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M_DCB: Matlab code for estimating GNSS satellite and receiver differential code biases

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Abstract Global navigation satellite systems (GNSS) have been widely used to monitor variations in the earth's ionosphere by estimating total electron content (TEC) using dual-frequency observations. Differential code biases (DCBs) are one of the important error sources in estimating precise TEC from GNSS data. The International GNSS Service (IGS) Analysis Centers have routinely provided DCB estimates for GNSS satellites and IGS ground receivers, but the DCBs for regional and local network receivers are not provided. Furthermore, the DCB values of GNSS satellites or receivers are assumed to be constant over 1 day or 1 month, which is not always the case. We describe Matlab code to estimate GNSS satellite and receiver DCBs for time intervals from hours to days; the software is called M_DCB. The DCBs of GNSS satellites and ground receivers are tested and evaluated using data from the IGS GNSS network. The estimates from M_DCB show good agreement with the IGS Analysis Centers with a mean difference of less than 0.7 ns and an RMS of less than 0.4 ns, even for a single station DCB estimate.

Keywords GNSS · Differential code biases (DCB) · TEC · Ionosphere

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Introduction

The global positioning system (GPS) has been widely used in navigation and positioning in the last few decades. It is well known that the earth's ionosphere is a dispersion medium and that GPS signals will be delayed as they propagate through the ionosphere. Therefore, ionospheric delay is one of the main GPS errors. The main part of the total ionospheric delay or total electron content (TEC) can be extracted from dual-frequency GPS measurements (Jin et al. 2004, 2007). The differential code biases (DCBs), as the inner delay difference between the two frequencies, have to be considered when estimating the TEC. Several meters of error can occur if the effect of the DCBs is ignored, and the TEC estimate value can even turn out to be negative (Sardon et al. 1994). Therefore, the DCBs should be estimated and removed for all GNSS TEC estimates and for all precise positioning applications.

The DCB values vary between different GNSS satellites and ground receivers. Most DCB estimates are based on the assumption that the DCB values of GPS satellites or receivers are constant over 1 day or 1 month (Schaer 1999; Sardon et al. 1994), while in fact they are often changing in hours or 1 day. Currently, two methods are normally used to estimate the GPS DCB according to theory. One is based on the least squares method (Jin et al. 2008; Ma and Maruyama 2003), and the other one is based on searching for the true value with a constraint condition through minimizing the standard deviation (Arikan et al. 2008). Both of these methods have been proven to be practical (Arikan et al. 2008). The second method needs a large amount of computation with an a priori search range. If the search range is too wide, the computation is huge. If the search range is too narrow, the true DCB value may not fall within this range, which can lead to a wrong DCB estimate. The International GNSS Service (IGS) Analysis Centers have routinely produced the DCBs of GNSS satellites and IGS ground receivers; for example, the Center for Orbit Determination in Europe (CODE), the Jet Propulsion Laboratory (JPL), the European Space Agency (ESA), and the Polytechnic University of Catalonia (UPC). However, most DCBs of GNSS satellites and receivers are given at an interval from 1 day to 1 month, and many regional and local GNSS network receivers' DCBs are not provided. Furthermore, some of IGS ground receiver DCB estimates are not available from all analysis centers, due to different groups using different data.

In order to calculate the GNSS DCBs for any GNSS station and/or satellite using an interval from hours to days, an open source tool is required to extract GNSS receiver and satellite DCBs for wider range of GNSS users. A Matlab code to estimate differential code biases for GNSS satellites and receivers is described (the M_DCB software). The method for estimating the GNSS DCBs is introduced in section "Method of GNSS DCB estimate." The M_DCB functions are described in section "M_DCB software." Test results and evaluations are presented in section "Results and discussion." The last section gives some final conclusions.

Method of GNSS DCB estimate

It is well known that there are various errors in GNSS carrier phase and pseudorange code observations. Although frequency differences can remove or attenuate several errors (such as clock errors, troposphere delay and so on), differential pseudorange observations need to be smoothed in order to get more precise DCB estimates. After smoothing, differential pseudorange observations can be used to extract reliable estimates using the least squares method.

GNSS observations and processing

GNSS observations consist of carrier phase and pseudorange observations stored in the Receiver Independent Exchange (RINEX) format. For example, the GPS observation equations for pseudorange and carrier phase observables are expressed as follows (Jin et al. 2008):

$$P_{k,j}^{i} = \rho_{0,j}^{i} + d_{\mathrm{ion},k,j}^{i} + d_{\mathrm{trop},j}^{i} + c(\tau^{i} - \tau_{j}) + d_{k}^{i} + d_{k,j} + \varepsilon_{P,k,j}^{i} \tag{1}$$

$$L_{k,j}^{i} = \rho_{0,j}^{i} - d_{\mathrm{ion},k,j}^{i} + d_{\mathrm{trop},j}^{i} + c(\tau^{i} - \tau_{j}) - \lambda(b_{k,j}^{i} + N_{k,j}^{i}) + \varepsilon_{L,k,j}^{i} \tag{2}$$

where P is the GPS pseudorange measurement, L is the GPS carrier phase measurement, ρ is true distance between the GPS receiver and satellite, d_{ion} is ionosphere delay, d_{trop} is troposphere delay, c is speed of light in a vacuum, τ^{i} is the satellite clock error, τ_{j} is the receiver clock error, the remaining d are the code delays for the satellite and receiver instrument biases, b is the phase advance of the satellite and receiver instrument biases, N is the ambiguity of the carrier phase, and ε are the residuals in the GPS measurements.

Here, the subscript k (= 1, 2) stands for the frequency, the superscript i stands for the sequence number of the GPS satellite, and the subscript j stands for the sequence number of the GPS receiver. With dual-frequency ($f_{L_1} = 1{,}575.42\,\mathrm{MHz}, f_{L_2} = 1{,}227.60\,\mathrm{MHz}$) observations, the ionospheric delays can be obtained through the following equations:

$$P_4 = P_{1,j}^{i} - P_{2,j}^{i} = (d_{\mathrm{ion},1,j}^{i} - d_{\mathrm{ion},2,j}^{i}) + \mathrm{DCB}^{i} + \mathrm{DCB}_{j} \tag{3}$$

$$L_4 = L_{1,j}^{i} - L_{2,j}^{i} = -(d_{\mathrm{ion},1,j}^{i} - d_{\mathrm{ion},2,j}^{i}) - \lambda(b_{1,j}^{i} - b_{2,j}^{i}) - \lambda(N_{1,j}^{i} - N_{2,j}^{i}) \tag{4}$$

where $\mathrm{DCB}^{i} = d_{1}^{i} - d_{2}^{i}$, and $\mathrm{DCB}_{j} = d_{1,j} - d_{2,j}$ stand for differential code biases of the satellites and differential code biases of the receivers, respectively. Since the pseudorange observations P_4 have larger noise, the carrier phases are used to smooth the pseudorange (Liu et al. 1998). Smoothed $P_{4,sm}$ observations can be expressed as follows:

$$P_{4,sm} = \omega_t P_4(t) + (1 - \omega_t) P_{4,prd}(t) \quad (t > 1) \tag{5}$$

where t stands for the epoch number, ω_t is the weight factor related with epoch t (Maybeck 1979) and

$$P_{4,prd}(t) = P_{4,sm}(t-1) + [L_4(t) - L_4(t-1)] \quad (t > 1) \tag{6}$$

when t is equal to 1, which means the first epoch of one observation arc, $P_{4,sm}$ is equal to P_4. Cycle slips and gross errors in the carrier phase observations should be removed before using the carrier phase observations to smooth the pseudorange observations. Here, both dual-frequency pseudorange code observations (Melbourne–Wubeena combination) and ionospheric residual observations are used to detect cycle slips and gross errors.

Only the first order of ionospheric refraction is considered while estimating the ionosphere delay in GPS processing, due to the minor effect of the higher orders (Li and Huang 2005). The ionosphere delay can be expressed as follows:

$$d_{\text{ion}} = \frac{40.3}{f^2}\text{STEC} \tag{7}$$

where f stands for the frequency of the carrier, and SETC stands for the slant total electron content along the path of the signal. Substituting (7) into (3), and replacing P_4 by smoothed $P_{4,sm}$, we get:

$$P_{4,sm} = 40.3\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right)\text{STEC} + \text{DCB}^i + \text{DCB}_j \tag{8}$$

After smoothing, more reliable DCB estimate values can be extracted from GPS data using the method described in the next section.

Method to determine the DCB

From (8), it is easy to extract slant total electron content (STEC) from GNSS dual-frequency observations as follow

$$\text{STEC} = -\frac{f_1^2 f_1^2}{40.3\,(f_1^2 - f_2^2)}\left(P_{4,sm} - c\text{DCB}_j - c\text{DCB}^i\right) \tag{9}$$

where DCB's unit is the time. The earth's ionosphere ranges in altitude from 60 to ~1,000 km. It is assumed that all electrons in the ionosphere are concentrated in a thin shell at altitude H, so the STEC can be translated into the vertical total electron content (VTEC) using the modified single-layer model (MSLM: http://aiuws.unibe.ch/spec/ion.php#processing_description), namely

$$\begin{aligned} &\text{VTEC} = \text{MF}\,(z)\,\text{STEC} \\ &\text{MF} = \cos\left(\arcsin\left(\frac{R}{R+H}\sin(\alpha z)\right)\right) \end{aligned} \tag{10}$$

where z is the satellite elevation angle, R is the earth's radius, and H is the attitude of the ionosphere thin shell (normally the approximate peak height of the F2 layer). R is set to 6,371 km. H and α can be set by users. Here, they are defaulted as $H = 506.7$ km and $\alpha = 0.9782$, which are consistent with the values used by the CODE group. An ionospheric spherical harmonic function is applied in the M_DCB software. The VTEC, $E(\beta, s)$ can be expressed as follows (Schaer 1999):

$$E(\beta, s) = \sum_{n=0}^{n_{\max}}\sum_{m=0}^{n}\tilde{P}_{nm}(\sin\beta)(a_{nm}\cos ms + b_{nm}\sin ms) \tag{11}$$

where β is the geocentric latitude of the ionosphere pierce point (IPP), $s = \lambda - \lambda_0$ is the sun-fixed longitude of the IPP, λ, λ_0 are the longitude of the IPP and the apparent solar time, respectively, a_{nm}, b_{nm} are the global or regional ionosphere model coefficients, $\tilde{P}_{nm} = \Lambda(n,m)P_{nm}$ are normalized Legendre polynomials. The Λ denotes the normalization function, and P_{nm} are unnormalized Legendre polynomials, with

$$\Lambda = \sqrt{2\frac{2n+1}{1+\delta_{0m}}\frac{(n-m)!}{(n+m)!}} \tag{12}$$

and with δ being the Kronecker Delta. Substituting (9) and (10) into (11), the following expression can be obtained:

$$\begin{aligned} &\sum_{n=0}^{n_{\max}}\sum_{m=0}^{n}\tilde{P}_{nm}(\sin\beta)(a_{nm}\cos ms + b_{nm}\sin ms) \\ &= \cos\left(\arcsin\left(\frac{R}{R+H}\sin(\alpha z)\right)\right) \\ &\quad\left[-\frac{f_1^2 f_1^2}{40.3(f_1^2 - f_2^2)}\left(P_4 - c\text{DCB}_j - c\text{DCB}^i\right)\right] \end{aligned} \tag{13}$$

where P_4 are the smoothed observations, and a_{nm}, b_{nm}, DCB_j and DCB^i are unknown parameters to be estimated, respectively. The order of spherical harmonics expansion depends on the areas. Users can set the appropriate order in the main program(s) on the command line. For the regional, continental, and global size, normally it uses 4th, 8th, and 15th order, respectively. Here, for our small areas tests, the spherical harmonics expansion is defaulted as fourth order. A set of ionosphere coefficients is assumed every 2 h, but of course can be changed. For one GPS station, there are more than 20,000 measurements every day. Thus, the number of observations is much more than the number of unknown parameters. According to the theory described above, the DCB and ionosphere coefficients can be estimated from GPS dual-frequency observations by the least squares (LS) method.

Before the LS estimate, carrier phase smoothing using pseudoranges is used in the data preprocessing. Since (13) is singular, one exterior constraint condition must be added in order to separate the DCBs of satellites and receivers. It is routinely assumed that the sum of all GPS satellite DCB values is zero. Under this constraint condition, Eq. (13) reaches full rank and the DCBs of the satellites and receivers can be separated.

M_DCB software

The M_DCB software was developed in Matlab (version: 2010b). GPS RINEX observation files and precise ephemerides are the input for M_DCB. Here, GPS RINEX observations containing P1 and P2 observations are defaulted. The outputs are the DCB estimates of the satellites and receivers and TEC ionosphere coefficients for

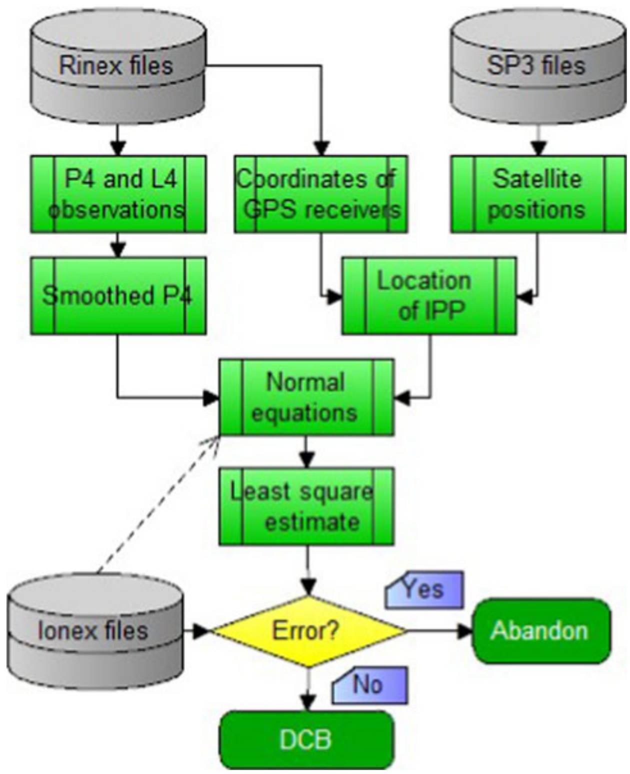

Fig. 1 Flowchart of M_DCB software

the relative region. IONEX files are used to check our DCB estimates. A flowchart for the M_DCB software is shown below (Fig. 1).

The M_DCB software package can estimate the DCB for a single station or for multiple stations. For a single station, usually not all the GPS satellites are available in one GPS receiver view. It is not convenient to use the constraint condition mentioned in section "Method to determine the DCB" for such a case. Here, IONEX files are used to confirm our estimate using the same constraint conditions. The DCBs of satellites without observations are set as known parameters.

Results and discussion

In order to test and validate the M_DCB software, the DCBs of GNSS satellites and receivers are estimated using data from the IGS GNSS network and evaluated using the solutions of the IGS Analysis Centers in this section. Some discussions on their differences are also given. Here, GPS RINEX observations containing P1 and P2 observations are tested below. There are some receivers that collect only C1 and P2 observations (Leica, Novatel, and newer Trimble receivers), or C1 and X2 observations (cross-correlation

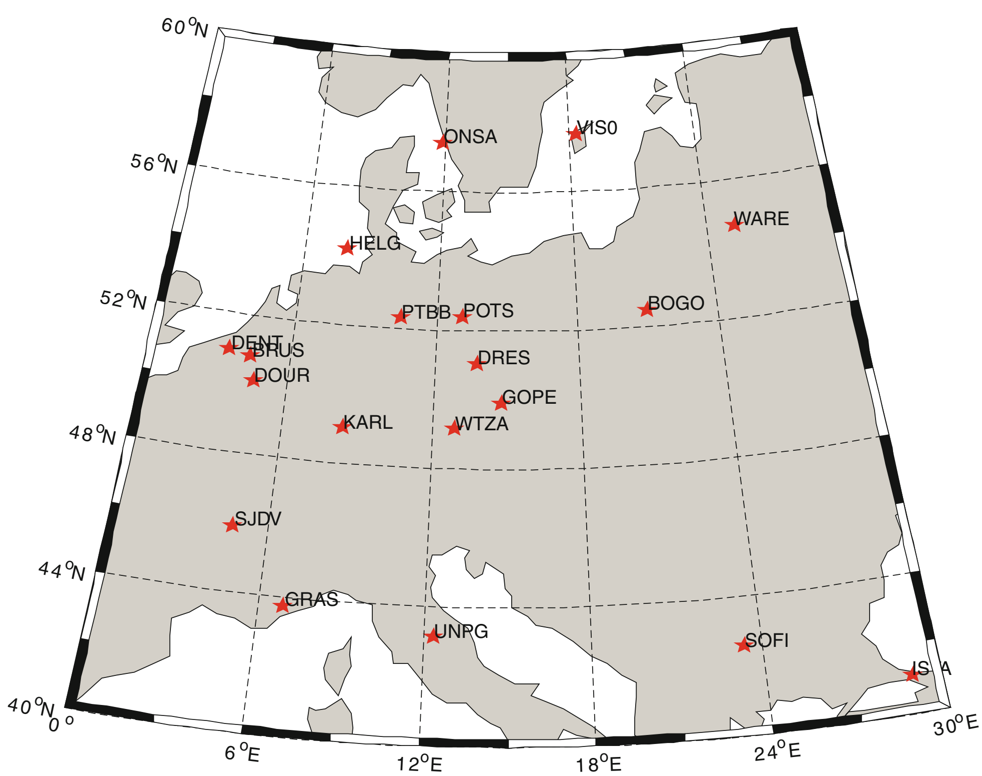

Fig. 2 Distributions of IGS stations chosen

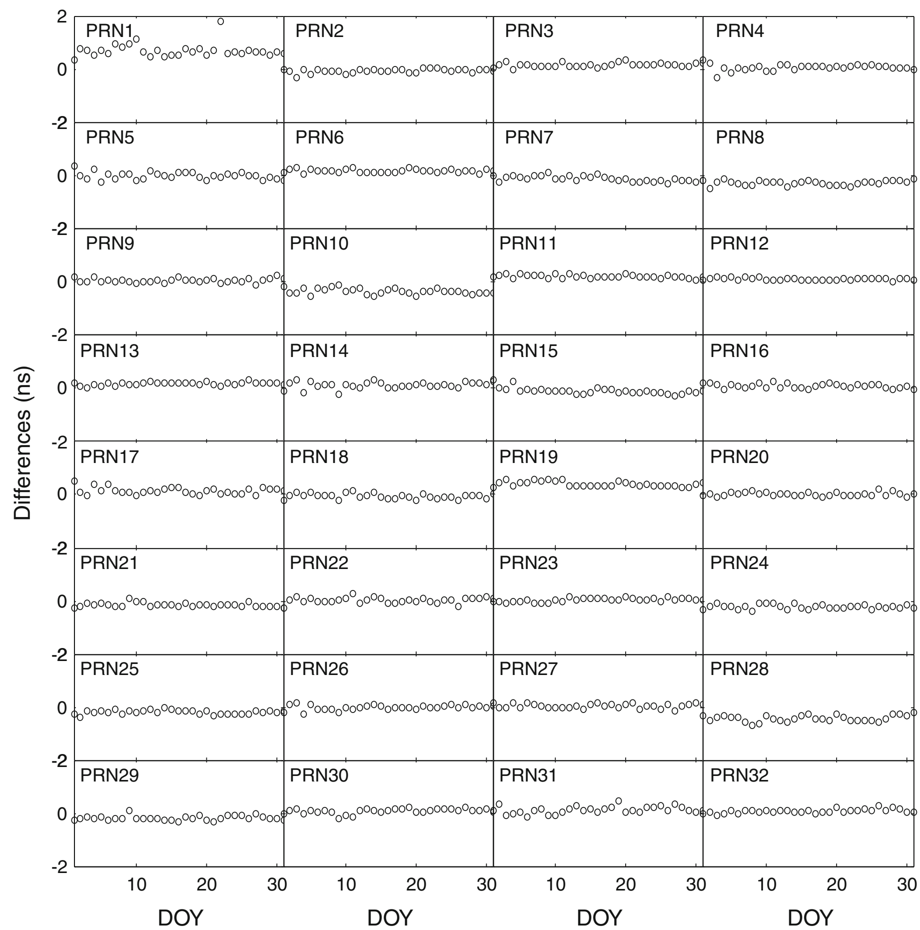

Fig. 3 The biases, that is, differences in the satellite DCB values from M_DCB and CODE. DOY is the day of year

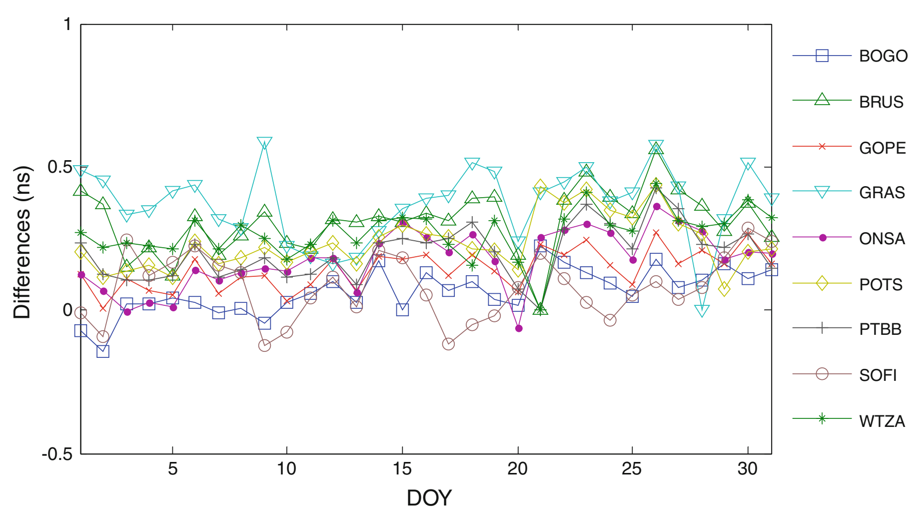

Fig. 4 The differences in the receiver DCB values from M_DCB and CODE

style receivers like the AOA TurboRogue and the older Trimble 4000-series receivers). The RINEX OBS files for these receiver types need to be run through a program called cc2noncc to make the C1 and X2 observations compatible with P1 and P2 (see IGS Mail 6571, April 18, 2012). For users who wish to do this, the M_DCB code will need to be modified to read in C1 (and X2) observations, which have been modified by cc2noncc.

Data for test

IGS stations that were chosen to test the M_DCB estimates are show in Fig. 2. RINEX files (http://sopac.ucsd.edu/cgi-bin/dbDataBySite.cgi or ftp://cddis.gsfc.nasa.gov/gps/data/), SP3 files (ftp://igscb.jpl.nasa.gov/igscb/), and IONEX files (ftp://cddis.nasa.gov/pub/gps/products/ionex/) are used in our experiment.

Table 1 The RMS and mean differences between satellite and receiver DCB estimates from January 1–31, 2010 using multiple GNSS stations (M_DCB minus CODE)

Satellite	RMS	Differences	Satellite	RMS	Differences
PRN1	0.251	0.746	PRN17	0.138	0.038
PRN2	0.087	−0.073	PRN18	0.100	−0.044
PRN3	0.066	0.194	PRN19	0.066	0.381
PRN4	0.123	0.003	PRN20	0.073	0.004
PRN5	0.111	−0.236	PRN21	0.088	−0.121
PRN6	0.061	0.169	PRN22	0.109	0.050
PRN7	0.085	−0.233	PRN23	0.053	0.052
PRN8	0.085	−0.271	PRN24	0.076	−0.221
PRN9	0.088	0.038	PRN25	0.085	−0.220
PRN10	0.095	−0.343	PRN26	0.092	−0.020
PRN11	0.063	0.202	PRN27	0.088	0.060
PRN12	0.051	0.049	PRN28	0.107	−0.340
PRN13	0.062	0.140	PRN29	0.091	−0.277
PRN14	0.126	0.150	PRN30	0.074	0.020
PRN15	0.117	−0.164	PRN31	0.138	0.057
PRN16	0.084	0.096	PRN32	0.077	0.115
BOGO	0.080	0.065	POTS	0.094	0.237
BRUS	0.111	0.309	PTBB	0.095	0.201
GOPE	0.068	0.142	SOFI	0.113	0.081
GRAS	0.131	0.370	WTZA	0.083	0.270
ONSA	0.103	0.178			

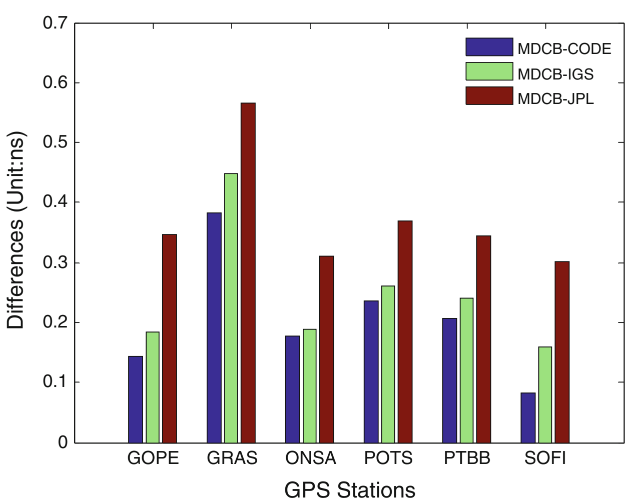

Fig. 5 The mean differences between receiver DCB values estimated by M_DCB and those released by CODE, JPL, and IGS combined

Test result

For some users, they may have only one GPS station or a multi-station network. The M_DCB can estimate the DCB for multiple stations or one station. In the following subsections, the test results using a multi-station network and a single station are presented, respectively, which are evaluated using the IGS solutions, such as those by CODE, JPL, and IGS combined.

Test results of multi-stations from M_DCB

The DCB values of the satellites and receivers are estimated from January 1–31, 2010 using the M_DCB software. Here, DCB estimate values released by CODE are regarded as reference values to validate the M_DCB result. CODE uses fifteen orders of spherical harmonic functions to describe the global total electron content of the earth's ionosphere every 2 h. Both global GPS and GLONASS observations are used during DCB estimation (http://www.aiub.unibe.ch/). DCB values estimated by M_DCB and those released by CODE are compared in Figs. 3 and 4. The vertical axis stands for biases, or differences (in nanoseconds) and the horizontal axis stand for the day of year in 2010. More details are displayed in Table 1. Receiver DCB biases are slightly larger than those for satellites, but most of them are less than 0.4 ns except PRN1 whose DCB bias reaches 0.746 ns. The RMS of all differences is lower than 0.3 ns. Since the number of valid observations (when the elevation angle is more than 20°) for PRN 1 is approximately a quarter of the other satellites

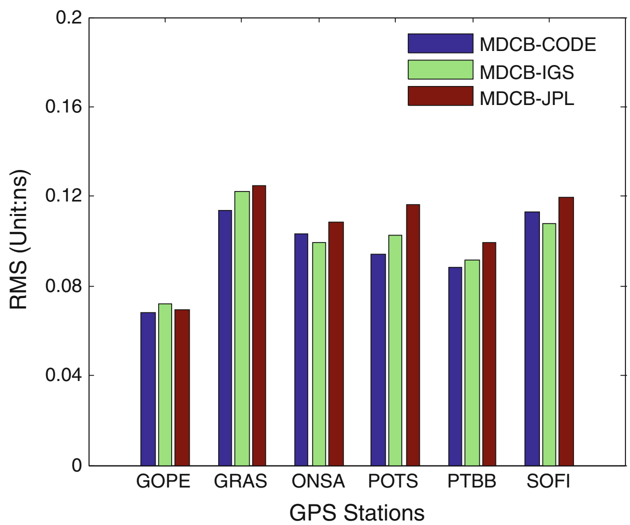

Fig. 6 The RMSs of the differences between receiver DCB values estimated by M_DCB and those released by CODE, JPL, and IGS combined

each day from January 1–31, the larger bias in PRN 1 is probably caused by fewer observations.

The mean differences and the RMS of these differences between DCBs estimated by M_DCB and those from CODE, JPL, and the IGS combination during January 1–30, 2010 are shown in Figs. 5 and 6, respectively. The M_DCB estimates are most consistent with the CODE solutions, and the differences between M_DCB estimates and the JPL solutions are larger. CODE's results have been estimated with an external calibration. The database and order of the spherical harmonic functions during DCB estimation are different. Here, we use GPS observations from just 19 IGS stations, while the JPL uses the triangular mesh model to describe the ionosphere while estimating DCB and TEC coefficients, and the IGS values are from the combination of several GNSS analysis centers. Some systematic differences may be from the processing strategies and models used, while the RMS values have almost no significant difference with respect to each other (Fig. 6).

Test result of single stations from M_DCB

Sometimes, one must estimate a DCB for a single station. In order to test the validation of a single station DCB estimate using the M_DCB software, the single station DCB is tested at GOPE, GRAS, ONSA, POTS, PTBB, and SOFI, respectively. Figure 7 shows the DCB estimate difference between the IGS combined DCB values and single station's DCB estimated by M_DCB. Mean differences and RMSs for these 30 days are presented in Table 2. It has been shown that one station also can get reliable results for a DCB estimate. In Table 2, all stations have a mean difference less than 0.7 ns and an RMS less than 0.4 ns. However, the result is not as good as the DCB estimate based on multiple stations. A multi-station estimate is recommended for local network receiver DCB computation. When we estimate a new receiver DCB, we should take advantage of the nearest IGS stations for more accurate DCB estimates.

Fig. 7 Differences between receiver DCBs estimated by M_DCB and IGS combined

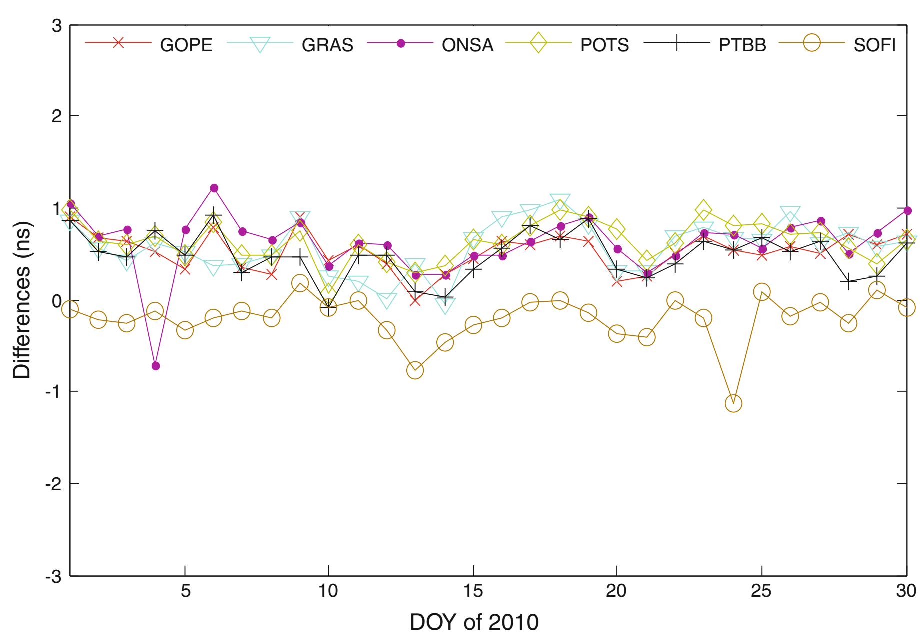

Table 2 The RMSs and mean differences of single station DCB estimate from January 1–31, 2010 (M_DCB minus IGS combined)

	Differences (ns)	RMS (ns)
GOPE	0.530	0.209
GRAS	0.577	0.280
ONSA	0.623	0.338
POTS	0.637	0.216
PTBB	0.483	0.247
SOFI	−0.205	0.257

Summary

Our Matlab software package called M_DCB can be used to estimate global or regional GNSS satellite and receiver DCBs using dual-frequency GPS observations. The test results have shown a good agreement with IGS analysis center products (e.g., JPL, CODE, and IGS combined) with differences of less than 0.7 ns and an RMS of less than 0.4 ns. The Matlab source code for M_DCB is available at www.ngs.noaa.gov/gps-toolbox. M_DCB is a convenient tool to estimate GNSS satellite and receiver DCB. This software package can also estimate precise TEC of the earth's ionosphere from GNSS dual-frequency observations. Some bugs may still exist in M_DCB. Comments and suggestions are welcome from readers and users.

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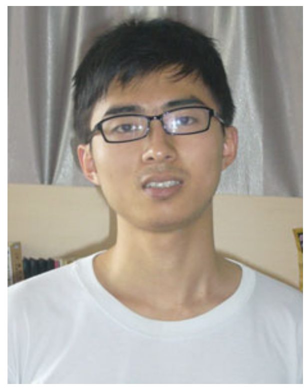

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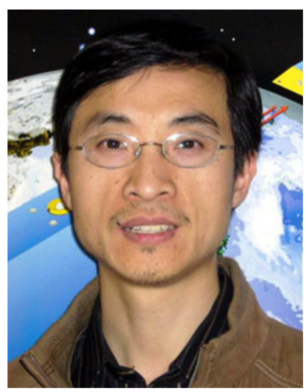

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