IGS 2026 WORKSHOP
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A flexible combination strategy for IGS Global Ionospheric Maps using DORIS observations

Adam Fron[1*], Ningbo Wang[2], Andrzej Krankowski[1], Zishen Li[2], Manuel Hernández-Pajares[3], Ang Liu[2], Runqing Liu[2]
[1]University of Warmia and Mazury in Olsztyn (UWM), Poland;
[2]Chinese Academy of Sciences (CAS), China;
[3]Polytechnic University of Catalonia (UPC), Spain

INTRODUCTION

Accurate ionospheric electron content is essential for satellite navigation and space-weather monitoring.

IGS Global Ionospheric Maps are widely used for ionospheric delay correction and ionospheric research.

However, some limitations remain:

- current GIM products are primarily derived from ground-based GNSS observations.
- A truly global and independent assessment of GIM products remains challenging.
- This limitation is more evident over oceanic regions with sparse GNSS receiver coverage.

The DORIS system provides independent ionospheric observations and can complement GNSS-based assessment.

Therefore, this study introduces DORIS observations as an independent and complementary data source for a flexible IGS GIM combination strategy.

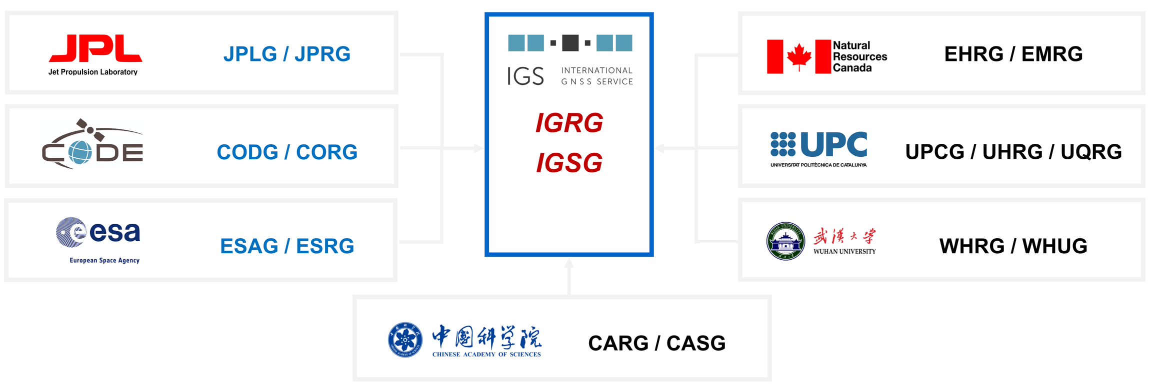

Figure 1: Current IGS GIM combination

DORIS OBSERVATIONS

DORIS provides complementary space-geodetic observations for ionospheric analysis.

- Ground beacon network + LEO satellites
- Wide spatial coverage over land and oceans
- Additional observations in GNSS-sparse regions
- Observation system independent of GNSS
- Valuable support for external GIM assessment
- Observational basis for DORIS-derived dSTEC

DORIS observations provide independent ionospheric information for assessing and combining IGS GIM products, especially over oceanic and GNSS-sparse regions.

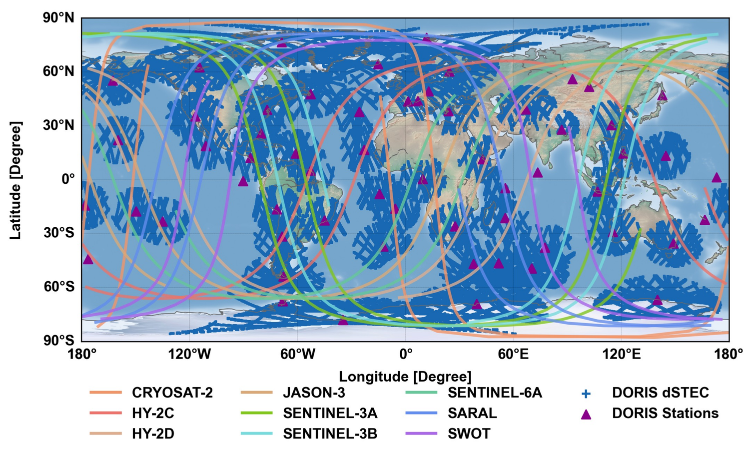

Figure 2: Sub-satellite ground tracks and DORIS dSTEC observations between 01:00 and 03:00 UTC on DOY 290, 2022, together with active DORIS ground beacon stations and the SWOT ground track on DOY 001, 2025.

DORIS DSTEC ANALYSIS

DORIS dSTEC is derived by extending the GNSS dSTEC concept to dual-frequency DORIS carrier-phase measurements.

$$dSTEC_{DORIS}(t) = \mu\left[L_I(t) - L_I(t_{E\max}) - \left(\Delta D(t) - \Delta D(t_{E\max})\right)\right]$$

- tmax: epoch with the highest satellite elevation in one continuous arc.
- ΔD denotes the geometry correction (i.e., the PCO correction)

DORIS dSTEC extraction:

- dual-frequency DORIS carrier phase
- phase-continuous observation arc
- reference to the highest satellite elevation
- geometry correction ΔD, including PCO correction
- dSTEC information up to LEO satellite height

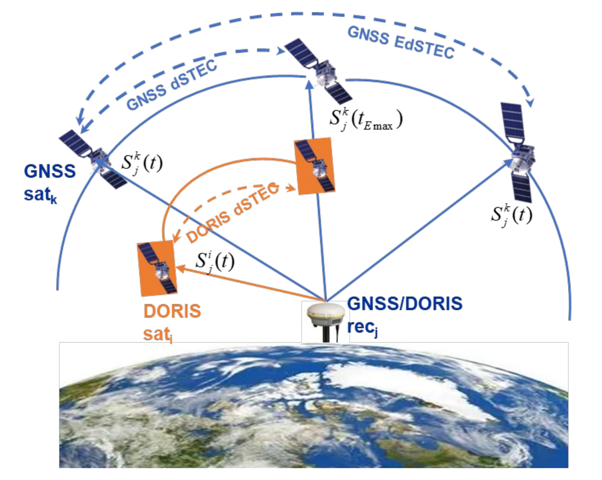

Figure 3: GIM combination strategies, including GNSS EdSTEC、GNSS dSTEC and DORIS dSTEC.

DORIS AND GNSS DSTEC CONSISTENCY

DORIS-derived dSTEC metrics are compared with GNSS-derived dSTEC metrics to examine whether DORIS can provide an independent ionospheric reference.

Data used in the comparison

- 48 DORIS beacons and co-located IGS stations
- DORIS dSTEC: Jason-3 altimetry satellite
- GNSS dSTEC: GPS + GLONASS
- Time span: DOY 001-110, 2022

Key result

- Correlation coefficient ≈ 0.8
- **DORIS-derived and GNSS-derived dSTEC metrics show strong agreement.**

Implication

- DORIS dSTEC provides ionospheric information consistent with GNSS dSTEC.
- This supports the use of DORIS dSTEC as an independent constraint for IGS GIM assessment and combination.

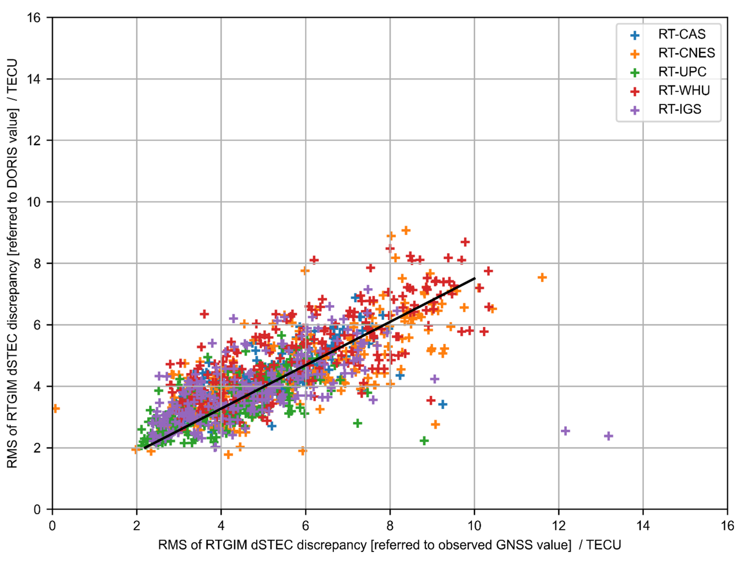

Figure 4: Consistency between DORIS-derived and GNSS-derived dSTEC.

IGS GIM COMBINATION SOLUTIONS

Combined method

IGS GIMs are combined as a weighted mean of individual IAAC products.

- The contribution of each IAAC GIM is determined by its agreement with external dSTEC references.

$$VTEC_{IGS}(\beta,\lambda,t) = \sum_{k=1}^{K} \omega_k \cdot VTEC_{AC_k}(\beta,\lambda,t)$$

- Weight computation for each analysis center

$$w_k = RMS_k^{-2} \Big/ \sum_{k=1}^{K} RMS_k^{-2}$$

$$RMS_k = \sqrt{\frac{\sum_{j=1}^{m} \delta_{GIM}(j)}{m}}$$

- GIM-VTEC residuals compared to iono. References

$$\delta_{GIM}(j) = dSTEC_{\mathrm{GIM}}(\varphi_j,\lambda_j) - dSTEC_{\mathrm{ref}}(\varphi_j,\lambda_j)$$

GNSS EdSTEC: $dSTEC_{\mathrm{ref}}(\varphi_j,\lambda_j) = dSTEC_{GNSS-EdSTEC}(\varphi_j,\lambda_j)$

DORIS dSTEC: $dSTEC_{\mathrm{ref}}(\varphi_j,\lambda_j) = dSTEC_{\mathrm{DORIS}-dSTEC}(\varphi_j,\lambda_j)$

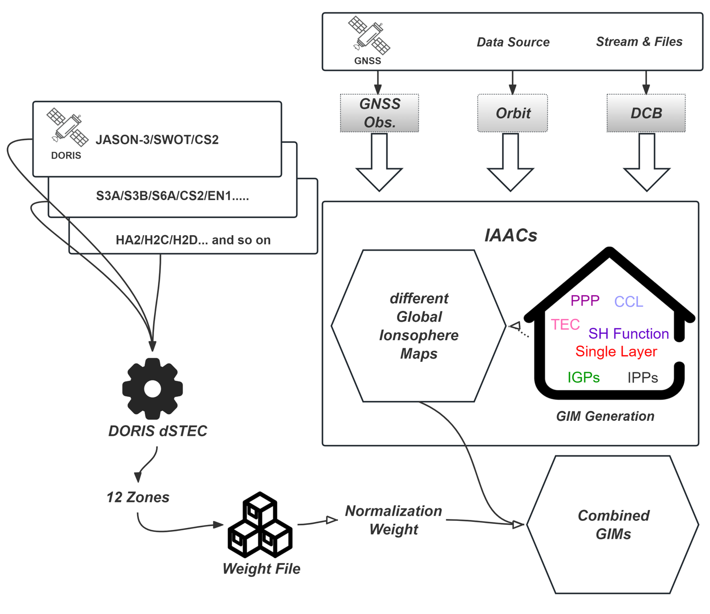

Figure 5: Diagram of the GIM combination process incorporating DORIS-based dSTEC constraints.

GIM WEIGHT COMPARISON

The residual-based weighting strategy assigns different contributions to individual IAAC GIMs under different dSTEC constraints.

Compared weighting strategies

- CAS1: GNSS-EdSTEC based
- CAS2: DORIS-dSTEC based
- CAS3: GNSS-dSTEC based

Key findings

- GNSS-based strategies show relatively concentrated weights for several IAAC GIMs.
- DORIS-dSTEC weighting gives a more balanced contribution among IAAC products.
- DORIS-dSTEC weighting leads to a less concentrated IAAC weight distribution.

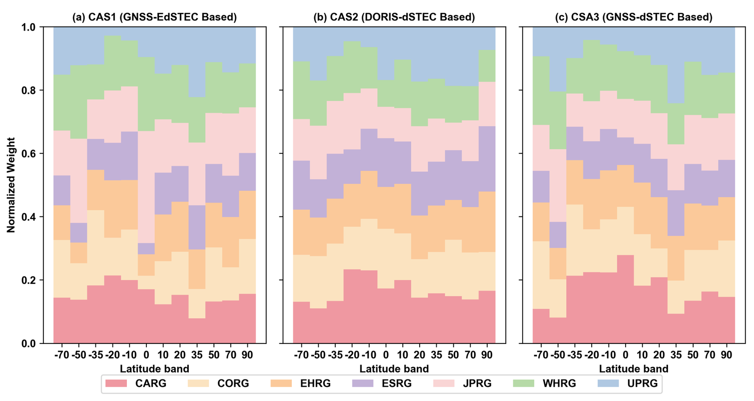

Figure 6: Normalized IAAC GIM weights under different dSTEC constraints.

GIM VALIDATION WITH JASON-3 VTEC

- Jason-3 altimeter-derived VTEC is used as an independent reference for evaluating GIM products, especially over oceanic regions.
- The validation covers CODG and three combined GIM solutions: CAS1, CAS2 and CAS3.
- RMS time series and boxplot statistics are used to assess the accuracy and stability of the different GIM products.

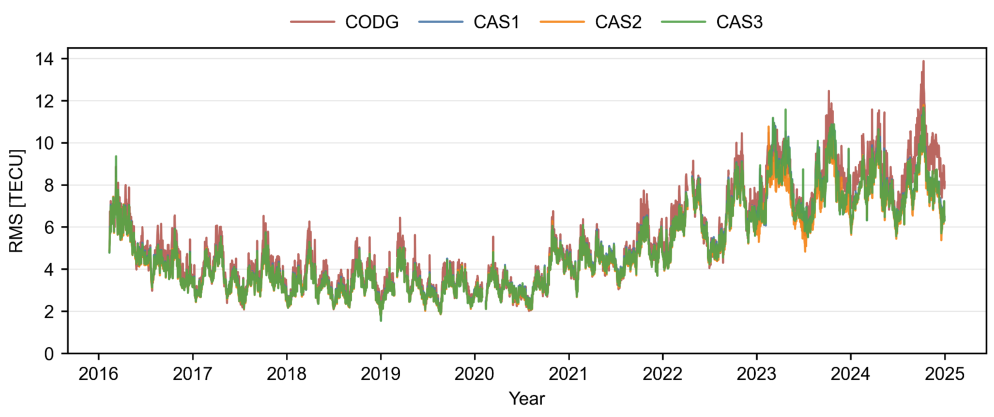

Figure 7: RMS series between GIM VTEC and JASON-3 VTEC (2016–2025).

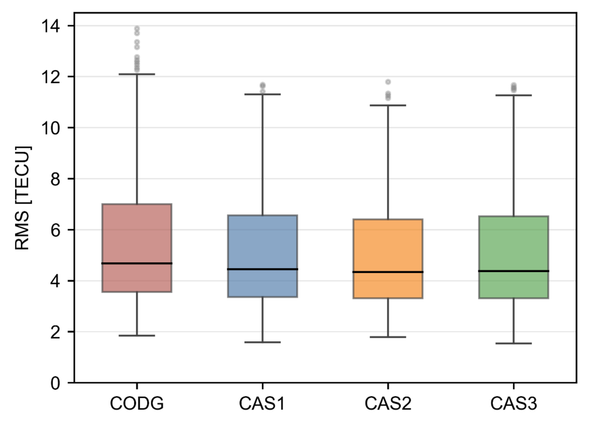

Figure 8: Boxplot of RMS differences between GIM VTEC and JASON-3 VTEC (2016–2025).

- **The DORIS-dSTEC constrained solution shows improved accuracy and stability in the Jason-3 VTEC validation.**

OUTLOOK & TODO

Operational implementation

- Prepare the DORIS-dSTEC constrained strategy for routine generation of new IGS combined GIM products.
- Keep the same flexible combination scheme for both DORIS-derived dSTEC and GNSS-derived dSTEC constraints.
- Extend the weighting process to the available IAAC GIM products, including CAS, CODE, ESA, JPL, NRCan, WHU and UPC.
- Maintain residual-based weight estimation by comparing GIM-derived ionospheric values with external dSTEC references.
- Investigate the use of near-real-time DORIS data for rapid GIM combination.

Validation and product release

- Continue independent validation using Jason-3 altimeter-derived VTEC over oceanic regions.
- Extend validation with independent GNSS STEC stations to check the consistency of VTEC- and STEC-based assessments.
- Pay particular attention to periods of elevated solar activity and stronger seasonal ionospheric variability.
- Release and maintain DORIS dSTEC products from 2015 onward to support reproducibility and community use.
- Provide combined GIM outputs together with clear product descriptions for routine assessment.

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