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Realtime three-dimensional tomography of the ionosphere over Japan based on GEONET GPS-TEC

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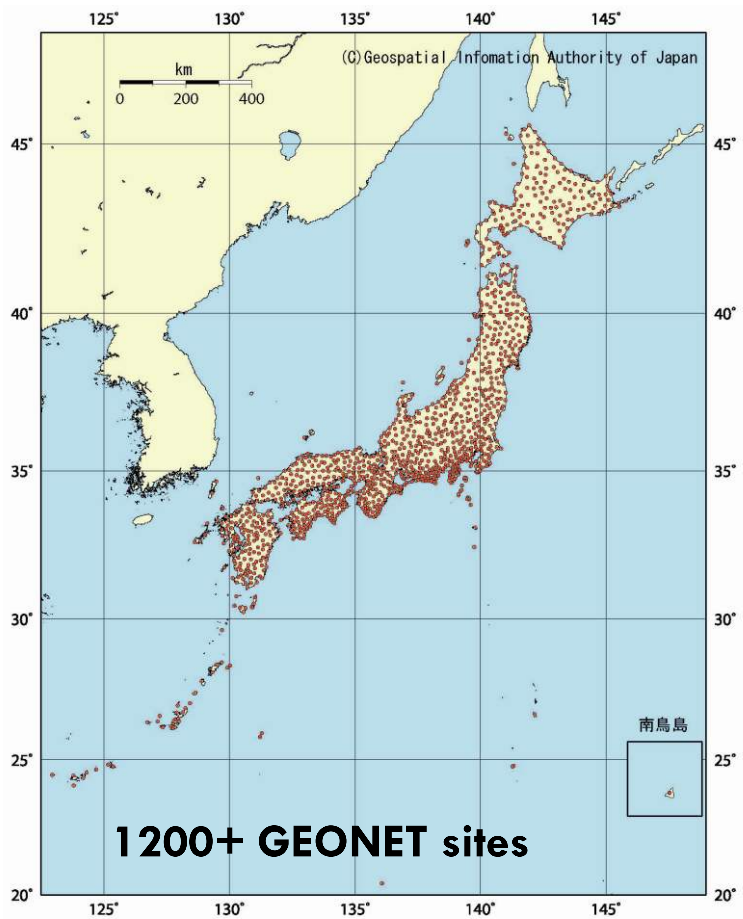
Contents

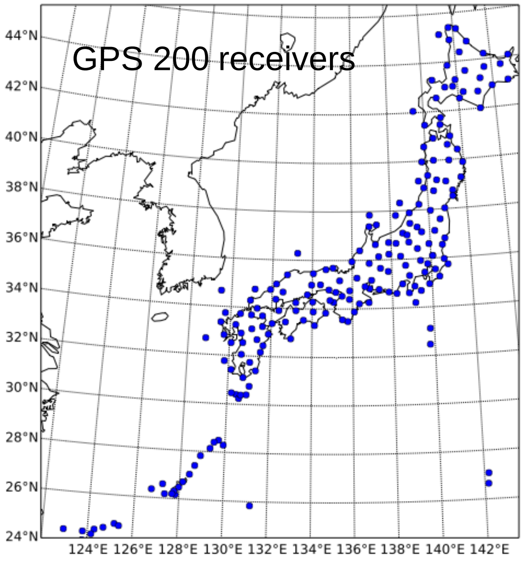
- GEONET
  - "GNSS Earth Observation Network System" by GSI (Geospatial Information Authority of Japan)
  - Every 30s data are available from 1200+ locations
  - Realtime 1s data are now available from most locations, but with costs
- Three dimensional (3D) Tomography analysis with constrained least-squares method
  - Technique, and results from model/real data
- Realtime 3D tomography service
  - System description and achievements We started the service since April 2016



Real-time GPS-TEC 3D tomography

Problems against the real-time system

- Number of stations is reduced to 200
  Original tomography analysis was using data from all GEONET stations (1200 locations). But for the real-time system we can use data from only 200 stations that comes from limitation of the ENRI-GSI contract.
  ➔ Need to obtain stable result from 200 data.



Distribution of 200 GPS stations where 1s data are available.

- Calculation speed-up
  Original 3D tomography analysis took about 30 minutes of calculation by MATLAB.
  ➔ Calculation speed-up is necessary. (Aimed period/latency is 15min)

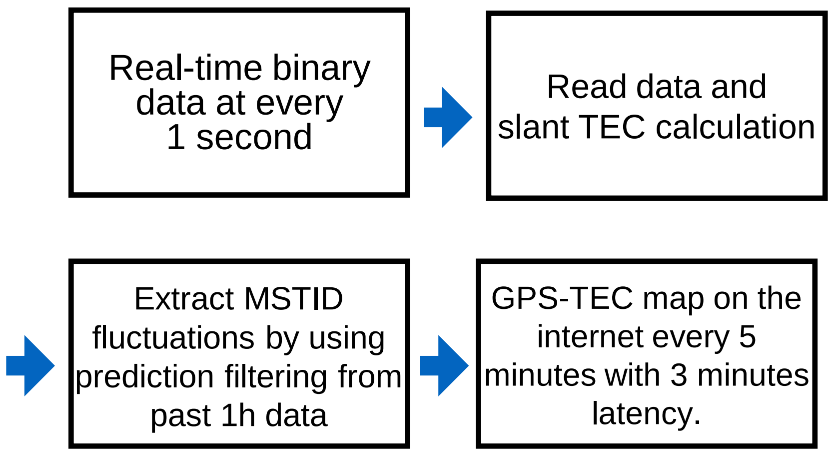
- Estimation of absolute TEC
  Estimation of absolute TEC is necessary before the tomography, in the original analysis, it was determined by other system.
  ➔ Absolute TEC estimation is necessary included in the real-time system.

Existing 2D GPS-TEC real-time monitor

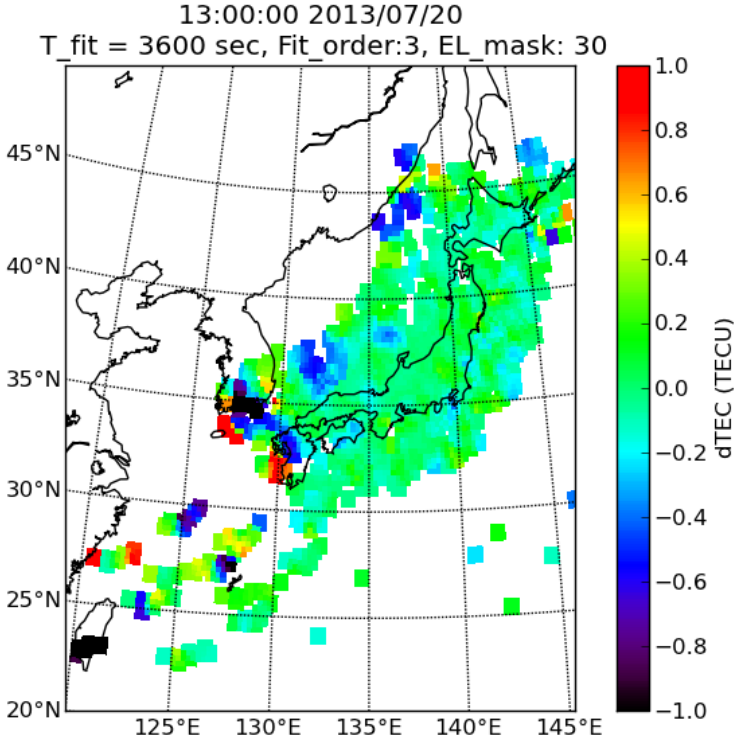
2D GPS-TEC real-time monitor was developed for rocket experiment in July 2013

http://www.enri.go.jp/cnspub/susaito/rocket/recent_mstid.html

Purpose of the system is to monitor the MSTID activity. Then the system shows fluctuation of TEC only. No absolute TEC estimation.



Data flow of the real-time 2D GPS-TEC fluctuation monitor



Example of the real-time 2D GPS-TEC fluctuation map

Realtime tomography analysis system

BINEX data flow from GEONET to data server at ENRI

Acquisition of BINEX data from data server
Obtain relative GPS-TEC and satellite ephemeris information (every 30 s)

2D TEC mapping analysis absolute TEC and fluctuation (removal of trend by 3rd order polynomial curve)

2D ablsoute TEC mapping
2D TEC fluctuation mapping
(every 30s, latency < 1minute)

3D tomography analysis from absolute TEC
(every 15 minutes)

3D ionospheric tomography result
(every 15 minutes, latency < 10minutes)

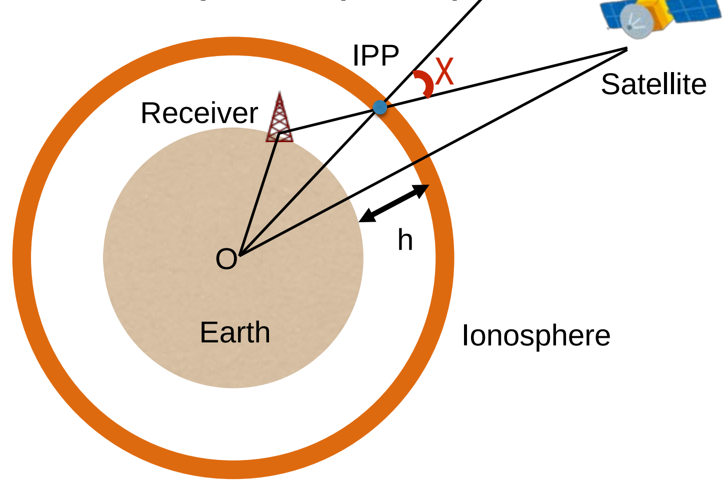
Satellite and receiver bias estimation by using latest 24-hour data
(every 1 hour)

Computer system

OS：CentOS 7
CPU：Intel Core i7, 8 cores
Memory：16GB

Estimation of biases

Based on Ma and Maruyama (2003)



Ionosphere as a sphere at height *h*

Assumption

- Ionosphere is a thin sphere at certain height.
- Biases do not change for 24 hours.
- TEC is constant within 2deg×2deg at any

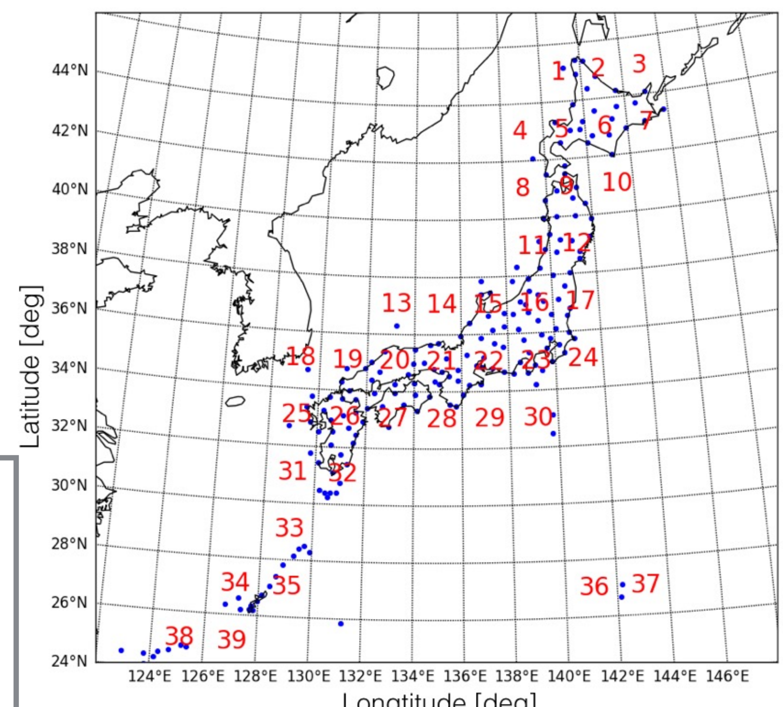
timi

$$\begin{bmatrix} \cdots & \cdot & \cdots\cdots\cdots \\ \cdots & \cdot & \cdots\cdots\cdots \\ 0.0 & \sec\chi_{jk} & 0.010.010.0 \\ \cdots & \cdot & \cdots\cdots\cdots \\ \cdots & \cdot & \cdots,\cdots\cdots \end{bmatrix} \cdot \begin{bmatrix} TEC_1 \\ \cdot \\ TEC_1 \\ b_{s1} \\ \cdot \\ b_{sJ} \\ b_{r1} \\ \cdot \\ b_{rK} \end{bmatrix} = \begin{bmatrix} \cdot \\ \cdot \\ TEC_{sl\,jk} \\ \cdot \\ \cdot \end{bmatrix}$$

Coefficient matrix

Unknown vector
（Vertical TEC + Satellite bias + Receiver bias）

Measured relative TEC with bias



39 areas of 2deg×2deg grid

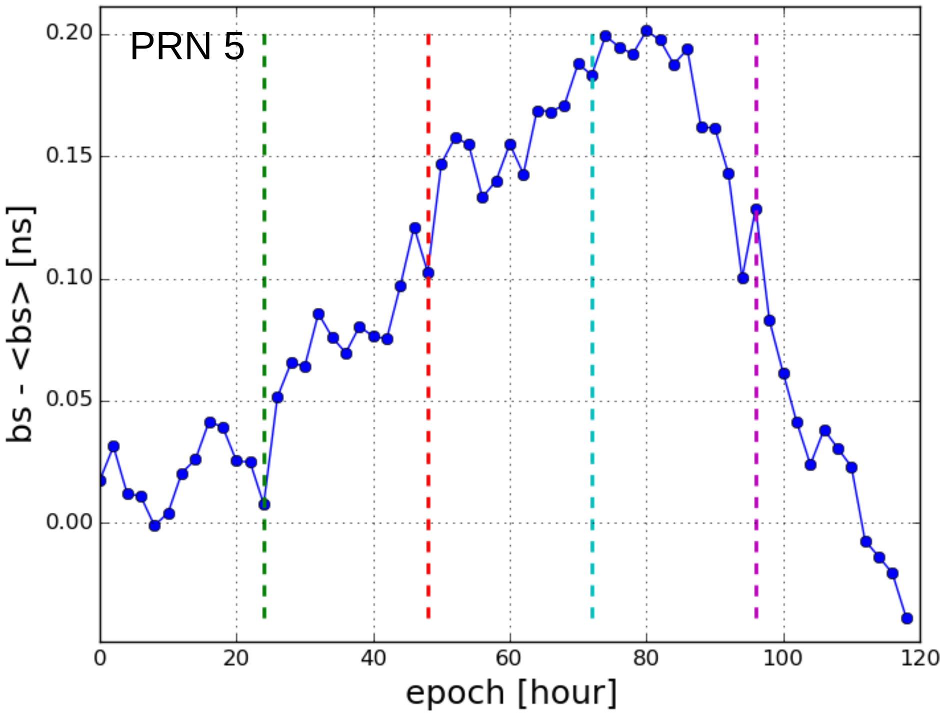
Maxtix size: about 50000 x 3000
Ratio of non-zero elements < 0.1%
⇒Large sparse matrix LSE solver
Improved over 10min → less than 1s

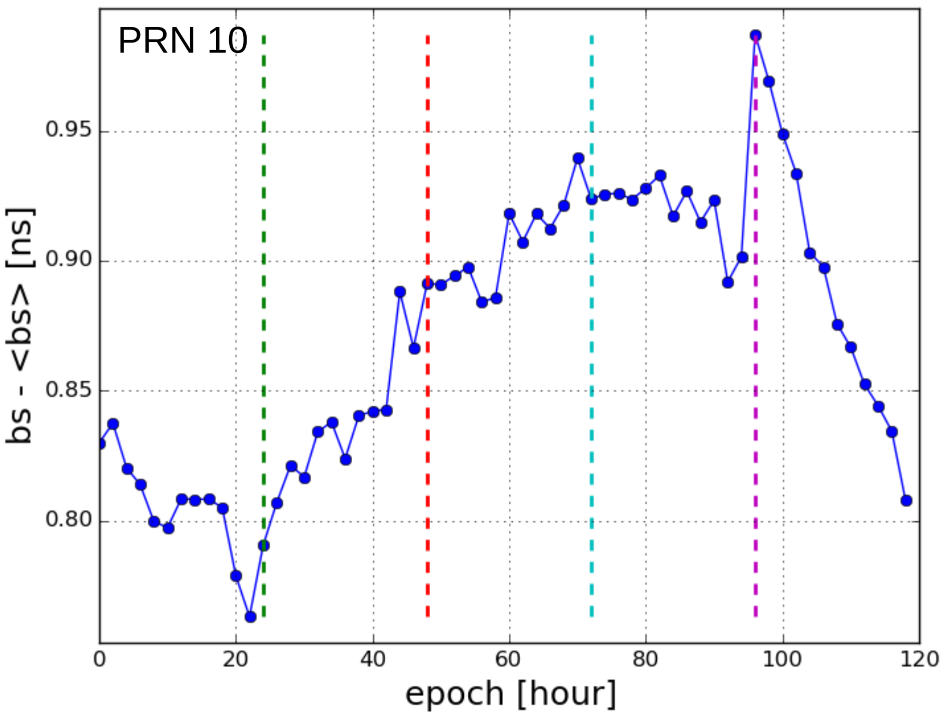
Improvement of bias estimation

Faster analysis made possible to estimate biases at every hour.

Originally biases are determined at every day

⇒ Now biases are determined at every hour.



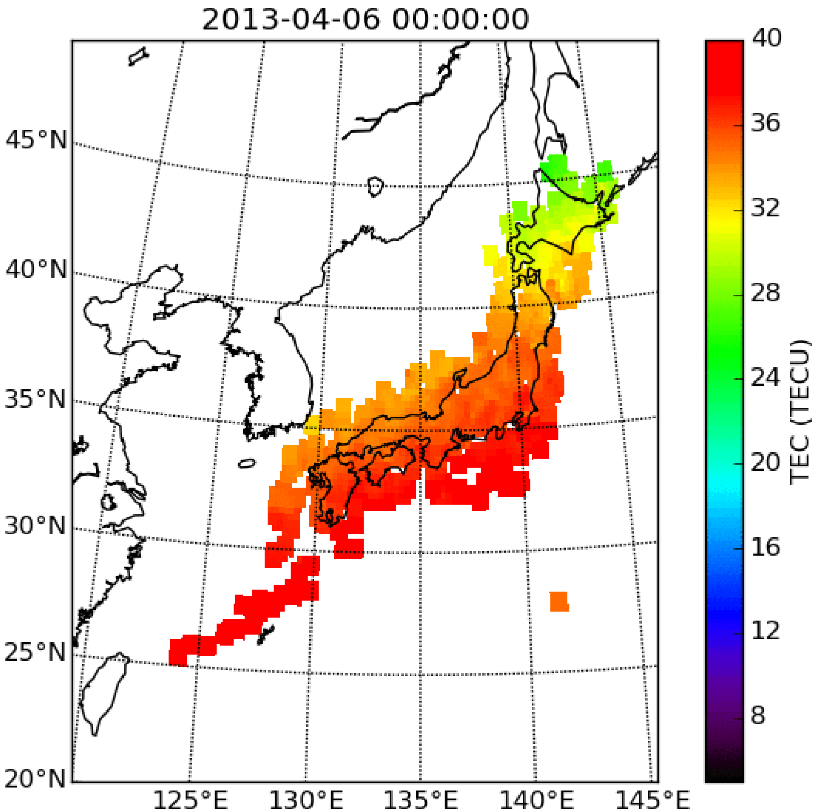


Variation of satellite bias for 5 days from April 1, 2013.
Each bias value is estimated from TEC of 24 hours before the data point.

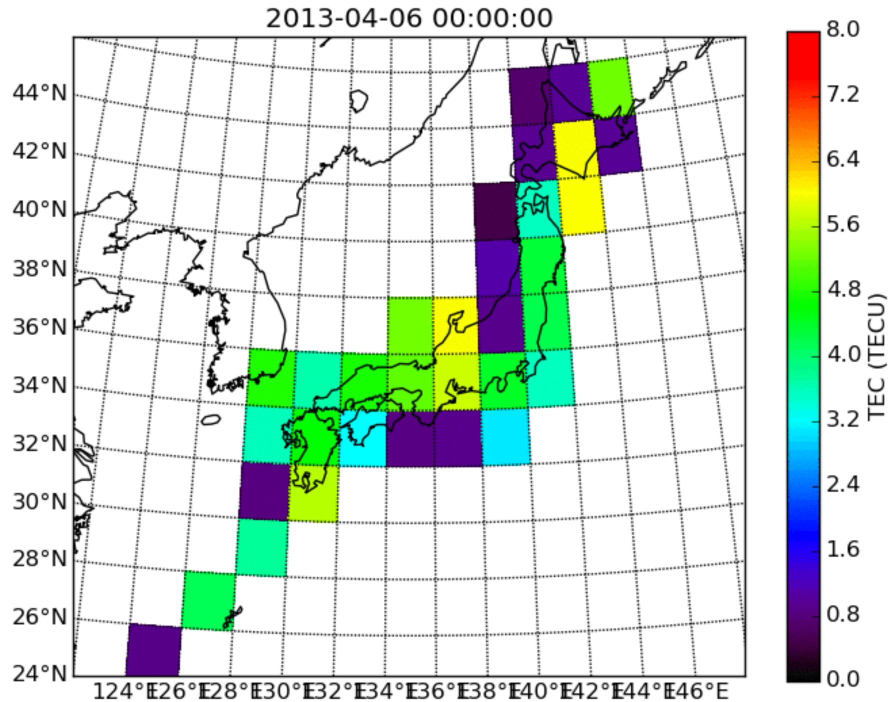
⇒Maximum 0.1ns variation exist even during daytime.

⇒More frequent estimation of the bias enables us to follow faster variation of the ionosphere.

Distribution of absolute TEC (with < 1 min latency)



Daily variation of absolute TEC



Standard deviation of TEC at each grid

Typical TEC variation

Morning (~0:00 UT) ⇒ Noon (~6:00 UT) Low latitude TEC is high. Area of high TEC moves westward.

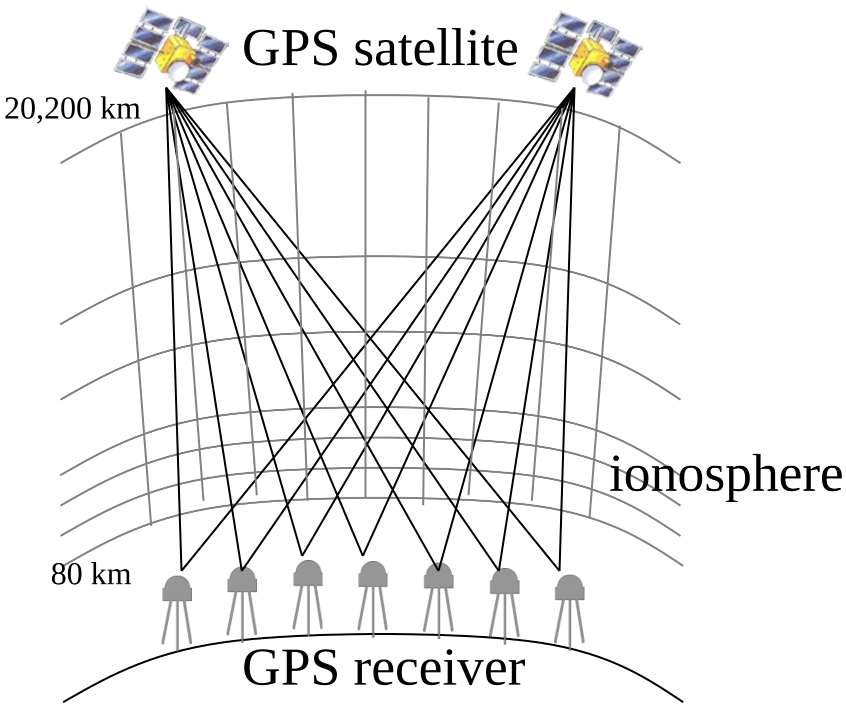
Noon (6:00 UT ~) ⇒ Night (~12:00 UT) TEC decreases from north-side.

Night (12:00 UT ~) ⇒ Morning (~18:00 UT) TEC gradually decreases, and flattened.

Standard deviation of of TEC at 2deg X 2deg cell is within several TEC units.

3D tomography with GPS-TEC

- Use the TEC data along the ray path from GPS satellite to GPS receiver



- GPS-TEC observation matrix

$$\vec{A}\vec{x} = \vec{b}$$

GPS-TEC value

Electron density in each grid

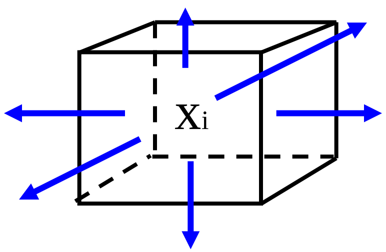
Length of path in each grid

- Limitation of the GPS observation: <u>lack of horizontal observation path</u>
- The proposed method combines **<u>least-square</u>** fit and **<u>constrain</u>** conditions.

Constrained least-squares method

- Constrain matrix

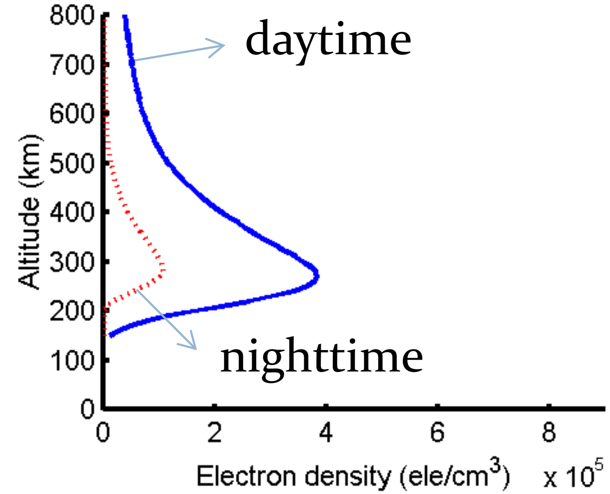
$$\vec{W}\vec{x} \approx 0$$



$$\vec{W}\vec{x} = \sum_{i=1}^{N} \sum_{j=1}^{6} C_{i,j}(x_i - x_{i,j})$$

Constrain parameter

- Strong constrain
  - 80 ~ 150 km; 800 km ~
- Weak constrain
  - 150 ~ 800 km



- Cost function:

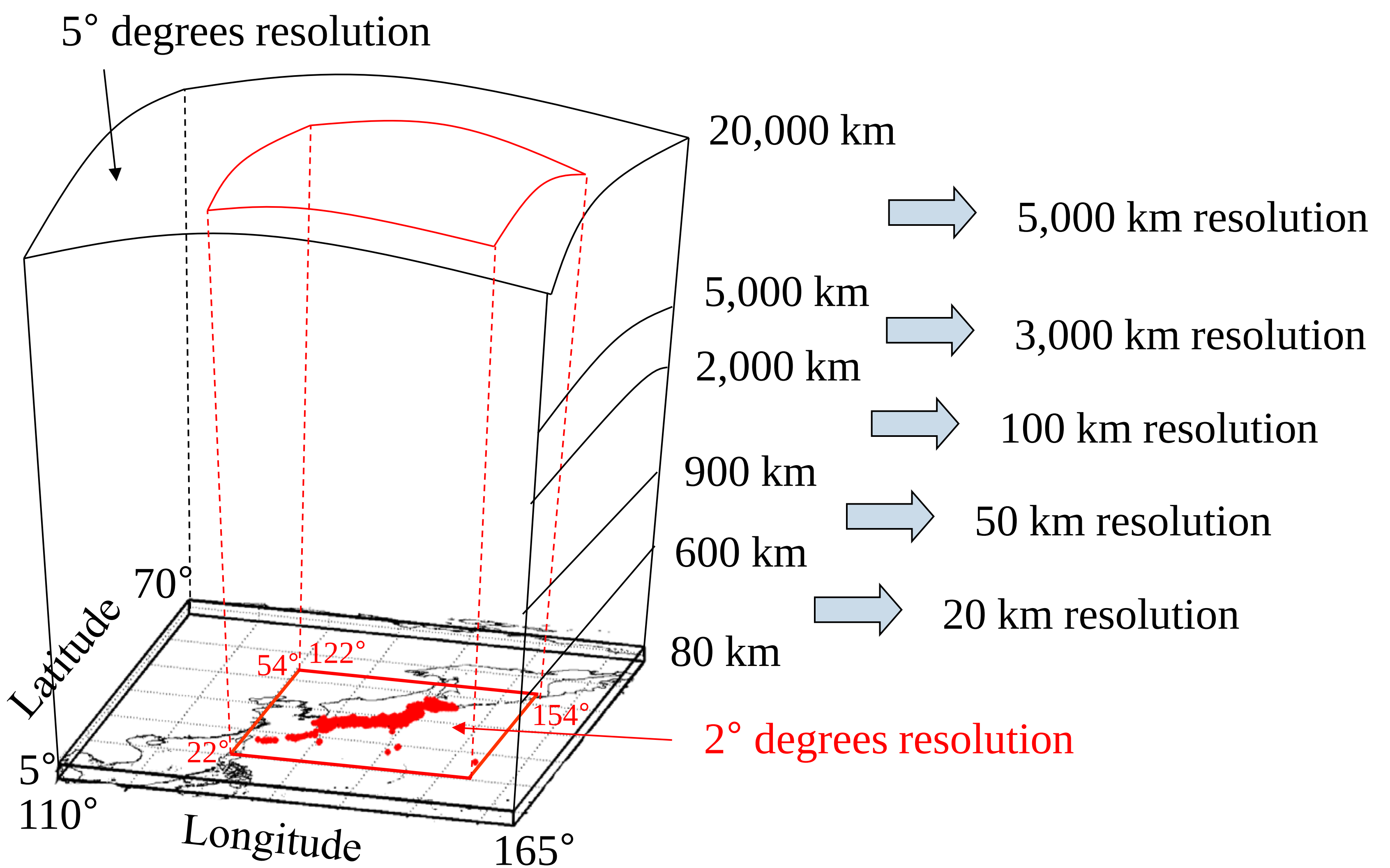
Least-square term

Hyper parameter

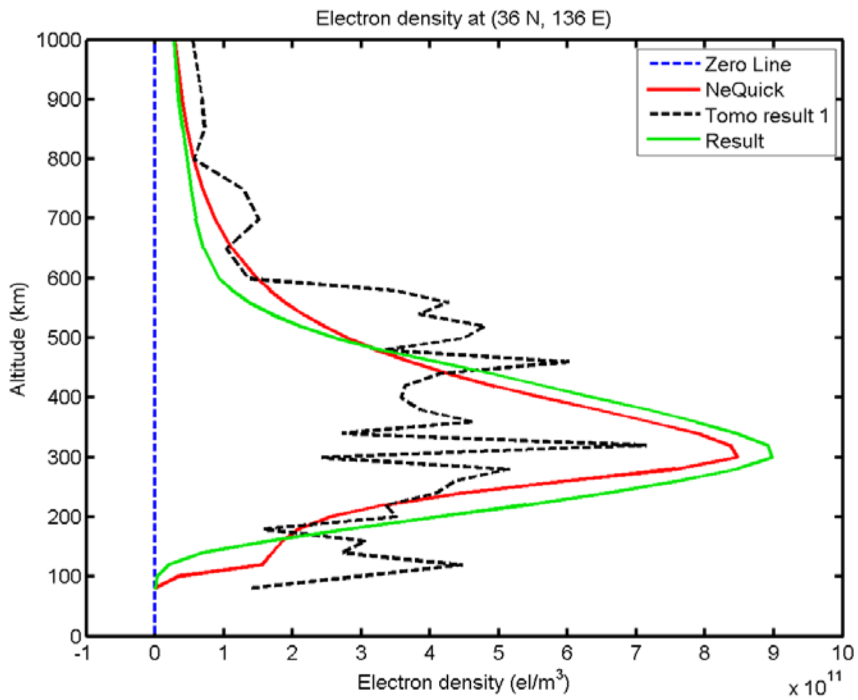
Constrain term

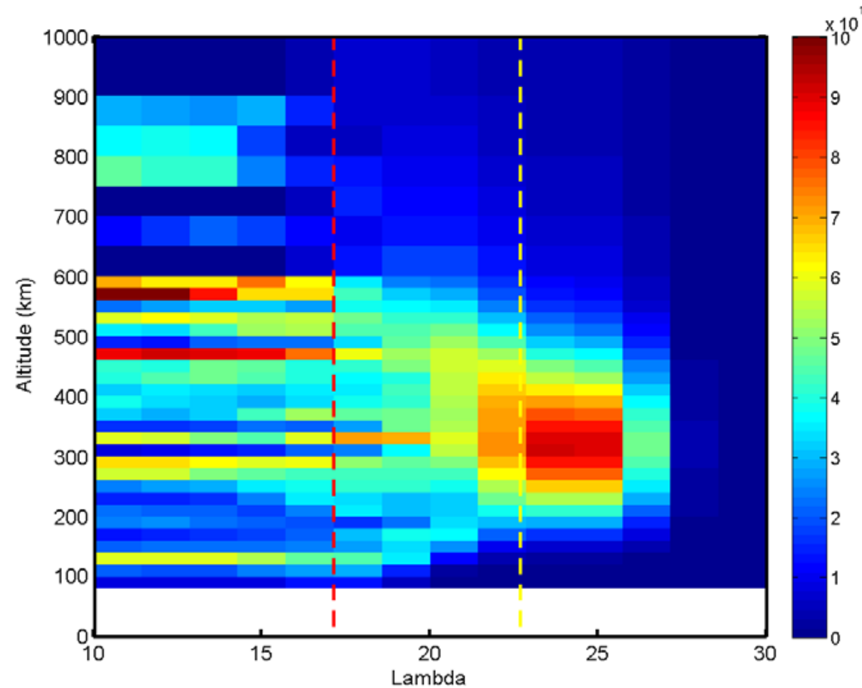
$$J(\vec{x}) = \left\| \vec{b} - \vec{A}\vec{x} \right\|^2 + \lambda \left\| \vec{W}\vec{x} \right\|^2$$

Area & grid of 3D GPS tomography



Example result of constrained least-squares fitting

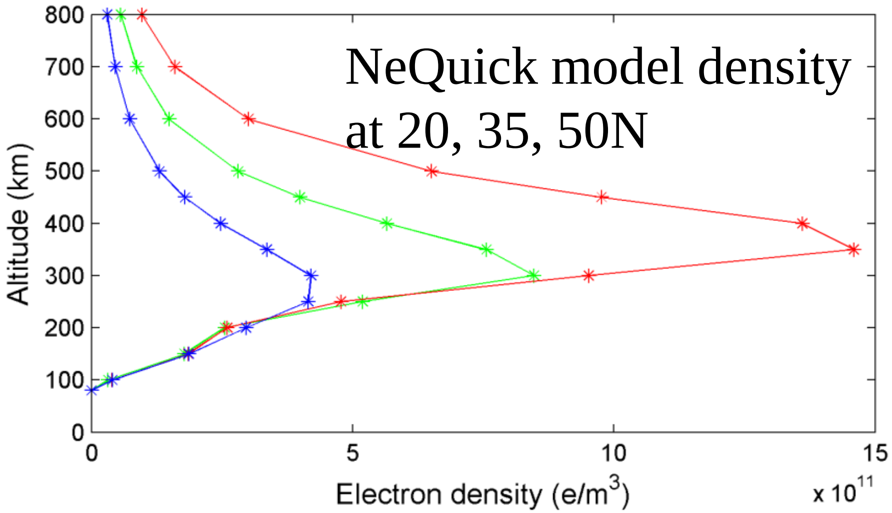


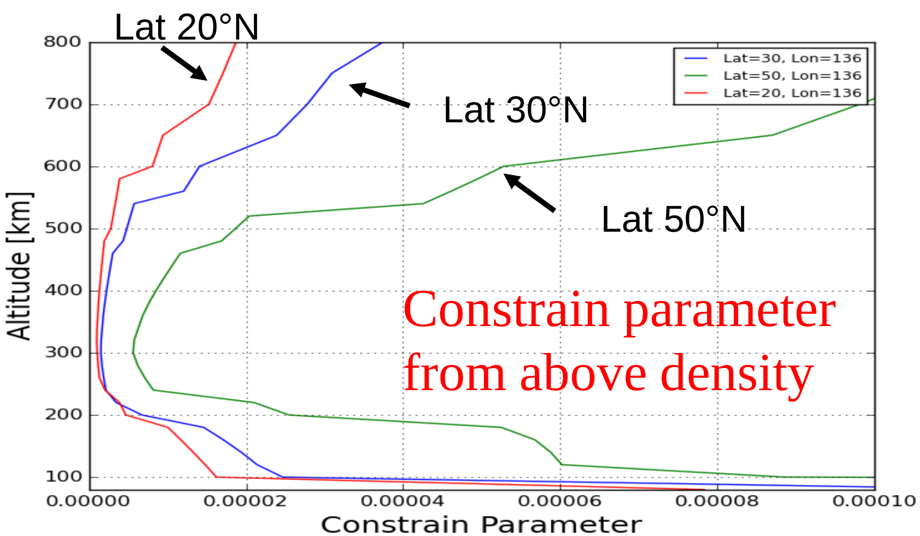


Hyper parameter λ

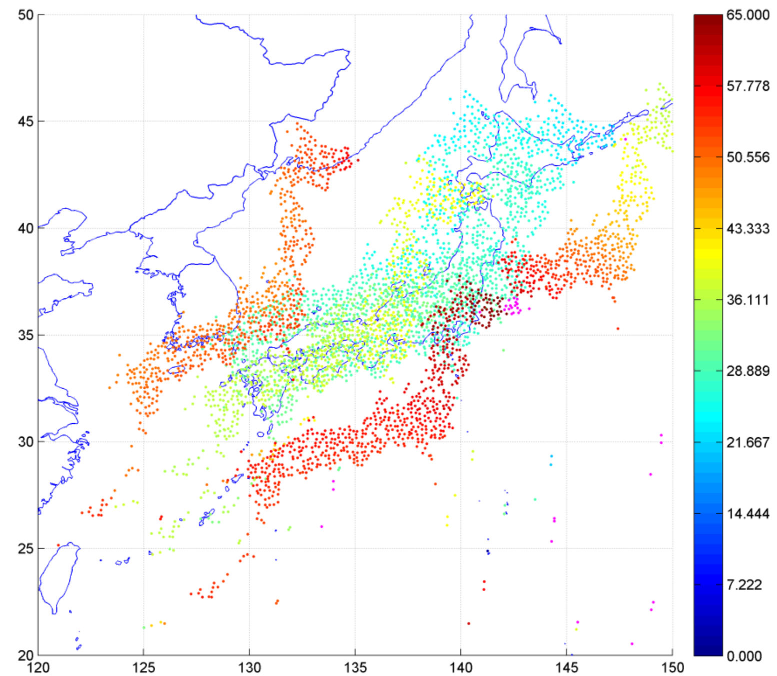
We conduct many fitting runs by changing hyper parameter, and select appropriate results from them. This selection scheme is the key!

Selection of constrain parameter



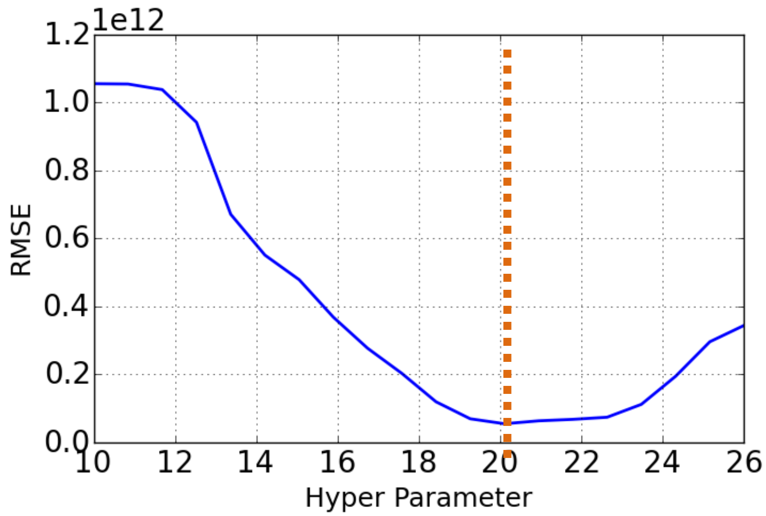


GPS TEC data 23rd May, 2012 at 03:30 UT



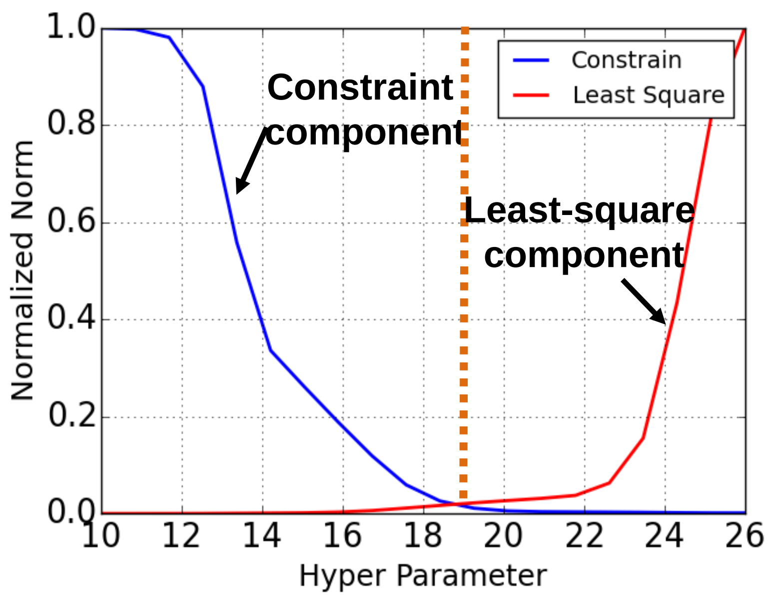
Based on Gopi Seemala et al (2014)

Selection of hyper parameter λ



Relationship between λ and RMSE

Select λ with minimum RMSE

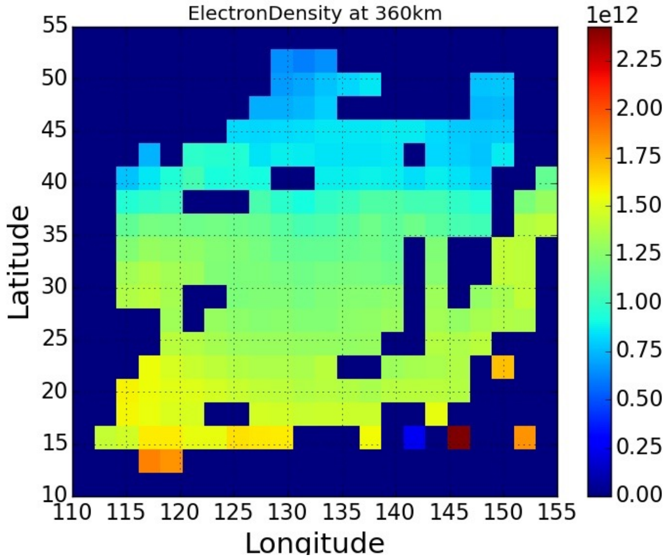


Relationship between λ and normalized least-squares and constraint components

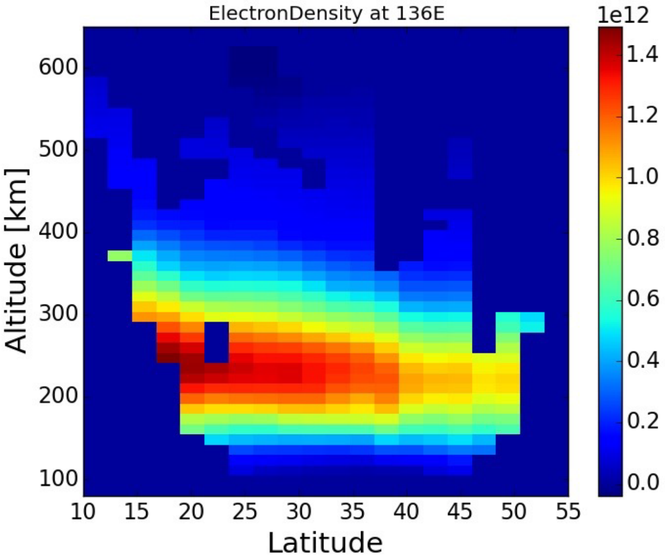
L-curve method … Select λ where least-squares component and constraint component balance.

Result of 3D tomography from the real GPS-TEC data

7:00:00(UT) 2012/05/23

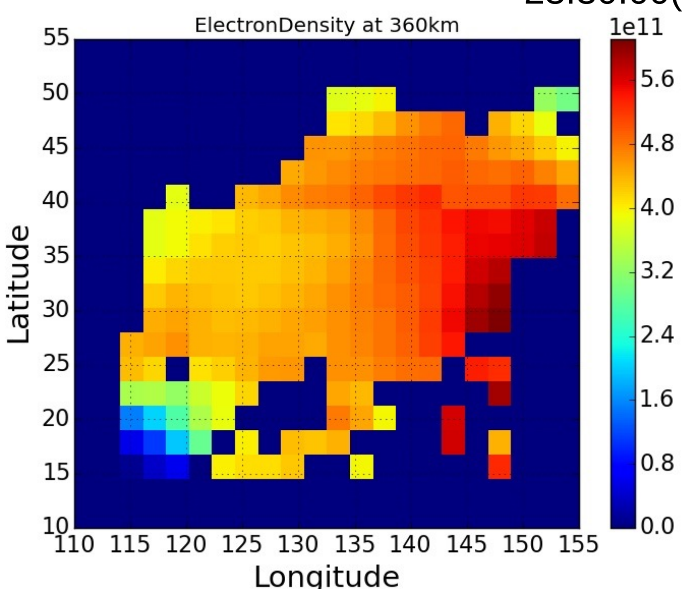


Horizontal distribution at 360km ALT

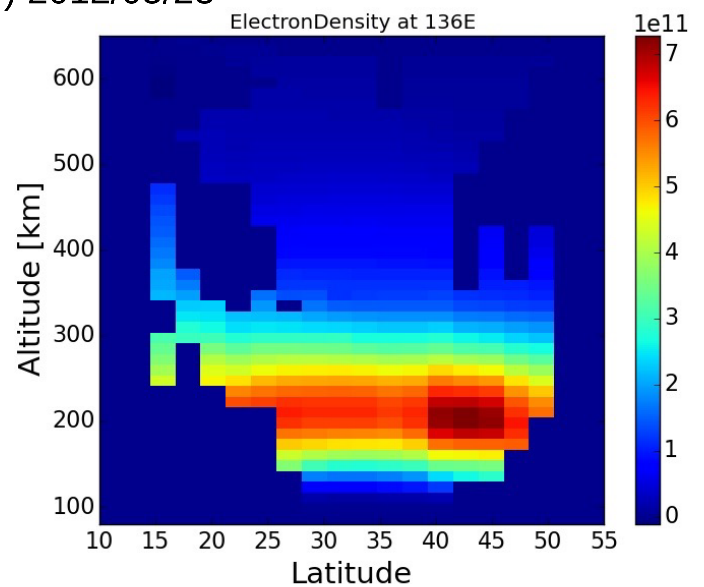


NS-Height distribution at 136°E

23:30:00(UT) 2012/05/23



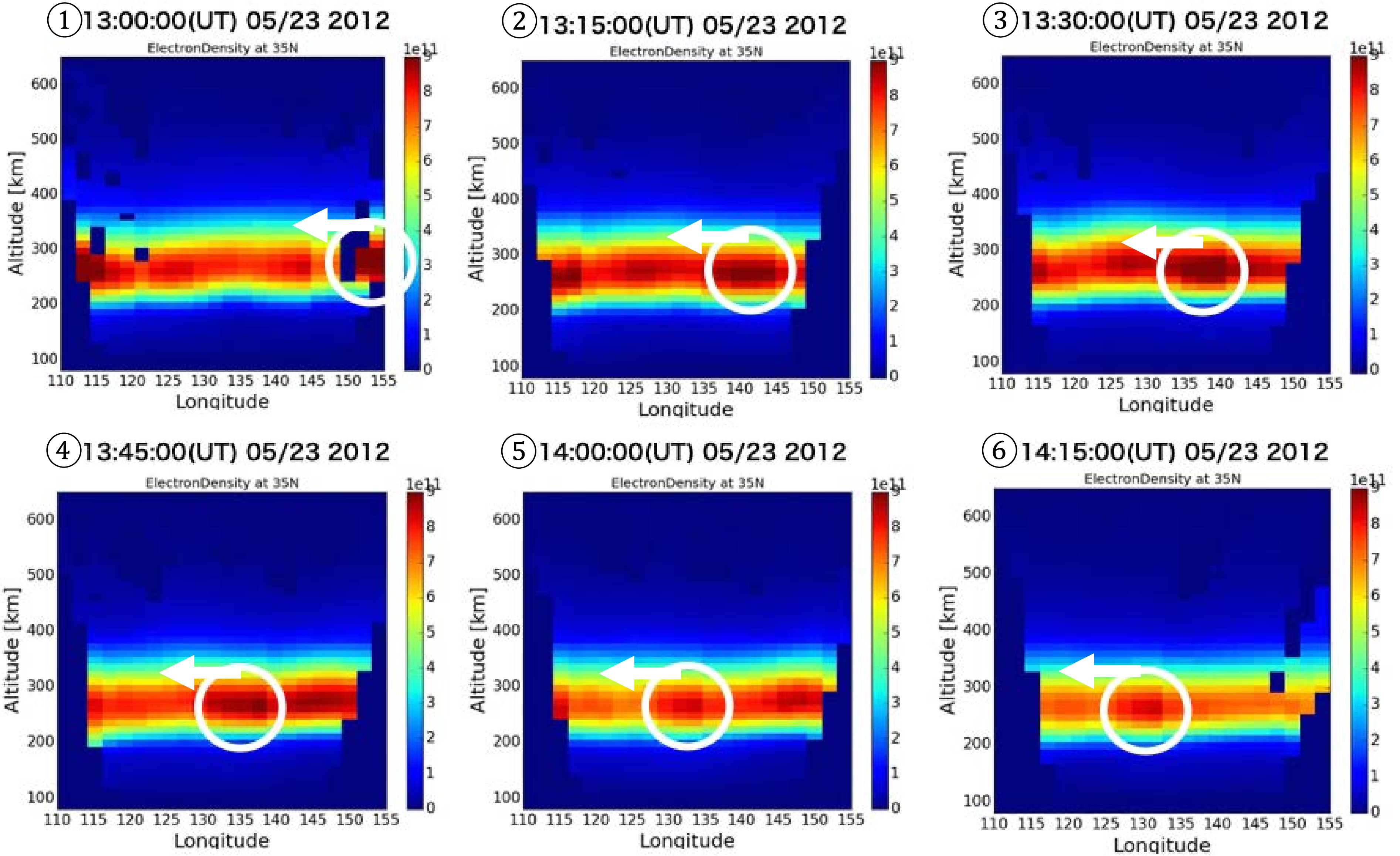
Horizontal distribution at 360km ALT



NS-Height distribution at 136°E

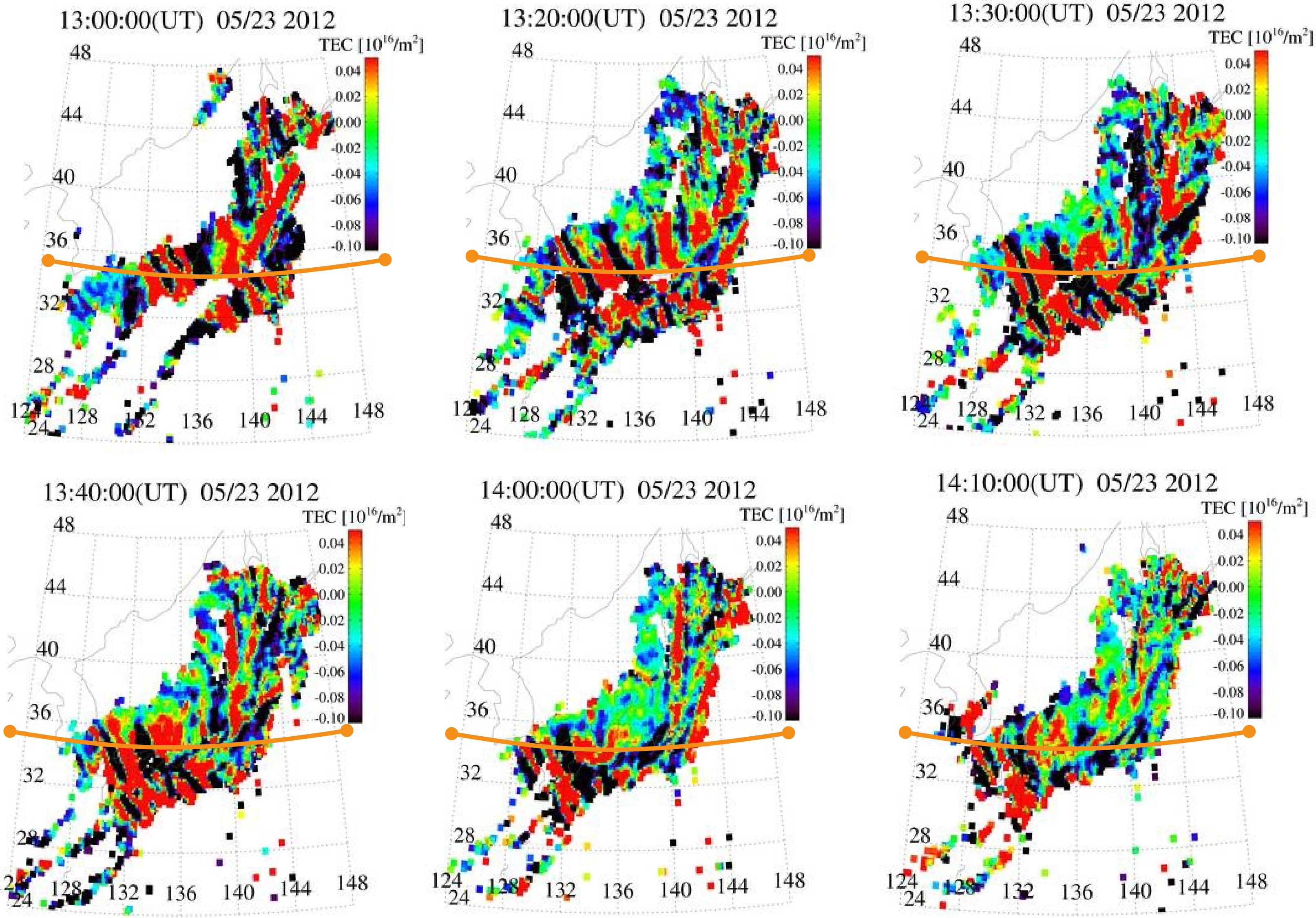
TEST

Zonal-height distribution of plasma density at 35N, estimation at every 15 minutes.



Westward propagation of the density fluctuations are measured.

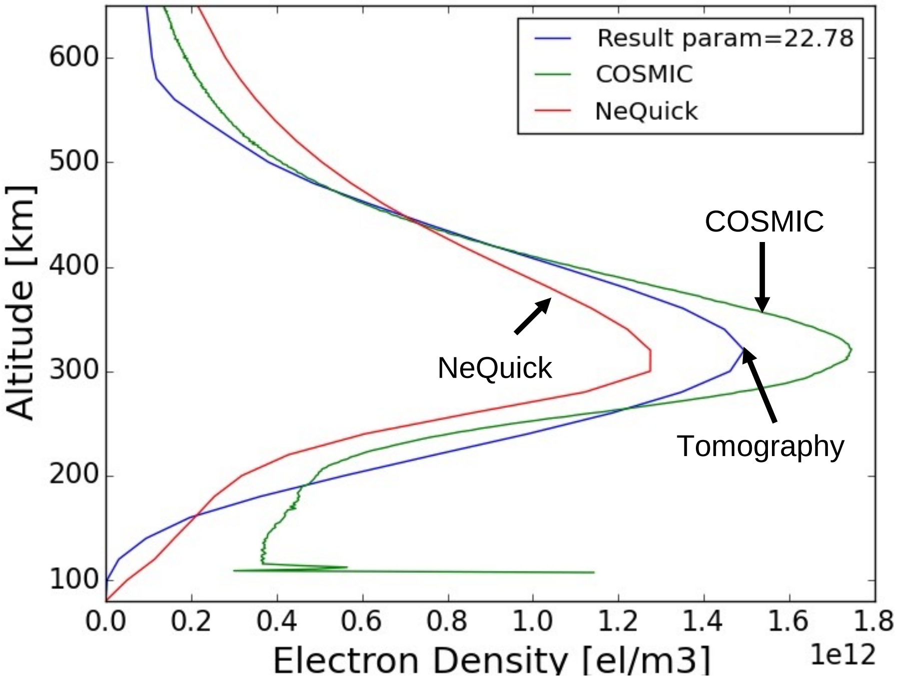
2D distribution of fluctuation GPS-TEC on May 23, 2012.



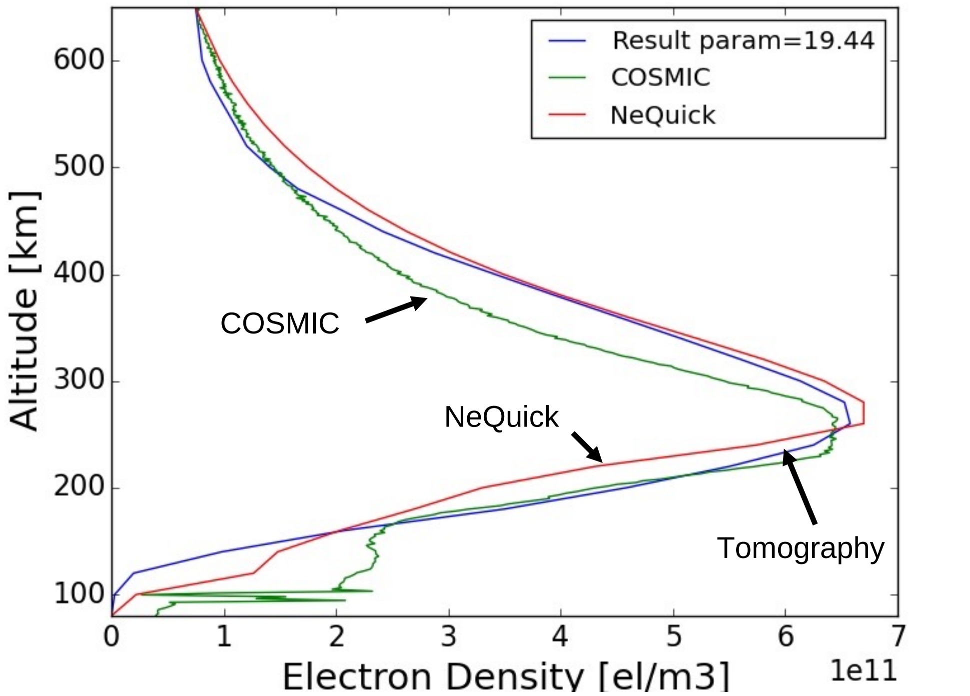
Nighttime MSTID occurred. South-westward propagation of the wave was measured.

Comparison to GPS occultation with COSMIC

7:00:00(UT) 2012/05/23

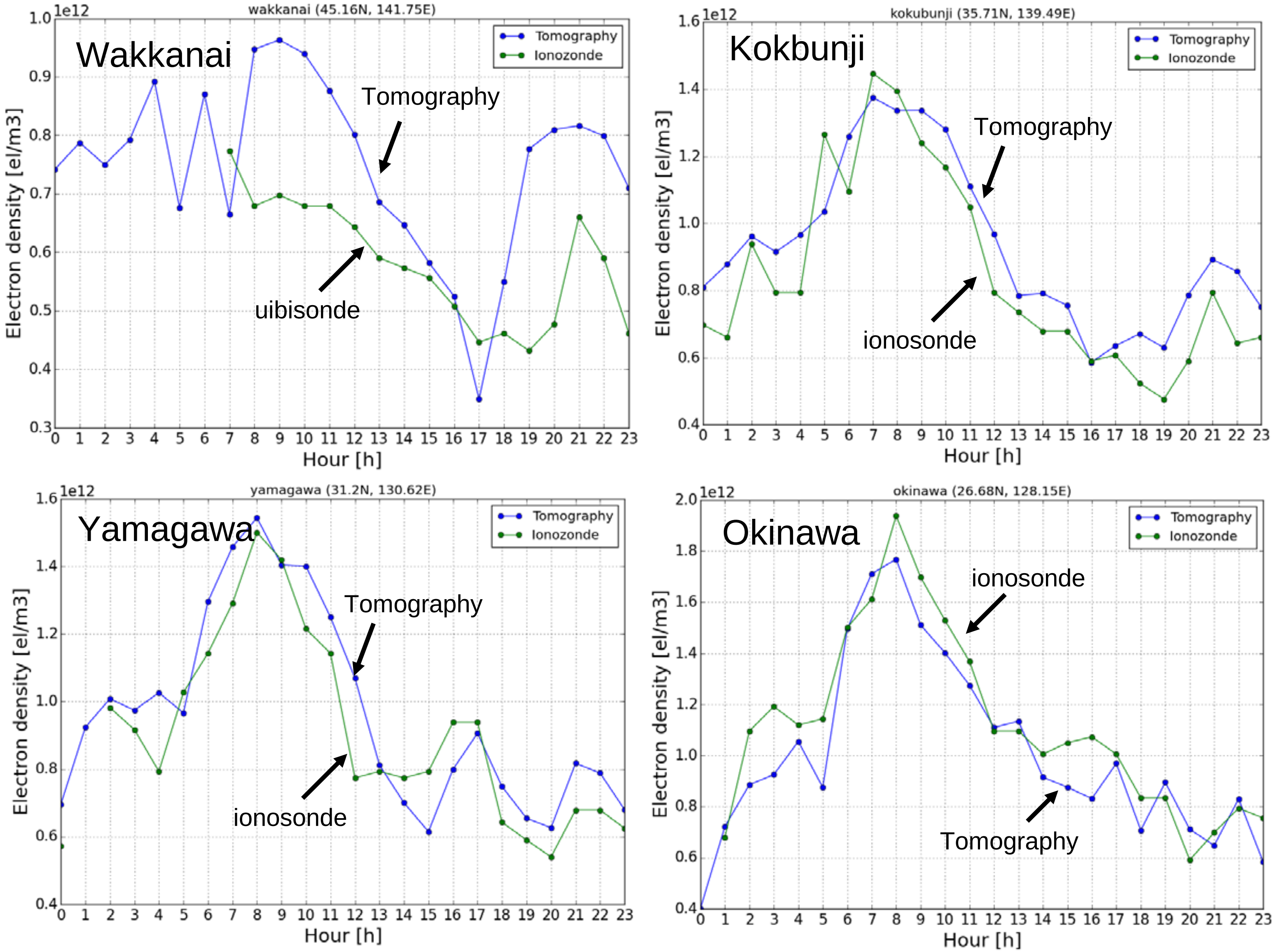


23:30:00(UT) 2012/05/23



Tomography results well resemble to COSMIC occultation density profile.
Tomography cannot resolve Sporadic-E layer that is found from COSMIC occultation.

Comparison to ionosonde F2 peak density



Tomography results well resemble F2-peak density from ionosondes at Kokubunji, Yamagawa, and Okinawa. Differences are large at Wakkanai, but this is edge of the analysis region

We started real-time service in April 2016

http://www.enri.go.jp/cnspub/tomo3/

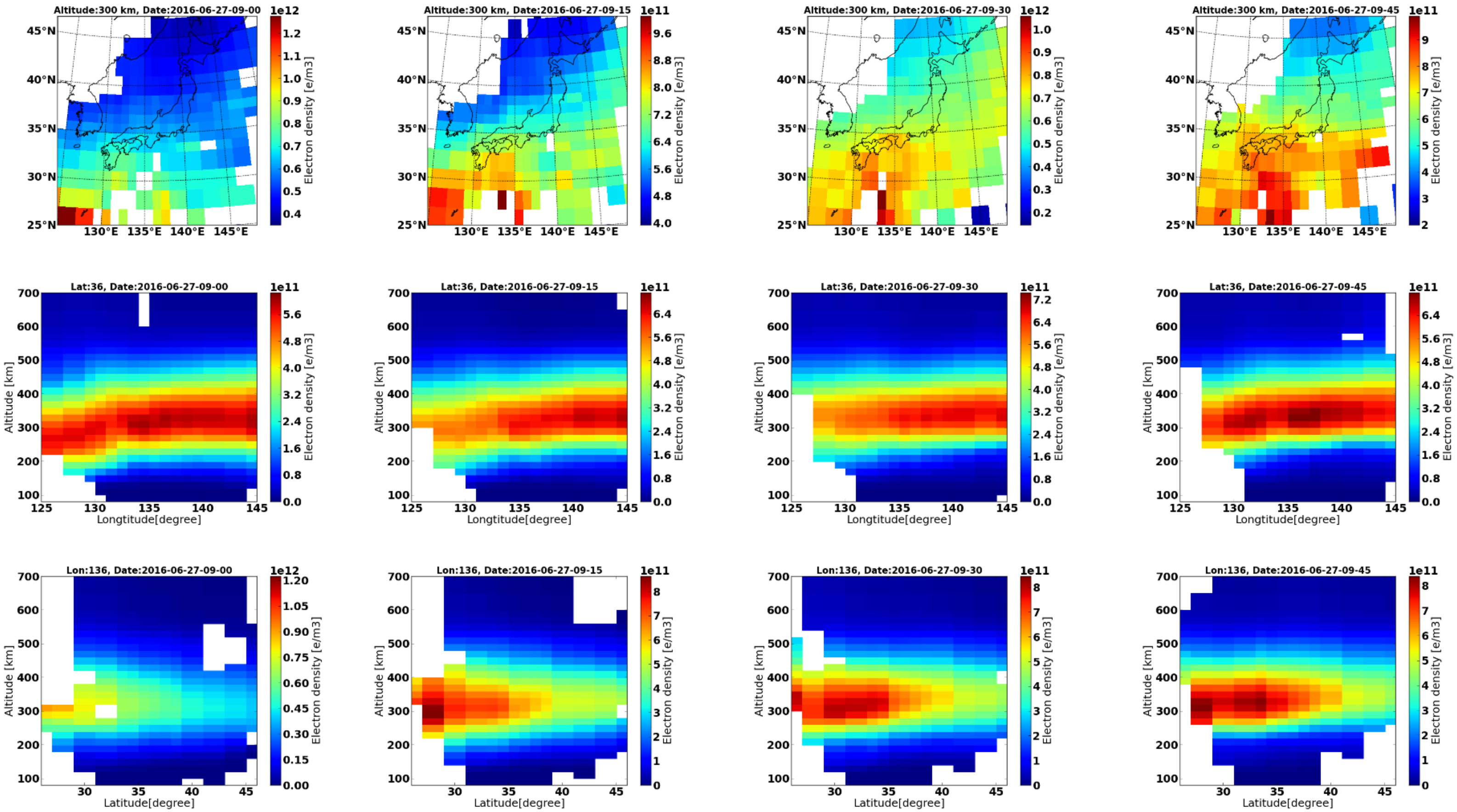
Example of today (June 27, 2016)

	09:00UT 18:00LT	09:15UT 18:15LT	09:30UT 18:30LT	09:45UT 18:45LT

Horizontal 300km ALT

EW-Height 36N LAT

NS-Height 136E LON



Summary

- We successfully developed the real-time 3D tomography analysis system. We used a LINUX PC (Intel i7 CPU) + Python codes.
- Processes for TEC extraction from the GPS standard BINEX/RINEX, Bias estimation, and 3D tomography analysis are running parallel. Achieved calculation times are, 30 seconds for TEC extraction and Bias estimation, and 10 minutes for 3D tomography.
- Bias estimation time is drastically reduced by utilizing the sparse-matrix calculation technique.
- 3D tomography with 200 real-time GPS-TEC data is now stable. We decided methods for constraint parameter C and hyper parameter λ. Results of the analysis well resemble to COSMIC GPS occultation profiles, and to ionosonde F2-peak densities.
- We started real-time 3D tomography service since April 2016. Data are on a web page http://www.enri.go.jp/cnspub/tomo3/ The system is running stable. We however, need more development of web-based data display, and conduct more test with other observations.

http://www.enri.go.jp/cnspub/tomo3/

結論

- 本研究で開発した電離圏3次元解析システムでは，TEC分布導出プロセス，計器バイアス推定プロセス，3次元トモグラフィ解析プロセスを並列に実装し，リアルタイム環境下においてTEC変動分布及び絶対値分布は30秒遅延の出力，３次元トモグラフィ解析は10分遅延の出力を実現した.
- 計器バイアス推定では行列計算を1秒以下に高速化させ，1時間ごとに過去24時間分のデータから推定を行うことで低誤差の計器バイアス推定が可能となった.
- 電離圏3次元トモグラフィ解析では，拘束係数C及びλの推定手法を決定した．リアルタイムの環境下における実データの解析では，GPS掩蔽観測データとよく一致し，さらに稚内を除いた国分寺，山川，沖縄のイオノゾンデ観測データとよく一致する結果が得られた.
- 本研究で開発したシステムは，電子航法研究所に設置した専用サーバーにて稼働準備中であり，2016年3月のローンチを予定している.

今後の課題

・大量解析結果とGPS掩蔽観測及びイオノゾンデ観測結果との比較による統計的な精度分析

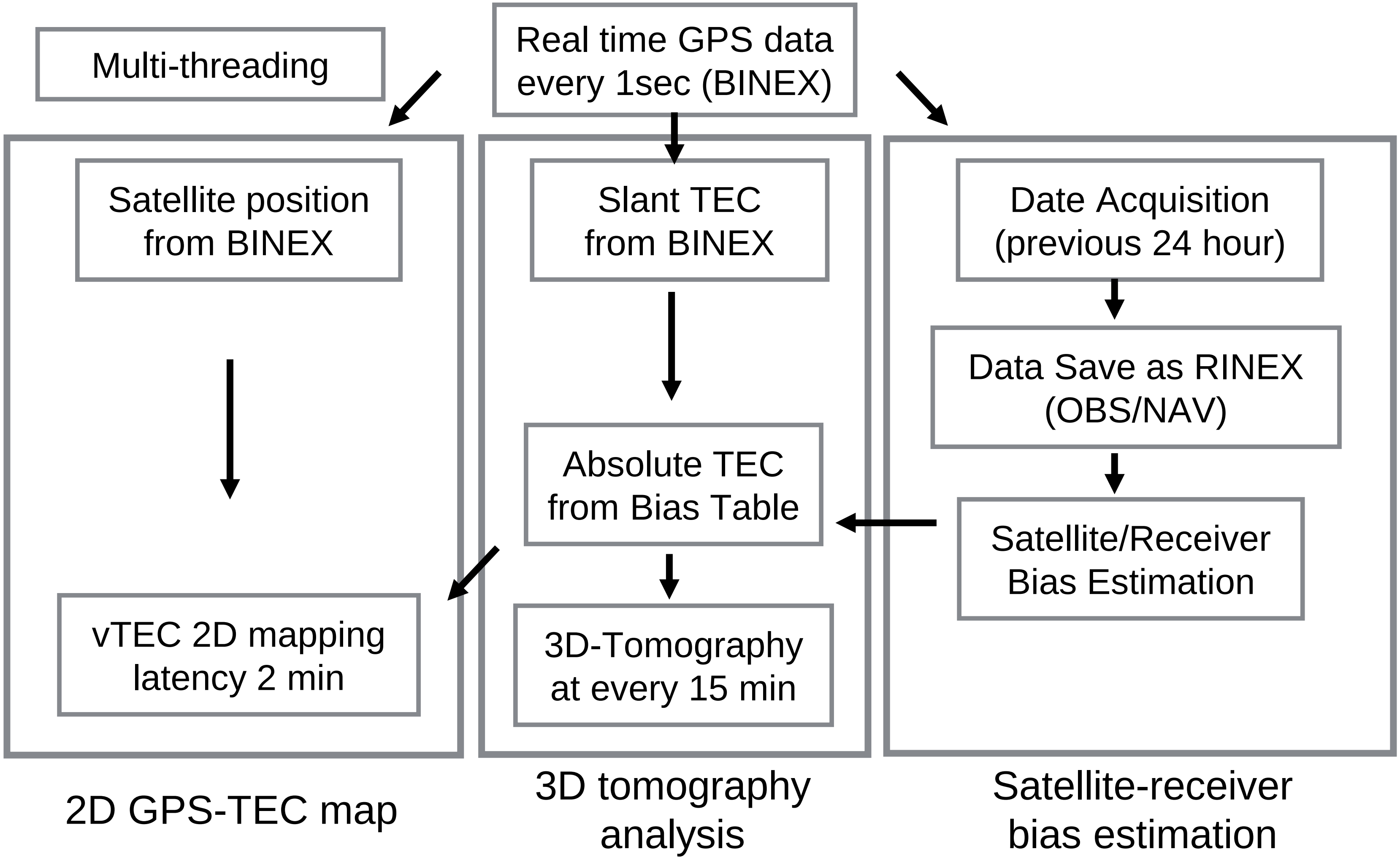
Summary

- We developed 3D tomography analysis with constrained least-square analysis. When using all GEONET data (1200 stations), the result looks reasonable. However, one analysis takes about 30 minutes of computation.
  - Seemala, G. K., M. Yamamoto, A. Saito, and C.-H. Chen (2014), J. Geophys. Res. Space Physics, 119, 3044-3052, doi:10.1002/2013JA019582.
- Now we develop real-time 3D tomography system. Implimentation is mostly done. Now
  - Bias estimation is 10 minutes by using past 24-hour data. We renew the bias everyday.
  - Tomography analysis is re-programmed with Python. Cacluation time is redued to about 10 minutes, which is sufficient to achieve 3D tomogram result at every 15 minutes.
  - 3D tomography test with model data is very good. But we need more stability with the real data. We will continue testing, and try to complete the system soon.

- このあとは、予備スライド

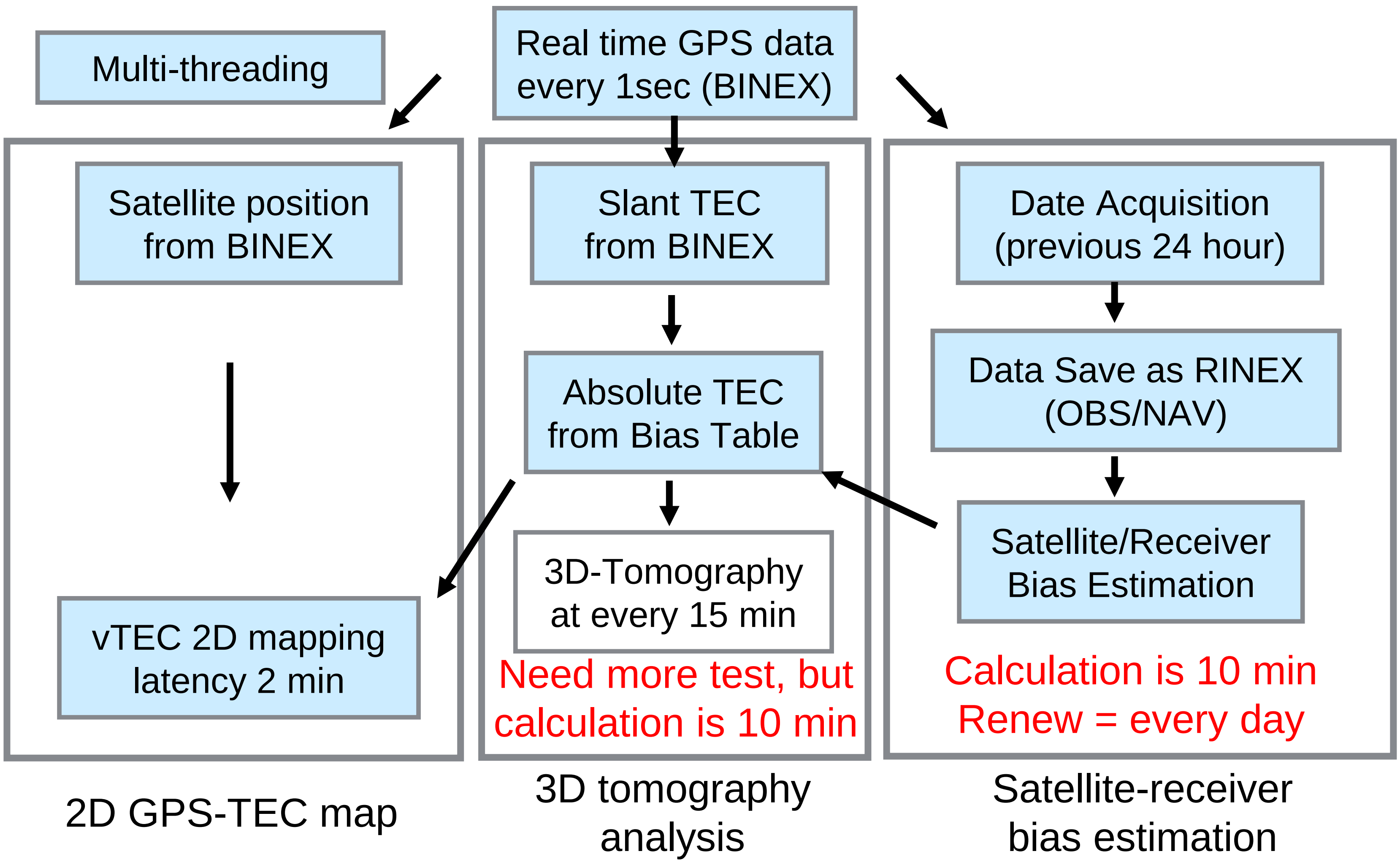
System for real-time 3D tomography

Design of the real-time data flow



System for real-time 3D tomography

Current achievement (Blue color = done)



Result with/without bias estimation error

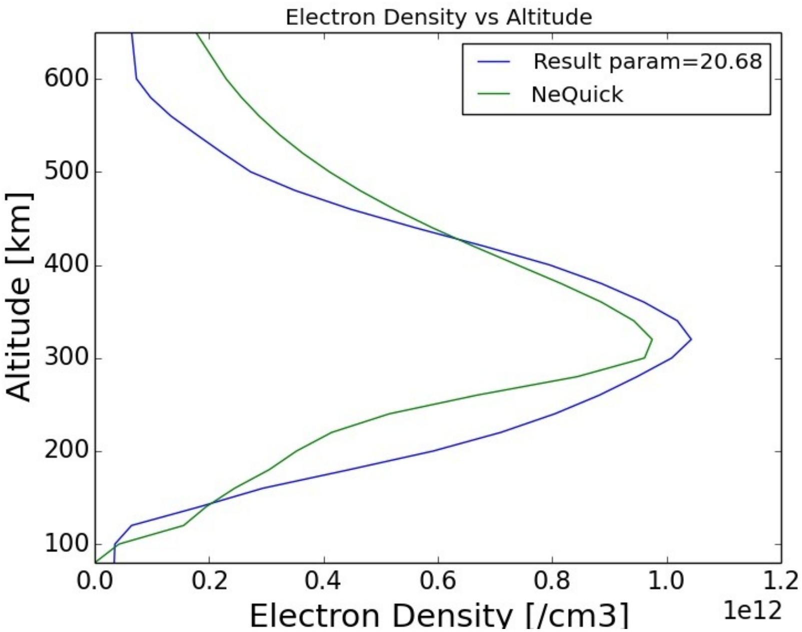


fig21. バイアス誤差有りの解析結果

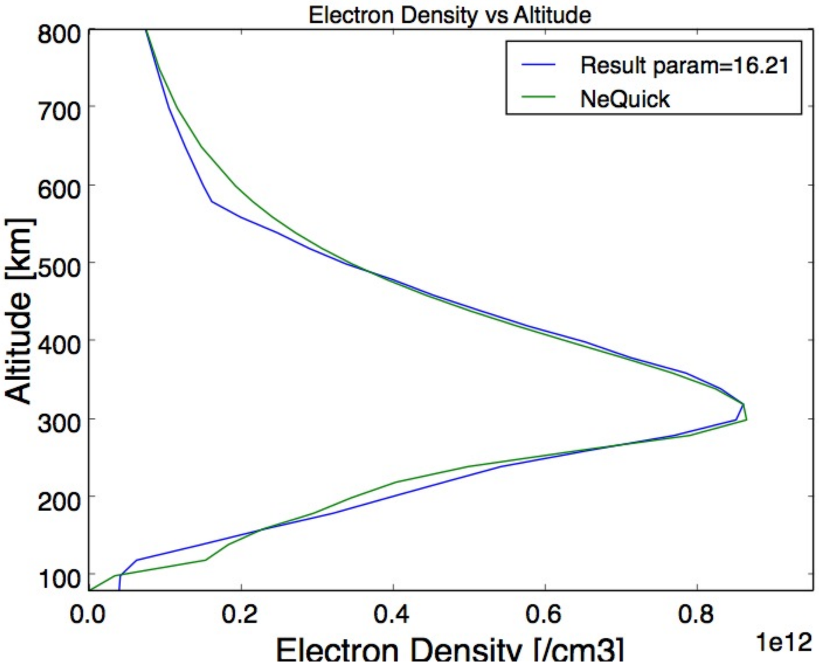


fig22. バイアス誤差なしの解析結果

Result of tomography analysis with 200 stations

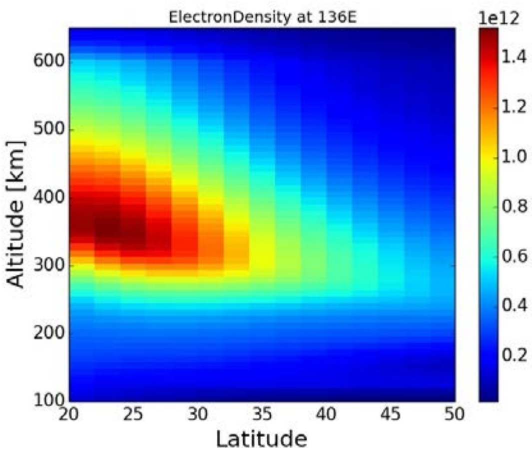


fig13. NeQuickによる電子密度

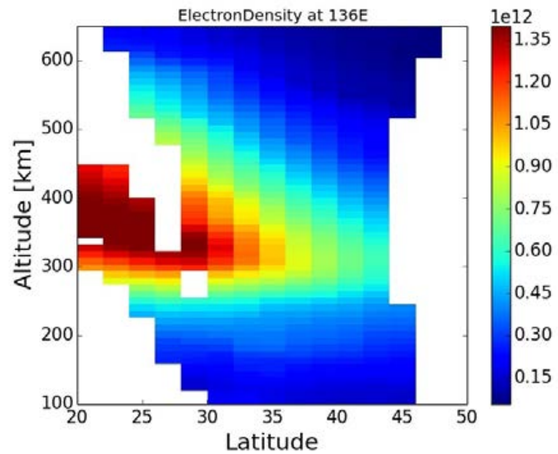


fig14. トモグラフィ解析結果

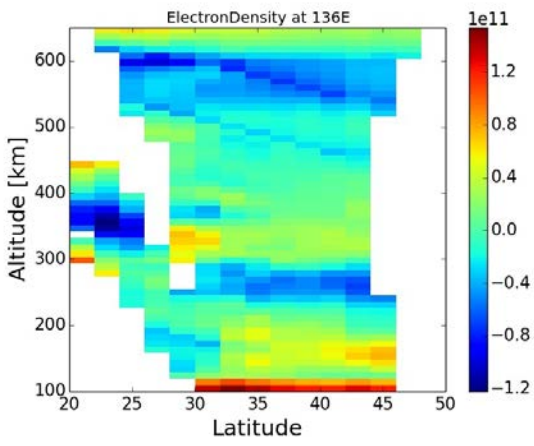


fig15. モデルと解析結果の差

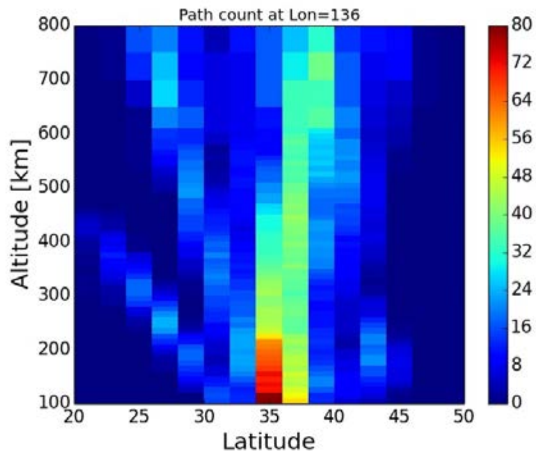


fig16. パスのカウント

⇒200点のGPS基地局数においても，よく一致する解析結果が得られている

3D Tomography with model + MSTID

南西方向の中規模伝搬性電離圏擾乱(MSTID)

$$N_e' = N_e\left(1 + \frac{2\alpha}{5} e^{-\alpha^2/(2\beta^2)}\right)$$

α = (lat.-46)+0.008alt.+0.25(lon.-100）， β=1°

Hunsucker(1982)

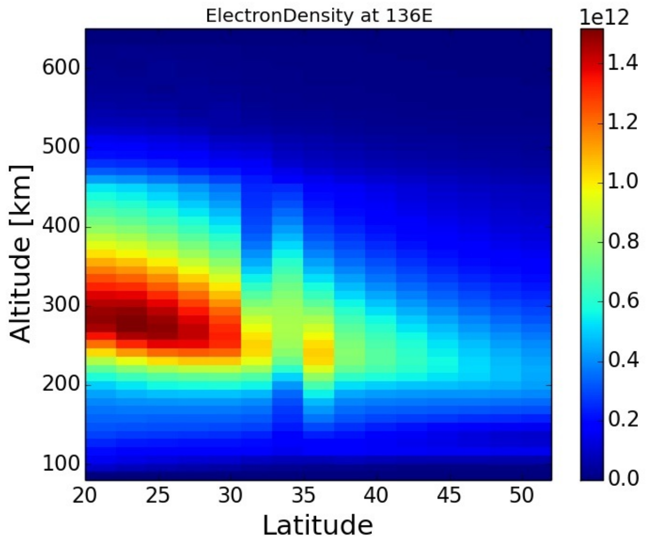


fig17. MSTIDを想定したNeQuickモデル

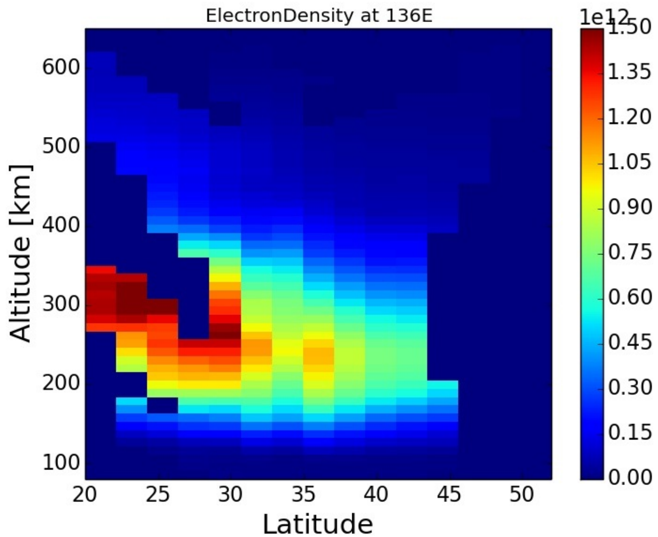


fig18. MSTID時のトモグラフィ解析結果

⇒MSTIDを捉えていることがわかる

計算の高速化

A行列が要素率1%程度の疎行列となるため，疎行列解析のアルゴリズムを利用した．また，エフェメリス等の読み込みは正規表現，各グリッドパス長の取得はスプライン補間を利用した．Intel Corei7 3.4GHz 8コアの環境においてデータの読み込みから解析結果の出力まで約10分程度であった．同スペックのPCによる従来プログラムと比較して3倍程度に高速化されている．

Tomography with real data

2012/05/23 03:30:00 UT における実データ解析結果

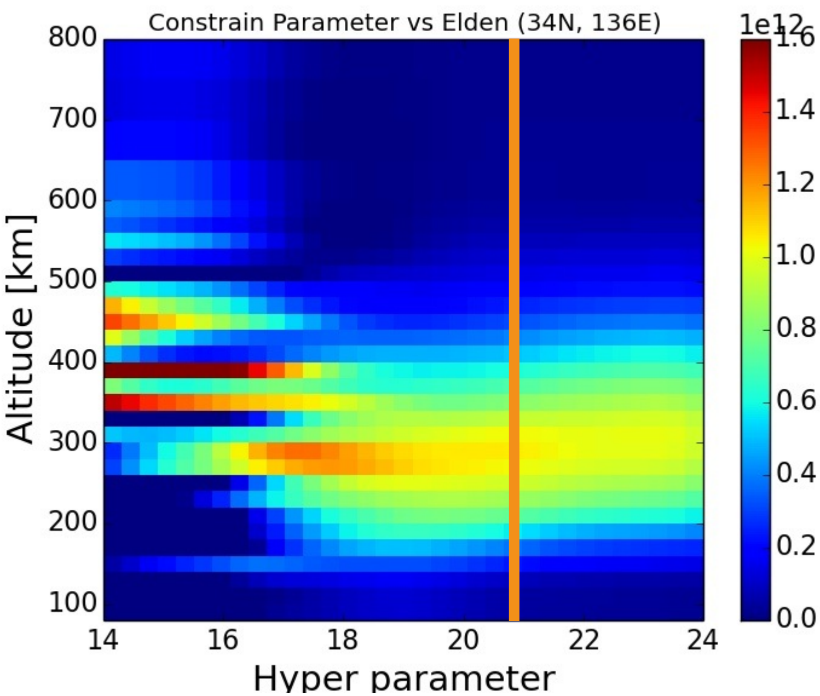


fig19. λと推定された電子密度の高度分布の関係

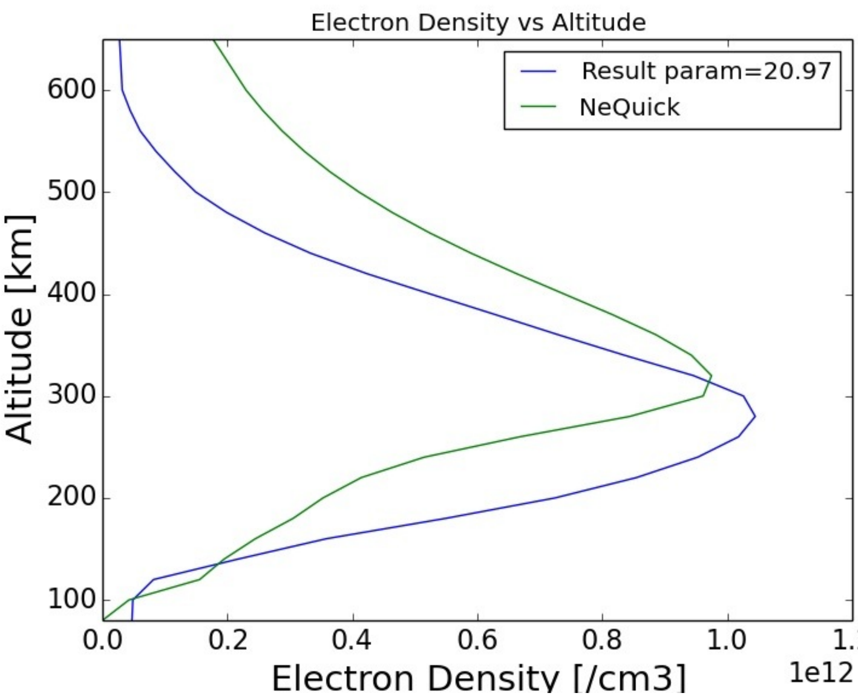


fig20. 電子密度の高度分布

- 実データの解析結果のピーク値がモデルより低い. ⇒グリッドレンジおよび拘束パラメータの決定が与える影響について詳細に検討する必要がある. (拘束を与えるグリッドの範囲など)
- イオノゾンデ観測およびCOSMIC掩蔽データ観測との比較からパラメータをチューニングする（現在進行中）