



International GNSS Service Workshop 2017

The Recent Activities of CAS Ionosphere Analysis Center on GNSS Ionospheric Modeling within IGS

Yunbin Yuan*, Zishen Li, Ningbo Wang, Min Li

Academy of Opto-Electronics (AOE), CAS
Institute of Geodesy and Geophysics (IGG), CAS

July 4, 2017, Paris

CAS: Chinese Academy of Sciences

Overview

1. Introduction of the CAS IAAC

2. Generation and validation of the CAS-GIM

3. Refinement of broadcast ionospheric models

4. Development of ionospheric irregularity maps

5. Conclusions

1. Introduction of the CAS IAAC

1.1 The research history of CAS IAAC

- 1995, start to study the variation of ionosphere using GPS.
- 1991, a new approach for generating the ionospheric TEC map over China region was developed, naming **DADS** (Different Areas Different Stations).
- 2004, the **GTSF function**, for modeling the variation of local ionospheric TEC was proposed. (GTSF: Generalized Trigonometric Series Function)
- 2007, a simplified and well-performance global ionospheric model was developed for **BDS's broadcast ionospheric model**.
- 2012, the two-step method, named **IGGDCB**, for the determination of satellite and receiver DCB using only a few global station was proposed.
- 2013, the **SHPTS** method for calculating the GIM was developed.
- 2015, GIMs from 1998 to 2015 were **re-processed** using SHPTS approach, and participated in the GIM validation organized by IGS ionospheric WG.

1995

2007

2015

1. Introduction of the CAS IAAC in China

1.2 CAS IAAC was nominated as the 5th IGS IAAC

- The CAS was nominated as a **new IGS ionosphere Associate Analysis Center** during the IGS Workshop held at Sydney, Australia in 2016.
- The **CAS IAAC is administered** by the Academy of Opto-Electronics (**AOE**, located at Beijing, China) and the Institute of Geodesy of Geophysics (**IGG**, located at Wuhan, China).
- The coordinator of CAS center is **Prof. Yunbin Yuan**, and the main researchers are Dr. **Zishen Li** and Dr. **Ningbo Wang** with more than 3 PhD candidates.



Institute of Geodesy of Geophysics
Wuhan, China



Academy of Opto-Electronics
Beijing, China

2. Generation and validation of the CAS-GIM

2.1 Basic idea of SHPTS (Spherical Harmonic Plus Trigonometric Series)

The global and local ionospheric TEC is modeled by SH and GTS functions and then are integrated to generate the global map based on DADS approach.

Spherical Harmonic
Function

$$VTEC(\phi, \lambda) = \sum_{n=0}^{n_{\max}} \sum_{m=0}^n \tilde{P}_{nm}(\sin \phi) \cdot (\tilde{A}_{nm} \cos(m\lambda) + \tilde{B}_{nm} \sin(m\lambda))$$

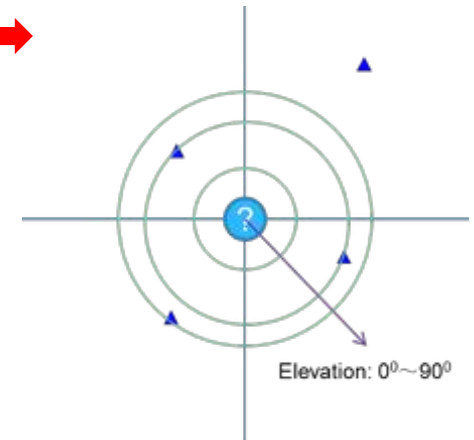
+

Trigonometric Series
Function

$$\begin{cases} TEC(\varphi, \lambda, z) = VTEC(\varphi, \lambda) \cdot M(z) \\ VTEC(\varphi, \lambda) = \sum_{n=0}^{n_{\max}} \sum_{m=0}^{m_{\max}} \{E_{nm}(\varphi - \varphi_0)^n \lambda^m\} \\ \quad + \sum_{k=1}^{k_{\max}} \{C_k \cos(k\lambda) + S_k \sin(k\lambda)\} \\ \lambda = \frac{2\pi(t-14)}{T}, (T = 24h) \end{cases}$$

$$E_i = \begin{cases} VTEC_{z,i} & M = 0 \\ \frac{\sum_{m=1}^M P_m \cdot VTEC_{z,i,m}}{\sum_{m=1}^M P_m} & M \neq 0 \end{cases}$$

$$P_m = \frac{1}{\sigma_{0,m}^2 \cdot [\cos^2(elev_{i,m}) + 1]}$$



Highlight: estimated the TEC at each grid point only using the nearby data so as to improve its accuracy.

(SHPTS: towards a new method for generating precise global ionospheric TEC map based on spherical harmonic and generalized trigonometric series functions. Journal of Geodesy. 2015.)

2. Generation and validation of the CAS-GIM

2.2 Reprocessing of GIM based on SHPTS (from 1998 to 2015)

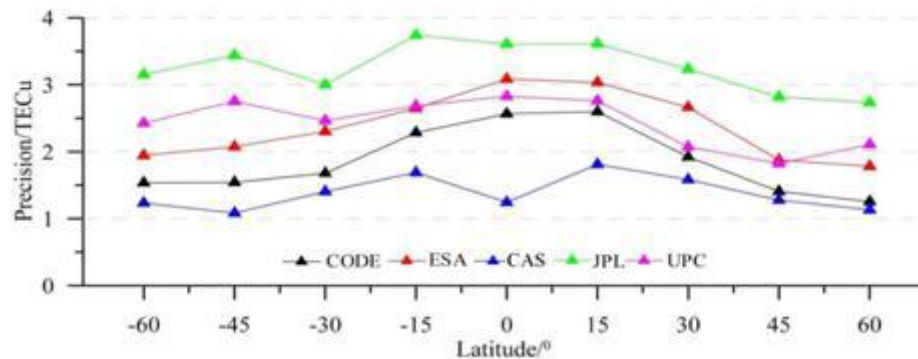
- The GIMs during **1998-2015** were re-processed using SHPTS approach.
- **The re-processed GIMs were validated with the following three data sources.**
 - ✓ TECs (slant) calculated from all the GPS stations contributing to the model (in **precision**)
 - ✓ TECs from the IGS-released final GIMs (in **consistency**)
 - ✓ TECs from the altimetry satellites (in **accuracy**)
- The GIMs from each of the four IAACs were also compared with our new GIM.

More validation results can be found in the Poster PS04-14.

2. Generation and validation of the CAS-GIM

2.3 Precision results (compared with GNSS TECs)

- The mean precision of GIMs from diff. IAACs and the new method at **different latitude bins** (the slant TECs are mapped to the zenith direction at each GNSS site)



$$Precision = \sqrt{\frac{\sum_{n=1}^N [(TEC_{m,n} - TEC_{g,n}) \cdot MF_n]^2}{N}}$$

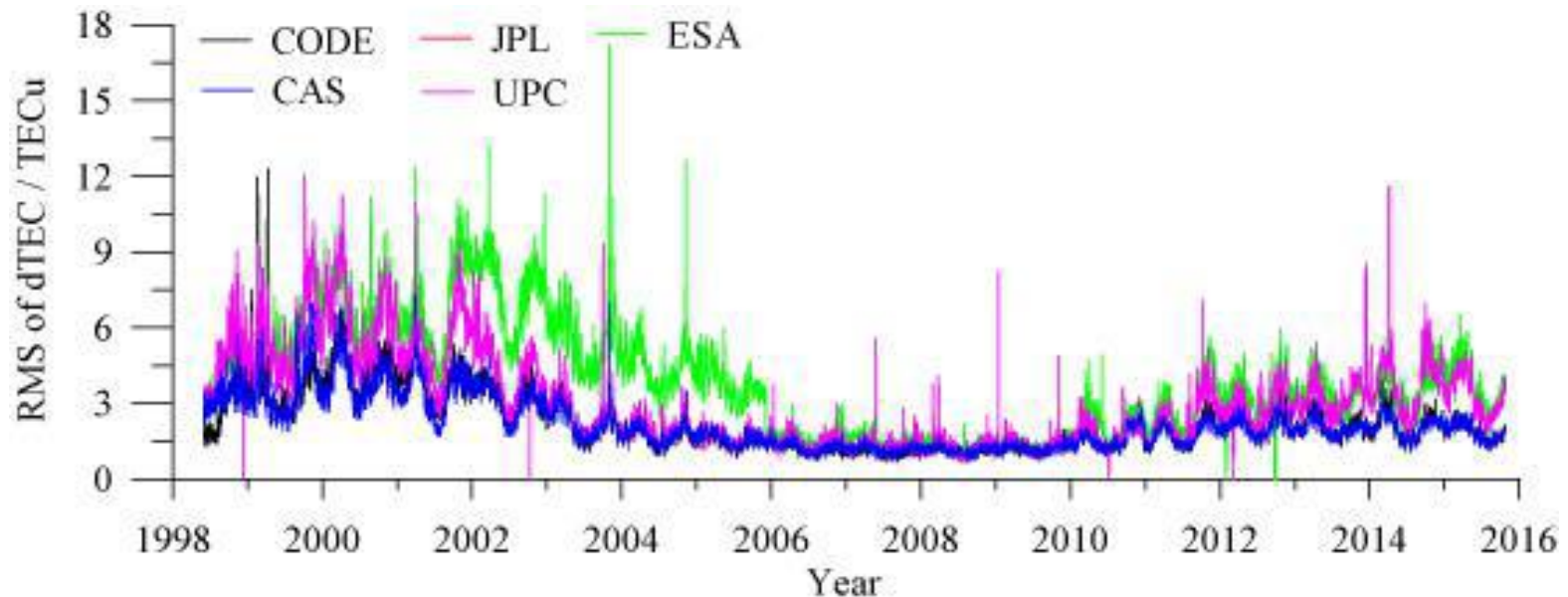
- Mean precision of GIMs in **different periods** (i.e. different levels of solar activity)

IAACs	2001-2003		2004-2006		2007-2009		2010-2011	
	S	N	S	N	S	N	S	N
CODE	2.32	1.88	1.56	1.22	1.17	1.04	3.03	2.53
ESA	3.30	3.32	2.26	1.91	1.62	1.33	3.05	2.26
CAS	1.51	1.50	1.18	1.08	0.96	0.95	2.31	2.02
JPL	3.95	3.63	3.04	2.57	2.66	2.31	4.08	3.70
UPC	3.49	2.94	2.25	1.64	1.99	1.46	3.38	2.43

(Unit: TECu)

2. Generation and validation of the CAS-GIM

2.4 Consistency results (compared with IGS final GIM)



Daily RMS of the differences between the GIMs and IGS final product during
1998 – 2015

(The GIM for comparison is from each IAAC and our approach.)

2. Generation and validation of the CAS-GIM

2.4 Consistency results (compared with IGS final GIM)

Yearly RMS of the differences between GIM from each IAAC, our approach and IGS final product. (Unit: TECu)

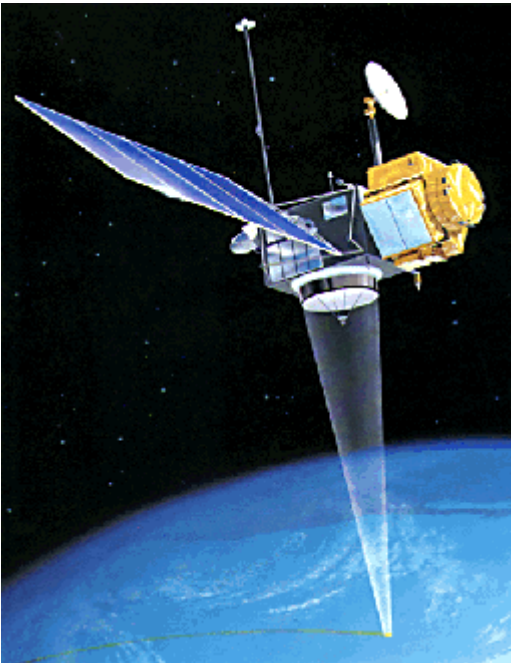
IAAC Year	CODE	CAS	JPL	UPC	ESA
1998	3.01	3.02	4.27	4.62	4.49
1999	3.64	3.54	4.64	5.64	5.79
2000	4.41	3.91	4.91	6.45	6.94
2001	3.87	3.47	4.34	5.21	6.81
2002	3.26	3.07	3.78	4.27	7.50
2003	2.23	2.21	2.71	2.56	5.57
2004	1.68	1.78	2.45	2.01	4.42
2005	1.49	1.59	2.17	1.68	3.57
2006	1.20	1.25	2.00	1.47	1.67
2007	1.08	1.18	1.92	1.32	1.52
2008	1.10	1.15	1.79	1.28	1.43
2009	1.23	1.22	1.82	1.40	1.45
2010	1.66	1.60	1.94	1.79	2.19
2011	1.88	1.76	2.45	2.44	2.92
2012	2.18	2.05	2.89	2.85	3.44
2013	2.09	2.00	2.73	3.20	3.38
2014	2.19	2.04	2.80	3.77	3.63
2015	1.89	1.86	2.10	3.24	3.71
Mean	2.43	2.31	3.05	3.44	4.35

2. Generation and validation of the CAS-GIM

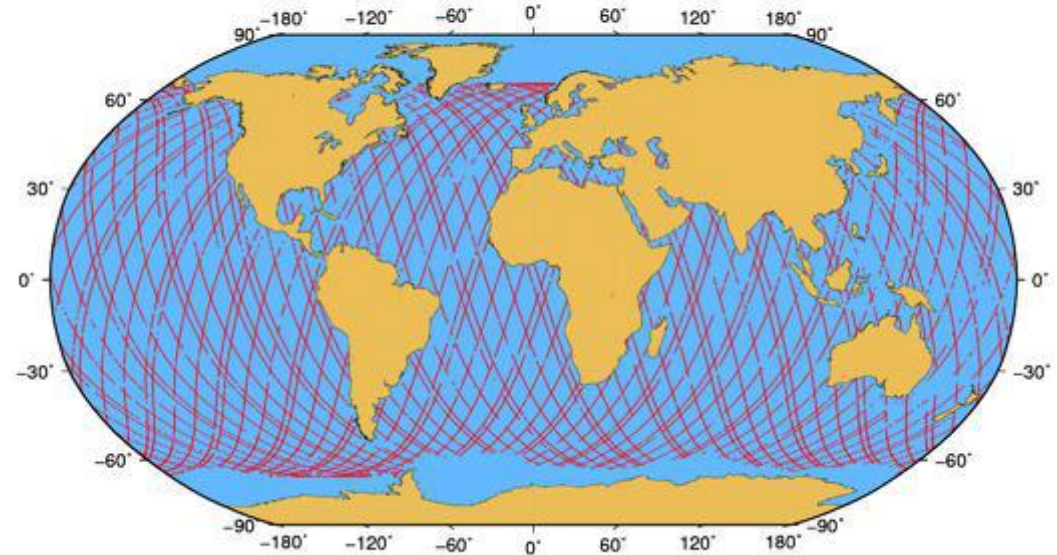
2.5 Accuracy results (compared with TOPEX TECs)

GIMs were also validated with high-quality ionospheric TECs derived from the satellite altimeters.

$$\begin{cases} Mean = \frac{\sum_{n=1}^N (TEC_{m,n} - TEC_{g,n}) \cdot MF_n}{N} \\ STD = \sqrt{\frac{\sum_{n=1}^N [(TEC_{m,n} - TEC_{g,n}) \cdot MF_n - Bias]^2}{N-1}} \end{cases}$$



IPP trajectory of the TOPEX ionospheric data



2. Generation and validation of the CAS-GIM

2.5 Accuracy results (compared with TOPEX TECs)

Statistical accuracy of GIM with respect to TOPEX data for different levels of solar activity

IAAC	areas	2001-2003 High solar activity		2004-2006 Middle solar activity		2007-2009 Low solar activity	
		Bias	STD	Bias	STD	Bias	STD
CODE	N	0.06	5.48	-2.67	3.59	-3.67	2.69
	S	-1.85	5.75	-4.24	3.79	-4.89	2.90
ESA	N	-1.99	6.55	-3.38	4.08	-3.73	2.91
	S	-2.20	7.06	-4.57	4.42	-4.72	3.15
CAS	N	-1.47	4.76	-2.88	3.16	-3.41	2.50
	S	-2.07	5.37	-3.65	3.67	-4.04	2.94
JPL	N	1.99	4.75	-0.55	3.44	-1.42	2.77
	S	0.76	4.50	-1.93	3.44	-2.78	2.78
UPC	N	0.04	5.16	-3.00	3.03	-3.64	2.29
	S	-0.69	5.15	-3.76	3.16	-4.04	2.47

N: Northern Hemisphere; S: Southern Hemisphere

3. Refinement of broadcast ionospheric models

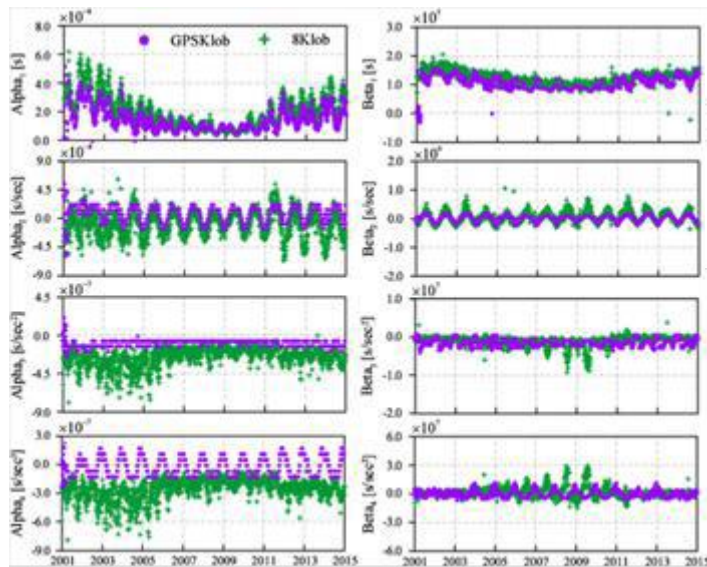
3.1 Motivation

- Broadcast ionospheric information is **an effective way** for real-time single-frequency users to mitigate the ionospheric delay.
 - GPS — Klobuchar
 - Galileo — NeQuickG
 - BDS-2 — Klobuchar-like (8-par and 14-par for civil and military users, respectively)
 - BDS-3 — BDSSH (BDS Spherical Harmonics)
- Performance of broadcast ionospheric models is limited due to the limitation of **data processing strategies, tracking station number and distribution** as well as **upload latency** in GNSS control centers.
- We intend to provide the **re-estimated broadcast ionospheric coefficients** of GPS, Galileo and BDS for the users of interest.
- It can be considered as **precise broadcast-like ionospheric models**.

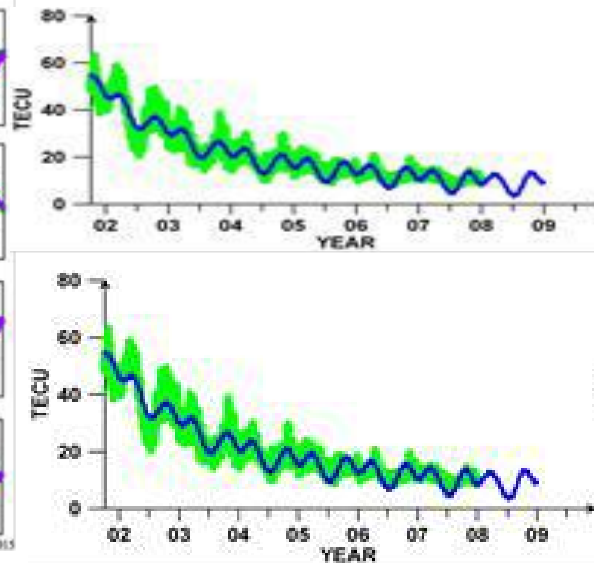
3. Refinement of broadcast ionospheric models

3.2 The re-estimated broadcast ionospheric coefficients

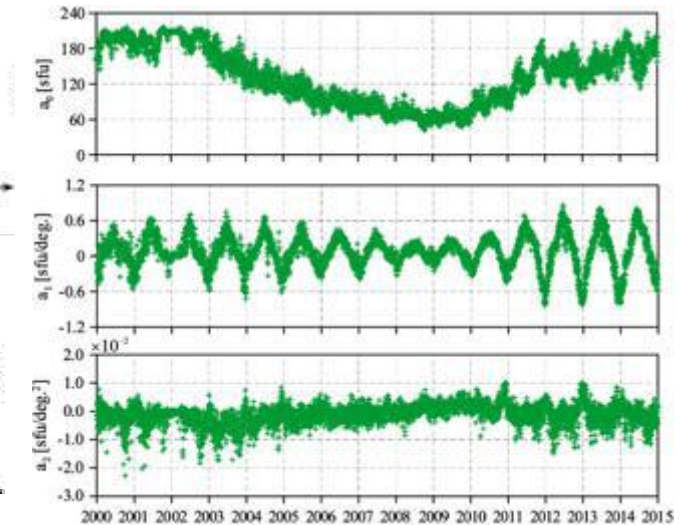
- The 8-par and 10-par Klobuchar, NeQuickC and BDSSH coefficients is estimated with GPS and GLONASS data obtained from ~30 globally distributed GNSS stations*.
- An example of the refined broadcast ionospheric coefficients for GPS, BDS and Galileo.



GPS Klobuchar model



BDSSH model



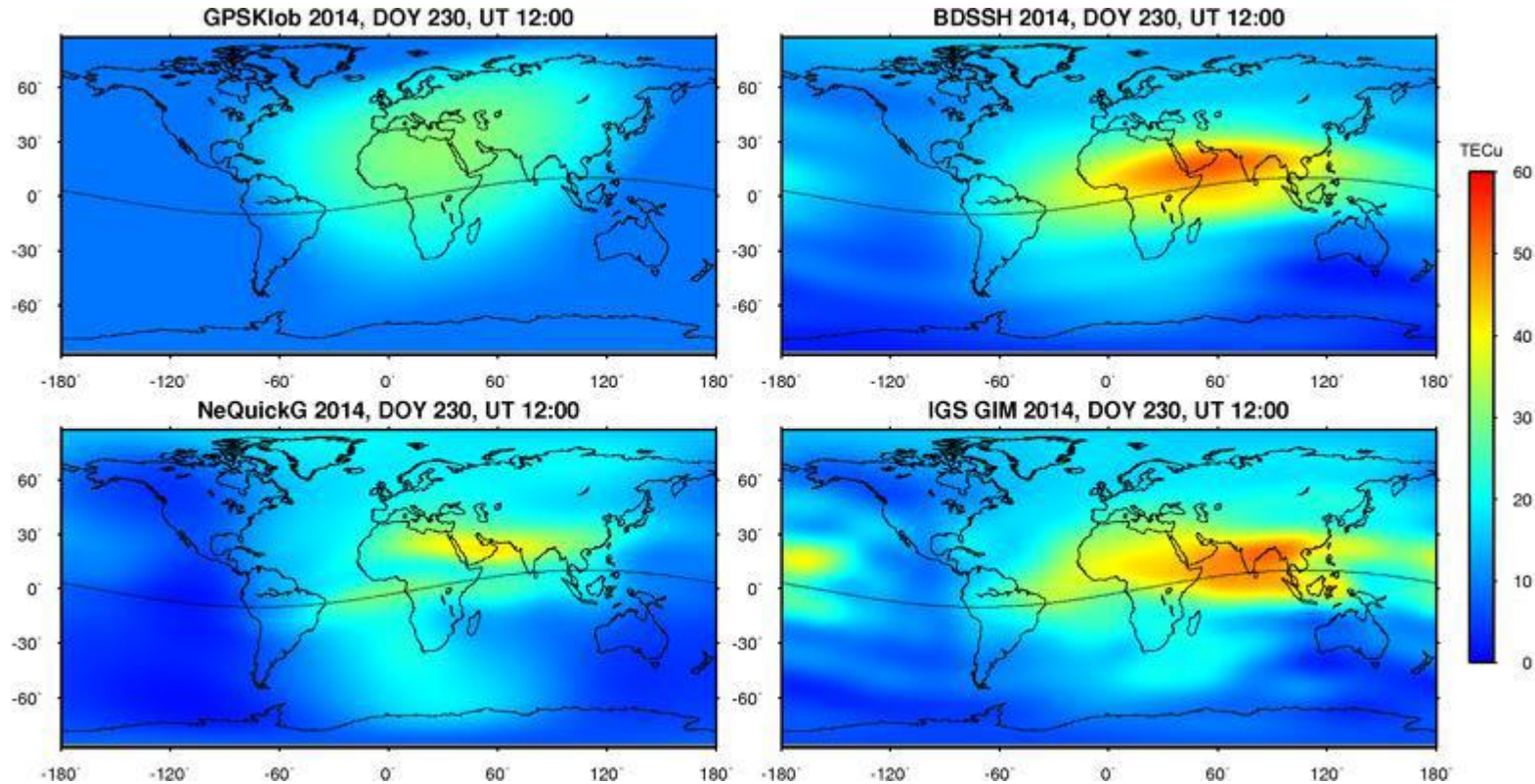
Galileo NeQuickC model

*Wang et al., Improvement of Klobuchar model for GNSS single-frequency ionospheric delay corrections, ASR, 2016.

Wang et al., An examination of the Galileo NeQuick model: comparison with GPS and JASON TEC, GPSS, 2017.

3. Refinement of broadcast ionospheric models

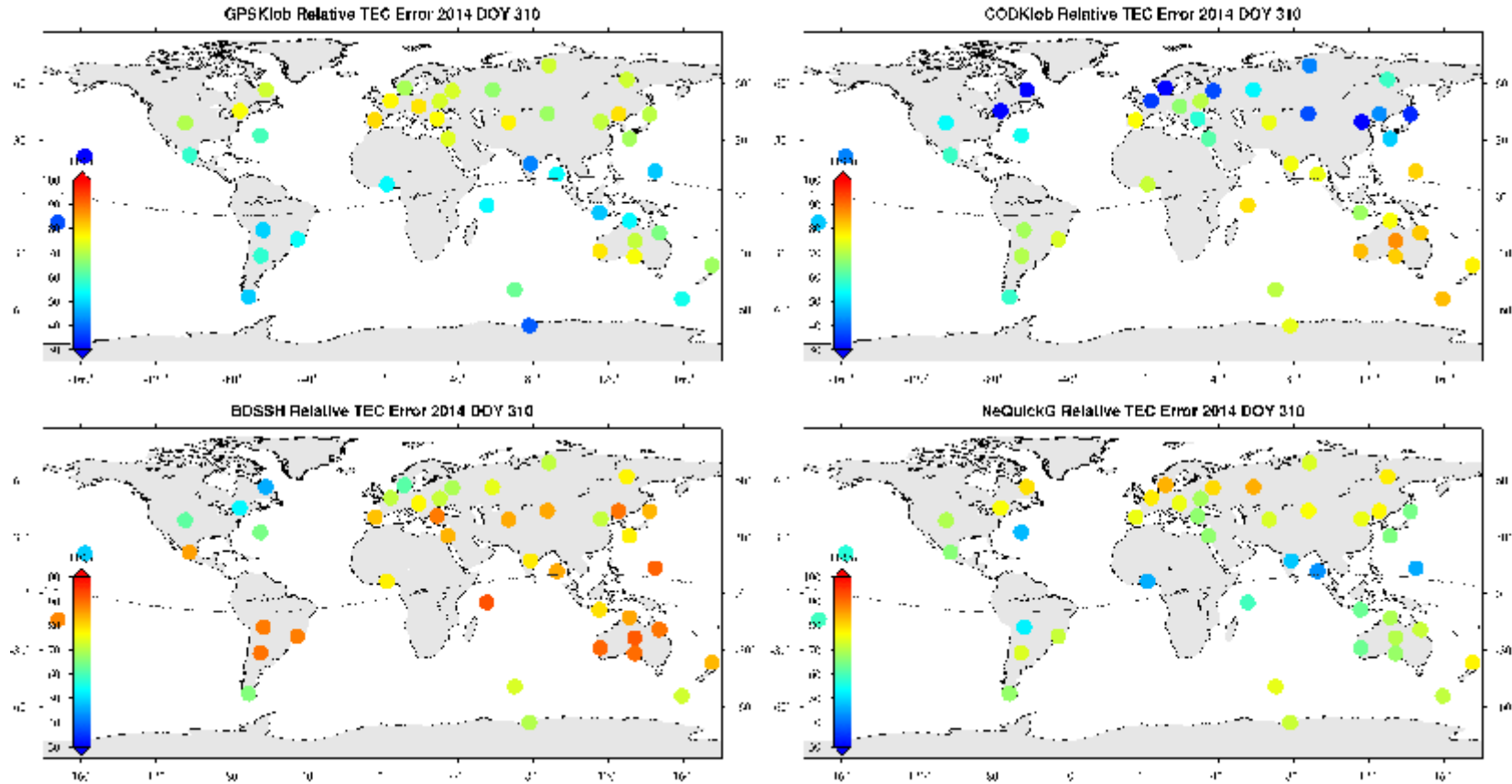
3.3 Validation (1/3)



Global ionospheric TEC maps derived from different ionospheric models
(2014-230, 12:00 UTC)

3. Refinement of broadcast ionospheric models

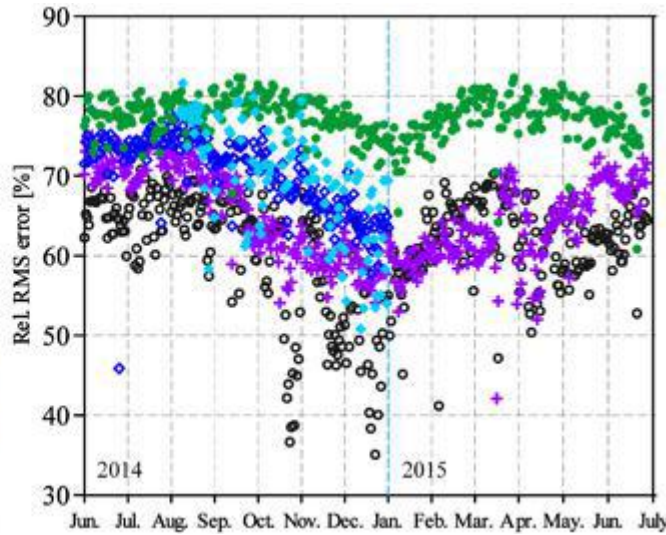
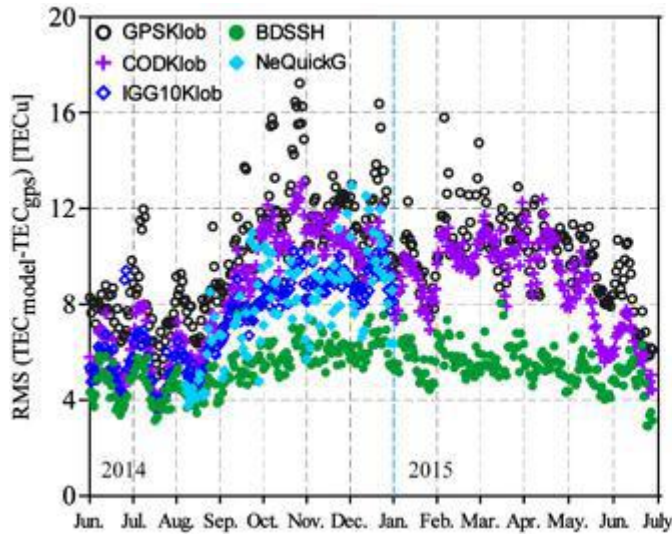
3.3 Validation (2/3)



Compared to GPS TEC: relative TEC correction accuracy, doy 310, 2014

3. Refinement of broadcast ionospheric models

3.3 Validation (3/3)



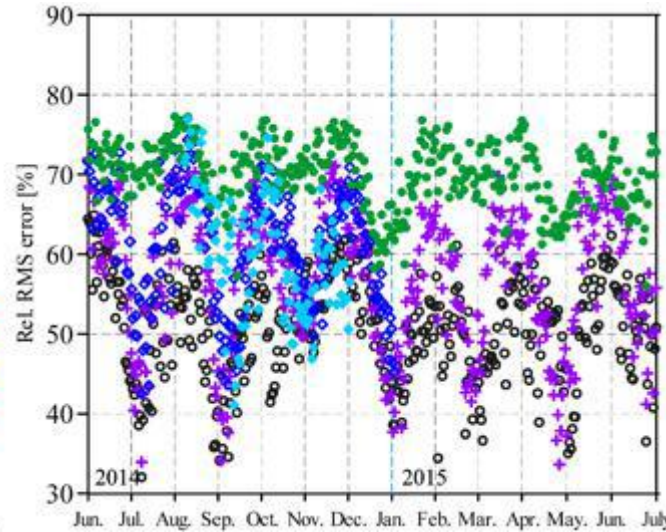
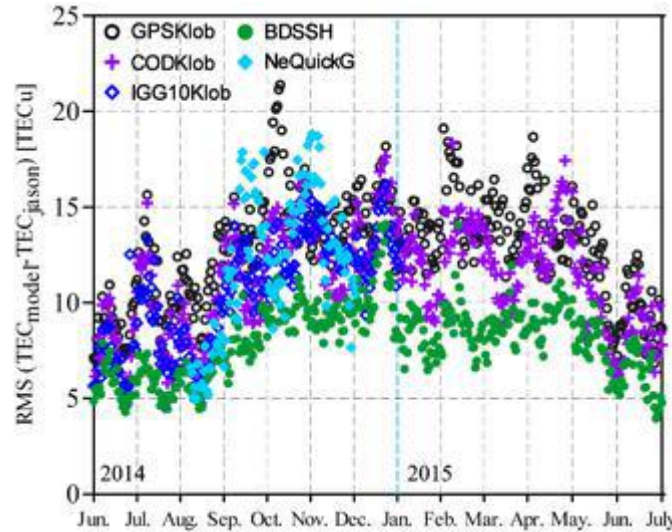
Compared with GPS TEC

GPSKlob: 9.9TECu, 59.8%

NeQuickG: 8.5TECu, 65.3%

BDSSH: 5.3TECu, 77.2%

(RMS, relative TEC accuracy)



Compared with JASON TEC

GPSKlob: 14.0TECu, 51.3%

NeQuickG: 12.3TECu, 58.9%

BDSSH: 8.6TECu, 71.4%

4. Development of ionospheric irregularity maps

4.1 Motivation

— The nominal ionospheric delay

- time delay in signal propagation of space-based radio systems like GNSS
- predicted and mitigated with various ionosphere correction models

— **The ionospheric irregularities**

- cause **rapid phase and amplitude fluctuations**
- induce unpredictable range errors and other serious problems for GNSS applications

— **IGS IONO WG Recommendation**

- Starting a new official/operational product—TEC fluctuation changes over the North Pole to study the dynamic of oval irregularities

— We intend to

- develop new ionospheric activity indicator to characterize the perturbation degree of the ionosphere
- provide ionospheric irregularity monitoring products (**post-processing → real-time**)

4. Development of ionospheric irregularity maps

4.2 Calculation of the new proposed RROT index

- **Step1:** calculate the rate of TEC (ROT) with dual-frequency phase data after cycle-slip detected

$$ROT = \frac{TEC_{t+\Delta t}^i - TEC_t^i}{\Delta t}$$

- **Step2:** calculate the single-differenced rot (drot) since ROT may still contain the trend term of ionospheric TEC in spite of small-scale fluctuations

$$drot(i) = rot(i) - rot(i-1) \quad \text{single-differenced rot, in TECu/min}^2$$

$$DROT = \sqrt{\langle drot^2 \rangle - \langle drot \rangle^2} \quad \text{std of drot changes, in TECu/min}^2$$

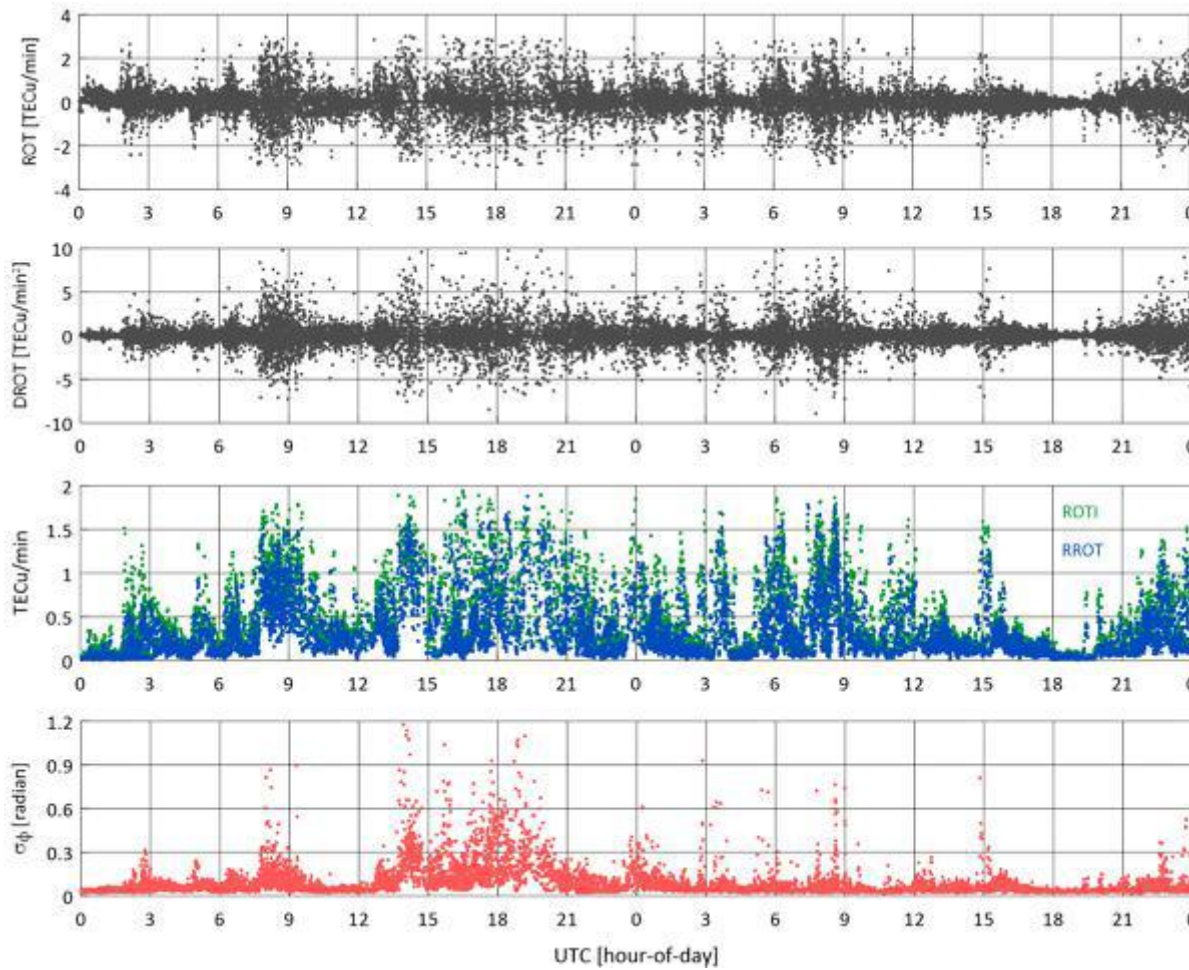
- **Step3:** form the ionosphere activity indicator, **RROT (Rate of ROT index)**, in TECu/min

$$RROT = \frac{\sigma_{rot}}{\sigma_{drot}} DROT \quad \sigma_{rot} \text{ and } \sigma_{drot} \text{ are related to the ionospheric TEC accuracy at epoch } i \rightarrow \sigma_{(i)}$$

4. Development of ionospheric irregularity maps

4.3 Validation (1/4)

Comparison of σ_{ϕ} (L1), ROTI and RROT



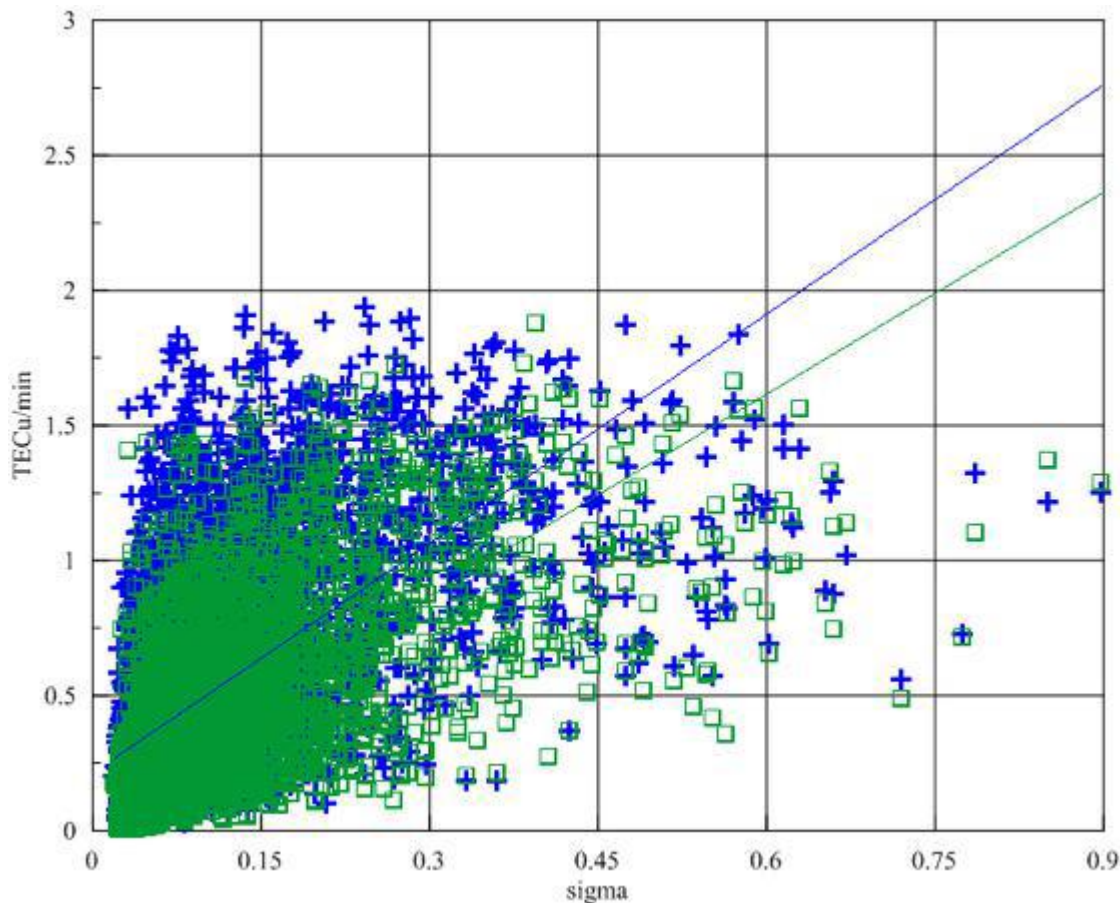
CHUC, Canada (Polar)
2015-03-17 (all sats.)

**RROT can capture the
ionospheric irregularity
period**

4. Development of ionospheric irregularity maps

4.4 Validation (2/4)

Correlation analysis σ_{ϕ} (L1), CHUC, Canada (Polar), 2015-03-17



ROTI

$$Y=0.213+2.830*X$$

Corr. Coef. 0.6186

RROT

$$Y=0.121+2.489*X$$

Corr. Coef. 0.6809

RROT index is applicable to monitor the ionospheric irregularities

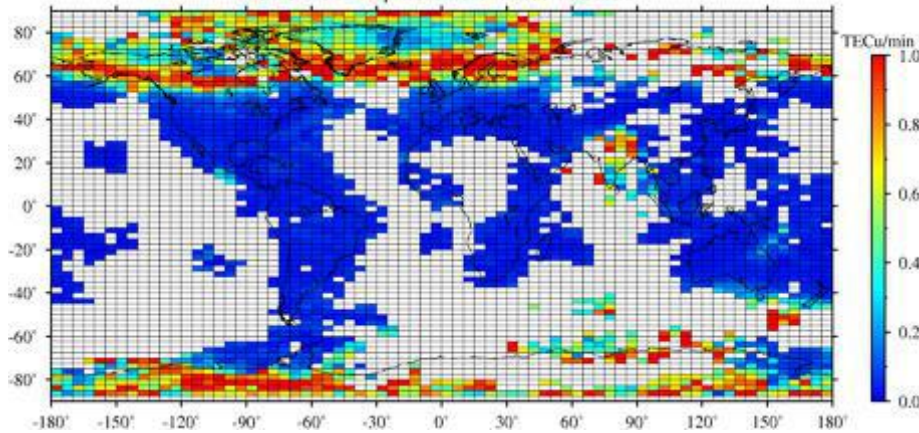
4. Development of ionospheric irregularity maps

4.4 Validation (3/4)

Global Ionospheric Irregularity Maps

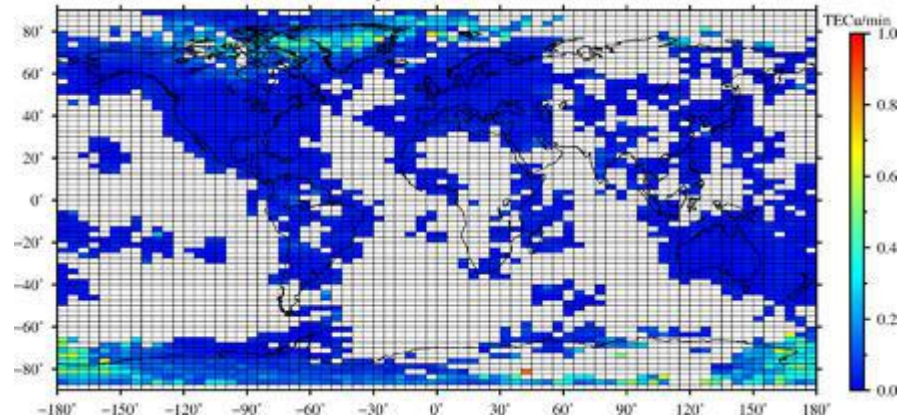
17/03-2015 ROTI

IONO ROTI Map 2015-03-17 15:00-16:00 UT



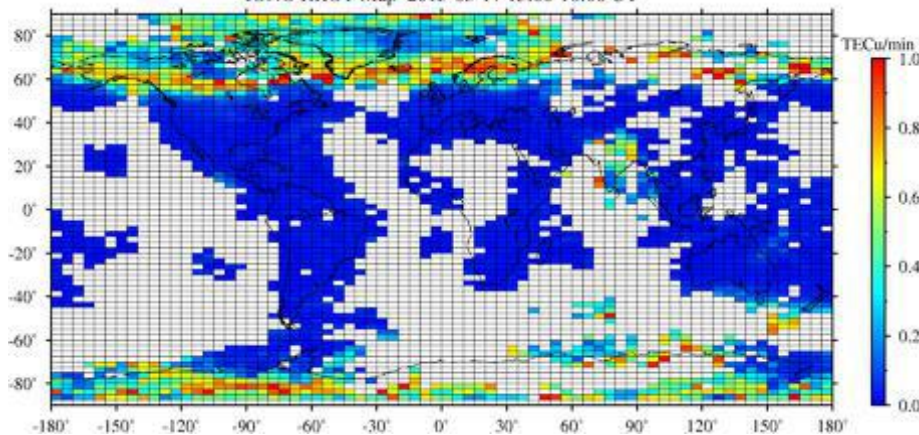
20/04-2017 ROTI

IONO ROTI Map 2017-04-20 15:00-16:00 UT



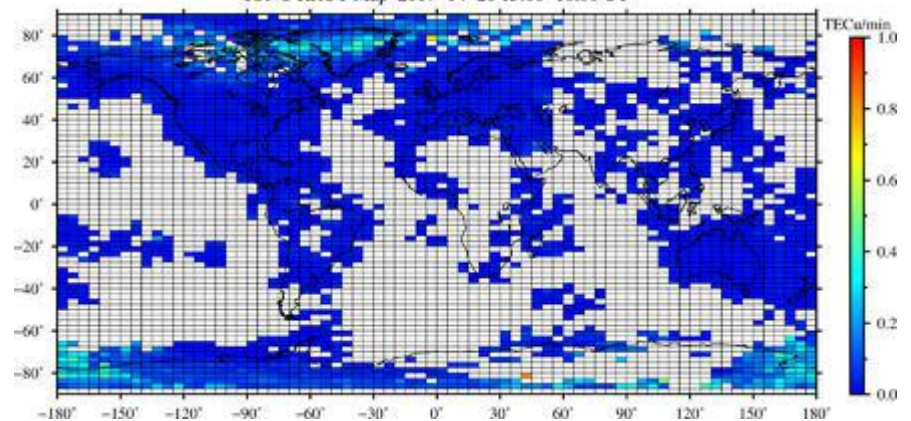
17/03-2015 RROT

IONO RROT Map 2015-03-17 15:00-16:00 UT



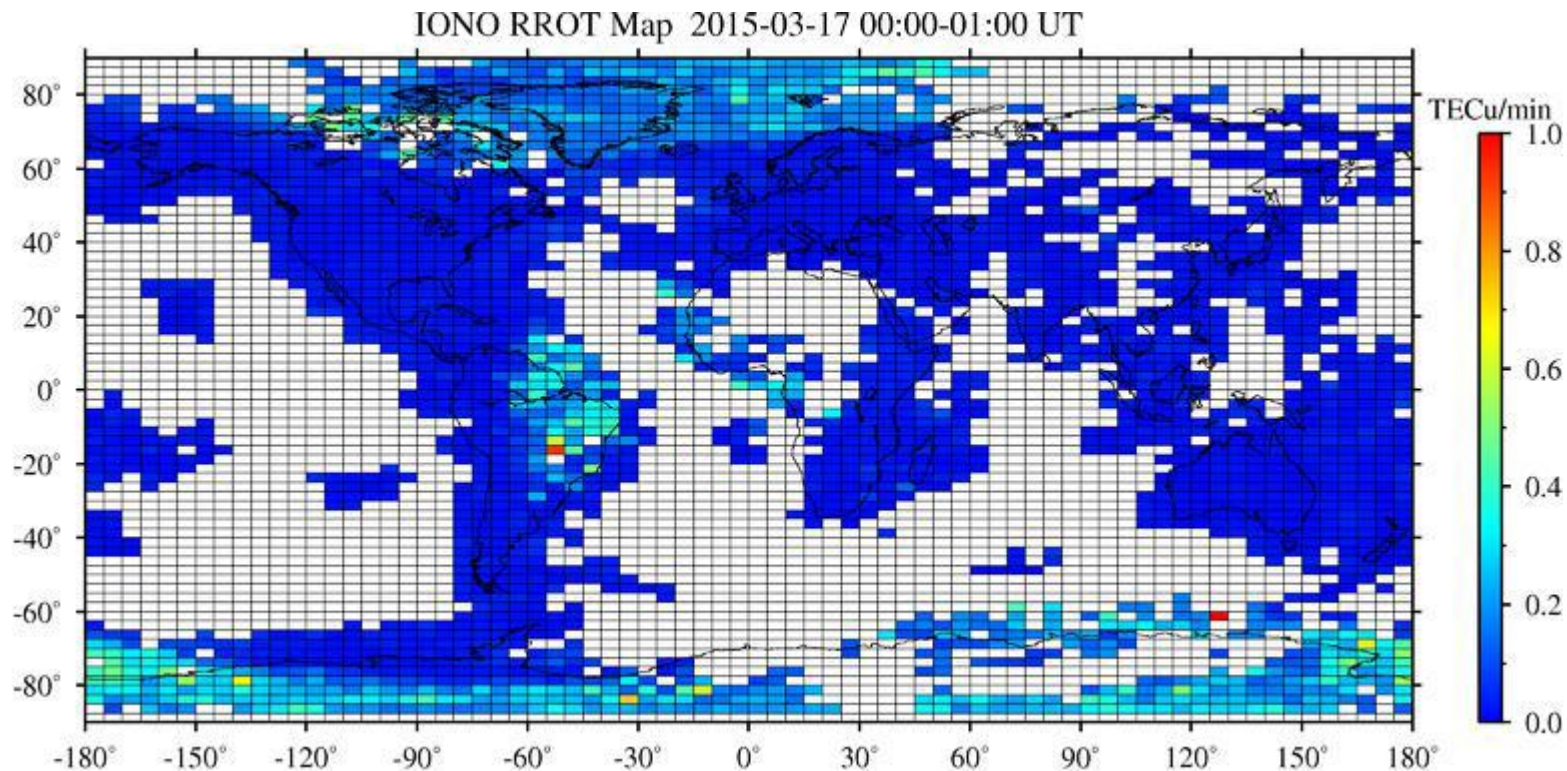
20/04-2017 RROT

IONO RROT Map 2017-04-20 15:00-16:00 UT



4. Development of ionospheric irregularity maps

4.4 Validation (4/4)



- Tracking networks – IGS+EPN+USCORS+ARGN (~2000 sites)
- Observations – GPS + GLONASS (L1+L2)
- Global grids – $\Delta\text{Lon} \times \Delta\text{Lat}$ (5.0 X 2.5) Temporal resolution – 1 h

5. Conclusions

Chinese Academy of Sciences (CAS) was nominated as a new Ionospheric Analysis Center (IAC) of the International GNSS Services (IGS) during the IGS workshop 2016 held in Sydney, Australia. **The following products are now provided by CAS:**

- **Global Ionospheric Maps (GIMs):** The rapid and final GIMs of CAS are now routinely uploaded to CDDIS since January 2017, with a latency of 1 and 4 days, respectively.
- **Refined Broadcast ionospheric models (BIMs):** The re-estimated BIM coefficients are calculated routinely based on 30 global stations, including GPS Klobuchar, BDS Klobuchar-like and BDSSH, as well as Galileo NequickC.
- **Ionospheric irregularity maps:** RROT and ROTI maps are routinely generated with multi-GNSS data obtained from ~2000 globally distributed stations.
- **Multi-GNSS differential code biases (DCBs):** CAS's DCB products are derived with IGGDCB method, which employs local ionospheric model for the combined estimation of DCBs and ionospheric activities. DCBs of all relevant signals of GPS, GLONASS, BDS, Galileo are included.

5. Conclusions

CAS Ionospheric Analysis Center of the IGS

Chinese Academy of Sciences (CAS) was nominated as a new Ionosphere Analysis Center (IAC) of the International GNSS Services (IGS) during the IGS workshop 2016 held in Sydney, Australia.

Global Ionospheric Maps (GIMs): CAS's GIMs are generated by SHPTS method, which takes advantages of the SH and GTS functions on global and local scales, respectively. The rapid and final GIMs of CAS are now routinely uploaded to CDDIS since January 2017, with a latency of 1 and 4 days.

Multi-GNSS differential code biases (DCBs): CAS's DCB products are derived by IGGDCB method, which employs local ionospheric model for the combined estimation of DCBs and ionospheric activities. DCBs of all relevant signals of GPS, GLONASS, BDS, Galileo are included.

Refined Broadcast Ionospheric models (BIMs): The re-estimated BIM coefficients of GPS (Klobuchar), BDS (Klobuchar-like and BDS5H) and Galileo (NeQuick) are calculated routinely based on GPS and GLONASS observations from around 30 global stations.

Ionospheric irregularity monitoring products: The ionosphere activity index, rate of ROT change index (RROT), was developed to characterize the perturbation degree of the ionosphere. RROT and ROTI maps are routinely generated with multi-GNSS data obtained from around 2000 globally stations.

Real-time (RT) TEC maps: The RT 2-dimensional ionospheric TEC maps of CAS are calculated by Spherical Harmonics (SH) with RT data streams as well as the high-quality ionospheric prediction products. CAS's global and regional (China, Europe and Australia) RT TEC maps are now in progress, which will be open to public by September, 2017.

Many thanks to Prof. Andrzej Krankowski, Prof. Manuel Hernández-Pajares and Dr. Oliver Montenbruck for their helpful discussions and comments as well as the coordination in the delivery of CAS's products to the IGS.



Institute of Geodesy and Geophysics
Academy of Opto-Electronics
Chinese Academy of Sciences

Overview of CAS's ionospheric products

Product	Type	FTP archive directory	File name/Mountpoint	Latency	Sample interval
GIM	rapid	ftp://ftp.gipp.org.cn/product/lonex/	casg5d4d0.Syri	1 day	30 mins
	final	ftp://ftp.gipp.org.cn/product/lonex/	casg5d4d0.Syri	4 days	
DCB	MGEX	ftp://ftp.gipp.org.cn/product/dcb/mgex/	CASMGEXPAR_YYYY5d4d0000_01D_01D_DCB.B5X	2 days	
	EPN	ftp://ftp.gipp.org.cn/product/dcb/epn/	CASGEPNPAR_YYYY5d4d0000_01D_01D_DCB.B5X	2 days	24 hours
	TGD	ftp://ftp.gipp.org.cn/product/dcb/tgd/	CASGTDPRM_YYYY5d4d0000_01D_01D_DCB.B5X	1 days	
BIM	8-Par Klobuchar		KLOB_08_5d4d0.SyriN		
	10-Par Klobuchar		KLOB_10_5d4d0.SyriN		
	BDS5H	ftp://ftp.gipp.org.cn/product/bim/bds/	GBDS5d4d0.SyriN	4 days	24 hours
	NeQuick5		GNQ5d4d0.SyriN		
Irregularity maps	ROTI		casg_rot5d4d0.Syri		1 hour
		ftp://ftp.gipp.org.cn/product/lonex/global/	casg_rot5d4d0.Syri		15 mins
	RROT		casg_rrot5d4d0.Syri	3 days	1 hour
			casg_rrot5d4d0.Syri		15 mins
RT TEC maps	global		cas10		
	China	products.gipp.org.cn	cas10		
	Europe	(in progress, be ready in Sep. 2017)	cas11	real-time	5 mins
	Australia		cas12		

If any problems or suggestions in using CAS's ionospheric products, please feel free to contact us:

Prof. Yunbin Yuan yybgps@asch.whigg.ac.cn

Dr. Zishen Li lizhisen@aoe.ac.cn

Dr. Ningbo Wang wangningbo@aoe.ac.cn

Welcome to the poster room for the short note of CAS's ionospheric products.

Many thanks to Prof. **Andrzej Krankowski**, Prof. **Manuel Hernández-Pajares** and Dr. **Oliver Montenbruck** for their helpful discussions and comments as well as the coordination in the delivery of CAS's products to the IGS.



Tanks for your attention!

[lizishen@aoe.ac](mailto:lizishen@aoe.ac.cn)
[.cn](mailto:lizishen@aoe.ac.cn)