IGS 2026 WORKSHOP
SANTIAGO DE CHILE
33°26' S 70°39' O

1-5 June 2026

Ionosphere Research Activities at SHAO

Shuli Song, Yuzhe Yang, Weili Zhou,Wei Li, Jialong Liu,Xulei Jin,Yi Sui

Shanghai Astronomical Observatory(SHAO),CAS,China

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Outline

1. Background

2. Ionosphere Modeling Method

3. GNSS Code Bias

4. Near real-time Ionosphere Nowcasting

5. Future Work In Ionosphere Modeling

6. Ionosphere Anomalous Monitoring

7. Summary and Outlook

1. Background

- Shanghai Astronomical Observatory(SHAO), as one of the GNSS Analysis Center(AC) of MGEX, has been uploading rapid and ultra-rapid orbit&clock&ERP of multi-GNSS to IGS since 2015 and 2017.
- In these years, it's upgraded to provide hourly Ultra-Rapid orbit&clock(30s sampling),and also provide real-time orbit&clock, and carrying on one of the IGS real-time data relays(gnss.shao.ac.cn).
- We are also working on ionospheric TEC modeling. The main objective is to realize ionospheric TEC modeling efficiently, operationally with multi-source data for high-precision applications and research.

1. Background

SHAO Ionospheric Products

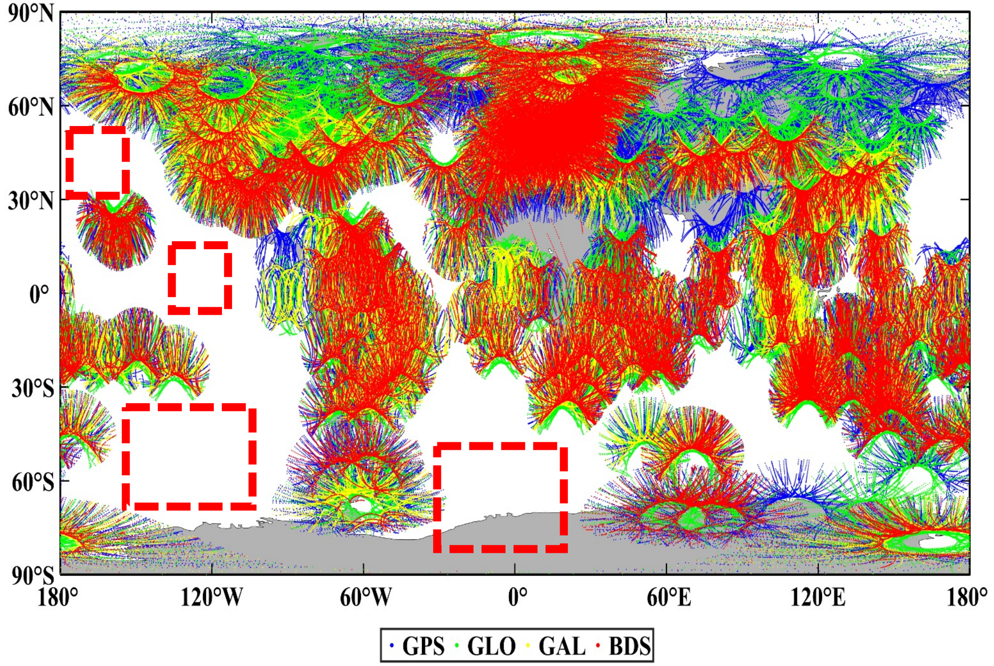
	Final/Rapid	Predicted	Hourly	Nowcasting	Real-time	3D	ROTI
Time latency	1~3 days	Real-time，daily update	1~2 hours	Real-time,hourly update	Real-time	1~2 hours	~1day
Data source	Daily	Rapid model	Hourly + Real-time	Hourly model	Real-time	Hourly + GNSS RO	Daily
Number of station	~400	-	~350	-	~200	~350	~5000
Time interval	1h	1h	1h	1h	5min	1h	1h
Content	VTEC	VTEC	VTEC	VTEC	VTEC	Electron density	Rate of TEC
Time consuming	<30min	<5min	<20min	<2min	<2min	<20min	<10min

SHAO is providing final/rapid+predicted,hourly+nowcasting,real-time,3D and ROTI ionosphere products.

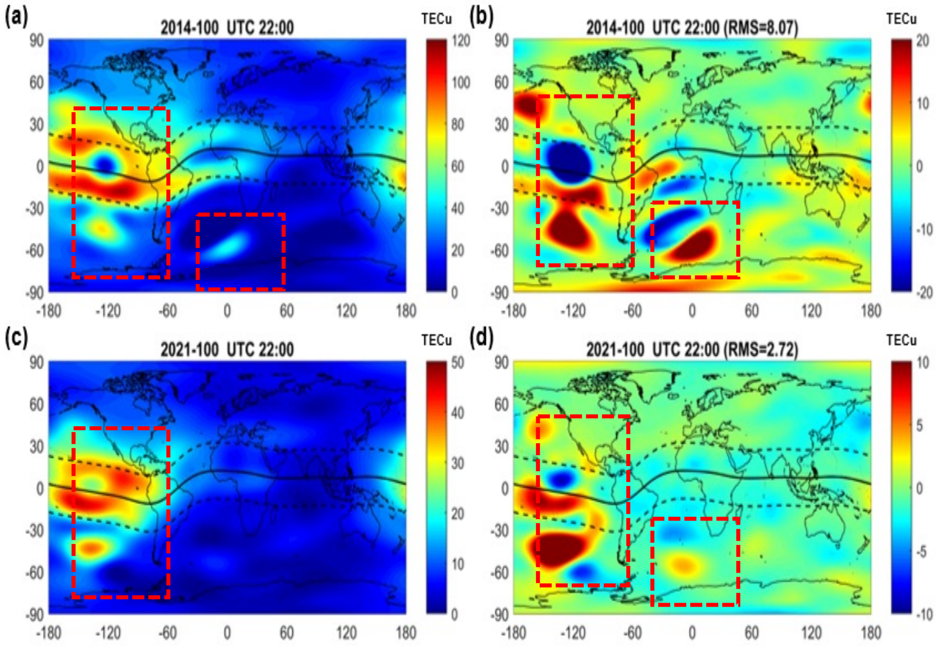
2. Ionosphere Modeling Method

➢ Augmentation with VOS for large data Gaps

Uneven GNSS data distribution reduces TEC accuracy notably in areas with large data gaps for real-time modeling. Virtual observing stations (VOS) based on the IRI model are deployed to supplement TEC measurements.



Distribution of GNSS quad system observations



TEC modeling results and deviations relative to IGSG

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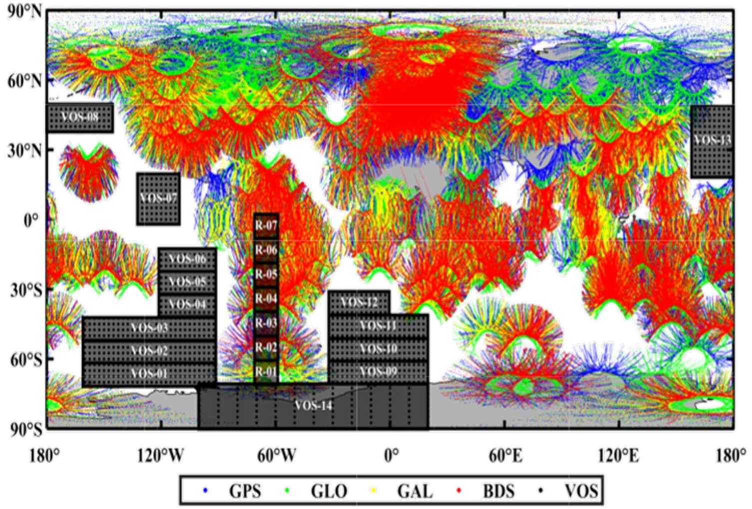
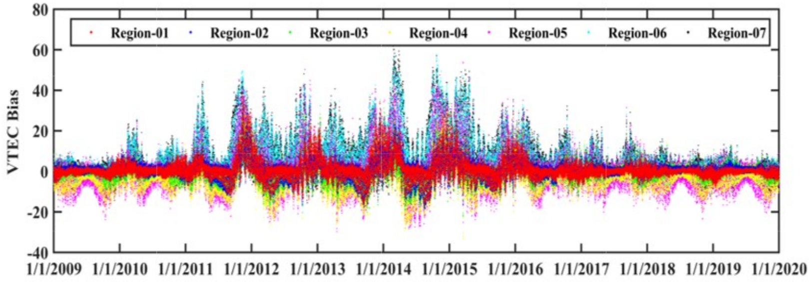
2. Ionosphere Modeling Method

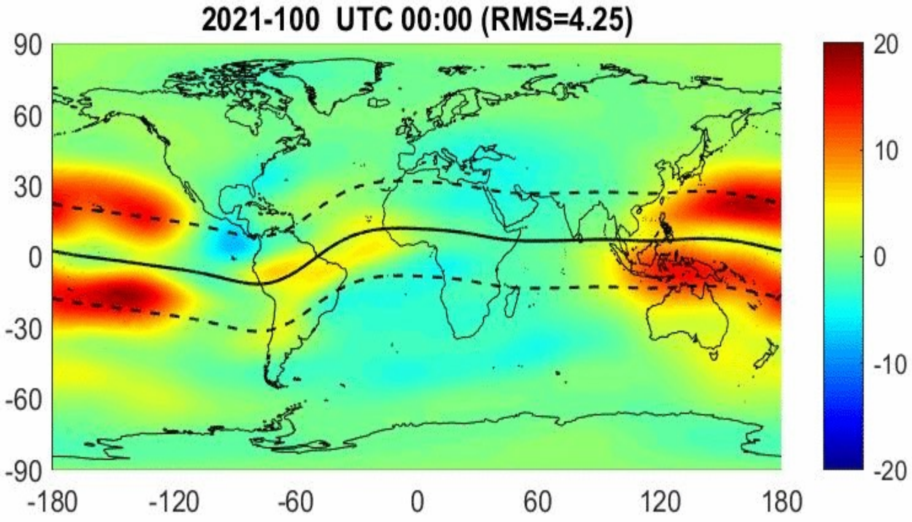
➢ Priori Noise of VOS



Distribution of virtual observatories and bias test stations



11-yearsGNSS GIM and IRI VTEC deviation



GNSS GIM and IRI VTEC deviation

	Lat. $\geq$ 40°	Lat. $<$ 40°
F10.7 $<$ 90	5 TECu	10 TECu
F10.7 $\geq$ 90	20 TECu	30 TECu

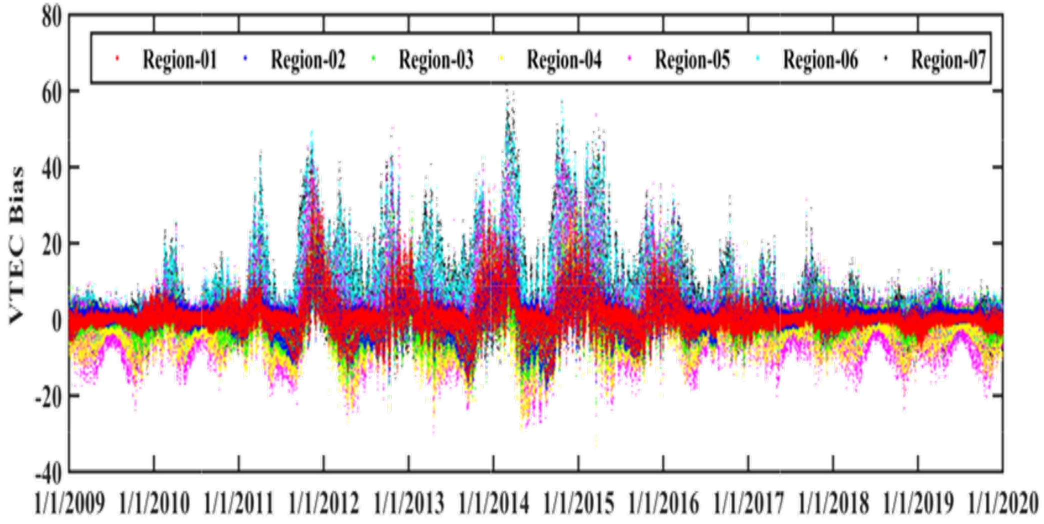
Priori noise IRI VTEC

Priori Noise from the statistic of 11-years GNSS GIM and IRI VTEC difference is used for the automatic fusion of GNSS data and VOS.

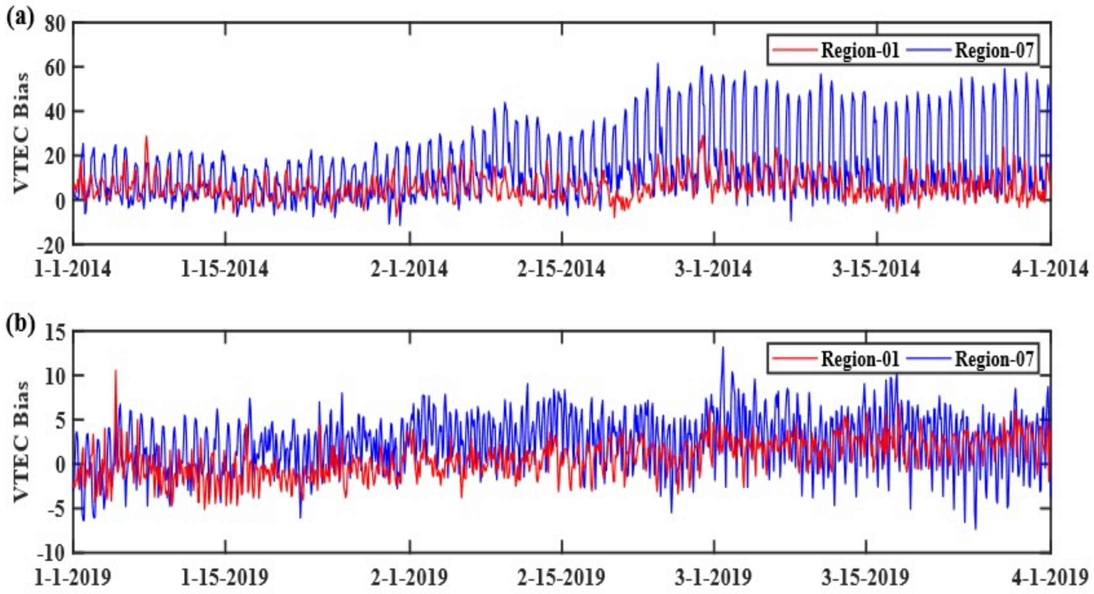
2. Ionosphere Modeling Method

➢ Additional Piecewise Linear Bias parameters Estimated

Due to the complex and time-varying bias between GNSS and IRI(or other) TEC, it is difficult to directly fuse the data, Piecewise linear Bias parameters to the virtual observatory (VBs) are used for realizing the automatic calibration and fusion modeling with multi-source data.



GNSS and IRI VTEC deviation

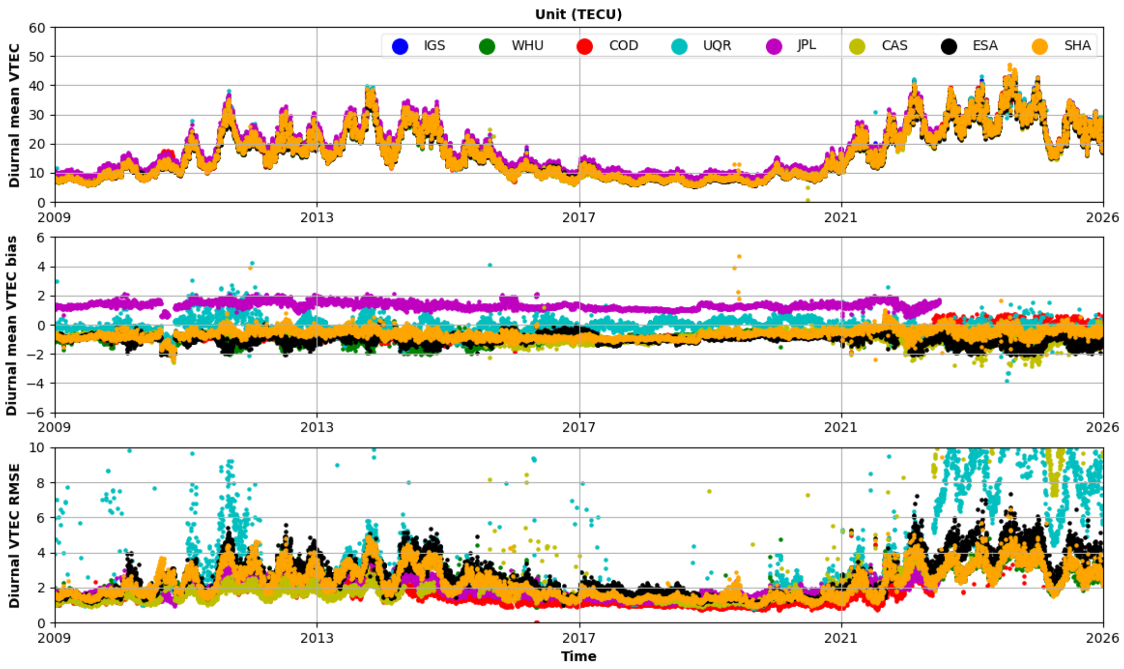


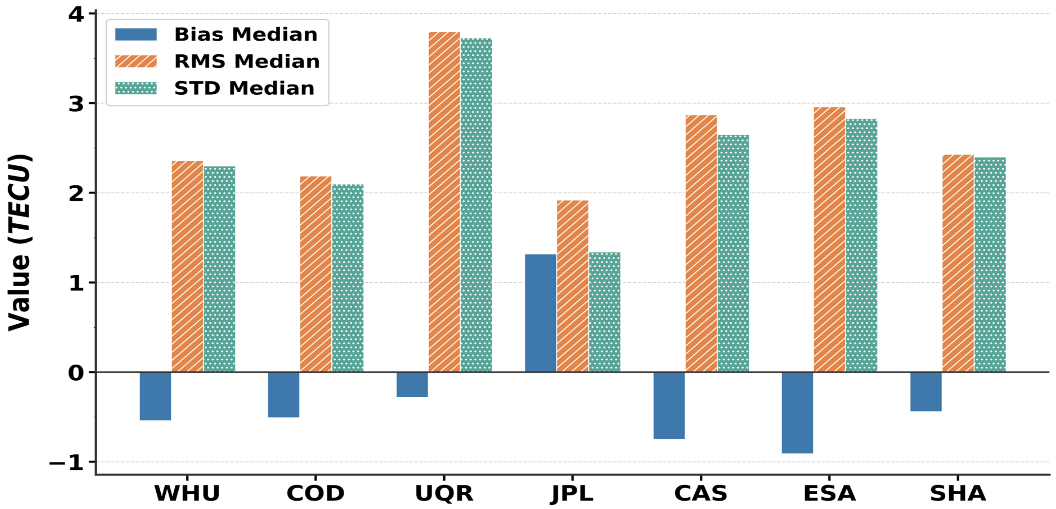
$$VTEC(\beta,\gamma,t,n) = \sum_{n=0}^{n_{max}} \sum_{m=0}^{n} \tilde{P}_{n,m}(\sin\beta)\left[\tilde{C}_{n,m}\cos(m\gamma) + \tilde{S}_{n,m}\sin(m\gamma)\right] + VB(t,n)$$

2. Ionosphere Modeling Method

➢ Validation with GIM： 17 years GIM from IGS analysis centers (2009–2026)

- ✓ Data & Methods: Compare VTEC time series (mean, bias, RMSE) of WHU/COD/UQR/JPL/CAS/ESA/SHA against the IGS combined product
- ✓ Quantitative summary via median bias/RMS/STD bar chart

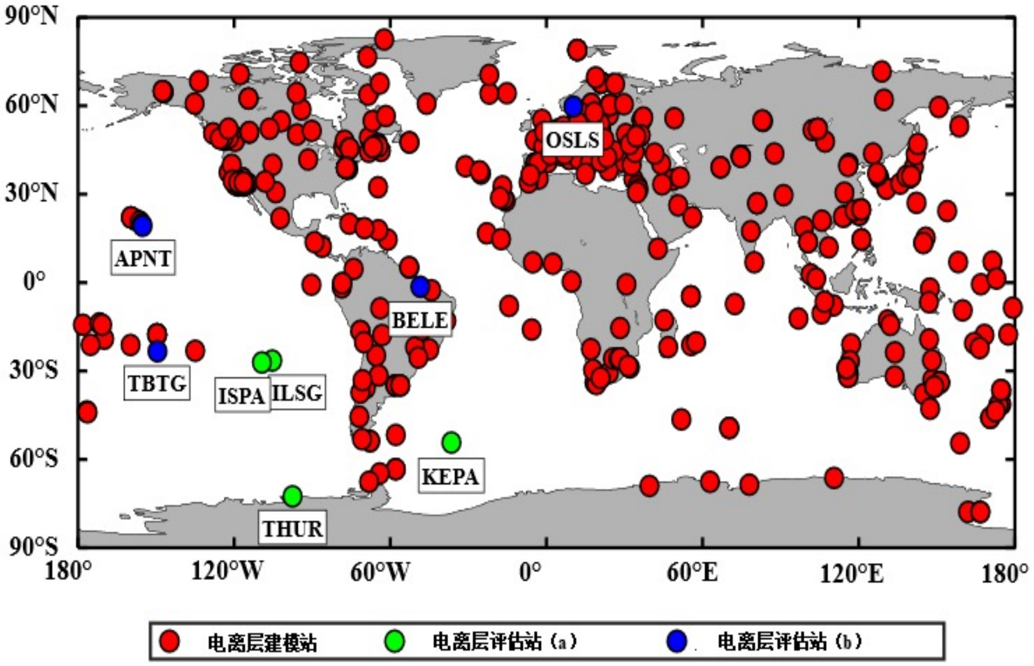




The SHA GIM achieves comparable accuracy to most other IGS analysis centers.

2. Ionosphere Modeling Method

➢ Validation-With measured VTEC



Global distribution of GNSS ionospheric modeling and assessment stations

Solar	VOS	VB	Gaps Area (a)				No Gaps (b)			
			ILSG	ISPA	KEPA	THUR	APNT	TBTG	BELE	OSLS
Active	Y	1 h	15.12	15.14	3.10	5.00	4.43	7.34	5.05	1.70
	Y	2 h	15.42	15.41	3.07	4.96	4.44	7.36	5.05	1.70
	Y	4 h	15.13	15.16	3.10	4.95	4.45	7.35	5.05	1.70
	Y	8 h	15.44	15.43	3.13	4.80	4.46	7.36	5.05	1.70
	Y	12 h	15.95	15.91	3.23	4.79	4.54	7.41	5.05	1.70
	Y	24 h	16.07	16.03	3.24	5.47	4.56	7.43	5.05	1.70
	N		19.30	19.82	6.40	7.28	4.37	7.27	5.05	1.70
Quiet	Y	1 h	4.72	3.92	1.77	1.24	1.34	1.71	1.60	1.52
	Y	2 h	4.73	3.94	1.76	1.23	1.34	1.71	1.60	1.52
	Y	4 h	4.75	3.96	1.79	1.25	1.34	1.70	1.60	1.52
	Y	8 h	4.65	3.90	1.78	1.28	1.34	1.70	1.60	1.52
	Y	12 h	4.66	4.04	1.73	1.30	1.34	1.70	1.60	1.52
	Y	24 h	5.22	4.57	1.72	1.31	1.36	1.70	1.60	1.52
	N		6.54	5.75	2.69	2.64	1.37	1.65	1.59	1.52

RMSE (in TECu) of the GIM solved by adding VOS and attaching VB parameters at different intervals, as well as without VOS, relative to the VTEC of the evaluation station during periods of solar activity and quiet periods

With the virtual stations, the accuracy of the gaps is significantly improved, and no affect on the area with dense GNSS stations ,under both active and quiet solar conditions.

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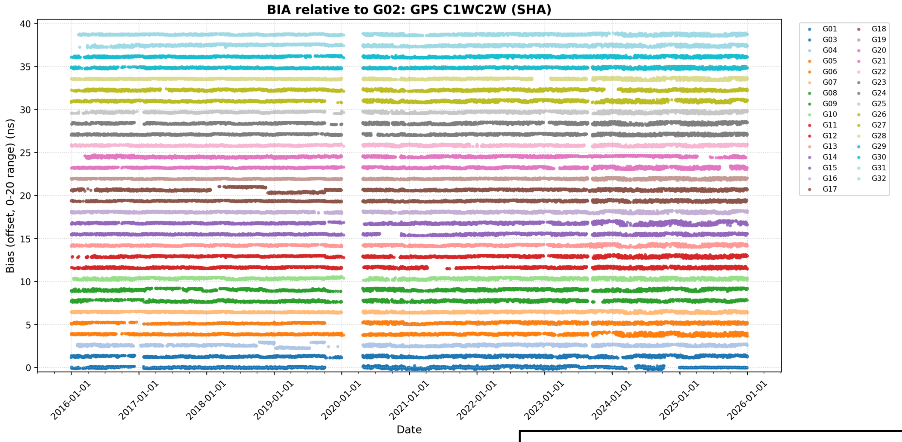
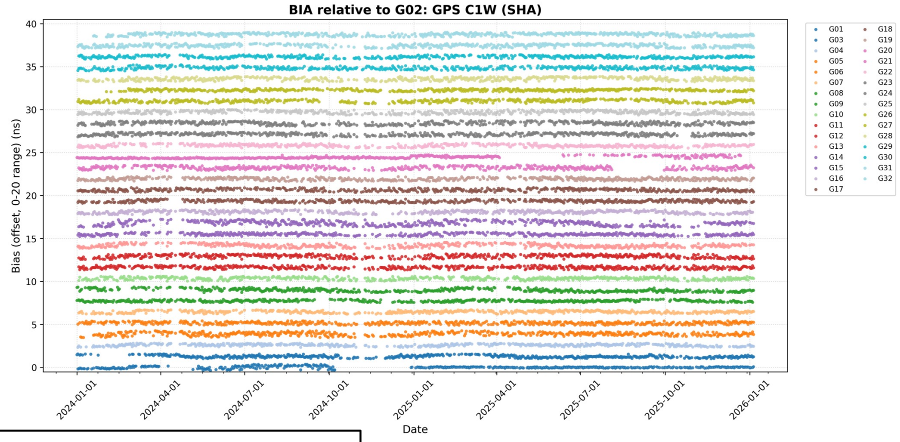
3. GNSS Code Bias

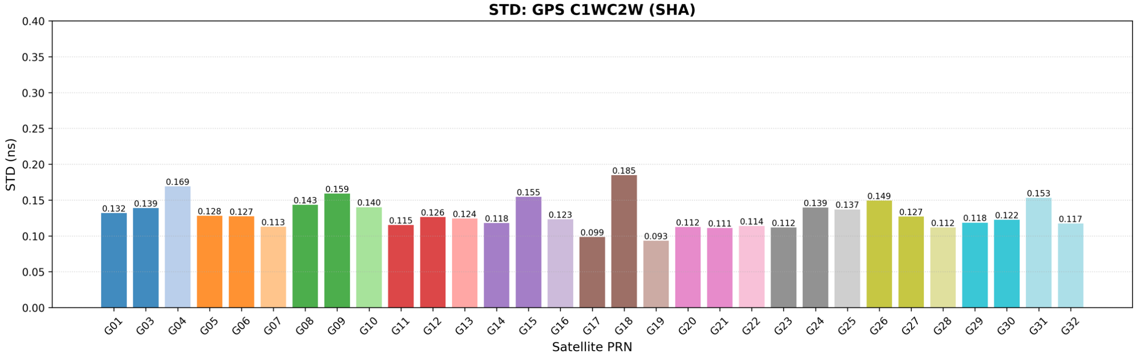
➢ **Analyze the long-term stability of GPS DCB/OSB using SHA products.**

- The datum of DCB/OSB has been unified for consistency(DCB:2016-2026,OSB:2024-2026)





Time series plots show the stability of individual satellite biases over time



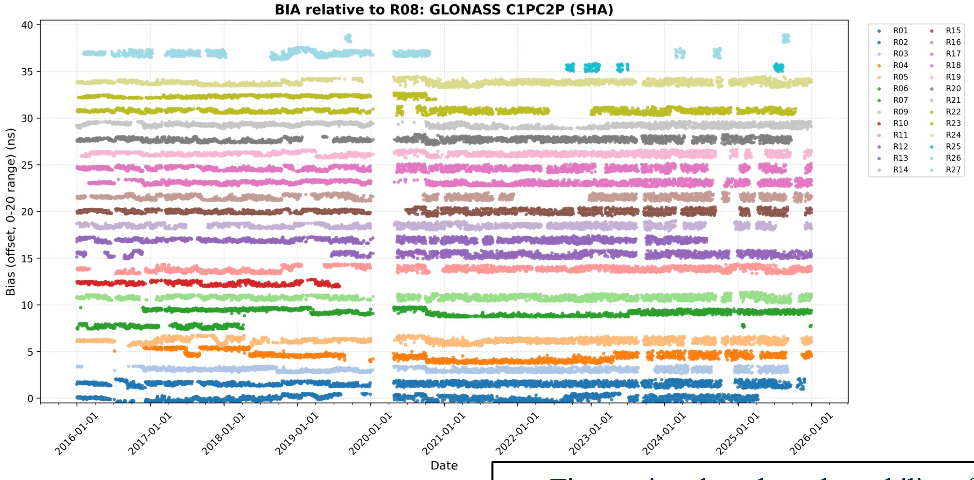
STD quantifies the variability of each satellite's DCB/OSB

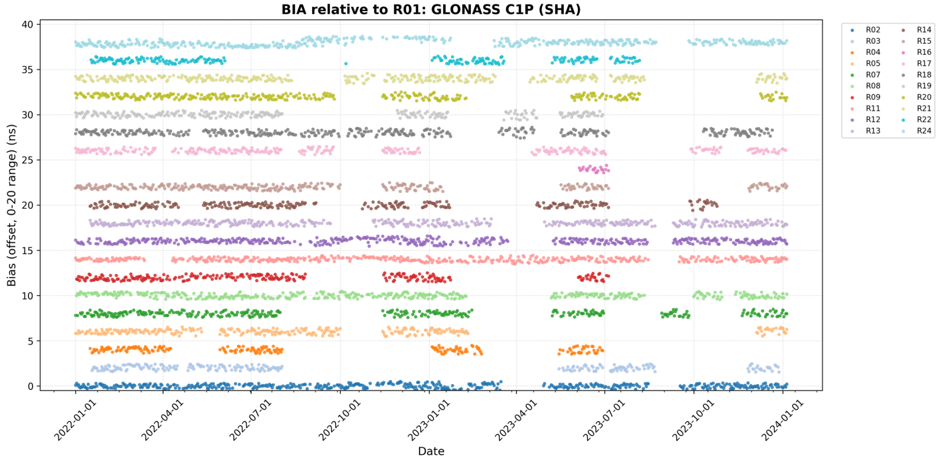
- GPS DCB/OSB are maintained with STD values ranging from 0.10–0.20 ns for most satellites.

3. GNSS Code Bias

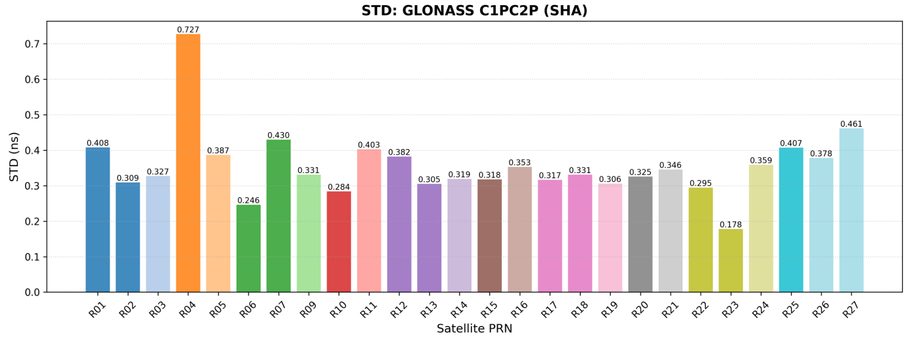
➢ **Analyze the long-term stability of GLO DCB/OSB using SHA products.**

- The datum of DCB/OSB has been unified for consistency (DCB:2016-2026,OSB:2022-2024)





Time series plots show the stability of individual satellite biases over time



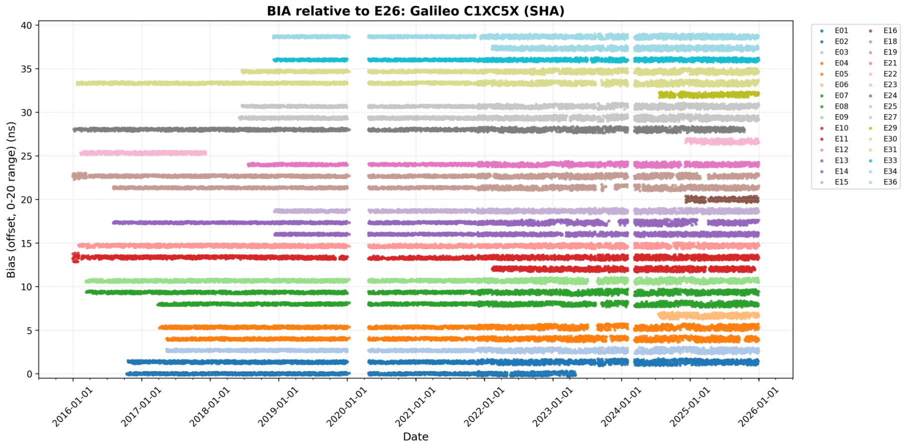
STD quantifies the variability of each satellite's DCB/OSB

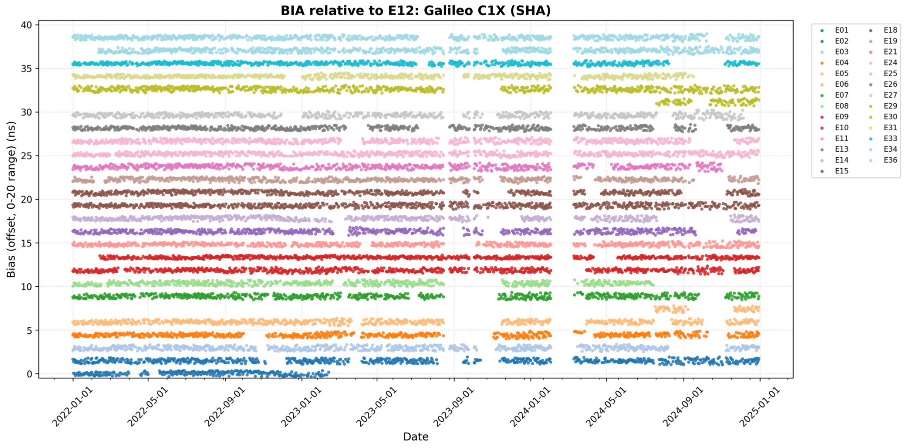
- GLONASS DCB/OSB are maintained with STD values mostly between 0.17–0.70 ns.

3. GNSS Code Bias

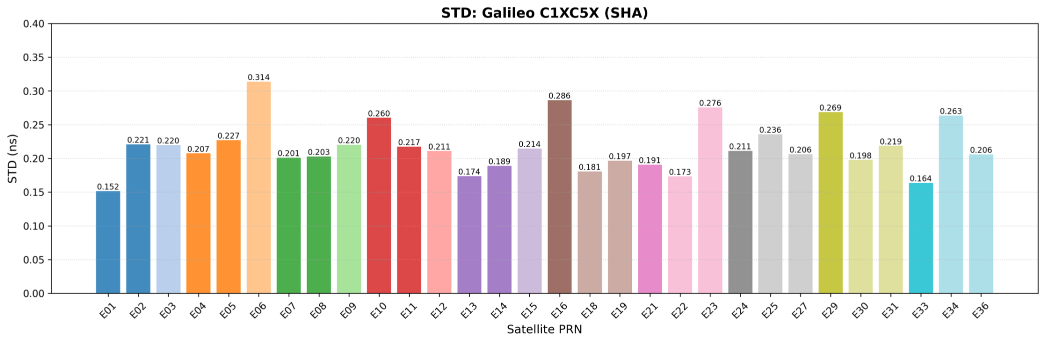
➢ **Analyze the long-term stability of GAL DCB/OSB using SHA products.**

- The datum of DCB/OSB has been unified for consistency (DCB:2016-2026,OSB:2022-2025)





Time series plots show the stability of individual satellite biases over time



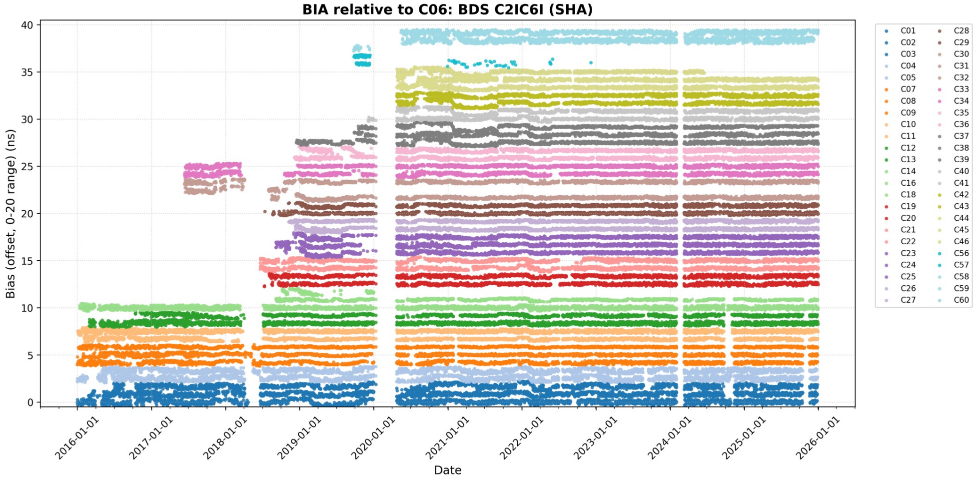
STD quantifies the variability of each satellite's DCB/OSB

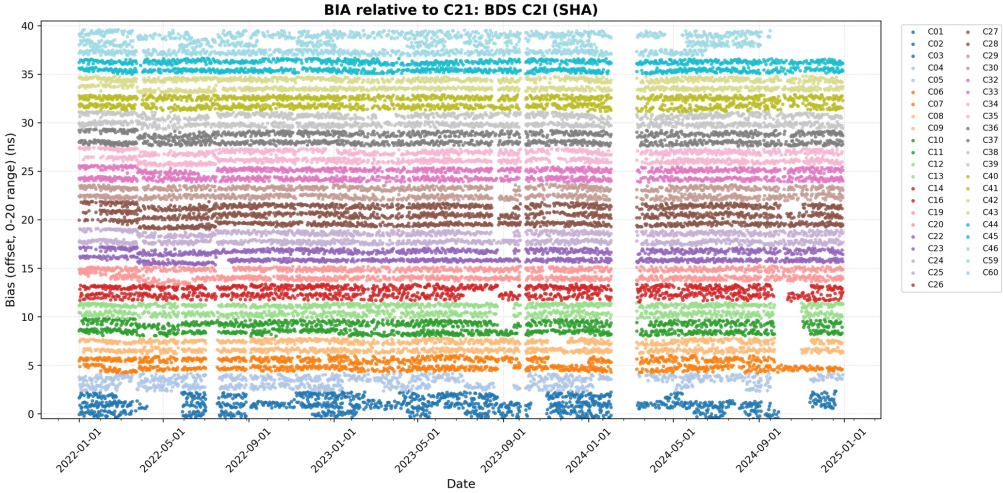
- Galileo DCB/OSB are maintained with STD values consistently within 0.15–0.35 ns.

3. GNSS Code Bias

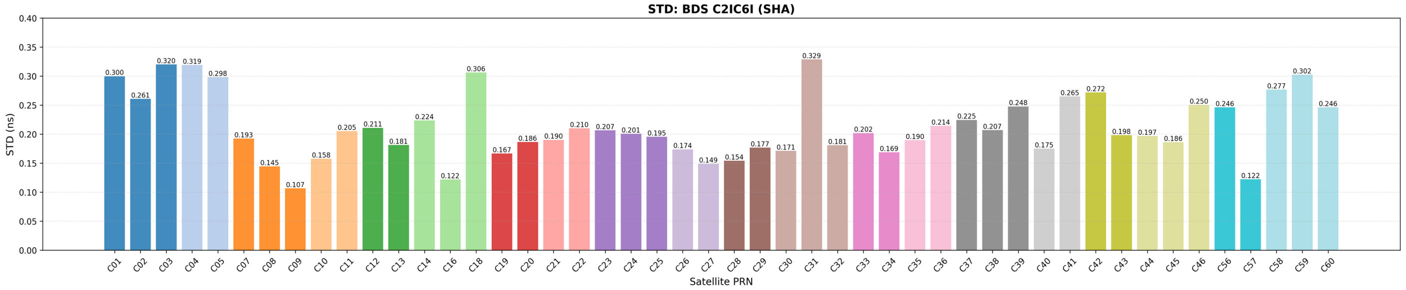
➢ Analyze the long-term stability of BDS DCB/OSB using SHA products.

- The datum of DCB/OSB has been unified for consistency (DCB:2016-2026,OSB:2022-2025)





Time series plots show the stability of individual satellite biases over time

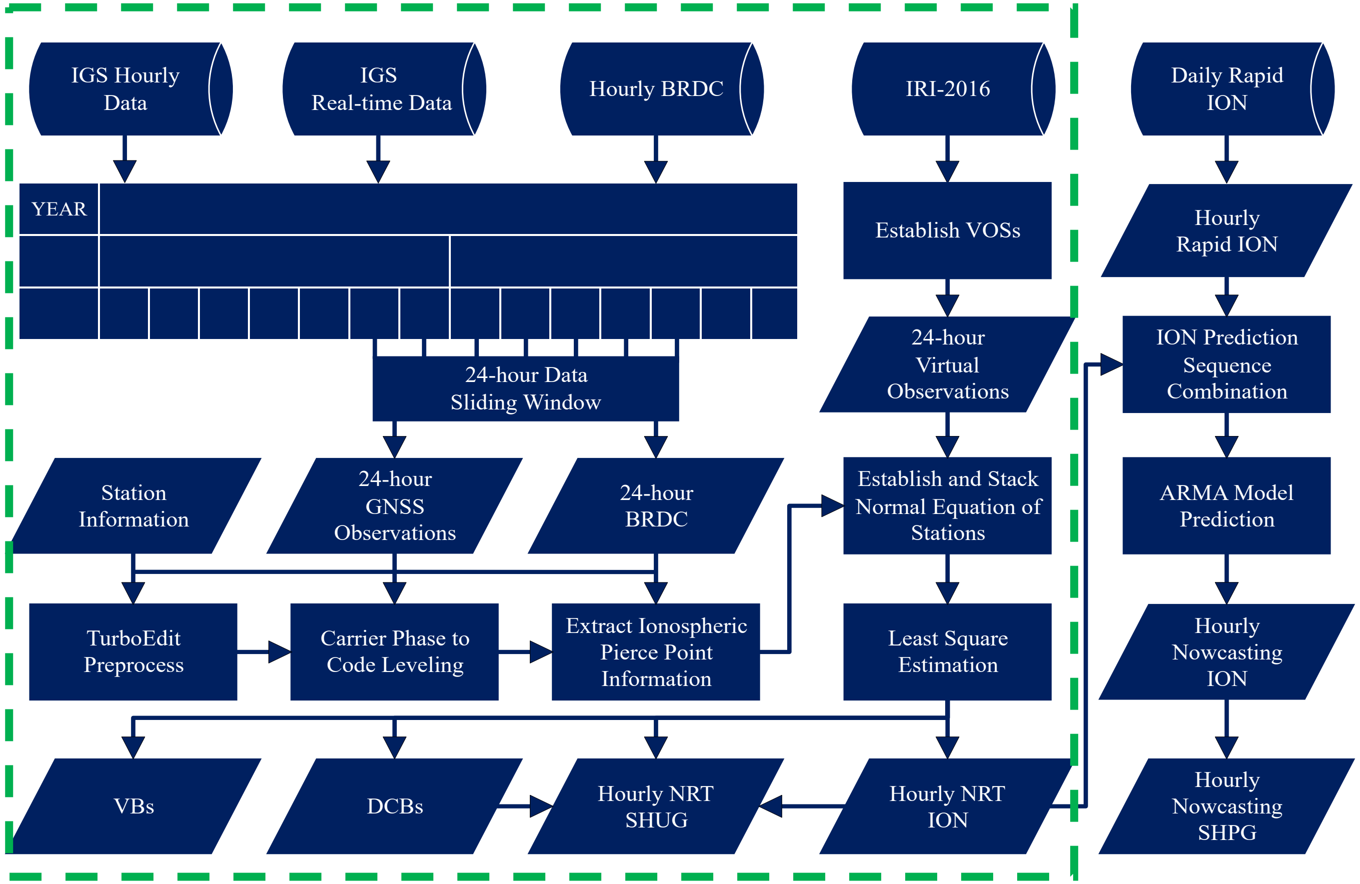


STD quantifies the variability of each satellite's DCB/OSB

- BDS DCB/OSB are maintained with STD values ranging from 0.10–0.35 ns for most satellites.

4. Hourly Updated ionosphere TEC Modeling

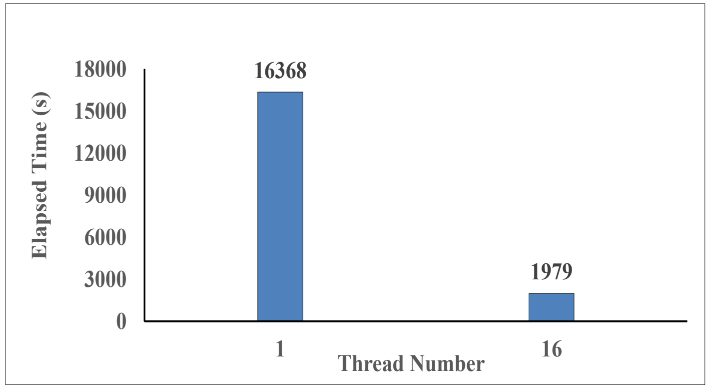
- For some accurate applications for real-time ionospheric TEC modeling, 1-hourly modeling and nowcasting of ionospheric TEC with sliding-window was carried out with Global/regional hourly/15min files and real-time streams.



Flowchart of the hourly modeling(SHUG) and forecast (SHPG) solution

Efficiency-CSR(Compressed Sparse Row) for sparse Matrix

- (CSR) format for sparse design matrices
- Multi-threaded parallel using OpenMP
- Average modeling time: 400+ stations
- 400+ stations, G+R, approx. 10 min.
- 400+ stations G+R+E+C ,30 minutes



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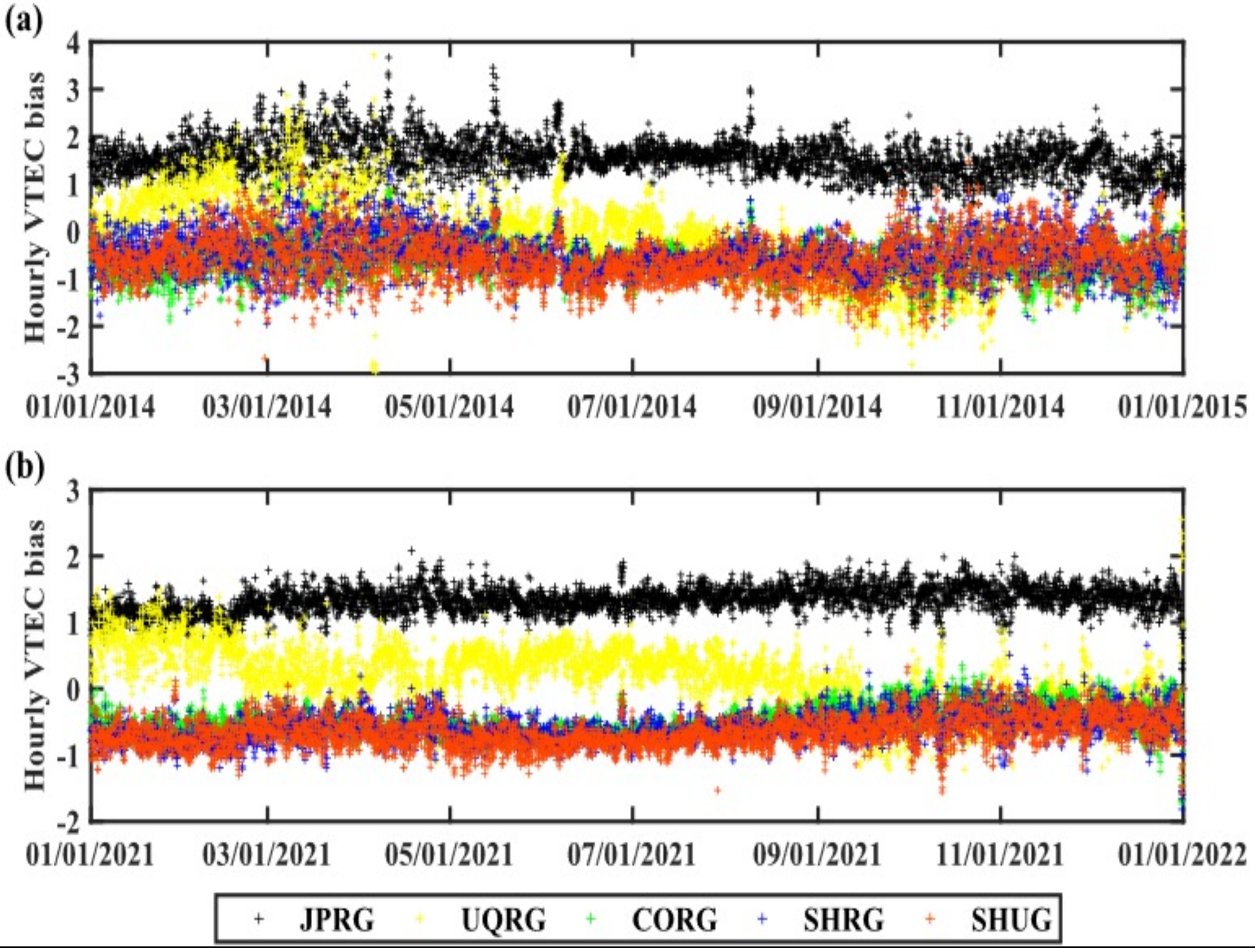
4. Hourly Updated ionosphere TEC Modeling

■ Validation with IGS Final GIM

Active Year

Quiet Year



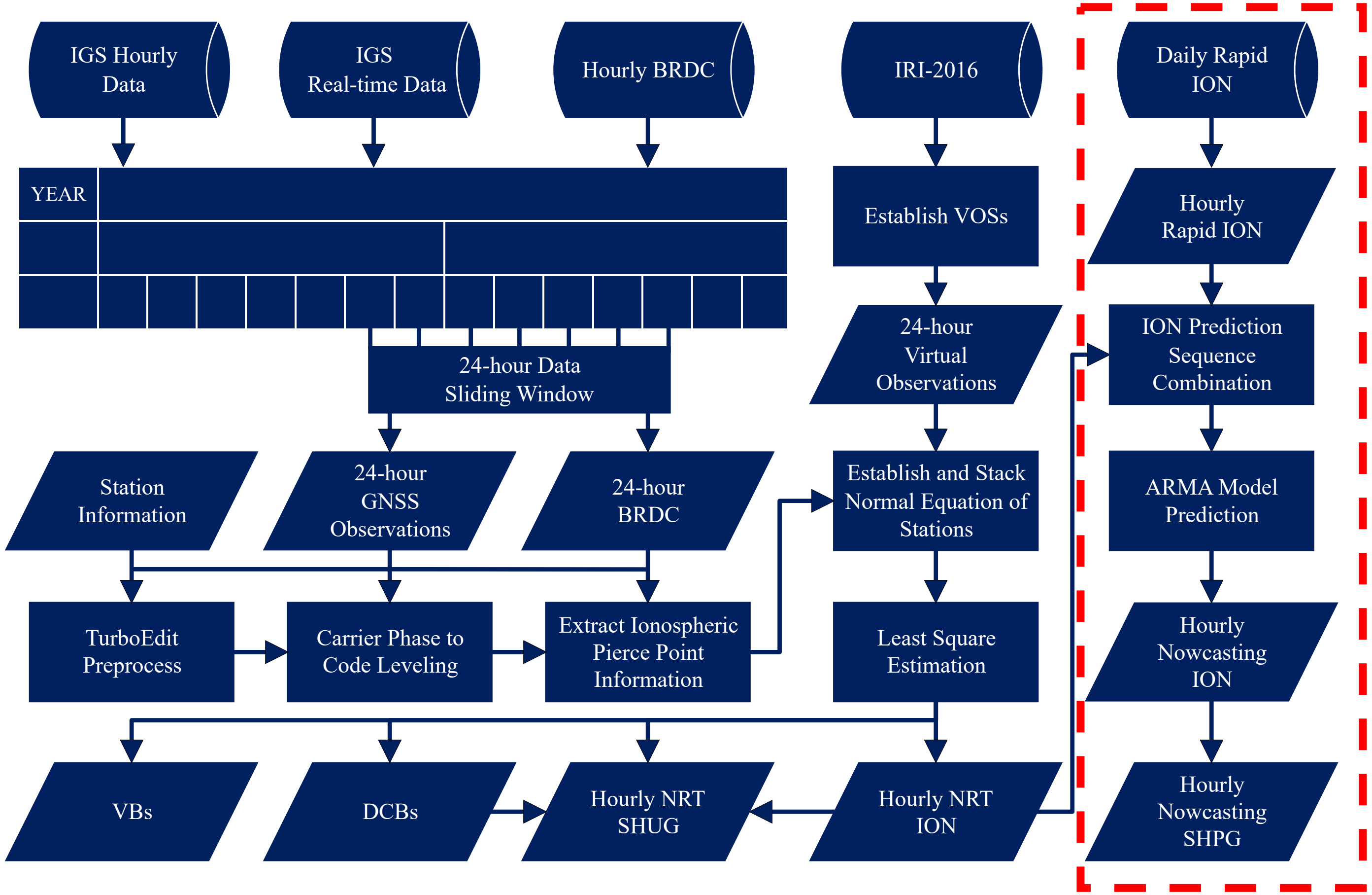
Hourly averaged deviation of JPRG, UQRG, CORG, SHRG and SHUG relative to IGSG in 2014 (a) and in 2021 (b) (Unit:TECU)
Hourly Ionosphere Modeling(SHUG) has almost the same accuracy as SHRG.

4. Near real-time ionospheric Nowcasting

➢ Nowcasting TEC based on hourly sliding-window ionospheric modeling

For some applications and providing accurate background for real-time ionospheric TEC modeling, the hourly nowcasting of ionospheric TEC was carried out.

The self-adaptive ARMA model was used to forecast the ionospheric TEC model coefficients.

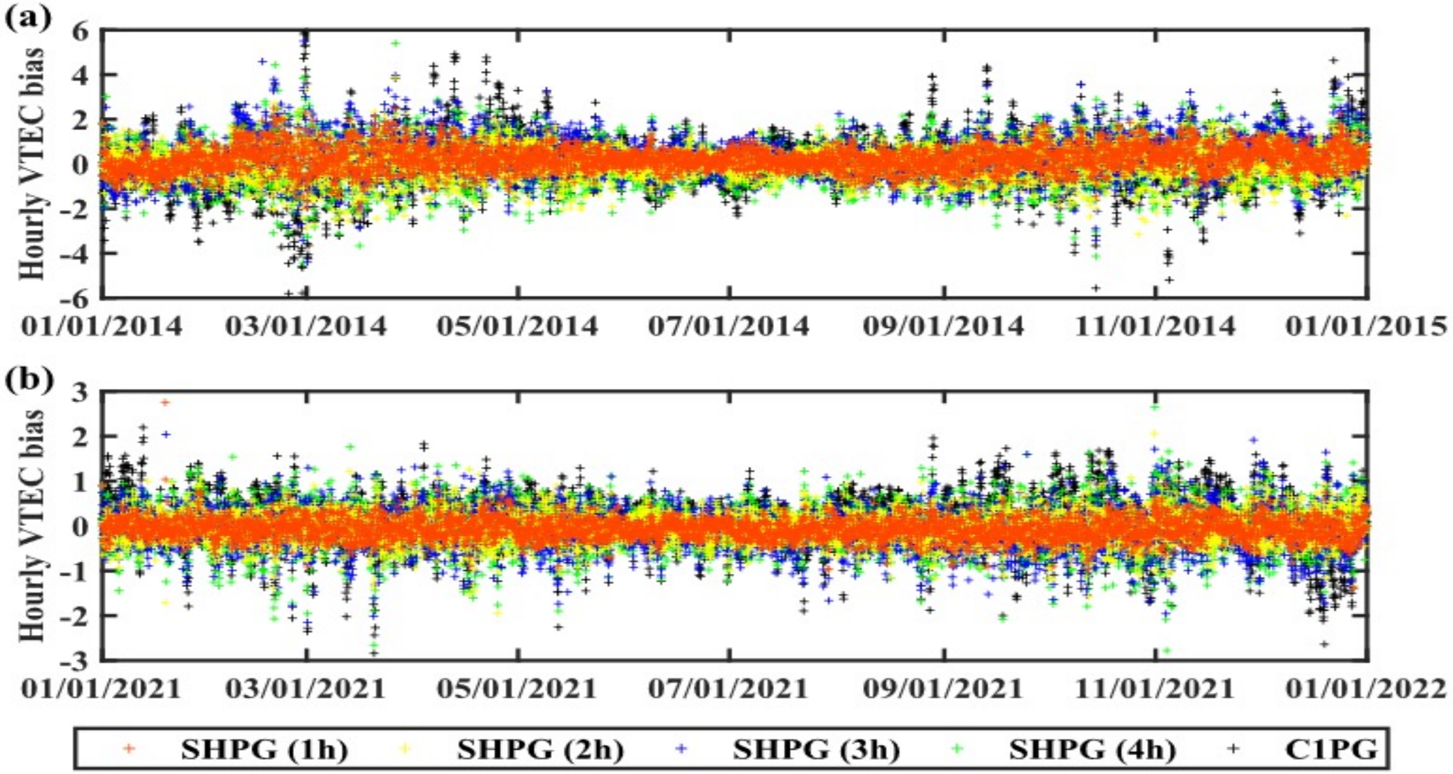


Flowchart of the hourly short-term forecast GIM (SHPG) solution

4. Near real-time ionospheric Nowcasting

➢ **Hourly forecast TEC GIM validation**

Hourly VTEC deviation for 1- to 4-hour nowcasting GIM SHPG (1h), SHPG (2h), SHPG (3h), SHPG (4h), and C1PG relative to CODG (in TECu)



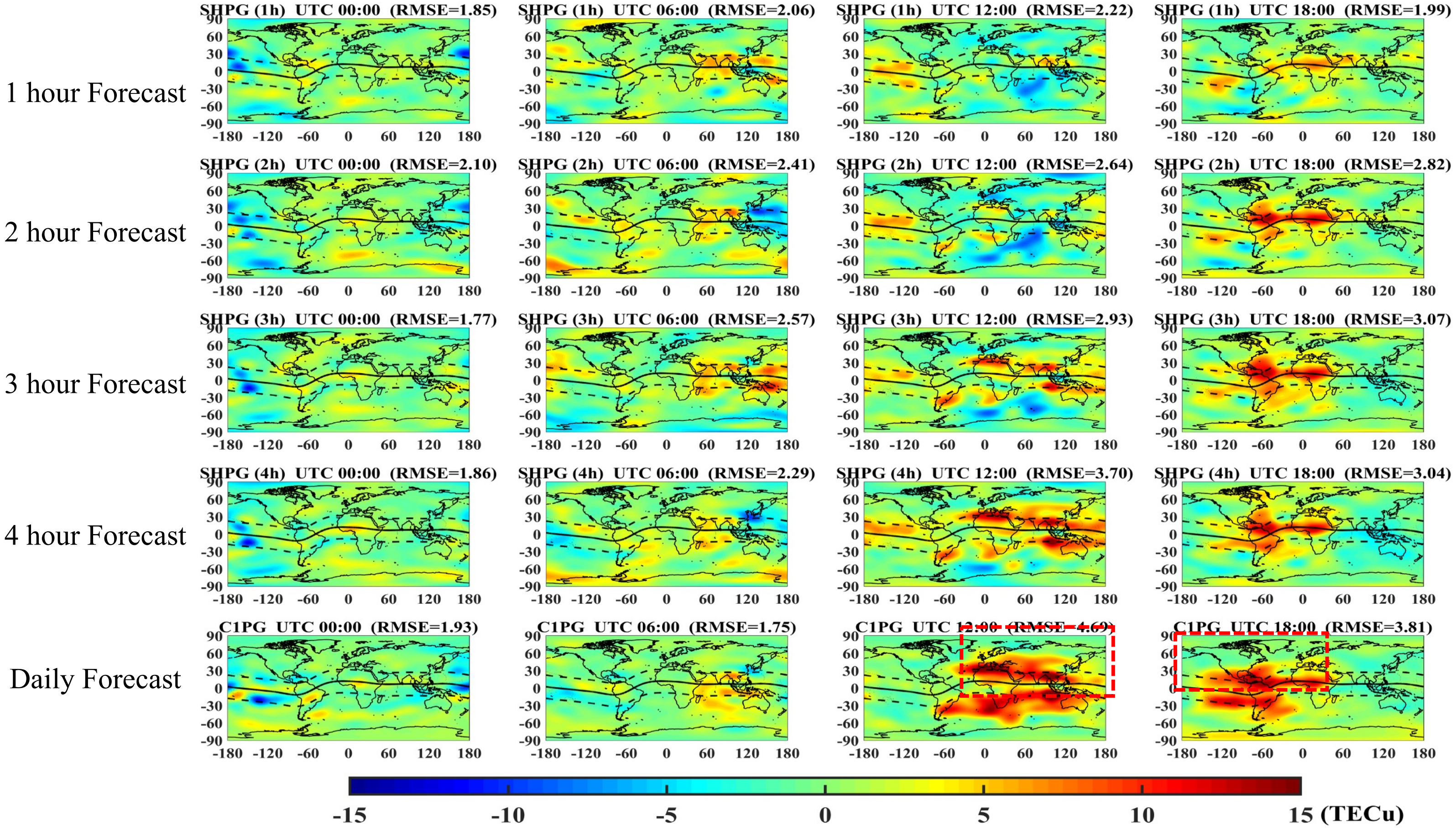
The deviation and dispersion of the 1-hr, 2-hr, 3-hr, 4-hr, and 1-day forecasts compared to the final GIMs. Apparently, the shorter the prediction time, the smaller the forecast error.

4. Near real-time ionospheric Nowcasting

➢ Hourly forecast TEC GIM validation

Deviation of the 1- to 4-hour forecast SHPG and C1PG on the 79th.

(spring equinox) of 2021 relative to CODG at 0:00 UTC, 06:00 UTC, 12:00 UTC, and 18:00 UTC



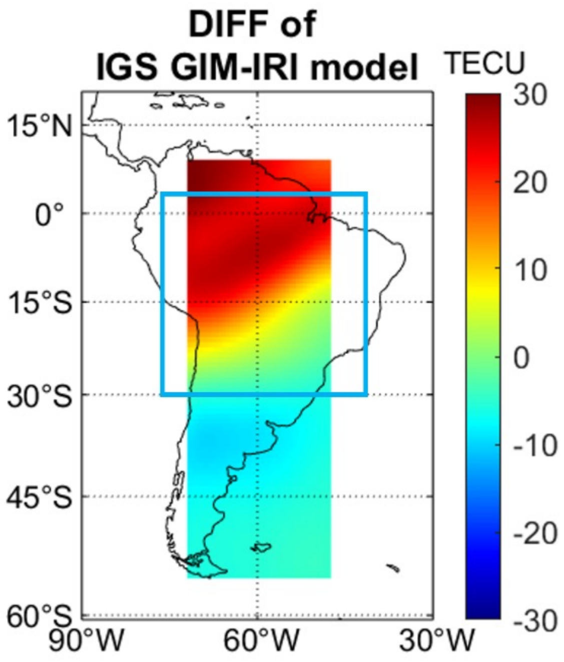
In the equatorial anomaly region, during the spring equinox, where the ionosphere are more active, the accuracy of the short-term forecasts is significantly better than daily forecast which is very important for anomalous monitoring.

5. Future Work In Ionosphere Modeling

➢ Enhance ionosphere modeling by spatial differenced VTEC from IRI-2020 model

Status: Two fusion schemes are experimentally evaluated.

Prospect: Further model construction and analysis will be conducted.



IGS GIM-IRI Model Differences

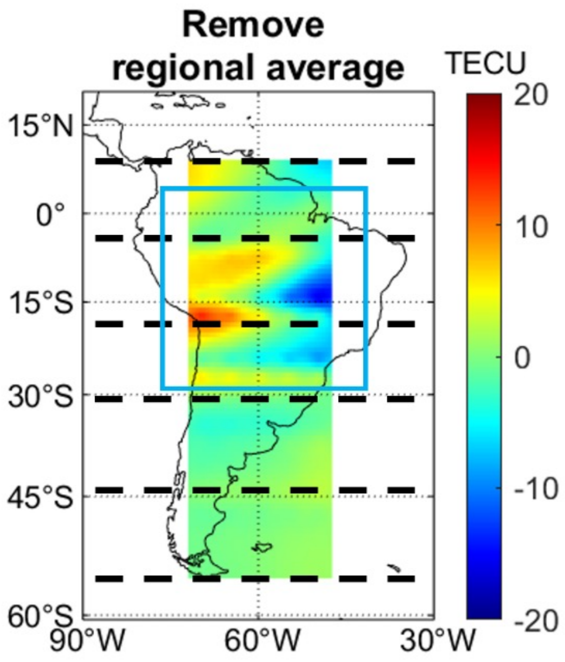


Figure: Differences between IGS GIM and IRI Models (Mean Removal by Latitude Bands; Eliminating Systematic Bias via Simulated Estimated Parameters)

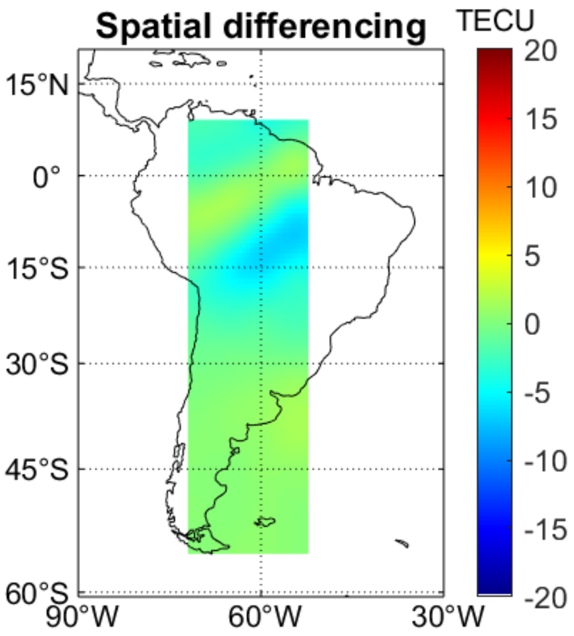
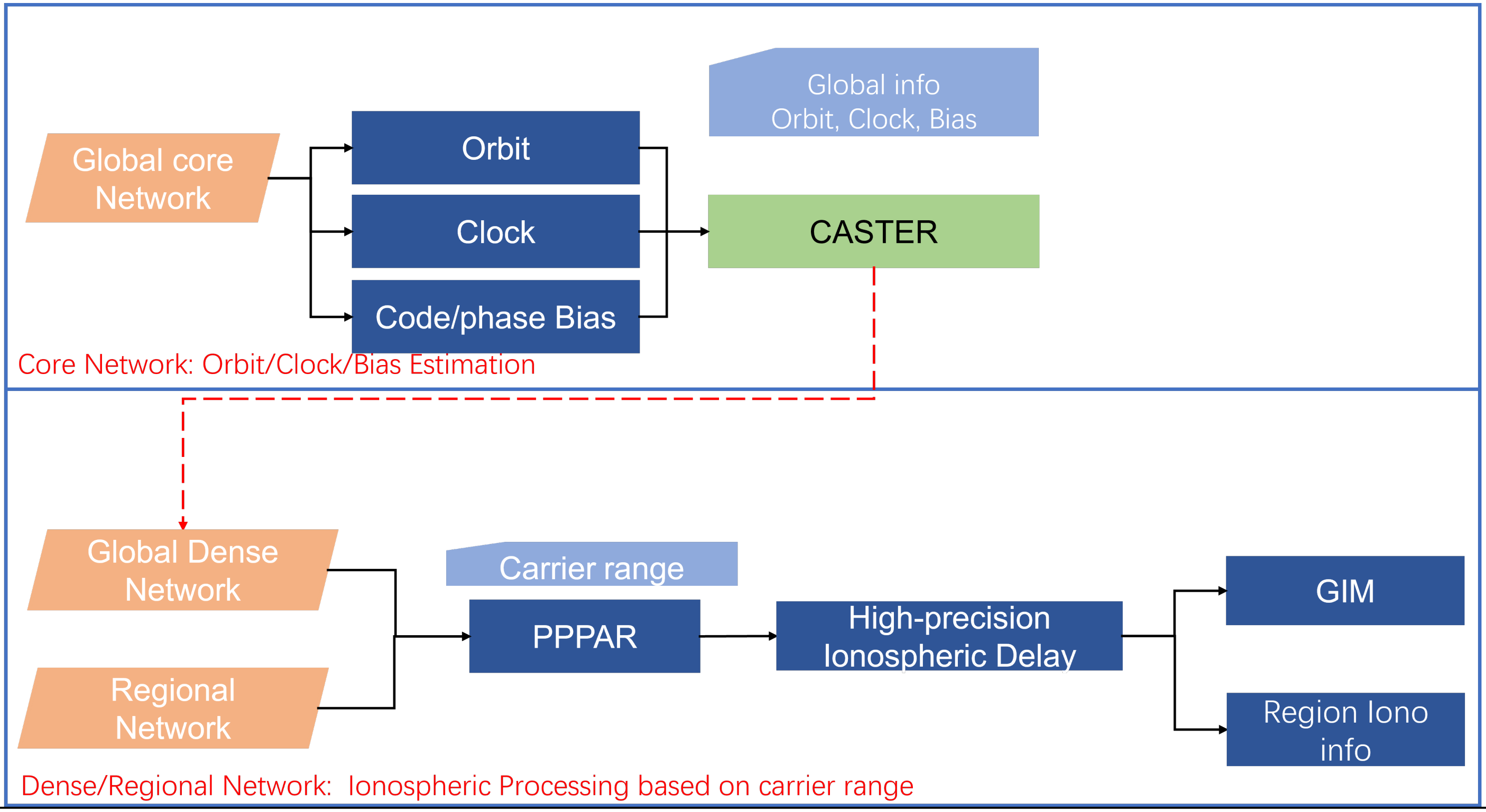


Figure: IGS GIM-IRI Model Differences after Geometric Differencing

5. Future Work In Ionosphere Modeling

➢ **Real-Time Carrier Range-Based Hierarchical Ionospheric Information Enhancement System is under development.**



Core challenges :

- ➢ Refined handling of biases: ensure the stable and reliable generation of high-quality carrier range observations.
- ➢ Optimization of the functional model: better represent and exploit the rich ionospheric information provided by high-density GNSS stations.

5. Future Work In Ionosphere Modeling

➢ **Preliminary PPPAR-STEC**

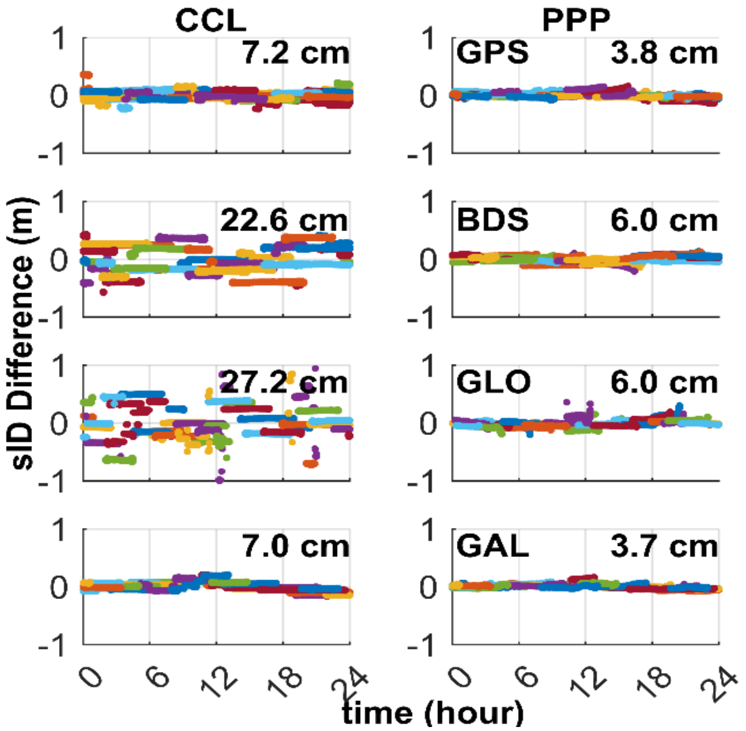


FIG. short baseline differential STEC

Single differences of the SID between two receivers GODS and GODN (The receiver types: JAVAD TRE_3 DELTA)

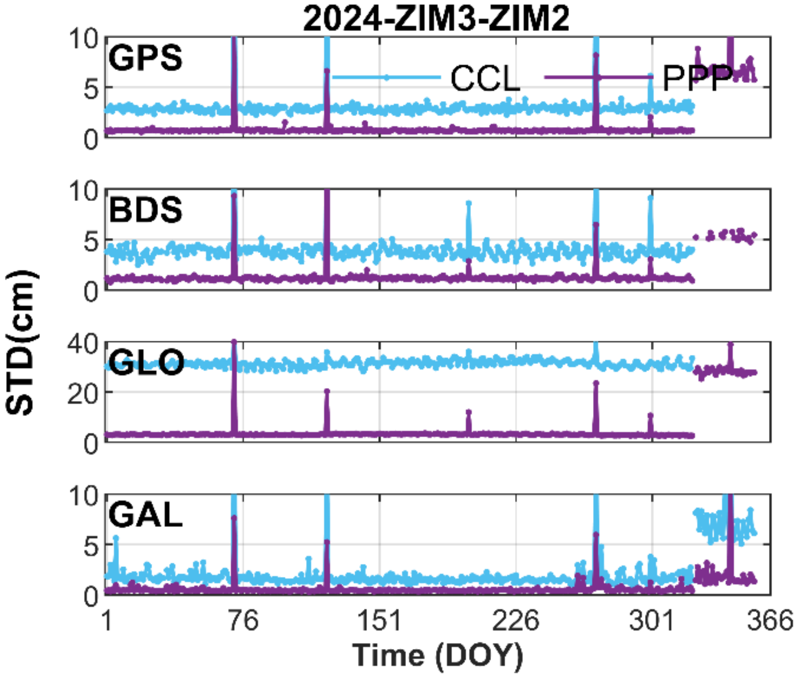


FIG. The standard deviation in 2024

ZIM3, receiver type: TRIMBLE NETR9;

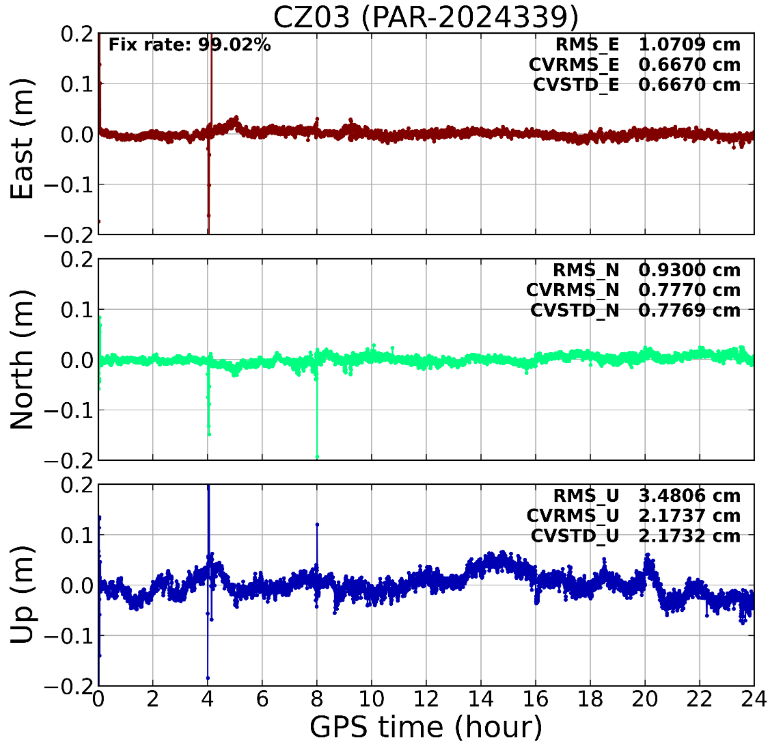
ZIM2, receiver types: TRIMBLE NETR9/ LEICA GR50(after DOY 324, 2024).

CCL-STEC contains more discrete points.CCL shows larger dispersion with an evident normal bias.PPPAR-STEC has clear advantages.

5. Future Work In Ionosphere Modeling

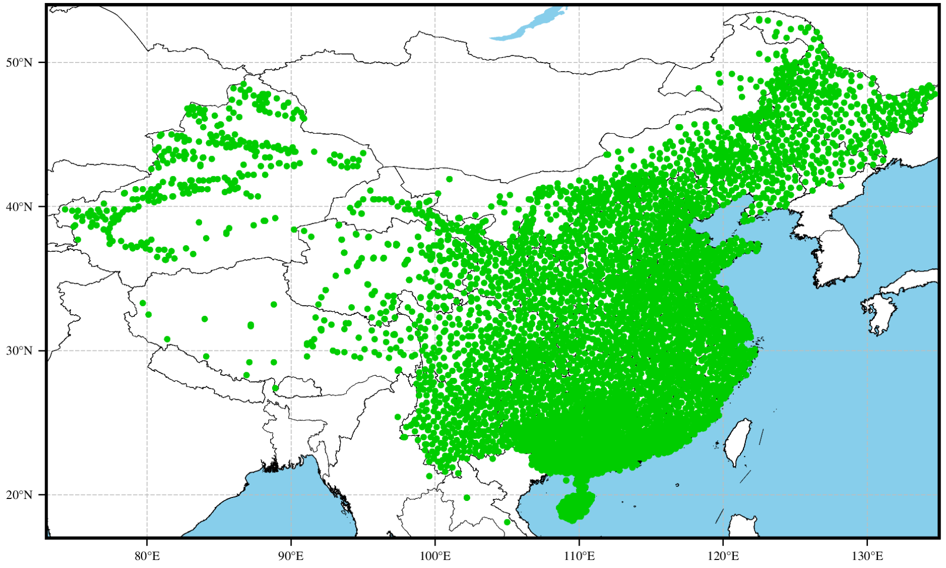
➢ **PPP-RTK with Real-Time Regional Ionospheric Augmentation**

Systems: GPS, BDS, GLONASS, GALILEO
Frequencies: Triple-frequency



Positioning Error Series of Monitoring Stations

Restart and reconverge every 4 hours



Spatial Distribution of Stations for Atmospheric Augmentation Services

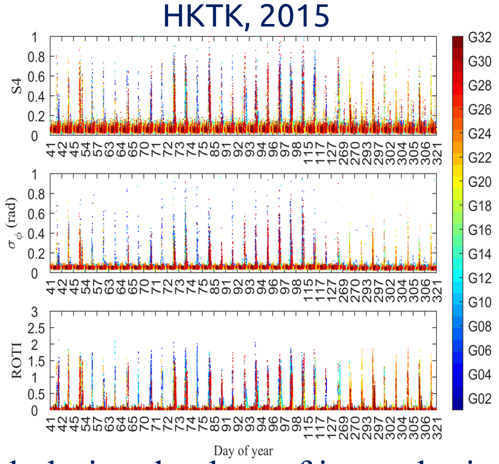
Horizontal RMSE: 0.9cm
Vertical RMSE: 2.5cm
Convergence Time Statistics (Unit: minutes)

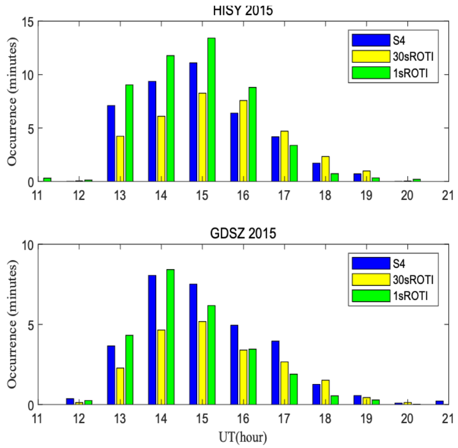
	Horizontal	**Vertical**
PPPRTK	**1.1**	**1.8**

6. Ionosphere Anomalous Monitoring

➢Performance of Scintillation Monitoring with Geo0detic Receivers

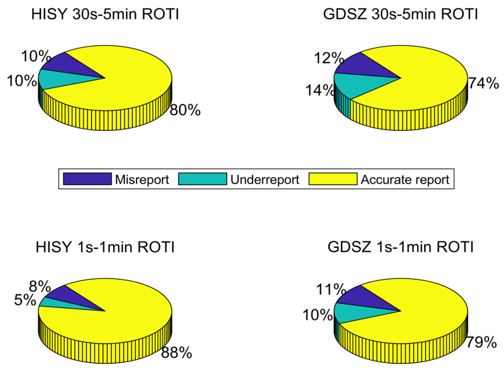
- Scintillation indices, ROTI at co-located stations

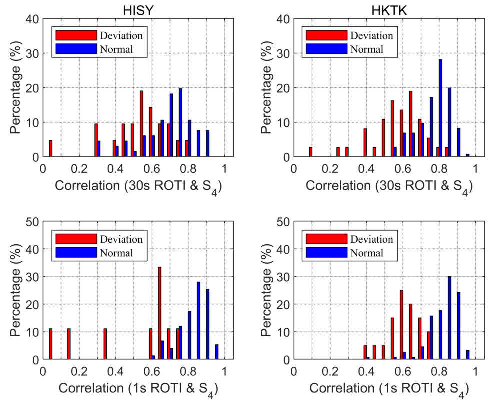




✓ In general, during the days of ionospheric scintillation, ROTI has a certain degree of response

✓ There is deviation between the duration of scintillation monitored by ROTI and ***S4*** index

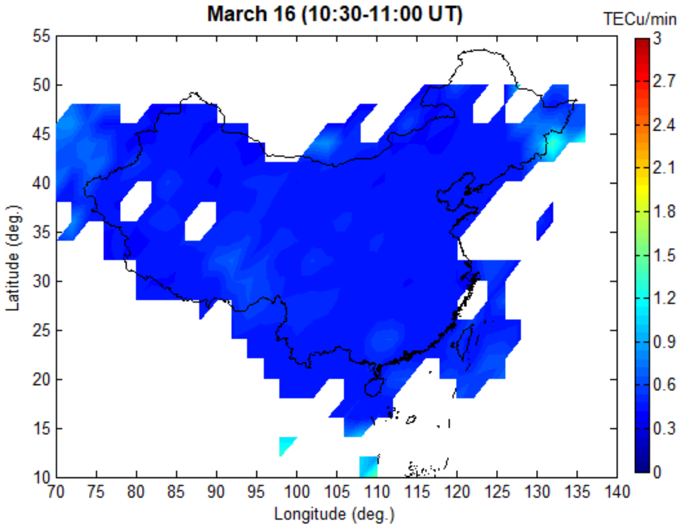


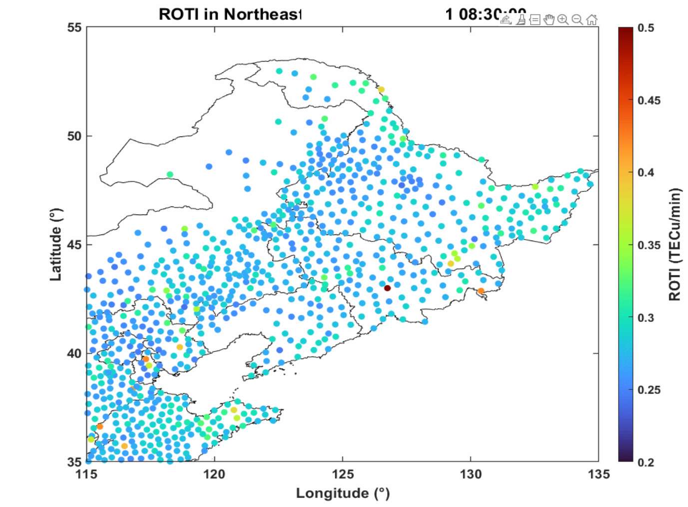


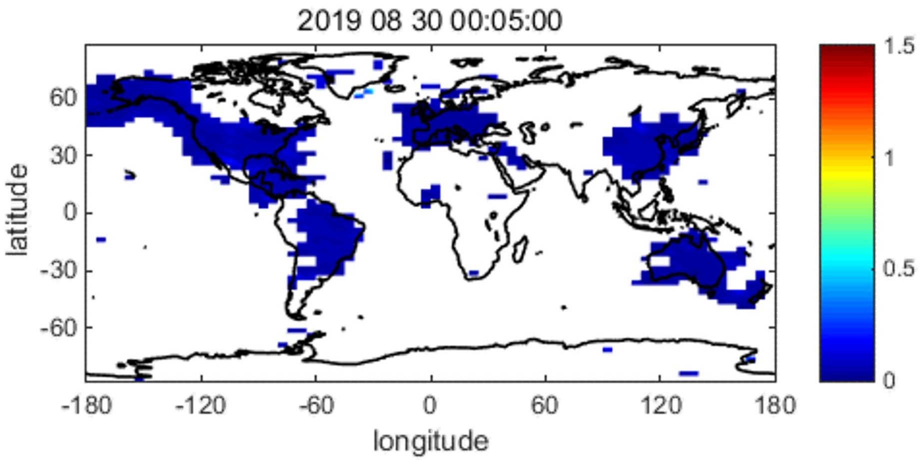
Study of the Performance of Scintillation Monitoring with Geodetic Receivers responding to ionospheric scintillation show that 30s-ROTI and 1s-ROTI in responding to ionospheric scintillation could reach 80% and 88%.

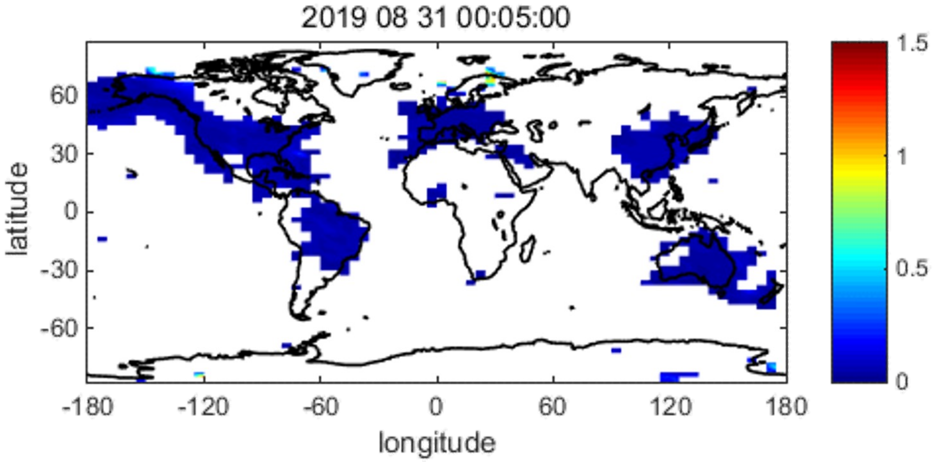
6. Ionosphere Anomalous Monitoring

- **ROTI MAP with global/region stations are under developed in SHAO**





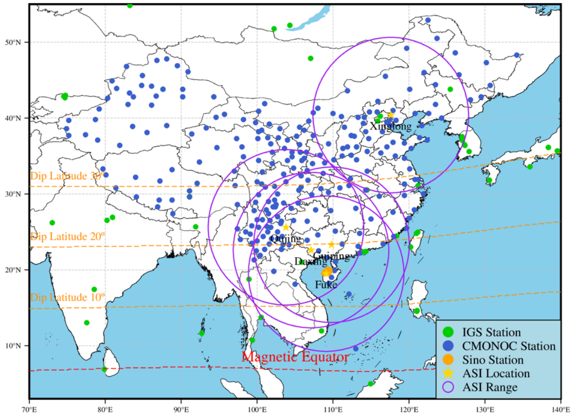


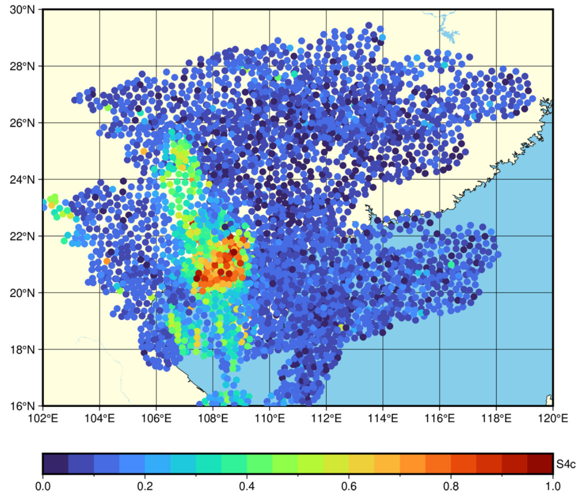


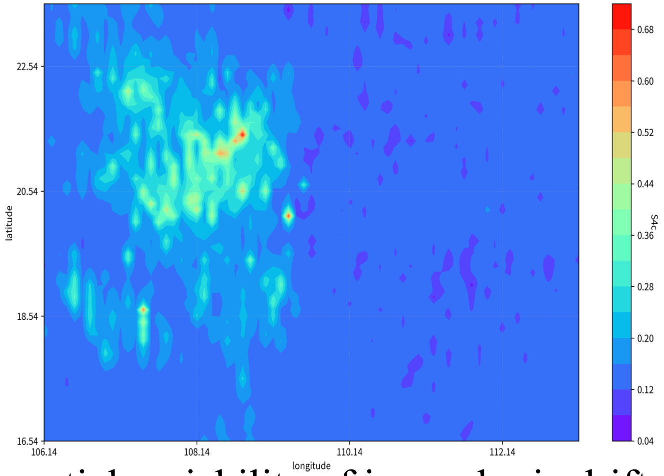
Ionospheric scintillation index: ROTI,S4c open for users(gnss.shao.ac.cn)

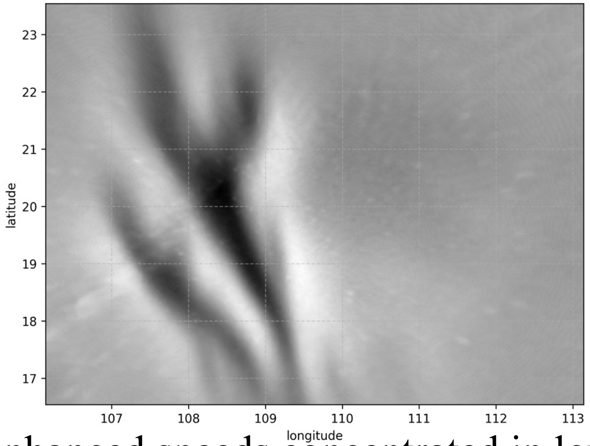
6. Ionosphere Anomalous Monitoring

Multi-sensor Integration: Combines large-scale GNSS networks and high-resolution all-sky imager optical observations.









- Reveals spatial variability of ionospheric drift velocity, with enhanced speeds concentrated in low-latitude anomaly zones.
- Validates the correlation between plasma drift and ionospheric irregularities via joint GNSS-optical analysis.

7. Summary and Outlook

- Additional virtual observatories are helpful in the wide-area gaps of ground-based GNSS stations for ionosphere TEC modeling.
- Attached piece-wise bias parameters are practicable for fusion of multi-source data to realize ionosphere modeling automatically.
- Hourly Ultra-Rapid and nowcasting of the global ionospheric TEC based on near-real-time data files(hourly,15min) and real-time stream multi-GNSS observations is a good choice for some real-time application and for providing background for real-time modeling.
- An operational platform for Final, Rapid, Hourly, Nowcasting, and Daily-casting GIM have been running for about five years(gnss.shao.ac.cn). Higher spatial-temporal resolutions of TEC model with Carrier observations,and really real-time modeling are under development.
- More accurate TEC retrieval from GNSS data is expectable for ionosphere modeling and anomalous monitoring.
- Hourly modeling is a good basis for stable real real-time ionosphere modeling.

SHAO is willing to contribute its products and expertise to IGS ionospheric research activities.

Thanks for your Attention!

slsong@shao.ac.cn

yzyang@shao.ac.cn

gnss.shao.ac.cn