Ionosphere Parameter Optimization Using GNSS Data Ingestion during Geomagnetic Storm in China

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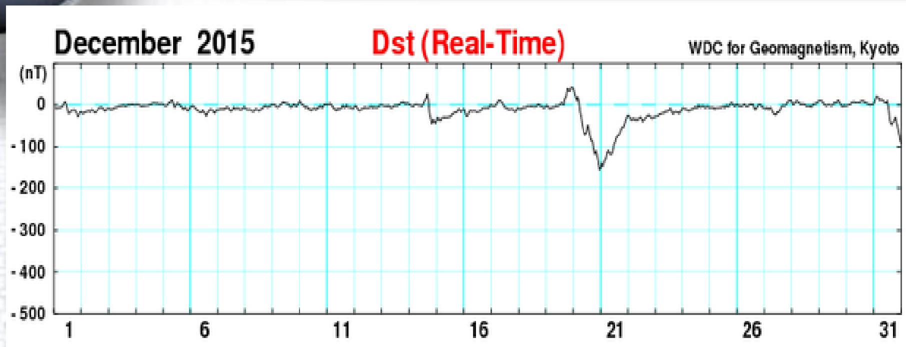
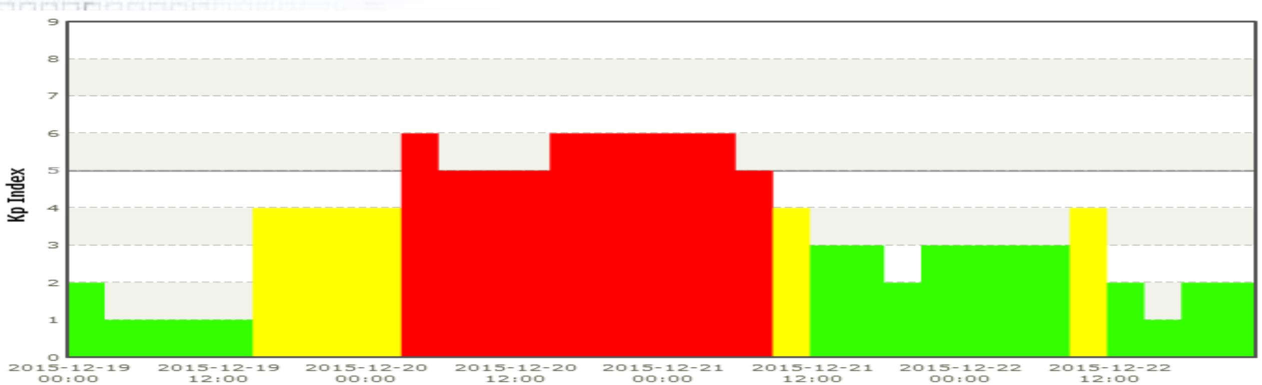
Background

- Maximum plasma frequency in the ionosphere usually located in the F2 layer and is called the critical frequency foF2.It is an important parameter for the High Frequency communications and could reflects the ionospheric variability
- A network of ground based vertical sounding instruments has been set up to accurately observe, monitor and forecast ionosphere parameters. However, most instruments are fairly expensive to maintain, large weight and size.
- Using the observed ionosonde foF2 data, missed observations are usually observed during enhanced solar activity or magnetic disturbance days. It was NOT caused by human intervention or by machine out of work. It`s a pure natural phenomena caused by the ionosphere itself variation.
- Using empirical ionosphere model to predict foF2, the performance is better during magnetic quiet days but poor at magnetic disturbance days. Using dual-frequency GNSS data, the accurate TEC could be retrieved. GNSS data ingestion to empirical model maybe a resolve may.

Magnetic Storm



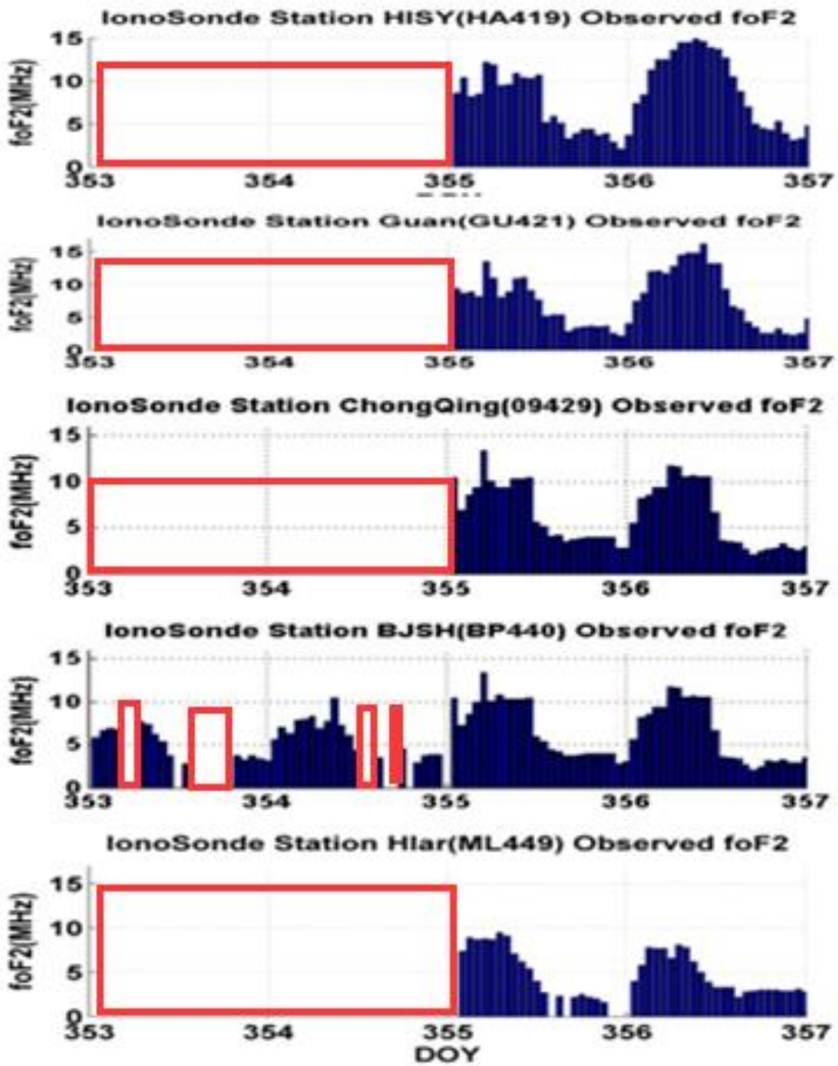
Dec.19 and Dec.23, 2015. Dst index reached below -160nT belong to Strong geomagnetic storm



Kp index reached 6-7 on Dec.20and Dec.21

HLAR (49.6° N ,117.5° E)
BJSH (40° N ,116.3° E)
CQCS (29.5° N, 116.4° E)
GUAN(113.4° E,23.1° N)
HISY(19.4° N,109° E)

foF2 missed Observations Observed by Ionosonde during DOY353-356



TEC Estimation by GPS+GLONASS

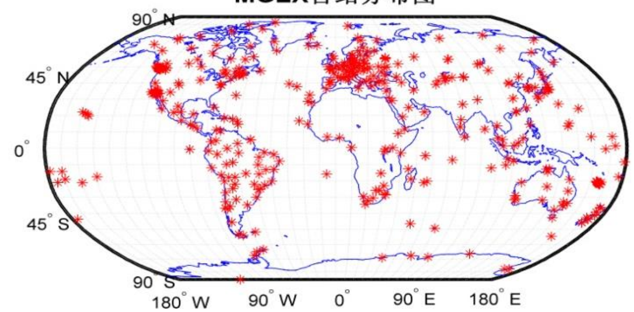
15 degree Spherical harmonics functions

$$VTEC = \sum_{n=0}^{n_{\max}} \sum_{m=0}^{n} \tilde{P}_{nm} (\sin \varphi)^i (\tilde{C}_{nm} \cos(m\lambda) + \tilde{S}_{nm} \sin(m\lambda))$$

$$\overline{P_4^G} = 40.28 \cdot \frac{f_i^2 - f_j^2}{f_i^2 f_j^2} VTEC^G(\varphi, \lambda) \cdot mf(z) + (DCB_s^G + DCB_r^G)$$

$$\overline{P_4^R} = 40.28 \cdot \frac{f_i^2 - f_j^2}{f_i^2 f_j^2} VTEC^R(\varphi, \lambda) \cdot mf(z) + (DCB_s^R + DCB_r^R)$$

MGEX台站分布图

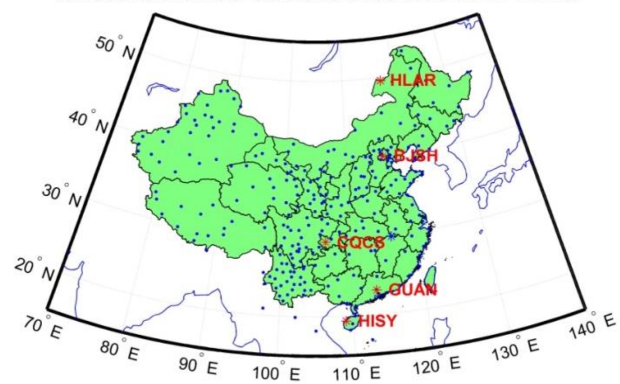


$$\sum_{j=1}^{32} DCB_s^{Gj} = 0$$

$$\sum_{j=1}^{24} DCB_s^{Rj} = 0$$

$$mf(z) = \frac{1}{\cos z'}; \sin z' = \frac{R}{R+H} \sin(\alpha z)$$

Ionosonde/GNSS Stations Distribution in China



$$X = (\tilde{C}_{nm} \tilde{S}_{nm} DCB_s^G DCB_r^G DCB_s^{Gj} DCB_s^{Rj})^T$$

The Galileo NeQuick Model

- Semi-empirical model which describes spatial and temporal variations of the ionosphere electron density
- Uses the peaks of the three main ionospheric regions (E, F1, and F2) as anchor points
- Bottom side model : ITUR coefficients for foF2 and M(3000)F2 and simplified models for foF1 and foE ,related with the solar zenith angle, season and solar activity.
- Topside model : Height region above the F2-layer peak, represented by a semi-Epstein layer with a height dependent thickness parameter.
- INPUT: Position, time and solar activity index (10.7cm radio flux F10.7 or the monthly smoothed sunspot number R12)
- OUTPUT: Electron density Integration to TEC

The Galileo NeQuick Model Cont.

Epstein Function

$$N_{Epstein}(\boldsymbol{h}; \boldsymbol{hmax}, \boldsymbol{Nmax}, \boldsymbol{B}) = \frac{\mathbf{4}\boldsymbol{Nmax}}{\mathbf{1}+\mathbf{exp}\left(\frac{\boldsymbol{h}-\boldsymbol{hmax}}{\boldsymbol{B}}\right)} \mathbf{exp}\left(\frac{\boldsymbol{h}-\boldsymbol{hmax}}{\boldsymbol{B}}\right)$$

BottomSide:

$$N(h) = NF_2(h) + NF_1(h) + NE(h)$$

$$NF_2(h) = \frac{4NmF_2}{1+exp\left(\frac{h-hmF2}{B_2}\right)} exp\left(\frac{h-hmF2}{B_2}\right)$$

$$NF_1(h) = \frac{4Nm*F_1}{1+exp\left(\frac{h-hmF1}{B_1}\xi(h)\right)} exp\left(\frac{h-hmF1}{B_1}\xi(h)\right)$$

$$NE(h) = \frac{4Nm*E}{1+exp\left(\frac{h-hmE}{B_E}\xi(h)\right)} exp\left(\frac{h-hmE}{B_E}\xi(h)\right)$$

$$\xi(h) = exp\left(\frac{10}{1+1|h-hmF_2|}\right)$$

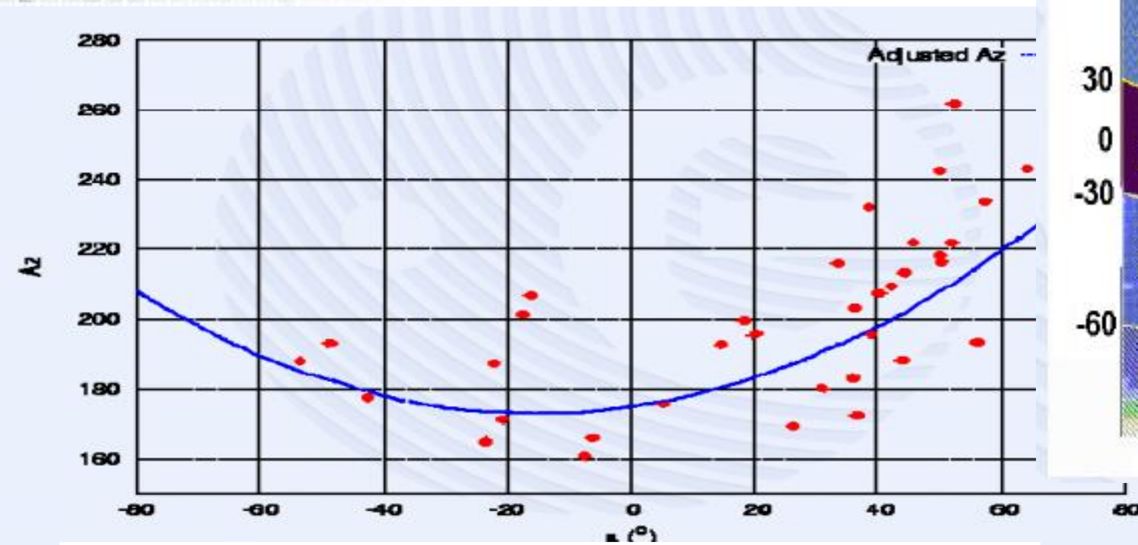
TopSide

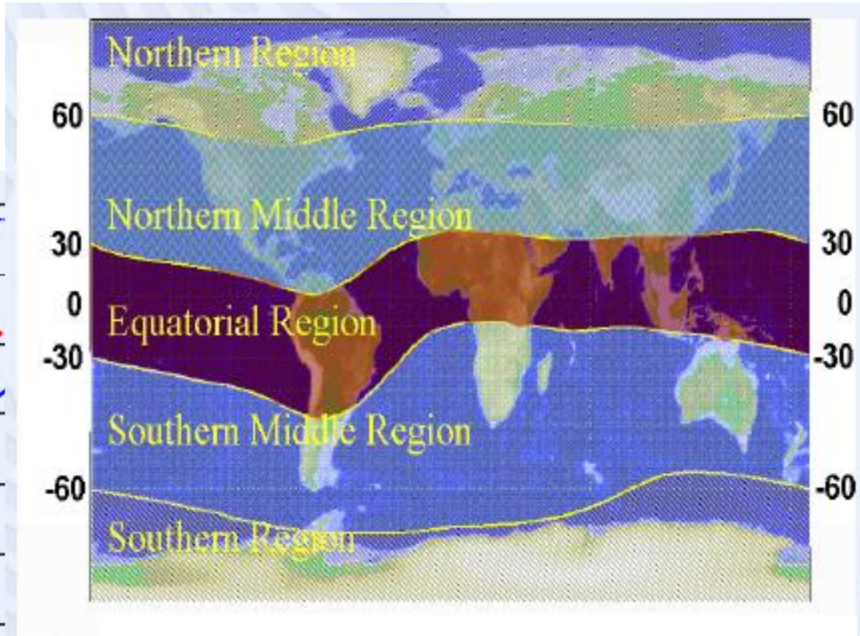
- $$N(h) = \frac{4NmF_2}{(1+exp(z))^2} exp(z)$$

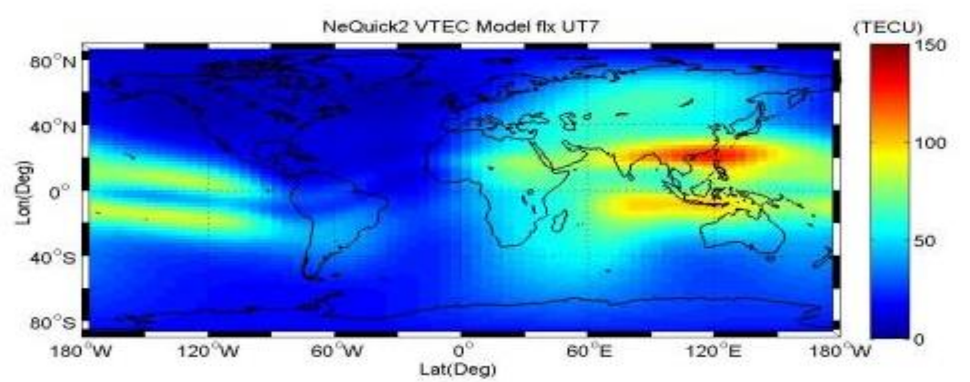
$$Z = \frac{h-hmF_2}{B_{F2top}\left[1+\frac{12.5(h-hmF2)}{100B_{F2top}+0.125(h-hmF2)}\right]}$$

The Galileo NeQuick Model Cont.

$$Az = a_{i0} + a_{i1} * \mu + a_{i2} * \mu^2$$



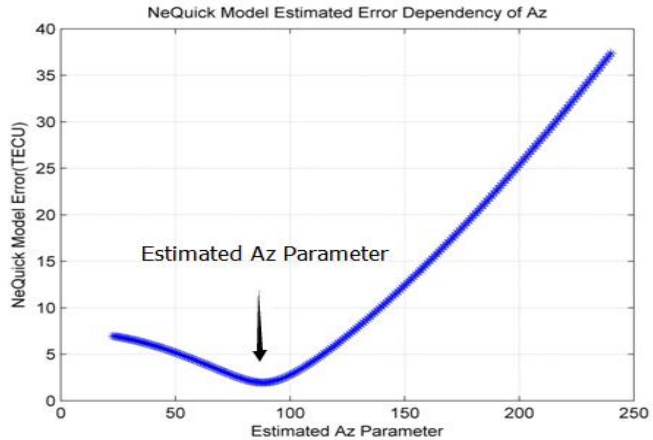




Region 1	60deg < *MODIP* ≤ 90deg
Region 2	30deg < *MODIP* ≤ 60deg
Region 3	-30deg ≤ *MODIP* ≤ 30deg
Region 4	-60deg ≤ *MODIP* < -30deg
Region 5	-90deg ≤ *MODIP* < -60deg

Az and foF2 Estimation

The effective ionization level ,Az parameter is an important index to introduce daily solar activity into NeQuick. It will be estimated by minimizing the squared model error for 24-hour period over a range of Az values



$$Az = \underset{\substack{Az \geq Az_{\min} \\ Az \leq Az_{\max}}}{\arg\min} \sum_{i=1}^{n} \left| TEC_{Measured} - TEC_{NeQuick(Az)} \right|_i^2$$

The critical frequency of F2 layer foF2 is expressed as the Fourier time series based on ITU-R ionosphere characteristics

$$foF2(\lambda,\theta,T,\mu) = \sum_{k=0}^{K} U_{0,k}\, G_k(\lambda,\theta,\mu) + \sum_{j=1}^{6} \left[\cos jT \sum_{k=0}^{K} U_{2j,k}\, G_k(\lambda,\theta,\mu) + \sin jT \sum_{k=0}^{K} U_{2j-1,k}\, G_k(\lambda,\theta,\mu) \right]$$

$$U_{j,k} = f2_0 \left(1 - \frac{R12}{100}\right) + f2_{100} \frac{R12}{100} \qquad T = (15^0 * UT - 180^0) * \pi / 180^0$$

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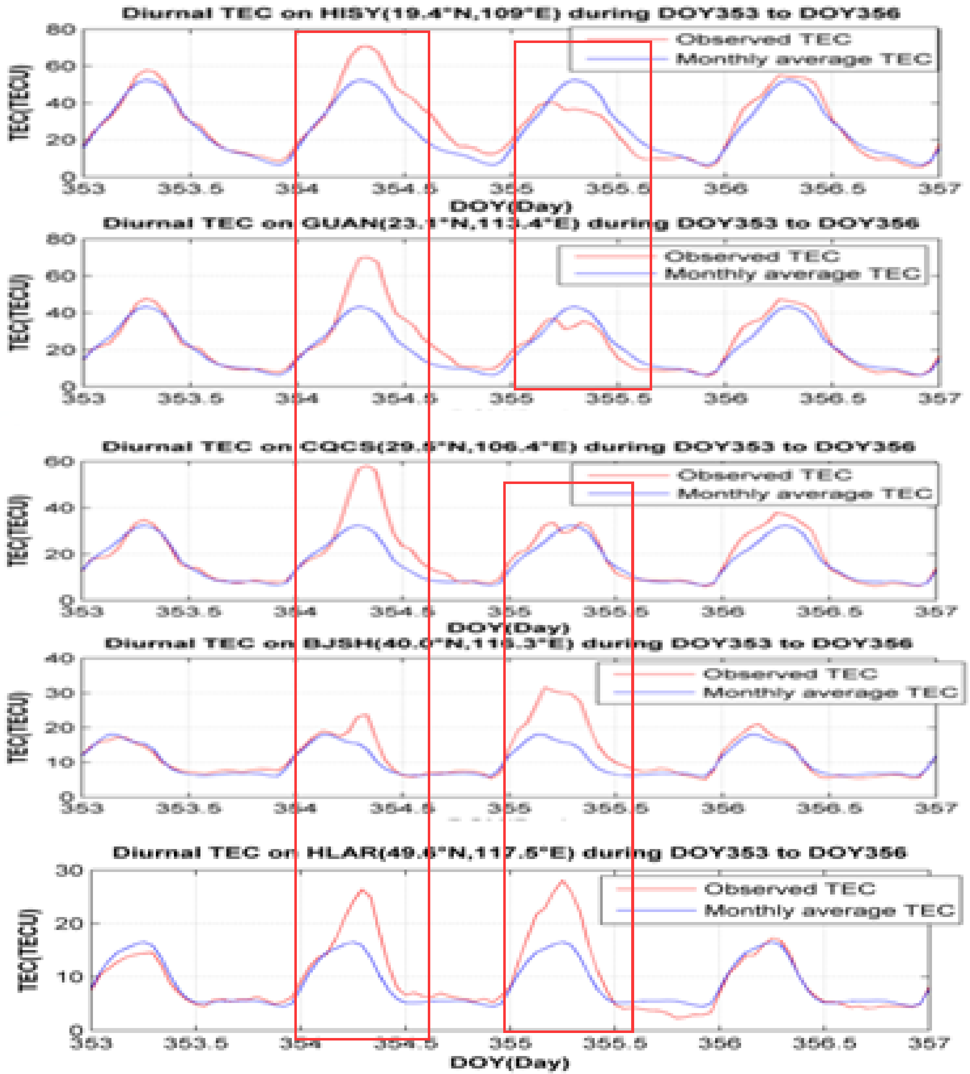
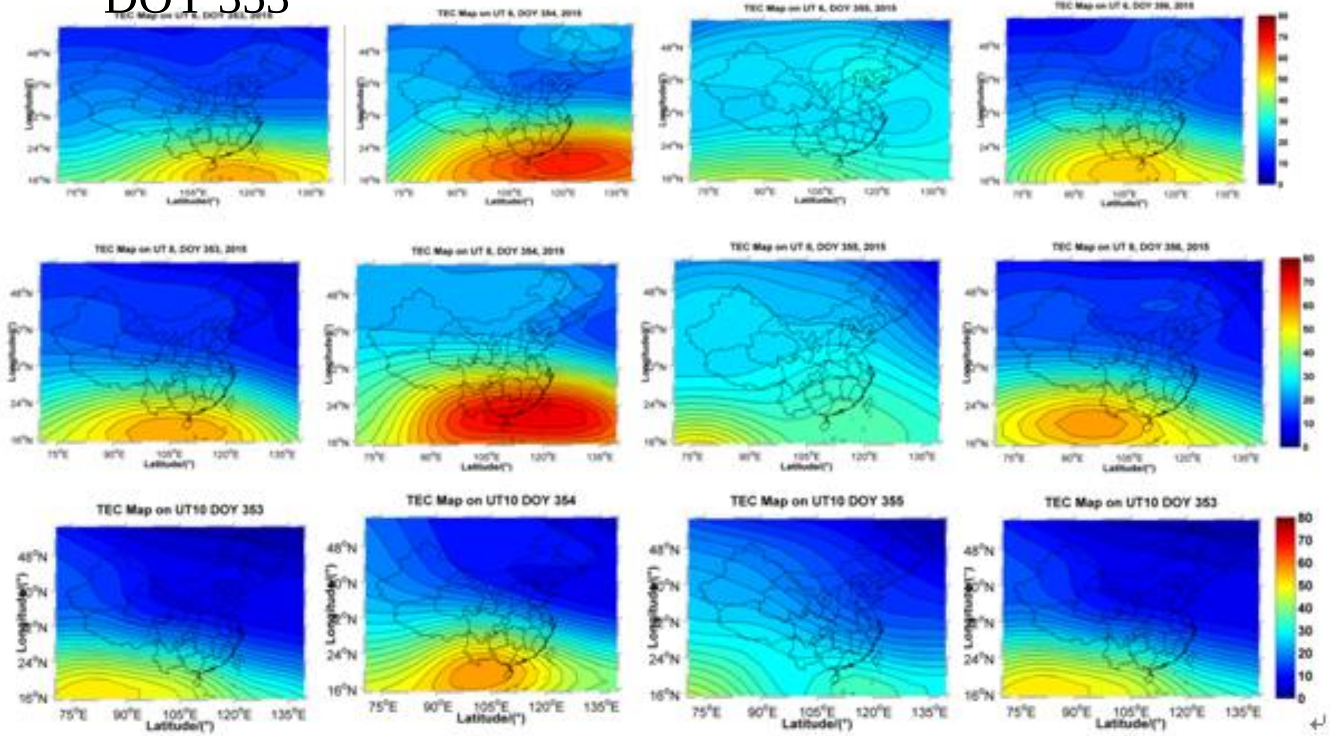
TEC response from DOY353 to 356



TEC Evolution Process

	DOY 353	DOY 354	DOY 355	DOY 356
UT 6				
UT 8				
UT 10				



1.Noticeable positive enhancement in the TEC at 6:00 UT to 10:00 UT on Dec.19(DOY354) at north hump area.

2.Obvious negative enhancement for low-latitude stations on Dec.20(DOY355) and the north hump area near equator was inhibited. But mid-high latitude stations still maintain positive enhancement like DOY354.

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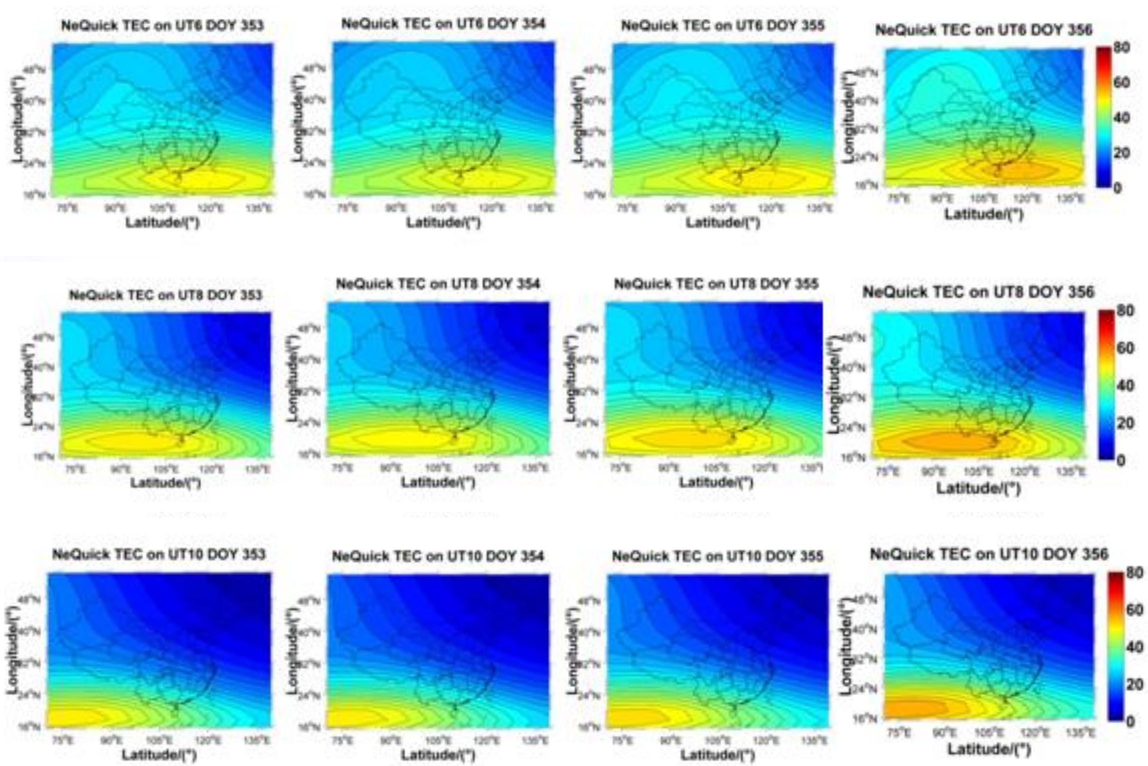
NeQuick Model Estimated TEC at Geomagnetic Storm

DOY 353 DOY 354 DOY 355 DOY 356

UT 6

UT 8

UT 10



The NeQuick model shows a very smooth variation during the geomagnetic storm period. It does not show any response to geomagnetic activity. Its reason may be its input parameters only associate with the sun's activity level, but do not relate with the geomagnetic index .It can only represents diurnal variation trend as similar level of magnetic quiet days.

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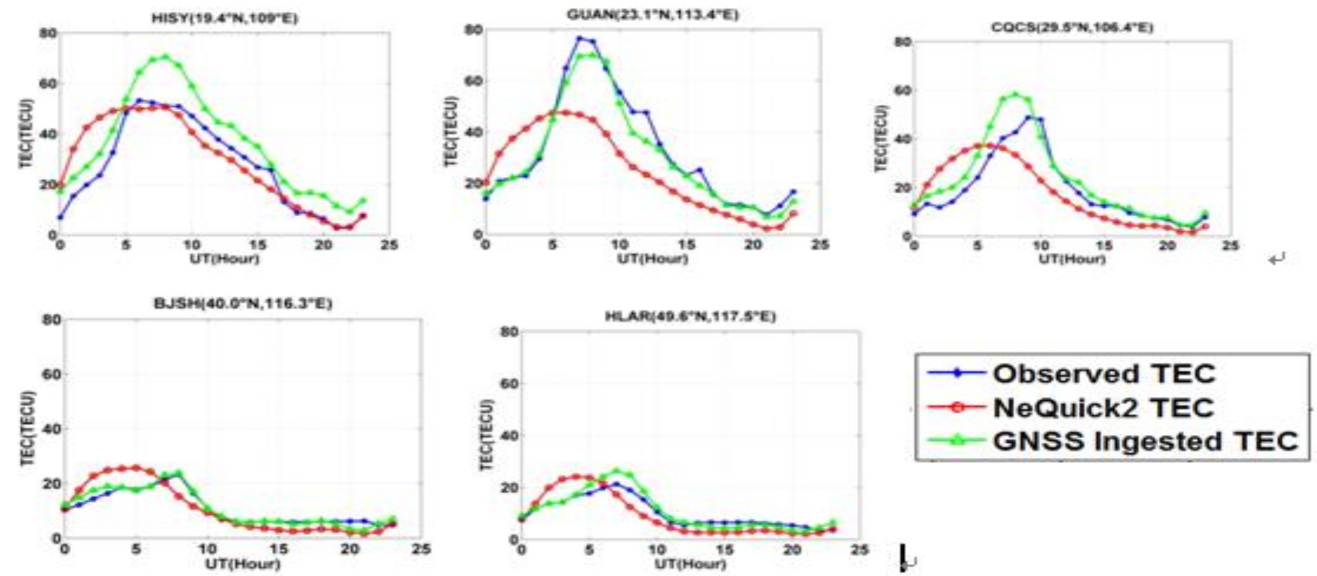
Improvement to TEC Accuracy - I



•TEC NeQuick model represents average diurnal variation in geomagnetic storm period and cannot describe geomagnetic storm from the beginning phase, main phase and recovery phase.

•The NeQuick under estimate the TEC about 10-30 TECU at UT8-10 at daytime.

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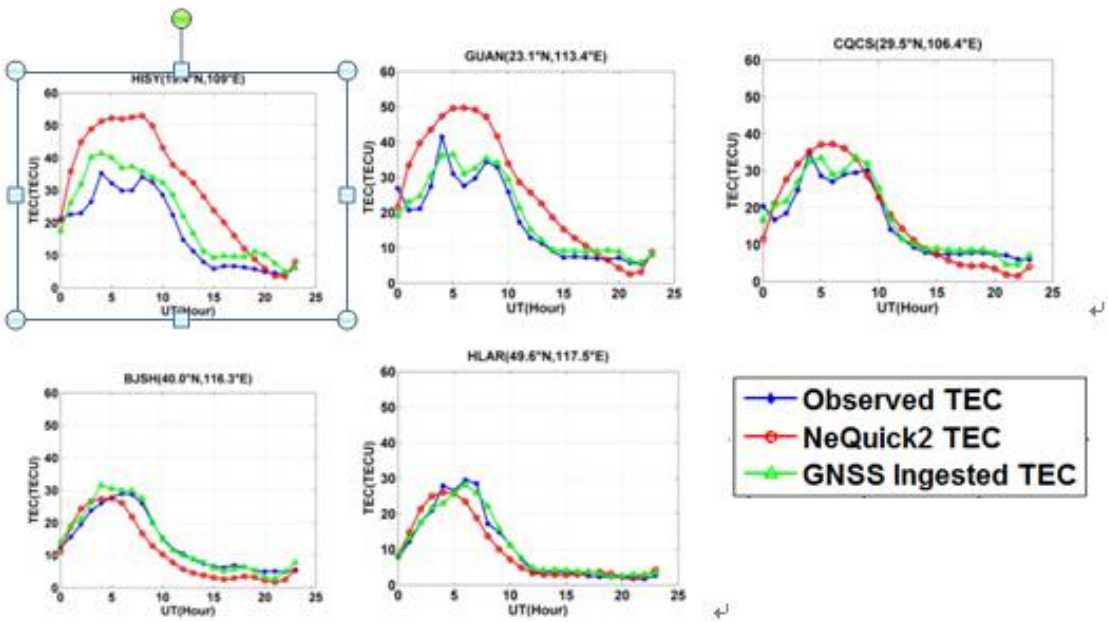
Improvement to TEC Accuracy - II



- The GNSS Ingested Model picks up both the positive enhancements on doy354 and negative enhancements on doy355 during the geomagnetic storm at all five stations.
- It could describe the double maximum peaks that exist within the observed date at low-latitude stations on DOY355.
- During the day time it is negative phase and then recovered to magnetic quite level at midnight .
- NeQuick over estimated the TEC about 10-20TECU for low –latitude stations.

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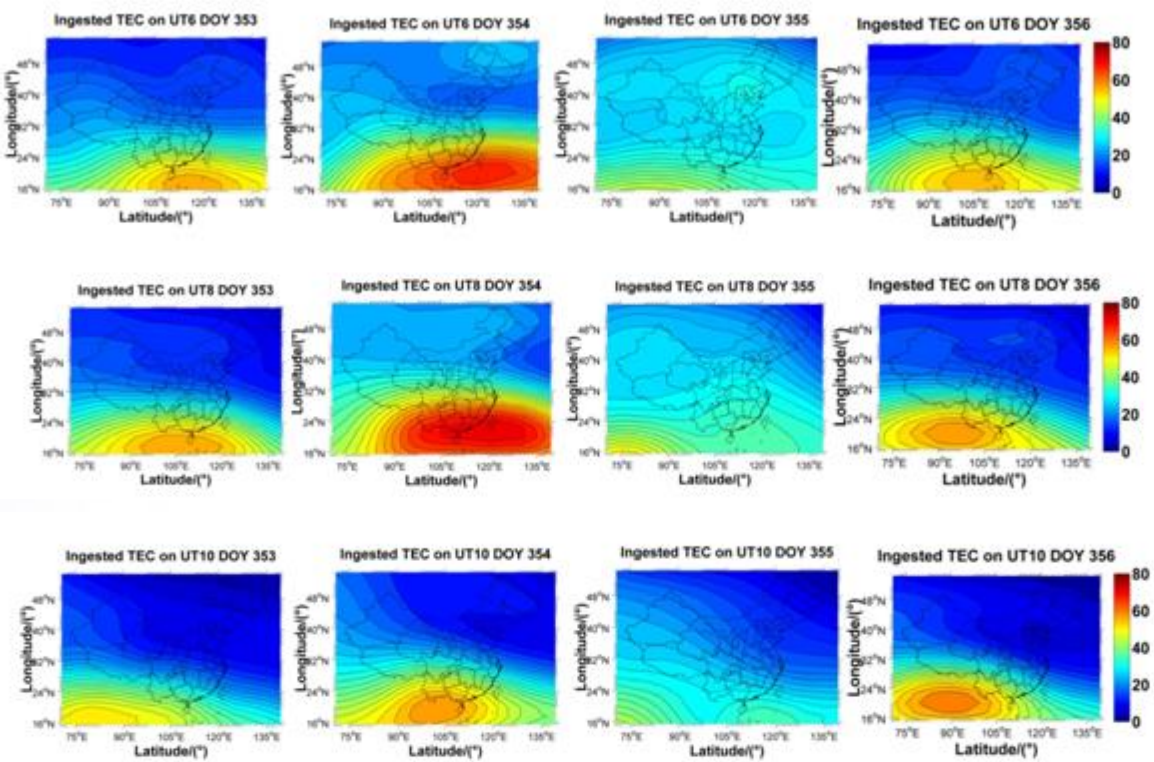
Ingested TEC Map

DOY 353 DOY 354 DOY 355 DOY 356

UT 6

UT 8

UT 10



1.In good agreement with TEC map retrieved by GNSS data.

2.Noticeable positive enhancement in the TEC at 6:00 UT to 10:00 UT on Dec.19(DOY354),

2.Obvious negative enhancement for low-latitude stations but positive enhancement for mid-high latitude stations on Dec.20(DOY355)

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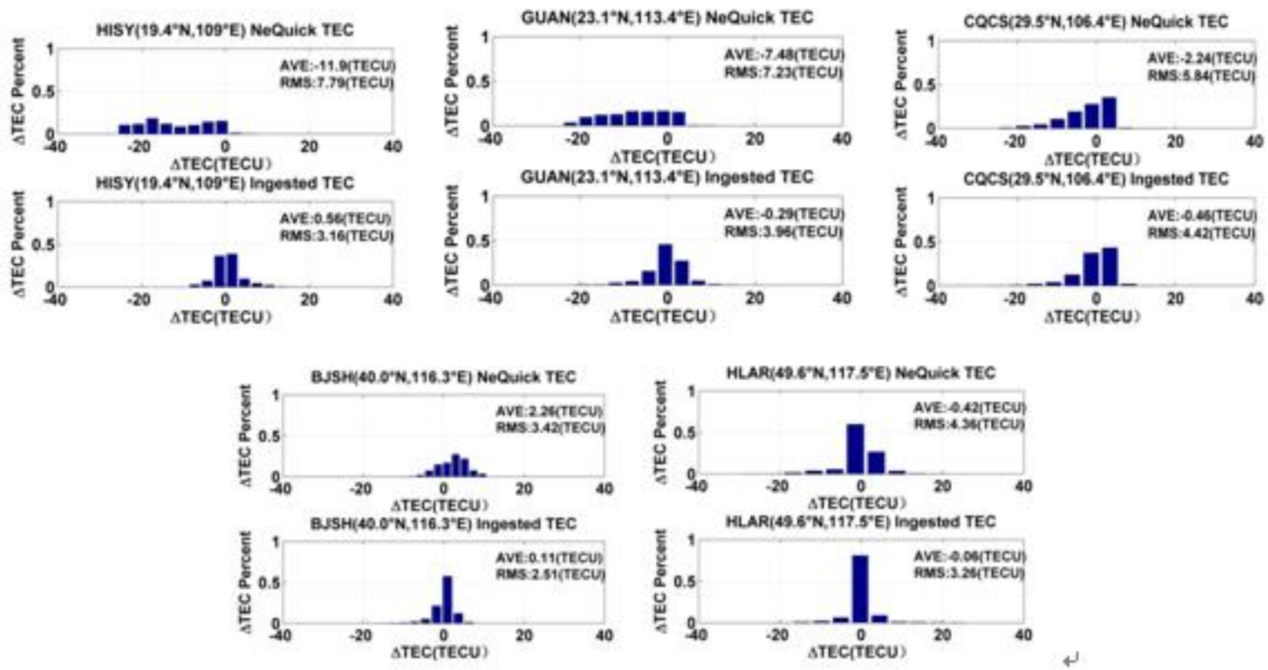
TEC Error Distributions



- NeQuick model overestimates the TEC for low-latitude stations during negative enhancement. The TEC average bias is -7.48TECU and -11.9 TECU for Guanzhou and Hainan.
- The TEC error distribution was optimized significantly after GNSS data ingestion. It become unbiased normal distributions from biased estimation .
- TEC RMS has been improved for all the latitude areas. The low latitude region improved more ,as shown in table.It is improved from 30% to 40% for low latitude area, for high-latitude improved from 10% to 20%.

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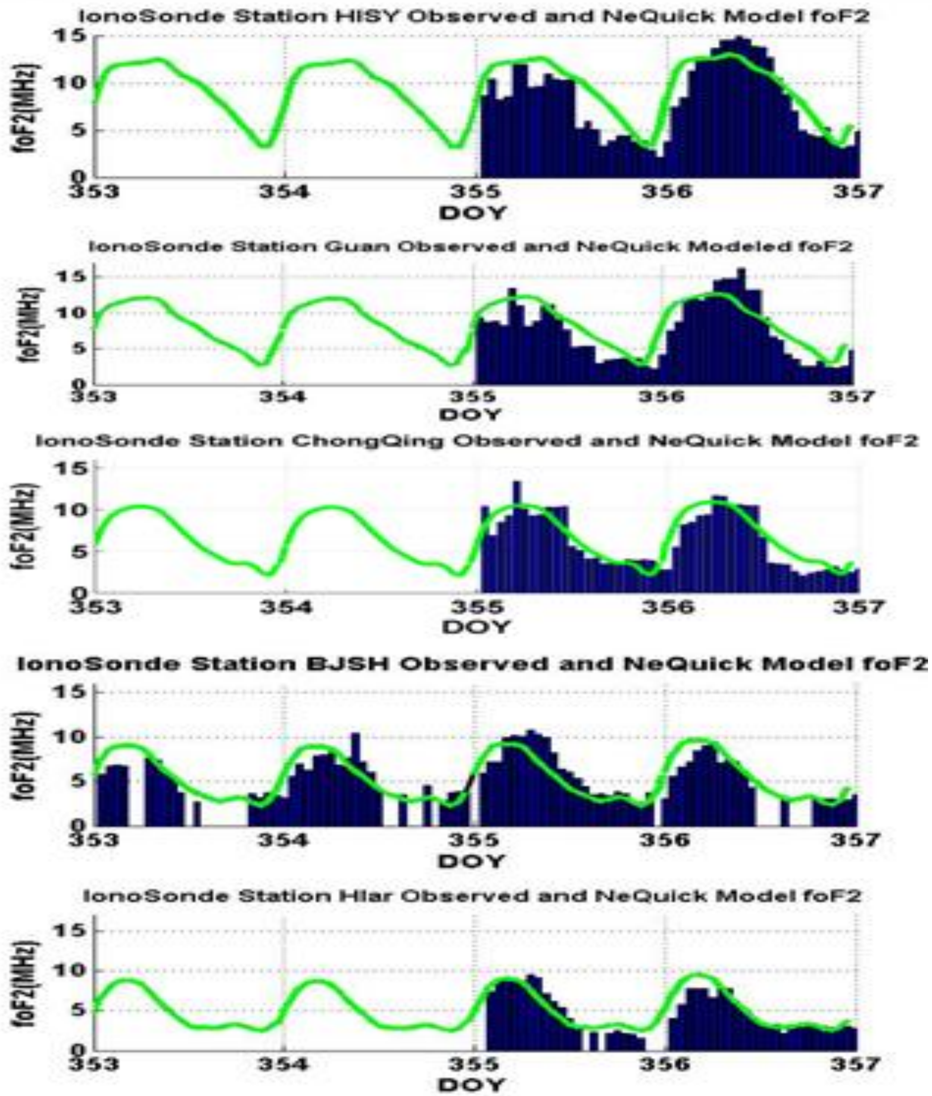
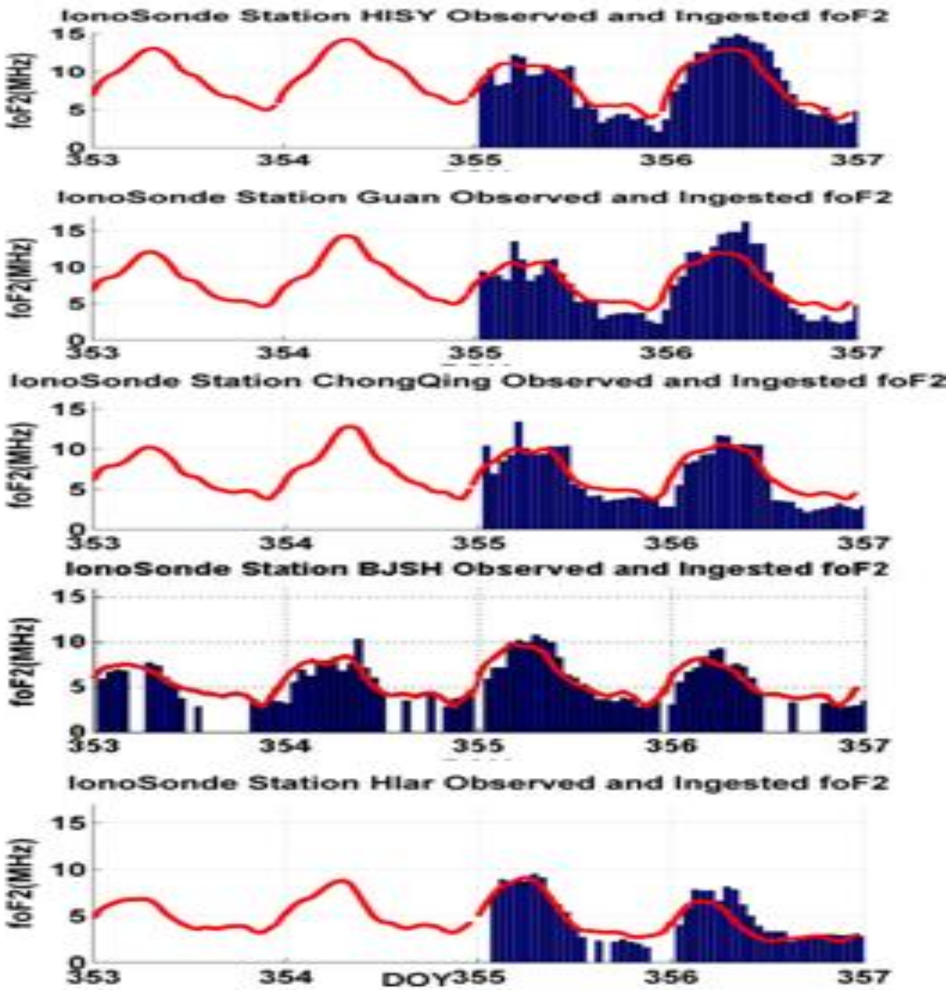
NeQuick Modeled Estimated foF2 at Geomagnetic Storm



Improvement to foF2 Evaluation-I



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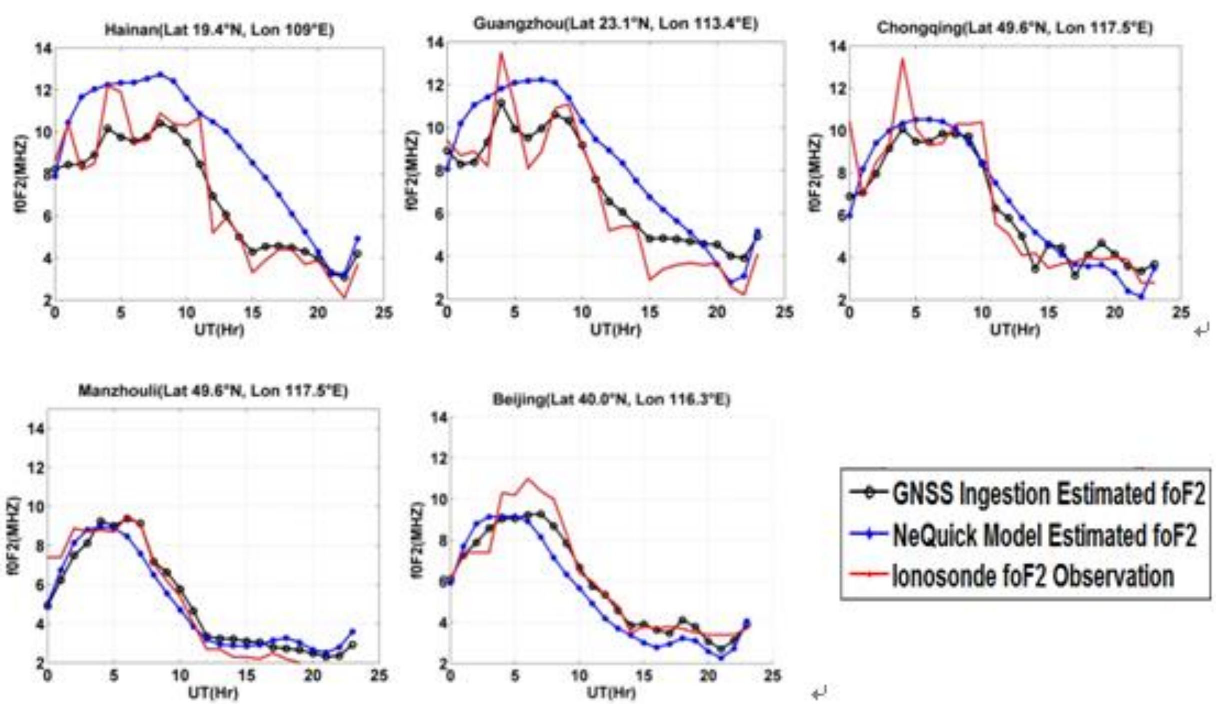
Improvement to foF2 Evaluation-II



- GNSS ingested foF2 are in good agreement with ionosonde observed data to reflect the ionosphere instantaneous the negative enhancement phase. Especially in the UT 4-5, 9-10 in guangzhou, chongqing, hainan station.
- NeQuick has obvious overestimation for foF2 similar like the TEC overestimation.
- The overall foF2 accuracy has been improved about 10% - 25% after data ingestion.

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TEC and foF2 Bias and RMS

$$Bias = \sum_{i=1}^{n} (P_{Obs}^{i} - P_{Calc}^{i})$$

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} (P_{Obs}^{i} - P_{Calc}^{i})^2}{n-1}}$$

Tab1 Improvement to TEC Error Distribution by GNSS Data Ingestion to NeQuick Model(AVE/RMS)/TECU

	NeQuick 模型		GNSS+NeQuick 模型	
	AVE	RMS	AVE	RMS
ManZhouLi	-0.42	4.36	-0.06	3.26
BeiJing	2.26	3.42	0.11	2.51
ChongQing	-2.24	5.54	-0.48	4.42
GuangZhou	-7.48	7.23	-0.29	3.96
HaiNan	-11.9	7.79	0.56	3.16

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Tab2 Improvement to foF2 Estimation by GNSS Data Ingestion to NeQuick Model(RMS)/MHZ

	NeQuick 模型		GNSS+NeQuick 模型	
	AVE	RMS	AVE	RMS
ManZhouLi	-0.42	0.99	-0.06	0.86
BeiJing	-0.74	1.04	-0.24	0.75
ChongQing	-0.21	1.55	-0.01	1.22
GuangZhou	1.62	1.52	0.47	1.04
HaiNan	2.07	1.73	0.13	1.03

Conclusion

- Using GNSS data ingestion to NeQuick2 model , compared with original model, the TEC accuracy has been improved about 20%-40%, foF2 accuracy has been improved about 10% - 25%.
- After the optimization of GNSS data, NeQuick model can accurately described the ionosphere whole evolution process from positive phase into a negative phase in China.
- As the original NeQuick model only depends on the input of solar activity level without involving the magnetic index. It could only reflect the ionosphere daily variation as magnetic quiet days.
- Using this method of TEC and foF2 experience model calculation accuracy can effectively improve the geomagnetic storm period. It can be a useful addition geomagnetic storm period the ionosphere vertical detectors or effective reference.

Thank you !