The estimation of receiver code bias for MyRTKnet stations

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Abstract. This paper presents the estimation of receiver code bias of Global Positioning System (GPS) continuously operating reference stations (CORS) over Malaysian region, MyRTKnet stations. In this study, we used the Bernese software and adopted the algorithm from IONOLAB method to estimate the receiver code bias (RCB). It has been found that the RCB from Bernese and IONOLAB show a good correlation with RCB from the International GNSS Service (IGS) analysis centre with $R^2$ values are within 0.3 ns to 0.7 ns and 0.6 ns to 0.9 ns, respectively. The estimation of RCB for MyRTKnet shows that there are no latitudinal dependencies of the RCB values. It has been found that 99% of the receivers have standard deviation below than 1 ns for both methods. It also found that both methods can provide reliable RCBs value as the mean vertical total electron content (VTEC) computed using RCBs from both methods shows a similar trend and fluctuation from IGS global ionospheric maps (GIM). Hence, it is suggested that further studies can be carried out using both methods to study the variations of RCB for a longer period to improve total electron content (TEC) estimation.

1. Introduction

The total electron content (TEC) is one of the key parameter that allows measuring and observing the variation and characteristic of ionosphere. The TEC can be obtained from the difference of dual frequency Global Positioning System (GPS) measurements as the propagation of GPS signals from satellites to receivers that passing through the ionospheric dispersive medium. This can cause delay and contributes to error in GPS positioning, navigation, accuracy and high precision monitoring and applications [1, 2, 3, 4, 5].

For decades, the GPS data has been used widely in ionospheric studies due to its availability and cost effectiveness [4, 5]. Although the ionospheric delay is embedded in GPS measurements, TEC can be efficiently estimated using the GPS data [6]. This would help to increase the accuracy and precision of the GPS positioning and navigation [6, 7, 8, 9, 10, 11, 12, 13]. However, the differential code bias (DCB) are exists in estimation of TEC from GPS measurements that produced by the satellite transmitters and receivers [13]. The DCB are consists of satellite code bias (SCB) and receiver code bias (RCB), where the estimation of both DCBs are based on the satellite and receiver, type of the observations and characteristics of satellites and receivers hardware [2].
The DCB are highly affected the accuracy of the estimation of TEC since the line-of-sight of TEC from GPS measurements are corrupted by these biases [1, 3, 12]. Hence, the DCBs have to be taken into account while estimating the TEC using GPS measurements. If the DCBs are not removed during estimation, it would be difficult to determine the TEC values [6]. Moreover, different types of satellites and receivers have different values of DCBs [2, 6]. Errors in estimations of DCB may lead to the negative values of TEC and may degrade the accuracy of TEC estimation, hence degrade the GPS accuracy and precision (1 ns = 2.823 TECu) [3, 14, 16].

There are several analysis centers such as The International GNSS Service (IGS) Analysis Center, The Center for Orbit Determination in Europe (CODE), the JPL, the European Space Agency (ESA) and Polytechnic University of Catalonia (UPC) which estimates the monthly DCB values. However, the daily estimation of DCB is not available for all analysis centers, especially for RCB which is crucial in estimation of TEC [14, 15]. Numbers of studies have been carried out to estimate the RCB values and some have been developed the suitable algorithms and approaches to estimate the RCB [1, 3, 10, 13, 14, 15, 16].

Earlier, a method to derive the TEC and to estimate the RCB and SCB in Japan has been presented by [13]. Then, the IONOLAB-BIAS, an online estimation for single station receiver bias algorithm, has been introduced by [3] to estimate the daily and monthly averages of RCB. Later, [18] compared the relative and single methods to estimate the RCB from Korean GPS network (KGN) to study the stability and compatibility of the estimated RCB. Recently, [19] compared the estimated RCB using minimisation of standard deviation with monthly RCB provided by CODE for both monthly and daily intervals. In Malaysia, [20] estimates the RCB over National R&D GPS continuously operating reference station network (NRC-net) using M_DCB from [14] and Bernese software to assess the performance of CODE-GIM and local TEC.

In this study, the RCB values for Malaysian Real-Time Kinematic Network (MyRTKnet) are estimated using Bernese software and adopted algorithm from [3]. The results are validated with the RCB values from the CODE analysis center and analysis is discussed. Then, the RCB for all MyRTKnet stations is estimated for 181 days using both approaches. The absolute TEC is estimated based on the estimated RCB values from both approaches and compared with the global TEC from IGS analysis center. The result is discussed and the summary presented in the last section in this paper.

2. Estimation of Ionospheric Delay and GPS Receiver Code Bias

2.1. GPS observation and ionospheric delay estimation

The TEC values derived from the GPS measurements are highly affected by the satellite and receiver code bias. In order to increase the accuracy of the TEC estimation, the DCBs values need to be reconsidered. GPS transmits $f_1$ and $f_2$ frequencies, which are 1575.42 MHz and 1227.60 MHz, respectively, where its signals propagate from satellites to receivers passing through the ionosphere layer and produce delay in its measurements. The ionospheric delay ($d_{ion}$) can be expressed mathematically as follow.

$$d_{ion} = \frac{40.3}{f_2^2}STEC$$

where $f$ represents the frequency of the GPS and $STEC$ represents as the slant TEC, the line-of-sight TEC from satellite to the receivers. The geometry-free linear combination ($P_4$) that derived from dual-frequency GPS code measurements are used in estimation of ionosphere delay using GPS [16, 17, 18] where most GPS errors are eliminated or reduced, except the ionosphere delay, RCB and SCB. The ($P_4$) can be expressed mathematically as follow.

$$P_4 = P_1 - P_2 = 40.3 \left( \frac{1}{f_1^2} - \frac{1}{f_2^2} \right)STEC + c(DCB^S + DCB_r)$$
where $P_1$ and $P_2$ represents the GPS pseudorange measurements for $f_1$ and $f_2$ frequencies, $STEC$ is the slant TEC; the line-of-sight TEC from GPS satellite to the receiver, $c$ is the speed of light, $DCB^s$ and $DCB_r$ represent the satellite and receiver differential code biases respectively.

2.2 Determination of GPS receiver code bias
Based on equation (2), the STEC can be extracted from GPS measurements as shown in equation (3). Since the ionosphere varies within range of altitude of 60 km to 1000 km, it is assumed that the electrons concentrated at the certain altitude. The altitude, $H$, is fixed so that the STEC can be converted to vertical TEC (VTEC) using the modified single layer model (MSLM) [3, 10, 11, 14].

$$STEC = \frac{1}{40.3} \left( \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} \right) (P_4 - cDCB_r - cDCB^s)$$  \hspace{1cm} (3)

$$VTEC = MF(z).STEC$$  \hspace{1cm} (4)

$$MF = \cos \left( \arcsin \left( \frac{R}{R + H} \sin(\alpha z) \right) \right)$$  \hspace{1cm} (5)

where $\alpha$ is the satellite elevation angle, $R$ is the Earth’s radius, $\alpha$ is the coefficient factor and $H$ is the altitude of the ionospheric thin shell. Basically, $H$ is the approximate peak height of the F$_2$-layer where in this study it is set to 400 km.

To determine the GPS receiver code bias, there are numbers of approaches that can be used, such as least square estimation (LSE) method [10,13,14], minimizing standard deviation [3,11], singular value decomposition (SVD) [17] and satellite-receiver geometry changes [15]. Most of the studies applied the LSE method and the minimising the standard deviation and both method are proven to be practical [3, 14]. In this study, both methods have been used where the LSE method represent by the Bernese software (see [14]) and the minimising the standard deviation have been adopted from [3] based on IONOLAB software.

2.2.1. Estimation of RCB using Bernese software. The estimation of the RCB using Bernese software is basically based on LSE method. However, the actual computations behind the software are not disclosed in user manual [3]. Bernese is capable to estimate both TEC and RCB for one or more stations. Both of the RCB and SCB are included in the model and solved using least square method, as the polynomial coefficients and the biases are remained unknowns [21]. [14, 22] has been reported adopting Bernese method to develop their algorithm to estimate the RCB. In Bernese, the VTEC are obtained based on the spherical harmonic function as shown below [23].

$$VTEC = \sum_{n=0}^{n_{\max}} \sum_{m=0}^{n} \tilde{P}_{nm}(\sin \beta)(a_{nm} \cos ms + b_{nm} \sin ms)$$  \hspace{1cm} (6)

where $n_{\max}$ is the maximum degree of the spherical harmonic expansion, $\tilde{P}_{nm} = A(n,m)P_{nm}$ are the normalised Legendre functions, $\beta$ is the geocentric latitude of the ionospheric pierce point (IPP), $a_{nm}$ and $b_{nm}$ are the unknown global/regional ionosphere model coefficient and $s$ is the sun-fixed longitude of the IPP. Hence, equation (7) can be obtained by substituted equation (3) and equation (5) into equation (6).

$$\sum_{n=0}^{n_{\max}} \sum_{m=0}^{n} \tilde{P}_{nm}(\sin \beta)(a_{nm} \cos ms + b_{nm} \sin ms)$$

$$= \cos \left( \arcsin \left( \frac{R_e}{R_e + H} \sin(\alpha z) \right) \right) \left[ -\frac{1}{40.3} \left( \frac{1}{f_1^2} - \frac{1}{f_2^2} \right) (P_4 - cSCB - cRCB) \right]$$  \hspace{1cm} (7)
where $a_{nm}$, $b_{nm}$ and $RCB$ are the unknown parameters that need to be estimated [23]. By implementing the spherical harmonic function, the order of the expansion is highly depend on the study area, where normally, 4th order is used for regional area, 8th order for continental area and 15th order for global area [14]. This method has been adopted by [22] to support GPS precise positioning and [14] to develop the M_DCB Matlab software.

2.2.2. Determination of RCB adopted from IONOLAB algorithm. In this study, we adopted the algorithm from IONOLAB method that introduced by [3] to estimate the RCB. The idea of the IONOLAB is to estimate the daily and monthly average RCB during the disturbed and quite days. This method is based on the ground truth of global ionospheric maps (GIM) especially from JPL GIM-TEC and CODE GIM-TEC. The suitable filtering has been applied to reduce the noise and converged the error between multiple satellite observations and one receiver.

In this method, the IGS ionosphere map exchange format (IONEX) has been used to obtain the VTEC values with two hours intervals. Then, the $P_4$ are obtained from the GPS observations file where the satellite ephemeris and DCB values are obtained from the IONEX files. Similar to the Bernese method, [3] also used both pseudo-range and carrier phase measurements to compute the STEC. This is due to the estimation of STEC using pseudo-range is simple and robust but noisy and vulnerable to the multipath effects [3,11]. Hence, in IONOLAB method, [3] proposed to use the data only from the satellites over 60° elevation angles to reduce the multipath. A de-noising Chebyshev filter is also applied to reduce the noise and finally the RCB can be extracted.

$$RCB = \left(\frac{40.3(f_1^2 - f_2^2)}{c f_1^2 f_2^2}\right)STEC - \frac{1}{c} P_4 + SCB \quad (8)$$

3. Assessment of RCB with IGS stations

In this study, the Bernese and the algorithm from the IONOLAB were used to estimate the RCB for 4 selected IGS stations (refer Table 1). In this section, the RCB from IGS IONosphere map Exchange format (IONEX) (from ftp://cddis.gsfc.nasa.gov) provided by IGS analysis centre have been used to assess the RCB values from Bernese and IONOLAB.

**Table 1.** This table shows the geographical coordinates of selected IGS stations.

| Stations Name | Latitude (N) | Longitude (E) |
|---------------|--------------|---------------|
| COCO          | -12° 11’ 17.88” | 96° 50’ 02.04” |
| DARW          | -12° 50’ 37.36” | 131° 07’ 57.85” |
| HYDE          | 17° 25’ 02.13” | 7° 72’ 03.13” |
| NTUS          | 1° 20’ 44.89” | 103° 40’ 47.84” |

For assessment purposes, 181 days of GPS observations over the half year of 2010 (1st January 2010 - 30th June 2010, with 30 seconds intervals) have been used to estimate the RCB for 4 selected IGS stations. Figure 1 present the mean RCB estimated from IONOLAB, Bernese and IGS analysis centre. The vertical axis stand for the mean RCB (in ns) and the horizontal axis stands for the IGS stations. The results show that the differences between RCB from Bernese and IONOLAB with RCB from IGS analysis centre are within 0.1 to 1.0 ns.
Figure 1. Figure presents the estimation of mean RCB for selected IGS stations.

\[ \text{Residual}_{\text{Bernese-IGS}} = RCB_{\text{Bernese}} - RCB_{\text{IGS}} \]  \hspace{1cm} (9)

\[ \text{Residual}_{\text{IONOLAB-IGS}} = RCB_{\text{IONOLAB}} - RCB_{\text{IGS}} \]  \hspace{1cm} (10)

For further analysis, the residual (refer equation (9) and equation (10)) and \( R^2 \) values have been computed. Scatter plot in figure 2 shows the comparison of the RCB\(_{\text{Bernese}}\) and RCB\(_{\text{IONOLAB}}\) with RCB\(_{\text{IGS}}\). The result shows that the estimation of the RCB\(_{\text{IONOLAB}}\) is more consistent and fitted to RCB\(_{\text{IGS}}\) compared to RCB\(_{\text{Bernese}}\) for all IGS stations. This can be observed as the standard deviation of RCB\(_{\text{IONOLAB-IGS}}\) is smaller and the \( R^2 \) value is higher compared to RCB\(_{\text{Bernese-IGS}}\) (refer Table 2).

Table 2 show that DARW has the lowest mean residual values for RCB\(_{\text{Bernese-IGS}}\) which is up to -1.131 ns with standard residual 0.843 ns. Meanwhile, NTUS has the lowest mean residual value for RCB\(_{\text{IONOLAB-IGS}}\) which is up to -0.289 ns with standard residual 0.431 ns. It is found that, COCO has the largest mean residual value for both RCB\(_{\text{Bernese-IGS}}\) and RCB\(_{\text{IONOLAB-IGS}}\) which are up to -0.639 ns with standard residual 0.681 ns and 0.766 ns with standard residual 0.372 ns, respectively. [3] also shows the largest different for COCO in their study where the values are up to 2.35 ns.

Table 2. This table summarizes the statistical analysis for the comparison of the estimation of RCB using Bernese and IONOLAB method with the estimation from IGS analysis centre.

| Station | Bernese - IGS | IONOLAB - IGS |
|---------|---------------|---------------|
|         | Mean Residual | Standard Deviation | \( R^2 \) value | Mean Residual | Standard Deviation | \( R^2 \) value |
| COCO    | -0.639        | 0.681          | 0.316            | 0.766        | 0.372              | 0.601             |
| DARW    | -1.131        | 0.843          | 0.764            | 0.135        | 0.213              | 0.919             |
| HYDE    | -0.819        | 0.557          | 0.712            | 0.161        | 0.247              | 0.923             |
| NTUS    | -0.948        | 0.563          | 0.489            | -0.289       | 0.431              | 0.727             |

It is noted that COCO has the largest mean residual values; therefore, it is relevant that COCO has the lowest \( R^2 \) values for both methods. This may due to the RCB for COCO might not stable as other IGS stations and lead to the inconsistency in estimation of RCB [3]. Based on the \( R^2 \) values, Bernese and IONOLAB methods can be seen to be fitted with the estimation of RCB from IGS analysis centre. Most of the \( R^2 \) values from IONOLAB methods have higher consistency compared to Bernese with range within 0.6 to 0.9 and within 0.3 to 0.7, respectively. [24] using the same method of estimation of RCB as IONOLAB, where in their studies, the estimation of the RCB are more consistent where the mean difference of TEC are 0.478±0.411 TECU and 0.530±0.44 TECU for daily and monthly estimation of RCB.

It can be concluded that the estimation of the RCB from both method are fitted and consistent with the IGS analysis centre. In the next section, both methods have been used to estimate the RCB values.
for GPS CORS network over Malaysian region, MyRTKnet. The consistency and the accuracy of the RCB have been investigated based on the estimation of regional VTEC.

(a) COCO

(b) DARW

(c) HYDE

(d) NTUS

Figure 2. Figures show the scatter plot for $RCB_{\text{Bernese}}$ versus $RCB_{\text{IGS}}$ and $RCB_{\text{IONOLAB}}$ versus $RCB_{\text{IGS}}$ for all IGS stations. The horizontal axis represents the $RCB_{\text{IGS}}$ while the vertical axis represents the $RCB_{\text{Bernese}}$ or $RCB_{\text{IONOLAB}}$. 
4. Estimation of RCB for MyRTKnet stations

In this section, the RCB for Malaysian GPS network, MyRTKnet stations (refer Figure 3) have been estimated using both IONOLAB and Bernese for 181 days (1 January 2010 – 30 June 2010). The consistencies of the bias for MyRTKnet stations and its latitudinal dependencies have been investigated based on the standard deviation of the RCB.

Figure 3. The distribution map of MyRTKnet stations all over the Malaysian region

Figure 4 presented the mean RCB for all MyRTKnet stations using Bernese and IONOLAB. Both methods show small/least differences in estimation of RCB for all MyRTKnet stations. It shows that station GETI has largest values where RCB\textsubscript{Bernese} is about -19.059 ns and RCB\textsubscript{IONOLAB} is about -18.024 ns. Meanwhile, CENE has smallest values of the bias where RCB\textsubscript{Bernese} is about -5.256 ns and RCB\textsubscript{IONOLAB} is about -4.667 ns. On the whole, it can be observed that the estimated RCB\textsubscript{IONOLAB} is smaller compared to RCB\textsubscript{Bernese}.

Figure 4. The estimation of mean RCB for MyRTKnet stations using Bernese and IONOLAB

Figure 5. The latitudinal variation of the standard deviation of the MyRTKnet RCB
Based on figure 5, it shows that the highest values for Bernese and IONOLAB for SEGI station are about 2.892 ns and 2.728 ns, respectively. 47% of the receivers had a standard deviation of RCB less than 0.5 ns based on Bernese method and 63% based on IONOLAB methods. Meanwhile, both Bernese and IONOLAB methods show 99% of the receivers had a standard deviation less than 1 ns. This result is smaller compared to [13], which only 69% of the standard deviation was smaller than 1 ns. It also shows that there are no systematic trends that can be found (refer figure 6). This can be an evidence of no latitudinal dependencies of the RCB variations as shown by [13] over GPS Earth Observation Networks (GEONET) in Japan. As a conclusion, the RCB over MyRTKnet stations are quietly stable and consistent.

Another comparison between Bernese and IONOLAB has also been carried out. The VTEC has been estimated using computed RCBs and the mean VTEC is compared with each other and validate with GIM IGS. Noted that the spatial resolution of GIM IGS is 2.5° in latitude and 5.0° in longitude, but it is reliable to use the VTEC from GIM IGS to validate the regional VTEC [17]. To perform this analysis, figure 6 shows 5 selected MyRTKnet stations, where 3 stations are located at Peninsular Malaysia and 2 stations at East Malaysia (Sabah and Sarawak).

**Figure 6.** Figure maps the geographical location of the selected MyRTKnet stations

**Figure 7.** The comparison of mean VTEC estimates between Bernese and IONOLAB with GIM IGS for all selected 5 MyRTKnet stations
Based on figure 7, it can be seen that the trend of the mean VTEC from Bernese and IONOLAB are similar with GIM IGS. The VTEC fluctuation that estimated from both methods also occurs during the same time with the GIM IGS. Similar results also found by [3] and [22] in their studies where the trend of estimated VTEC computed based on RCBs values from minimizing standard deviation and least square methods shows a good agreement with others analysis centre. By comparing the VTEC values with GIM IGS, it is found that the VTEC estimated using Bernese have higher values compared to IONOLAB methods for all stations. This also can be related to the RCBs values, where the RCB\textsubscript{IONOLAB} have a smaller values compared to RCB\textsubscript{Bernese}. The results that presented in this section demonstrate that the IONOLAB method capable to provide a good estimation of RCB and VTEC compared to Bernese as presented by [3].

5. Summary
This paper assessed the compatibility of two existing software, Bernese and IONOLAB method to estimate the RCBs. It is found that both methods have a good agreement with IGS analysis centre while estimating the RCB values for selected IGS stations. The RCBs for all MyRTKnet stations has been estimated using both methods. It is found that 99% of the receivers have standard deviations below than 1 ns which are more lower compared to [13]. It is found that no latitudinal dependencies of the RCB variations as shown by [3]. The mean VTEC computed RCBs from both methods shows a similar trend and fluctuation of mean VTEC with IGS GIM. Therefore, both methods can provide a reliable RCBs value in order to improve the accuracy in TEC estimation. It is suggested that further studies should be carried out to study the variations of RCB in localized area for longer period to improve the TEC estimation.

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