Efficient global ionospheric modeling based on multi-source and massive observation data

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EGU 2020

May 8, 2020

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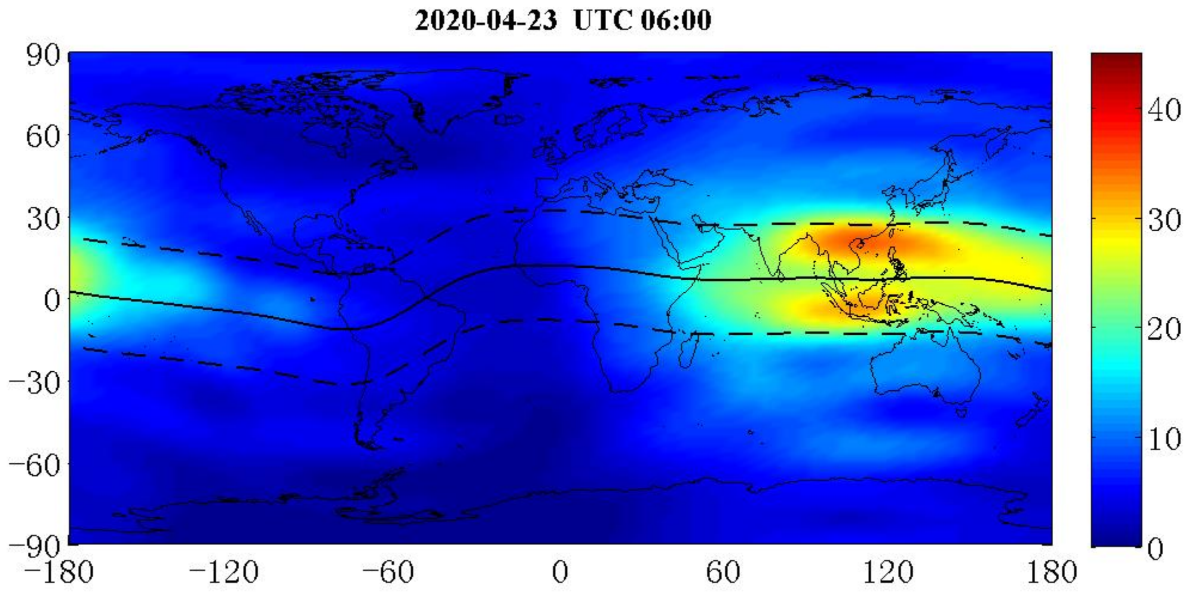
Motivation

- Ionosphere is an important error source of satellite navigation and a key component of space weather.
- Ground-based GNSS has become one of the main technologies to build global ionospheric model, but its inherent defects will affect the precision of model.
- With the rapid development of multi-GNSS and other ionospheric research technologies, massive and high-precision ionospheric observing data was generated.
- Navigation, positioning, timing, space weather monitoring and other applications require high timeliness of ionospheric model.

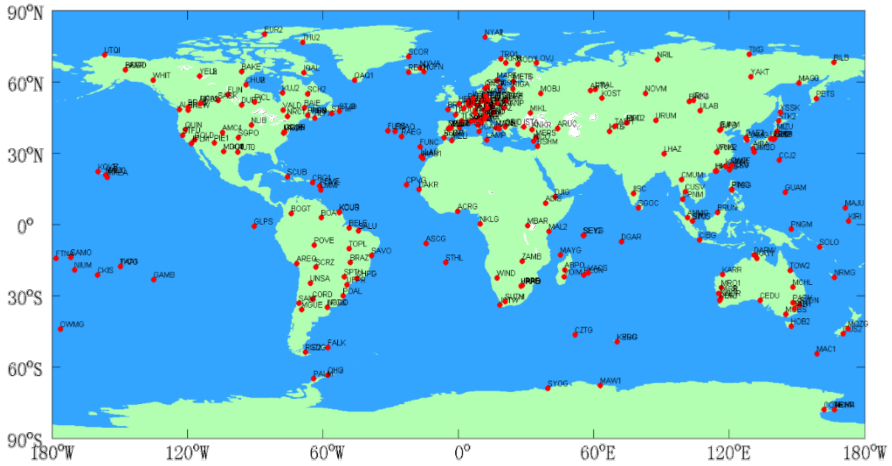


Multi-source data

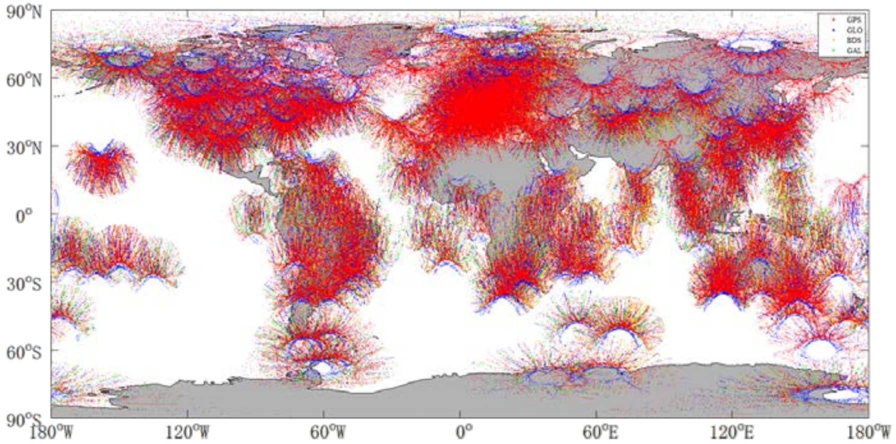
■ Ground-based Global Navigation Satellite System (GNSS)

■ Advantages
- High accuracy
- Low cost
- Global distribution
- Real time
- Massive data
- Multi-system(GPS GLONASS BEIDOU Galileo and QZSS …)
- …….

■ Disadvantages
- Few stations in marine and polar regions
- Large amounts of computation
- ……



IGS and MEGX station distribution



Ionosphere pierce point (IPP)

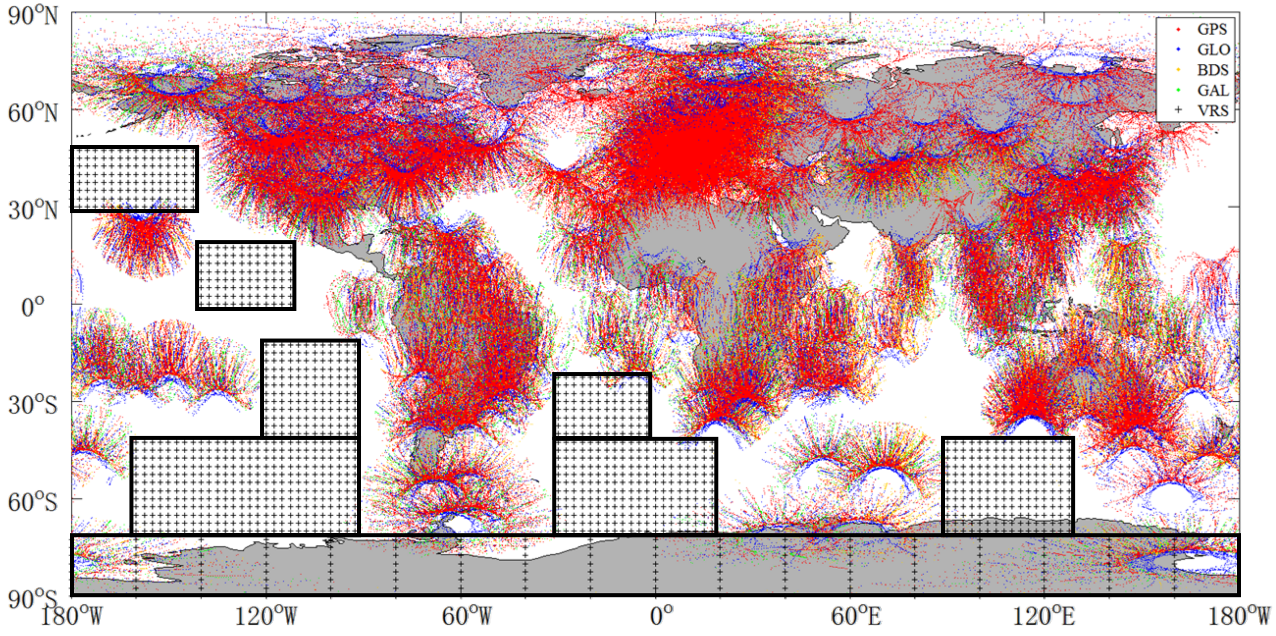
Multi-source data

Virtual Reference Station (VRS)

- **It is difficult to set up GNSS stations in marine and polar regions, so there is a lack of observing data in these areas. Therefore, the precision of global ionospheric model will be decreased.**

- **To make up this shortcoming of ground-based GNSS, we set up 8 virtual reference stations (see the black rectangles in the picture) at the regions where the IPPs are a wide range of absence.**

- **We add Total Electron Content (TEC) obtained by other models or technologies (International Reference Ionosphere, GNSS Radio Occultation, etc) to virtual reference stations and build global ionospheric model with GNSS observing data together.**



Virtual reference station distribution

Efficient global ionospheric Modeling

Modeling strategy

Method	Description
ION Model	Spherical Harmonic (SH) Model
Model Height	450KM (one shell)
Data Period	Three consecutive days
Parameter Interval	2h for SH coefficients and 1day for DCBs
Station	IGS、MGEX and VRS
GNSS System	GPS/GLONASS/BEIDOU/Galileo
Estimate Method	Least squares
Resolution	Latitude: 2.5° Longitude:5.0° Time: 2hour

SH expansion (Schaer et al,1995)

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

GNSS pseudorange and carrier phase L4 combination

$$P4_i^s = P1_i^s - P2_i^s = 40.31 \cdot \left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right) \cdot STEC + c \cdot DCB_{12}^s + c \cdot DCB_{12}^r$$

$$L4_i^s = L1_i^s - L2_i^s = -40.31 \cdot \left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right) \cdot STEC + N_1\lambda_1 - N_2\lambda_2$$

Levelling carrier phase to code (Mannucci et al,1993)

$$\Delta L4_i^s = \sum_{i=arc\_start}^{arc\_end} (P4_i^s + L4_i^s)$$

$$\widehat{L4}_i^s = L4_i^s - \Delta L4_i^s = 40.31 \cdot \left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right) \cdot VTEC \cdot MF(z) + c \cdot DCB_{12}^s + c \cdot DCB_{12}^r$$

Virtual reference station observing data

$$VRS_i^s = VTEC + c \cdot BIA_i$$

Efficient global ionospheric Modeling

■ Processing multi-source and massive observing data

- GNSS and VRS data fusion and one system bias was added to observation equations
- Adopt normal equation superposition method to process observing data of each station
- Adopt least squares method to solve equations
- Adopt Intel® Math Kernel Library in ionospheric modeling
  - Use Sparse BLAS Routines to store and operate sparse matrix
  - Use LAPACK Routines to solve the inversion of large-scale matrix

Take the data processing capacity of April 28, 2020 for example:

Item	Quantity	Detail
GNSS Station	324	287 MGEX and 37 IGS stations
VRS Station	8	
GNSS System	4	GPS+GLONASS+BEIDOU+Galileo
Satellite	125	GPS(32) + GLO(25) + BDS(44) + GAL(24)
Equation	19,721,243	19,655,159 GNSS and 66,084 VRS
Parameter	26,083	3072 SH coefficients, 23010 DCBs and 1 bias

Efficient global ionospheric Modeling

Parallel modeling of multiple stations

- **Use OpenMP multi-threaded parallel computing technology**
  - **Set up VRS in parallel**
  - **Data preprocessing in parallel**
  - **Establish normal equations in parallel**
  - **Estimate parameters in parallel**

- **Global ionospheric modeling time:**
  - **About 10minutes (300+ GNSS station, GPS+GLONASS, 1 day’s data)**
  - **About 30minutes (300+ GNSS station, GPS+GLONASS+BEIDOU+Galileo, 1 day’s data)**

Efficient global ionospheric Modeling

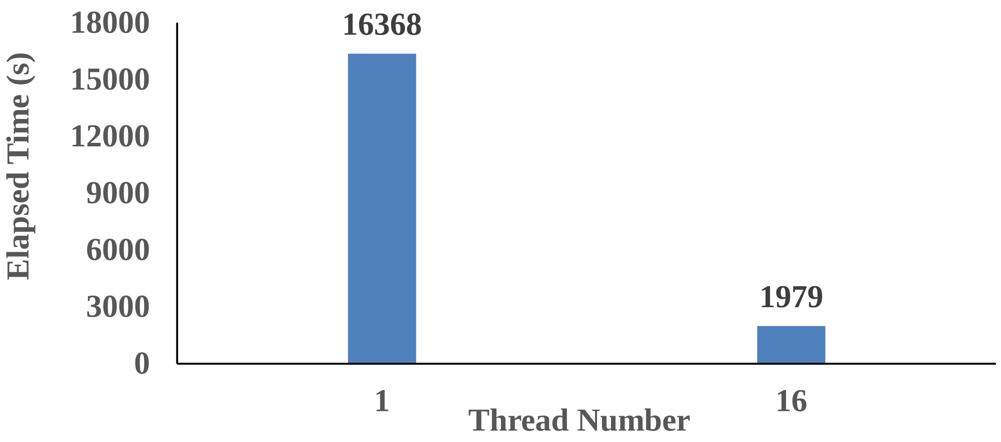
■ Parallel modeling time test

■ **Parallel modeling test condition:**

- CPU: Intel(R) Xeon(R) CPU E5-2620 v4 @ 2.10GHz 16threads
- RAM size: 64GB
- Observing data of April 28, 2020
- 324 GNSS stations and four systems of observing data
- 125 GNSS satellites
- 8 VRS stations
- 19,655,159 GNSS and 66,084 VRS observations
- 26083 parameters to be evaluated

■ **Parallel modeling test result:**

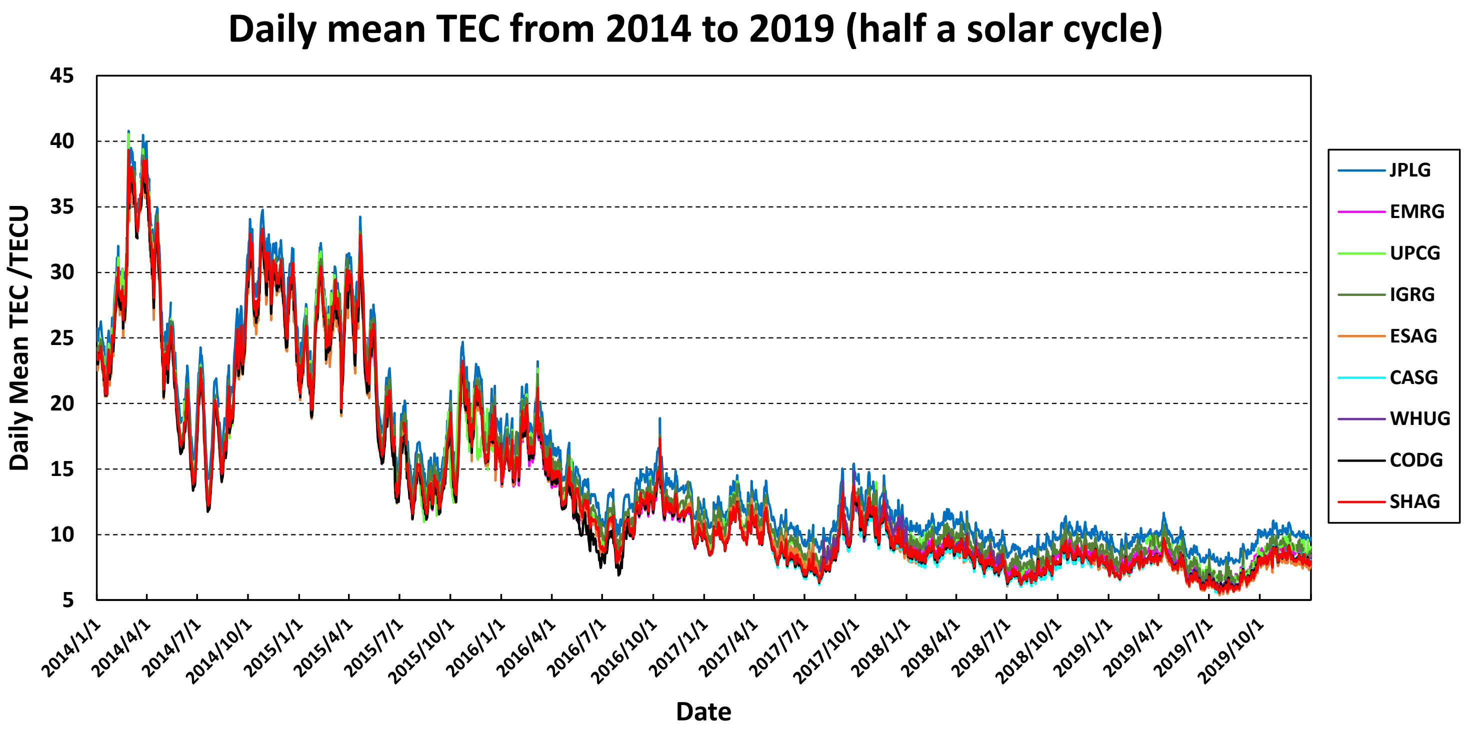
Thread Number	Elapsed Time (hour)	Speedup
1	4.55	
16	0.55	827.3%



Global Ionospheric model precision assessment

■ Compare with IGS Global Ionosphere Map (GIM) product

Institute	GIM	Period
IGS	IGRG	2014-2019
JPL	JPLG	2014-2019
CODE	CODG	2014-2019
ESA	ESAG	2014-2019
UPC	UPCG	2014-2019
EMR	EMRG	2015-2019
CAS	CASG	2017-2019
WHU	WHUG	2017-2019
SHA	SHAG	2014-2019



Global Ionospheric model precision assessment

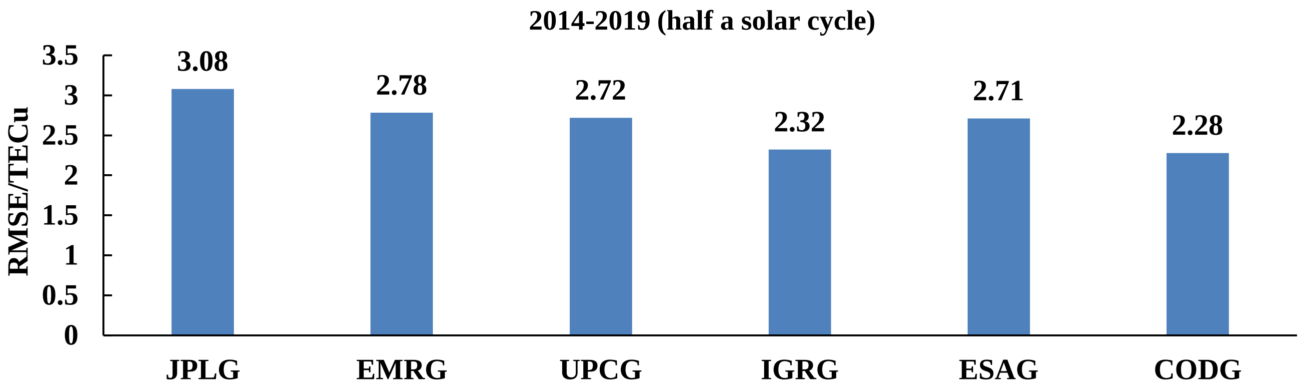
■ Compare with IGS GIM product

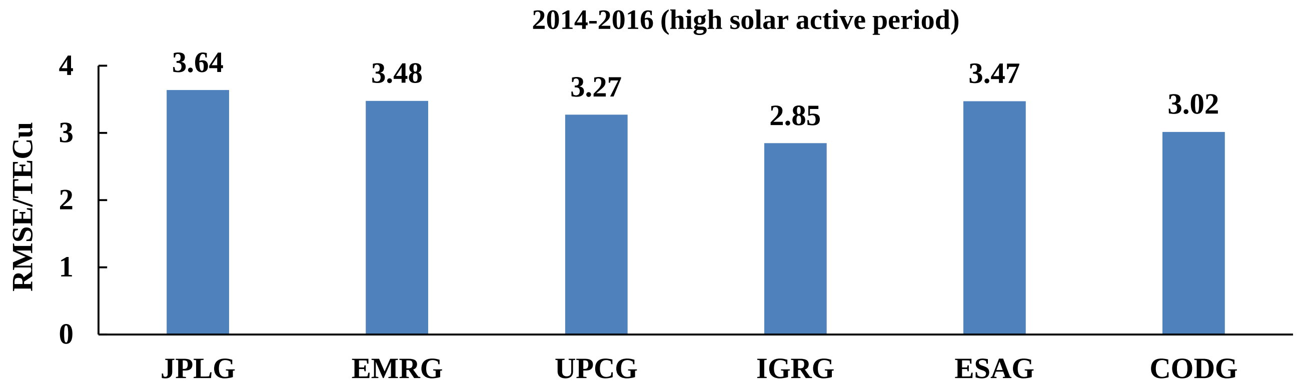
The three histograms show the RMSEs of SHAG relative to JPLG, EMRG, UPCG, IGRG, ESAG, CODG, CASG and WHUG during half a solar cycle, high and low solar active period respectively.

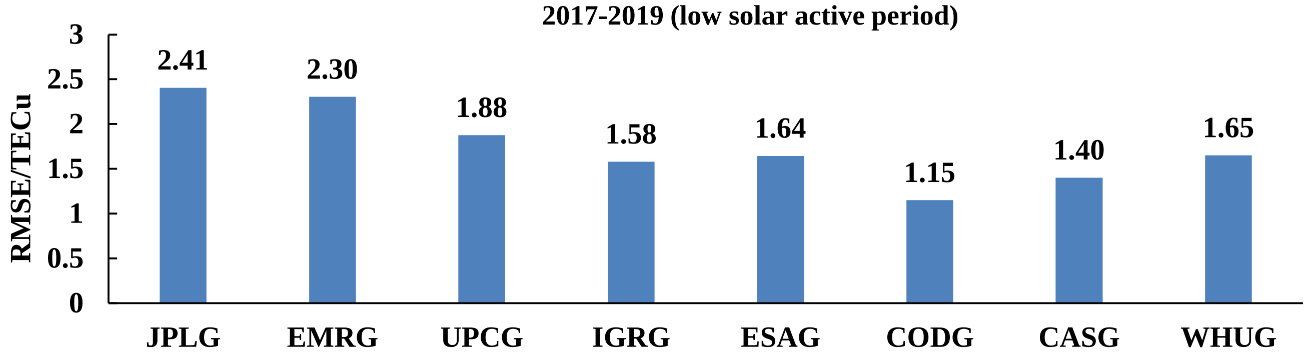
- ➢ During half a solar cycle, the RMSEs of SHAG were almost all less than 3 TECu, and SHAG is closest to IGRG and CODG.

- ➢ During high solar active period, the RMSEs of SHAG were almost all greater than 3TECu, which were greater than that during half a solar cycle and SHAG is closest to IGRG.

- ➢ During low solar active period, the RMSEs of SHAG were all less than 2.5 TECu, which were less than that during half a solar cycle and SHAG is closest to CODG.



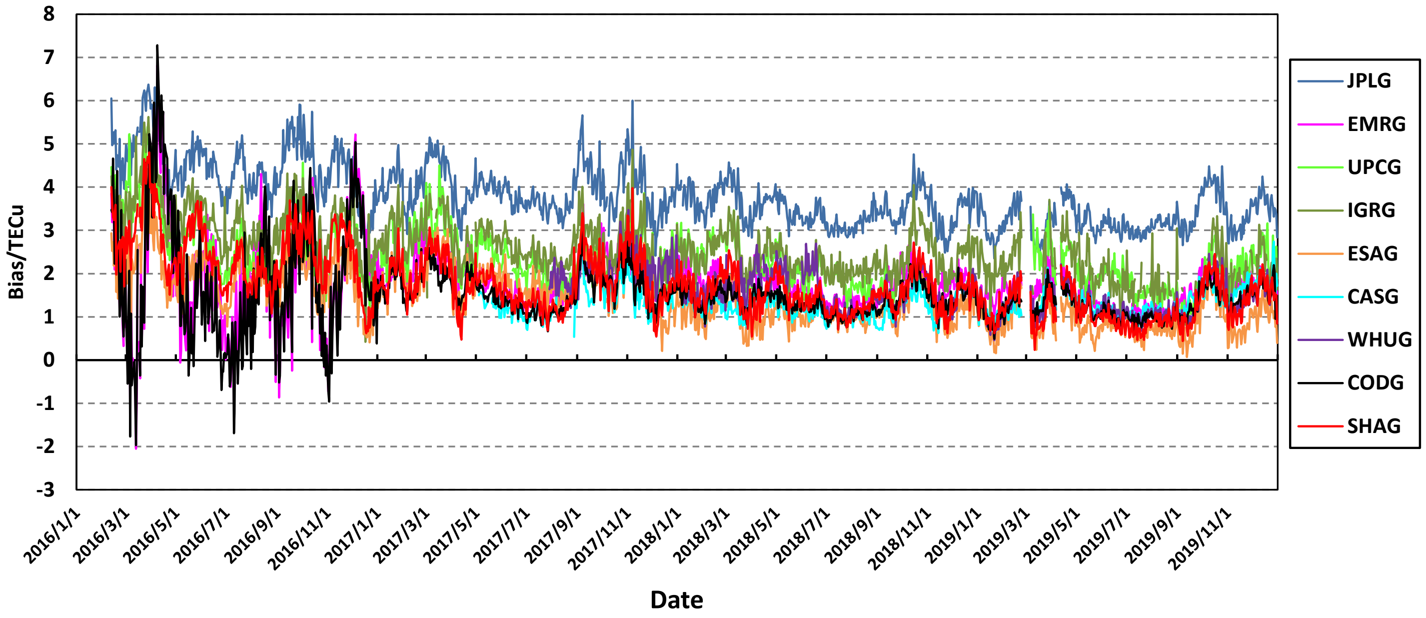




Global Ionospheric model precision assessment

■ Compare with TECs from Jason-3 Altimeter Satellite

- The Jason-3 Altimeter satellite TECs were extracted from MLE4 altimeter ionosphere correction (iono_corr_alt_ku) in Jason-3 gdr-ssha product.
- The orbit altitude of Jason-3 satellite is 1336KM and GNSS satellites are about 20000KM, so there exist a bias between the TEC obtained by Jason-3 and GNSS (the bias can be clearly seen from the picture).
- Because the bias has not been precisely determined, we introduced STD (stability of bias) to describe the precision of GIMs and mean bias to describe the consistency of GIMs.



$$Bias = TEC^{GNSS} - TEC^{Jason-3}$$

Global Ionospheric model precision assessment

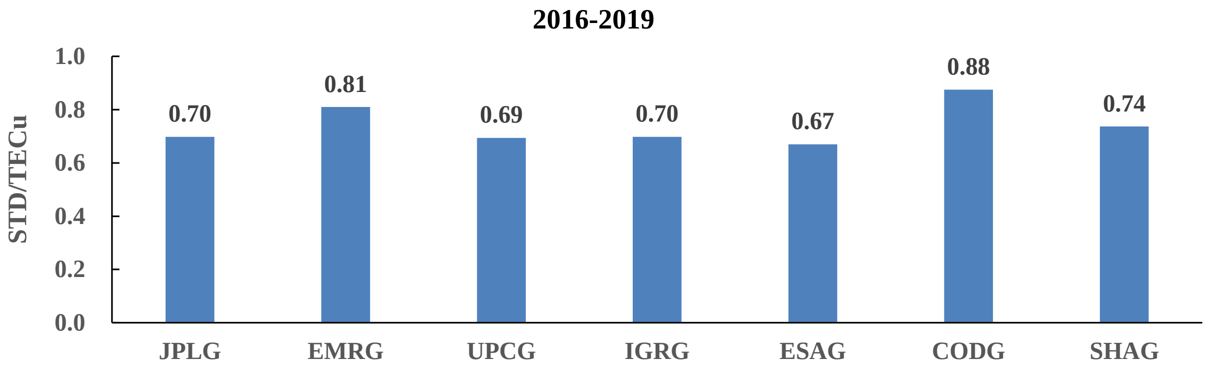
■ Compare with TECs from Jason-3 Altimeter Satellite

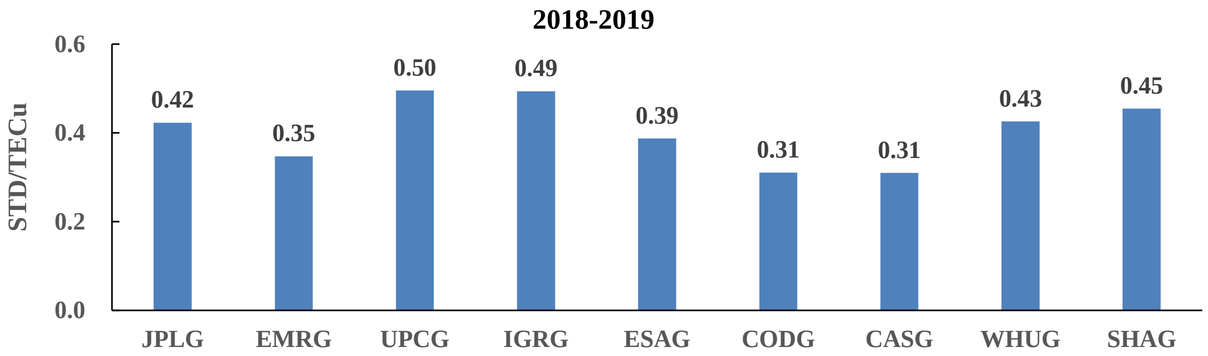
The three histograms on the right show the STD and mean bias between GIMs and Jason-3 TEC. Because the GIMs of CASG and WHUG are incomplete from 2016 to 2017, so we compared the precision of CASG and WHUG only from 2018 to 2019.

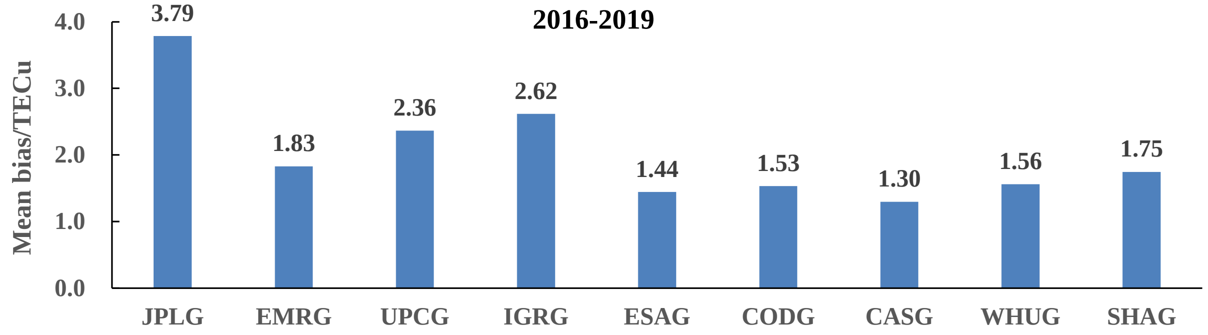
- **From Jason-3 mission stared to 2019, the STDs of 7 GIMs were between 0.67 and 0.88, ESAG showed the strongest stability. The biggest difference of STD was only 0.21.**

- **From 2018 to 2019, the STDs of 9 GIMs were between 0.31 and 0.50, and CODG, CASG, EMRG were relatively more stable. The biggest difference of STD is only 0.19.**

- **The mean biases of EMRG, ESAG, CODG, CASG, WHUG and SHAG were relatively consistent.**

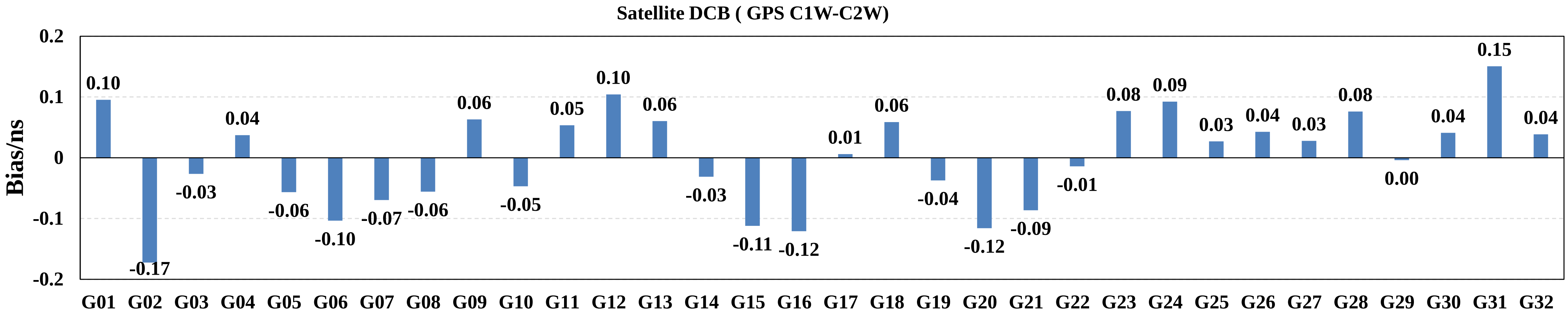


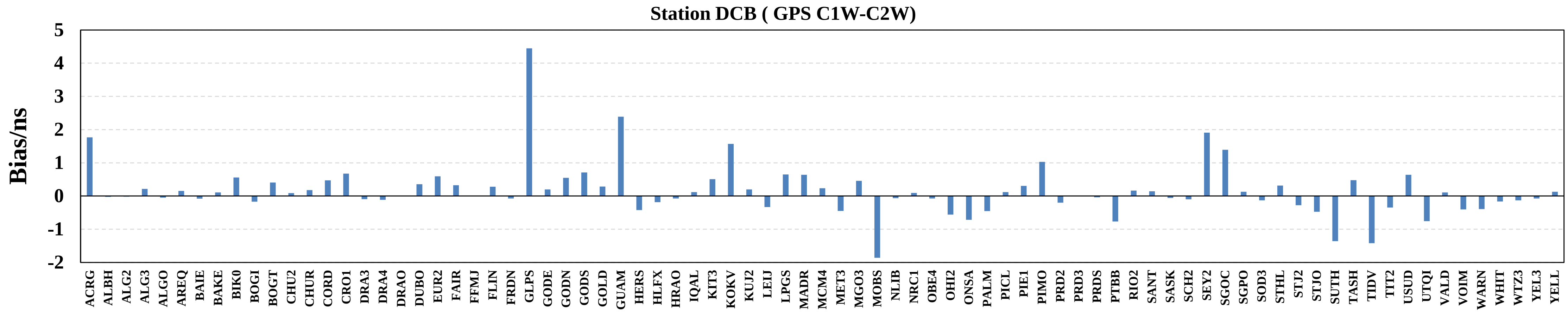




DCB precision assessment

■ Compare with IGS DCB product (Take GPS for example)

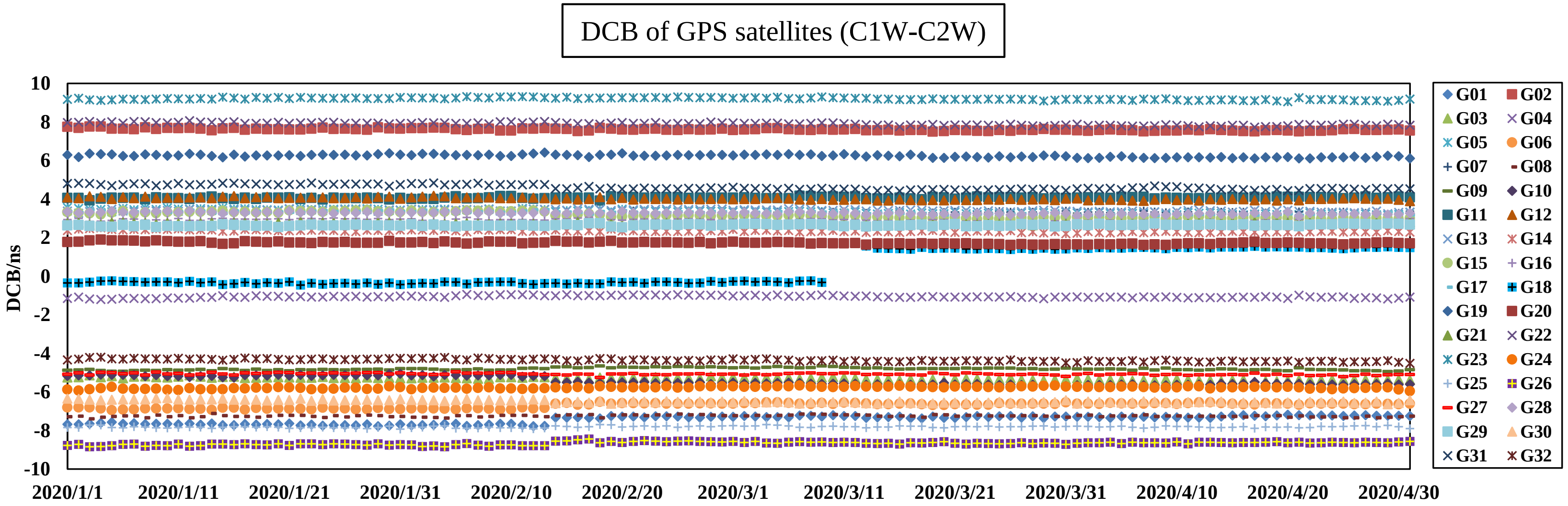


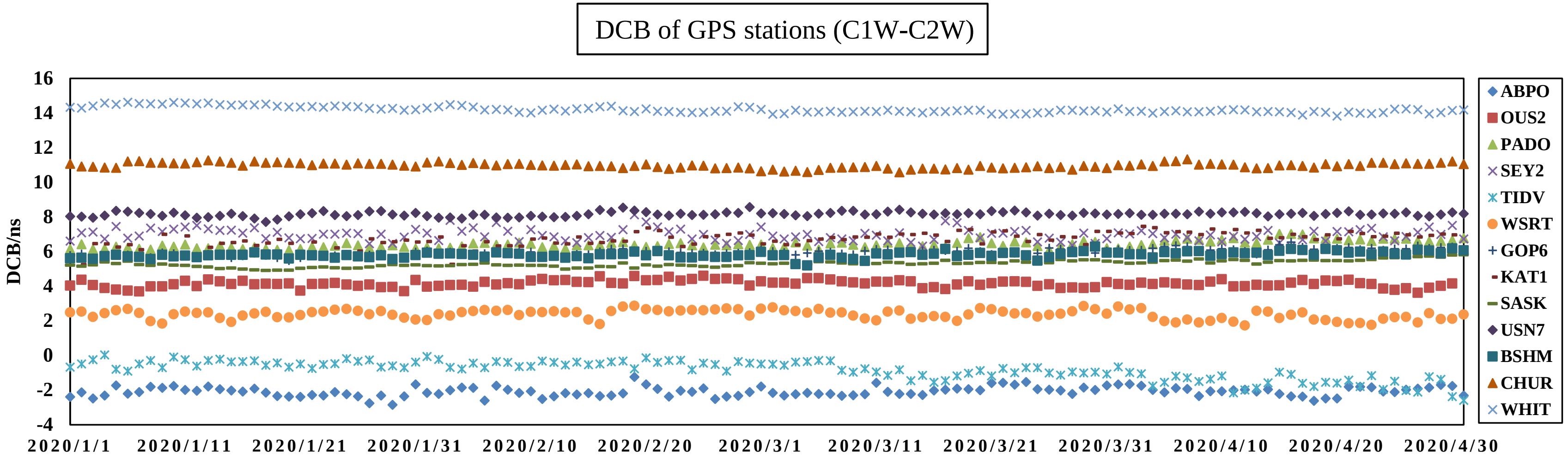


	Satellite DCB (GPS C1W-C2W)	Station DCB (GPS C1W-C2W)
RMSE(ns)	0.08	0.82

DCB precision assessment

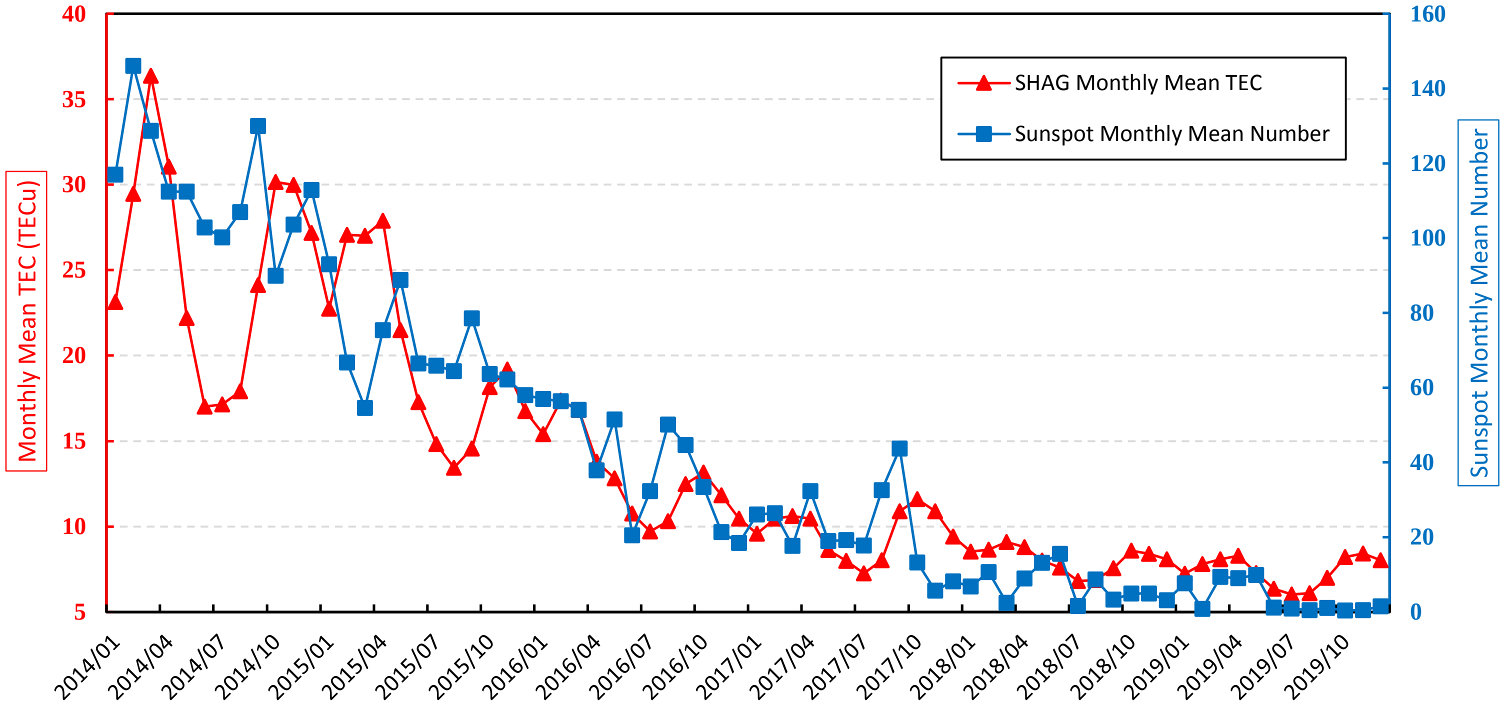
■ DCB time series (Take GPS for example)





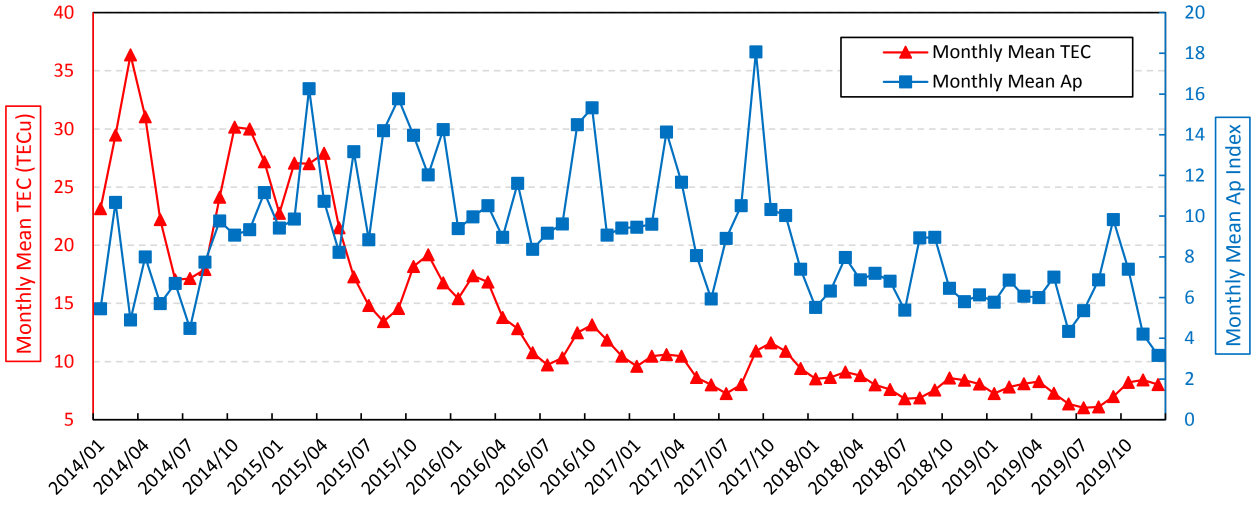
TEC responds to solar activity verification

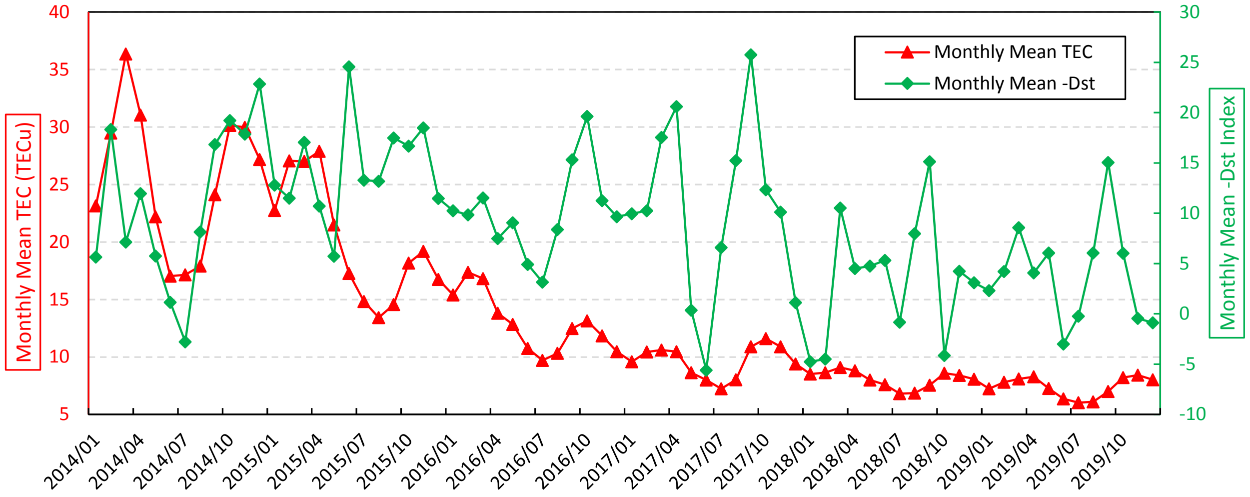
■ TEC responds to sunspot number verification



TEC responds to geomagnetic activity verification

■ TEC responds to Ap and Dst index verification





Conclusion

Characteristics:

- ✓ The capacity of processing multi-source data
- ✓ The capacity of processing massive data
- ✓ Efficient parallel modeling
- ✓ GIM precision is comparable to IGS product
- ✓ DCB precision is comparable to IGS product
- ✓ The capacity of responding to solar activity
- ✓ The capacity of responding to geomagnetic activity

Future:

- ◻ Real-time solution
- ◻ Global ionospheric modeling with multi-source heterogeneous data fusion (Ground-based GNSS, GNSS Radio Occultation, Satellite Altimetry, Ionospheric Altimeter, and so on)

Thanks for listening!

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