RTIM-WG: IAG's Real Time Ionosphere Monitoring Working Group
Current status, outcomes and first results

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Outline

1. IAG's RTIM-WG Introduction
2. Main goals and outcomes / new potential ideas
3. On-going activities and first results
4. Conclusions

IAG's RTIM-WG - Introduction

- The **Real Time Ionosphere Monitoring** is a new Working Group (**RTIM-WG**) within the International Association of Geodesy (**IAG**) Subcomission 4.3 on Atmosphere Remote Sensing.
- The WG will run for the next four years (**2016-2019**).
- The current number of members is 25 from 21 international institutions, including experts in the field from multiple countries world-wide:

  Australia, Belgium, Canada, China, Cyprus, France, Germany, the Netherlands, Poland, Russia, Spain, UK and USA
- The expertise of the participating research groups is complementary.
- There are real-time (**RT**) and near real-time (**NRT**) models, mainly based on **GNSS** and **ionosonde** data (based on IGS Iono-WG Global Ionospheric Maps, **GIMs**, or the International Reference Ionosphere, **IRI**).
- Possibility to derive **global and regional** maps on multiple ionospheric parameters, including Total Electron Content (**TEC**), F2 layer critical frequency (**foF2**), F2 layer peak (**hmF2**), bottomside thickness (**B0**) and ionospheric disturbance **W-index**.

IAG's RTIM-WG main goals and outcomes

(1) A summary of the **current status** of RT Ionosphere Monitoring

(2) **Comparison** of existing RT Ionosphere Monitoring approaches from different perspectives **for a specific period**

(3) A **procedure to automatically compare** on a daily basis a subset of **real time ionosphere products** providing the results in a common compatible **IONEX**-like format (or a future IONEX version supporting it). Potential validation with external data sources, such as dual-frequency altimeters

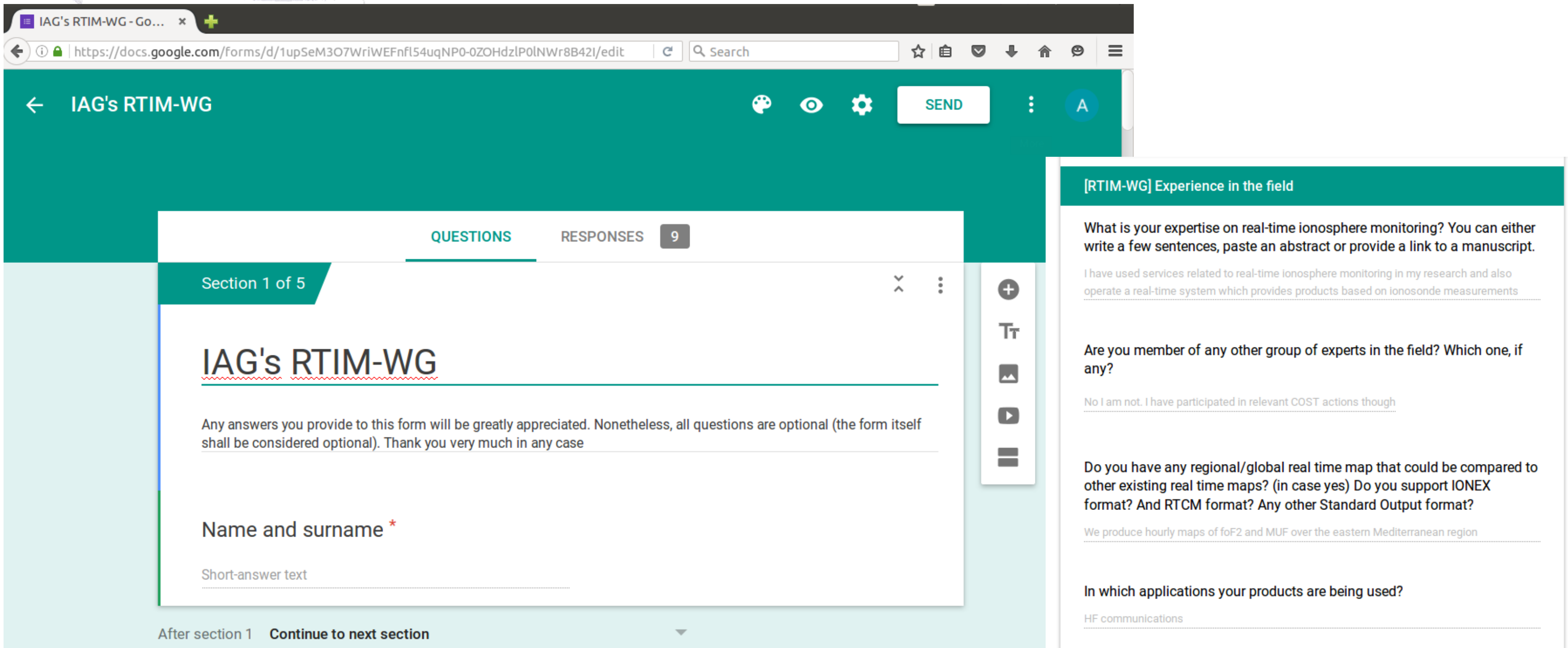
(4) **Open discussion** (through a common mailing list) towards **new concepts** on RT Ionosphere Monitoring.

IAG's RTIM-WG new potential ideas

- Beyond the stated goals, new ideas for potential work have already arisen after discussions within the team. Of particular interest are:
  - The **improvement** in the dissemination and format of **GIMs** in order **to properly support real time** usage (expecting progress in the time delay between their production and their online availability)
  - The team potential support on **quality control and validation of existing products/services** (including the possibility to assess the performance by means of standard and precise point positioning techniques)
  - Find out ways to **combine different regional/global products** (keeping in mind the importance on disturbed periods)
  - Drawing **recommendations and arranging training and dissemination activities** for the community.

On-going activities: RT/NRT status

- A Google form has proven to be useful as a first step to summarize the status of RT/NRT ionosphere monitoring activities within the group.



- Some RT/NRT ionospheric products within the group are shown at a glance in the next slides (kindly provided by **DGFI-TUM**, **Lowell**, **NRCan**, **and** **ROB**).

DGFI-TUM Ionosphere Model

Globally distributed GNSS data from the IGS network are sequentially preprocessed in hourly batches using the geometry free linear combination technique. These batches are used to compute global VTEC maps in near-real time.

The spatial representation of VTEC is performed by a **two-dimensional series expansion in polynomial and trigonometric B-splines functions**.

A Kalman filter is fed sequentially with the preprocessed observations to estimate the unknown parameters of our VTEC model.

$$y_{GPS} + e_{GPS} = m(z)\,VTEC + b_{r,GPS} + b^{S}_{GPS}$$

$$y_{GLO} + e_{GLO} = m(z)\,VTEC + b_{r,GLO} + b^{S}_{GLO}$$

$$VTEC(\lambda,\varphi) = \sum_{k_1=0}^{K_{J_1}-1} \sum_{k_2=0}^{K_{J_2}-1} d^{J_1,J_2}_{k_1,k_2} N^2_{J_1,k_1}(\varphi)\, T^2_{J_2,k_2}(\lambda)$$

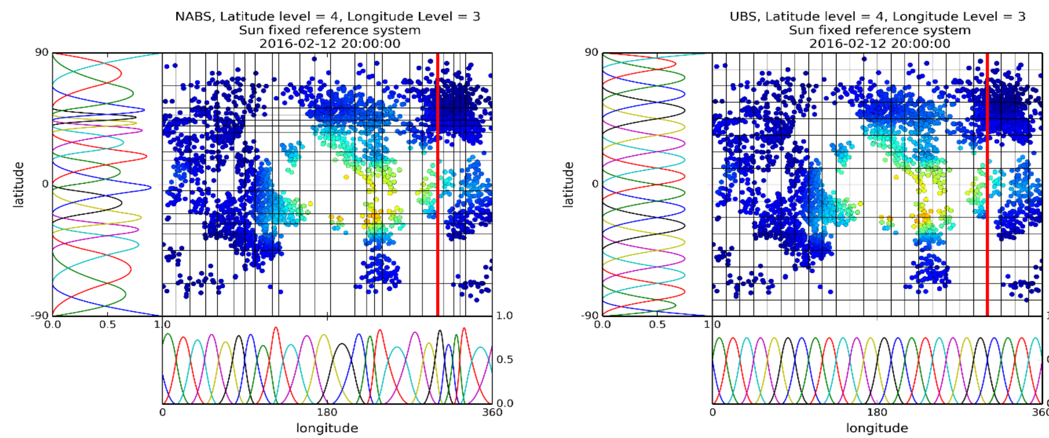
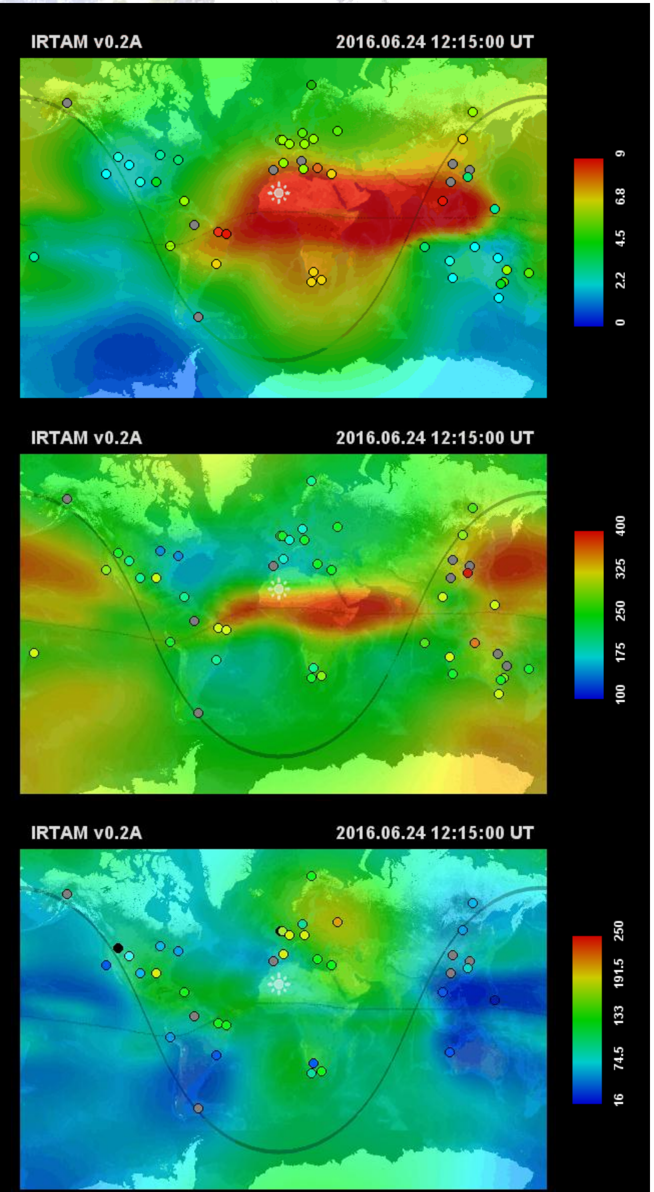


Figure 1: Global VTEC **modeling using B-spline representation**. The B-spline coefficients $d_{\cdots}^{\cdots}$ are the unknowns (high-lighted by the red edge in the last equation) as well as the DCBs $b_{\cdots}^{\cdots}$ (highlighted by the red boxes in the first two equations)

Figure 2 Left: **Non-uniform adaptive B-spline representation (NABS)**, right: **uniform B-splines representation (UBS)**. The colored dots show the data locations (Ionospheric Pierce Points, **IPPs**); the colors mean the VTEC magnitude (blue low, red high), The red line is the Greenwich meridian



REAL TIME IRI Assimilative Mapping

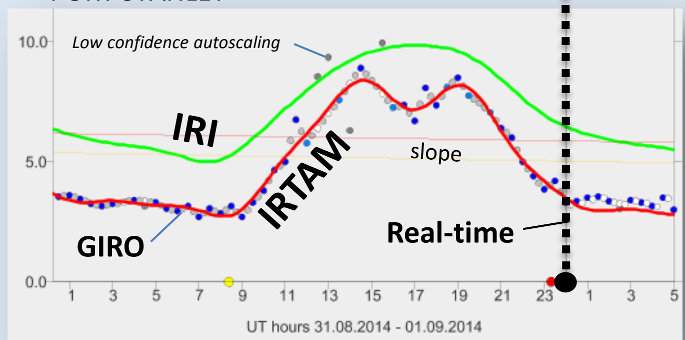
IRTAM

15 minute cadence

Real-Time IRI

3D global bottomside ionosphere in real-time

GIRO



Diurnal fit to GIRO data

***4D** data assimilation:*

24-hour fit of differences between IRI and GIRO

+ diurnal trend analysis

Port Stanley data courtesy Sarah James, RAL UK

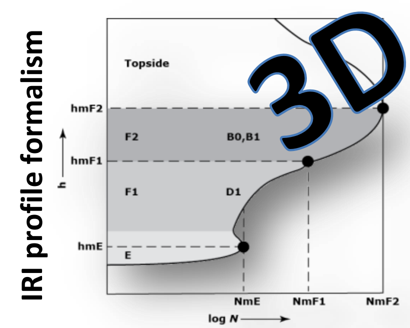
x 52 GIRO stations

Global Spatial fit

Jones-Gallet Gk basis (76)

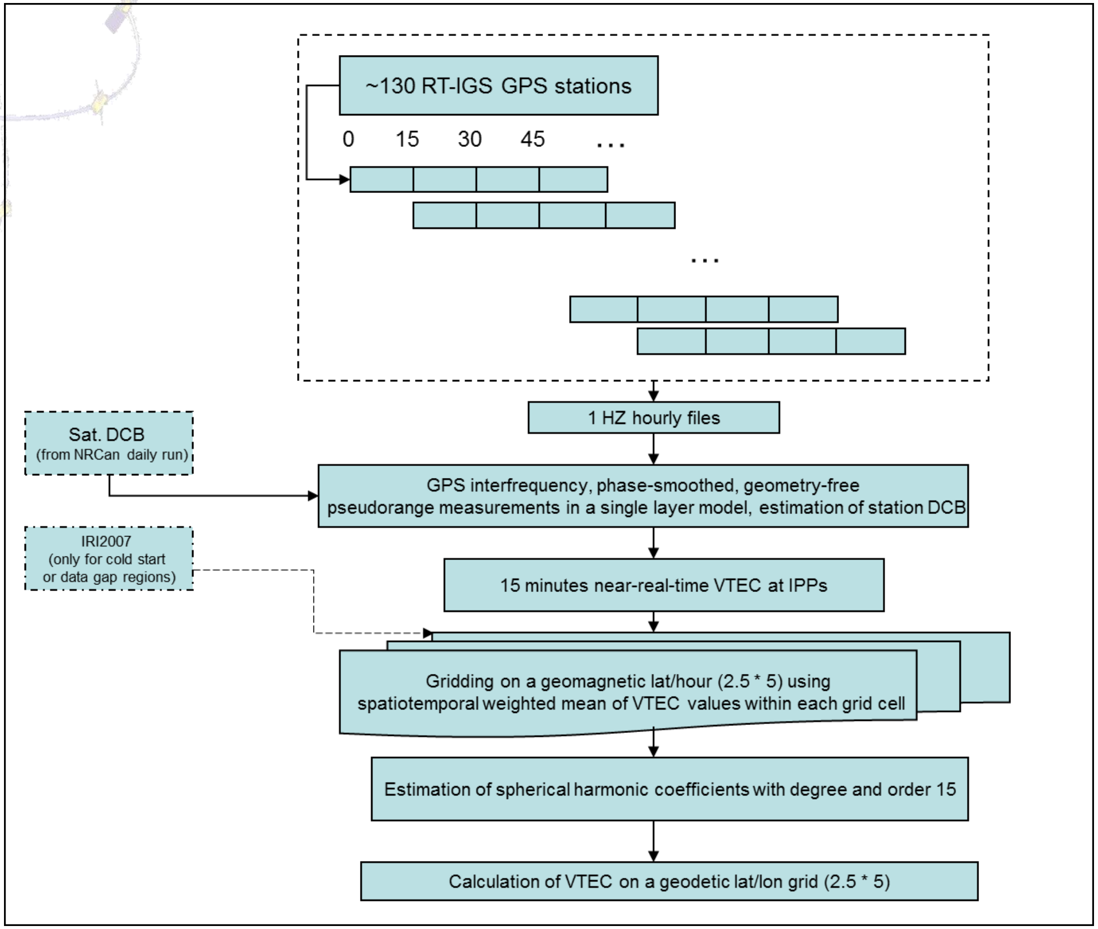
= total map coefficients: **1064**

[24-hour global weather of *C*]



NmF2, hmF2, B0 anchors

Flow diagram of NRCan's near-real-time global TEC map generation



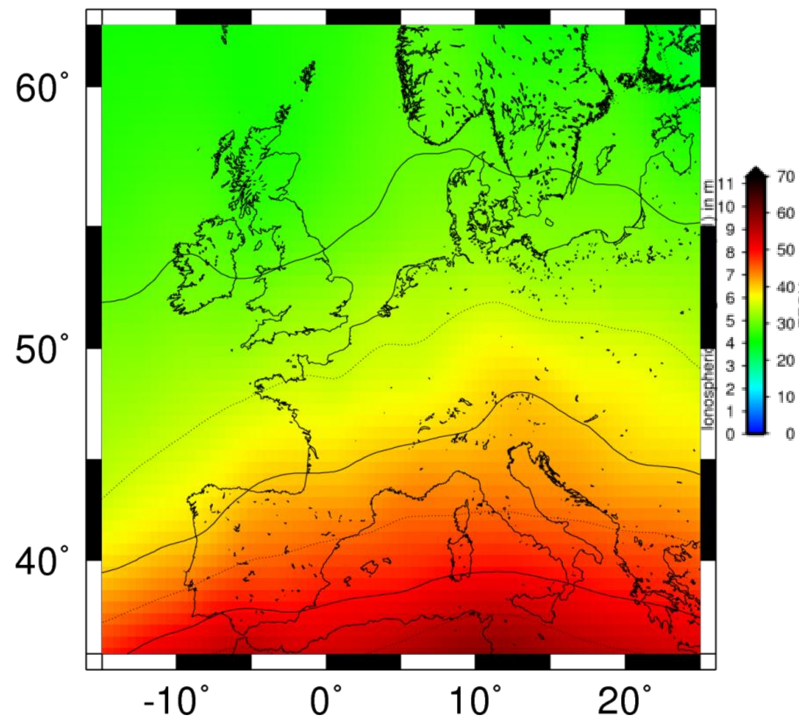
For further details about other Natural Resources Canada (NRCan) GPS ionospheric products see:

Ghoddousi-Fard R. (2014) "GPS ionospheric mapping at Natural Resources Canada". Poster presentation given at IGS Workshop 2014, June 23-27, 2014, Pasadena, California, USA.

ROB-IONO software

- Input data: Real-time data from the EUREF Permanent Network (~120 stations, Bruyninx et al. 2012)

- ROB-TEC maps since 2012 (Bergeot et al. 2014):
  - **vTEC maps over Europe +Variability**
    www.gnss.be
  - **IONEX files**
    ftp://gnss.oma.be



Sampling rate: 15 min.

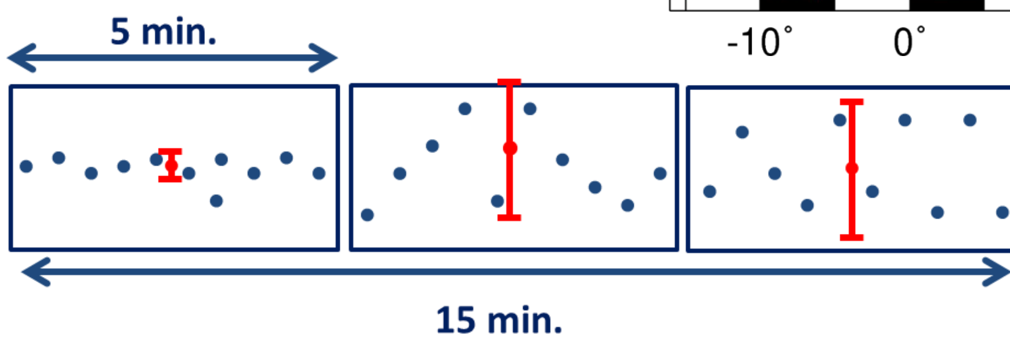
Grid extent: Long W15º / E25º

: Lat N35º / N62º

Grid resolution: 0.5º x 0.5º

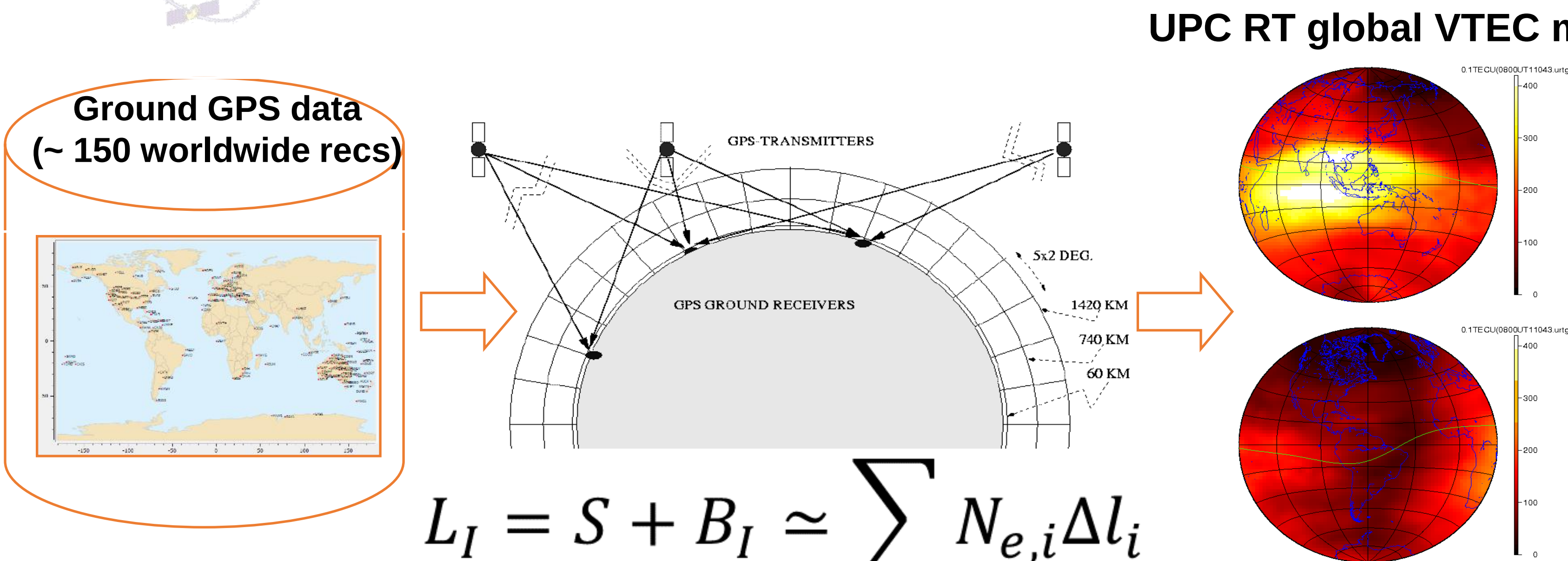
Latency: ~3 minutes

Variability maps (Index)



UPC-IonSAT TOMION: Computation of global VTEC maps (UPC)

The **TOmographic Model of the IONospheric electron content** (**TOMION**) is fed with global GPS NTRIP datastreams in order to compute in real time, among others, UPC global VTEC maps.



$$L_I = S + B_I \simeq \sum_{i=1} N_{e,i} \Delta l_i$$

Fig. 1. Layout summarizing the global VTEC computation from ground GPS data by means of the UPC TOMION software, including the main **tomographic equation** solved for (data: ionospheric combination of carrier phases L_I , and length intersection within each voxel, Δl_i; unknowns: its ambiguity B_I, the STEC, S, which includes the mean electron density within each given **voxel**, $N_{e,i}$).

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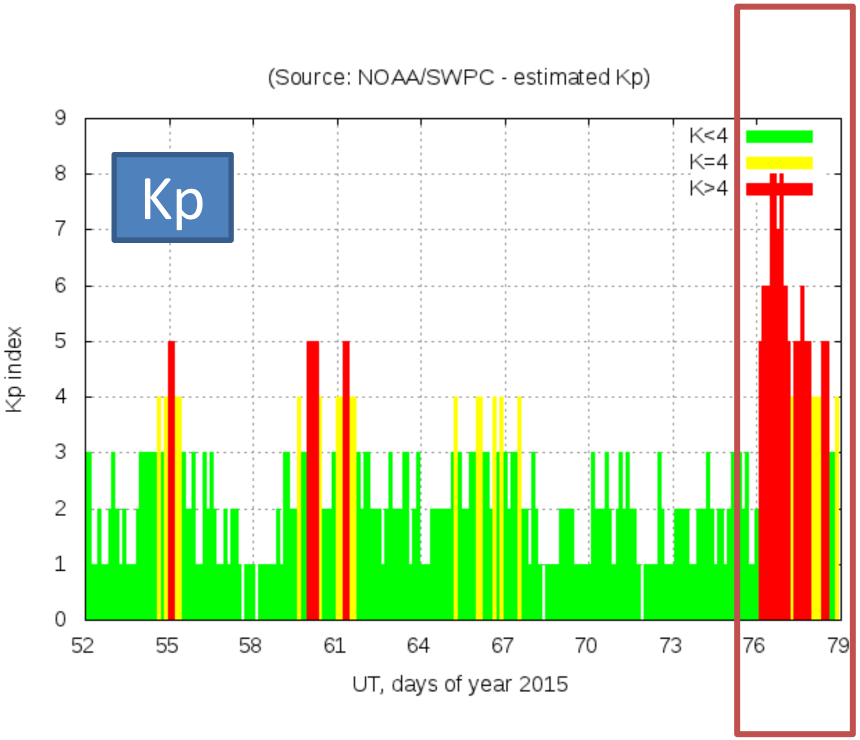
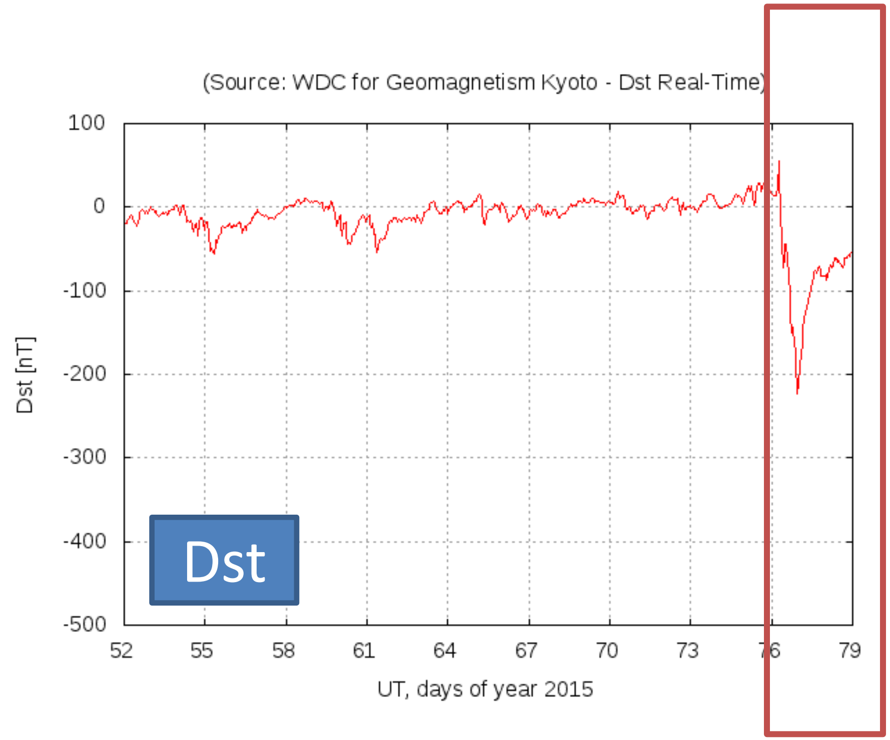
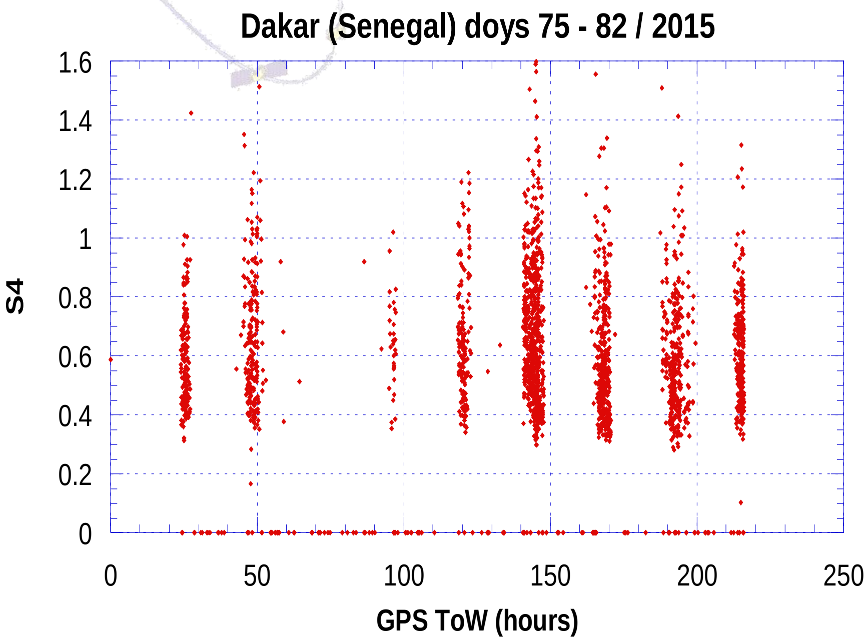
On-going activities: St. Patrick storm

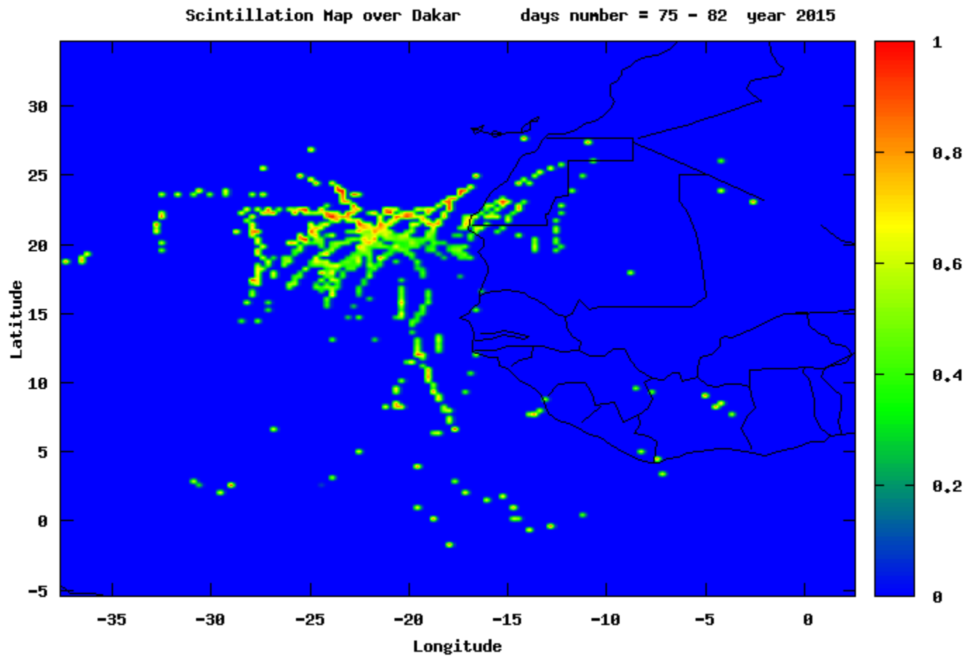
- Results on the RT/NRT products (plots and/or textual) for the days surrounding St. Patrick storm (on day of year 76, 2015) are being provided by the different members to get a global **overview of the impact on ionosphere** from multiple perspectives. First inputs are shown in the next slides (kindly provided by **IEEA**, **IZMIRAN**, **Lowell**, **NRCan** **and** **ROB**).





St. Patrick storm: Scintillation observations / doys 75-82 2015 (IEEA)





S4 index Dakar

Scintillation map over Dakar

St. Patrick storm: W-index global maps (IZMIRAN)

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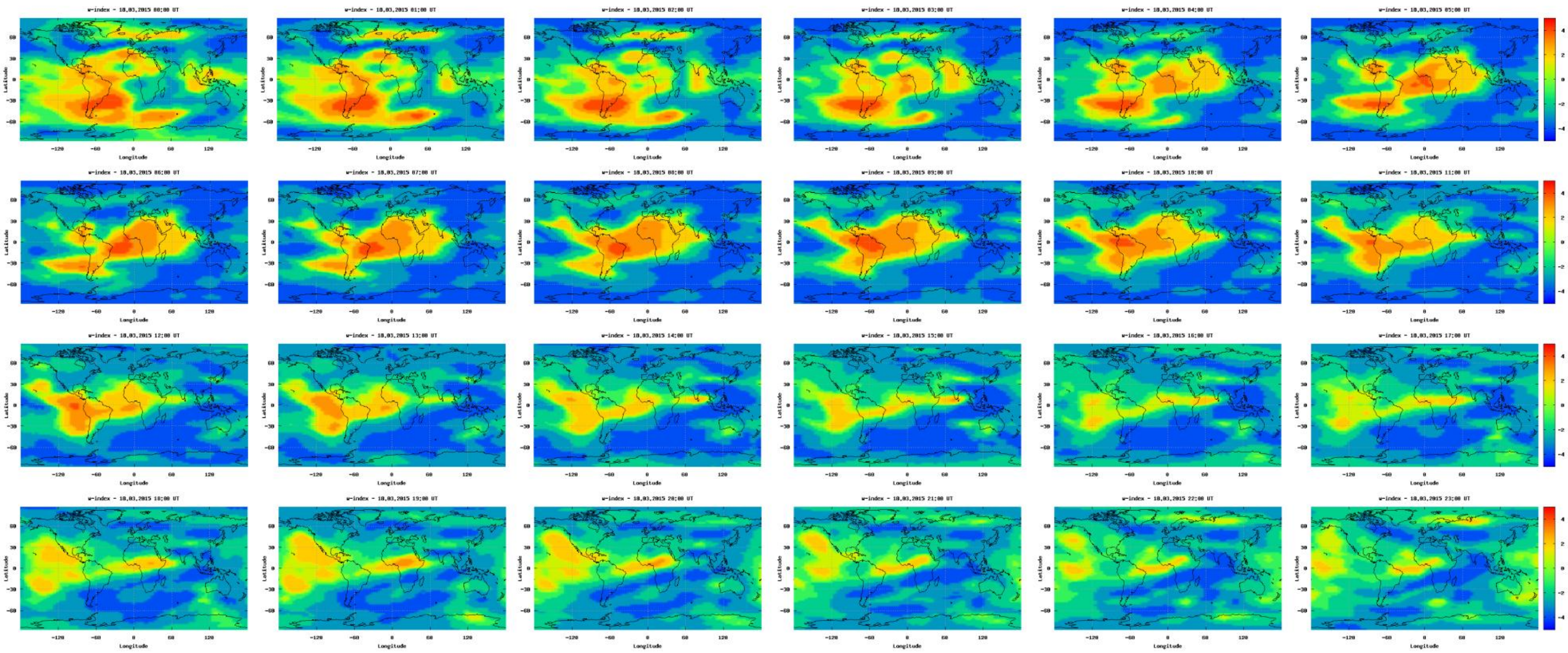
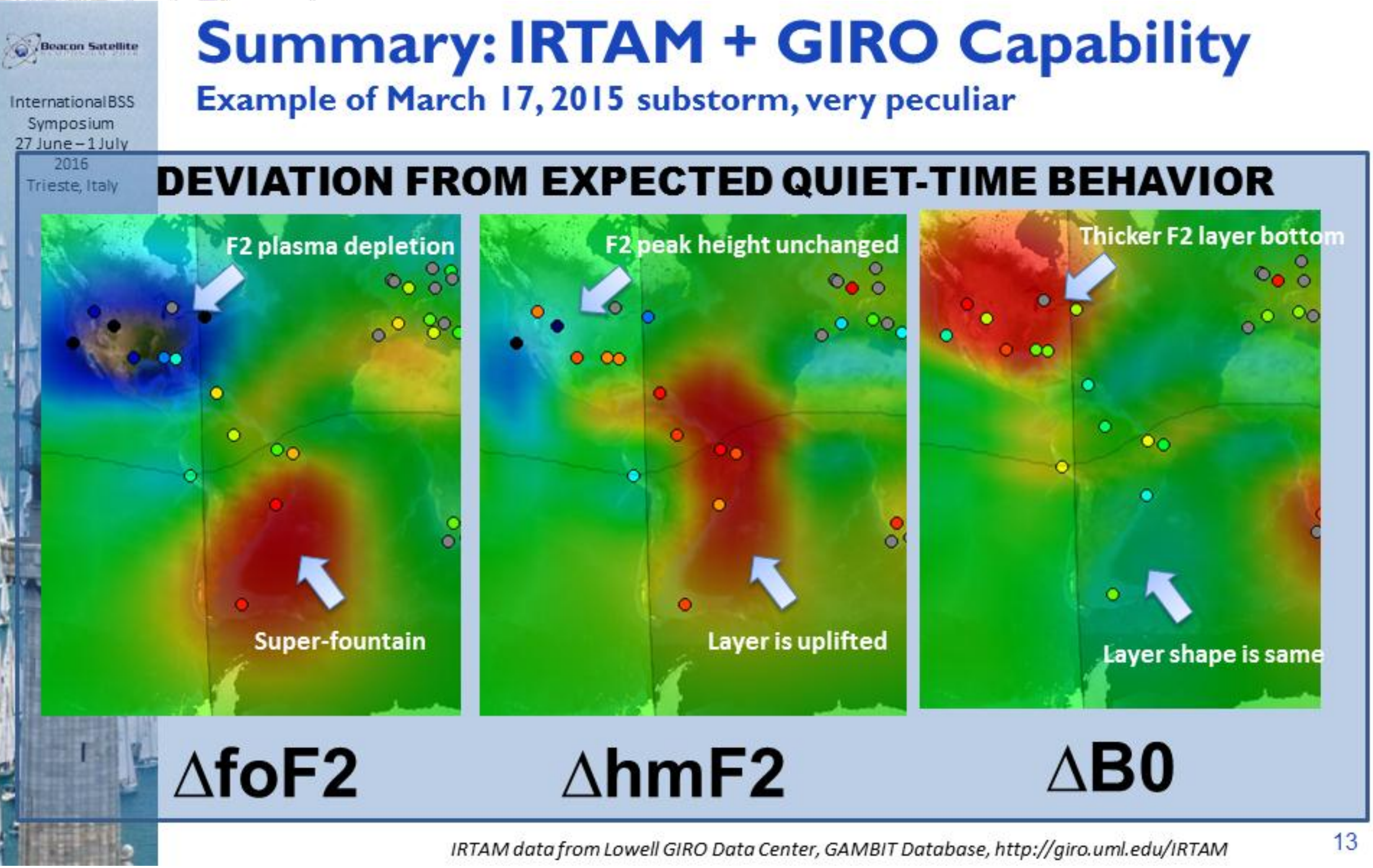
Fig. 8. Dynamics of the global maps of W-index in 1h resolution during the super-storm on 18 March, 2016, derived from JPL GIM-TEC maps **http://www.izmiran.ru/services/iweather/**; **http://www.cbk.waw.pl/rwc/**

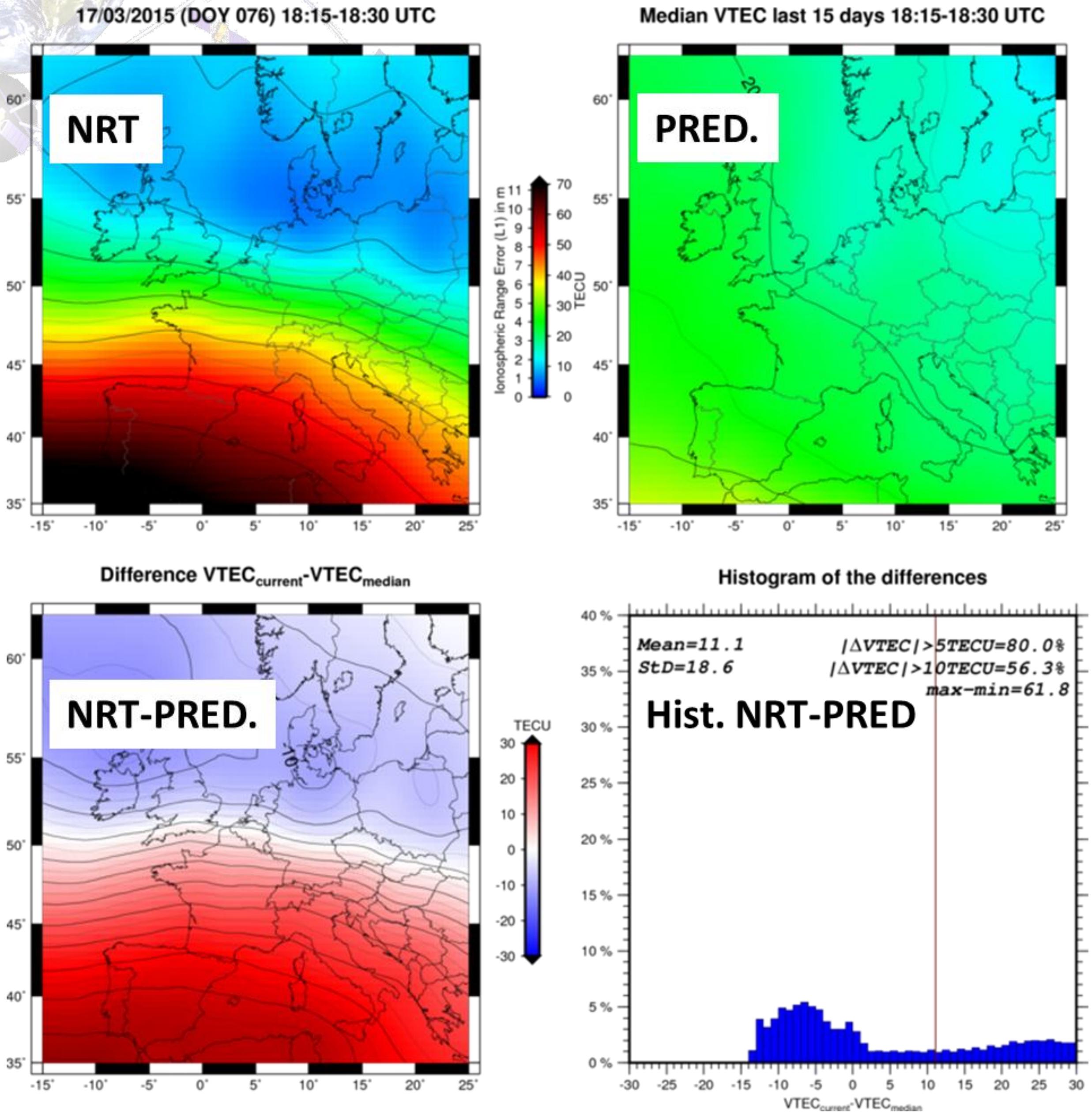


[Gulyaeva et al. Ionosphere: Modelling the ionospheric weather for telecommunication and navigation. In: Scientific cooperation between RAS and PAS in the field of Space Research: Results of joint investigations . Moscow, IKI, RAS, 2016, in Russian and Polska (in press)]

St. Patrick storm: IRTAM + GIRO (Lowell)



St. Patrick storm: VTEC EU maps (ROB)



March 17th 2015 event

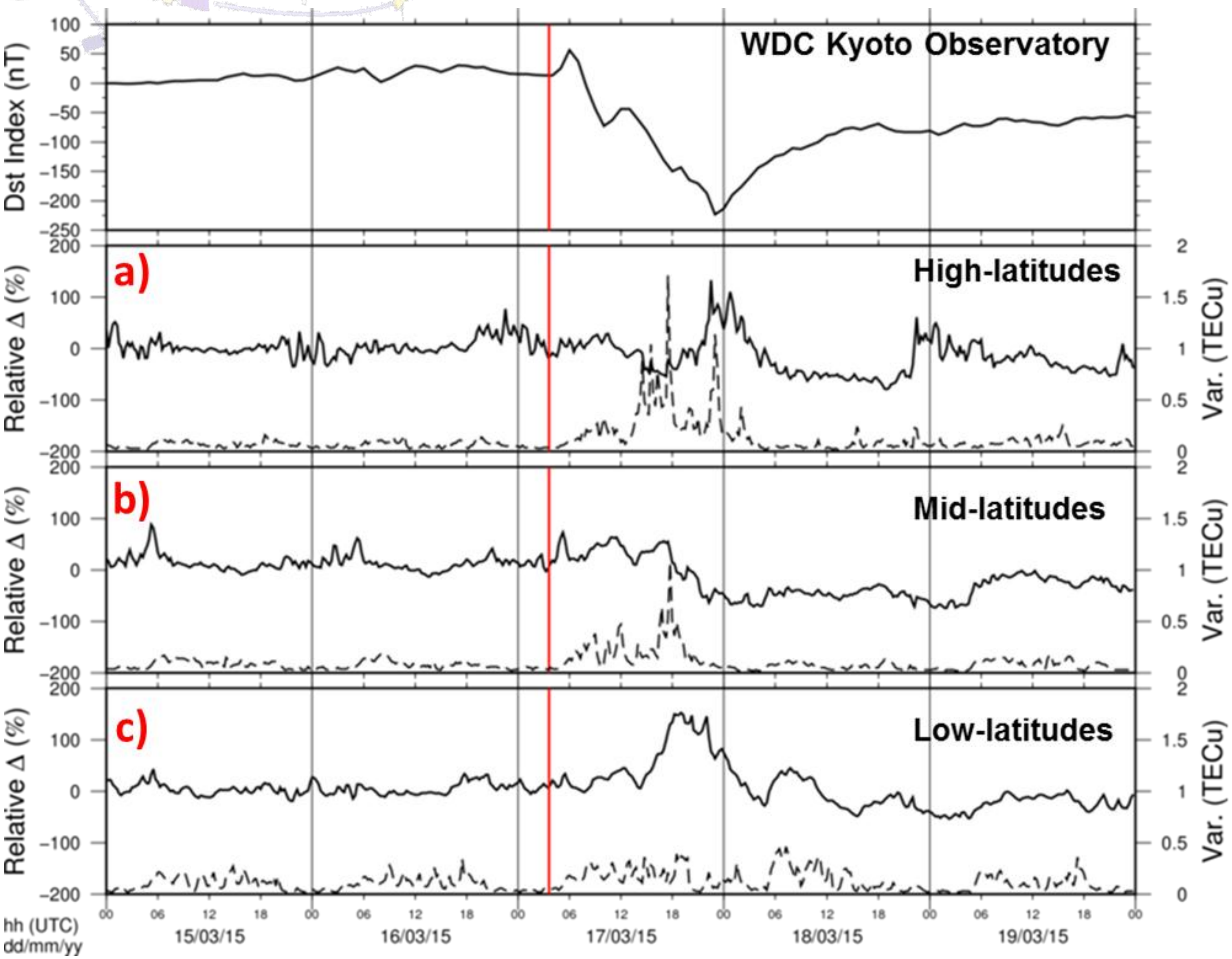
Statistical products

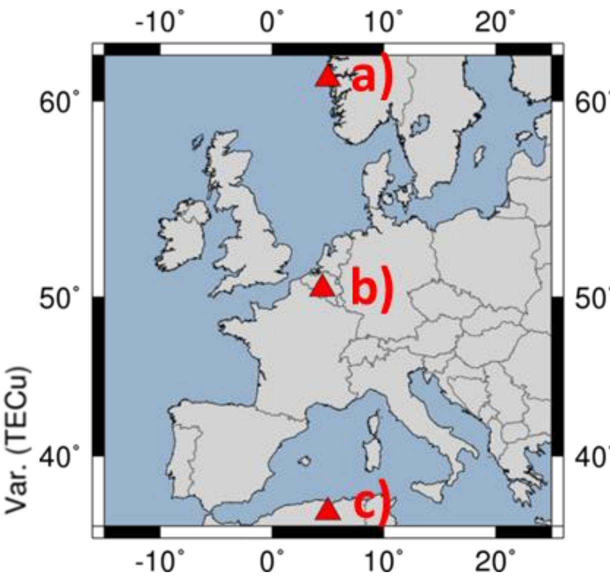
Prediction :

Median of the VTEC for the 15 previous days.

St. Patrick storm: VTEC EU maps (ROB)

March 17, 2015 - Onset 05:00 UTC – Dst = -223 nT – Geom. Storm (Kp=7)





$$\frac{vTEC_{NRT} - v\widetilde{TEC}_{15\ prev\ days}}{v\widetilde{TEC}_{15\ prev\ days}}$$

—— Relative vTEC (%)

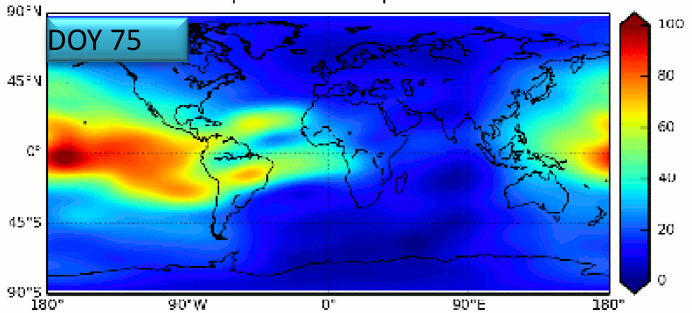
- - - Variability

St. Patrick storm: Ionosphere VTEC response (DGFI- TUM)

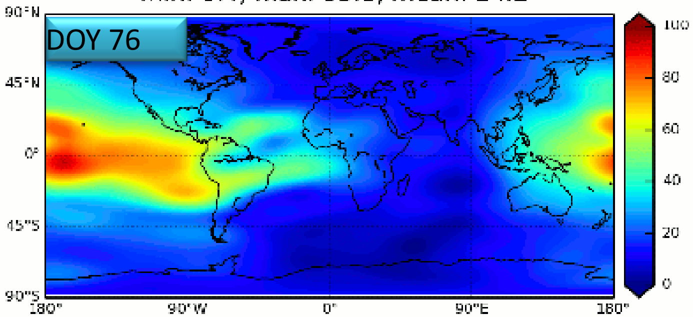
DGFI-TUM

00:00:00

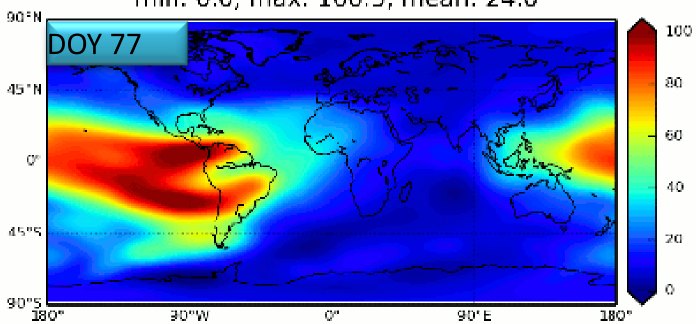
min: 0.0, max: 101.7, mean: 24.5



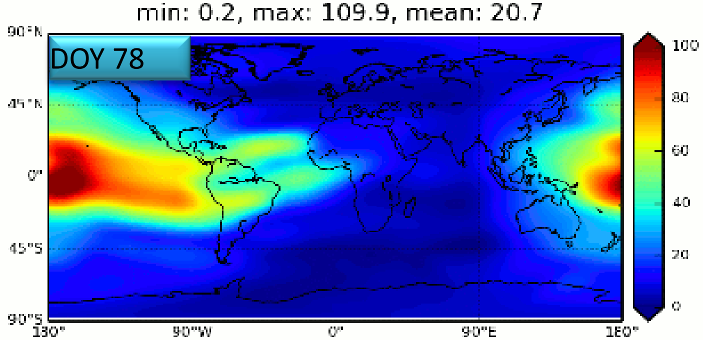
min: 0.4, max: 93.8, mean: 24.2



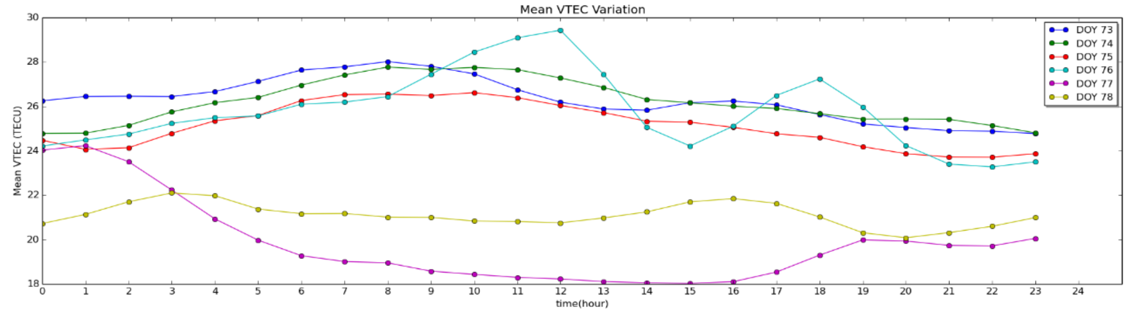
min: 0.0, max: 106.5, mean: 24.0



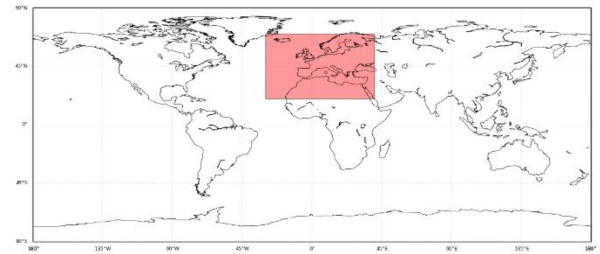
min: 0.2, max: 109.9, mean: 20.7

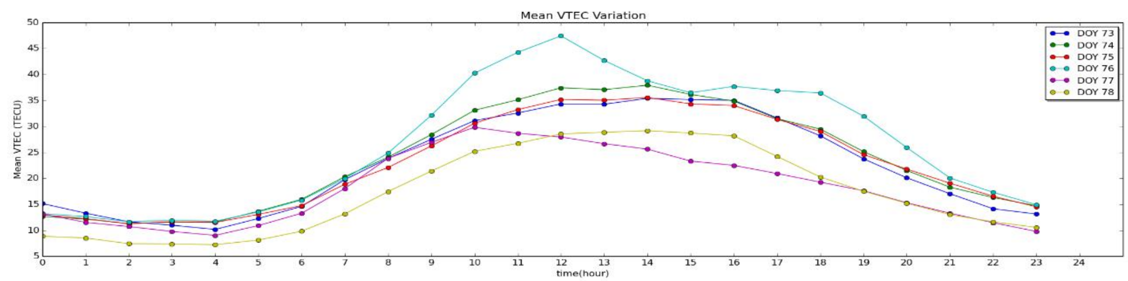


- **Global hourly mean VTEC variation during days between DOY 73 and DOY 78**



- **European Region hourly mean VTEC variation during days between DOY 73 and DOY 78**





- ❑ At day **76**, 2015, a **peak of the mean VTEC variations** at the European region (lower image) as well as at the whole globe (upper image) are clearly shown.
- ❑ At the following days (**77 and 78**), the **mean VTEC variations decrease** dramatically and can be clearly seen in the global mean VTEC map.

It should be noted that in a near real time run, some of the hourly GNSS stations cannot provide data on time, but they are available with latency. The dataset used in the computations is downloaded in the offline mode and, therefore, the computation includes some additional GNSS receivers.

St. Patrick storm: global maps of inter-frequency phase rate variations (NRCan)

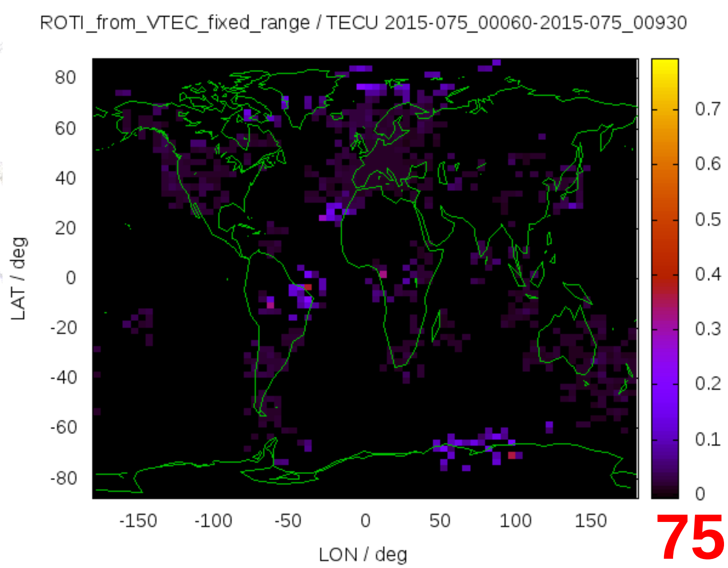
At the Canadian Geodetic Survey of Natural Resources Canada about 130-150 globally distributed 1-Hz GPS stations (mostly those of the RT-IGS network with additional stations over Canadian region) are used in near-real-time to derive, among other statistics and products **inter-frequency phase rate variations** by means of mapped-to-zenith standard deviation of delta phase rate (sDPR) over 30 sec.

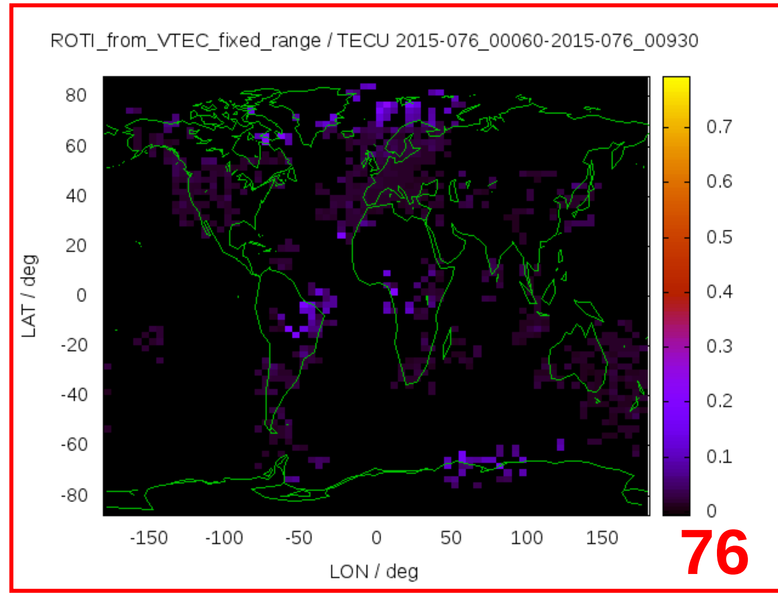
Inter-frequency GPS phase rate variations from RT-IGS stations over stormy day of March 17, 2015 and rather quiet day of March 16 as monitored in near-real-time are studied. Global maps of GPS phase irregularities (sDPR) derived at each ionospheric pierce point are presented in a UT hour and geomagnetic latitude coordinate system for comparison against common geomagnetic indices. For further details see:

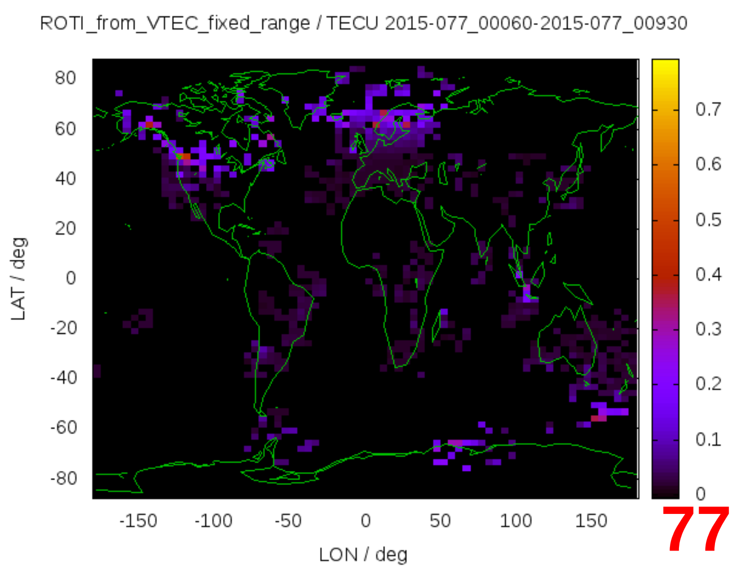
Ghoddousi-Fard et al. (2016). Geomagnetic storm of March 17, 2015: global RT-IGS GPS phase irregularities and effects in the Canadian auroral region. Oral presentation given at Beacon Satellite Symposium, Trieste, Italy, June 27 – July 1, 2016.

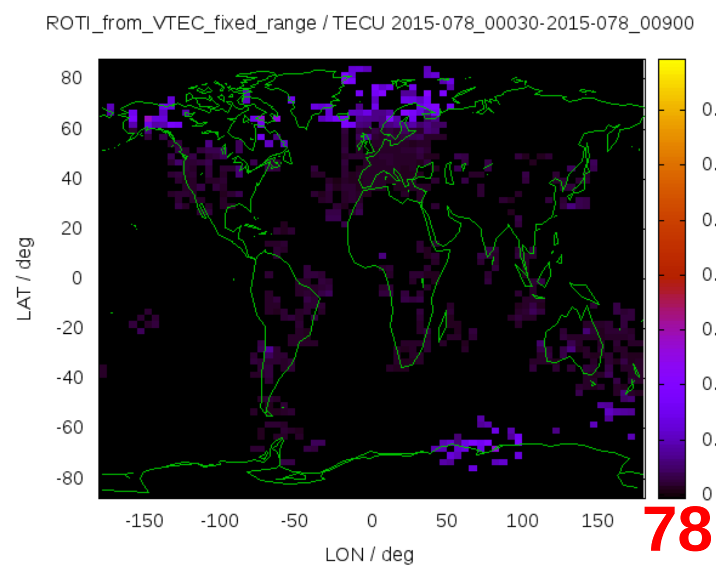
An study of **GPS phase scintillation occurrence** in the context of solar wind coupling to the magnetosphere-ionosphere system and auroral electrojet currents during March 17-18, 2015 has been submitted to JGR.

St. Patrick storm: Rate of TEC index (ROTI)



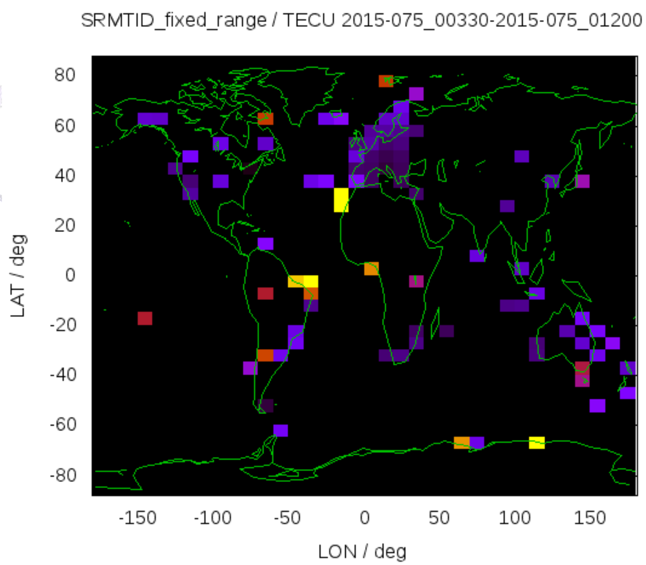




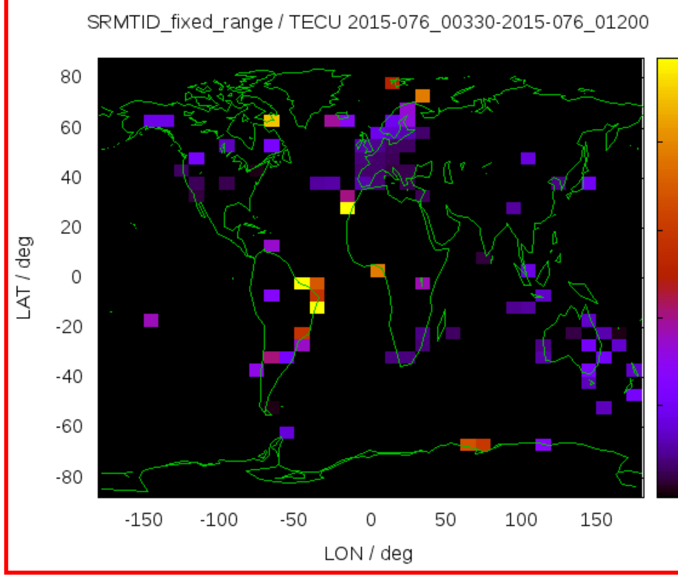


The results in this and next slides have been obtained in the frame of **European Space Agency**'s **MONITOR** & **MONITOR2** projects (**ESA/ESTEC TEC-EEP**).

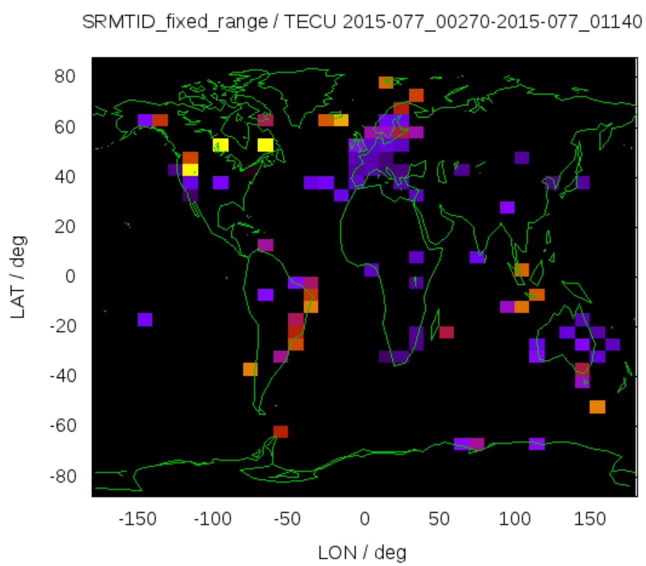
St. Patrick storm: Single Receiver Medium Scale TIDs index (SRMTID)



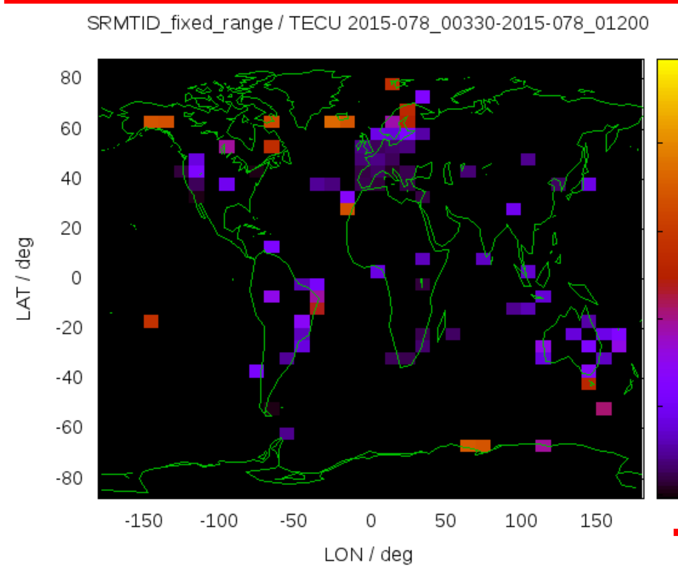
75



76

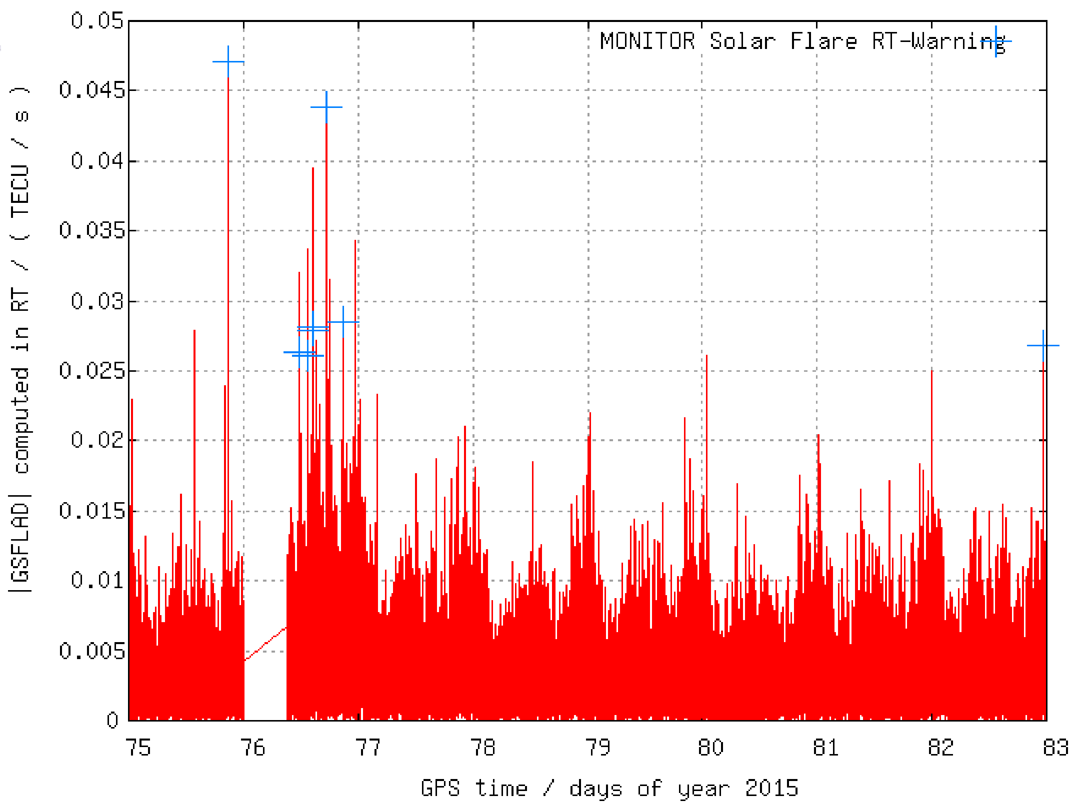


77



78

St. Patrick storm: GSFLAI EUV rate proxy & SISTED solar flare detector (UPC)



Clear solar flare activity on doy 76 and previous days

These results have been obtained in the frame of **European Space Agency**'s **MONITOR** & **MONITOR2** projects (**ESA/ESTEC TEC-EEP**)

On-going activities: VTEC IONEXs

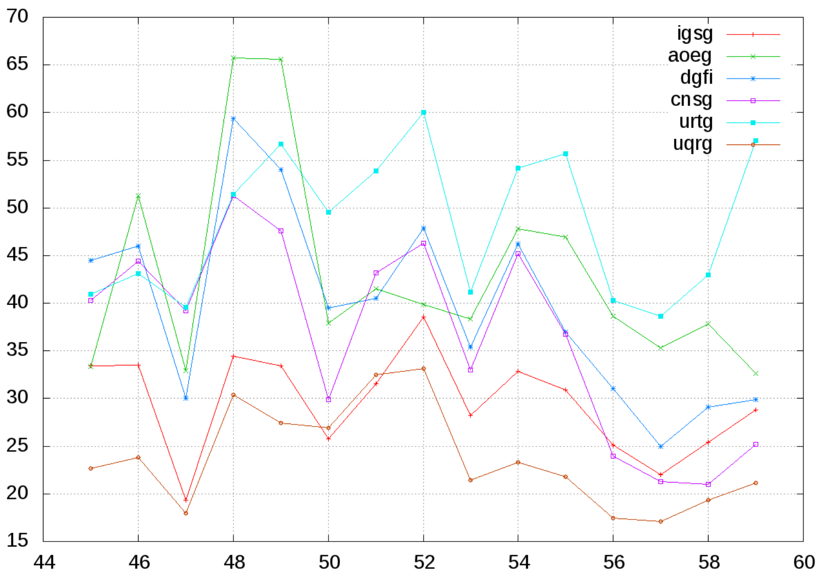
- **RT/NRT Vertical TEC IONEX** files have been solicited on the period **45 to 59, 2016**. This shall be used as a **first check/comparison** of Vertical TEC products in IONEX format from entities providing them within RTIM-WG.
- The **consistency and accuracy** of the products **can be analysed against external assessment techniques** (as it is done within **IGS Iono-WG**): for both vertical geometries over the oceans/seas (vs **altimeter-VTEC**) and for slant variation (**GPS-dSTEC**) over independent GPS receivers.
- It is important that the accuracy should be assessed from independent ionospheric measurements not taking part in the generation of any of the products.

VTEC IONEXs: CAS/DGFI/URTG first comp.

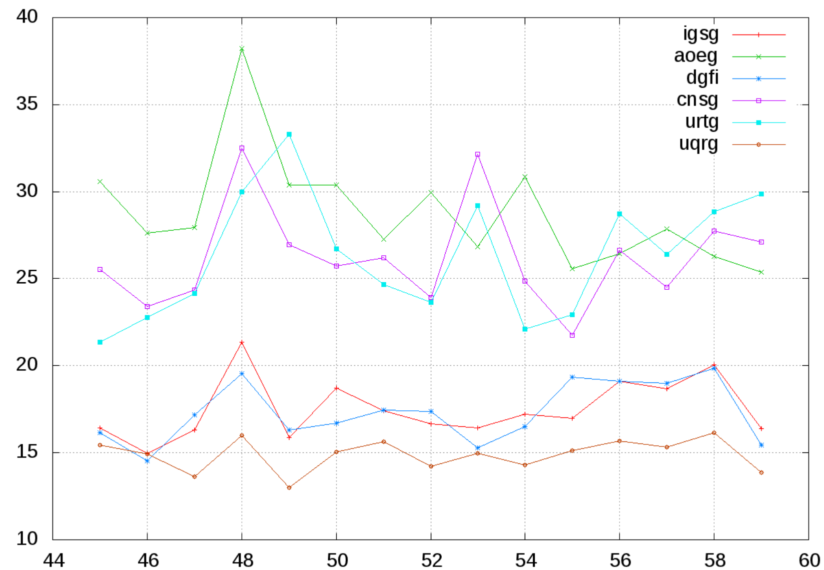
- **Comparison of six different VTEC products**: three RT from CAS (aoeg), CNES (cnsg) and UPC (urtg); one NRT from TUM (dgfi) and two traditional GIMs for reference, from UPC (uqrg) and IGS (igs).

JASON altimeter assessment

Europe



Global



Relative RMS error (%) for days of year 2016 from 45 to 59

For the details, please refer to D. Roma-Dollase, M. Hernández-Pajares, A. García-Rigo, D. Laurichesse, M. Schmidt, E. Erdogan, Y. Yuan, Zishen Li, J.M. Gómez-Cama, A. Krankowski. “Real Time Global Ionospheric Maps: a low latency alternative to traditional GIMs”, Poster at Beacon Sat. Symp. (BSS), June 2016, Trieste, Italy.

VTEC IONEXs: CAS/DGFI/URTG first comp

dSTEC assessment

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

From left to right: GIM, square root of the arithmetic mean of the RMS for all stations and days; maximum and minimum RMS for all stations; bias for all stations and days.

For the details, please refer to D. Roma-Dollase, M. Hernández-Pajares, A. García-Rigo, D. Laurichesse, M. Schmidt, E. Erdogan, Y. Yuan, Zishen Li, J.M. Gómez-Cama, A. Krankowski. “Real Time Global Ionospheric Maps: a low latency alternative to traditional GIMs”, Poster at Beacon Sat. Symp. (BSS), June 2016, Trieste, Italy.

Conclusions

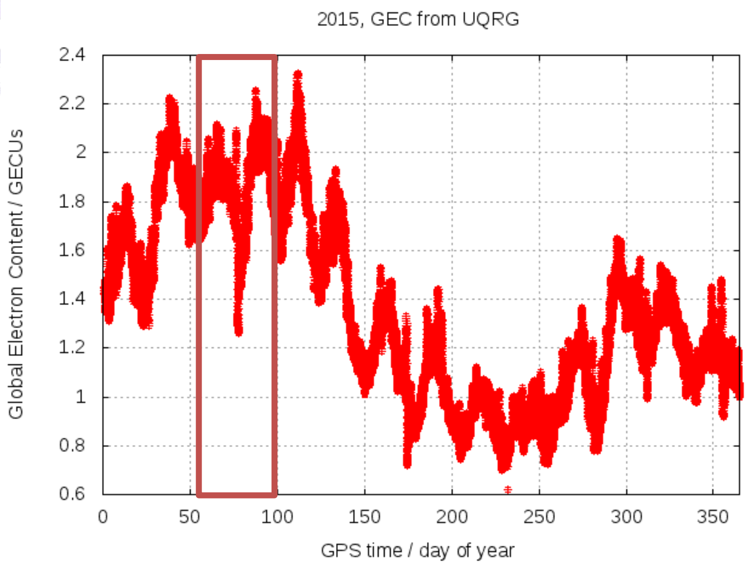
- First steps taken within the RTIM-WG are presented towards the identified objectives.
- First inputs on St. Patrick storm are presented. Data within the group will be analysed in more detail.
- A comparison of existing IONEX VTEC maps within the group has also started.

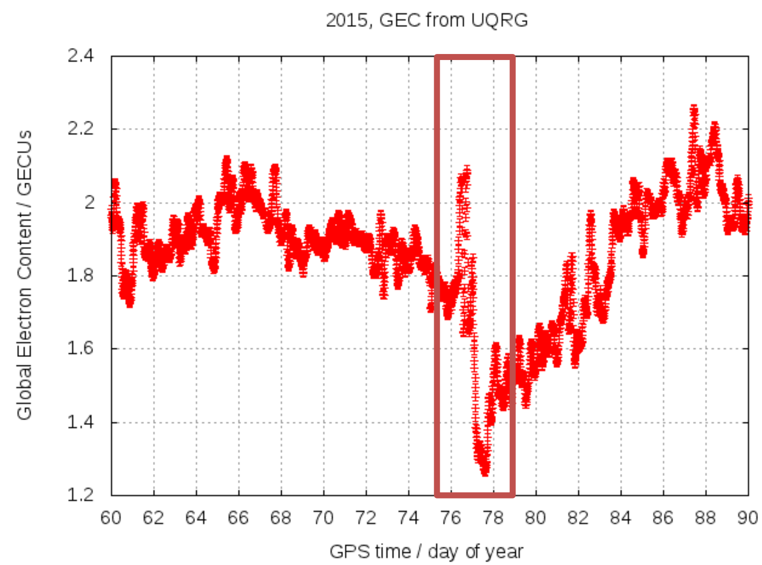
Thank you very much

Thank you very much

Back-up slides

St. Patrick storm: Global Electron Content (GEC from UQRG; 2-day latency)

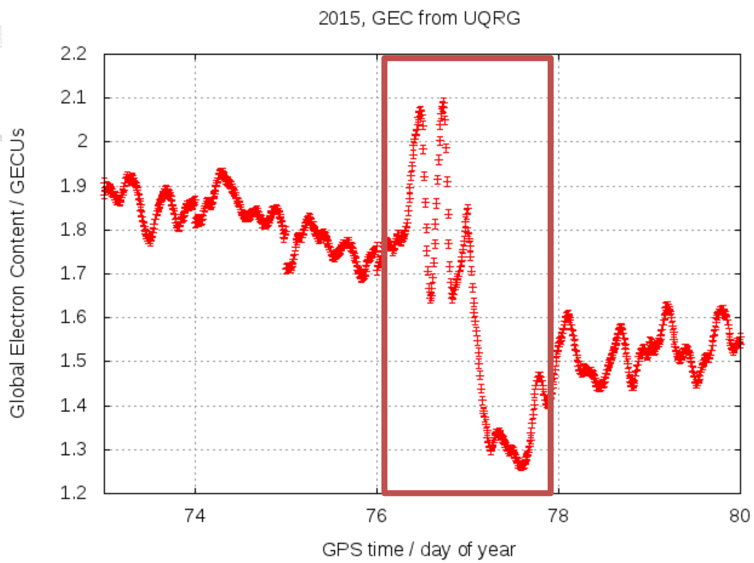


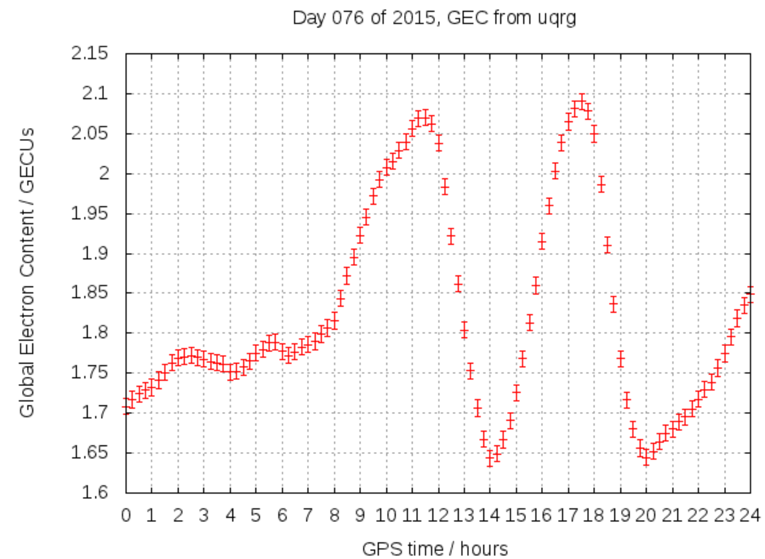


- Clear impact on Global Electron Content trend (a positive phase, followed by a negative phase) from UQRG rapid GIMs.
- This shall also be checked with **URTG** GIMs (UPC real time VTEC global maps)

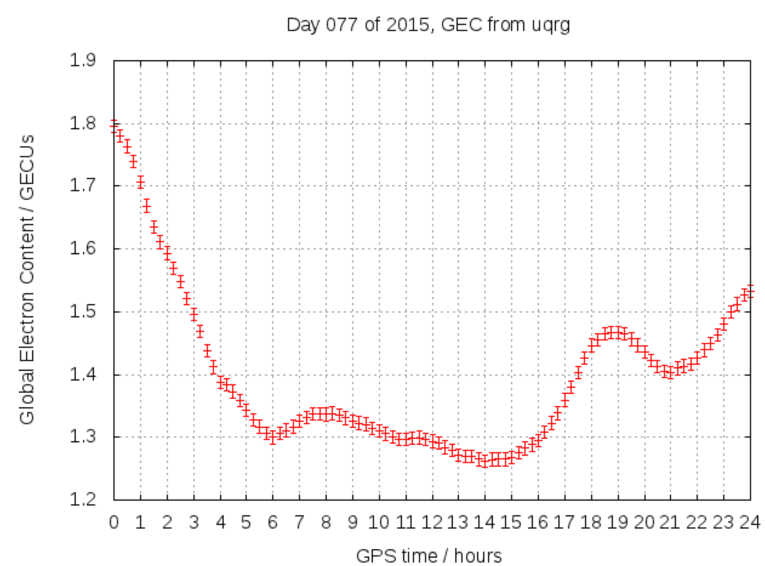
These results have been obtained in the frame of **European Space Agency**'s **MONITOR** & **MONITOR2** projects (**ESA/ESTEC TEC-EEP**)

St. Patrick storm: Global Electron Content (GEC from UQRG; 2-day latency)

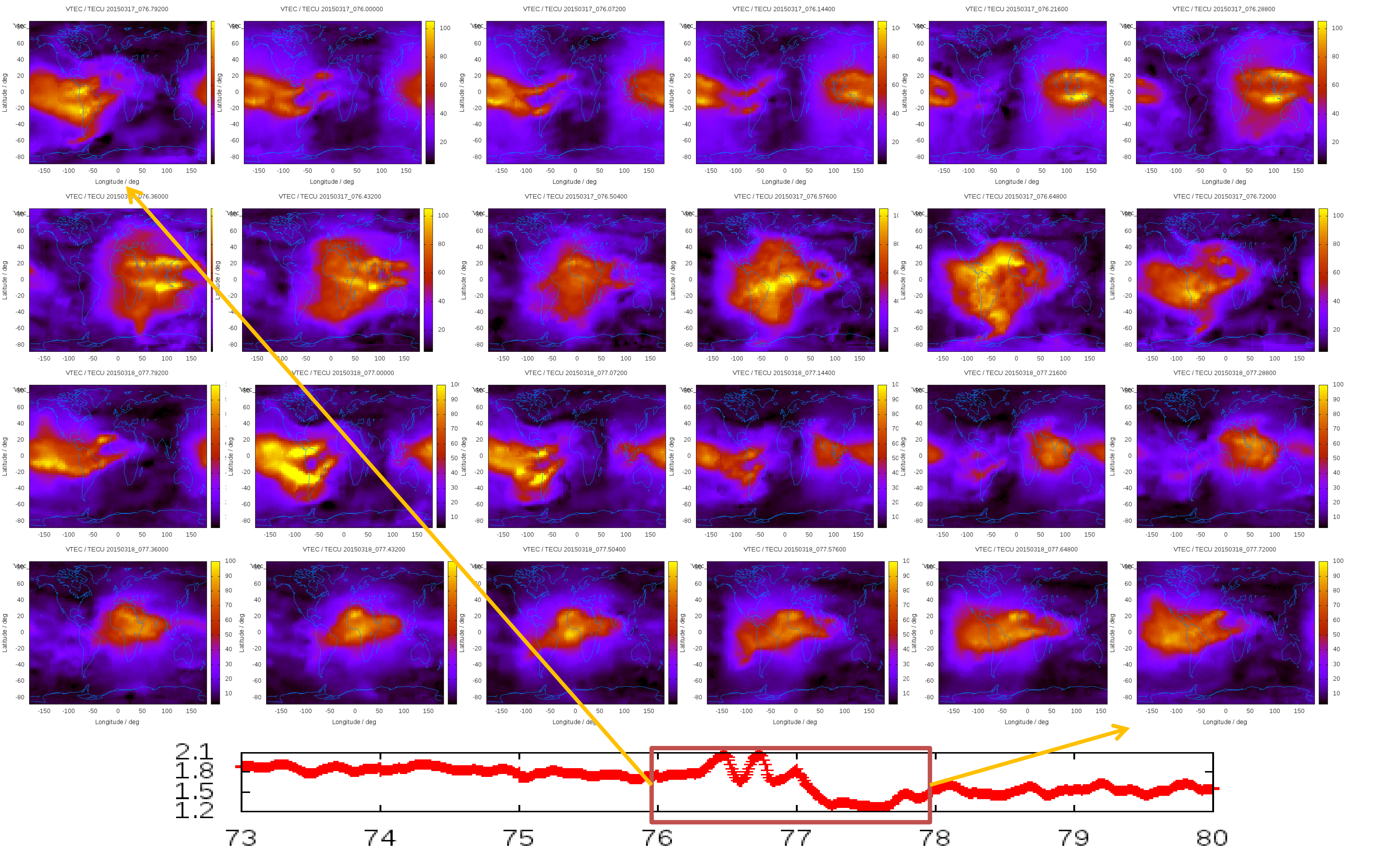




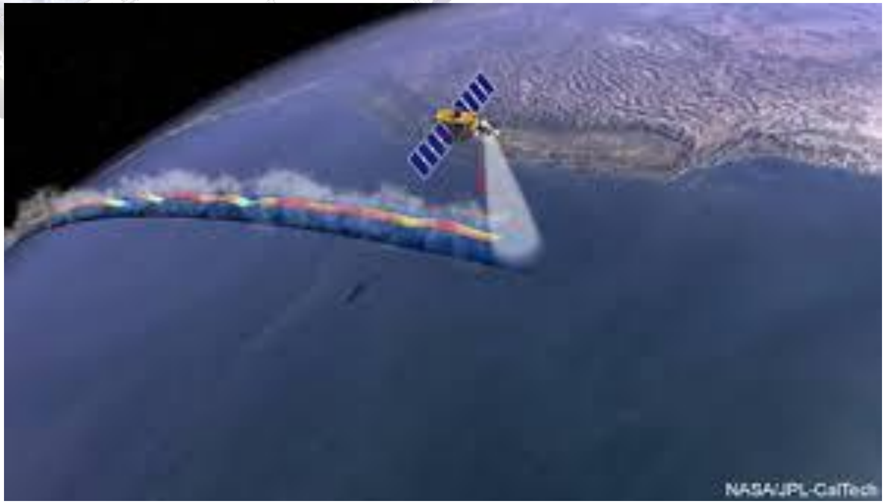
The detailed view shows two important GEC increases (+20%), separated by 6 hours, followed by a deep negative phase (almost -25%) ~18 hours later

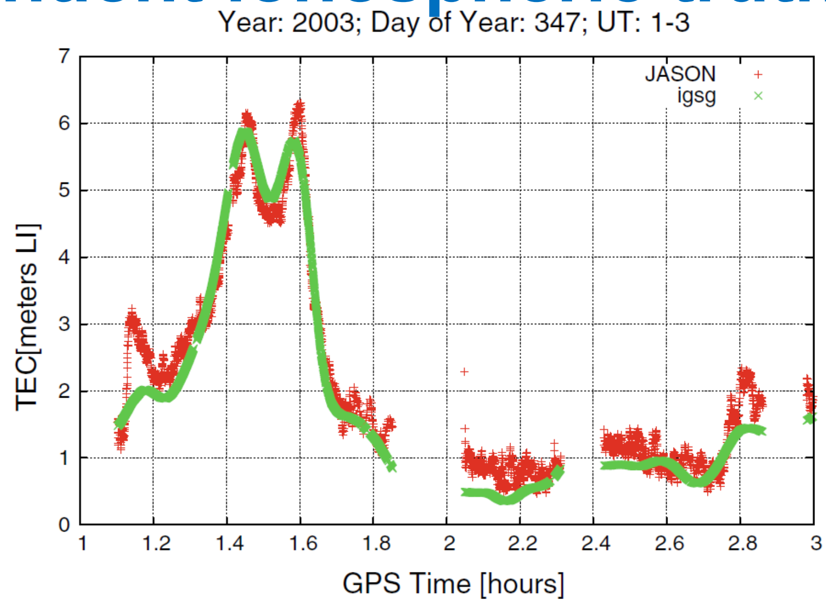


St. Patrick storm: UQRG VTEC snapshots @ 2h



VTEC directly observed from dual-frequency altimeters: a GNSS-independent ionospheric truth



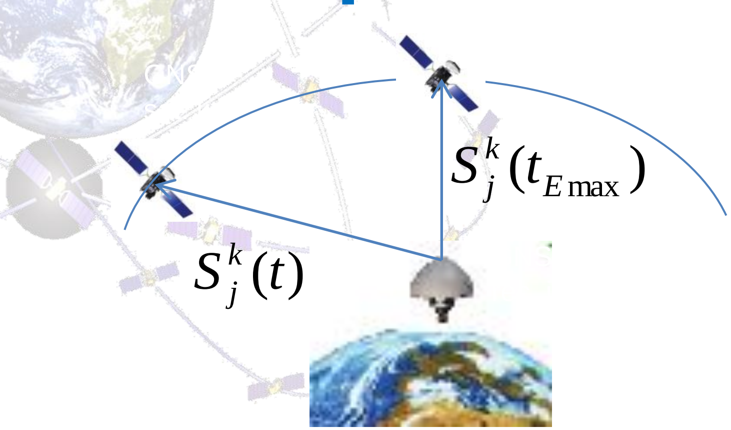


Dual-frequency altimeter measurements provide an excellent and independent source for assessing GNSS-based VTEC models in difficult conditions (over seas & far from rec.).

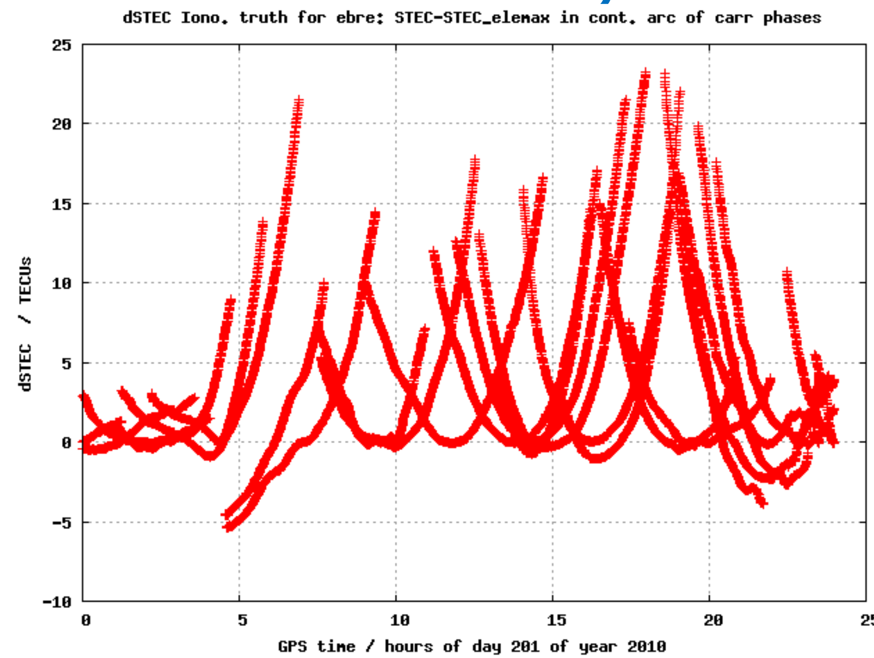
In spite of the noise of the altimeter measurements (reduced by an sliding window of ~16 sec.; see right-hand figure, compared vs. final IGSG VTEC), the missing altimeter-topside electron content (typically up to few TECUs only) and the well known altimeter bias excess (few TECUs only), it still **allows a very clear assessment and comparison of the errors of the different ionospheric models (considering in particular the daily standard deviations of VTEC_altimeter – VTEC_GIM),** typically much larger and systematic

(see for instance Ho, C. M., Wilson, B. D., Mannucci, A. J., Lindqwister, U. J., & Yuan, D. N. (1997). A comparative study of ionospheric total electron content measurements using global ionospheric maps of GPS, TOPEX radar, and the Bent model. Radio Science, 32(4), 1499-1512.).

Ionospheric Truth: STEC Variation, dSTEC



$$\Delta S_O \equiv S_j^k(t) - S_j^k(t_{E\max}) =$$
$$= [(L_I)_j^k(t) - (L_I)_j^k(t_{E\max})] / \alpha \equiv \Delta L_I / \alpha$$



The GPS ionospheric carrier phase difference, ΔLI for a given pair rec.(j)-sat.(k), (regarding to the value corresponding to the higher elevation –Emax- ray in the phase-continuous arc of data), provides a **very precise ionospheric truth of the STEC referred to the value at maximum elevation, dSTEC,** in space and time (typically more accurate than 0.1 TECU).

It can be used to compare the performance of ionospheric models, which can be interpreted as an assessment of the corresponding VTEC (V), the mapping function being considered (M) and their time evolution.

(see for instance Hernández-Pajares, M., Juan, J. M., Sanz, J., Orus, R., Garcia-Rigo, A., Feltens J., Komjathy, A., Schaer, S., & Krankowski, A. (2009). *The IGS VTEC maps: a reliable source of ionospheric information since 1998*. Journal of Geodesy, 83(3-4), 263-275).

PROS and CONS

Technique	PROS.	CONS.
VTEC-altimeter	Independent VTEC assessment (accuracy of few TECU)	Only over oceans and seas
dSTEC-GNSS	Independent STEC assessment (precision ~ 0.05 TECU)	Close or over continents mainly

Complementary assessments