where ionospheric modelling challenges, sparse GNSS networks and less funding availability for farmers coincide (ongoing AUDITOR H2020 EC project).

C) RT-GIMs: opportunities for combined IGS product

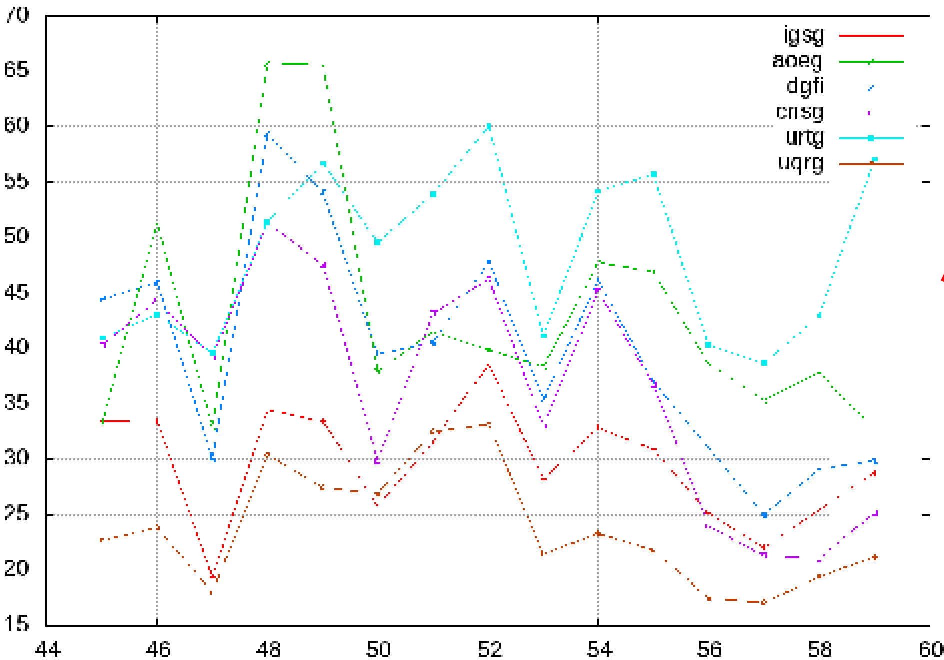
Real-time GIMs

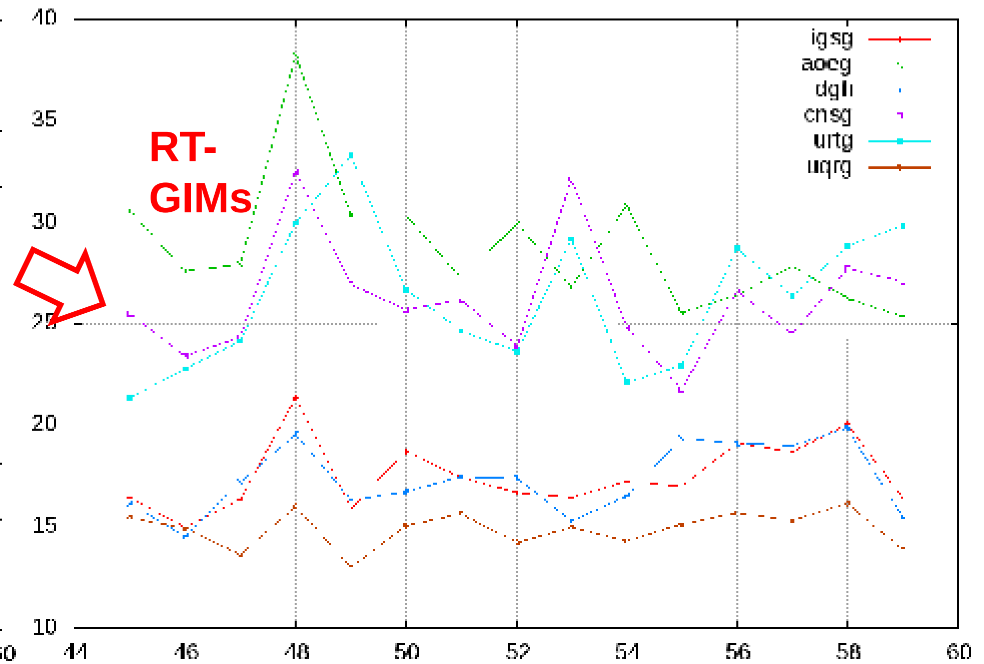
The availability of the IGS RT datastreams with latencies of less than few seconds, containing the multi-frequency, multi-constellation GNSS measurements of hundreds of worldwide permanent receivers, is being crutial to extend the computation of ionospheric models in real-time at continental or global scale.

We are going to summarize some recent initiatives, comparison and results in this regard, since IGS2016 WS:

1) Recent comparison of some RT and NRT VTEC models (Roma-Dollase et al. 2016).
2) Questionnaire & Analysis centers already in position to contribute to a combined IGS RT-GIM soon (starting by the end of 2017, García-Rigo et al. 2017).
3) Thoughts on potential RT combination strategies.
4) Apparent limitation of present ionospheric RTCM message and simple solution.
5) Conclusions and recommendations.

1) Recent comparison of some RT and NRT VTEC models: *External validation vs VTEC-JASON2*





VTEC Relative RMS error (%, taken as reference VTEC-JASON2) vs day of year 2016: Left plot is only for the European region while right plot is worldwide (extracted from Roma-Dollase et al. 2016 @ BSS2016).

1) (Cont) External validation vs dSTEC-GPS @ independent receivers

RT-GIMs

GIM	RMS [TECU]	RMS max [TECU]	RMS min [TECU]	BIAS [TECU]
AOEG	11.8	22.6	4.8	-1.43
CNSG	9.2	18.8	3.0	0.21
URTG	8.2	14.9	3.4	0.30
DGFI	5.6	10.8	1.8	-0.57
IGSG	6.2	11.6	1.9	-1.01
UQRG	4.6	9.1	1.1	-0.61

35 GPS stations have been used. The dSTEC RMS has been calculated for the days of year 2016 from 45 to 59.

RT-GIMs assessed and compared following a clear vertical and slant methodology

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ORIGINAL ARTICLE

Methodology and consistency of slant and vertical assessments for ionospheric electron content models

Manuel Hernández-Pajares[1] · David Roma-Dollase[1,2] · Andrzej Krankowski[3] · Alberto García-Rigo[1] · Raül Orús-Pérez[4]

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Abstract A summary of the main concepts on global ionospheric map(s) [hereinafter GIM(s)] of vertical total electron content (VTEC), with special emphasis on their assessment, is presented in this paper. It is based on the experience accumulated during almost two decades of collaborative work in the context of the international global navigation satellite systems (GNSS) service (IGS) ionosphere working group. A representative comparison of the two main assessments of ionospheric electron content models (VTEC-altimeter and difference of Slant TEC, based on independent global positioning system data GPS, dSTEC-GPS) is performed. It is based on 26 GPS receivers worldwide distributed and mostly placed on islands, from the last quarter of 2010 to the end of 2016. The consistency between dSTEC-GPS and VTEC-altimeter assessments for one of the most accurate IGS GIMs (the tomographic-kriging GIM 'UQRG' computed by UPC) is shown. Typical error RMS values of 2 TECU for VTEC-altimeter and 0.5 TECU for dSTEC-GPS assessments are found. And, as expected by following a simple random model, there is a significant correlation between both RMS and specially relative errors, mainly evident when large enough number of observations per pass is considered. The authors expect that this manuscript will be useful for new analysis contributor centres and in general for the scientific and technical community interested in simple and truly external ways of validating electron content models of the ionosphere.

Keywords Satellite navigation systems · Ionosphere · Validation of ionospheric electron content models

1 Introduction

The multifrequency global positioning system (GPS) and in general the global navigation satellite systems (GNSS) have become excellent ionospheric sounding systems in the last 20 years. This has been possible by exploiting the very well-known predominant (>99.9%) ionospheric electron content dependence affecting to the transionospheric electromagnetic signals like those of GPS. This dependence is proportional to the integrated electron density and inversely proportional to the squared frequency (see for instance Hernández-Pajares et al. 2011, 2014).

Dual-frequency GNSS measurements provide numerous simultaneous precise ionospheric delays in different directions and regions, and with an unprecedented temporal and spatial resolution (towards a delivery in real time). This fact has been facilitated by the large number of transmit-

UPC

IonSAT

2) Questionnaire & Analysis centers to contribute to an IGS RT-GIM:

Questionnaire on Real Time (RT) and Near Real Time (NRT) Data Products performed in the RT-IM WG

Global and regional ionosphere maps of different parameters, available with latencies ranging from 15 minutes down to 2 minutes.

- Vertical Total Electron Content (VTEC)
- F2 layer critical frequency (foF2)
- F2 layer maximum height (hmF2)
- W index
- F2 layer bottomside thickness (B0) and shape (B2)
- Rate of TEC Index (ROTI)

(Most usual, but they may be others we are not currently aware)

2 (Cont.) RT/NRT Data Products Distribution

Only two specific formats for ionosphere data:

- IONEX
- RTCM SSR

Other general purpose formats:

- HDF5
- Web page
- Image
- General Purpose text format: HDF5, CSV, JSON
- ASCII Text data with internal formats

Distribution itself is done through:

- HTTP or web service
- FTP

And only one method exclusive for GNSS/ionosphere data: Network Transport of RTCM over Internet Protocol (NTRIP)

2 (Cont.) Analysis centers which might contribute to a combined IGS RT-GIM soon

CNES already transmits RT-GIM (RTCM iono. Messages from PRODUCTS.IGS-IP NTRIP caster)

UPC-IonSAT already transmits RT-GIM (IONEX format)

WHU already transmits RT-GIM (IONEX format)

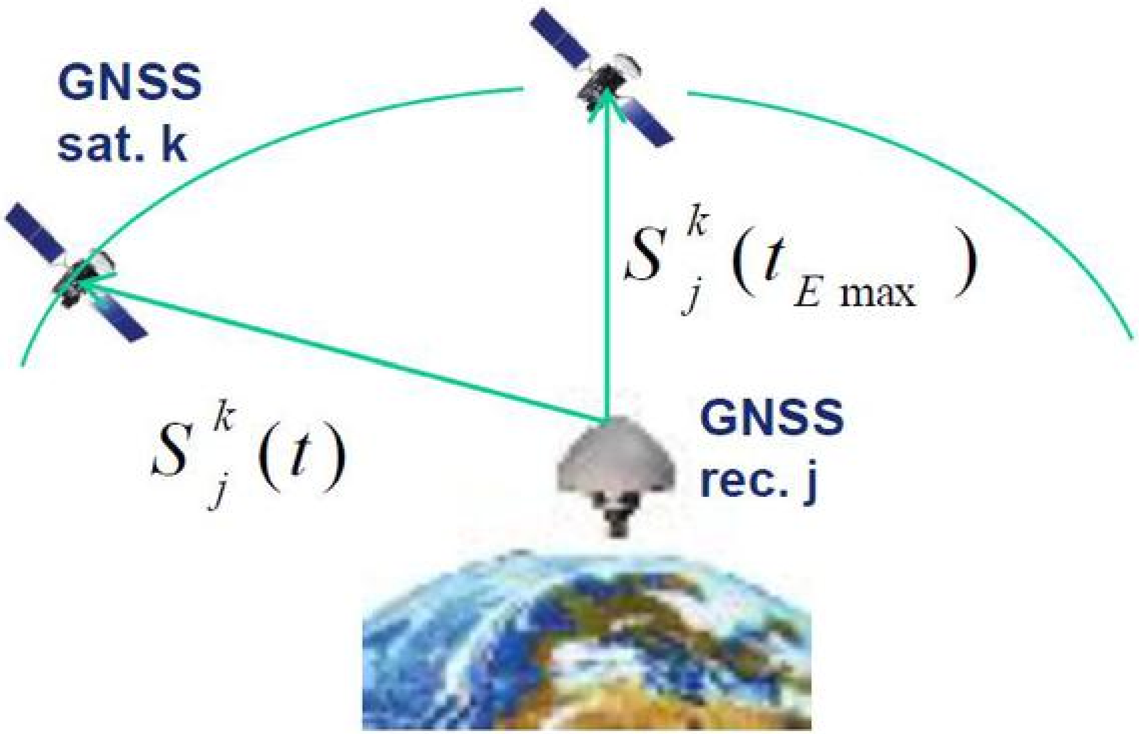
CAS is very interested to transmit RT-GIM by the end 2017 for the RT IGS combination. Currently testing the stability of software, accuracy of RT-GIM, and trying to get more global real-time data streams (internal format, but it can be adapted).

NRCAN interested to join future RT-GIM IGS product. Currently, they produce near-real-time global vTEC maps (IONEX and spherical harmonic coefficients, no schedule yet for RTCM format). An offline comparison and comb. is suggested.

3) Thoughts on potential RT ionospheric combination strategies: *i) weighting*

RT Weighting scheme	PROS	CONS
[A] "Self-consistency" (reference: L1-L2 at the same elevation in the same phase continuous arc...)	The same which is being already applied for final and rapid combination with common mapping	We have to wait to the second (elevation-decreasing) half of each arc, i.e. half number of performance estimations...
[B] "dSTEC" (reference: L1-L2 at max. elev. ....)	Well characterized (e.g. recent paper); it only demands to store the reference LI, which is less affected by mapping errors	Same than [A] "Self-consistency"
[C] "RT-dSTEC" (The first L1-L2 measurement in the arc is taken as reference)	Full data availability, only one data stored per arc	The low elev. Ref. STEC is typically the (or one of the) very bad estimated ones, affecting all the time series.
[D] = [C] (during the ascending arc part) + [A] (during the descending part)	Full data availability, only one memory record per arc (updated at max. elevation).	Potential "overweight" of the first low-elevation reference ray (potentially mitigated with elev. mask).

dSTEC-GPS layout



$$\Delta S_O \equiv S_j^k(t) - S_j^k(t_{E\,max})$$
$$\approx M \cdot V(t) - M_{E\,max} \cdot V(t_{E\,max})$$

3) (Cont.) Other considerations in RT ionospheric weighting strategies

ii) Weighting directly the SH coefficients (taking into account the analysis centers contributing to such order degree) seems feasible (due to the corresponding orthogonality of the basis function on the complete ionosphere) and faster.

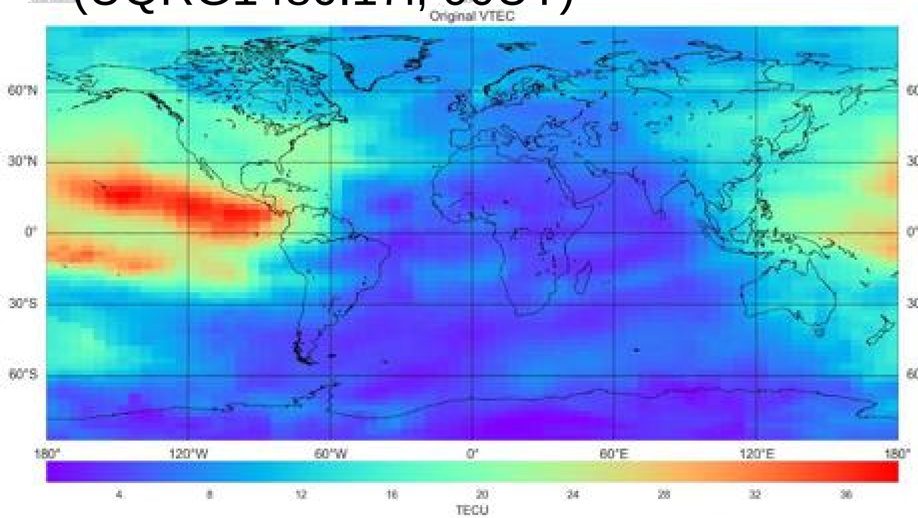
iii) Performance temporal prediction of weights: This can be an important aid for the weight estimation, in order to avoid any latency inconvenient. A potential low / variable degree polynomial might be used for this task among other posibilities.

4) Apparent limitation of present ionospheric RTCM message and simple solution: *RTCM VTEC*

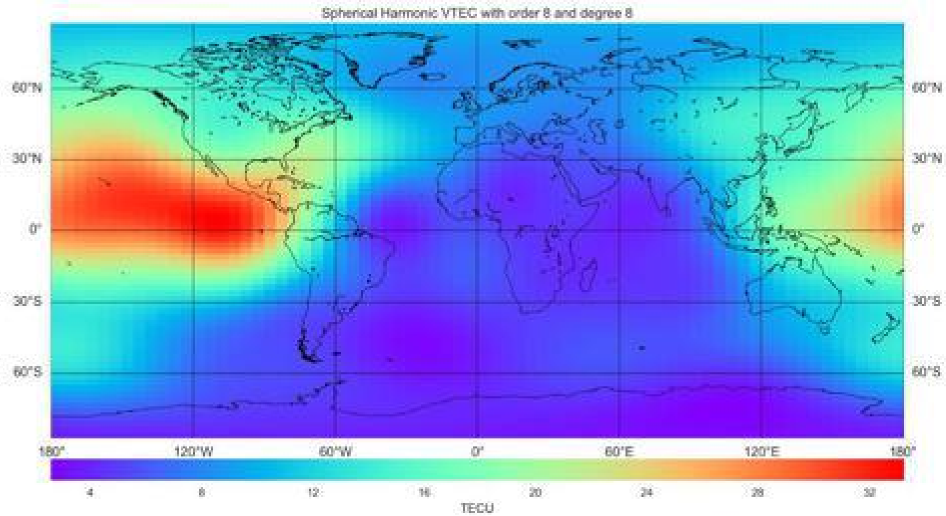
- RTCM currently only defines one way to provide VTEC information to the users, as a spherical harmonic series to a given order and degree (message type 1264).
- At some point at least it was under discussion as far as we know to have a message type with data representing a grid, equivalent to the IONEX file content.
- In our knowledge, the maximum order and degree allowed by the standard is 16.
- We want to analyze which is the loss of precision for the end user by using spherical harmonics instead of directly the IONEX content.

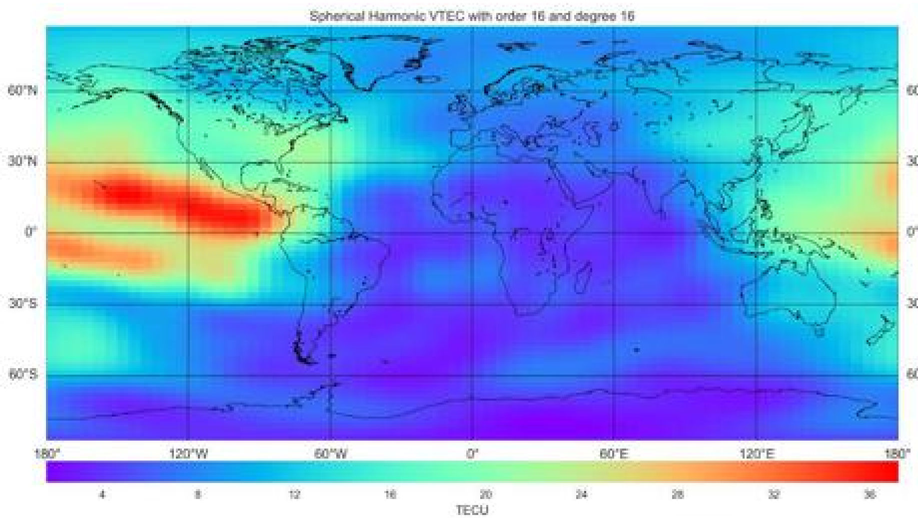
4.(Cont) *Importance of using the right SH order/degree*

ORIGINAL GIM
(UQRG1480.17i, 00UT)

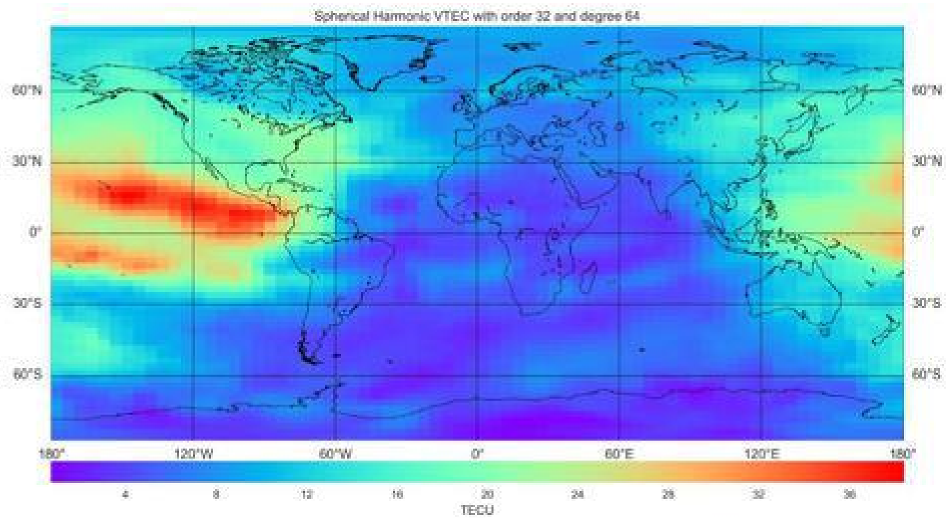


Reconstructed GIM **13% error** **(deg.=8 & ord.=8)**





Reconstructed GIM **5.8% error**
(deg=16 & ord=16, max. RTCM?)



Reconstructed GIM **1.8% error**
(degree=64 & order=32)

4.(Cont) *Distribution of relative errors*

RMS relative error $100 * \sqrt{\sum(VTEC_{SphHarm} - VTEC)^2} / \sqrt{\sum VTEC^2}$

Conclusions / recomendation

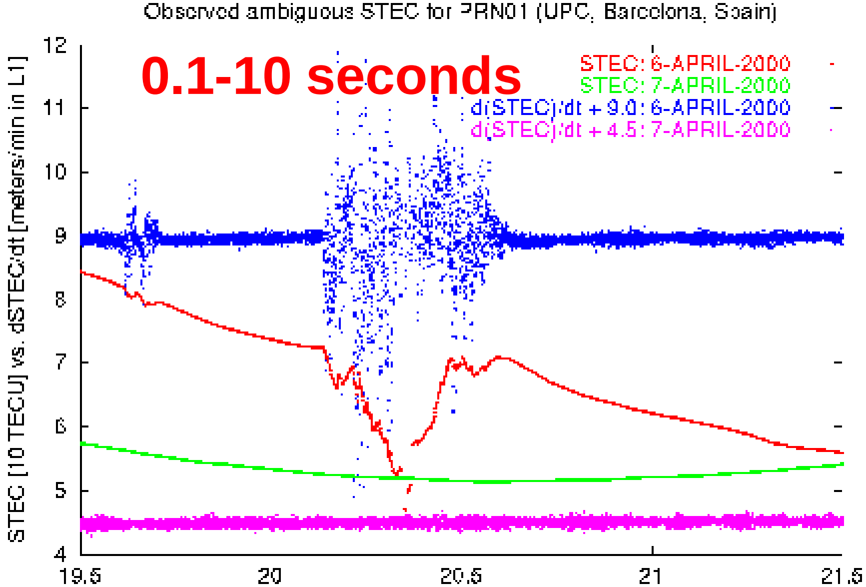
- The availability of RT-IGS GNSS is already allowing the continuous monitoring of ionospheric electron content distribution (RT-GIMs), variability (ROTI) and Space Weather response (e.g. EUV flux rate during solar flares), among practical applications (precise farming).
- We have focused on new results which can facilitate the generation of a combined IGS RT-GIM soon:
  1) Recent comparison of some RT and NRT VTEC models.
  2) Analysis centers ready or interested to contribute to a combined IGS RT-GIM soon.
  3) Initial discussion of potential RT combination strategies.
- Apparent limitation (order & degree not larger than 16) of present ionospheric RTCM message and simple solution.
- Recommendation: to increase maximum supported RTCM SH order & degree

Many thanks for your attention!

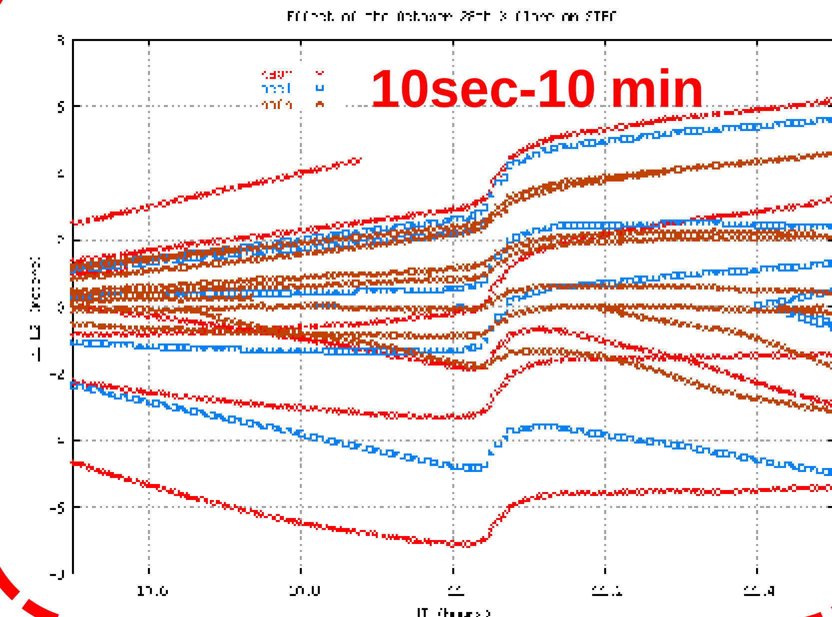
BACKUP SLIDES

Introduction: iono. time variability

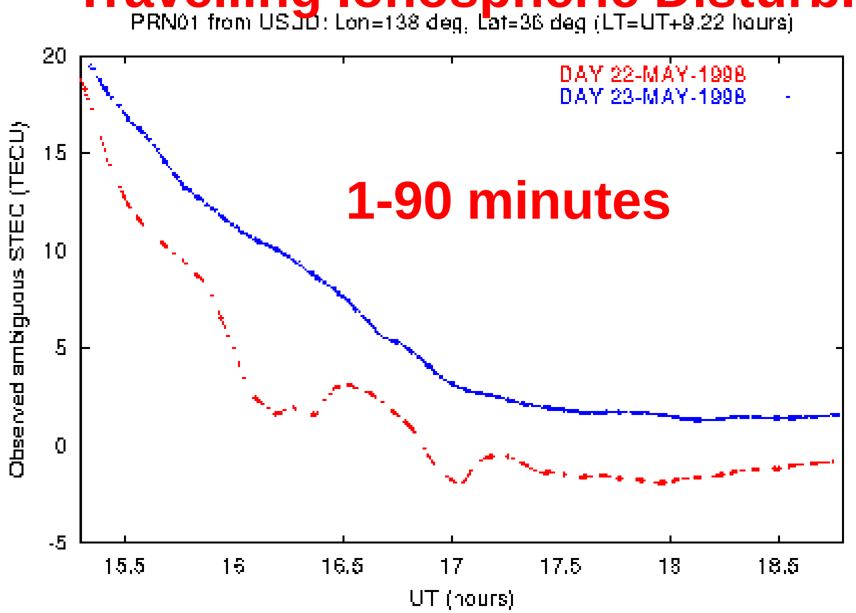
Scintillation



Solar Flare sudden overioniz.



Travelling Ionospheric Disturb.



Solar-cycle,seasonal, solar rot.