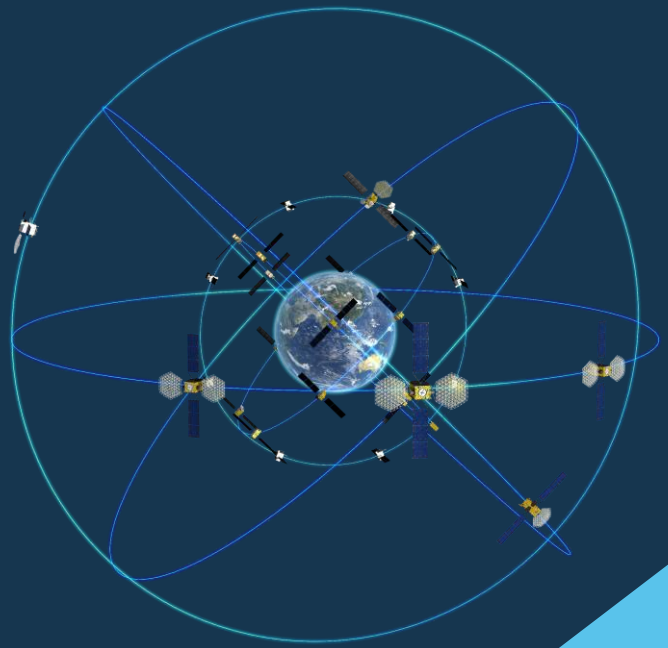
The cooperative monitoring and warning of ionospheric impacts on GNSS during the 25th high solar activity period

Zishen Li[1], Qi Liu[2,3], Xiaodong Ren[4], Ang Liu[1], Yueling Cao[5]

1. Aerospace Information Research institute, Chinese Academy of Sciences, China
2. The college of geography and environmental science, Henan University, China
3. Henan Industrial Technology Academy of Spatio-Temporal Big Data, Henan University, China
4. School of Geodesy and Geomatics, Wuhan University, China
5. Shanghai Astronomical Observatory, Chinese Academy of Sciences, China

Madrid, Oct. 2023

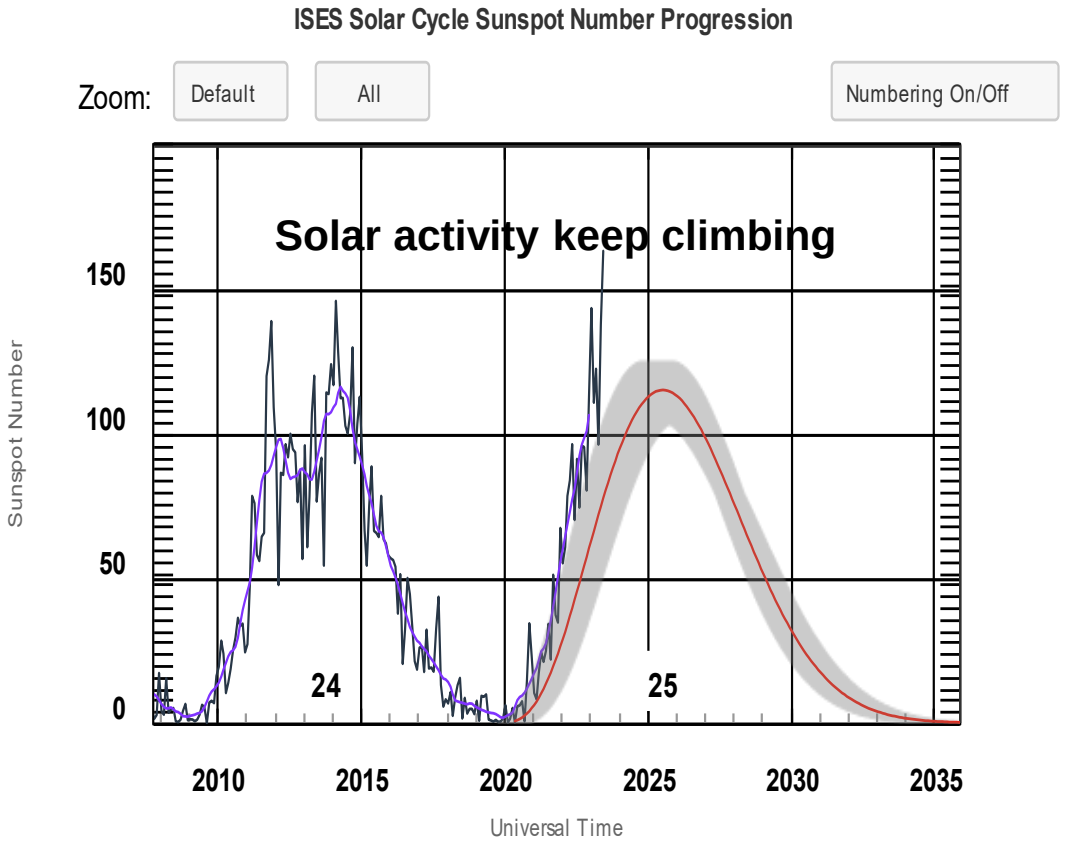
CONTENTS



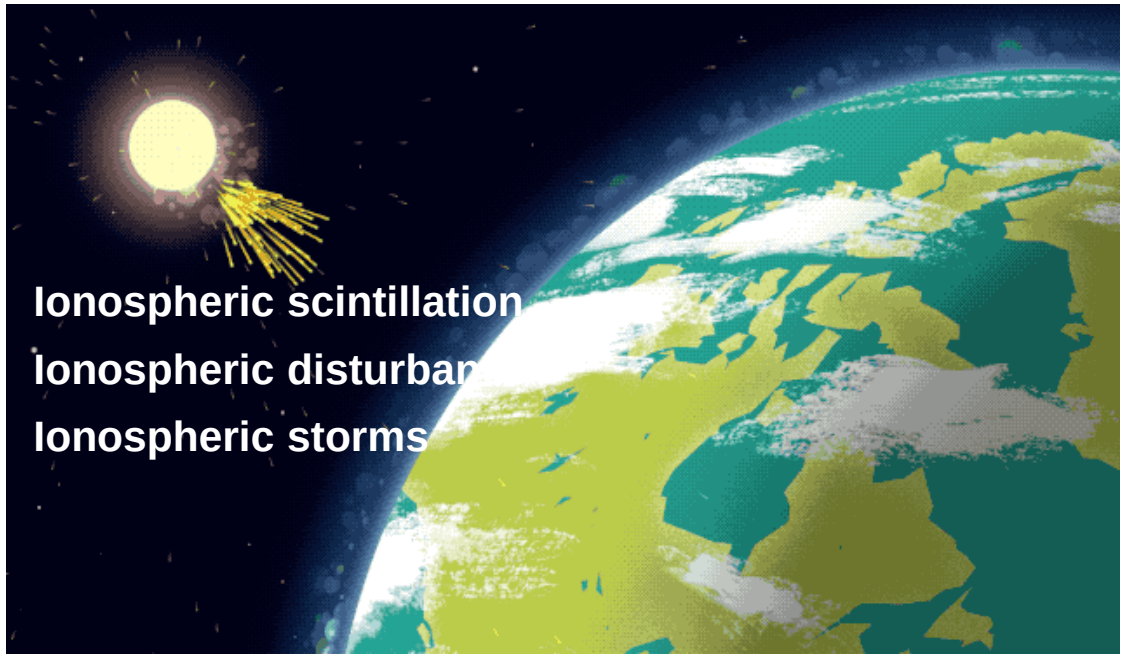
The variation of ionosphere during 25th solar cycle

01

- The 25th solar cycle is approaching its peak year, which is expected to be 2025-2028.
- The frequency and amplitude of ionospheric anomalies will be significantly increased.

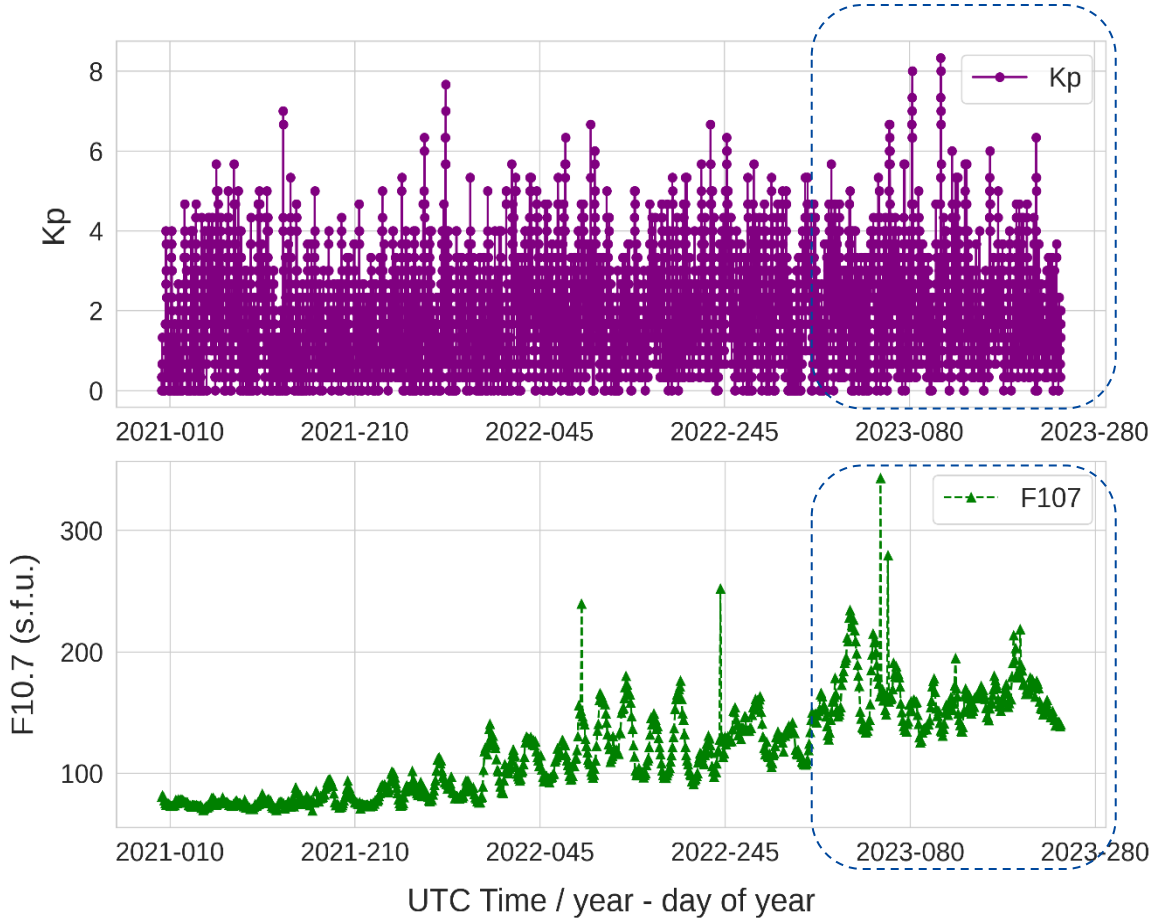


The time series of Sunspot number
（*from NOAA*）

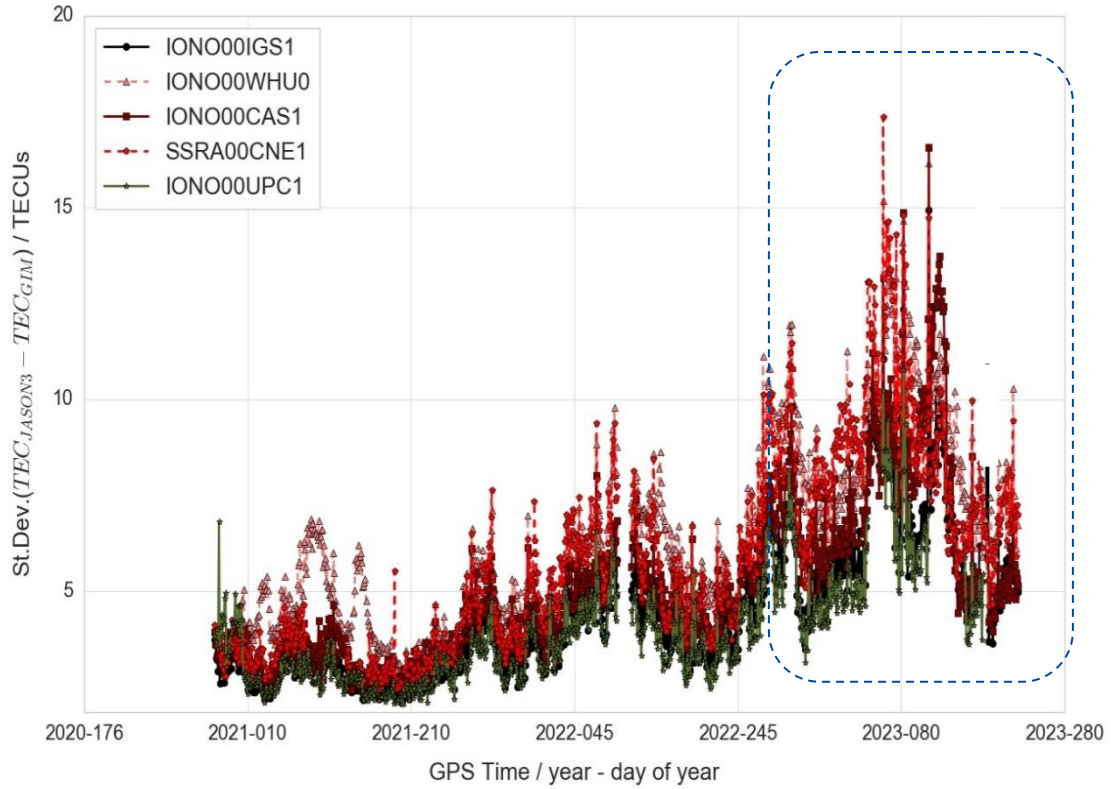


Solar activities is the main driver of ionospheric variations

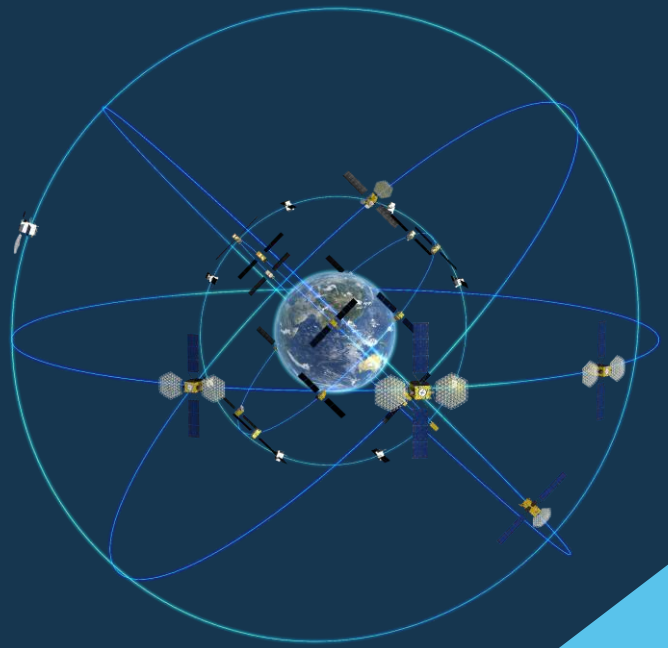
■ The accuracy of the global real-time TEC map (GIM) decreased significantly



Geomagnetic and solar activity levels



The accuracy of real-time GIM



The ionospheric impacts on GNSS

02

■ Experiments of ionospheric impacts on GNSS during 25th solar cycle

Different Types of GNSS-based positioning

1) GNSS standard positioning: different broadcast ionospheric models (BDGIM， NeQuickG, Klobuchar)

2) SBAS-aided positioning: Ionospheric GIVD and GIVE

3) PPP-B2b of BDS-3: BDS GEO service area

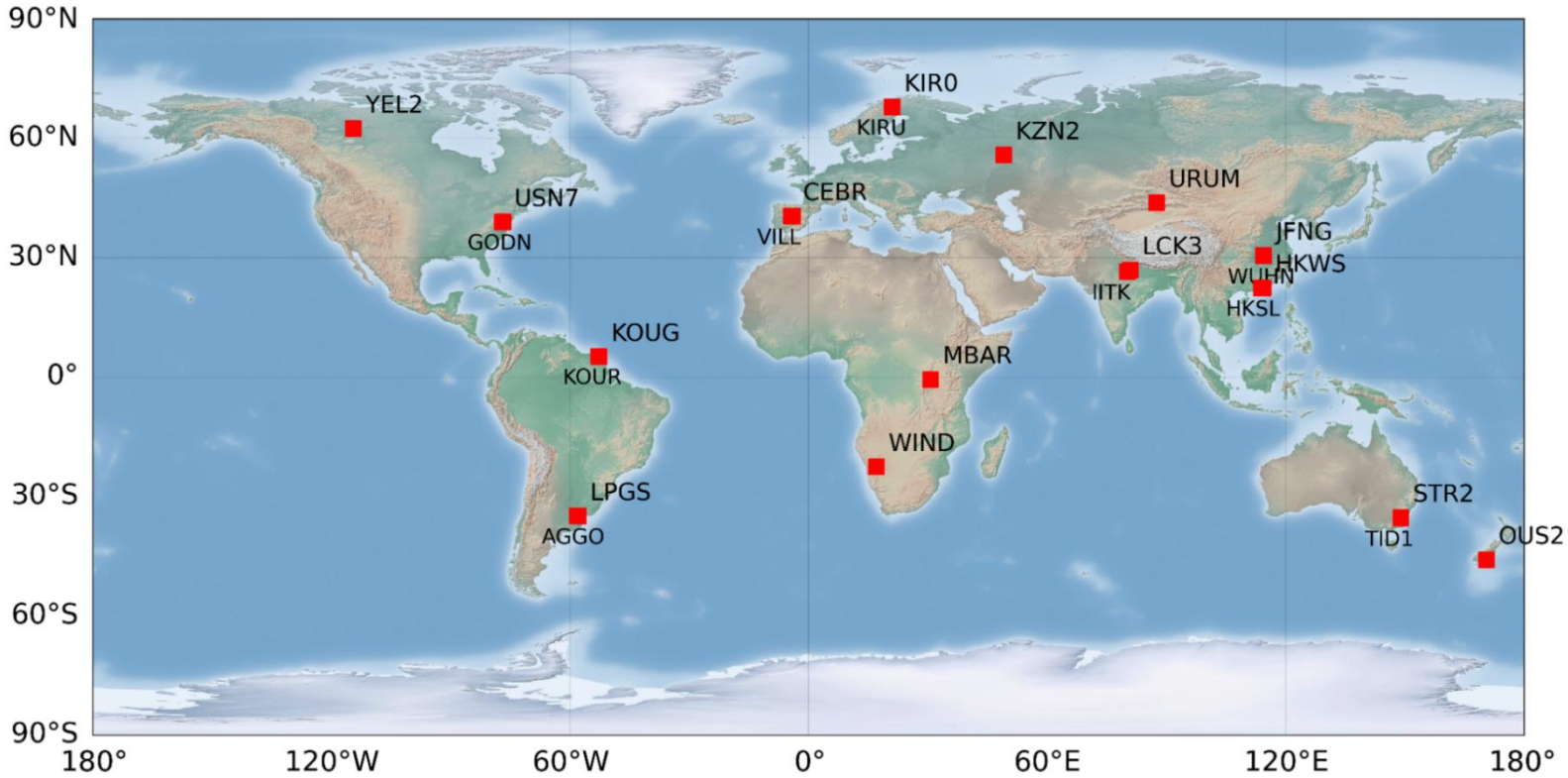
4) PPP : Uncombined PPP in different regions of the world (SSR from IGS)

5) RTK positioning: Short baseline RTK positioning in different regions of the world

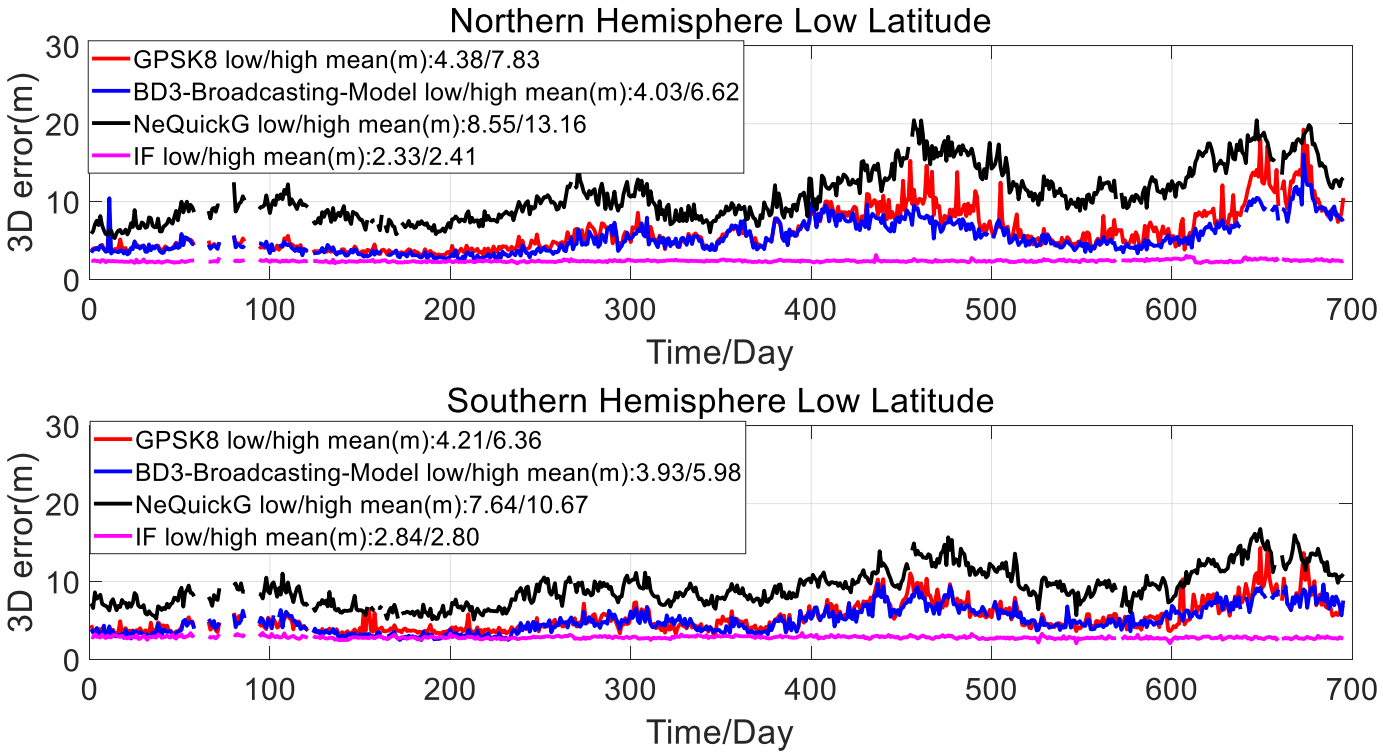
✓ **Ionospheric impacts on GNSS will be analyzed**

✓ **Potential solutions to mitigate the ionospheric impacts will be proposed**

- **Selected stations:** 24 stations, covering different latitudes and tracking 4 GNSS constellations
- **Experimental period:** January 1, 2021 to August 27, 2023 (starting from solar cycle 25)



■ The ionospheric impacts on standard positioning



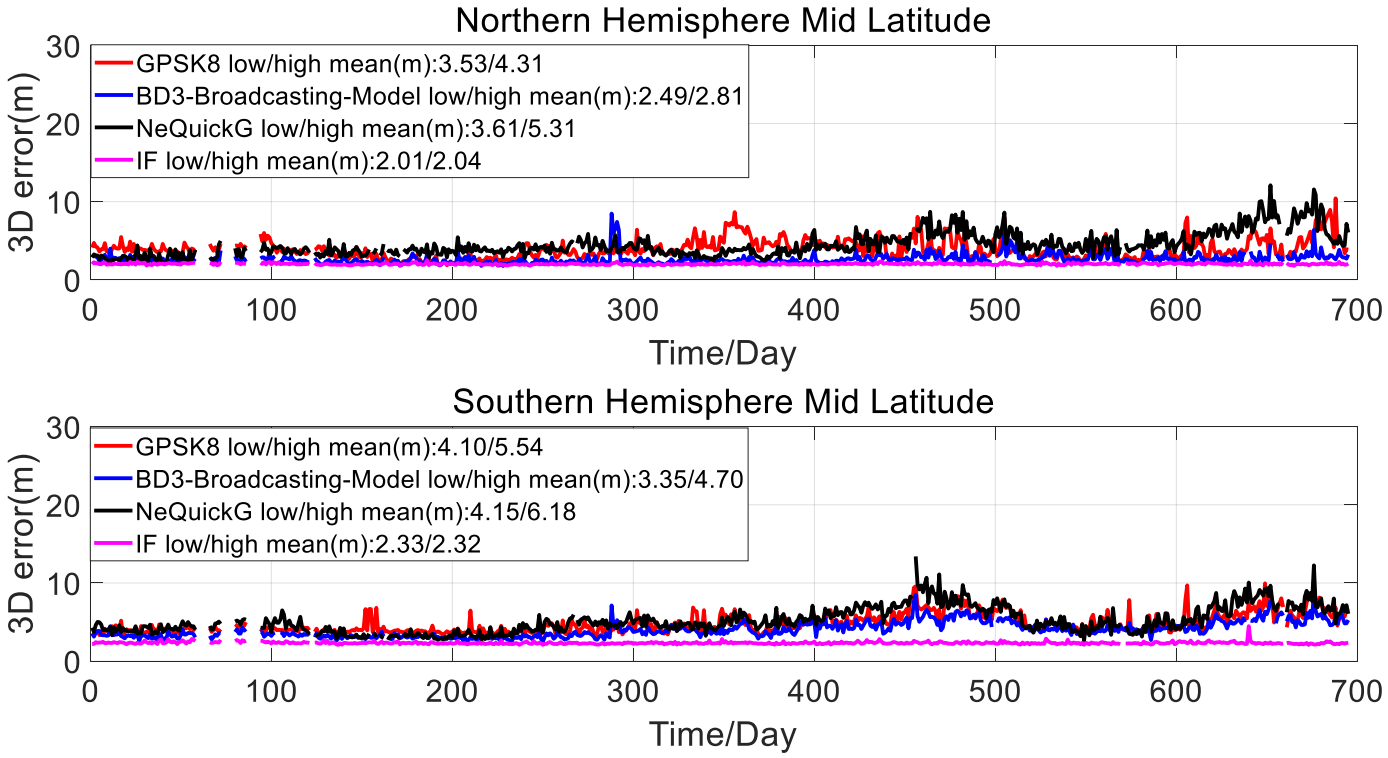
From 1 January 2021 to 26 November 2022

Low-latitude region

Broadcast model	3D error (m) in 2021	3D error (m) in 2022
GPS	4.3	7.3
BDS-3	3.9	6.3
GAL	8.0	12.4

- The positioning accuracy of broadcast ionospheric model is degraded seriously
- The positioning accuracy of ionosphere-free (IF) combination is basically stable

The ionospheric impacts on standard positioning



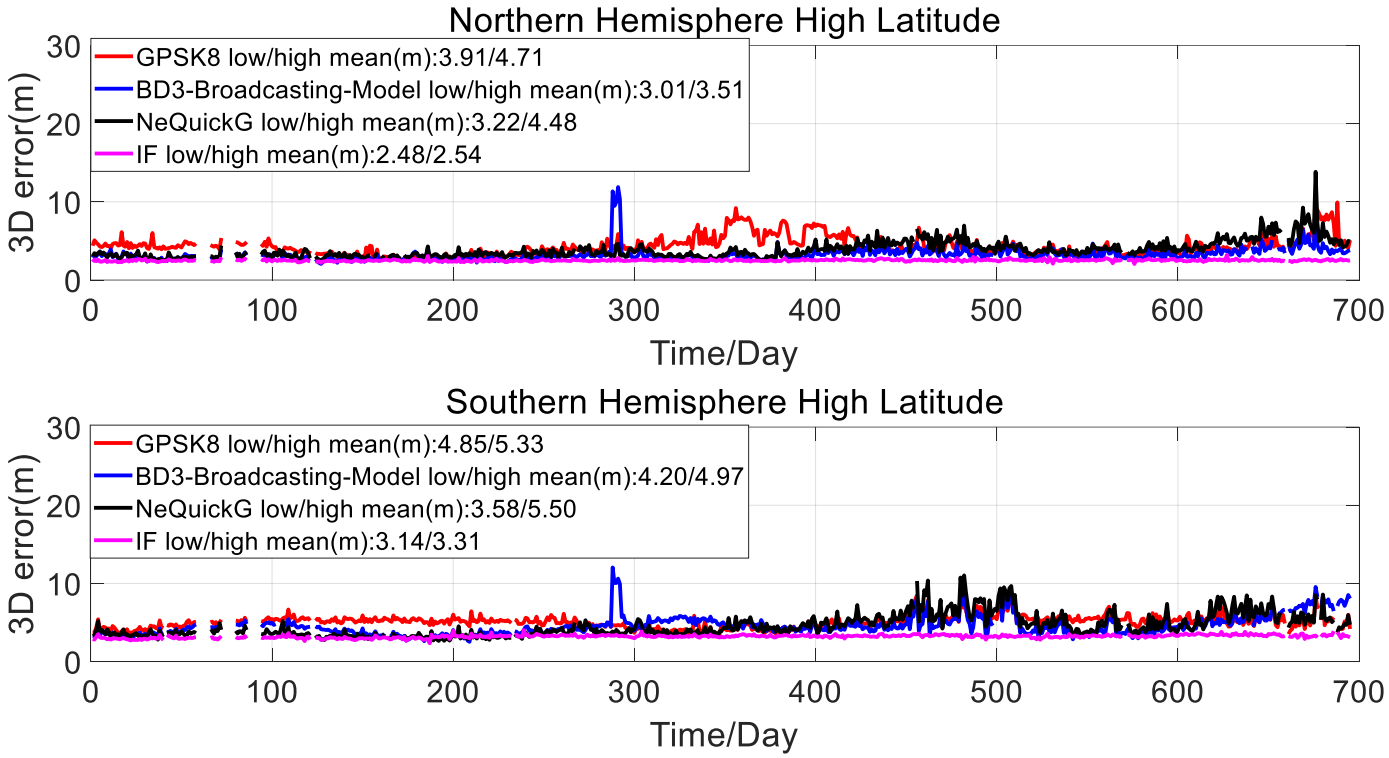
From 1 January 2021 to 26 November 2022

Mid-latitude region

Broadcast model	3D error (m) in 2021	3D error (m) in 2022
GPS	3.8	4.9
BDS-3	2.9	3.8
GAL	**3.8**	**5.7**

- The positioning accuracy of broadcast ionospheric model is degraded
- The positioning accuracy of ionosphere-free (IF) combination is basically stable

The ionospheric impacts on standard positioning



From 1 January 2021 to 26 November 2022

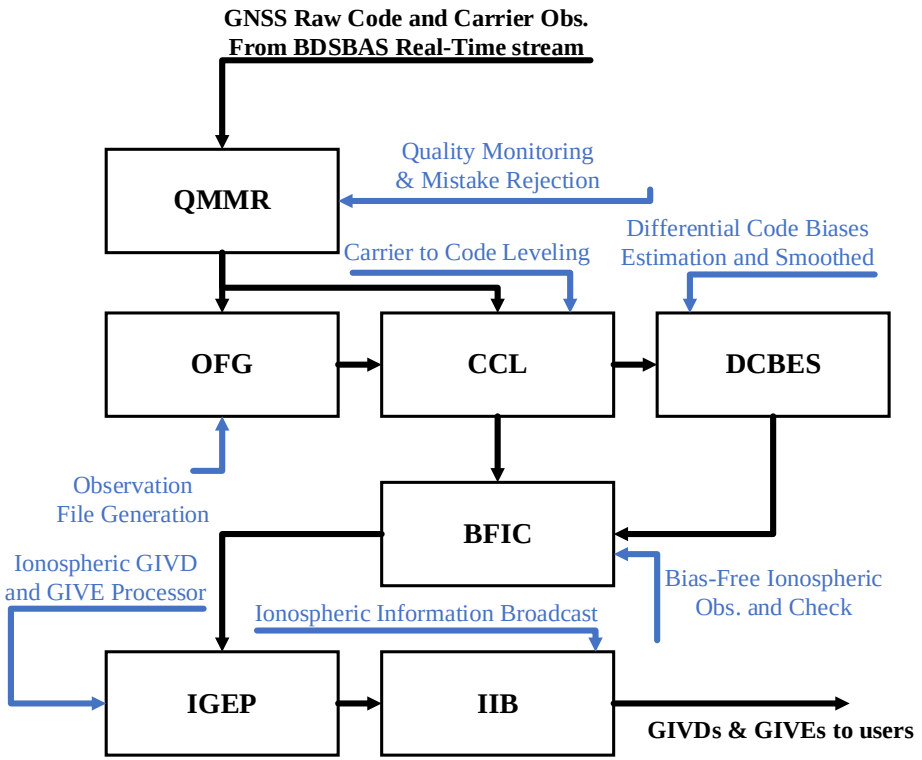
High-latitude region

Broadcast model	3D error (m) in 2021	3D error (m) in 2022
GPS	**4.4**	**5.0**
BDS-3	3.6	4.2
GAL	3.4	5.0

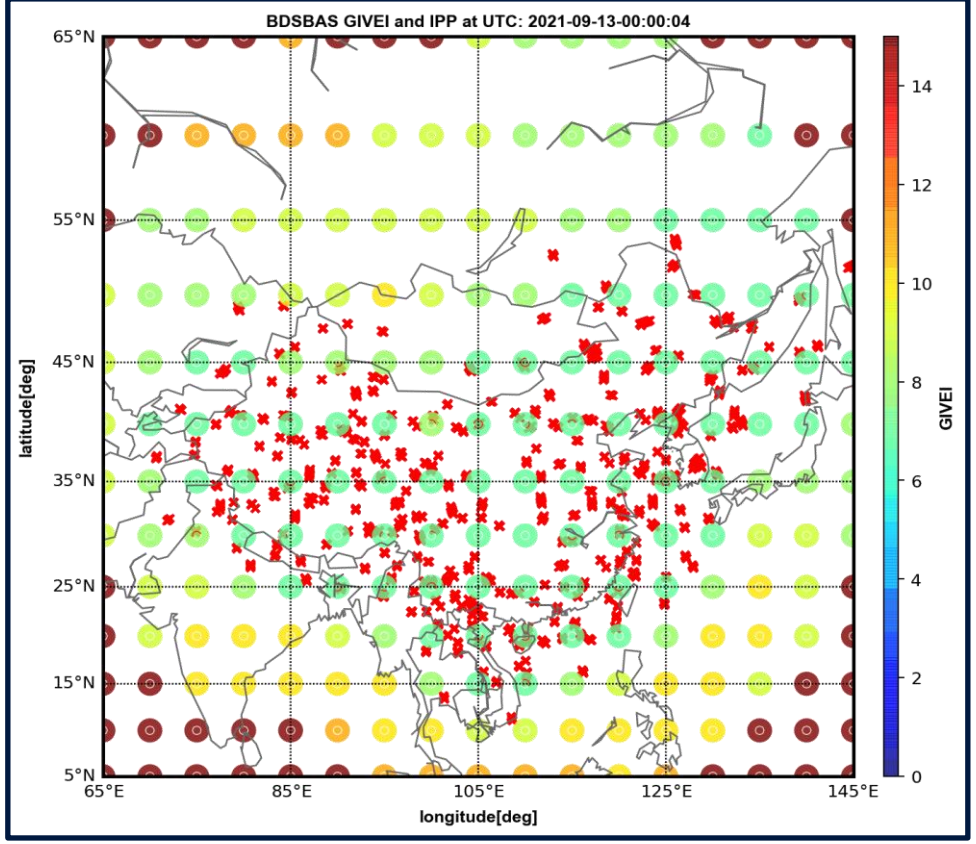
- The positioning accuracy of the broadcast ionospheric model deteriorates seriously only on some dates
- The positioning accuracy of ionosphere-free (IF) combination is basically stable

The ionospheric impacts on SBAS-aided positioning (13 September 2021)

BDSBAS ionospheric monitoring method



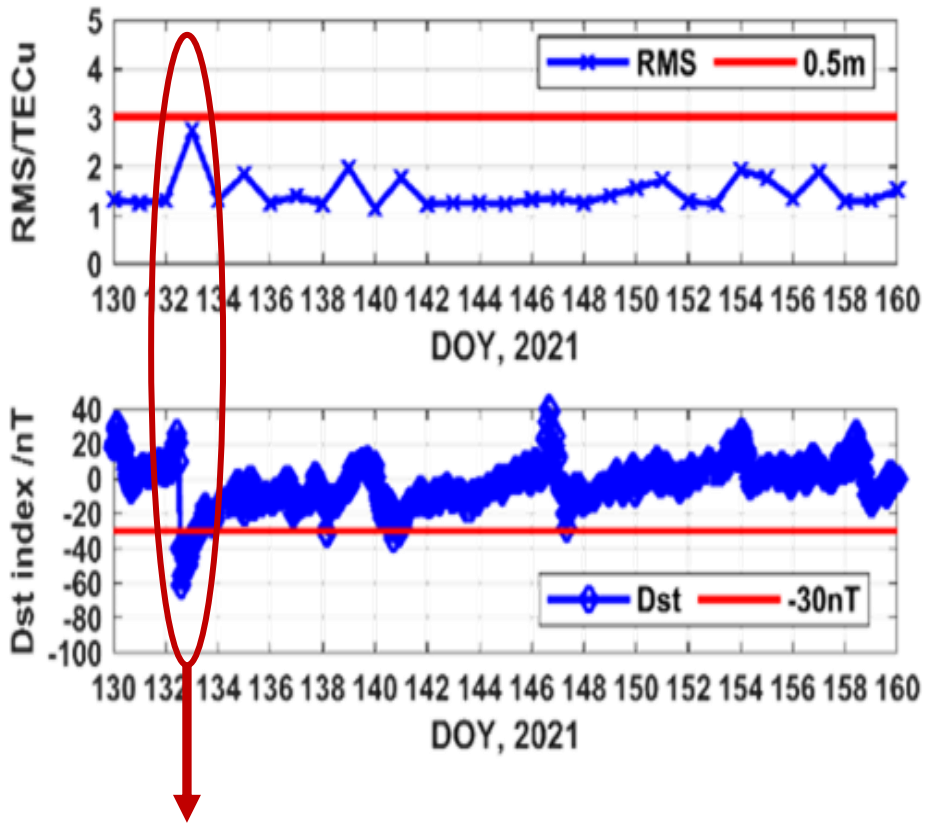
BDSBAS GIVE Indicators



BDSBAS is severely affected by ionosphere at low-latitude

■ The ionospheric impacts on SBAS-aided positioning (13 September 2021)

BDSBAS GIVD accuracy

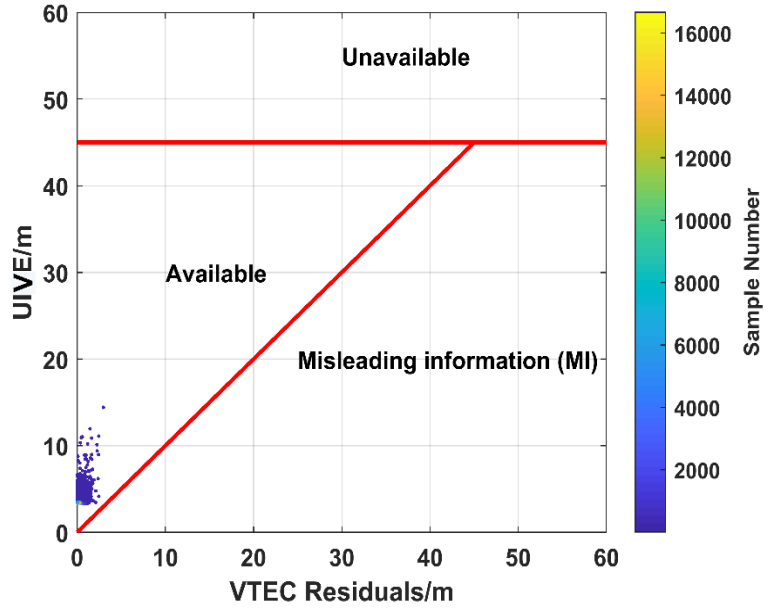


The accuracy of GIVD decreased to 3-4 TECU

BDSBAS GIVE Stanford Diagram

GIVE Indicators (**GIVEI**)

User Ionospheric Vertical Error(**UIVE**)

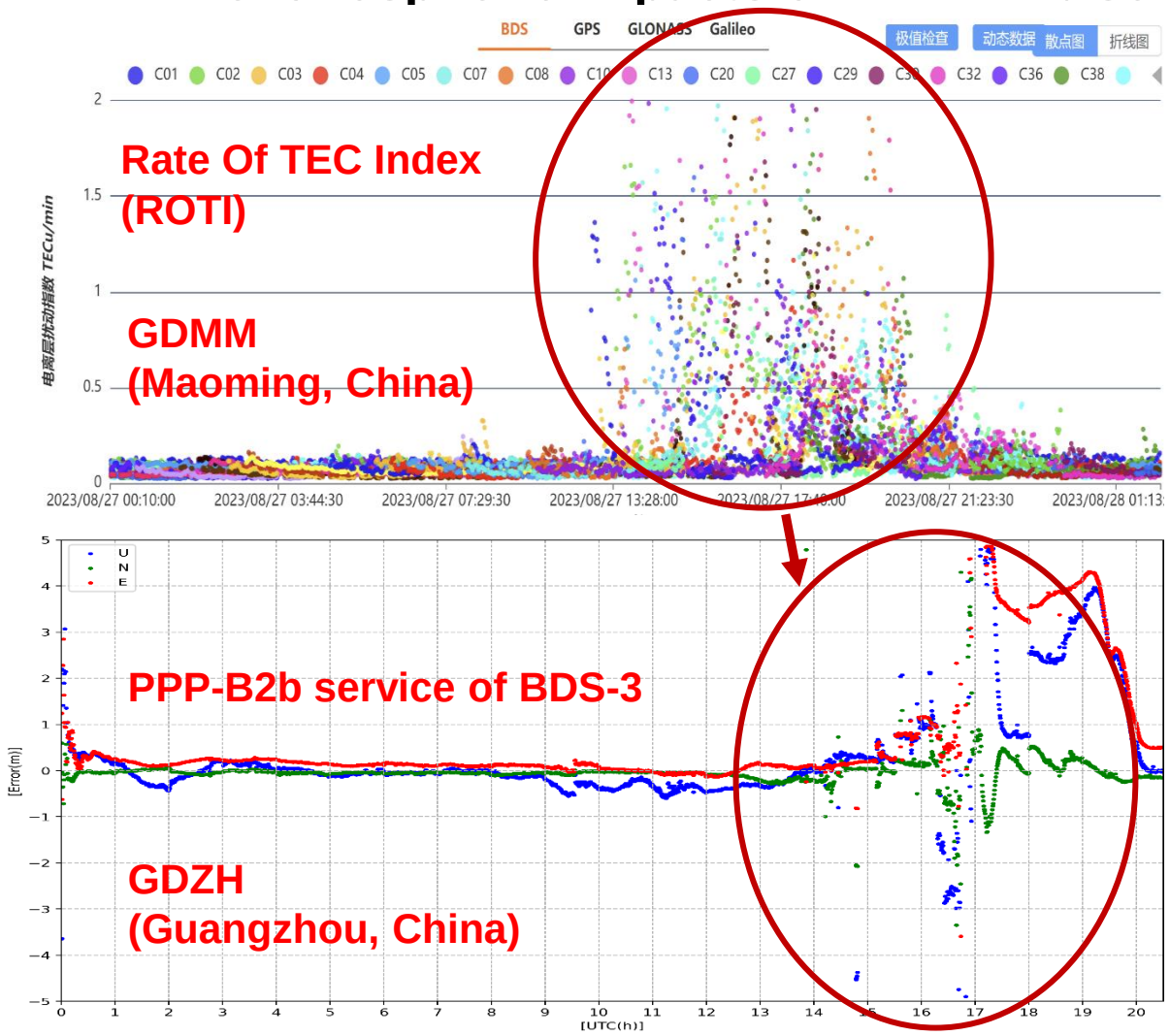


Not available — GIVEI = 15 (>45m)

Misleading information — UIVE < ionospheric residual

usable — UIVE > ionospheric residual

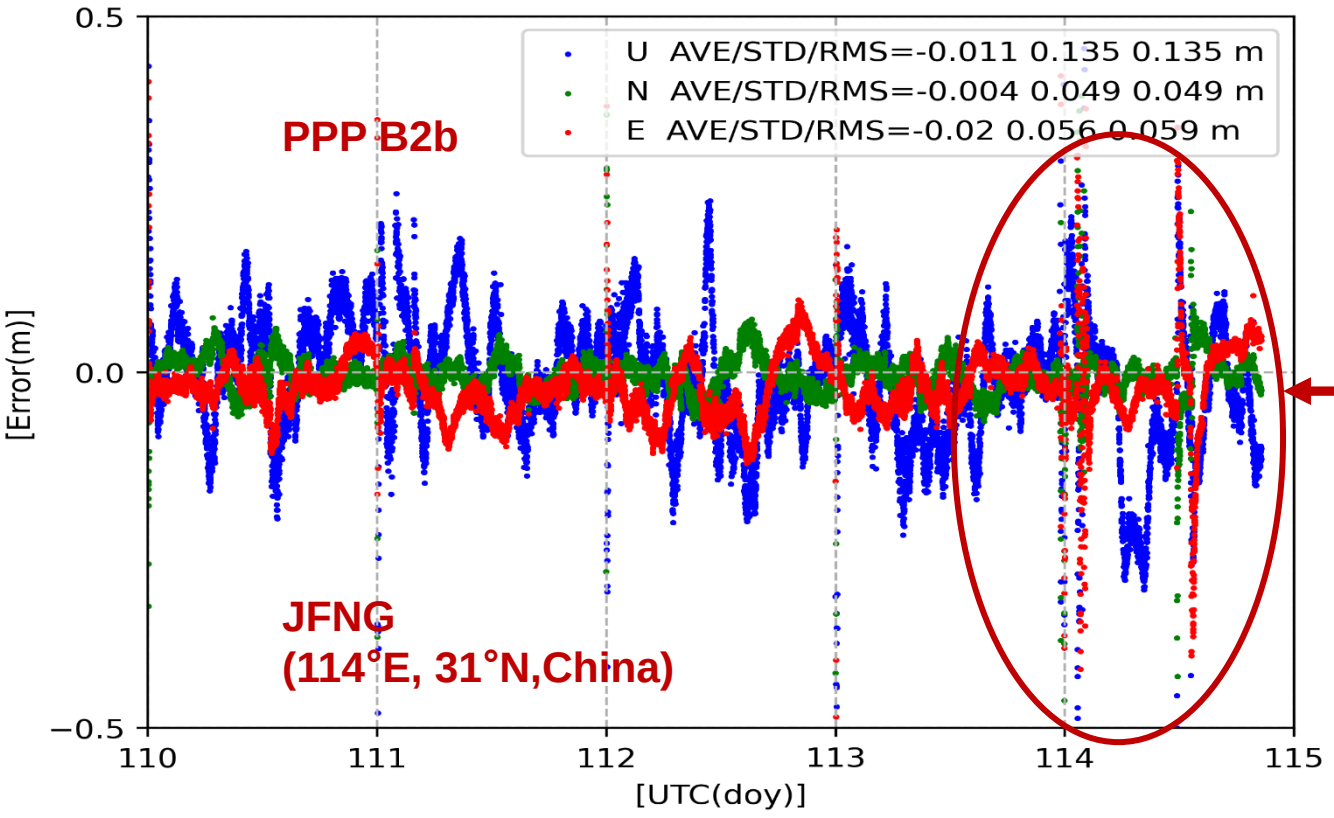
The ionospheric impacts on PPP-B2b service of BDS-3 (August 27, 2023)

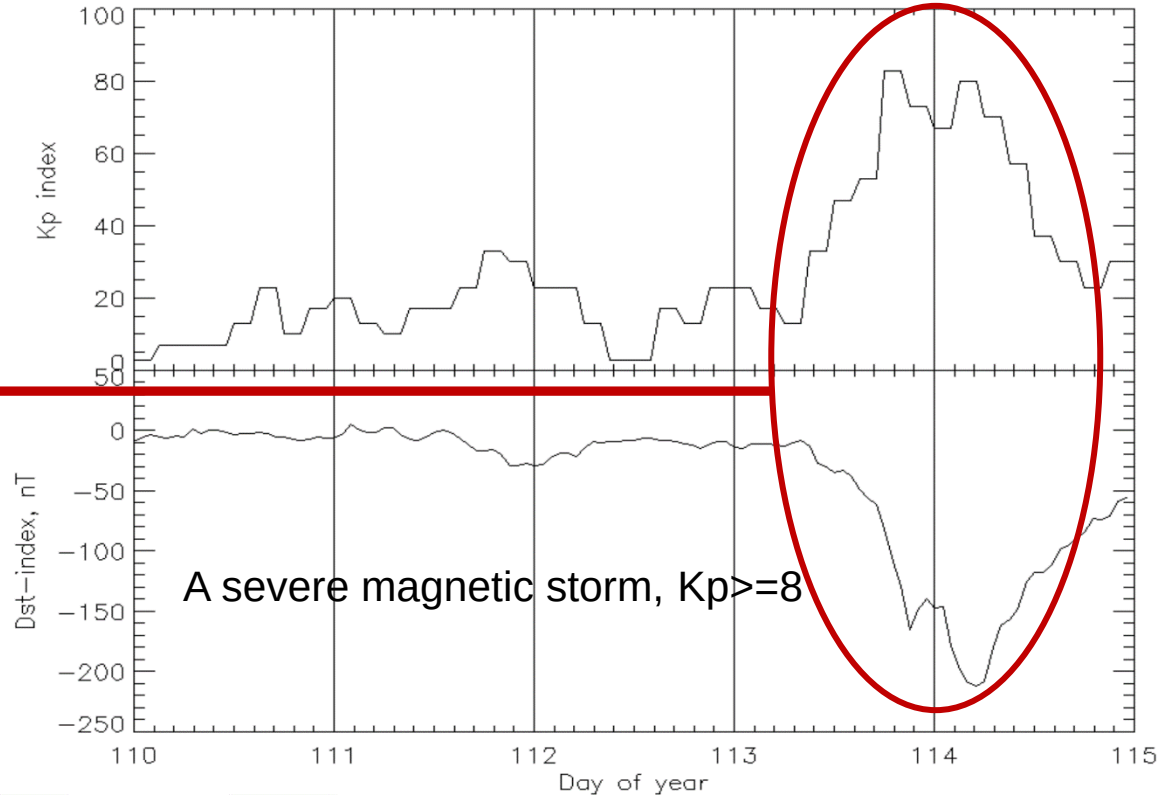


- ROTI station: GDMM (111°E, 22°N), China
- The real-time ROTI is based on 1Hz data
- B2b station: GDZH (113°E, 23°N), China

- ROTI increased to more than **2 TECU/min**
- BDS-3 B2b PPP accuracy dropped to **2-4 m**

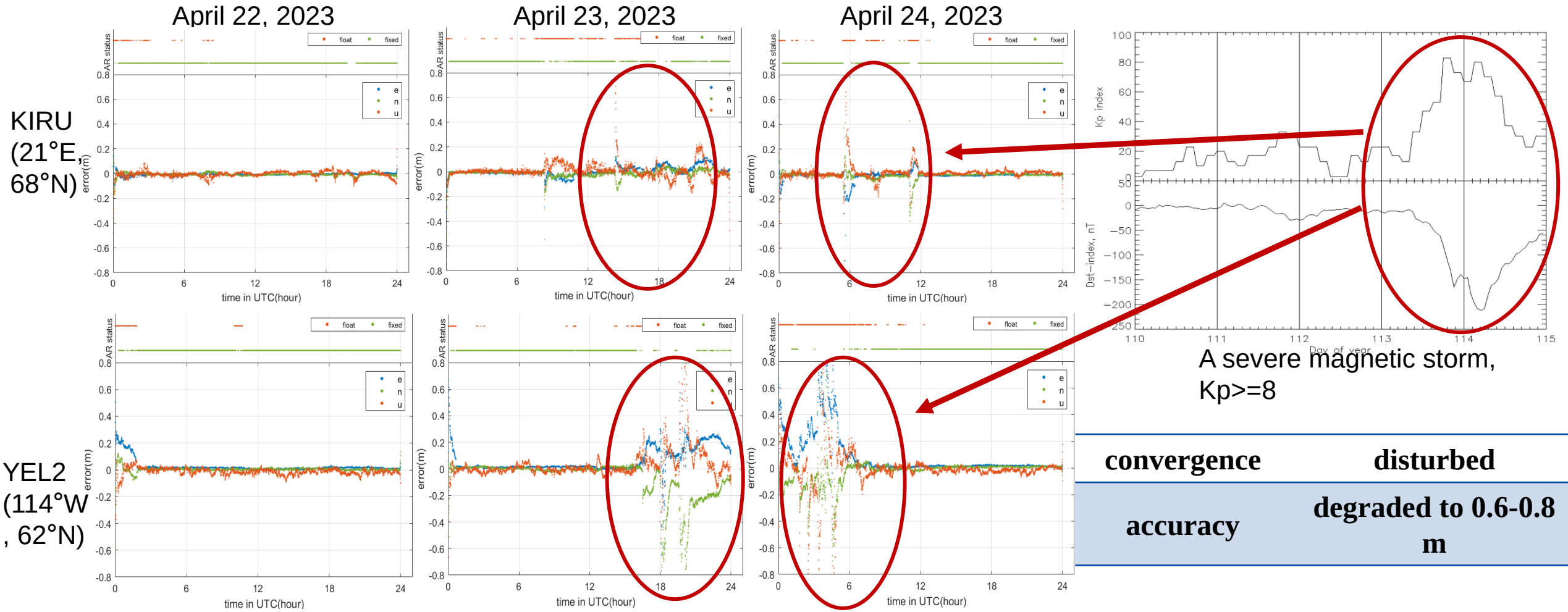
■ The ionospheric impacts on PPP-B2b service of BDS-3 during 20-24 April, 2023





The horizonal accuracy dropped from 4.20 m to 27.60 m, while the vertical accuracy decreased from 4.1cm to 12.6cm

The ionospheric impacts on global PPP using the SSR product from IGS

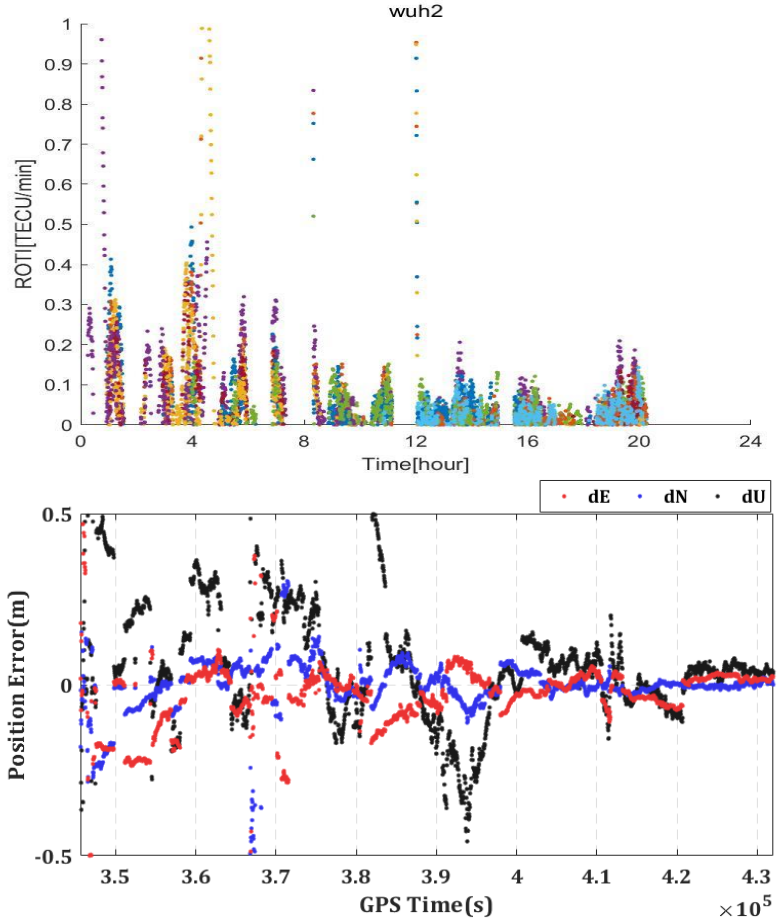


convergence	disturbed
accuracy	degraded to 0.6-0.8 m

PPP is degraded when the ionosphere is highly perturbed

■ The ionospheric impacts on short baseline RTK (WHU2-JFNG, 114.5°E, 30.5°N)

Major geomagnetic storm, Kp=8, on **April 24, 2023**



RTK data processing strategy

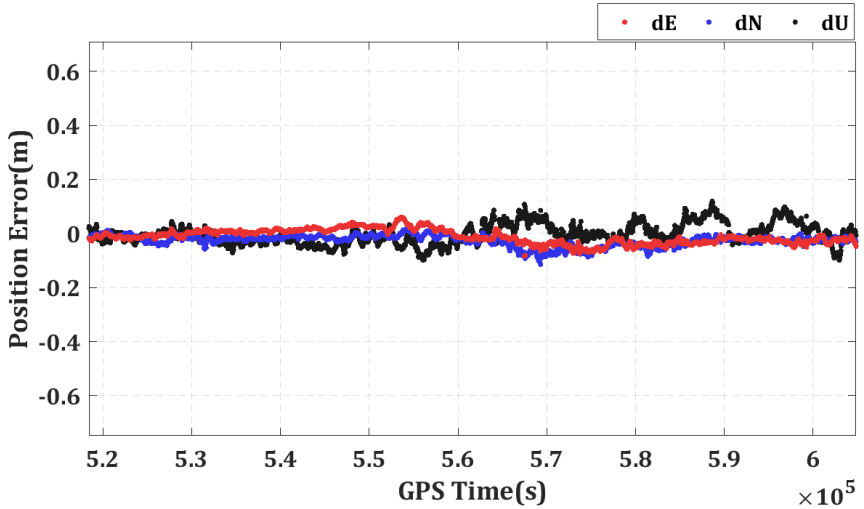
System	G, E, C
Observation	BDS:B1C, B2a GPS: L1, L2 GAL:E1, E5a
Base length	13 km
Ionosphere	uncombined

ROTI	Increased to around 1 TECU/min
RTK convergence	**Hardly converge**
RTK accuracy	**Degraded to 0.5 m**

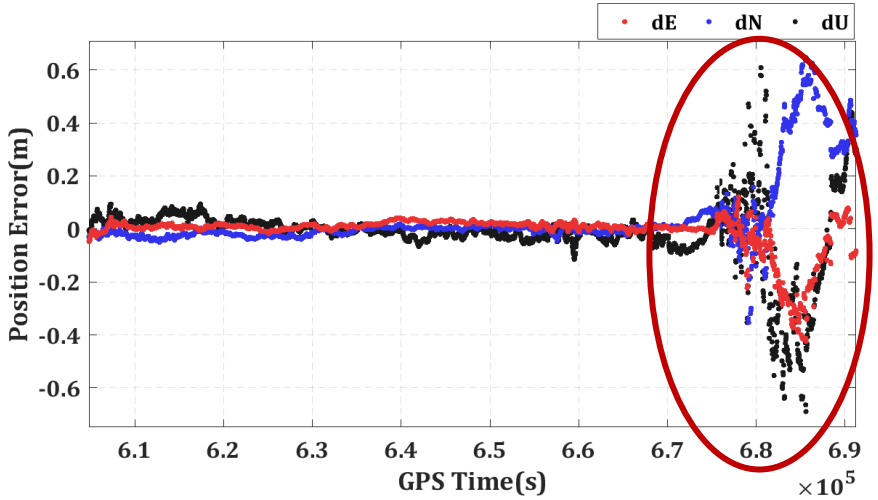
RTK is degraded when the ionosphere is highly perturbed

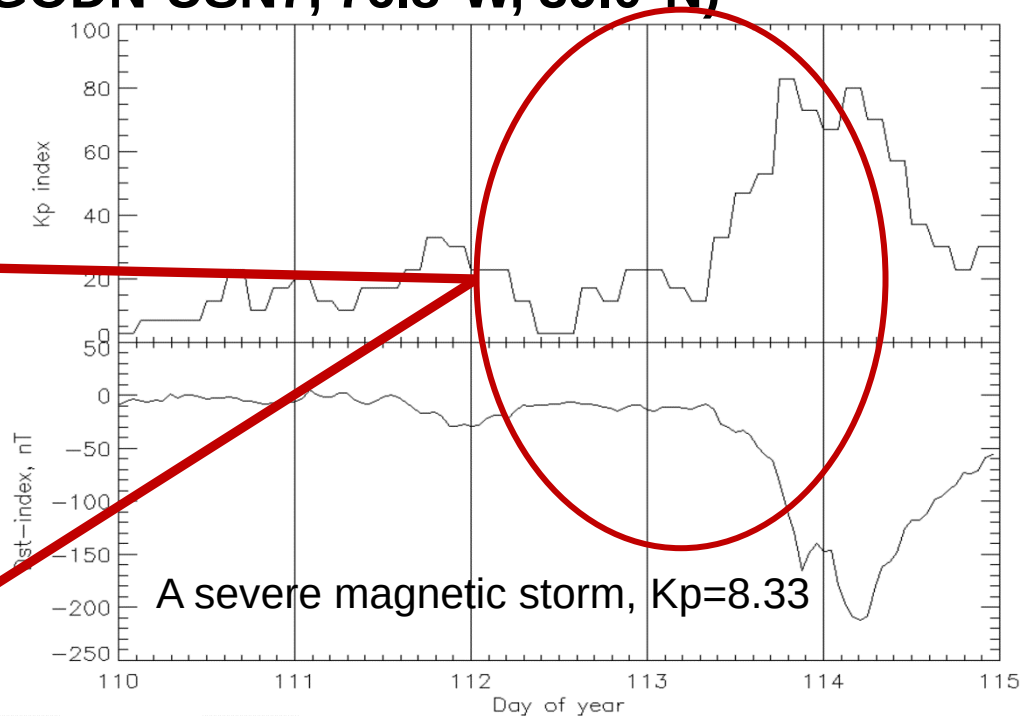
■ The ionospheric impacts on short baseline RTK (GODN-USN7, 76.8°W, 39.0°N)

April 22, 2023



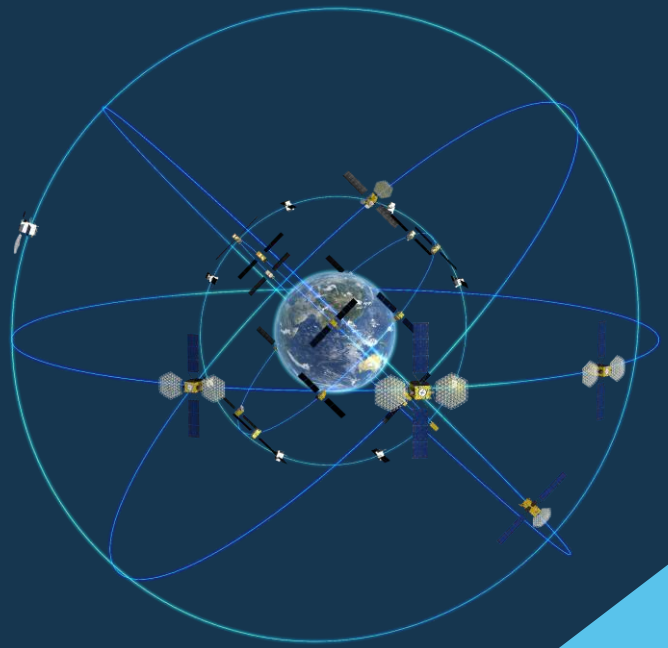
April 23, 2023





RTK convergence	disturbed
RTK accuracy	Degraded to 0.6 m

RTK is degraded when the ionosphere is highly perturbed



Recommendations for mitigating ionospheric impacts on GNSS

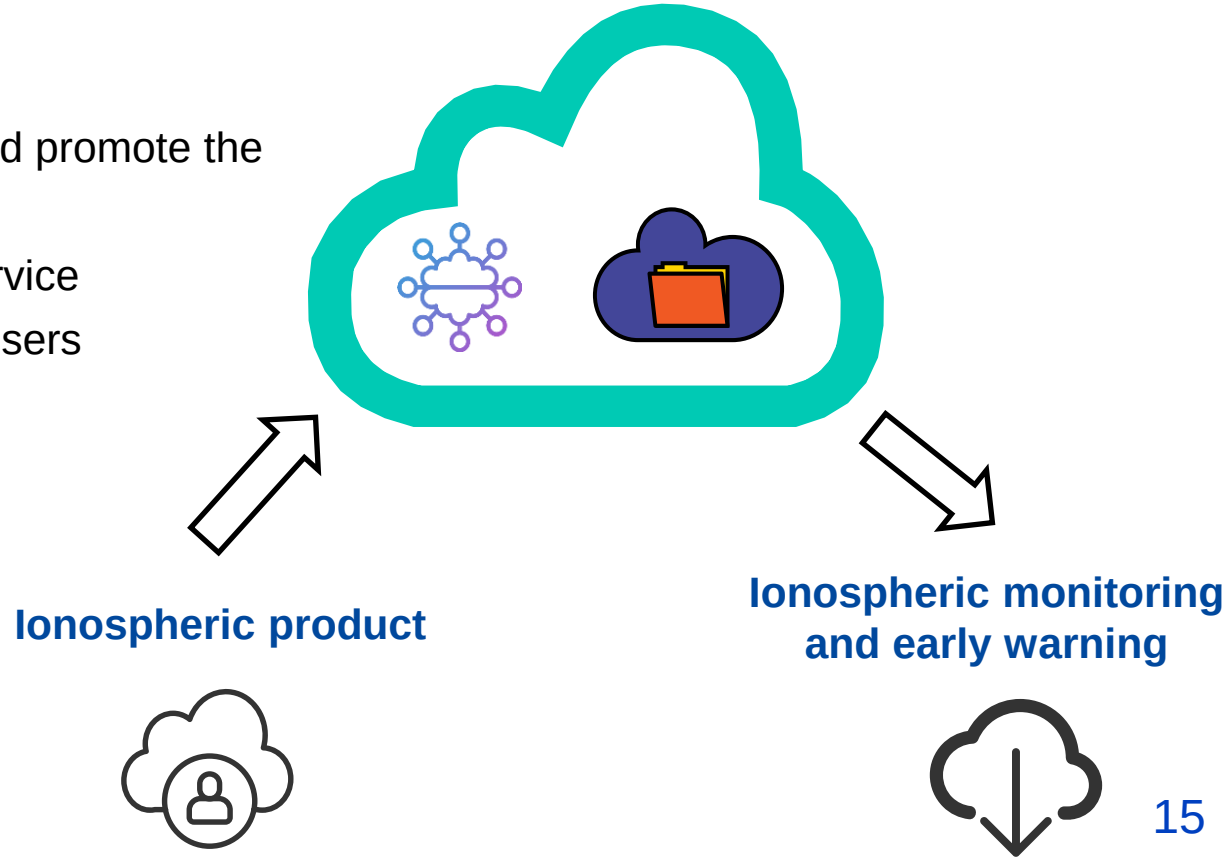
03

Recommendation:

Establish a monitoring and early warning platform based on the ICG multi-lateral arena for ionospheric impacts on GNSS during solar maximum (2024-2028) to mitigate the adverse effects on GNSS worldwide users

- ✓ Integrate ionospheric products from multiple sources and promote the sharing of ionospheric information products
- ✓ Provide monitoring of ionospheric impacts on GNSS service performance and timely issue early warnings to global users

- ☐ **Free & public**
- ☐ **User friendly**
- ☐ **Global access**



- The ionospheric impacts on GNSS services is consistent, and the ionospheric monitoring is global
- Joint monitoring and early warning of ionospheric impacts on GNSS would be of benefit to all satellite navigation systems

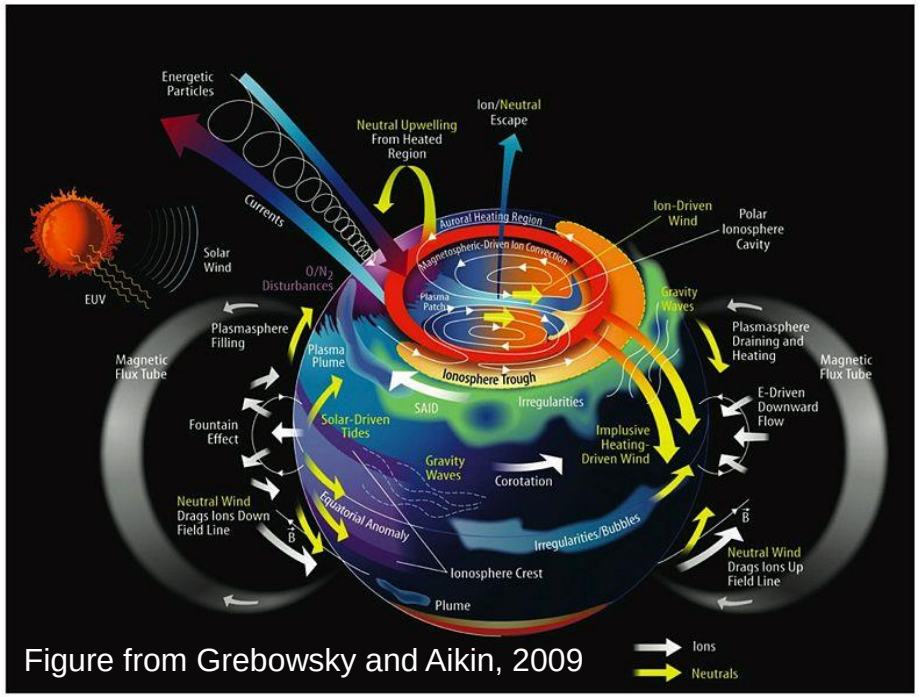
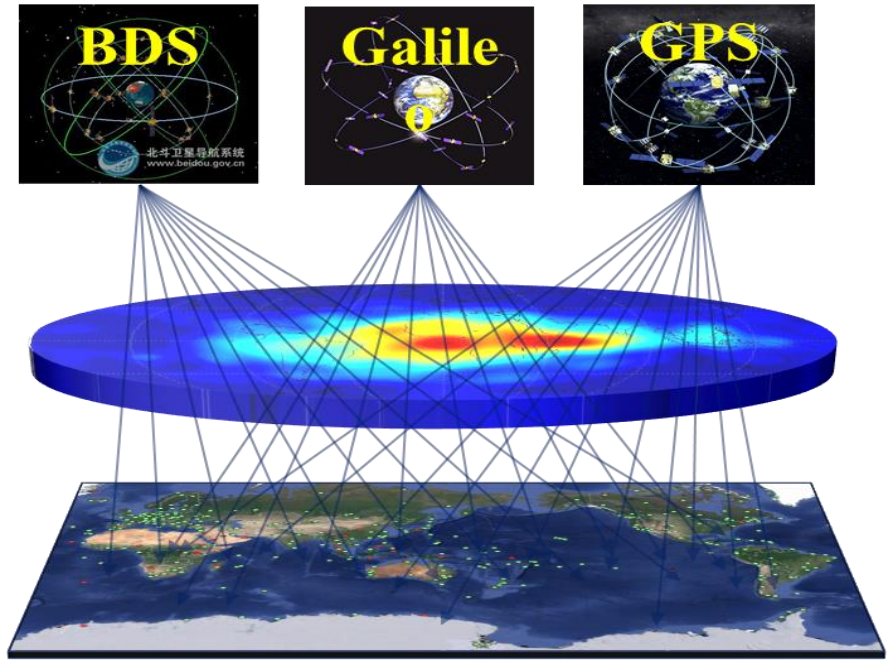


Figure from Grebowsky and Aikin, 2009

Complex ionospheric changes



Joint monitoring based on Multi-GNSS

Real-time Global Ionosphere Map (GIM)

Real-time GIM

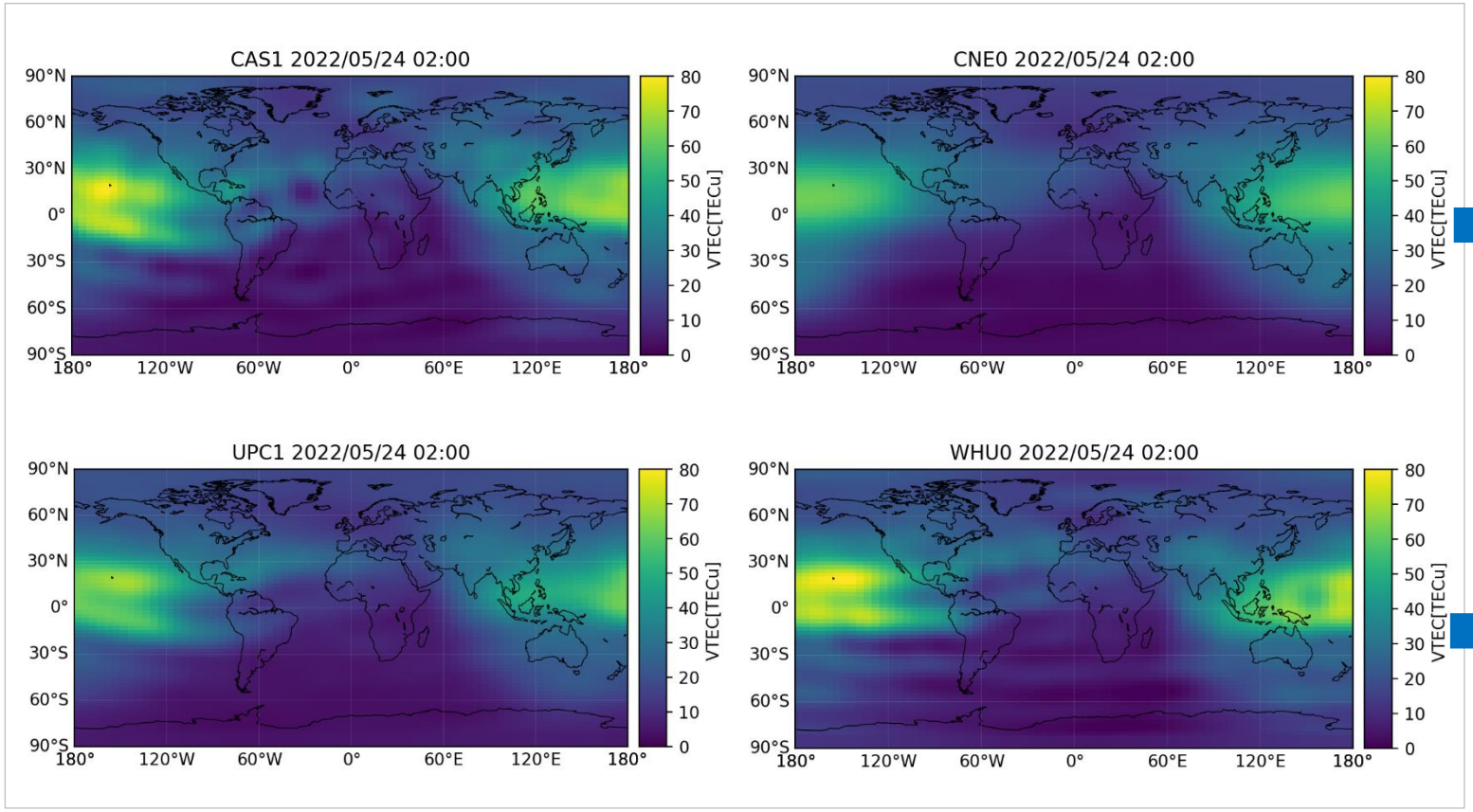
- **Spherical harmonic coefficient** Real-time global ionospheric information broadcasting based on RTCM-SSR and IGS-SSR protocols
- **IGS Real-Time Ionospheric Analysis Center:** Chinese Academy of Sciences (CAS), Polytechnic University of Catalonia (UPC), Centre National D'Etudes Spatiales (CNES) & Wuhan University (WHU)
- **Chinese Academy of Sciences:** Prediction + Modeling Approach (Li et al.,JoGE,2020), updated from 2021
- **Polytechnic University of Catalonia:** An ADGIM method based on compressed sensing (Yang et al.,JoGE,2021)
- **Center for CNES & Wuhan University**: Real-time global ionospheric inversion based on spherical harmonics

Real-time combined GIM

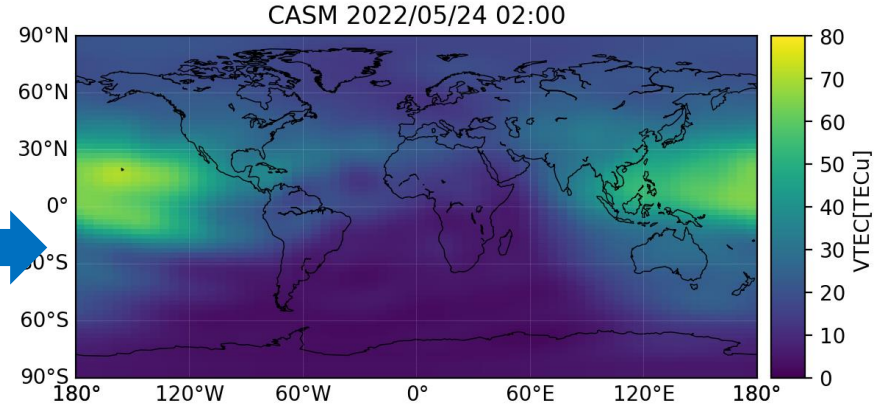
- **Product Input:** : SSRC00CAS1, SSRC00CNE1, IONO00UPC1 and IONO00WHU0
- **Real-time combination strategy:** dSTEC weighting method based on real-time GNSS data
- **GNSS real-time weighted stations**: 30 stations, G(L1/L2)+E(E1/E5a)+C(B1/B3)
- **Product output**: IONO01IGS0 (RTCM-SSR) + IONO01IGS1 (IGS-SSR)

☐ Snapshots of real-time GIM

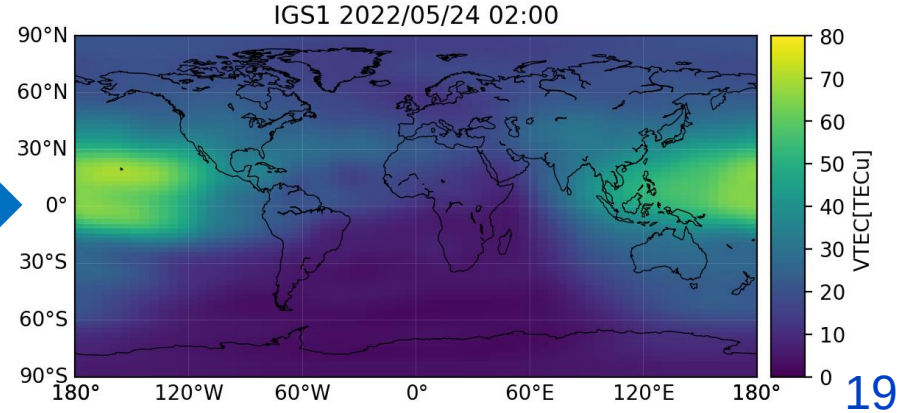
The Chinese Academy of Sciences, Wuhan University and Henan University jointly collaborate with CNES, DLR, UPC to carried out global ionospheric monitoring（IGS、IAG、iGMAS）



CAS real-time combined GIM



HENU+UPC real-time combined GIM

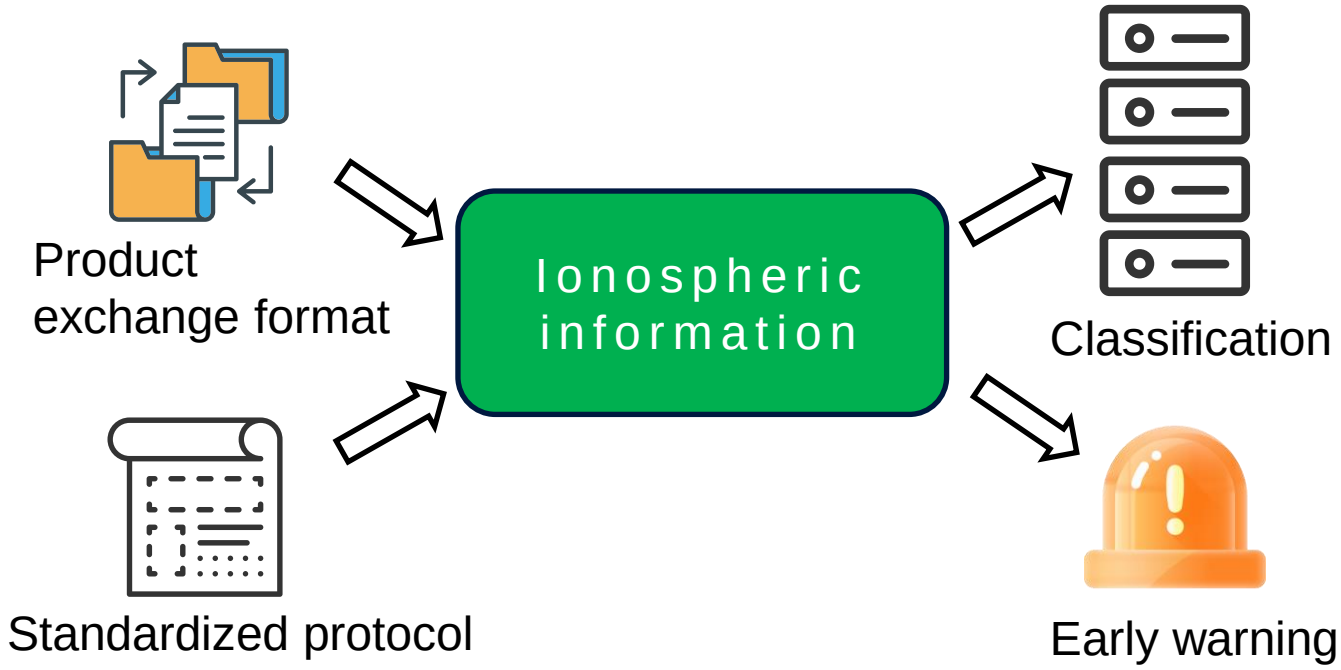


☐ Selectable ionospheric monitoring indices

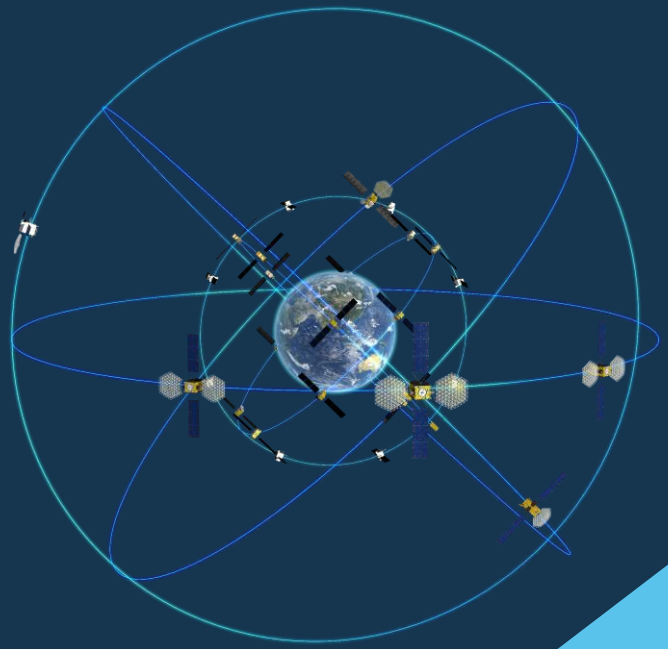
Time resolution	Spatial resolution					
	global	region	1000 km	5°×2.5°	100 km	Single station
Every month	IG12					
1 hour				IsUG		AATR
15 minutes		$R12_{eff}$	W	VgUG		
5 minutes				ROTI	ROTI	IROTI, AATR
1 minutes	$DIXSG_P$	SIDX, GIX, VGUG	DIXSG		ROTI, DIXSG, S4,σ_φ	S4,σ_φ

It is suggested to determine unified parameters for monitoring the ionospheric impact of on GNSS service performance, and define product exchange formats

- ✓ TEC
- ✓ ROTI
- ✓ S4 、 σ_{φ}
- ✓ GIX、VgUG (new format)
- ✓ IsUG、I-scale (new format)
- ✓ … ..



Integrate ionospheric product from multiple sources



Conclusions and outlooks

04

- During the 25th solar cycle, the ionosphere has a significant impact on GNSS service performance and is likely to **continue to increase** in the next few years.
- It is proposed to carry out international joint researches of GNSS performance during the peak solar activity period (2024-2028), as well as establish a **monitoring and early warning platform** for the impact of ionosphere on GNSS (latency < 5 minutes).
- **More countries and scientific organizations** are encouraged to participate in the joint monitoring and early warning services for the global impact of ionosphere.

- **Which group of indices should be selected for precisely capturing the ionospheric anomalies?**
- **Which way should be determined for sharing the ionospheric anomaly information for results combination?**

Thanks for your attention!

Email: lizishen@aircas.ac.cn or qi.liu@henu.edu.cn