Improving Ionospheric Model Accuracy Using Multi-Source Geodetic Data Integration in Data-Sparse Regions

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Abstract

The consistency of Global Ionospheric Maps (GIMs) is essential for accurate ionospheric correction in satellite geodesy and precise orbit determination. This study compares the International GNSS Service (IGS) and Centre for Orbit Determination in Europe (CODE) GIM products over January–June 2024 (DOY 1–160). The analysis shows that the IGS GIM consistently estimates higher Vertical Total Electron Content (VTEC) than the CODE GIM, with mean values of 32.08 TECU and 30.87 TECU, respectively, resulting in an average positive bias of 1.21 TECU. The mean daily RMS difference between the two products is 2.61 TECU, ranging from a minimum of 1.40 TECU on the quietest days to a mean of 2.38 TECU during the pre-storm quiet period, and up to 5.63 TECU at the storm peak. Temporal analysis reveals that inter-product discrepancies increase significantly during periods of enhanced ionospheric activity, reaching a mean RMS of 4.05 TECU during the storm period (DOY 105–117), with a single-day peak of 5.63 TECU on DOY 110, before returning to near-normal levels afterward.

Spatially, the largest differences between the IGS and CODE GIMs occur over the Indian Ocean region, where limited GNSS ground station coverage reduces observational constraints. This finding highlights the importance of incorporating additional ionospheric observations in data-sparse oceanic regions. DORIS-equipped satellite altimeters, such as Jason-3 and Sentinel-3, provide extensive ionospheric measurements over these areas and represent a promising source of complementary data for future GIM generation. The observed mean RMS difference of 2.61 TECU and peak difference of 5.63 TECU are significant for DORIS-based precise orbit determination, emphasizing the need for improved ionospheric products. Integrating DORIS-derived VTEC observations into GIM estimation frameworks is proposed as a strategy that may reduce inter-product inconsistencies; validation remains as future work for satellite geodesy applications.

Keyword: Global Ionospheric Maps (GIMs), Total Electron Content (TEC), DORIS, Precise Orbit Determination (POD).

Introduction

The ionosphere introduces frequency-dependent delays in satellite signals, making accurate ionospheric correction essential for satellite geodesy, navigation, and precise orbit determination (POD). Global Ionospheric Maps (GIMs) are the primary operational products used for this purpose, providing global estimates of Vertical Total Electron Content (VTEC). Among the most widely used GIM products are the IGS combined GIM, generated from multiple analysis centres, and the independently produced CODE GIM.

This study compares the IGS and CODE GIM products over DOY 1–160 of 2024 to assess their consistency and quantify inter-product differences. The analysis focuses on systematic bias, RMS differences, and spatial variability, particularly during geomagnetic disturbances and in regions with sparse GNSS coverage. The findings are evaluated in the context of DORIS-based precise orbit determination, where accurate ionospheric corrections are critical for achieving high-precision satellite orbit solutions.

Motivation

Ground-based GNSS networks are the main data source for GIMs, but their coverage is sparse over oceans, especially the Indian Ocean and southern hemisphere. Consequently, GIM accuracy is reduced in these data-sparse regions.

This is particularly important for DORIS satellites such as Jason-3 and Sentinel-3, which rely on GIM-based ionospheric corrections while operating mainly over oceans. Inter-product differences of 2–5 TECU can affect orbit determination accuracy, motivating this study to assess GIM discrepancies and explore the use of DORIS-derived observations to improve ionospheric modelling in oceanic regions.

DORIS: The Missing Link

DORIS is a dual-frequency satellite geodesy system that provides independent VTEC measurements. Its satellites, such as Jason-3 and Sentinel-3, offer dense coverage over oceanic regions where GNSS observations are limited.

Since the largest IGS–CODE GIM discrepancies occur over the Indian Ocean, DORIS observations could help fill this data gap. Integrating DORIS-derived VTEC into future GIM models could improve ionospheric accuracy and reduce inter-product differences.

Methodology and Validation

Data Sources: IGS combined GIM (5° × 2.5°, 2-hour resolution) and CODE GIM (450 km single-layer model, degree/order 15 spherical harmonics).

Study Period: DOY 1–160 of 2024 (1 January–8 June 2024).

Processing: Daily mean VTEC was calculated from all grid points and 2-hour epochs.

Comparison Metrics: Daily RMS difference and mean bias (IGS − CODE) were used to quantify inter-product discrepancies.

Spatial Analysis: Grid-point-wise mean VTEC difference maps (IGS − CODE) were computed by averaging across all 2-hour epochs over the 160-day period, then interpolated to a 5° × 2.5° global grid to identify persistent regional patterns.

Validation: Inter-product consistency was assessed between IGS and CODE GIMs; future validation using Jason-3 altimetry and DORIS-derived VTEC is proposed for absolute accuracy assessment.

Result and Discussion

IGS and CODE GIMs show similar global TEC patterns, with peak VTEC (>80 TECU) occurring in the Equatorial Ionisation Anomaly (EIA) region over Africa, the Indian subcontinent, and the western Pacific.

CODE systematically underestimates TEC compared to IGS, with a mean global TEC of 30.87 TECU versus 32.08 TECU for IGS, resulting in a persistent positive bias of 1.21 TECU.

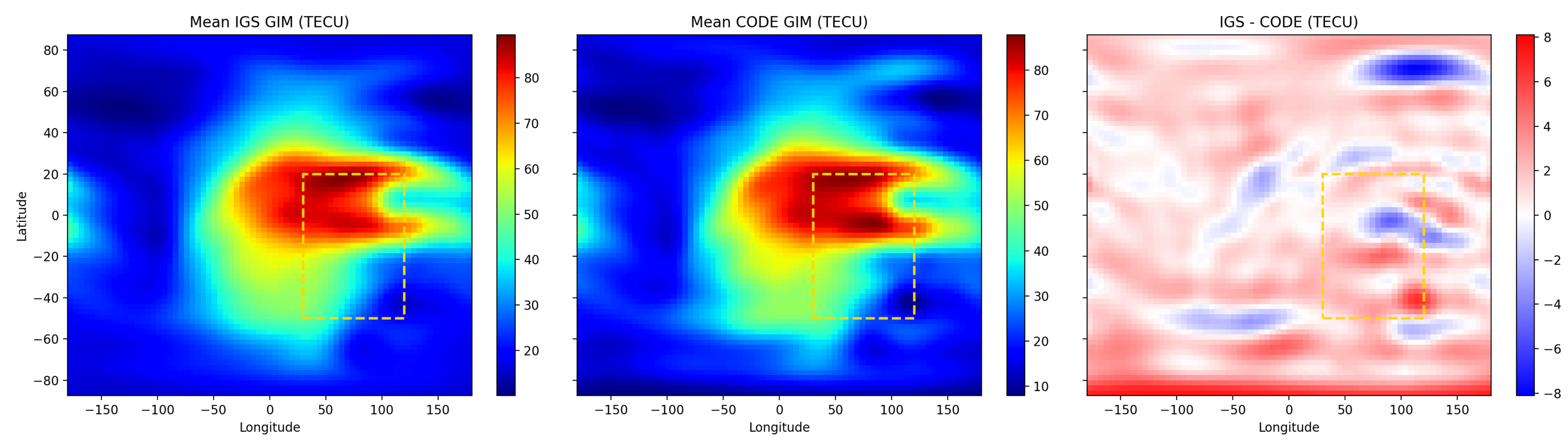
The largest inter-product discrepancies occur over the Indian Ocean, with additional differences over the southern Atlantic and Pacific Oceans, reflecting sparse GNSS station coverage in these regions.

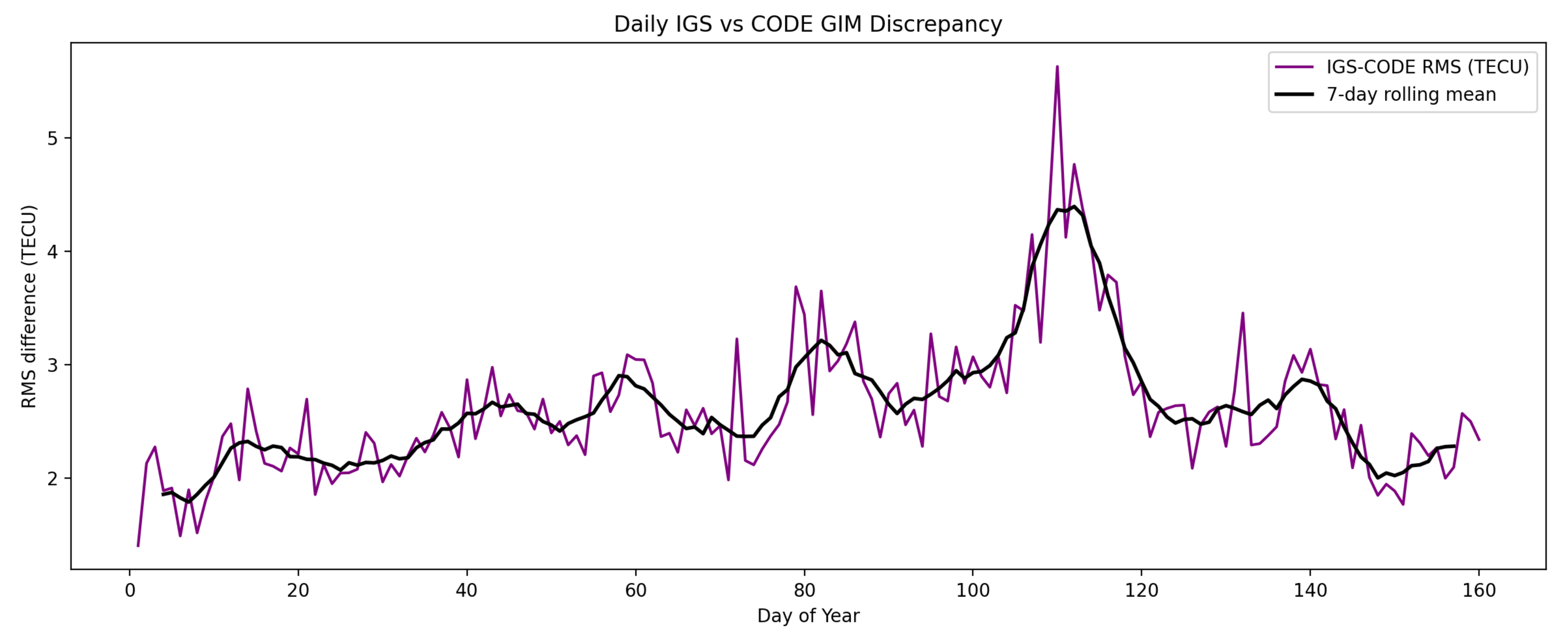
The mean global RMS difference is 2.61 TECU, ranging from 1.40 TECU during quiet conditions to 5.63 TECU during the geomagnetic storm peak (DOY 110).

Inter-product differences increase with ionospheric activity, with RMS rising from a mean of 2.38 TECU during the pre-storm quiet period (DOY 1–104) to a mean of 4.05 TECU during the storm period (DOY 105–117) and mean bias increasing from 1.11 TECU to 1.83 TECU.

Storm-time discrepancies are significantly larger, showing a 70% increase in RMS and 65% increase in bias relative to quiet conditions, indicating strong sensitivity to geomagnetic disturbances.

The average TEC difference is 3.78%, with IGS exceeding CODE by more than 6% during storm peak days.





Conclusion

The study found a systematic bias of 1.21 TECU, with IGS consistently estimating higher TEC than CODE. The mean RMS difference was 2.61 TECU, increasing significantly during geomagnetic storms and reaching 5.63 TECU at the storm peak (DOY 110). The largest discrepancies occurred over the Indian Ocean due to sparse GNSS station coverage. After the storm, agreement between the two GIMs returned to near-normal levels by approximately DOY 120, with ~40 days of post-storm data (DOY 120–160) confirming sustained recovery in both products.

Future Work

Integrate DORIS VTEC into multi-source GIM generation.

Assess POD improvements using DORIS-enhanced GIMs.

Evaluate storm-time performance during geomagnetic disturbances.

Extend analysis to full-year 2024 under Solar Cycle 25 maximum.

Validate results with IDS centres and DORIS orbit solutions.

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