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Two-station method with variable mean ionospheric height for latitudinal GRBR-TEC estimation

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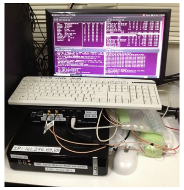
GNU-Radio Beacon Receiver (GRBR)

- GRBR is an "open" digital receiver to measure total electron density of the ionosphere.
- The system is based on GNU Radio. (toolkit for software-defined radio)
- Developed in RISH. (http://www.rish.kyoto-u.ac.jp/digitalbeacon/)
- Receiving dual frequency data from LEO satellites.
  - C/NOFS (E-W), 400km-orbit.
  - DMSP (N-S), 830km-orbit.
  - COSMOS (N-S), 1000km-orbit.
  - RADCAL (N-S), 800km-orbit.

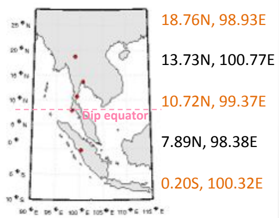


Introduction

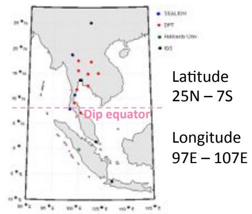
- Latitudinal distributed GRBRs can detect latitudinal structure of TEC with the wide coverage.
- Mean ionospheric height variation is a function of latitude.
- Presumption: Using the variable ionospheric height in stead of a single height may better reveal some longitudinal variation of the GRBR-TEC.
- Estimate of the absolute GRBR-TEC is not easy.
- Estimate technique for GPS-TEC is well established.
- To utilize advantages of both GRBR and GPS networks, the GRBR-TEC is determined by employing the GPS-TEC as an initial guess.

Data and methods

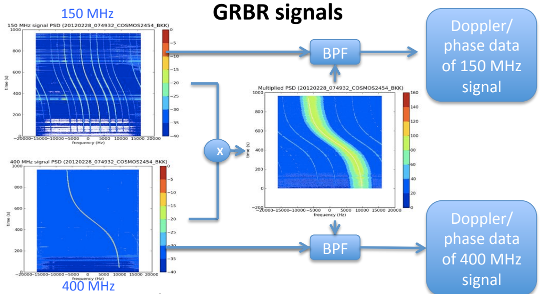
GRBR (5 stations)



GPS (17 stations)



GRBR signals

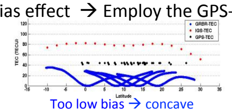


TEC was calculated from the phase leveling technique. [Yamamoto. M, 2008]

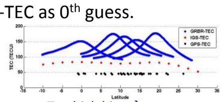
Absolute TEC = (measured TEC + Bias) *cosine(zenith angle of the satellite)

Effects on GRBR-TEC

- ✓ Ionospheric height effect → Employ variable ionospheric height.
  (The mean ionospheric height used in this work is "hmf2 + 50" (km).)
- ✓ Bias effect → Employ the GPS-TEC as 0^{th} guess.



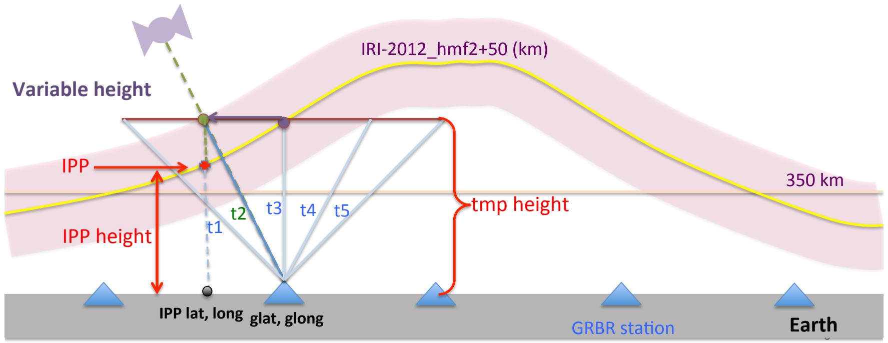
Too low bias → concave



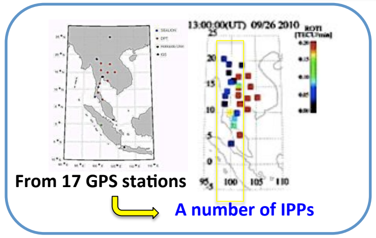
Too high bias → convex

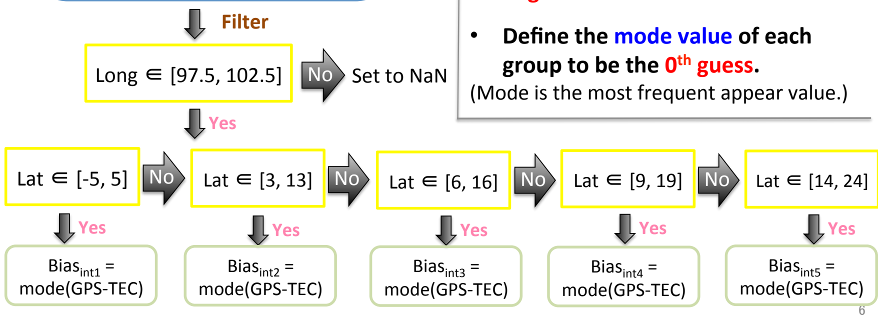
IPP with variable ionospheric height

- Known glat, glong.
- Lookup table for ionospheric height at glat, glong from IRI-2012 model.
- Calculate the IPP lat and long from that height.
- Lookup table for ionospheric height at IPP lat and long from IRI-2012 model.
- Converse slant TEC to absolute TEC at the IPP with the IPP height.



0^{th} guess based on GPS-TEC

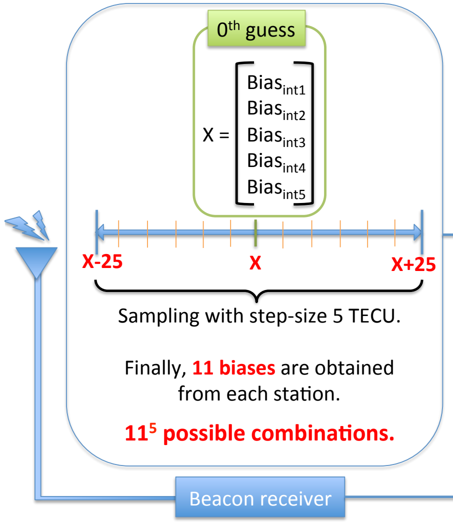




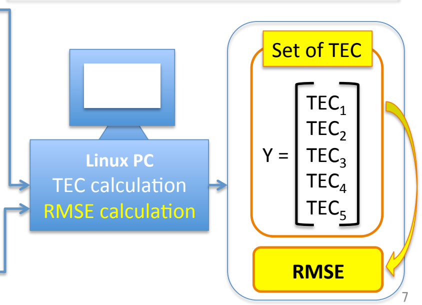
- **Select the GPS-TEC derived from the IPP along longitude 100E with window size +-2.5 degree.**
- **Group the data into 5 groups centering at latitude of the GRBR locations with window size +-5 degree.**
- **Define the mode value of each group to be the 0^{th} guess.**

(Mode is the most frequent appear value.)

GRBR-bias dataset (1^{st} iteration)



- **Define the bias set from the 0^{th} guess values with +- 25-TECU window.**
- **Sampling with 5-TECU step-size.**
- **Run all possible combinations to obtain the minimum RMSE.**



RMSE calculation 1

- **Find the intersect latitude of each station with 1-degree sampling rate.**
- **Calculate the square-error for every station-pairs.**
- **Average the square-errors. MSEs are gotten here.**
- **Calculate the square-root of the MSE. RMSE is gotten.**

$$SE1_{lat} = (TEC_{1,lat} - TEC_{2,lat})^2 + (TEC_{1,lat} - TEC_{3,lat})^2 + (TEC_{1,lat} - TEC_{4,lat})^2 + (TEC_{1,lat} - TEC_{5,lat})^2$$
$$SE2_{lat} = (TEC_{2,lat} - TEC_{1,lat})^2 + (TEC_{2,lat} - TEC_{3,lat})^2 + (TEC_{2,lat} - TEC_{4,lat})^2 + (TEC_{2,lat} - TEC_{5,lat})^2$$
$$SE3_{lat} = (TEC_{3,lat} - TEC_{1,lat})^2 + (TEC_{3,lat} - TEC_{2,lat})^2 + (TEC_{3,lat} - TEC_{4,lat})^2 + (TEC_{3,lat} - TEC_{5,lat})^2$$
$$SE4_{lat} = (TEC_{4,lat} - TEC_{1,lat})^2 + (TEC_{4,lat} - TEC_{2,lat})^2 + (TEC_{4,lat} - TEC_{3,lat})^2 + (TEC_{4,lat} - TEC_{5,lat})^2$$
$$SE5_{lat} = (TEC_{5,lat} - TEC_{1,lat})^2 + (TEC_{5,lat} - TEC_{2,lat})^2 + (TEC_{5,lat} - TEC_{3,lat})^2 + (TEC_{5,lat} - TEC_{4,lat})^2$$

$$MSE1 = \frac{1}{\Delta lat}\sum_{Lat=start}^{end} SE1_{lat},\quad MSE2 = \frac{1}{\Delta lat}\sum_{Lat=start}^{end} SE2_{lat},\quad MSE3 = \frac{1}{\Delta lat}\sum_{Lat=start}^{end} SE3_{lat}$$

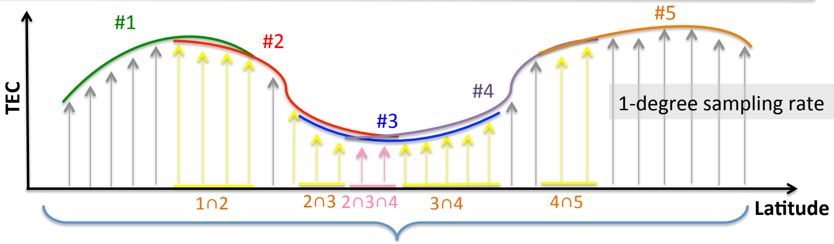
$$MSE4 = \frac{1}{\Delta lat}\sum_{Lat=start}^{end} SE4_{lat},\quad MSE5 = \frac{1}{\Delta lat}\sum_{Lat=start}^{end} SE5_{lat}$$

start: start of an intersect latitude
end: end of an intersect latitude
Δ lat: end – start

$$RMSE = \sqrt{\text{mean([MSE1 MSE2 MSE3 MSE4 MSE5])}}$$

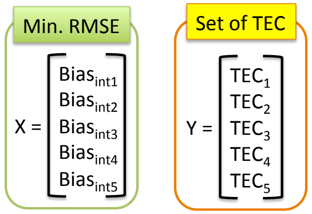
RMSE for one set of biases

RMSE calculation 2

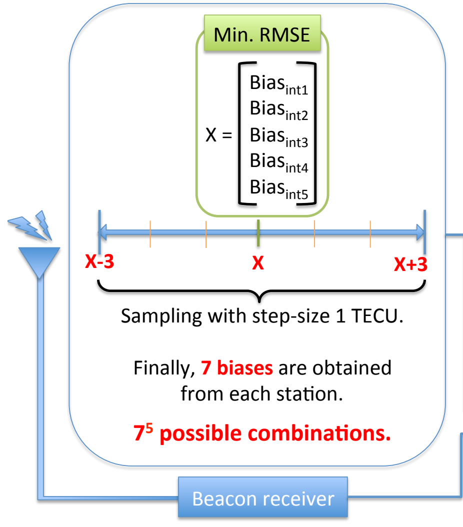


11^5 RMSEs are calculated regarding to the number of the bias sets.

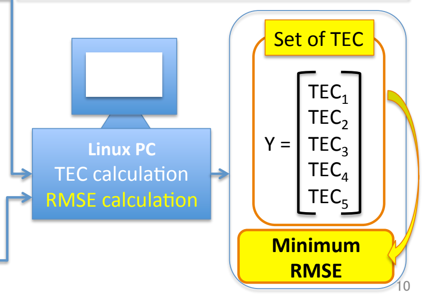
Find the bias set which yield the minimum RMSE.



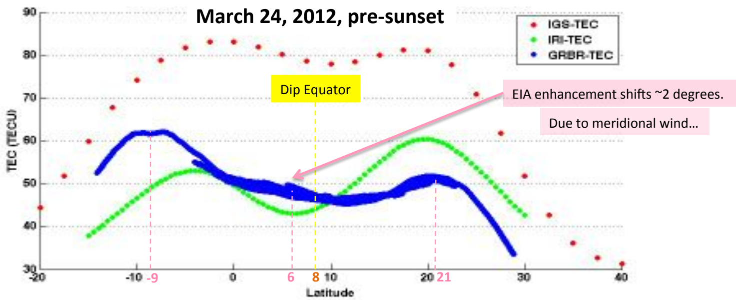
GRBR-bias dataset (2nd iteration)



- Define the bias set from the previous process.
- Use the best bias set, which yields the smallest RMSE values, with +- 3-TECU window.
- Sampling with 1-TECU step-size.
- Run all possible combinations to obtain the minimum RMSE.



Result: variable height method



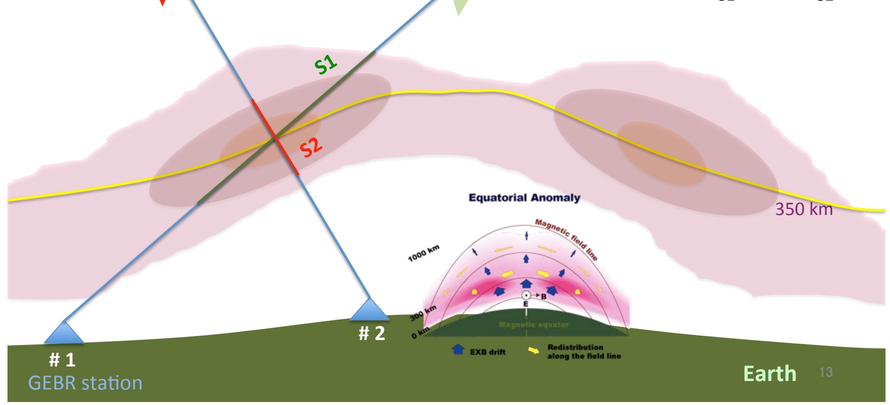
Satellite	Orbit	Start obs. time	End obs. time	Obs. duration	GRBR-TEC RMSE
COSMOS2494	South → North	~10:29UT (17:29LT)	~10:52UT (~17:52LT)	~23 min.	0.90 TECU

- Two crests of the EIA enhancement on March 24, 2012 (an equinox day) at pre-sunset hour are seen from the GRBR-TEC. They shift southward.

  It may be due to the meridional wind associated with Equatorial Temperature and Wind Anomaly (ETWA) which is linked to EIA. [Devasia et al., 2002].

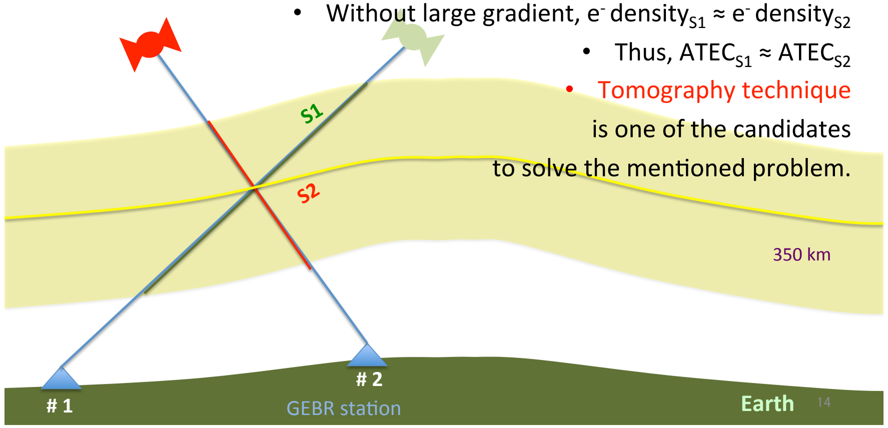
Error Analysis (1)

- Latitudinal gradient of the TEC in equatorial region is quite large.
  - Two-station method assumption: $ATEC_{S1} = ATEC_{S2}$
- However, with large gradient, e^- $density_{S1} >> e^-$ $density_{S2}$
  - Thus, $ATEC_{S1} \neq ATEC_{S2}$



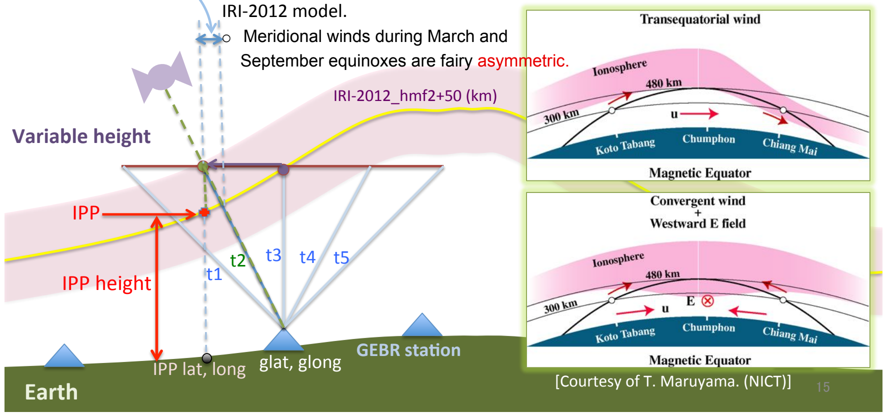
Suggestion based on Error Analysis(1)

- Latitudinal gradient of the TEC in mid-latitude area is not large compared with that in equatorial → Verify this technique with mid-latitude data.
  - Two-station method assumption: $ATEC_{S1} = ATEC_{S2}$
  - Without large gradient, e^{-} $density_{S1} \approx e^{-}$ $density_{S2}$
  - Thus, $ATEC_{S1} \approx ATEC_{S2}$
  - Tomography technique is one of the candidates to solve the mentioned problem.



Error Analysis (2)

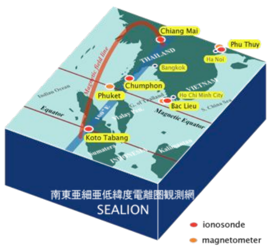
- Location error from Ionospheric Piercing Point (IPP) estimation process (variable height method).
  - Unrealistic IRI-2012 hmF2
    - For equatorial region, TE and convergent wind effect on hmF2 is not included in the IRI-2012 model.
    - Meridional winds during March and September equinoxes are fairy asymmetric.



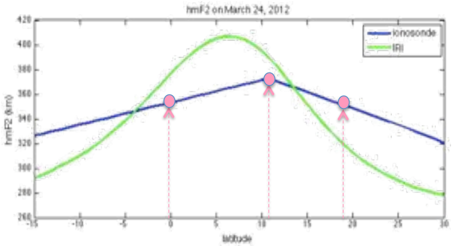
[Courtesy of T. Maruyama. (NICT)]

Suggestion based on Error Analysis(2)

- Run the IPP estimation process with more iterations to try to approach the true IPP.
- Employ the hmF2 from ionosonde instead of IRI-2012 hmF2.
  - There are 3 available ionosondes at 100-degree longitude sector.
  - Interpolation and extrapolation are needed if ionosonde hmF2 is used.



[Courtesy of SEALION project (NICT)]



Comparison of ionosonde-hmF2 and IRI-hmF2 on March 24, 2012.

Blue line: Ionosonde-hmF2 with first order linear interpolation and extrapolation.

Discussions and conclusions

- Variable ionospheric height based on the hmf2 value from IRI-2012 model was applied.
- The bias adjustment algorithm for the GRBRs with meridional alignment has been developed by employing the 0th guess technique based on the GPS-TEC.
- The two- station method was successful to derived GRBR-TEC from polar orbit satellite. We used 5 stations, and were finding minimum of RMSE by the "brute-force attack "" way.
- The GRBR-TEC calculated from the proposed method can reveal the latitudinal variation of the TEC in the low latitude region.

Future works

- Employ the ionosonde data to estimate the IPP height for variable height method.
- Confirm GRBR-TEC with ionosonde TEC.
- Extend the dataset to include new GRBR-chain in Malaysia and latitudinal GRBR-chain in Japan as well.
- Further investigate an efficiency of the proposed method with a number of events and conditions.
- Comparing the ground-based data (GPS, GRBR, etc.) with the satellite-based data from the ISS-IMAP project (630 nm airglow).