Estimation and analysis of GNSS receiver differential code bias in Southeast Asia using a new method

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Abstract. The receiver differential code bias (DCB) is one of the main errors in GNSS navigation and positioning as well as ionospheric monitoring. In this paper, we present a new method to estimate the receiver differential code bias (DCB) using Multi-GNSS observations in Southeast Asia. Different from the traditional method by using ionosphere modeling or Global ionospheric map (GIM), the total electron content (TEC) of station in the new method is estimated directly together with the receiver DCB. The data of one year with 34 stations were used to evaluate the performance of the presented method. The results show a good agreement between our estimated receiver DCBs and the MGEX DCB products and the RMS of eight types of GNSS receiver DCB are mostly less than 1 ns with respect to the MGEX products. Finally, the stability of GNSS receiver DCB was analysed for eight stations located in Southeast Asia as examples. The result indicates that those stations were relatively stable with mostly less than 1 ns of STD of receiver DCB. Moreover, no evidence of latitudinal and receiver type dependencies of the stability of receiver DCB for those selected stations was found.

1. Introduction
The total electron content (TEC) is one of the main parameters in the research of ionosphere, which can be obtained using the geometry-free linear combination of dual-frequency GNSS observations [1-4]. Generally, the satellite and receiver differential code bias (DCB) exist in the observations of TEC, which cannot be ignored and are also important error source in GNSS positioning, navigation and ionospheric monitoring [5-9].

Since the GPS and GLONASS observations were used to monitor the ionosphere, several International GNSS Service (IGS) Analysis Center (IAC) including the Center for Orbit Determination in Europe (CODE), the Jet Propulsion Laboratory (JPL), the European Space Agency (ESA) and the Universitat Politècnica de Catalunya (UPC) began to provide GPS and GLONASS DCB as a byproduct of the ionosphere to users [10, 11]. However, the stations used in those IACs have mainly been from IGS network, and the receiver DCBs provided by IACs have been limited to those stations [9, 12-14]. Thus, there is a greater demand for DCB estimation of single-station receivers from other stations.
For the single receiver DCB estimation, the satellite DCB parameters can generally be eliminated by using IGS products. There are two main methods that can be used to estimate the single receiver DCB. The first one is to estimate the receiver DCB by using the regional ionosphere model [2, 5]. Moreover, in order to simplify DCB estimation, the other method that estimates the receiver DCB using the existing GIM is presented [13]. Apart from those two commonly methods, some other methods are also proposed to estimate the single-station receiver DCB. Ma and Maruyama [12] propose the minimization of standard deviations (MSD) method, in which the true value of receiver DCB is searched through minimization of standard deviation of TEC. Obviously, the efficiency of this method depends on the search width, and it is not suitable for multi types DCB estimation. The other method that optimization by adding the ionospheric residual parameters based on the GIM is proposed by Arikan, Nayir, Sezen and Arikan [13]. In addition, some researchers also estimate the receiver DCB based on the relative GPS network [1].

On the whole, these estimation methods for single receiver DCB are mostly aimed at GPS. With the rapid development of Multi-GNSS, it provides us a good opportunity to monitor and study ionosphere with multi-GNSS and multi frequency GNSS observation data [15-17]. Thus, the multi types of DCBs are formed based on the multi-GNSS and multi frequency GNSS observations. Obviously, the multi types of DCBs estimation for single receiver also needs to be carried out. Table 1 gives the information of MGEX DCB products provided by CAS and DLR in 2019[18, 19], in total 19 types of DCBs need to be estimated.

In this paper, we present a new method to estimate the multi types of receiver differential code biases (DCBs) using Multi-GNSS observations. Different from the general method by using ionosphere modeling or Global ionospheric map (GIM), the total electron content (TEC) of station in the new method is estimated directly together with the receiver DCB. The data of 200 days with more than 300 stations were used to evaluate the performance of the presented method. Finally, the stability of GNSS receiver DCB was analyzed by taking 8 stations located in the Southeast Asia as examples. In the following sections, the new method is first presented in detail, and then the assessment of receiver DCBs estimated by the presented method is shown and the analysis of receiver DCBs for the selected stations is given. The corresponding conclusion is finally presented.

Table 1. Information of MGEX DCB products provided by CAS and DLR in 2019.

| No. | System | Bias type | CAS | DLR | No. | System | Bias type | CAS | DLR |
|-----|--------|-----------|-----|-----|-----|--------|-----------|-----|-----|
| 1   | GPS    | G1        | ✔  ✔ |      | 10  | Galileo | E1        | ✔  ✔ |      |
| 2   |        | G2        | ✔  ✔ |      | 11  |        | E2        | ✔  ✔ |      |
| 3   |        | G3        | ✔  ✔ |      | 12  |        | E3        | ✔  ✔ |      |
| 4   |        | G4        | ✔  ✔ |      | 13  |        | E4        | ✔  ✔ |      |
| 5   | GLONASS| R1        | ✔  ✔ |      | 14  |        | E5        | ✔  ✔ |      |
| 6   |        | R2        | ✔  ✔ |      | 15  |        | E6        | ✔  ✔ |      |
| 7   |        | R3        | ✔  ✔ |      | 16  | QZSS   | J1        | ✔  ✔ |      |
| 8   | BDS    | B1        | ✔  ✔ |      | 17  |        | J2        | ✔  ✔ |      |
| 9   |        | B2        | ✔  ✔ |      | 18  |        | J3        | ✔  ✔ |      |
|     |        |           |     |      | 19  |        | J4        | ✔  ✔ |      |

2. New receiver DCB estimation method
It is well known that, by using the geometry-free linear combination of dual-frequency GNSS observations, the frequency independent parameter including geometric range, clock offsets, and
tropospheric delay can be eliminated. The corresponding GNSS code observation equation can be described as [20, 21]:

\[ P_s^i - P_s^j = 40.3 \left( \frac{1}{f_1^2} - \frac{1}{f_2^2} \right) STEC_j + DCB_j - DCB_i \]  

(1)

where \( S \) refers to the GNSS constellation type (here \( G \) is for GPS, \( R \) for GLONASS, \( C \) for BDS, \( E \) for Galileo and \( J \) for QZSS); \( P_s^i \) refers to the geometry-free linear combination of dual-frequency GNSS code observations; \( P_s^i \) and \( P_s^j \) refer to the GNSS code observations at the first and second frequencies, respectively; \( f_i \) and \( f_j \) refer to the first and second frequencies of GNSS, respectively; \( STEC_j \) refers to the slant total electron content in the signal propagation path between GNSS satellite \( i \) and ground receiver \( j \); DCB\(^i\) and DCB\(^j\) refer to the satellite and receiver DCB. STEC can be converted to vertical TEC (VTEC) by using the single layer mapping function. The mapping function used in this study is the modified single-layer model (MSLM), which can be expressed as [20]:

\[ M(z) = \cos \left( \arcsin \left( \frac{R}{R+H} \sin(az) \right) \right) \]  

(2)

where \( R \) is the mean radius of the Earth (\( R=6371\) km); \( H \) is the height of assumed single-layer ionosphere (\( H=506.7\) km); \( a \) is a correction factor (\( a=0.9782 \)); \( z \) is the satellite zenith angle of a satellite at the receiver.

Based on Equation (1) and (2), we can know that the unknown parameters including satellite DCB, receiver DCB and VTEC need to be estimated for each single station. For receiver DCB estimation, the value of satellite DCB can be obtained by MGEX products. Thus, the corresponding equation for receiver DCB estimation can be expressed as:

\[ F_j^i VTEC_j + DCB_j - P_s^i - DCB_i \]

\[ F_j^i = 40.3 \left( \frac{1}{f_1^2} - \frac{1}{f_2^2} \right) M(z)_j \]  

(3)

According to Equation (3), the number of unknown parameters is \( n+1 \) when the number of available observations is \( n \). Thus, it is impossible to obtain the estimation of parameters through least square adjustment. To implement the estimation, two methods, including ionospheric modeling and use of prior GIM, can be used to estimate receiver DCB. In this study, a new method is adopted to estimate the receiver DCB, in which the mean value of VTEC of all ionosphere pierce points at epoch \( k \) is regarded as the VTEC of station. It is feasible since the ionospheric VTEC changes slowly within a certain range at the same epoch. Thus, the corresponding equation can be expressed as:

\[
\begin{bmatrix}
1 & F_1 \\
1 & \\
\vdots & \\
1 & \\
1 & \\
\end{bmatrix}
\begin{bmatrix}
DCB_j \\
VTEC_1 \\
\vdots \\
VTEC_i \\
\end{bmatrix}
=
\begin{bmatrix}
P_s^{i1} - DCB_i \\
\vdots \\
P_s^{ij} - DCB_i \\
\end{bmatrix}
\]  

(4)

By using Equation (4), the receiver DCB and the VTEC of a station can be calculated through the least square adjustment. However, we should also consider that the ionospheric VTEC changes slowly between the adjacent epochs. Thus, a virtual observation equation is added into the adjustment, which can be expressed as:

\[
\begin{bmatrix}
1 & -1 \\
1 & -1 \\
\vdots & \\
1 & -1 \\
\end{bmatrix}
\begin{bmatrix}
VTEC_1 \\
VTEC_2 \\
\vdots \\
VTEC_i \\
\end{bmatrix}
=
\begin{bmatrix}
0 \\
0 \\
\vdots \\
0 \\
\end{bmatrix}
\]  

(5)

Based on the combination of Equation (4) and Equation (5), using the least square to estimate the receiver DCB. Noted that the weight of virtual observation is set using an empirical value. Therefore,
the daily receiver DCB and epoch-by-epoch VTEC of station can be obtained using the Multi-GNSS observations.

3. Assessment of receiver DCB estimation method

In order to verify the performance of the new receiver DCB estimation method, two factors including VTEC of station and receiver DCB were used to perform the evaluation. One year of GNSS observations with 34 MGEX stations located near Southeast Asia were used to estimate the VTEC of station and receiver DCB. It can be seen that these stations are located in low latitude areas where ionospheric variation is active. Thus, it can better evaluate the method using these data.

Figure 1 shows the distribution of selected MGEX stations for assessment. Figure 2 shows the RMS of VTEC estimated by the presented method with respect to the VTEC obtained by CODE. Where $|3|$ and $|6|$ represent that the percentage of the value of RMS is less than 3 TECu and less than 6 TECu, respectively. As can be seen, the RMS of VTEC is less than 3 TECu with 62% of the cases for all stations, and the RMS values are mostly less than 6 TECu. Moreover, the mean RMS values of all stations is 2.61 TECu. It indicates a good agreement between our estimated VTEC of stations and the value obtained by CODE.

In terms of the performance of receiver DCB estimation, the MGEX DCB products were taken as reference to evaluate our estimated receiver DCB. Note that 8 types of NSS receiver DCB are estimated to evaluate the present method. Figure 3 and 4 show the RMS of GPS, GLONASS, BDS, Galileo and QZSS receiver DCB estimated by the presented method with respect to the DCB provided by MGEX products. Where G1 represents the corresponding type of receiver DCB (e.g. G1 represents the GPS C1C-C2W receiver DCB; R2 represents the GLONASS C1P-C2P receiver DCB). As shown from Figure 3 and 4, the RMS values are within 2ns. For GPS C1C-C2W (G1) and C1C-C5X (G3) receiver DCBs, the mean values of RMS are 0.74 and 0.80ns, respectively. For GLONASS C1P-C2P (R2) and BDS C2I-C7I (B1) receiver DCBs, the mean values of RMS are 0.66 and 0.91ns, respectively. For Galileo and QZSS receiver DCBs, the mean RMS shows larger values with about 1ns, which may be due to the few observations that could be tracked by those stations. Generally, the RMS values of 8 types of NSS receiver DCBs are mostly less than 1ns. It indicates a good agreement between our estimated receiver DCBs and the MGEX DCB products. Results of the assessment demonstrate a good performance of the presented new method in estimating the GNSS receiver DCB.

Figure 1. The distribution of selected MGEX stations for assessment.
Figure 2. RMS of VTEC estimated by the presented method with respect to the VTEC obtained by CODE.

Figure 3. RMS of GPS, GLONASS and BDS receiver DCB estimated by the presented method with respect to the DCB provided by MGEX products.
4. Analysis of receiver DCB for Southeast Asia MGEX stations

In this section, eight MGEX stations located in Southeast Asia were collected to estimate and analyze the receiver DCB. The data collected covers one year in 2019. Figure 5 shows the distribution of the eight MGEX stations located in Southeast Asia. These eight MGEX stations are all located in low latitudes area. Since ionospheric variations are more active in low latitudes, the selected data from these eight MGEX stations can better test the performance of this method. In the following analysis, the comparison of mean VTEC estimated by the new method and that calculated by GIM of CODE for eight MGEX stations was first carried out. Then, the standard deviation (STD) of GNSS receiver DCBs were shown and analyzed.

Based on Figure 6, it is clear that the trend of VTEC estimated by the presented new method and that calculated by GIM of CODE for 8 MGEX stations are similar. It indicates that the VTEC estimated by
this presented new method can show the intraday variation of ionosphere well. Moreover, some values close to 0 can be found in estimated VTEC time series, which relate to active ionospheric variations in the area.

Figure 6. The comparison of mean VTEC estimated by the presented new method and that calculated by GIM of CODE for 8 MGEX stations, red line represents the presented method and blue line represents the CODE.

Since not all code observations could be tracked by these eight stations, we mainly focused on the following 8 types DCB: GPS C1C-C2W and C1C-C5X DCB, GLONASS C1P-C2P and BDS C2I-C7I DCB, Galileo C1X-C5X and C1X-C7X DCB as well as QZSS C1X-C2X and C1X-C5X DCB. Figure 7 shows the STD of GNSS receiver DCBs, different colors are used to distinguish the STD of different types of DCB. It is clear that all stations can track the GPS C1C and C2W code observations, and their STD are less than 1ns. Also, the STD of GLONASS C1P-C2P and BDS C2I-C7I DCB are within 1ns for stations with observations. However, for Galileo and QZSS receiver DCB, their STD present larger values, which relate to few number of observations from Galileo and QZSS that could be tracked by those stations. Note that two stations namely BAKO and NTUS only tracked the GPS and BDS observations. As a conclusion, those stations have relatively stable GPS receiver DCB, due to a great quantity of GPS observations that could be tracked by those stations. In addition, three receiver types, including TRIMBLE NETR9, LEICA GR50 and JAVAD TRE_G3TH, were used in those stations. However, there was not obvious evidence to present the relationship between the STD of the receiver DCB and the receiver type. Moreover, no evidence of latitudinal dependencies of the stability of receiver DCB for those selected stations could be found.
Figure 7. STD of GNSS receiver DCBs, G1, G3, R2 and B1 represent GPS C1C-C2W, GPS C1C-C5X, GLONASS C1P-C2P and BDS C2I-C7I DCB, respectively; E1, E2, J1 and J2 represent Galileo C1X-C5X, Galileo C1X-C7X, QZSS C1X-C2X and C1X-C5X DCB, respectively.

5. Conclusion
The receiver differential code bias (DCB) is one of the main errors in GNSS navigation and positioning as well as ionospheric monitoring. Since the stations used in those IACs are mainly from IGS network, the receiver DCBs provided by IACs are limited to those stations. Thus, there is a greater demand for DCB estimation of single-station receivers from other stations. With the rapid development of Multi-GNSS, the multi types of DCBs are formed when we monitor and study ionosphere using the multi-GNSS and multi frequency GNSS observations. Thus, the multi types of DCBs estimation for single receiver also needs to be carried out.

In this paper, we present a new method to estimate the multi types of receiver differential code biases (DCBs) using Multi-GNSS observations. Different from the traditional method by using ionosphere modeling or Global ionospheric map (GIM), the total electron content (TEC) of station in the new method is estimated directly together with the receiver DCB. The data of one year from 34 stations were used to evaluate the performance of the presented method. The results show a good agreement between our estimated receiver DCBs and the MGEX DCB products, and the RMS of eight types of GNSS receiver DCB are mostly less than 1ns with respect to the MGEX products. Finally, the stability of GNSS receiver DCB was analysed for eight stations located in the Southeast Asia as examples. The result indicates that those stations were relatively stable with mostly less than 1ns of STD of receiver DCB. Moreover, no evidence of latitudinal and receiver type dependencies of the stability of receiver DCB for those selected stations could be found.
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