XXXVII SIMPÓSIO BRASILEIRO DE TELECOMUNICAÇÕES E PROCESSAMENTO DE SINAIS – SBrT2019, 29/09/2019–02/10/2019, PETROPOLIS, RJ

Estimation and Analysis of Differential Code Biases Based on GPS Data from Brazilian Network

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Abstract—**The uncertainty of differential code bias (DCB) is one of the main error sources in ionospheric delay of the signal GPS based total electron content (TEC). In this paper, we propose a combination of DCB estimation methods using ZERO method and least square method based on the assumption that the TEC can reach zero. This work estimates receiver differential code biases using GPS measurements of five receivers located within Brazilian network region where ionospheric anomalies exist. The results showed that the estimated values of the receiver differential code biases present stability in comparison to CODE values estimated. The results of differential code biases for Brazilian stations vary much with latitude and longitude and the year of solar activity.**

***Index Terms*—Ionosphere, global positing system, measurements, propagation.**

I. INTRODUCTION

Nowadays, Global Positioning System (GPS) is extensively used for navigation and positioning in static or kinematic condition in a large number of applications. Ionosphere affects the propagation of the signal GPS and can reduce the accuracy of positioning by tens of meters [1]. The ionospheric influence could be more than a hundred meters during the presence of plasma bubbles.

The presence of Total Electron Content (TEC) in the ionospheric layer can be estimated from the combination of GPS measurements. GPS data can be used to estimate TEC values but they carry an uncertainty because each GPS satellite and each receiver station has a hardware that has associated biases that seriously affect the estimated value of the ionospheric TEC [2].

The delay in the GPS signal that occurs due to the Differential Code Bias (DCB) is considered an instrumental effect due to the difference between the propagation time of the different carriers in the hardware. Further delays to DCB occur due to imperfect synchronization in code modulation in signal generation (satellite) and code demodulation (receiver) [3], [4]. The differential code biases are a non-negligible error source. The magnitude of the combined satellite and receiver DCBs can add up to several nanoseconds (ns), for example, ignoring the satellite and receiver DCBs when computing TEC may result in an error of up to 20 TEC units (or 7 ns) for satellites and 40 TECU (or 14 ns) for receivers, one ns corresponds to approximately 28.5 cm in range units [5]. For this reason, to improve the accuracy of TEC estimates, it is necessary to precisely estimate GPS satellite and receiver DCBs.

II. METHODOLOGY

The pseudorange and carrier phase observations are recorded at the two GPS frequencies ($f_1 = 1575.42\,MHz$ and $f_2 = 1227.60\,MHz$). Before processing the data, the outliers are eliminated, and cycle slips are detected and corrected to create continuous arcs using the algorithm based in high-order phase differencing and combination of carrier phase and code measurements [6], [7].

Slant TEC (TEC_{sl}) information can be obtained from the difference of GPS observations as follows:

$$TEC_{slp} = \frac{2\,(f_1 f_2)^2}{K(f_1^2 - f_2^2)}(P_2 - P_1) + b_r + b_s \qquad (1)$$

$$TEC_{sll} = \frac{2\,(f_1 f_2)^2}{K(f_1^2 - f_2^2)}(L_1\lambda_1 - L_2\lambda_2) + (\lambda_1 N_1 - \lambda_2 N_2) \qquad (2)$$

where K is the ionospheric refraction, 80.62 (m^2/s^2), λ_1 and λ_2 are the wavelength corresponding to f_1 and f_2, respectively. P_1 and P_2 are pseudoranges, L_1 and L_2 are carrier phase observations at the two frequencies, b_s and b_r are the instrumental differential code biases of the satellite and receiver, respectively, $\lambda_1 N_1$ and $\lambda_2 N_2$ are the integer cycle ambiguity terms.

The difference of the carrier phase between (L_1 and L_2) is precise and less noisy, not providing the absolute TEC. However, to retain phase path accuracy for the slant path TEC_{sl}. TEC_{sll} is fitted to TEC_{slp}, adding a baseline B_{rs} for the difference phase TEC_{sll}. The procedure in detail is described in [8].

One limitation of the slant $\boldsymbol{TEC_{sl}}$ is the dependency of the ray path geometry through the ionosphere. In order to compute more precise ionospheric measurements from GPS, we need to calculate the equivalent Vertical TEC value which is independent of the elevation angle of the ray path [9], [10]. To calculate a TEC value from paths with various elevation angles, the $\boldsymbol{TEC_{sl}}$ should be transformed into a VTEC value, by using a simple mapping function and a simplified model.

This model is related with an ionospheric pierce point (IPP) latitude and longitude, assuming the ionosphere is compressed into a thin shell over the peak ionospheric height.

$$VTEC = \frac{(TEC_{sl} - b_s - b_r)}{S(\varepsilon)} \quad (3)$$

where $S(\varepsilon)$ is described by:

$$S(\varepsilon) = \frac{1}{\cos\left[\arcsin\left(\frac{R_E \cos\varepsilon}{R_E + H}\right)\right]} \quad (4)$$

where ε is the elevation angle, R_E is the radius of the earth, and H is the height of the ionospheric layer; which is assumed to be 400 km.

The instrumental bias b_s and b_r of each receiver and satellite are obtained by comparing the hourly averages of uncalibrated TEC_{sl} values from all of the satellite and single receiver combinations using the least mean square fitting method (LMSQ). Based on the consideration that the VTEC is uniform in small area and not change during one hour, the instrumentals biases are estimated by using the hourly (TEC_{sl}) average that is obtained in the first step. Finally, the biases are removed from measured (TEC_{sl}) to derive absolute (TEC_{sl}) [11]. Here, we will assume that the hourly average of vertical TEC ($VTEC_k$) is uniform within an area covered by a receiver given by:

$$E = \sum_i^{N_s} \sum_k^{N_t} \left[\frac{(TEC_{sl})_k}{S(\varepsilon)} - \overline{VTEC_k} - \frac{1}{S(\varepsilon)}(b_s + b_r)\right]^2 \quad (5)$$

where k=1,2,…, N_t and i=1,2,…, N_s where N_t is the number of hourly VTEC average and N_s is the number of satellites which are observed by the receiver.

Then, applied the LMSQ, in case that the minimum $sTEC^r_{dailymin}$ ($sTEC^r_{dailymin}$ is the relative TEC with the GPS satellite DCB calibrated but still biased with the receiver DCB) continues to be negative it is possible to assume that the receiver DCB is equal to $sTEC^r_{dailymin}$ [12], [13]. Generally, the DCB calculated from the ZERO TEC method can be expressed as follows:

$$b_r = 0 - sTEC^r_{dailymin} \quad (6)$$

where $sTEC^r_{dailymin}$is the daily minimum of the relative TEC. This method is simple and fast and it will be combined with the mean square fitting method.

III. DATA

In this work, RINEX (Receiver Independent Exchange Format) files were used from January to December 2008 and January to December 2013, from the following stations of the Brazilian Network for Continuous Monitoring of GNSS Systems listed in Table I. The Brazilian Network (RBMC) located stations around all the territory, depicted in the Fig. 1. (Blue dots). The selected stations are located in several latitudinal regions of the ionosphere and comprise the Brazilian receiver stations used by CODE in the modeling of the ionosphere for the years of interest, depicted in the Fig. 1. (Red dots). It is emphasized that the quality of the estimated DCB is highly dependent on the measurements of TEC estimated from the RINEX files.

The original data were in RINEX format with 15 second sampling rate. The elevation cut-off angle of 20° was used for the collected data. Data from the Brazilian Continuous Monitoring Network of the Brazilian Institute of Geography and Statistics (RBMC / IBGE) were obtained to study the variation of the TEC as a function of local time, season and solar activity over the Brazilian region.

TABLE I. RECEIVER STATIONS DESCRIPTION

Receiver Station	City	Geographic Coordinates	Geomagnetic latitude
SALU	Sao Luis, Brazil	02.53° S 44.22° W	02.44° S
BRFT	Fortaleza, Brazil	03.87° S 38.42° W	06.76° S
BRAZ	Brasilia, Brazil	15.93° S 47.82° W	11.24° S
RECF	Recife, Brazil	08.05° S 34.97° W	11.61° S
CHPI	Cachoeira Paulista, Brazil	22.68° S 44.98° W	16.09° S

The precise ephemeris (SP3) are taken from the International GNSS Service (IGS) However, the limit of precise orbits is that the reported satellite positions are at an interval of 15 minutes. Thus, to circumvent this problem, the satellite positions are interpolated at every 15 seconds via cubic interpolation.

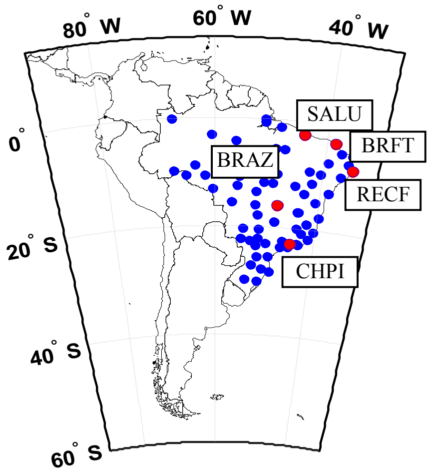

Fig. 1. Positions of the all ground-based RBMC stations (Blue dots) and the ground-based RBMC-IGS stations (Red dots) in 2008.

To validate the methodology, the DCB values of the receiver stations are obtained from the IONEX (IONospheric EXchange) file. The International GNSS Service (IGS) worked in the production of IONEX files, which in addition to the estimates of the VTEC values also includes the DCBs of the satellites and receivers of the network. The DCBs of the IONEX archives of the IGS (Center for Orbit Determination in Europe (JPL) - European Space Agency) are presented in a daily resolution.

IV. RESULTS

Results of the DCB for two different years will be presented: a year with low geomagnetic and solar activity (2008) and a year with high solar and geomagnetic activity (2013) determined by the solar and geomagnetic indices (F10.7 index and Kp index, respectively).

Fig. 2 to Fig. 6 show the DCB values calculated by the CODE and the estimated values using pseudorange and carrier phase measurements, in order to quantify the quality of the method for Brazilian receiver stations on 2008 (Low geomagnetic and solar activity). In some cases, the selected stations were not used in the daily production of the IONEX files, or there is a lack of data in the RINEX files.

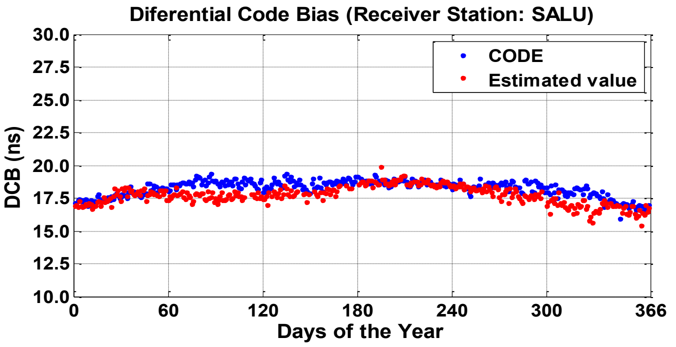

Fig. 2. DCB estimated and calculated by CODE for SALU station (2008)

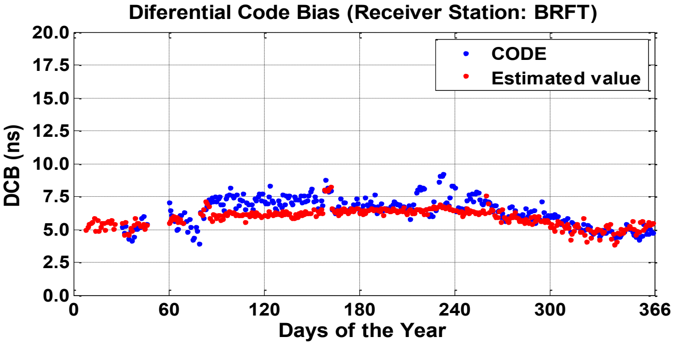

Fig. 3. DCB estimated and calculated by CODE for BRFT station (2008)

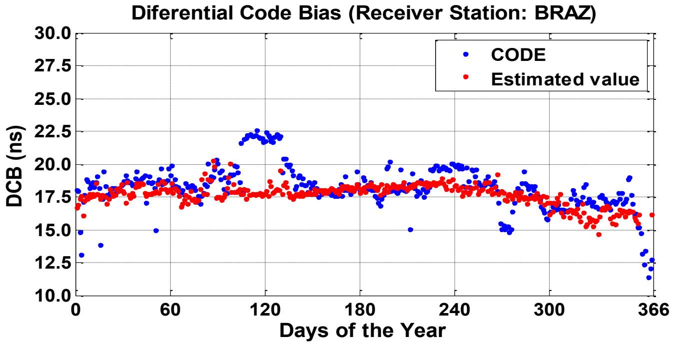

Fig. 4. DCB estimated and calculated by CODE for BRAZ station (2008)

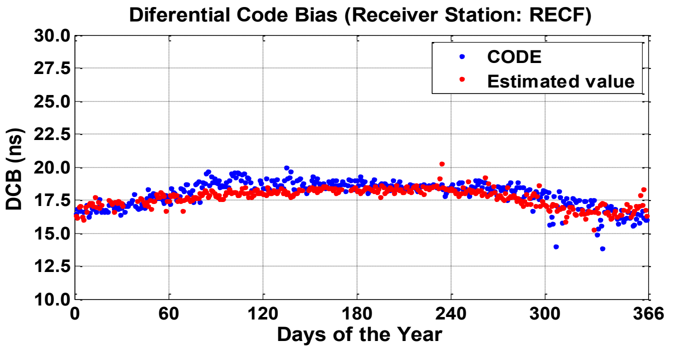

Fig. 5. DCB estimated and calculated by CODE for RECF station (2008)

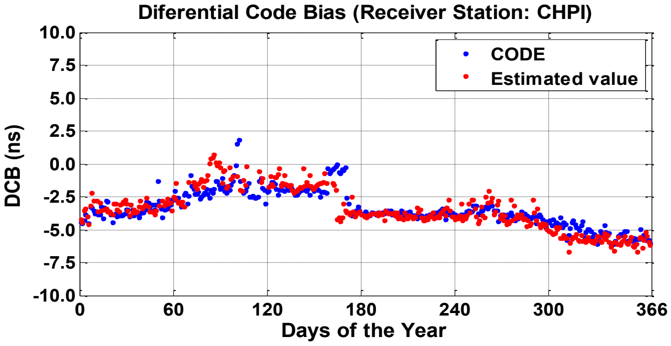

Fig. 6. DCB estimated and calculated by CODE for CHPI station (2008)

The means annual and standard annual deviations of the DCBs estimated by CODE and combined methods in 2008 are compared on the table II:

TABLE II. STATISTIC OF DCB ESTIMATED (2008)

Receiver Station	Mean (combined method) (ns)	Standard deviation (combined method) (ns)	Mean (CODE) (ns)	Standard deviation (CODE) (ns)
SALU	17.73	0.71	18.18	1.66
BRFT	5.91	0.68	6.37	1.07
BRAZ	17.68	0.87	18.23	1.76
RECF	17.71	0.69	17.90	1.81
CHPI	-3.50	1.57	-3.40	1.34

The results showed on the table II indicate a good approximation between DCBs estimated by the algorithm used here and CODE estimated available values. The results show that the means using the combined method and the means calculated for CODE data present low variation, for example the worst difference is showed in BRAZ station we have a difference of 0.55 ns. In addition, the combination of methods presents small values of standard deviation in the major part of results showing low dispersion of values, one exception was the case of CHPI station that present 1.57 ns and it was found 1.34 ns for the standard deviation calculated by CODE.

Fig. 7 to Fig. 11 show the DCB values calculated by the CODE and the estimated values using pseudorange and carrier phase measurements, in order to quantify the quality of the method for Brazilian receiver stations on 2013 (High geomagnetic and solar activity).

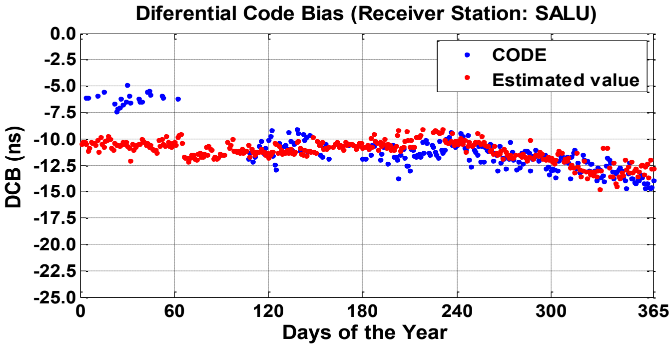

Fig. 7. DCB estimated and calculated by CODE for SALU station (2013)

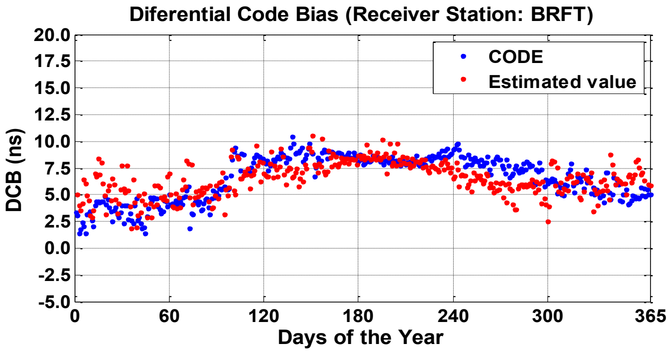

Fig. 8. DCB estimated and calculated by CODE for BRFT station (2013)

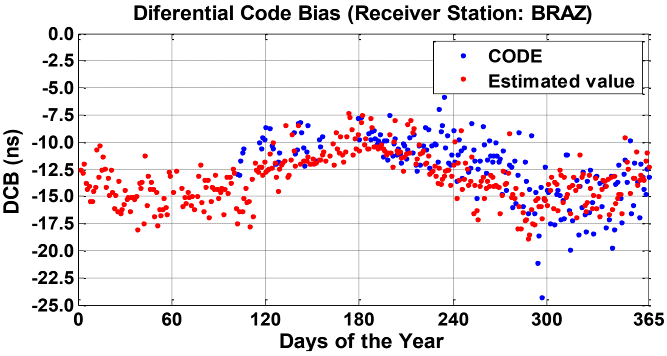

Fig. 9. DCB estimated and calculated by CODE for BRAZ station (2013)

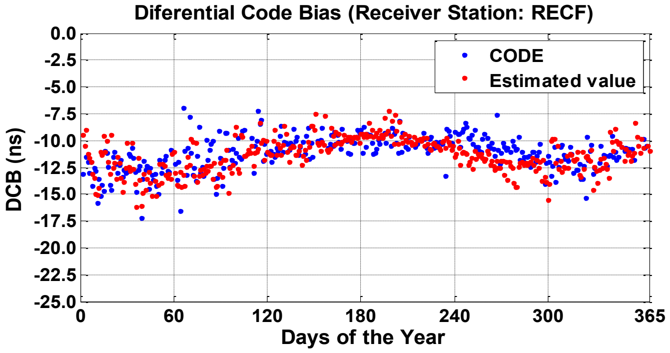

Fig. 10. DCB estimated and calculated by CODE for RECF station (2013)

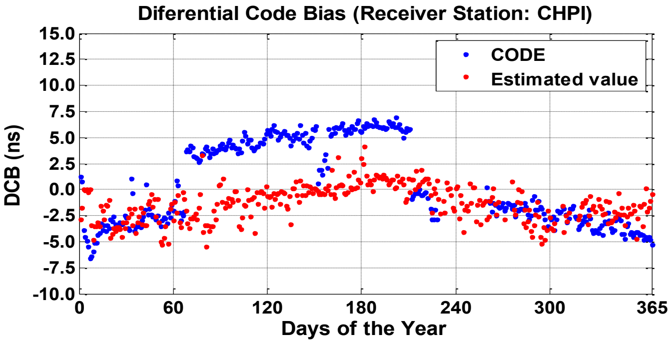

Fig. 11. DCB estimated and calculated by CODE for CHPI station (2013)

The means annual and standard annual deviations of the DCBs estimated by CODE and combined methods in 2013 are compared on the table III:

TABLE III. STATISTIC OF DCB ESTIMATED (2013)

Receiver Station	**Mean (combined method) (ns)**	**Standard deviation (combined method) (ns)**	**Mean (CODE) (ns)**	**Standard deviation (CODE) (ns)**
SALU	-11.15	1.02	-11.23	2.03
BRFT	6.49	1.60	6.59	2.10
BRAZ	-13.24	2.76	-12.31	2.96
RECF	-11.38	1.63	-11.13	1.60
CHPI	-1.33	1.71	0.59	3.98

The results showed on the table III indicate a good approximation between DCBs estimated by the algorithm described and CODE estimated available values. The results show that the means using the combined method and the means calculated for CODE data present low variation, for example the worst difference is showed in BRAZ station we have a difference of 0.93 ns. In addition, the combination of methods presents small values of standard deviation in the major part of results showing low dispersion of values. In contrast to standard deviation values estimated on 2008 were exist low dispersion of data, the standard deviation calculated in 2013 present high dispersion of data caused by the Ionospheric activity.

V. CONCLUSIONS

In this paper, we have proposed an improved combination between a ZERO method and LMSQ method to estimate the DCB of the GPS receiver, in order to illustrate the results of this methodology are estimated the DCB for five receivers of the Brazilian Network for Continuous Monitoring using its own GPS measurements in two years with different geomagnetic and solar activity (2008 and 2013). The results are validated using the estimated values of CODE.

In brief, the mean calculated using the combined method (zero method and LMQS method) and the mean estimated by CODE do not present large differences, and the standard deviation using the combined method are small in comparison to the estimated values by CODE.

ACKNOWLEDGMENT

This material is based upon work performed in the framework of the National Institute of Science and Technology – GNSS Technology to Support Air Navigation (INCT GNSS-NavAer) program, supported by CNPq/MCTIC awards 465648/2014-2 and 309013/2016-0, FAPESP award 2017/01550-0, and CAPES/MEC.

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