Progress of the CAS GIM During Solar Cycle 25: Methodology and Results

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Motivation

As a member of the Ionospheric Associated Analysis Centers (IAACs) of the International GNSS Service (IGS), the Chinese Academy of Sciences (CAS) provides open ionospheric application services, including but not limited to rapid and final GIMs, real-time ionospheric correction services, ionospheric forecast products, multi-GNSS DCB correction services, and ionospheric indices monitoring. We continuously update our algorithms related to ionospheric models to improve product accuracy. Here, we will mainly introduce some recent advancements in CAS ionospheric services.

CAS Ionospheric Service

CAS Atmospheric services (ionosphere)
- One of the Ionospheric Associated Analysis Centers of the International GNSS Service (IGS)
- Providing open access to the ionospheric service from 1998 to present

Post-processed Final/Rapid GIM（CASG and CARG）

- **TEC MAP**
  - SHPTS: Spherical Harmonic function plus generalized Trigonometric Series function
  - **GNSS STEC**
    - Extracting TEC with carrier-to-code leveling
    - Multi-GNSS contribution, and 150-200 stations
  - **JASON VTEC**
    - Plan to introduce
  - **DORIS dSTEC**
    - Plan to introduce
- **RMS MAP**
  - Covariance estimate（before 2020）
  - Accuracy Index Driven by Empirical factor and actual Residual method (New)

Real-Time GIM (IONO01IGS1)

- **Real-time GIM**
  - PPP extraction of TEC from 170-220 stations
  - Introduce predicted background ionospheric information
  - Spherical harmonic function model (with order 15 and degree 15)
- **Real-time Regional ionospheric map (RIM)**
  - ASH: Adjusted Spherical Harmonics function model
  - SHAKING: adjusted Spherical Harmonics Adding KrigING

Combined GIM
- Improve continuity and precision
- Combined products from different Ionospheric Associated Analysis Centers

- **DORIS dSTEC (CAS2OPSRAP_SYYYYSDOY0000_01D_30M_GIM.INX)**
  - New methods developed, and used in CAS Final/Rapid GIM combination
  - More independent
- **GNSS EdSTEC CAS1OPSRAP_SYYYYSDOY0000_01D_30M_GIM.INX)**
  - IGS used in Final/Rapid GIM combination
- **GNSS dSTEC CAS3OPSRAP_SYYYYSDOY0000_01D_30M_GIM.INX)**
  - For CAS Real-time Combined GIM

Predicted GIM
- Prediction of Global Ionospheric Map using the Theory of Maximum Posterior Estimation
- The 1-, 2- and 5-day predicted Global Ionospheric Maps (GIM) are routinely generated

Differential Code Biases (DCB)
- DCB products corrected with PCO
- DCB values for all frequency points of the four systems

Ionospheric status monitoring
- Rate Of TEC Index (ROTI)
- S4/Sigma Phi
- Gradient Ionosphere index (GIX)

CAS Predict GIMs (P1 & P2 & P5)

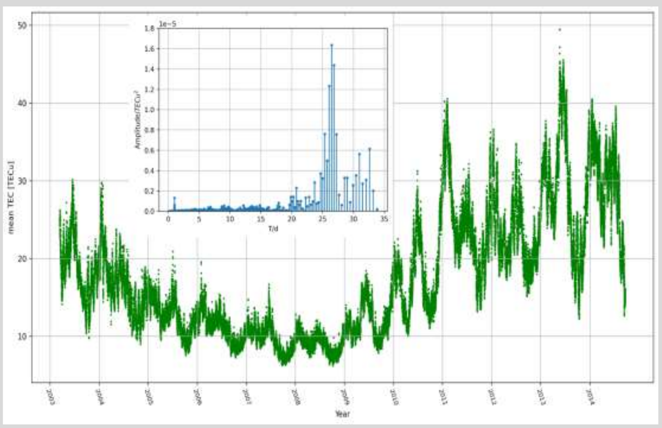
- Maximum Posterior Estimation

$$C_{nm}(t)=\sum_{i=0}^{K}[a_i cos(2pf_i t)+b_i sin(2pf_i t)]+S+N$$

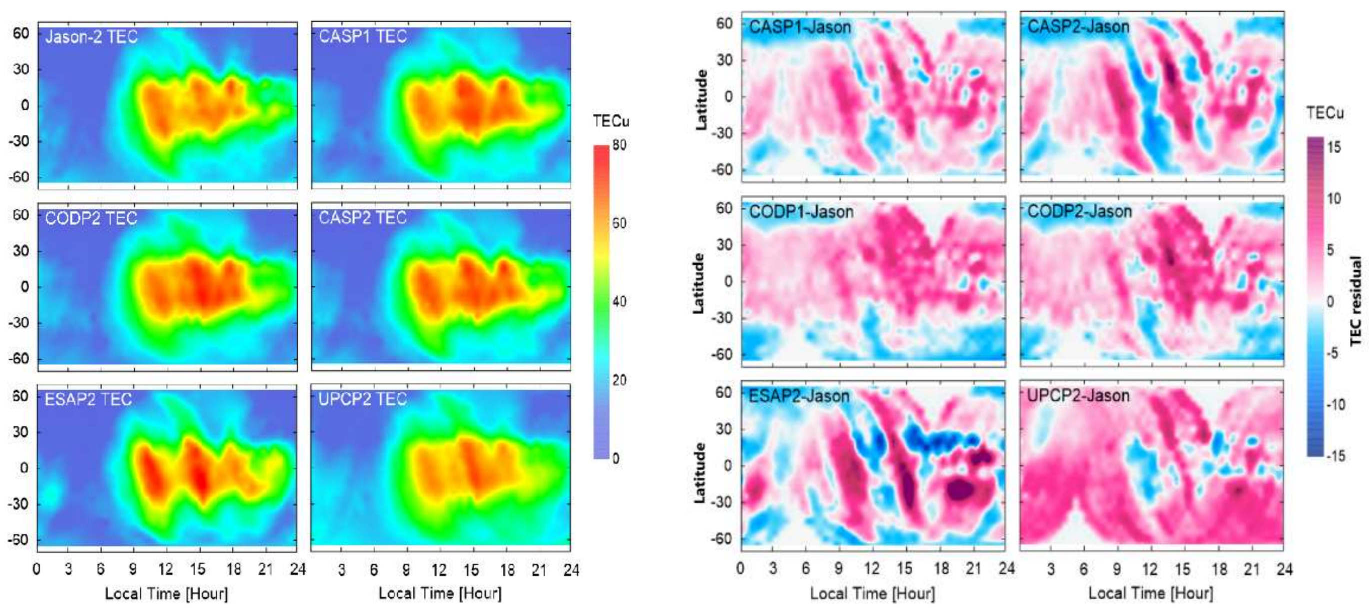
$$\begin{cases}\hat{X}=(G^T(D_S+D_N)^{-1}G)^{-1}G^T(D_S+D_N)^{-1}C_{nm}\\ D_{\hat{X}}=(G^T(D_S+D_N)^{-1}G)^{-1}\\ \hat{S}=\bar{C}_{nm}-G\hat{X}\end{cases}$$

$$\hat{S}'=\mu_{S'}+D_{S'S}(D_S+D_N)^{-1}(C_{nm}-G\hat{X})$$

- **Steps:**
- Trend Periods: Power spectrum estimation.
- Trend Fitting: Least squares method.
- Covariance Calculation: Fit residuals' autocovariance.
- Posterior Estimation: Extrapolate unfit parameters.
- TEC Prediction: Generate 1-, 2-, 5-day GIMs.



➢ Zero-order spherical harmonic coefficient time series and its spectrum analysis diagram

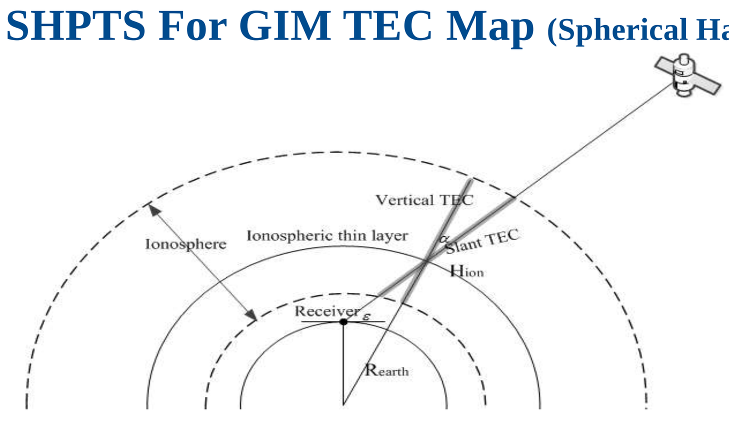


➢ Predicted GIM in geographic latitude and local time coordinates (left) and VTEC difference map compared to Jason-2 vTEC (right)

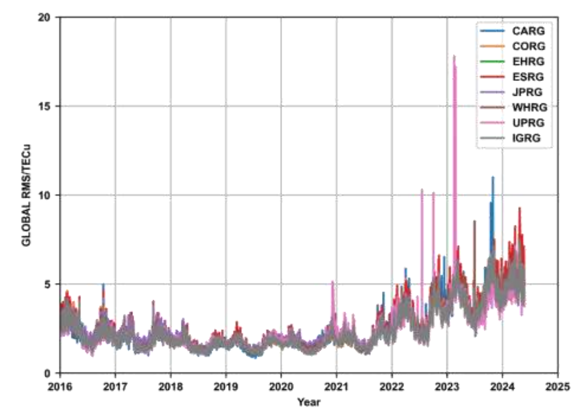
- **Innovative Prediction Method**: Proposed maximum posterior estimation for global ionosphere prediction using CAS products.
- **Routine Generation and Evaluation**: Generates 1-, 2-, 5-day predicted GIMs evaluated against IGS, Jason, and GNSS references.
- **High Consistency and Precision:** CAS predicted GIMs have 2.4~3.1 TECu consistency with IGS final GIMs.
- **Superior Accuracy:** CAS predicted GIMs show better than 80% ionospheric delay correction accuracy.

CAS GIMs (Final GIM & Rapid GIM)

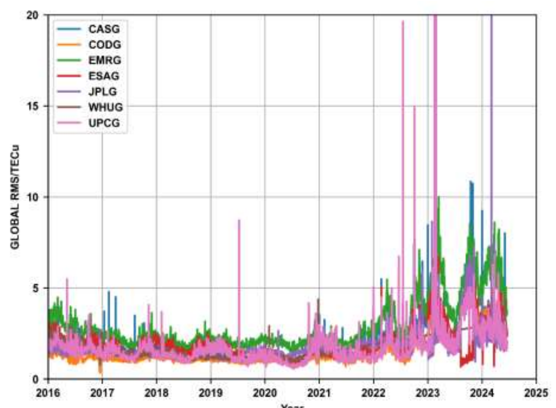
SHPTS For GIM TEC Map (Spherical Harmonic function plus generalized Trigonometric Series function)



- One-layer approximation.
- GTS function for the local variation of ionospheric TEC over one station.
- SH function for representing variations in ionospheric TEC on a global scale.



- The RMS of Rapid GIM w.r.t DORIS dSTEC.
- During geomagnetic quiet periods (2016-2021), the accuracy of CARG is 2-5 TECU.
- During geomagnetic active periods (2023-2024), the accuracy of CARG is 3-8 TECU.



- The RMS of Final GIM w.r.t IGSG VTEC.
- During geomagnetic quiet periods (2016-2021), the accuracy of CARG is approximately 1.5-3.5 TECU.
- During geomagnetic active periods (2023-2024), the accuracy of CARG is 3- 10 TECU.

AIDER For GIM RMS Map (Accuracy Index Driven by Empirical factor and actual Residual method)

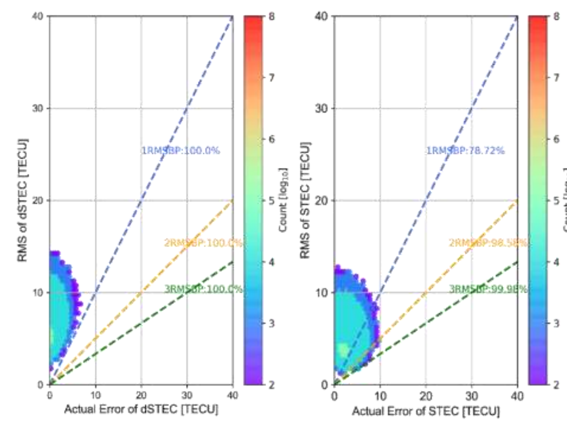
$$\sigma_{improved}=\sigma_0 f_{SK}$$

$$f_{SK}=\frac{1}{2}\left(\frac{|S_K|}{E[|S_K|]}+\frac{|K_E|}{E[|K_E|]}\right)$$

$$w=\begin{cases}0 & \text{NMP with } N<N_{min}\\ \min(\exp(\frac{N}{2N_{min}}-0.5)-1,1.0) & \text{MP with } N\geq N_{min}\end{cases}$$

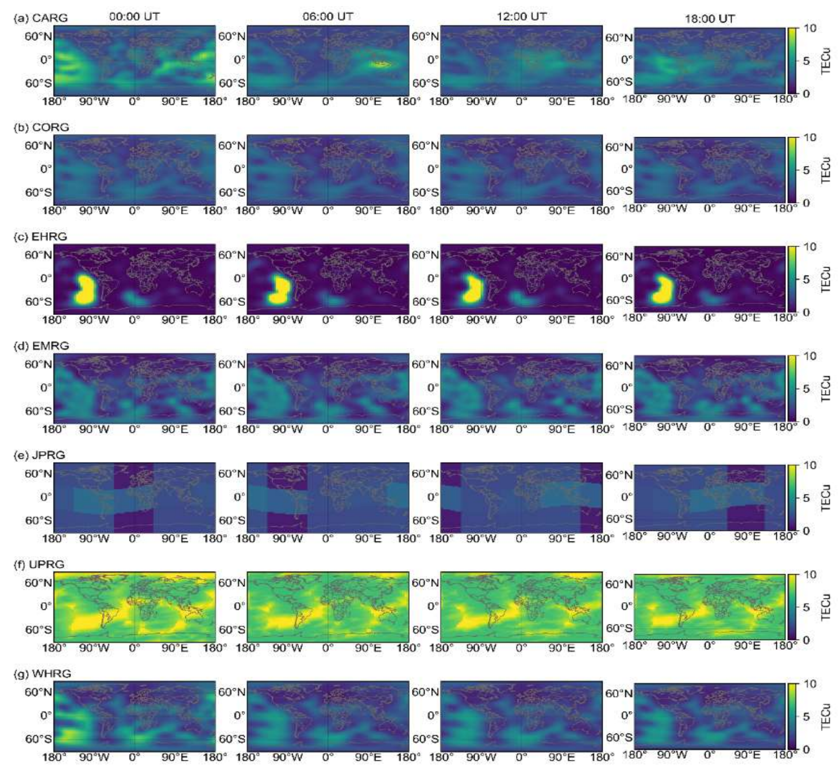
$$\mu=\frac{\sum nR/\sigma_{improved}}{\sum n}$$

$$AI_{GIM}=\sqrt{(1-w)s\mu^2\sigma^2_{improved}f^2_{SK}BQ_{XX}B^T+wR^2}$$



Ionospheric Errors-Accuracy Diagram

- Using the AIDER method, the CAS rapid GIM product for 2022-2023 was reconstructed.
- Download From: ftp.gipp.org.cn:/product/ionex

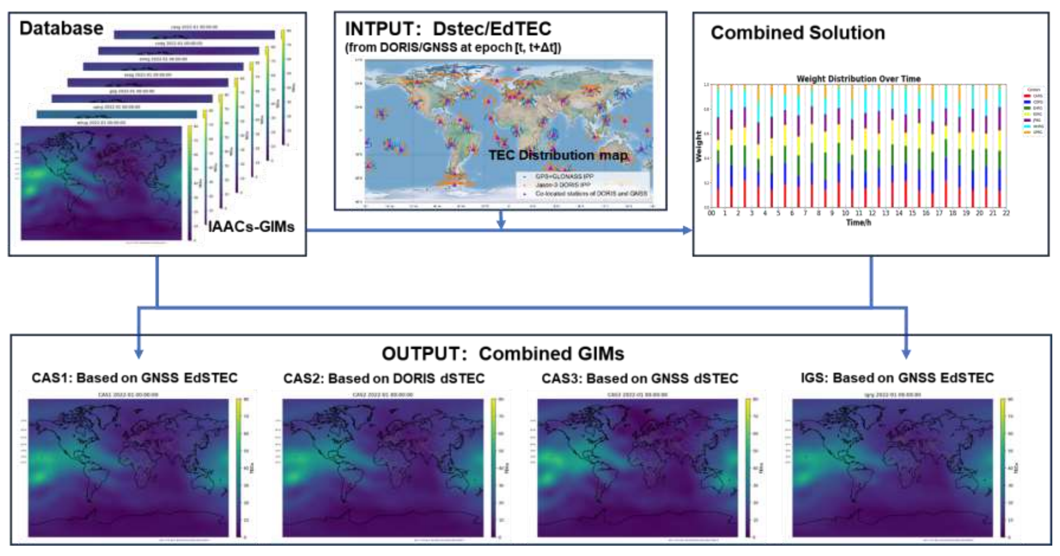


- GIM RMS map of seven IAACs

CAS Combined GIMs (Post-mode & Real-Time)

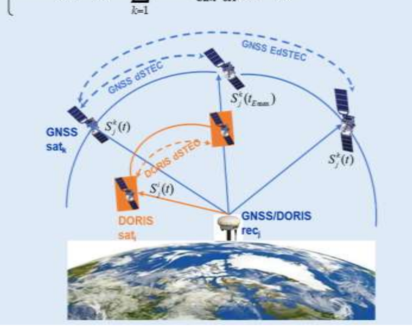
DORIS-dSTEC derived Final/Rapid Combined GIM

Based on DORIS dSTEC, GNSS dSTEC and GNSS EdSTEC

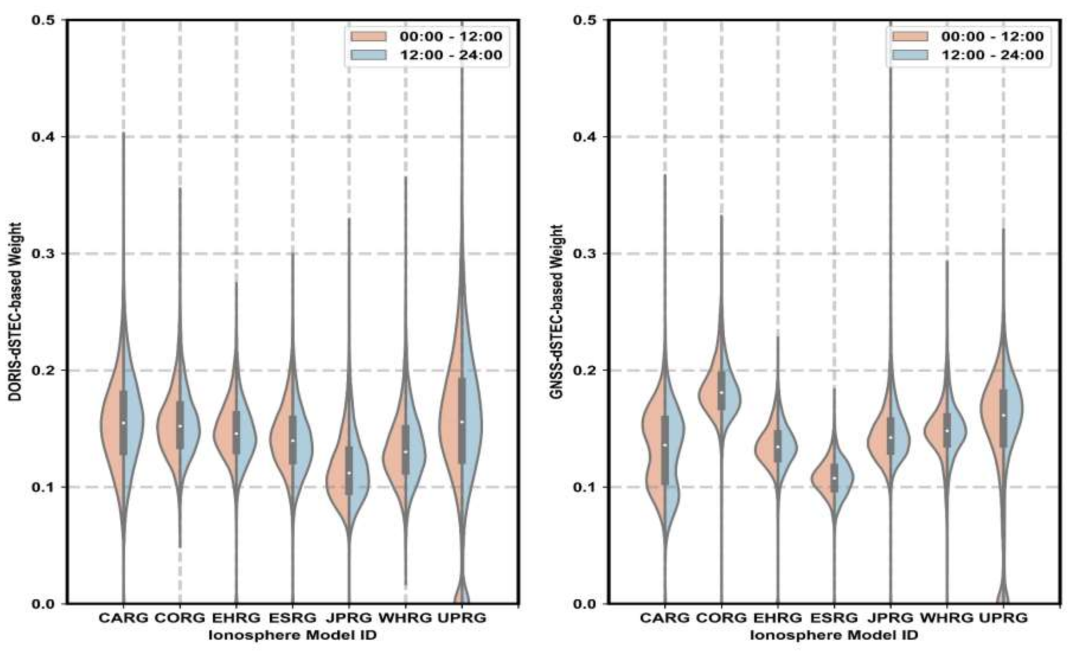


Combined Method

$$\begin{cases}\delta_{GIM-DORIS}(j)=dSTEC_{GIM-SH}(\varphi_j,\lambda_j)-dSTEC_{DORIS}(\varphi_j,\lambda_j)\\ STD_i=\sqrt{\sum_{j=1}^{N}\delta_{GIM-DORIS}(j)}\\ w_i=STD_i^{-2}/\sum_{k=1}^{n}STD_k^{-2}\\ VTEC(\beta,\lambda,t)=\sum_{k=1}^{n}VTEC_{GIM-SH}(\beta,\lambda,t)\end{cases}$$



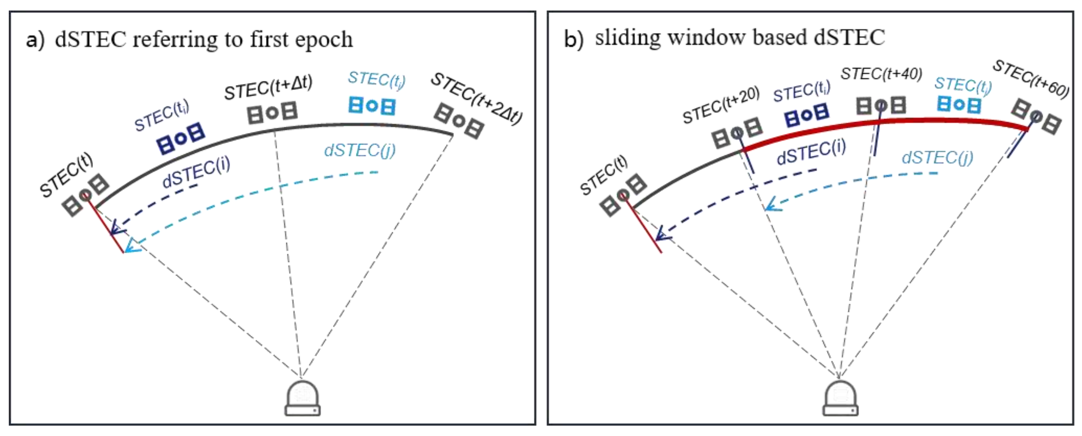
- The precision of DORIS observed dSTEC reaches 0.028 TECu (σ_{L1}=1.5 mm and σ_{L2}=7.5 mm), and that of GNSS dSTEC is about 0.25 TECu ($\sigma_{L1}=\sigma_{L2}$=2.0 mm)
- The precision of derived dSTEC benefits from the larger frequency difference (i.e., f_1- f_2)
- The RMS of rapid combined GIM is 2.0 – 6.5 TECU w.r.t JASON VTEC during 2020-2023.



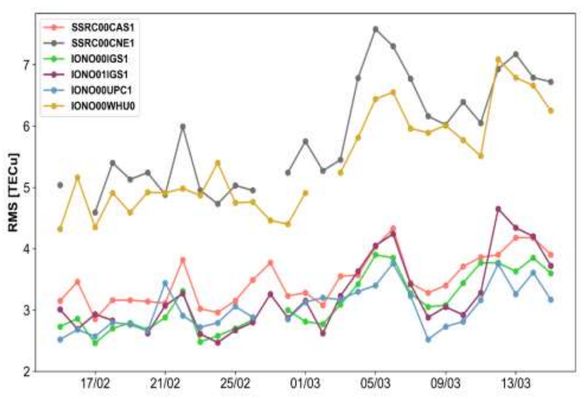
➢ Violin plots of weight distribution, with curves representing probability density.

Real-Time Combined GIM (mounting point: IONO01IGS1)

Based on GNSS dSTEC with sliding window



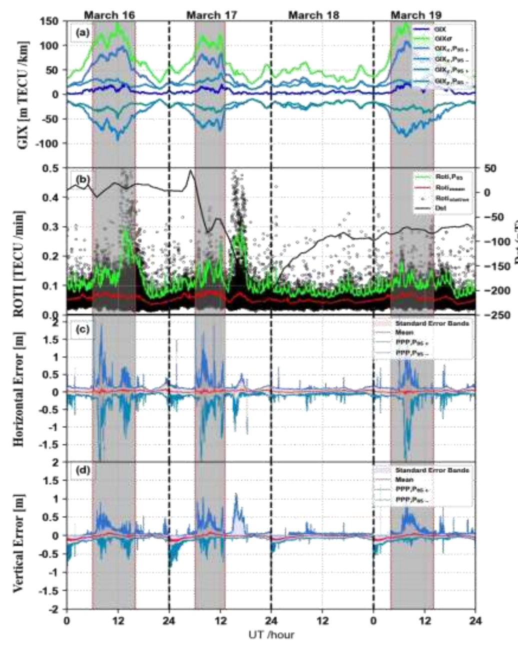
Agency	Ntrip Caster	mounting point	Interval	Format
CAS	products.igs-ip.net:2101	SSRC00CAS1 (RT)	60s	IGS-SSR
	products.igs-ip.net:2101	IONO01IGS0	60s	RTCM-SSR
	products.igs-ip.net:2101	IONO01IGS1	60s	IGS-SSR



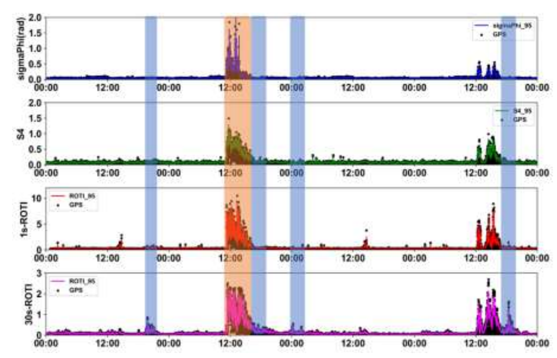
- The RMS of CAS RT combined GIM IS ABOUT 2.5-5.0 TECU w.r.t IGSG.

ID	Bias	STD	RMS	Related Error%
CAS	-0.56	3.49	3.58	19.2
CNES	-3.21	4.76	5.89	35.8
UPC	-0.86	2.92	3.06	18.9
WHU	-1.38	5.23	5.28	30.9
IONO01IGS1	-1.45	2.91	3.30	20.1
IONO00IGS1	-1.41	2.81	3.20	19.6

Other Products (GIX, ROTI, etc.)



➢ The evolution of (a) GIX indices; (b) ROTI and Dst; (c) Horizontal error; and (d) Vertical error of Kinematic PPP solutions (16–19 March 2015).



- Ionospheric indices calculated using different sampling rate data, including S4 and SigmaPhi from 50 Hz data, ROTI from 1 Hz data, and ROTI from 1/30 Hz data.
- Additionally, we generated ROTI maps for the China region using an inverse distance weighting method.

Next Steps to go

In the next phase, a list of further corrections will be implemented, e.g.,
- Updating post-processed GIM algorithms and introducing multi-source ionospheric observation data, such as JASON VTEC and DORIS dSTEC.
- Handling RMS MAP in the integration of ionospheric products.
- Constructing ionospheric index models.

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