Using Near-Real-Time DORIS Data for Validating Real-Time GNSS Ionospheric Maps

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- Background and Motivation
- GNSS and DORIS dSTEC assessments
  - GNSS derived dSTEC observables
  - DORIS derived dSTEC observables
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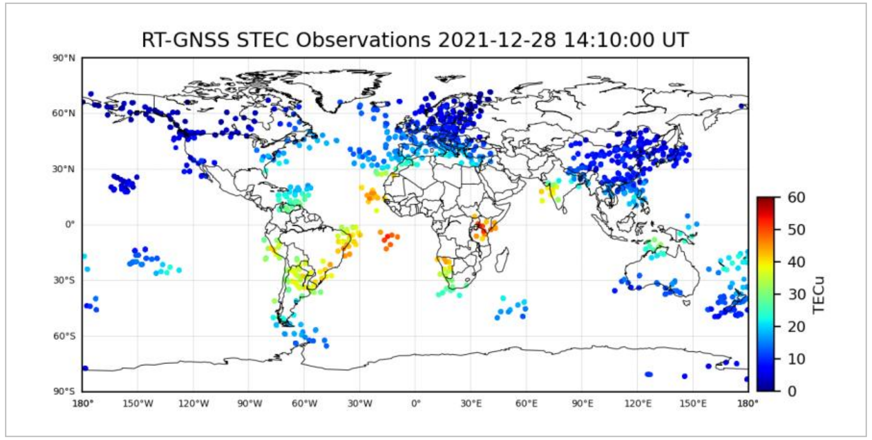
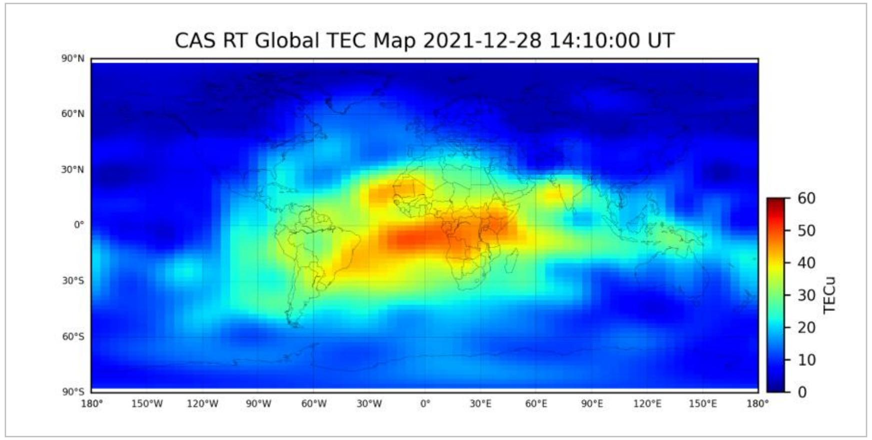
Generation of Real-Time Global Ionospheric Maps (RT-GIMs)

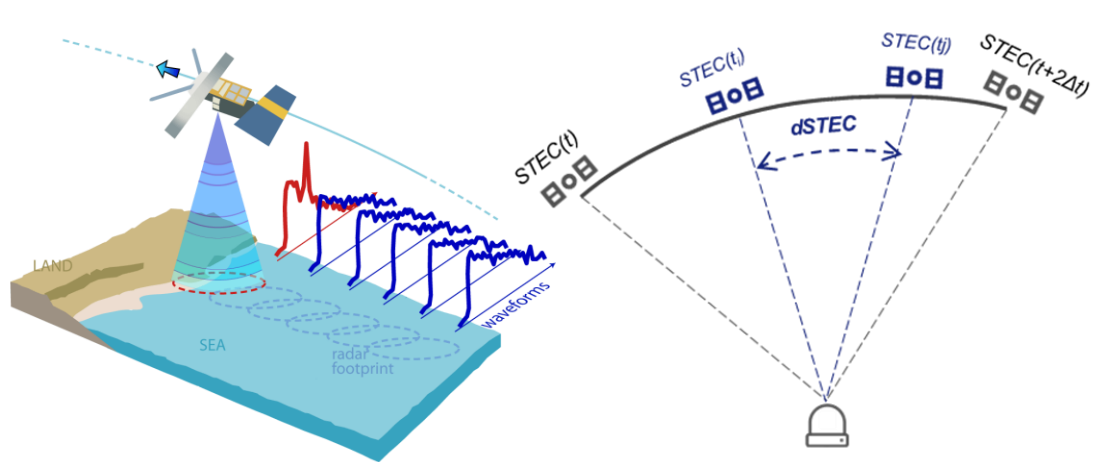
- Regional and global real-time GNSS data streams (1 Hz), containing multi-frequency (L1/L2/L5) and multi-constellation (G/R/E/C) GNSS measurements, are available for RT-GIM computation.
- Within the International GNSS Service (IGS), RT-GIMs are routinely generated by 4 Analysis Centers (ACs): CAS, CNES, UPC and WHU.
- The IGS combined RT-GIMs are independently generated by CAS and UPC since January 2022.
- RT-GIMs are widely used in ionospheric space weather and precise GNSS positioning applications.





Validation of Real-Time Global Ionospheric Maps (RT-GIMs)

- **Self-consistency check**
  - **GNSS-derived STEC**: *code smoothing* or *precise point positioning* (PPP) derived, S/R DCB removed.
  - **GNSS-derived dSTEC**: carrier phase geometry-free combination derived, differential STEC b.w.t. two epochs along individual continuous arcs, low level of observation noises.
  - GNSS derived STEC and dSTEC are available in real-time (few seconds in time latency).
- **External-consistency check**
  - Altimetry-derived VTECs, available over the oceanic regions.
  - Fully independent to GNSS measurements.
  - Near-real-time DORIS data provided by **Jason-3** (~3 hours in latency)



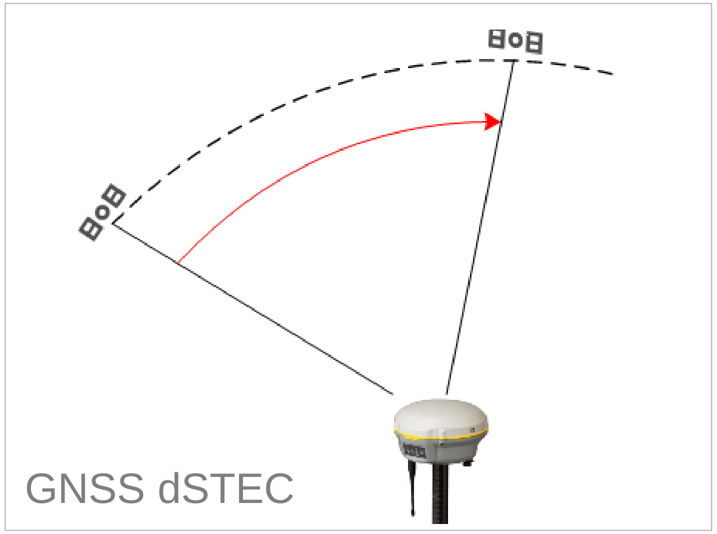
Using DORIS Data to Validate GNSS-generated RT-GIMs

- **DORIS data: valuable and external data sources to examine the Earth's ionosphere.**
- Homogeneous distribution of DORIS ground beacons, covering continental and oceanic regions.
- DORIS data are available from 8 satellites: CRYOSAT-2, HY-2C, HY-2D, Jason-3, SARAL, Sentinel-3A, Sentinel-3B and Sentinel-6A
- The relative frequency ratio between two frequencies of DORIS is about 5, more sensitive to detect the ionospheric information and less prone to measurement noises.
- The standardization of DORIS data formats, i.e., RINEX DORIS 3.0, similar to the existing GNSS RINEX format.
- The decreasing time latency in obtaining DORIS data (2-3 hours for Jason-3 DORIS data).
- "NRT DORIS DATA WG" established in IDS since 2018.

GNSS dSTEC analysis

- GNSS dSTEC: differential phase STEC along a continuous arc referring to the highest satellite elevation (Hernández-Pajares et al. 2017).
- dual-frequency carrier phase measurements used to form the geometry-free linear combination.
- avoiding the negative effects of amplified pseudorange noises as well as the intra-day variation of receiver biases in code-smoothing technique derived STEC/VTEC.
- providing a slant but not vertical assessment of different ionospheric models (containing mapping errors)

$$dSTEC_{GNSS}(t) = 40.3 \times \left(f_1^{-2} - f_2^{-2} \right) \times \left[L_I(t) - L_I(t_{E\max}) \right]$$

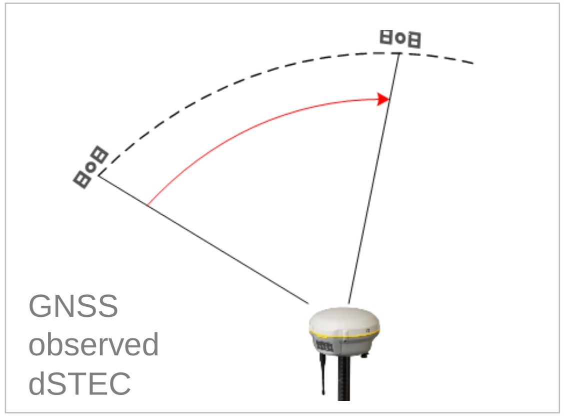


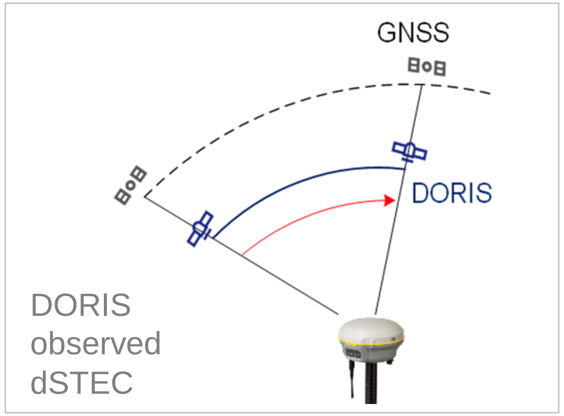
DORIS dSTEC analysis

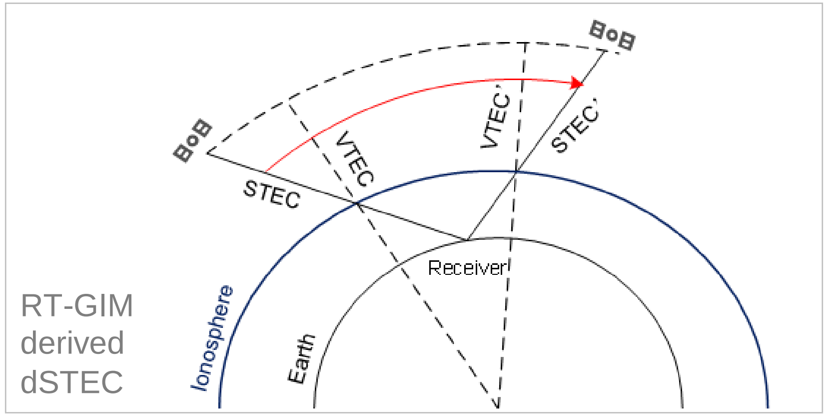
- The calculation of DORIS dSTEC is very similar to that of GNSS dSTEC, generated based on dual-frequency DORIS carrier phase measurements.
- Containing dSTEC information to the height of LEO satellites, e.g. ~1,300 km for Jason-3.

$$dSTEC_{DORIS}(t) = 40.3 \times \left(f_1^{-2} - f_2^{-2} \right) \times \left[L_I(t) - L_I(t_{E\max}) - \left(\Delta D(t) - \Delta D(t_{E\max}) \right) \right]$$

ΔD denotes the geometry correction (or the PCO correction)







Precision analysis of DORIS/GNSS observed dSTEC

- Ignoring the correlation b.w.t. L1/L2 carrier phase measurements, the theoretical precision of DORIS or GNSS dSTEC can be estimated by

$$\begin{cases} \sigma_{dSTEC}^{2} = 2\mu^{2}\sigma_{L_I}^{2} \\ \sigma_{LI}^{2} \approx \sigma_{L_1}^{2} + \sigma_{L_2}^{2} \end{cases}$$

σ_{LI} denotes the precision of geometry-free linear combination of dual-frequency DORIS/GNSS phase measurements

- The precision of DORIS observed dSTEC reaches 0.028 TECu (σ_{L1}=1.5 mm and σ_{L2}=7.5 mm)
- The precision of GNSS observed dSTEC is about 0.25 TECu (σ_{L1}= σ_{L2}=2.0 mm)
- The precision of derived dSTEC benefits from the larger frequency difference (i.e., f_1- f_2)
- Overall, the theoretical precision of DORIS dSTEC is about 10 times better than GNSS dSTEC

Overview of RT-GIMs provided by different ACs

AC	Caster	Mountpoint	Interval
CAS	products.igs-ip.net:2101	SSRC00CAS1 (*IGS-SSR*)	60s
CNES	products.igs-ip.net:2101	SSRC00CNE1 (*IGS-SSR*)	60s
UPC	products.igs-ip.net:2101	IONO00UPC1 (*IGS-SSR*)	15s
WHU	58.49.94.212:2101	IONO00WHU0 (*RTCM-SSR*)	60s
UPC-combined	products.igs-ip.net:2101	IONO00IGS0 (*IGS-SSR*)	15s
CAS-combined	products.igs-ip.net:2101	IONO01IGS0 (*RTCM-SSR*) IONO01IGS0 (*IGS-SSR*)	60s

NRT DORIS Data and Associated Ephemeris Data

- Link to Jason-3 NRT DORIS RINEX data

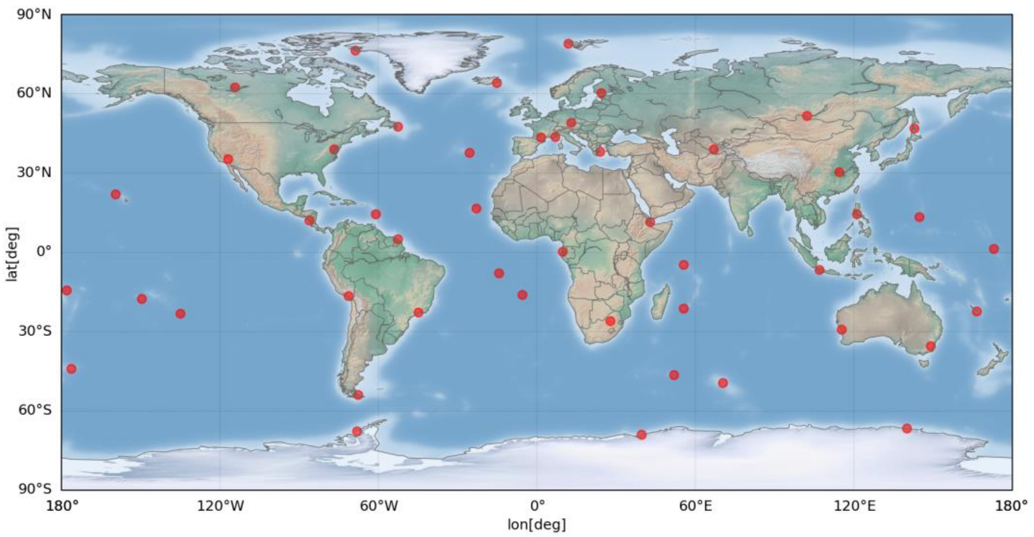
  ftp://doris.ign.fr/pub/doris/data/ja3/NRT/

- Link to Jason-3 NRT ephemeris data

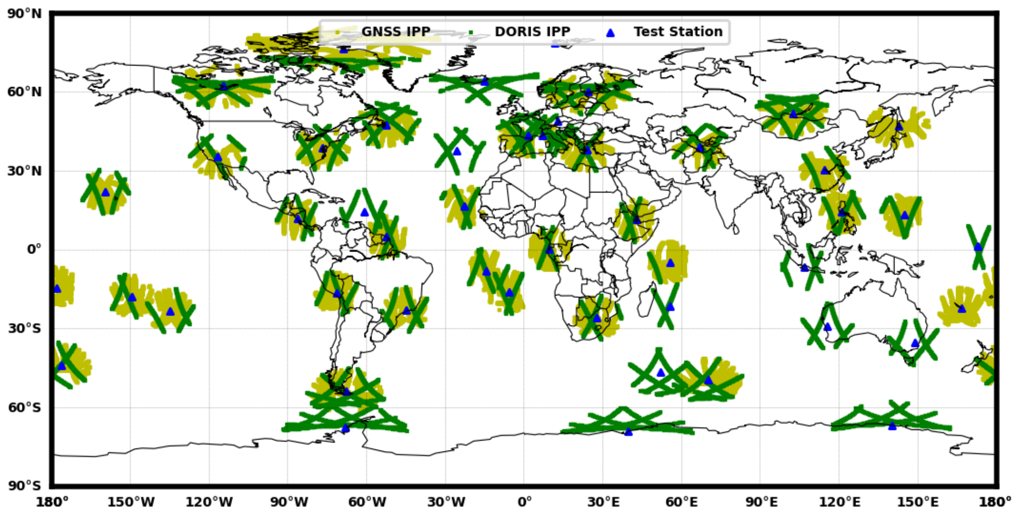
  ftp://doris.ign.fr/pub/doris/products/orbits/ssa/ja3/NRT/

The selected 48 DORIS beacons and co-located GNSS stations

- NRT DORIS data from Jason-3 altimetry used for DORIS dSTEC analysis
- GPS and GLONASS observations of the IGS network used for GNSS dSTEC analysis

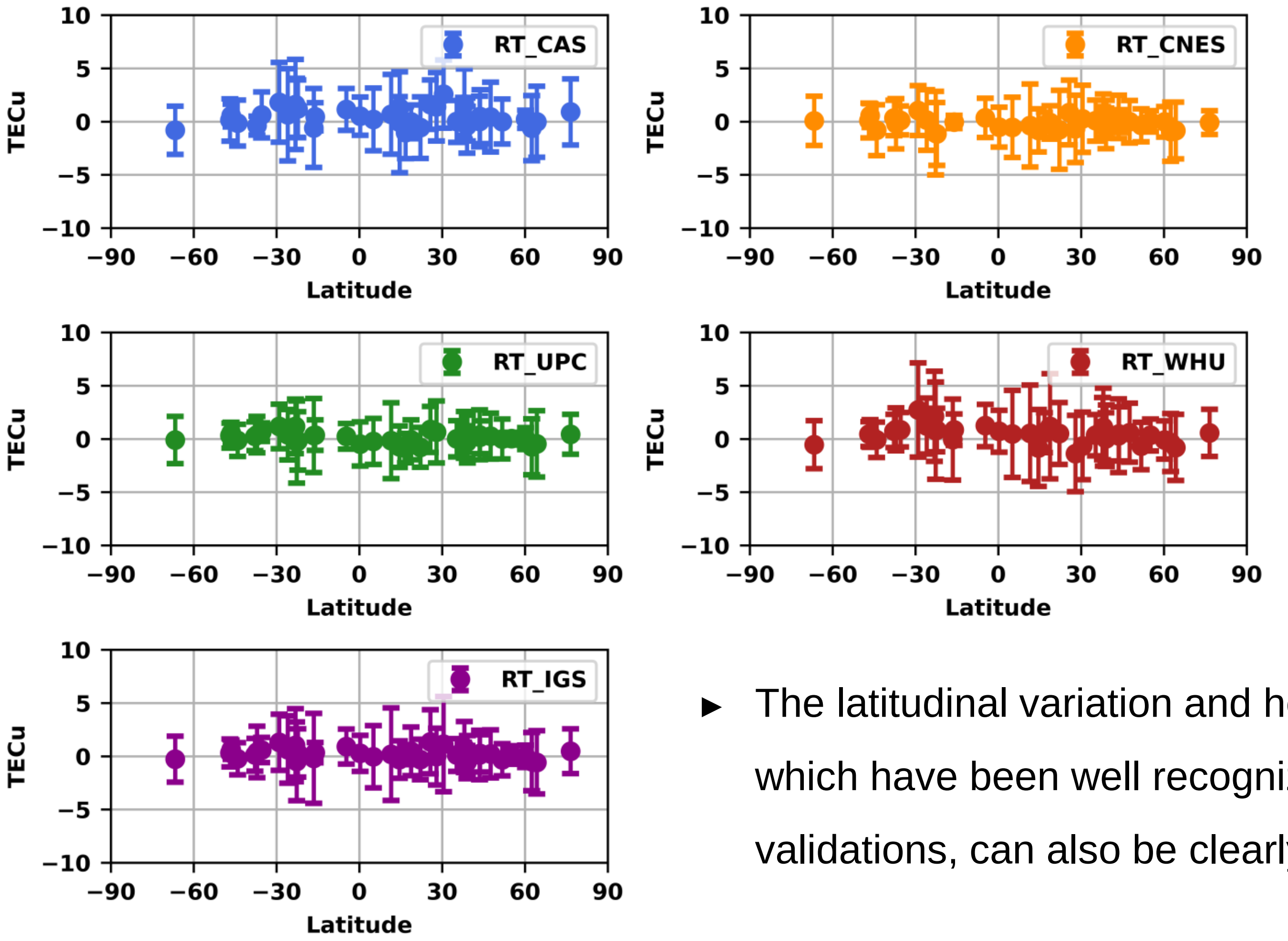


Distribution of the selected DORIS beacons



DORIS (green) and GNSS (yellow) derived ionospheric information (UT 00-02, DoY 098, 2022)

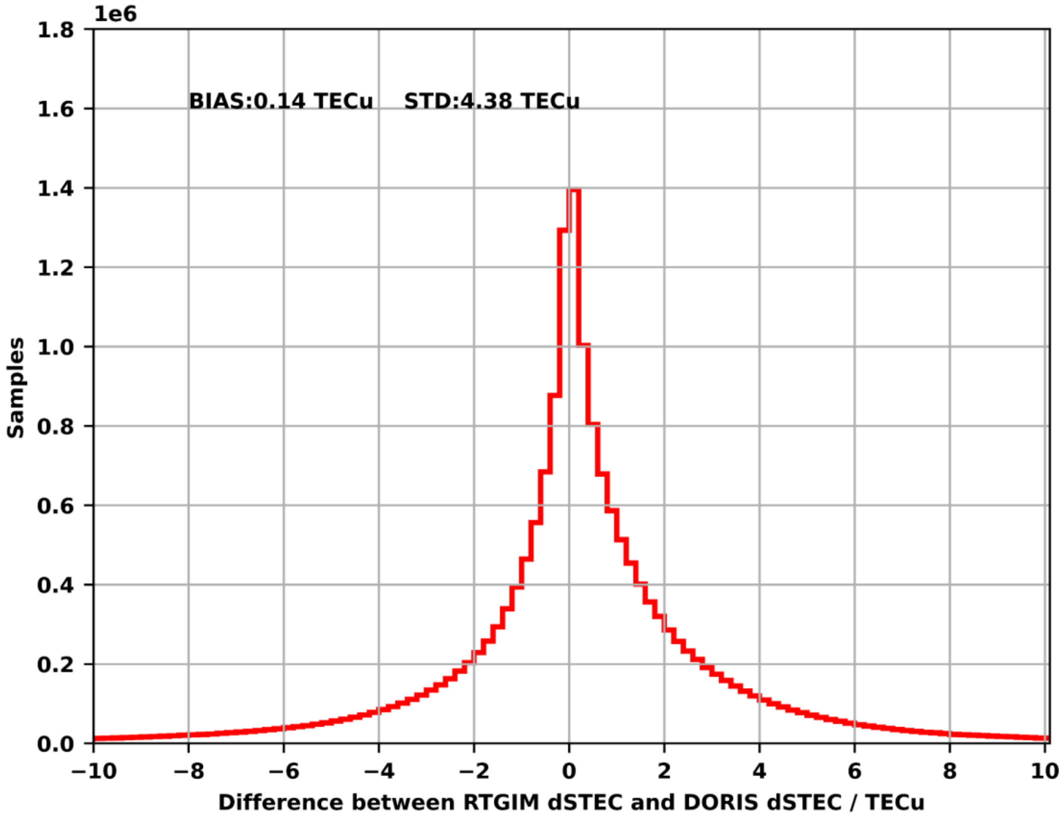
Consistency b.w.t. RT-GIM derived and DORIS observed dSTECs



Bias and STD of different RT-GIMs compared to observed dSTEC at individual DORIS beacons on DOY 098, 2022.

- The latitudinal variation and hemispheric asymmetry of RT-GIM errors, which have been well recognized in GPS-dSTEC or altimetry-VTEC validations, can also be clearly observed in DORIS dSTEC assessment.

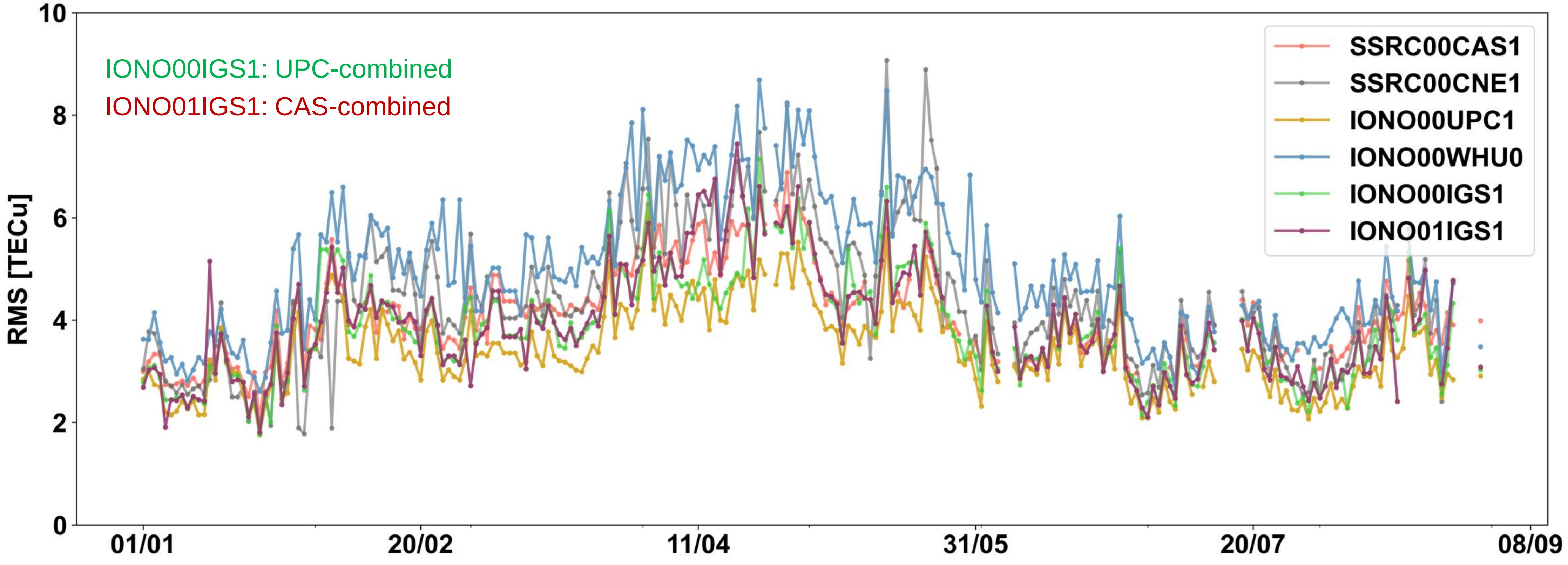
Consistency b.w.t. RT-GIM derived and DORIS observed dSTECs



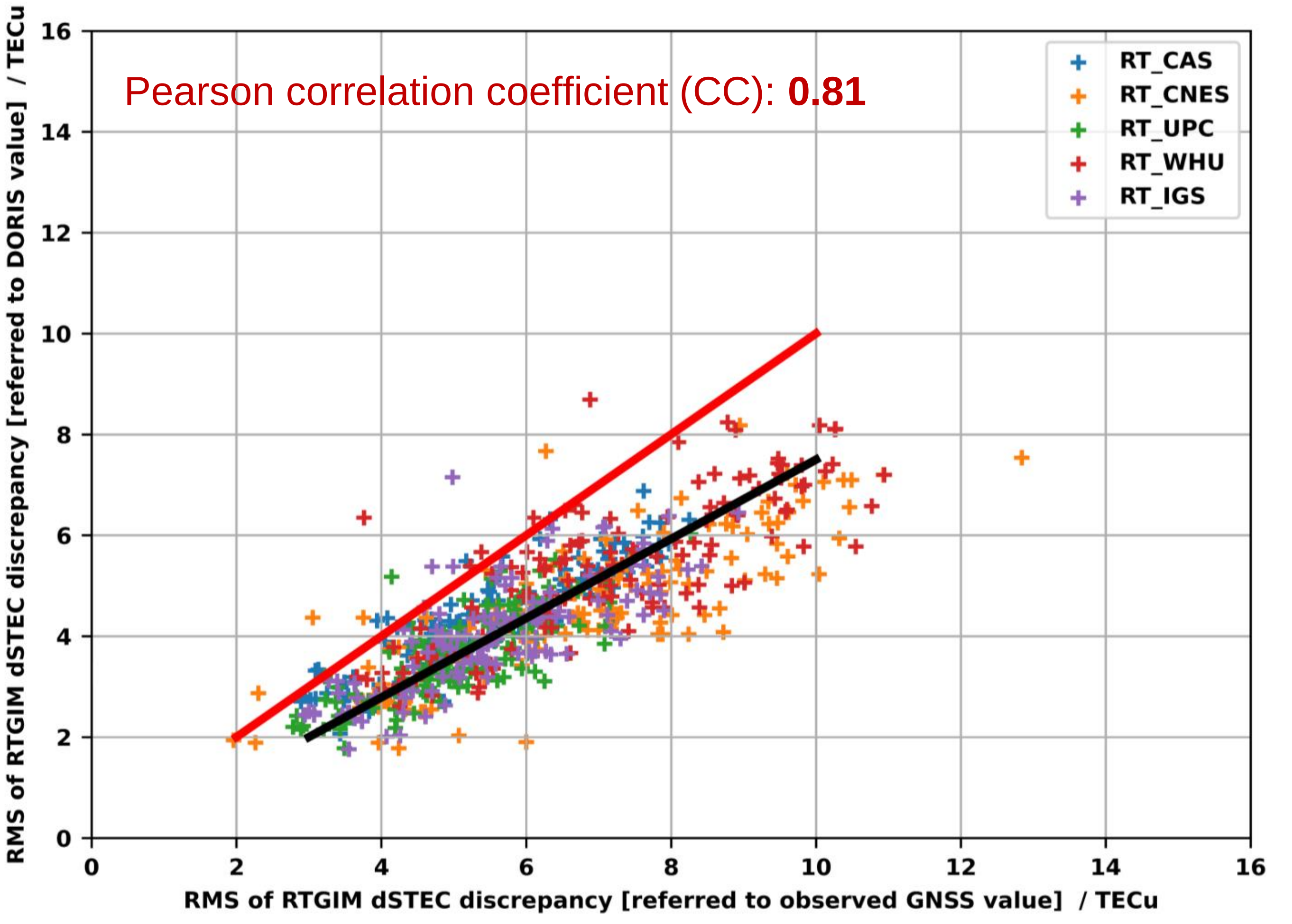
Histogram of differences b.w.t. RT-GIM derived and DORIS observed dSTECs during DOY 001–110, 2022

- more than 18,000,000 DORIS dSTEC observables used for the analysis.
- around 77.1% of the dSTEC differences is below +/- 3.0 TECu.
- no systematic bias found b.w.t. Jason-3 DORIS observed dSTEC and RT-GIM derived dSTEC.

Compared to **Jason-3 DORIS dSTEC** – 01/01-31/08, 2022

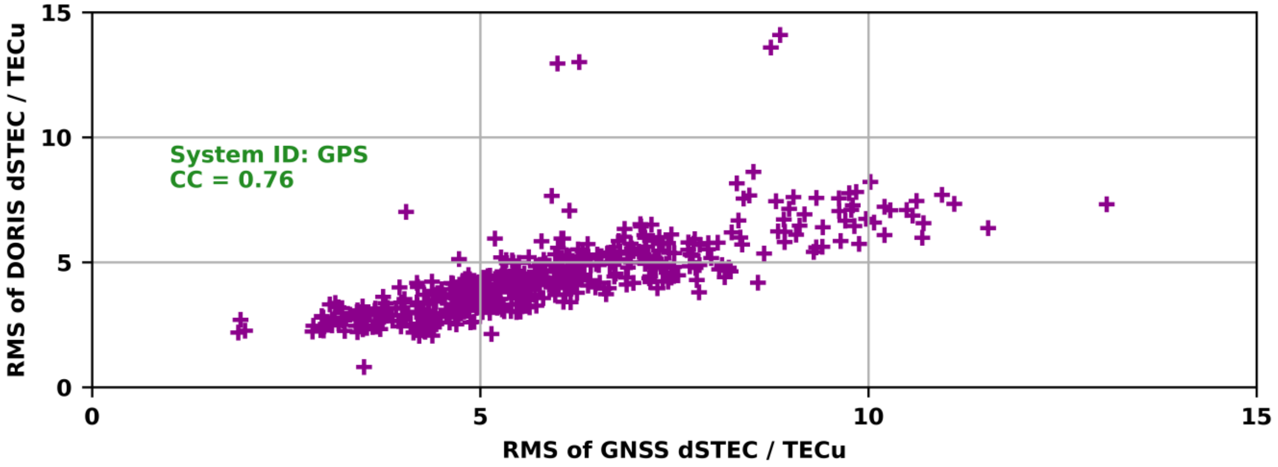


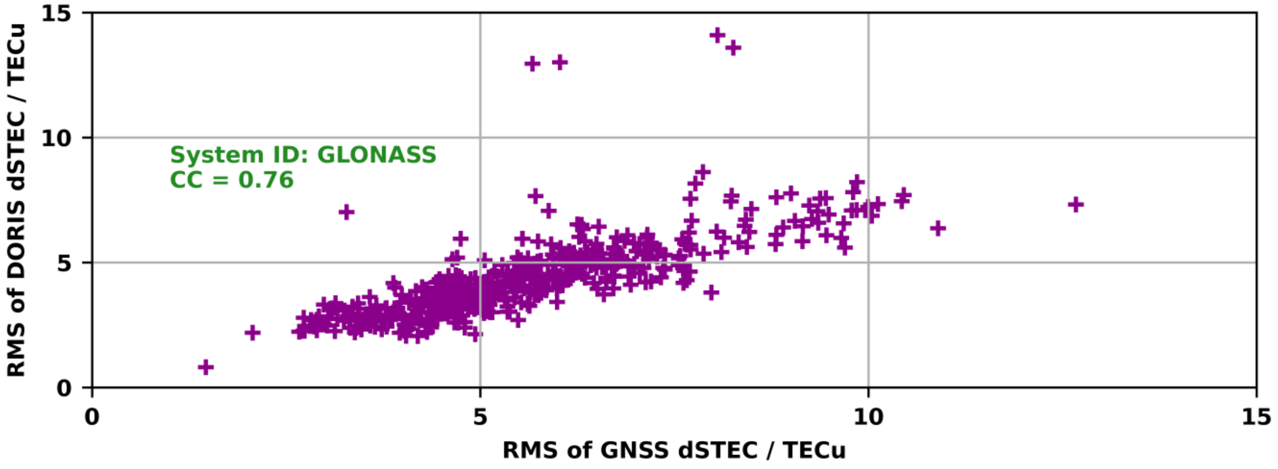
Consistency b.w.t. DORIS (Jason-3) and GNSS (G/R) dSTEC assessments



RMS of RT-GIM dSTEC discrepancy referring to DORIS data versus that referring to GPS/GLONASS data during DOY 001-110, 2022.

Consistency b.w.t. DORIS (Jason-3) and GNSS (G/R) dSTEC assessments





- **no significant dependence** on the GNSS data used
- require further verification with the use of Galileo and BeiDou observation data

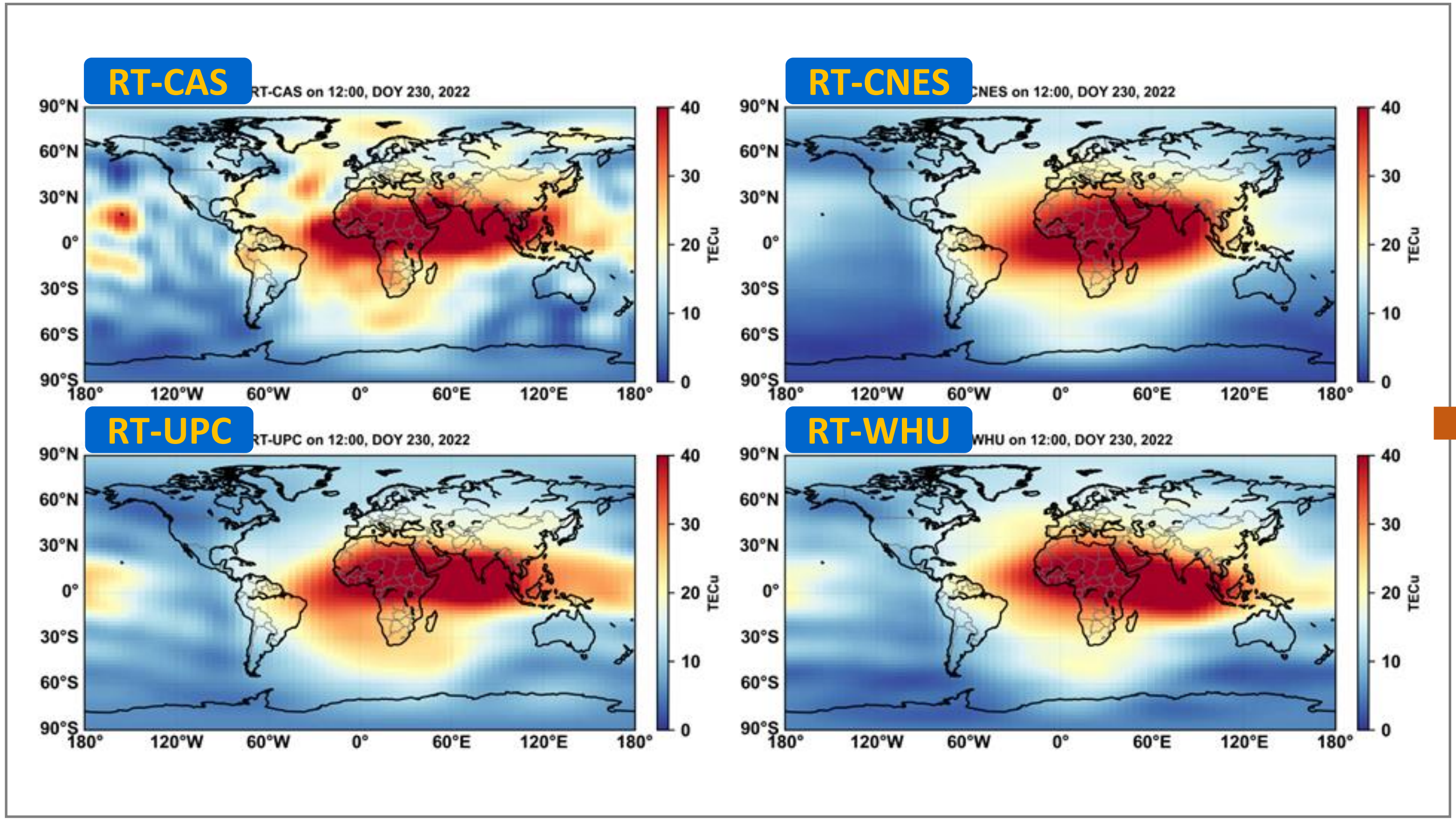
Experimental NRT-GIM combination using Jason-3 NRT DORIS Data

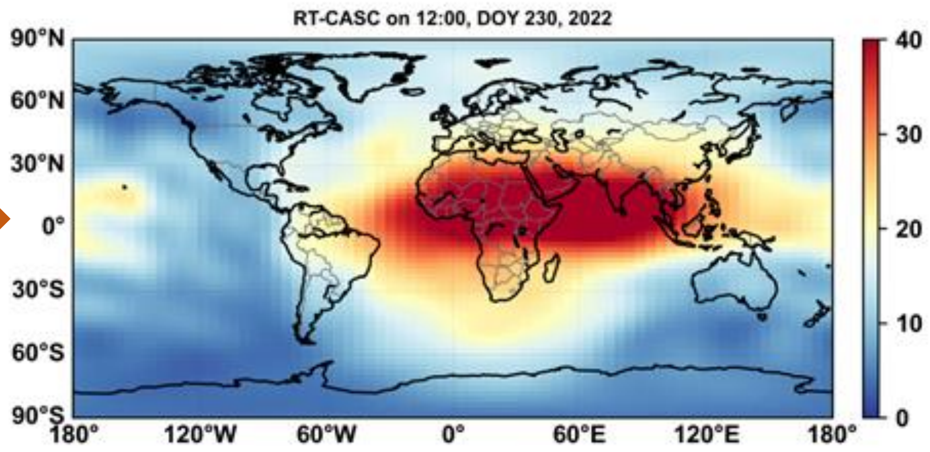
- Input RT-GIMs: RT-CAS, RT-CNES, RT-UPC & RT-WHU
- Input DORIS data: Jason-3 NRT DORIS data
- Generated NRT-GIM: RT-CASC

RT-GIMs	GNSS-dSTEC derived weights	DORIS-dSTEC derived weights
RT-CAS	0.29	0.24
RT-CNES	0.19	0.21
RT-UPC	0.35	0.35
RT-WHU	0.17	0.20

DOYs 001-270, 2022

Experimental NRT-GIM combination using Jason-3 NRT DORIS Data

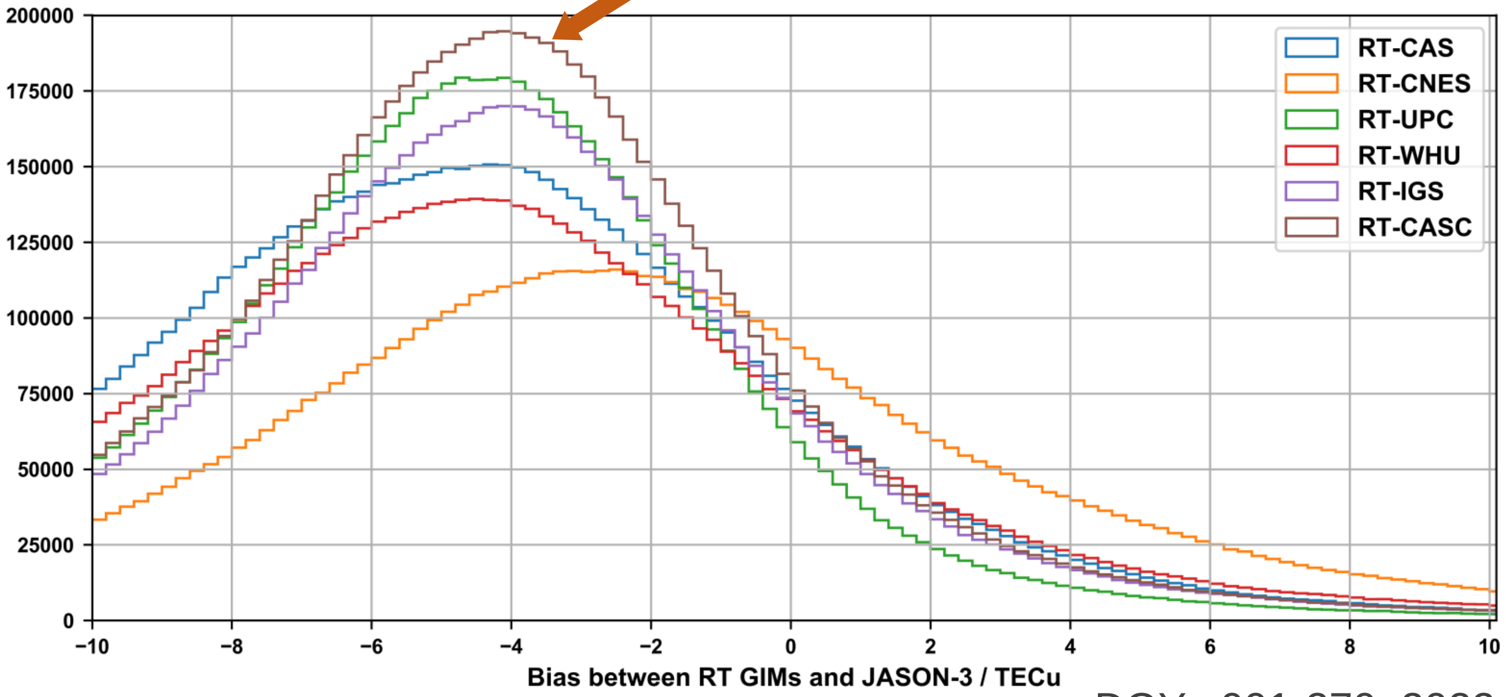




DORIS combined NRT GIM (RT-CASC)

Experimental NRT-GIM combination using Jason-3 NRT DORIS Data

DORIS combined NRT GIM



DOYs 001-270, 2022

	STD / TECu
RT-CAS	5.46
RT-CNES	6.83
RT-UPC	4.36
RT-WHU	6.11
RT-IGS*	4.80
RT-CASC**	**4.71**

* RT-IGS: UPC combined RT-GIM using GNSS dSTEC

** RT-CASC: Jason-3 NRT DORIS data combined NRT-GIM

Summary and conclusions

- The concept of DORIS dSTEC assessment is proposed, which is the extension of the existing GNSS dSTEC validation method.
- Benefiting from the large relative frequency ratio between DORIS L1/L2 frequencies, the precision of DORIS dSTEC reaches 0.028 TECu, which is about 10 times better than that of GNSS L1/L2 dSTEC.
- Using more than 18,000,000 DORIS dSTEC observables, the bias and STD is 0.14 and 4.38 TECu between RT-GIM derived dSTEC and DORIS observed dSTEC and no systematical bias is found.
- The overall correlation coefficient is 0.81 for the validation result using DORIS and GNSS dSTEC.
- DORIS dSTEC assessment can be used an independent way to validate the quality of those ground GPS/GNSS generated ionospheric models.
- Using independent DORIS data for NRT & rapid GIM combination is in progress.

Paper in review in ASR (DORIS Special Issue)

Thanks for your attention

In case of any questions, please feel free to contact
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