Comprehensive assessment of ionospheric electron content models: Methodology

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Outline

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- GPS & Ionosphere

- IIWG

- Assessment techniques

2. Description of external assessment techniques

3. Direct comparison of VTEC-altimeter & dSTEC-GPS assessments

4. Conclusions

Introduction (GPS & Ionosphere)

- Dual-frequency GPS can be considered an excellent ionospheric sounder.
- By means of GPS we can exploit the very well known predominant (>99.9%) ionospheric delay dependence affecting the transionospheric electromagnetic signals.
- This dependence is proportional to the integrated electron density and inversely proportional to the squared frequency.
- With +30 transmitters and thousands of permanent GPS receivers, a high spatial and temporal simultaneous ionospheric sampling is achieved.
- In this work, we focus on the Global Ionospheric Maps (GIMs) of Vertical Total Electron Content (VTEC).

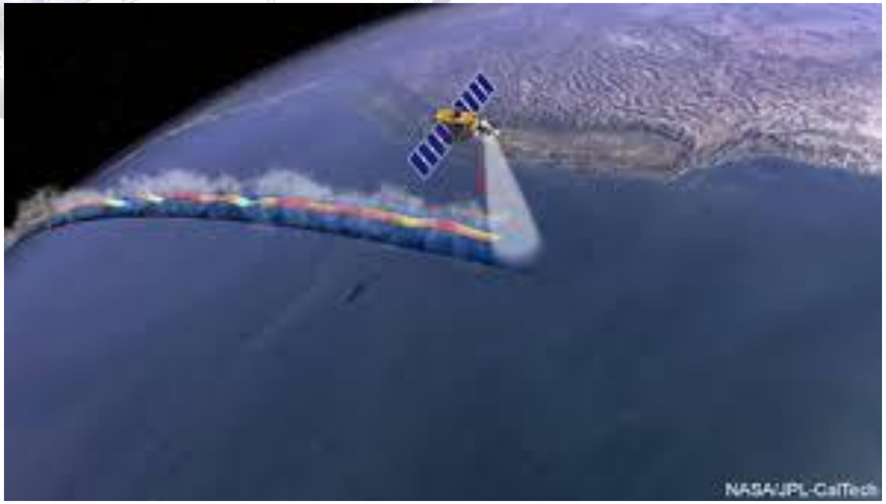
Introduction (IIWG)

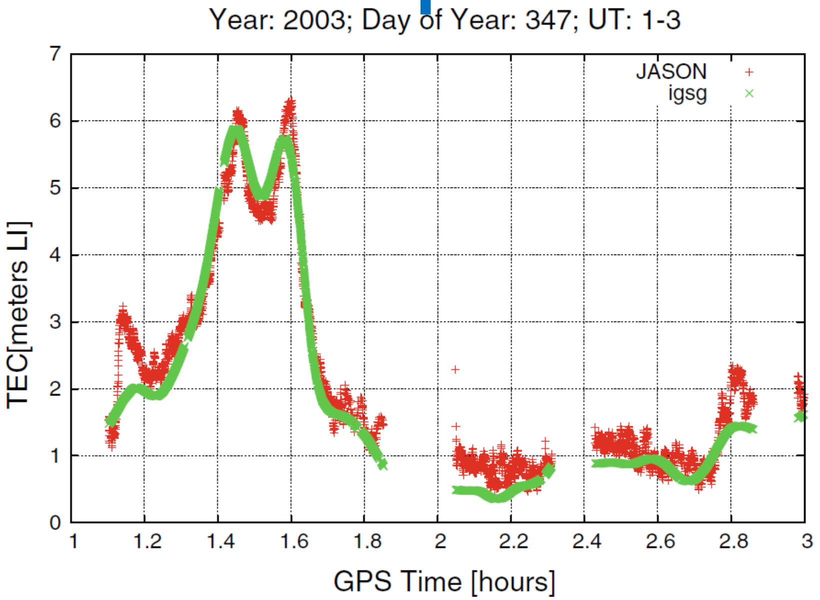
- The GIMs are systematically computed and distributed by the **International GNSS Service (IGS) Ionospheric WG** (IIWG) since day 152, 1998.
- **Different techniques** are used by different ionospheric analysis centers (4 to 7), in particular for the slant-to-vertical **mapping** (e.g. common worldwide effective height, tomographic model…) and for **interpolation** to avoid VTEC gaps (e.g. Sph. Harmonics, Kriging).
- The GIMs accuracy has been increased from 1998, thanks to an open daily-basis independent assessment, comparison, and **combination to derive the IGS combined GIM**.
- The combined GIM is characterized not only by a **high accuracy** but specially a very **high reliability** (availability/continuity) in all combination circumstances.

Introduction (Assessment)

- The reliability and accuracy of the combined IGS GIM is supported by the fair **assessment of the consistency and accuracy of the individual GIMs**, provided by different IIWG centers
- It has been crucial to define fair, external assessment techniques, for both vertical geometries over the oceans/seas (vs **altimeter-VTEC**) and for slant variation (**GPS-dSTEC**) over independent GPS receivers.
- The GIMs accuracy should be assessed from **independent** ionospheric measurements not taking part in any GIM estimation.
- The **direct comparison of these independent assessments**, likely for the first time, is the main target of this presentation.

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



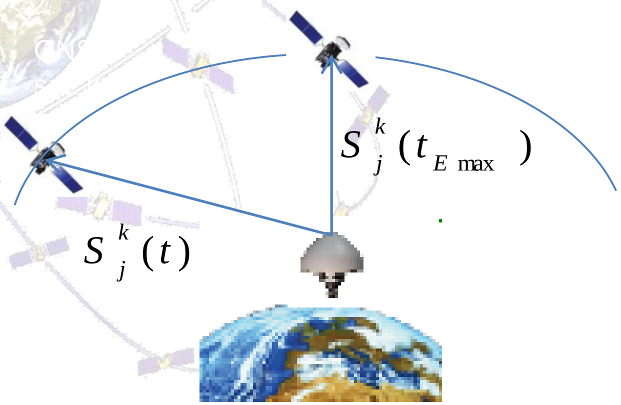


Dual-frequency altimeter measurements provide an excellent and independent source for assessing GNSS-based VTEC models in difficult conditions (over seas & far from rec.).

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

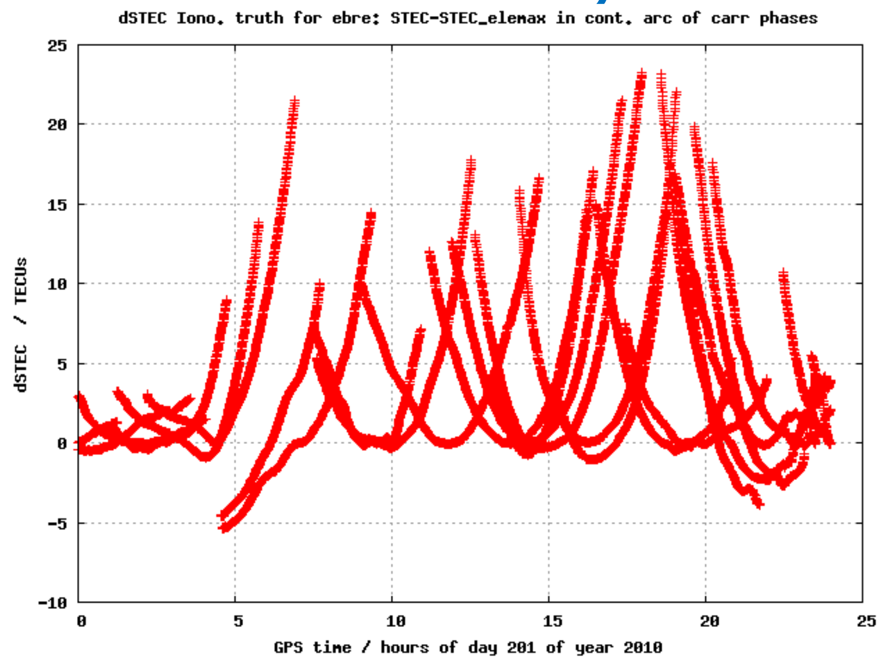
(see for instance Ho, C. M., Wilson, B. D., Mannucci, A. J., Lindqwister, U. J., & Yuan, D. N. (1997). A comparative study of ionospheric total electron content measurements using global ionospheric maps of GPS, TOPEX radar, and the Bent model. Radio Science, 32(4), 1499-1512.).

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., Orús, R., García-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

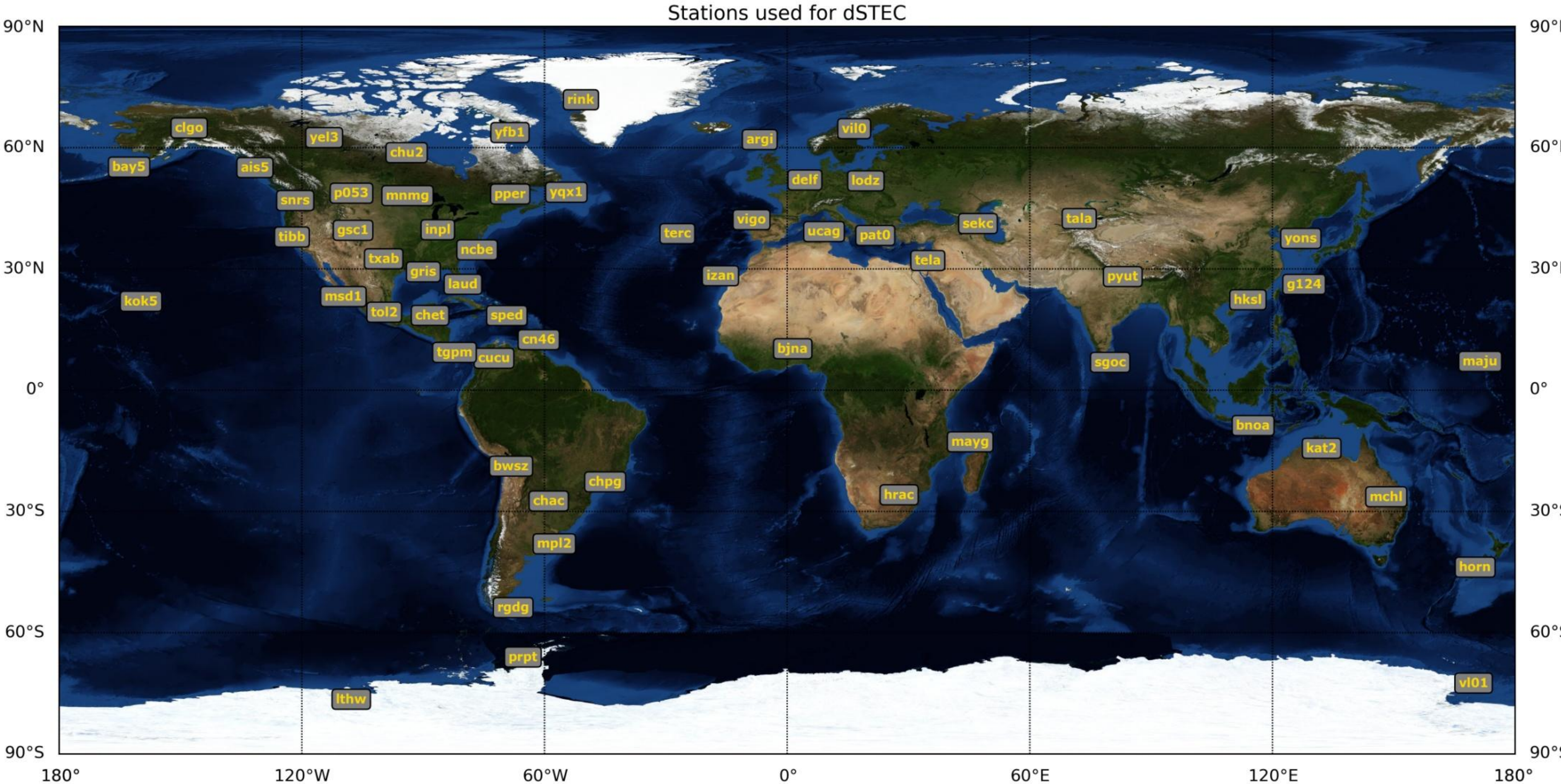
Technique	PROS.	CONS.
VTEC-altimeter	Independent VTEC assessment (accuracy of few TECU)	Only over oceans and seas
dSTEC-GNSS	Independent STEC assessment (precision ~ 0.05 TECU)	Close or over continents mainly

Complementary assessments

Direct comparison of VTEC-altimeter & dSTEC-GPS assessments: target

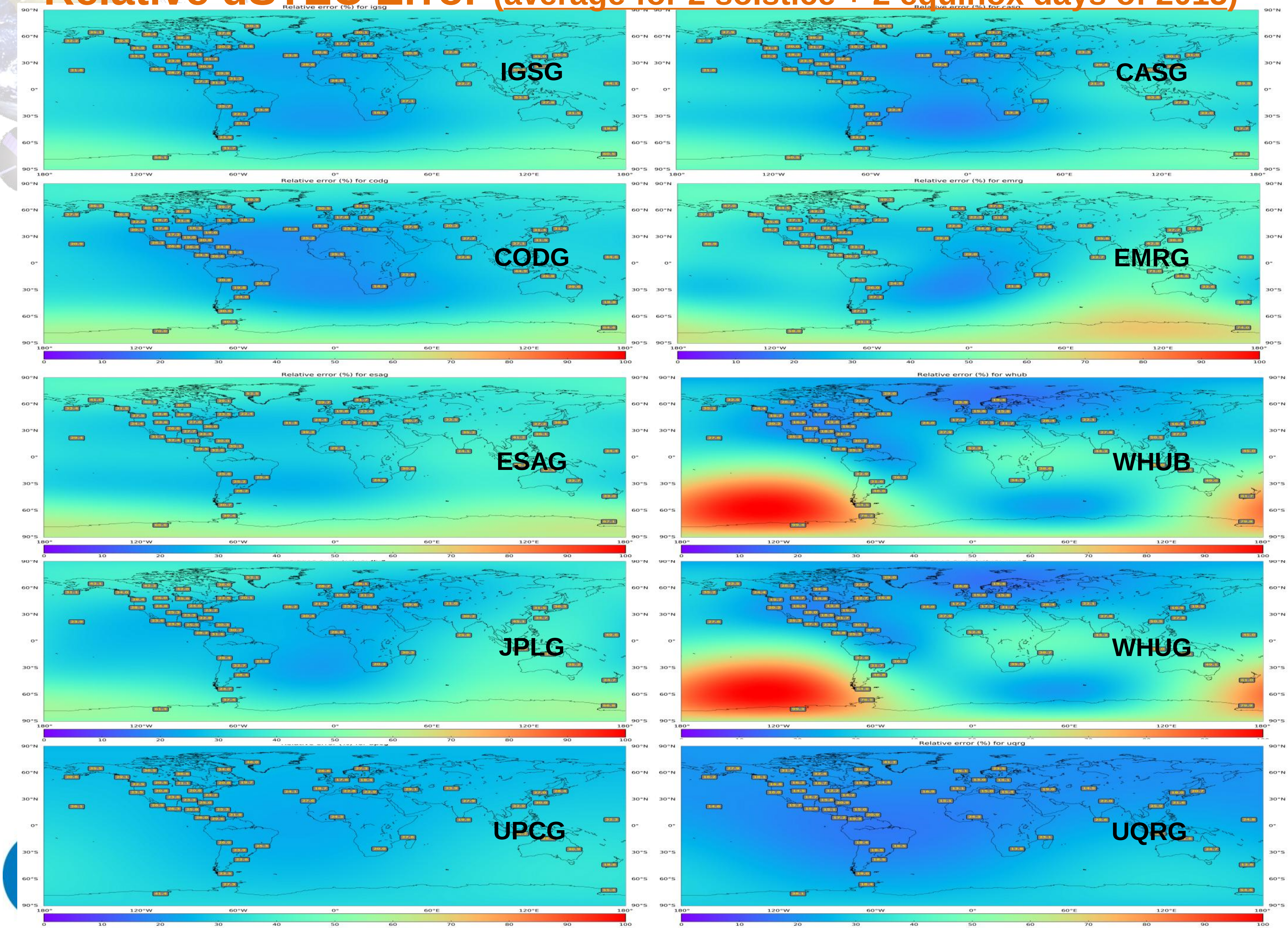
- Our purpose is to compare the assessment for one representative VTEC GIM product by means of **independent and collocated** (e.g. on **islands**) VTEC-altimeter and dSTEC-GNSS **measurements**.
- We select the **rapid 15-min. UQRG GIM** (UPC with TOMION soft.) implementing tomography & kriging, which performance has been recently compared with other GIMs (*Hernández-Pajares et al., IGS WS, Sydney, Feb. 2016*).
- A summary of **UQRG performance** can be seen in next 3 slides:

Selection of independent GPS receivers for external dSTEC assessment



+50 permanent GPS receivers to provide directly observed dSTEC, not used in any of the GIMs under assessment (from their list of receivers used in the IONEX header file)**,** have been selected guaranteeing the most feasible homogenous distribution <u>during 2 solstice and 2 equinox days in 2015: 082, 146, 280 and 330.</u>

Relative dSTEC Error (average for 2 solstice + 2 equinox days of 2015)



Recent GIMs assessment vs VTEC-altimeter & dSTEC-GPS[*]

GIM Id.	VTEC_Altimeter - VTEC_GIM Rel. Error [2015,117-2016,007] / %	# Days
IGSG	21.1	21
CODG	21.8	21
ESAG	25.5	21
JPLG	21.9	21
UPCG	**19.1**	**21**
CASG	21.1	21
EMRG	26.5	21
WHUB	25.0	21
WHUG	25.0	21
UQRG	**16.3**	**21**

GIM Id.	dSTEC_GNSS – dSTEC_GIM Rel.Error [days 082, 146, 280, 330 2015] / %	# Rec* Days
IGSG	28.9	238
CODG	27.8	238
ESAG	33.0	238
JPLG	31.0	180
UPCG	**26.9**	**238**
CASG	28.0	178
EMRG	33.6	178
WHUB	30.7	60
WHUG	30.7	60
UQRG	**20.5**	**233**

[*] By using +50 GPS receivers

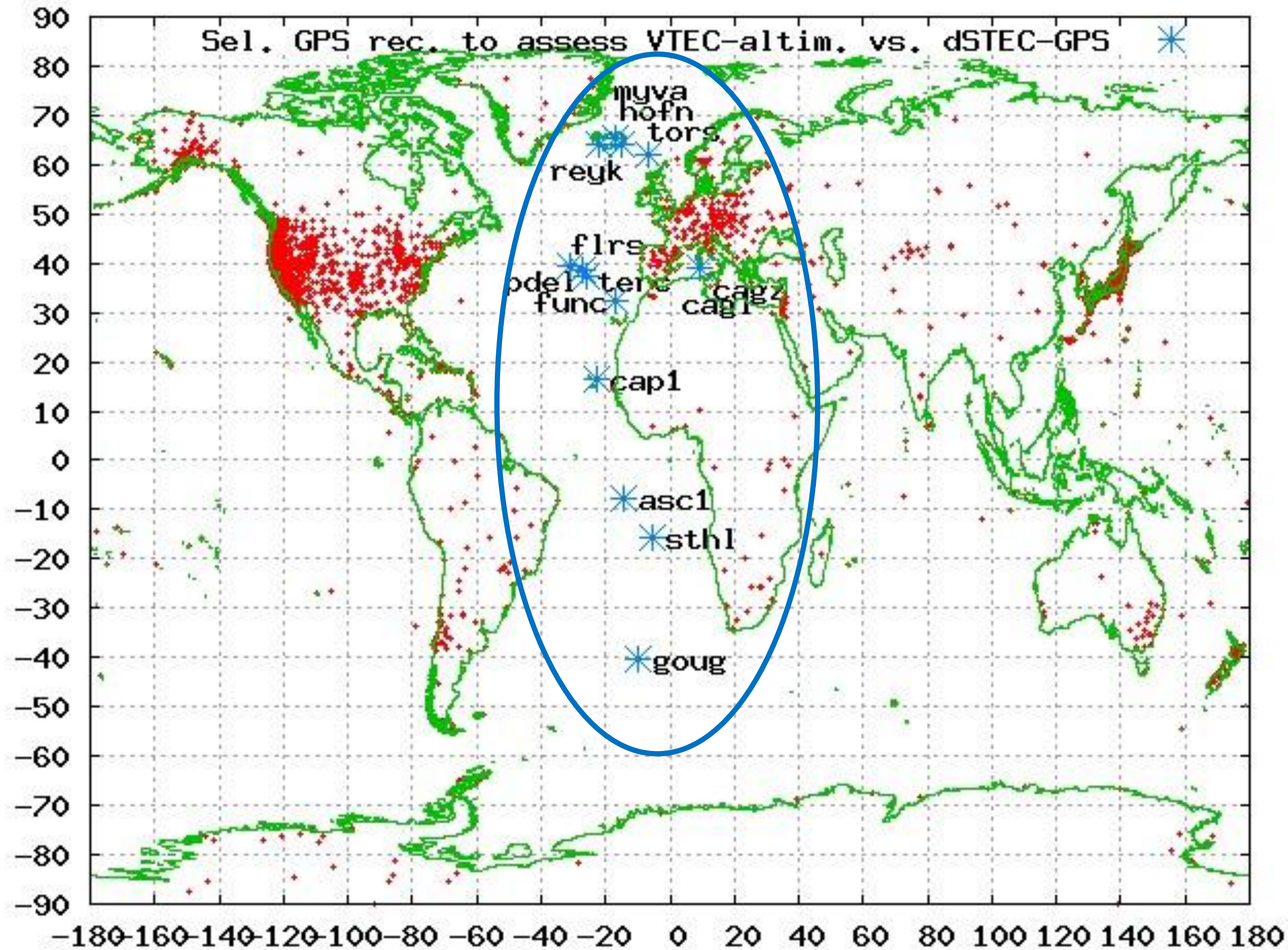
Direct comparison of VTEC-altimeter & dSTEC-GPS assessments: receivers

- **14 GPS receivers over islands** have been selected during **40 days** evenly distributed from **2011** to **2015** (mostly on an Atlantic "chain").

Collocation of GPS and JASON2 measurements:

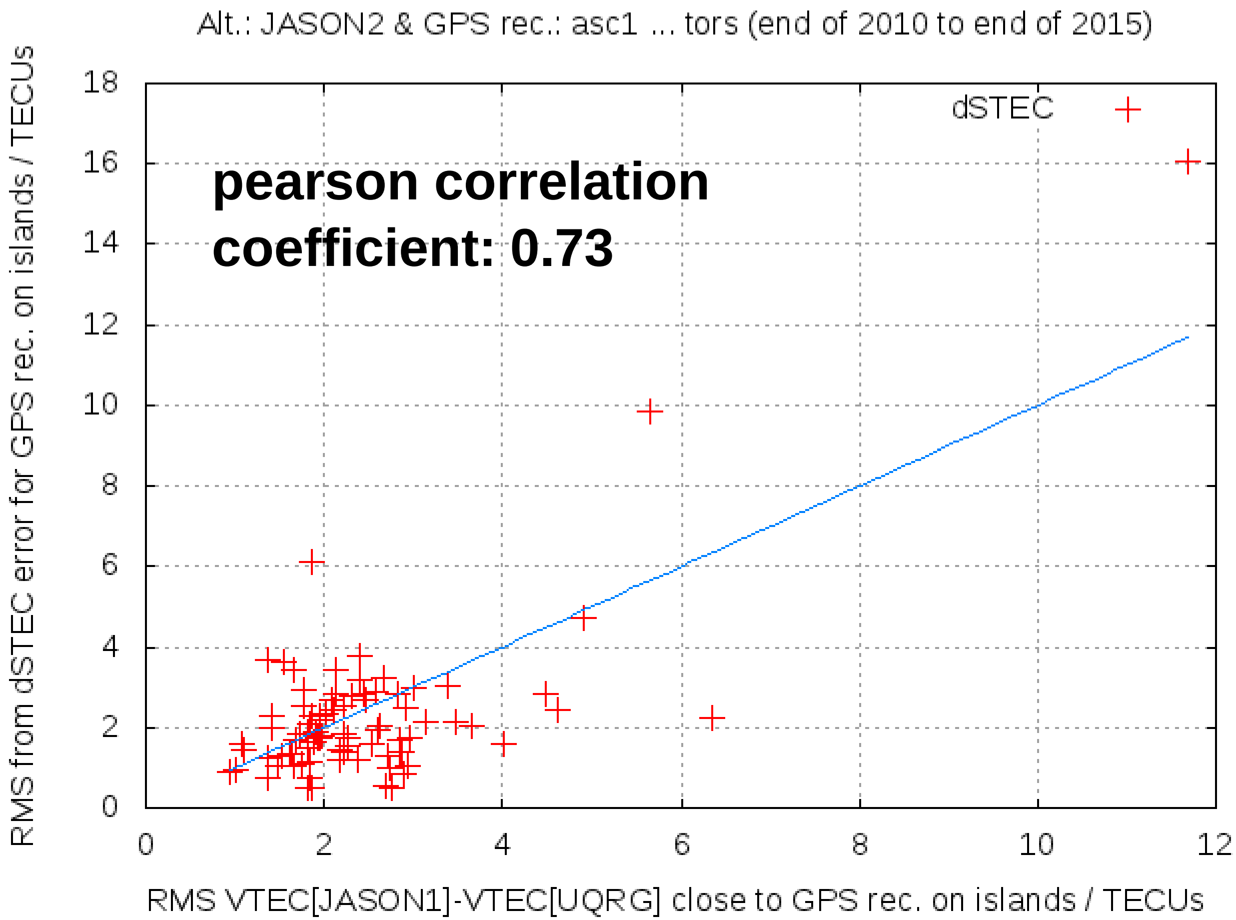
Δ longitude < 12º
Δ latitude < 10º
Δ time < 900 sec
obs.[*] >= 175

[*] Condition for both dSTEC-GPS & VTEC-altimeter



UQRG RMS: dSTEC vs VTEC

- **RMS of UQRG dSTEC discrepancy** (referred to observed GPS value) vs **RMS of UQRG VTEC discrepancy** (vs. JASON2 value) for each one of the 88 colocated passes (with a typical range of 1-4 TECU, up to 12-16 TECU):



Explanation: Qualitative dSTEC error model

- The **correlation of dSTEC and VTEC GIM errors** (always referred to external GPS and altimeter truths), and with compatible values, **can be qualitative explained**.
- Indeed, taking profit of the high elevation value of the reference dSTEC observation (its mapping function error is almost zero), assuming VTEC constancy during fast pass of altimeter, and neglecting as well the lowest elevation ray mapping function error (the most tough hipothesis in spite of E > 15º), then:

$$\varepsilon[\Delta S] = \varepsilon[S - S(E\ \max)] =$$

$$= \varepsilon[M \cdot V] - \varepsilon[M(E\ \max) \cdot V(E\ \max)] \cong$$

$$\cong M \cdot \varepsilon[V] + \varepsilon[M] \cdot V - M(E\ \max) \cdot \varepsilon[V(E\ \max)] \approx$$

$$\approx (M - M(E\ \max)) \cdot \varepsilon[V] \Rightarrow$$

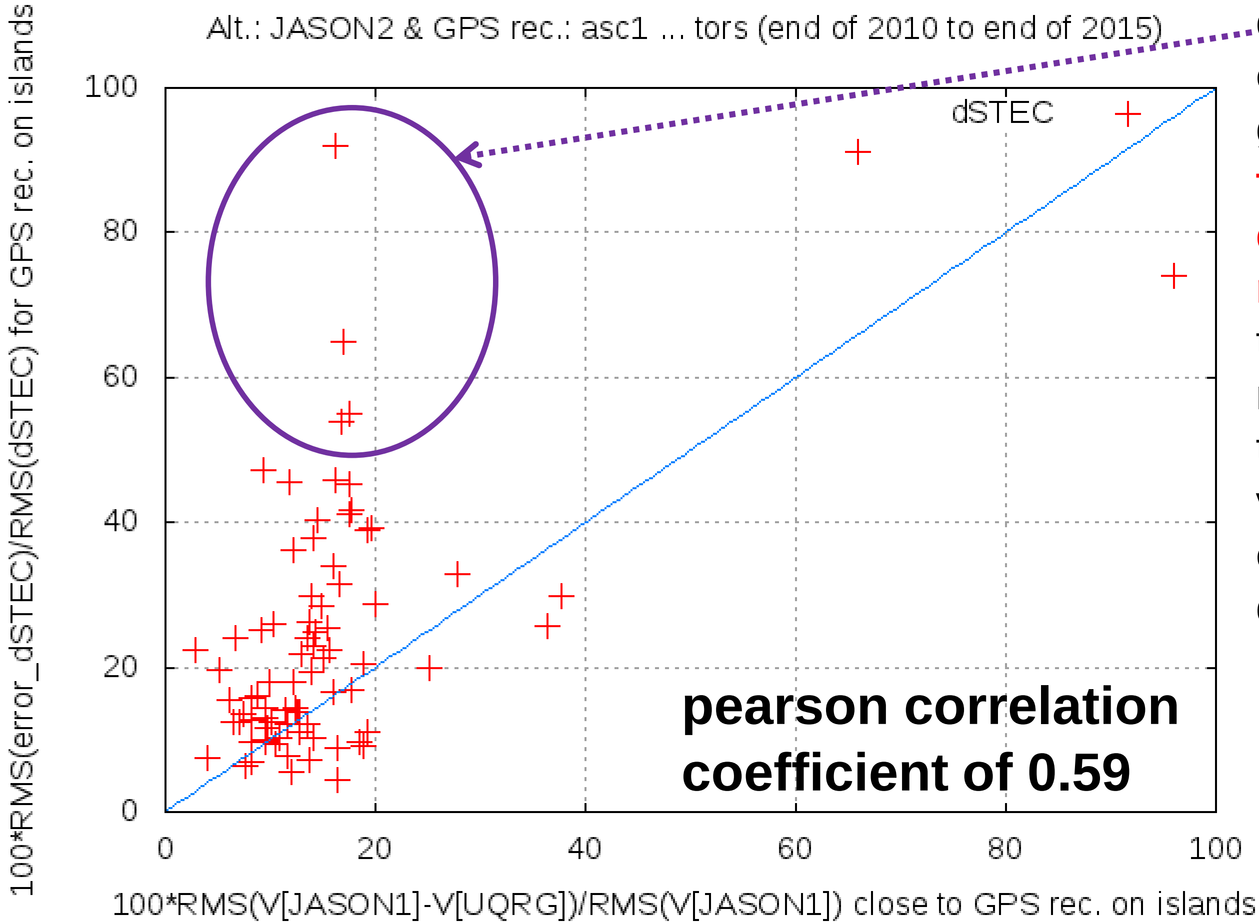
$$\Rightarrow RMS(\varepsilon[\Delta S]) = \sqrt{E\{\varepsilon[\Delta S] \cdot \varepsilon[\Delta S]\}} \sim$$

$$\sim \sqrt{(M^2 + M^2(E\ \max)) \cdot E\{\varepsilon[V] \cdot \varepsilon[V]\}} =$$

$$= \sqrt{(M^2 + M^2(E\ \max))} \cdot RMS(\varepsilon[V])$$

UQRG Rel.Error: dSTEC vs VTEC

- **Relative Error(%) of UQRG dSTEC discrepancy** (referred to observed GPS value) vs **Relative Error (%) of UQRG VTEC discrepancy** (vs. JASON2 value) for each one of the 88 colocated GPS receivers / altimeter passes events[*]



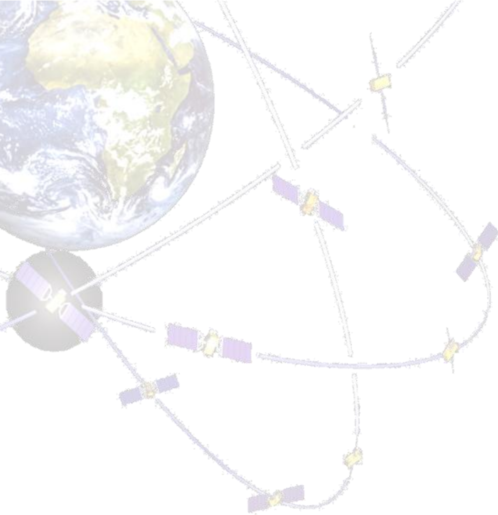
dSTEC relative error trends to be greater because **the reference dSTEC can be much smaller** than VTEC ([*] not showing up two passes with values relative error > 100% for dSTEC)

Conclusions (1 of 2)

- Two independent and complementary ionospheric assessing techniques of VTEC GIMs, taking as reference the direct dSTEC-GPS and VTEC-altimeter observations are, likely by the first time, compared with collocated observations.
- For such purpose, we have adopted the best performing UPC GIMs ("UQRG") and we have considered JASON2 collocated observations over a latitudinal chain of 14 GPS IGS receivers placed on islands in the Atlantic ocean, during 40 days within 2011-2015.

Conclusions (2 of 2)

- The RMS for each JASON2 pass are in good agreement (with a range of 1 to 12-16 TECU and pearson corr. coef. of 0.73), qualitatively explained with a simple error model.
- The relative errors are as well in agreement (mostly below 20%) but with a tendency to bigger values for dSTEC, due to its lowest ref. values.
- In conclusion: *both complementing and independent assessing techniques, dSTEC-GPS and VTEC-altimeter, successively used in previous works to rank VTEC GIMs, show its quantitative consistency as well, when they are directly compared in collocated scenarios.*



Thank you!

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