Evaluation of Different GPS Calibration Techniques

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Motivation

- GNSS-TEC has become a very important data source for scientific analysis, validation of theoretical and empirical models and data assimilation into these models.

- When using GNSS-TEC, one has to keep in mind that these are not direct measurements but quantities derived from the raw data involving several data analysis steps and calibration methods that vary from data analysis group to data analysis group. These calibration steps have to account for receiver and transmitter biases, multi-path corrections, slant-to-vertical transformation, and other error sources.

- The goal of this study is to evaluate the accuracy of some of these calibration techniques using NeQuick simulated scenarios as “known” ionosphere.

GNSS calibration schemes

The Azpilicueta et al. (2006) and Brunini et al. (2010) calibration scheme was developed as part of LPIM (La Plata Ionospheric Model). It is based on the geometry-free combination (L4) carrier-phase leveled to code (P4) and the assumption of constant calibration terms (DCBs) for at least one day. The slant TEC is mapped with the standard mapping function and the vertical TEC is geographically modeled with polynomial functions or spherical harmonics. The temporal variations of the coefficients are modeled with periodic functions.

The method of Seemala and Valladares (2011) uses the combination of both phase and code values at L1 and L2 frequencies to eliminate the effect of clock errors and tropospheric water vapor to calculate absolute values of slant TEC. The differential satellite bias corrections published by University of Bern are used. The receiver bias is calculated by minimizing the TEC variability between 0200 and 0600 LT (when spatial variability is less) or for the entire data of day (depending on data length). The resultant slant TEC is converted to vertical TEC using the single shell mapping function assuming 350 km altitude for the centroid of the ionosphere.

The Single-Station Arc-Offset method of Ciraolo et al. (2007) forms the geometry-free combination L4 for each arc from the observations in the RINEX files. L4 gives TEC, which is expanded by a Vertical Equivalent 2-D function of time (LT) and horizontal coordinates (Modip), plus an arc unknown offset. Standard Least Square methods are used to estimate the unknown coefficients of VEQ expansion and the arc offsets. The default height is 400km for the single shell mapping and can be also provided by the user.

LPIM calibration technique details

GPS Ionospheric obserbables – P4 and L4

$$P_{i\ 4}^{k} = P_{i\ 2}^{k} - P_{i\ 1}^{k}$$

$$P_{i\ 4}^{k} = sTEC + b_i + b^k + \varepsilon_P$$

$P_{i\ 1}^{k}$ *and* $P_{i\ 2}^{k}$ *GPS code observations*

where :

b_i *is the DCB of the receiver i*

b^k *is the DCB of the receiver k*

ε_P *is the code measurement error*

$$L_{i\,4}^{k} = L_{i\,1}^{k} - L_{i\,2}^{k}$$

$$L_{i\,4}^{k} = sTEC + B_i + B^k + C_{arc} + \varepsilon_L$$

$L_{i\,1}^{k}$ *and* $L_{i\,2}^{k}$ *GPS carrier phase observations*

where :

C_{arc} *represents the combination of the phase ambiguities*

B_i *is the phase inter-frequency bias for the receiver i*

B^k *is the phase inter-frequency bias for the satellite k*

ε_L *is the phase measurement error*

Carrier-to-code leveling technique

$$P_{i\ 4}^{k} = sTEC + b_i + b^k + \varepsilon_P \qquad L_{i\ 4}^{k} = sTEC + B_i + B^k + C_{arc} + \varepsilon_L$$

$$\langle L_4 - P_4 \rangle_{arc} = {}^1\!/_N \sum_{j=1}^{N} (L_4 - P_4)_j$$

$$\langle L_4 - P_4 \rangle_{arc} = C_{arc} + B_i - b_i + B^k - b^k$$

Combining P4 and L4, we compute one calibration constant per continuous arc

$$\tilde{L}_4 \equiv L_4 - \langle L_4 - P_4 \rangle_{arc}$$

Definition of the smoothed L4

$$\tilde{L}_4 = sTEC + B_i + B^k + C_{arc} + \varepsilon_L - \left(C_{arc} + B_i - b_i + B^k - b^k \right)$$

$$\tilde{L}_4 = sTEC + b_i + b^k + \varepsilon_L$$

Receiver DCB (b_i) — Satellite DCB (b^k)

Smoothed L4 is equivalent to carrier-to-code leveling observable

Model for the spatial and temporal variation for the VTEC

$$\tilde{L}_{4\ i}^{\ k} = F(z) * VTEC(h,\varphi) + b_i + b^k + \varepsilon_L$$

$where:$

$$F(z) = \frac{R}{R+H} \sin z$$ is the mapping function

$$VTEC(h,\varphi) = \sum_{i=0}^{N} \left(VTEC_{0\,i} + a_{1\,i}\left(\lambda - \lambda_0\right) + a_{2\,i}\left(\varphi - \varphi_0\right) \right)$$

$where:$

z is the elevation of the satellite

λ is the longitude of the pierce point

φ is the latitude of the pierce point

λ_0 is the longitude of the GPS station

φ_0 is the latitude of the GPS station

R is the radius of the Earth

H is the height of the single layer

A set of coefficients a0,a1 and a2 is computed every 15 minutes and a set of DCBs is computed for every day.

Differences between the Calibration Methods

TEC can be obtained from the GPS carrier phase or from the group delay (code) measurement. Calculation of TEC from group delay measurement is absolute and noisy. The relative phase delay between the two carrier frequencies gives a more precise measure of relative TEC, but is ambiguous because the actual number of cycles of phase is unknown. These two estimates can be combined to form an improved estimate for absolute TEC.

LPIM and GOBI use both the phase and group delay (L and P) while GIGI is more strongly based on the phase measurement.

LPIM and GIGI calculate the station and satellite biases as part of the analysis process while GOBI takes the bias factors provided by Bern.

Small differences in the mapping procedure , e.g., the height of the single-shell model. and also in the functions used to describe the spatial and temporal variation of TEC.

Stations for which GPS data were simulated

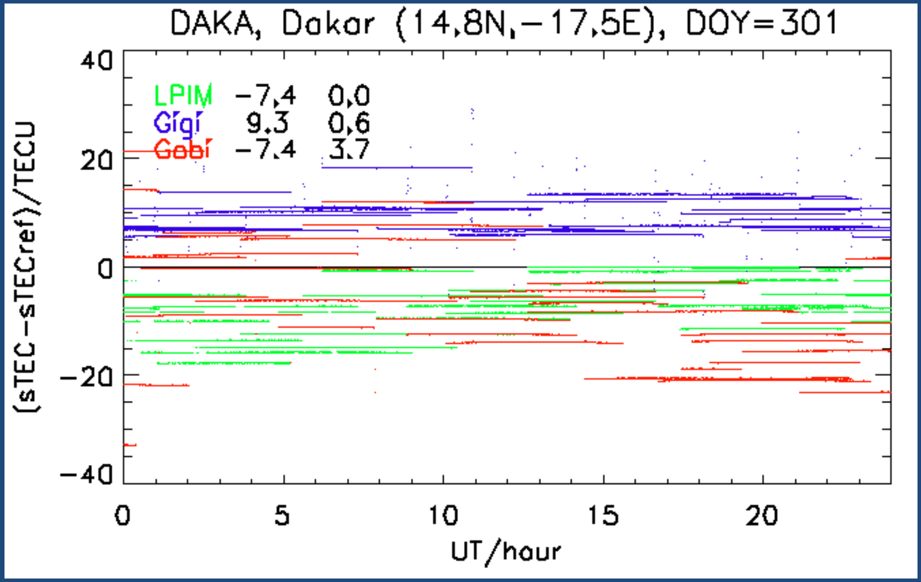
Location	Station ID	Network	Geographic Latitude	Geographic Longitude	Modip
Dakar/Senegal	DAKA	AFREF/IGS	14.75	343.51	9.77
Toro/Nigeria	CGGA	NIGNET	10.12	9.12	-2.23
Libreville/Gabon	NKLA	AFREF/IGS	0.35	9.67	-24.59

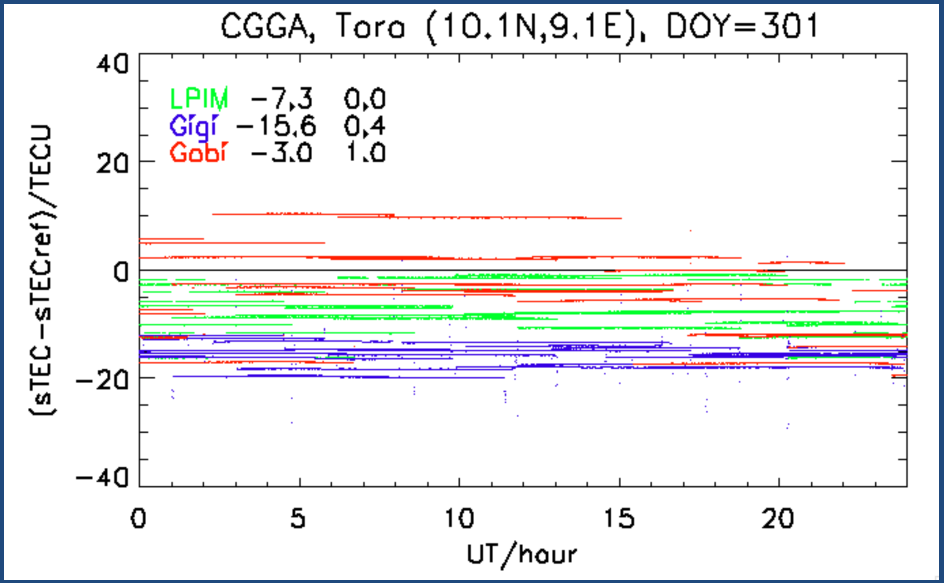
These stations were chosen considering that they are under the effect of the Ionospheric Equatorial Anomaly, a critical region of the ionosphere dominated by significant temporal and spatial gradients.

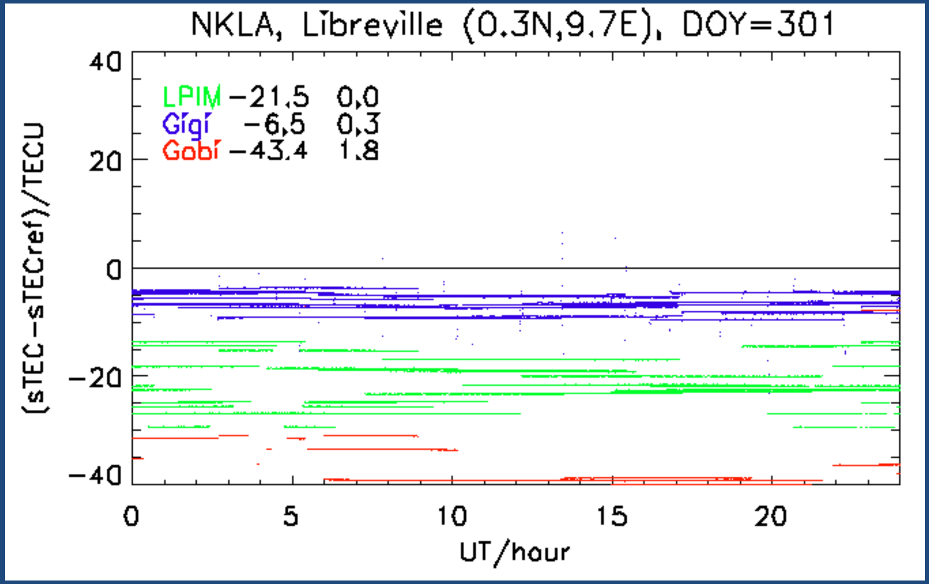
For the validation exercise equinox conditions with a F10.7 solar flux of 193 were used (day 301 of year 2013).

Each team used their calibration method with the provided simulated data and their sTEC results were then compared back to the NeQuick reference data

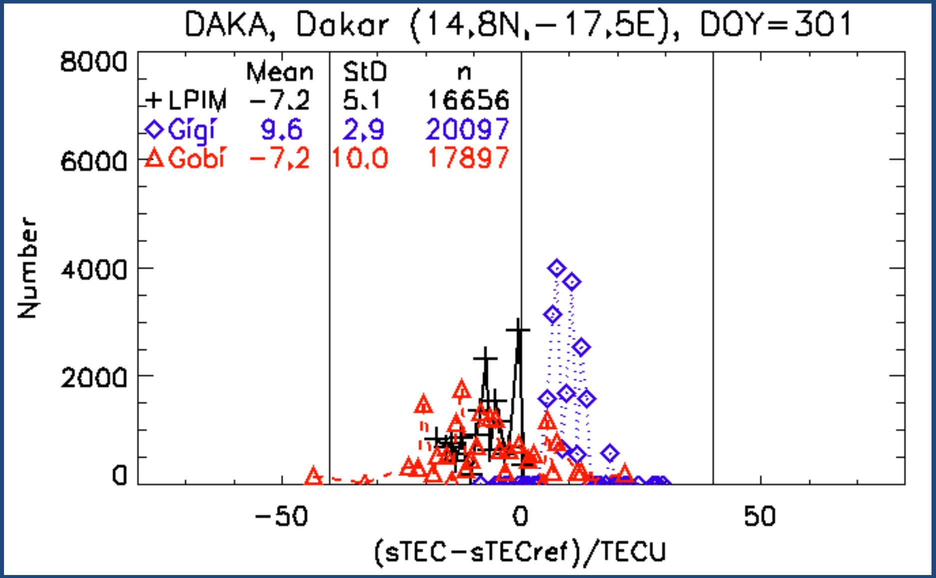
Absolute differences against UT

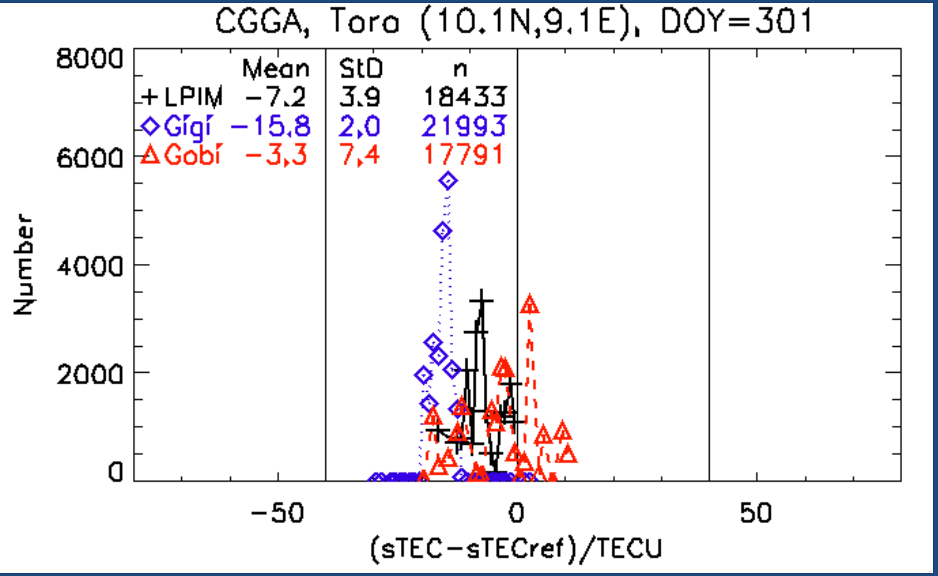






Histograms of Differences Method-Reference





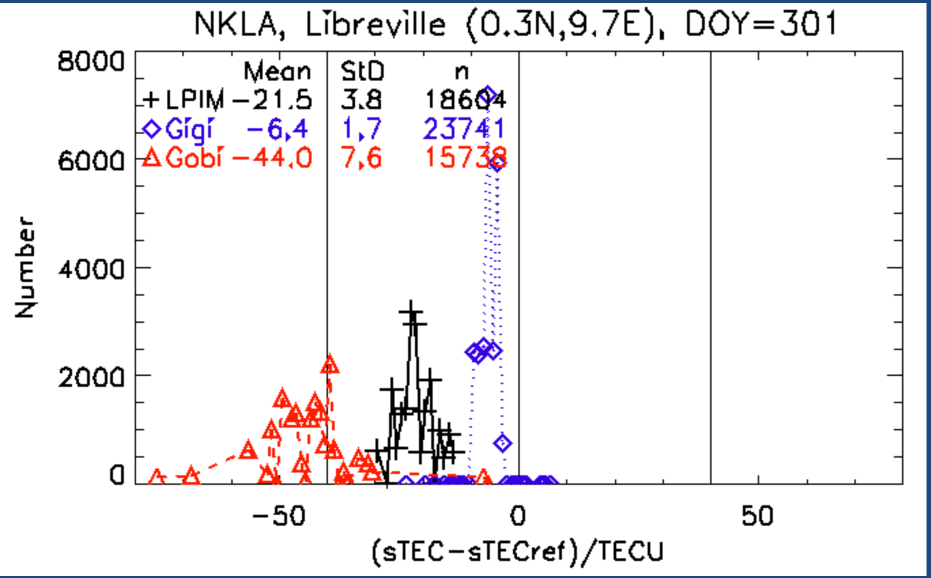


TABLE: Mean and Standard Deviation of Differences between Methods and Reference

	Mesn/TECU			Standard deviation/TECU		
	Dakar	Toro	Librevilee	Dakar	Toro	Libreville
LPIM	-7.2	-7.2	-21.5	5.1	3.9	3.8
Gigi	9.6	-15.8	-6.4	2.9	2.0	1.7
Gobi	-7.2	-3.3	-44.0	10.0	7.4	7.6

- **Best overall results with the GIGI method**
- **Largest discrepancies for Libreville, station on/near anomaly crest**
- **Assessment highlights the importance and impact of the calibration method on GPS-TEC**

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