GPS Instrumental Biases Estimation Using Continuous Operating Receivers Network

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Abstract

Precise Total Electron Content (TEC) are required to produce accurate spatial and temporal resolution of Global Ionosphere Maps (GIMs). Receivers and Satellites Instrumental Biases (IBs) are one of the main error sources in estimating precise TEC from Global Positioning Systems (GPS) data. Recently, researchers are interested in developing models and algorithms to compute IBs of receivers and satellites close to those computed from the Ionosphere Associated Analysis Centers (IAAC). Here we introduce a MATLAB code called Multi Station IBs Estimation (MSIBE) to calculate satellites and codeless tracking receivers IBs from GPS data. MSIBE based on spherical harmonic function and geometry free combination of GPS carrier phase and pseudo-range code observations and weighted least square were applied to solve observation equations, to improve estimation of IBs values. There are many factors affecting estimated value of IBs. The premier factor is the observations weighting function which relying on the satellite elevation angle. The second factor concerned with estimating IBs using single GPS Station Precise Point Positioning (PPP) or using GPS network. The third factor is the number of GPS receivers in the network. Results from MSIBE were evaluated and compared with data from IAAC and other codes like M_DCB and ZDDCBE. The results of weighted (MSIBE) least square shows an improvement for estimated IBs, where mean differences from CODE less than 0.746 ns. IBs estimated from Continuous Operating Receivers (CORs) GPS network shows a good agreement with IAAC than IBs estimated from PPP where the mean differences are less than 0.1477 ns and 1.1866 ns, respectively. The mean differences of computed IBs improved by increasing number of GPS stations in the network.

Keywords: DCBs, IBs, Multi Station, Elevation Angle, Total Electron Content.

1. INTRODUCTION

TEC is an important parameter in the study of ionospheric dynamics, structures, and variabilities. The ionosphere is a dispersive medium for space geodetic techniques operating in the microwave band that allows calculation of TEC using GPS dual-frequency radio transmissions [1]. The global availability of GPS has made it a valuable tool for sensing the Earth' the regional and global ionosphere estimation [2, 3, 4, 5, 6]. Regrettably, GPS-derived TEC observations are adversely influenced by an inherent interfrequency bias within the receiver and satellite hardware, typically referred to as the IBs. Careful estimation of the IBs is required to obtain accurate TEC, which is used in several applications, such as in several ionospheric prediction models, and in the correction of GPS positioning measurements [7]. A number of methods have been proposed for the estimation of GPS receiver IBs, each with varying requirements and limitations including: making assumptions about the ionospheric structure; the use of internal calibration [8, 9, 10]; or the use of a reference instrument or model. Estimating IBs for receivers and satellites from GPS observations depending on two approaches, the relative and absolute methods. The relative method utilizes a GPS network, while the absolute method determines IBs from a single station [11]. In the current study, we applied relative method to calculate IBs of satellites and GPS receivers.

There has also been growing interest in measuring the accuracy of these methods, and how different factors, e.g. ionospheric activity, plays a role in these methods [7]. Nowadays, reliable GIMs and accurate IBs of satellites and receivers. The International GNSS Service (IGS) stations can be obtained from IAAC like Center for Orbit Determination in Europe CODE (University of Bern, Switzerland) [12], European Space Agency (ESA, Germany) [13], Jet Propulsion Laboratory (JPL, USA) [14], and UPC (Technical University of Catalonia, Spain) [2, 15]. However, the availability of IAAC IB receivers' values, it is only available for IGS stations. Furthermore, some of IGS ground receiver IB estimates are not available from all analysis centers. Likewise, some regions like our country Egypt don't have any IGS ground stations, which mean the TEC values over them would be interpolated from nearest calculated values. As TEC values depended on IB values it is required a mathematical model to calculate IBs from GPS data.

In this study we introduce a mathematical model estimating satellites & receiver IBs for A GPS network based on Spherical Harmonic Function (SHF) written under MATLAB language, the progressing mathematical model uses geometry free combination of pseudo-range observables (P-code). Weighted Least Square (WLS) was applied to consider variation of satellites elevation angle. The code was tested and compared with other researchers' codes in section "Results and analysis". In the "Conclusion" section we summarize the gross paper results.

2. GPS OBSERVATION MODEL

For a GPS satellite, the pseudorange and carrier phase observations between a receiver and a satellite can be expressed as [16, 17, 18, 19]:

$$\mathbf{P}_{r,j}^{s}(\mathbf{i}) = \boldsymbol{\rho}_{r}^{s}(\mathbf{i}) + \mathbf{c}(\mathbf{dt}_{r} - \mathbf{dt}^{s}) + \mathbf{T}_{r}^{s} + \mathbf{I}_{r,j,P}^{s} + \mathbf{IB}_{r}^{P1-P2} - \mathbf{IB}_{s}^{P1-P2} + \mathbf{M}_{j} + \mathbf{E}_{j} \quad \textbf{(1)}$$

$$\boldsymbol{\Phi}_{r,j}^{s}(i) = \boldsymbol{\rho}_{r}^{s}(i) + c(dt_{r} - \mathbf{dt}^{s}) + T_{r}^{s} - I_{r,j,\Phi}^{s} + \lambda_{j}N_{j} + pb_{r,j} - \mathbf{pb}_{s,j} + IB_{r}^{\Phi1-\Phi2} - \mathbf{IB}_{s}^{\Phi1-\Phi2} + m_{j} + e_{j} \quad \textbf{(2)}$$

With r, s, j and i the receiver, satellite, frequency and epoch indices, and where:

$\mathbf{P}_{r,j}^{s}(\mathbf{i})$ Pseudo-range measurements, in meter,
$\boldsymbol{\Phi}_{r,j}^{s}(\mathbf{i})$ Carrier-phase measurements, in meter,
$\boldsymbol{\rho}_{r}^{s}(\mathbf{i})$ The geometric distance between satellite and receiver antennas, in meters,
c The speed of light, in meters per second,
$\mathbf{dt}_{r}$ and dt^{s} Receiver and satellite clock errors, respectively, in seconds,
$\mathbf{T}_{r}^{s}$ The neutral troposphere delay, in meters,
$\mathbf{I}_{r,j,P}^{s}$ and $\mathbf{I}_{r,j,\Phi}^{s}$ Ionosphere delay of pseudo range and carrier phase observations, in metric,
$\mathbf{N}_{j}$ Carrier-phase integer ambiguities, in cycles,
$\boldsymbol{\lambda}_{j}$ Carrier-phase wave length, in meters,
$\mathbf{IB}_{r,}^{P1-P2}$ **and** $\mathbf{IB}_{s}^{P1-P2}$ Receiver and satellite pseudo-range instrumental biases, respectively in metric,
$\mathbf{IB}_{r}^{\Phi1-\Phi2}$ **and** $\mathbf{IB}_{s}^{\Phi1-\Phi2}$ Receiver and satellite carrier-phase instrumental biases, respectively, in metric,
$\mathbf{M}_{j}$ Pseudo-range multipath on, in meters,
$\mathbf{E}_{j}$ Other un-modeled errors of pseudo-range measurements, in meters,
$pb_{r,j}$ ***and*** $\mathbf{pb}_{s,j}$ Receiver and satellite carrier-phase initial phase bias, respectively, in metric,
$\mathbf{m}_{j}$ Carrier-phase multipath, in meters and
$\mathbf{e}_{j}$ Other un-modeled errors of carrier-phase measurements, in meters.

Initially, the Rinex files and extract the pseudo range and carrier phase observations will be read by the code, which are the range distances between the receivers and satellites, measured using L1 and L2 frequencies. The "geometry-free" linear combination of GPS observations is used to derive the observable. The clock-offsets, geometric range and tropospheric delay are recurrence independent and can be discarded using this combination. The "geometry-free" linear combinations for pseudo range and carrier phase observations are given as [20]:

$$P_4 = P^s_{r,1}(i) - P^s_{r,2}(i) = I^s_{r,1,p} - I^s_{r,2,p} + IB^{P1-P2}_r + IB^{P1-P2}_s + E_{12} \quad (3)$$

$$\Phi_4 = \Phi^s_{r,1}(i) - \Phi^s_{r,2}(i) = I^s_{r,2,\Phi} - I^s_{r,1,\Phi} + \lambda_1 N_1 - \lambda_2 N_2 + IB^{\Phi1-\Phi2}_r + IB^{\Phi1-\Phi2}_s + e_{12} \quad (4)$$

$E_{12} = \sqrt{(E_1)^2 + (E_2)^2}$ is the combination of multipath and measurement noise on $P^s_{r,1}(i)$ and $P^s_{r,2}(i)$,

$e_{12} = \sqrt{(e_1)^2 + (e_2)^2}$ is the combination of multipath and measurement noise on $\Phi^s_{r,1}(i)$ and $\Phi^s_{r,2}(i)$.

To decrease the noise level and multipath in the pseudo range observables, the carrier phase observables are used to compute a more precise relative smoothed range. Although the carrier-phase measurements are more accurate than the code derived, they are ambiguous due to the presence of integer phase ambiguities in the carrier phase measurements. To take advantage of the low-noise carrier phase derived and unambiguous nature of the pseudo range, both measurements are combined to collect the best of both observations.

Smoothed $P_{4,sm}$ observations can be expressed as follows [21]:

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

where t stands for the epoch number, ω_t is the weight factor related with epoch t, and

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

When t is equal to 1, which means the first epoch of one observation arc, $P_{4,sm}$ is equal to P_4.

3. SPHERICAL HARMONIC MODEL

To estimate the receiver IB, two different methods can be used. The first method is to calibrate the receiver instrument and obtain the IB directly. This method computes the IB of the receiver device neglecting that from the antenna cabling used during measurement [22]. The second method estimates the receiver IB as a part of GPS signal time delay which is independent on type of antenna. The proposed code (MSIBE) run as the second methods (figure1). The ionosphere delay can be expressed as follows [23]:

$$I^s_r = \frac{40.3}{f^2} STEC \quad (7)$$

Where f stands for the frequency of the carrier and Slant Total Electron Content (STEC) is the total electron content along the path of the signal. The measurmet equation can be formed by Substituting (7) into (3), and replacing P_4 by smoothed $P_{4,sm}$, we get [23]:

$$P_{4,sm} = 40.3\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right) STEC + c * IB^{P1-P2}_r + c * IB^{P1-P2}_s \quad (8)$$

Where: c is the speed of light and IB^{p1-P2}_r and IB^{p1-P2}_s are differential code bias for receiver and satellites in seconds.

STEC can be translated into Vertical Total Electron Content (VTEC) using the modified single-layer model (MSLM) [21, 24]:

$$VTEC = MF(z) STEC \quad (9)$$

$$\mathbf{MF}=\cos\left(arcsin\left(\frac{R}{R+H}sin(\alpha z)\right)\right) \quad \mathbf{(10)}$$

Where:
MF is the mapping function,
z is the satellite elevation angle,
R is the radius of the Earth=6371 km and
H is the attitude of the ionosphere thin shell (assumed as used by CODE=506.7 km),
α=0.9782.

The present study applies a model based on spherical harmonic function to estimate the satellite and receiver IBs. The used model is expressed as follows [4, 12]:

$$\mathbf{VTEC(\beta,s)}=\sum_{n=0}^{N}\sum_{m=0}^{n}\mathbf{P_n^m}(\sin(\boldsymbol{\beta}))(\mathbf{A_n^m}\cos(\mathbf{m}\boldsymbol{\lambda})+\mathbf{B_n^m}\sin(\mathbf{m}\boldsymbol{\lambda})) \quad \mathbf{(11)}$$

Where:
β is the geocentric latitude of IPPs (Ionosphere Peirce Point),
s is the solar fixed longitude of IPPs,
N is the degree of the spherical function,
M is the order of spherical harmonic function,
P_{mn} is regularization Legendre series and
A_{mn} and B_{mn} are the estimated spherical harmonics coefficients.

By substituting eq (10) and eq (11) into eq (9) we get:

$$\sum_{n=0}^{N}\sum_{m=0}^{n}\mathbf{P_n^m}(\sin(\boldsymbol{\beta}))(\mathbf{A_n^m}\cos(\mathbf{m}\boldsymbol{\lambda})+\mathbf{B_n^m}\sin(\mathbf{m}\boldsymbol{\lambda}))$$
$$=\cos\left(\arcsin\left(\frac{R}{R+H}\sin(\alpha z)\right)\right)\left[-\frac{f_1^2f_2^2}{40.3(f_1^2-f_2^2)}(P_{4,sm}-c*IB_r^{P1-P2}-c*IB_s^{P1-P2})\right] \quad \mathbf{(12)}$$

Only one GPS station has more than 20,000 observations per a day. When applying equation (12) using stations observation data, there are number of equations much more than the number of unknown coefficients. These coefficients were determined using weighted least square method. General form of weighted least square function can be expressed as [25]:

$$\mathbf{X=(A^TPA)^{-1}\,A^TPL} \quad \mathbf{(13)}$$

Where:
X : is the unknown parameters vector namely, A_n^m, B_n^m, IB_r and IB_s ,
A: is the coefficient (design) matrix (coefficients of A_n^m, B_n^m, IB_r and IB_s),
L : is the observation vector (values of $P_{4,sm}$) and
P: is the weight matrix.

IBs of the satellites that has no observations all the day are taken from the IONEX file. As known, the quality of observations is affected by satellite elevation angle, each observation has a weight value depend on its satellite elevation angle. The weight value can be computed from the following equations [26]:

$$\boldsymbol{w}=\frac{\sigma_0^2}{\sigma^2} \quad \mathbf{(14)}$$

$$\boldsymbol{\sigma}^2=\left[\mathbf{0.05}+\frac{0.02}{sin(z)^2}\right]^2 \quad \mathbf{(15)}$$

$$\boldsymbol{\sigma}_0^2=(\boldsymbol{c}+\boldsymbol{d})^2 \quad \mathbf{(16)}$$

Where: c & d are two constants equal to 5 and 2 cm, respectively,

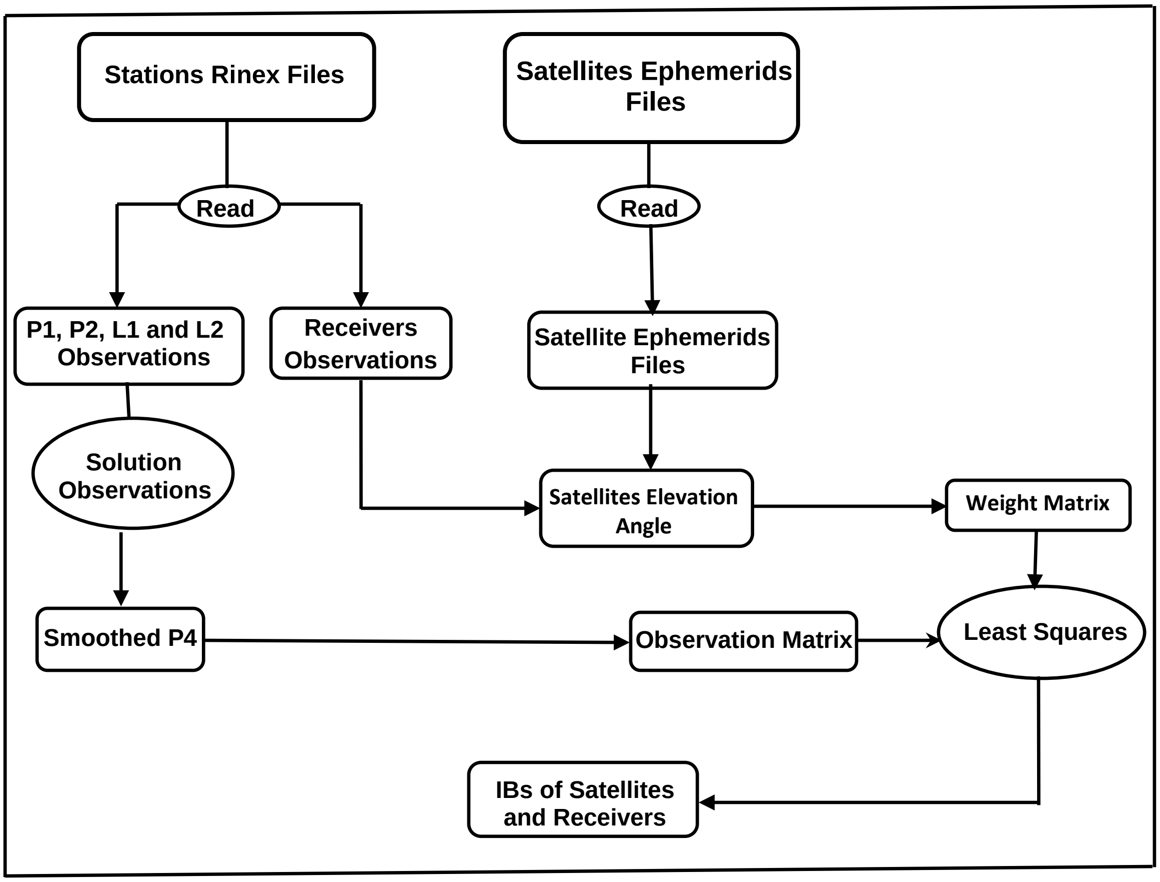

FIGURE 1: Flow Chart of the Proposed Code (MSIBE).

4. MATHEMATICAL MODEL EVALUATION

The proposed code (MSIBE) was written in MATLAB language version 2016a, figure (1) shows the steps of solution details for estimate IBs of satellites and receiver. The initial input is GPS measurements in Receiver Independent Exchange (RINEX) format according to the selected stations (figure 2) downloaded from (ftp://garner.ucsd.edu/rinex) and precise ephemerides (SP3) files of evaluated days downloaded from (http://www.GPScalendar.com/index.html?year=2010). In addition, IONosphere Map EXchange Format (IONEX) files of IGS, CODE and JPL are downloaded - as a threshold values - from (ftp://cddis.gsfc.nasa.gov/GPS/products/ionex/).

In the current contribution, to evaluate the performance of the developed model, numerical case studies were performed. The main goals of the numerical case-studies are to investigate three issues:

First issue is to check the effect of applying weighted least square instead of least square on satellites and GPS receiver IBs, and this is done by comparing results from MSIBE which applying weighted least square with the published results of M_DCB by Jin et al. (2012), and with those of IAAC.

IGS stations data, as Figure (2), from 1 to 31 January 2010 were applied as it was the same network used by [21].

Second issue is to investigate the correlation between size (number of receivers) of the GPS network and estimated IBs for satellite and GPS receiver, and this is done by comparing IB values of three stations namely, GOPE, GRAS and ONSA estimated from a network consists of 3

GPS receiver and a network consists of 9 GPS receiver. The present contribution was applied using IGS Stations data from 1 to 5 January 2010 of these stations (Figure (2) shows the placed of these stations).

Third issue is to examine the congruence of IBs calculated from absolute and relative methods with other IAAC, and this is done by comparing results from MSIBE with the published results of ZDDCBE by [11]. Six stations (GOPE, GRAS, ONSA, MADR, PTBB, and SOFI) which was the same network used by [11, 21] were used in the present study.

4.1 Comparison of Multi-station Test Results from MSIBE and M_DCB

The first evaluation made by this paper is the evaluation of weight function. MSIBE used a weight function depending on the satellite elevation angle as mentioned before. Table 1 shows the differences and RMS between satellites and receivers estimated from 1 to 31 January 2010 using multiple GPS stations of both MSIBE (weighted) and M_DCB (unweighted).

From Table (1), one can see that the differences of MSIBE estimated satellites IBs are less than 0.302 ns and the RMS of all satellites IBs differences are less than 0.128 except G1 whose RMS = 0.250. The maximum difference of MSIBE estimated receivers IBs is 0.150 ns of receiver GOPE and the minimum is 0.045 ns of receiver SOFI (Figure 3). The maximum RMS of MSIBE estimated receivers IBs is 0.125. On the other side, M_DCB results show that Receiver IB biases are slightly larger than those for satellites are, but most of them are less than 0.4 ns except G1 whose IBs reaches 0.746 ns.

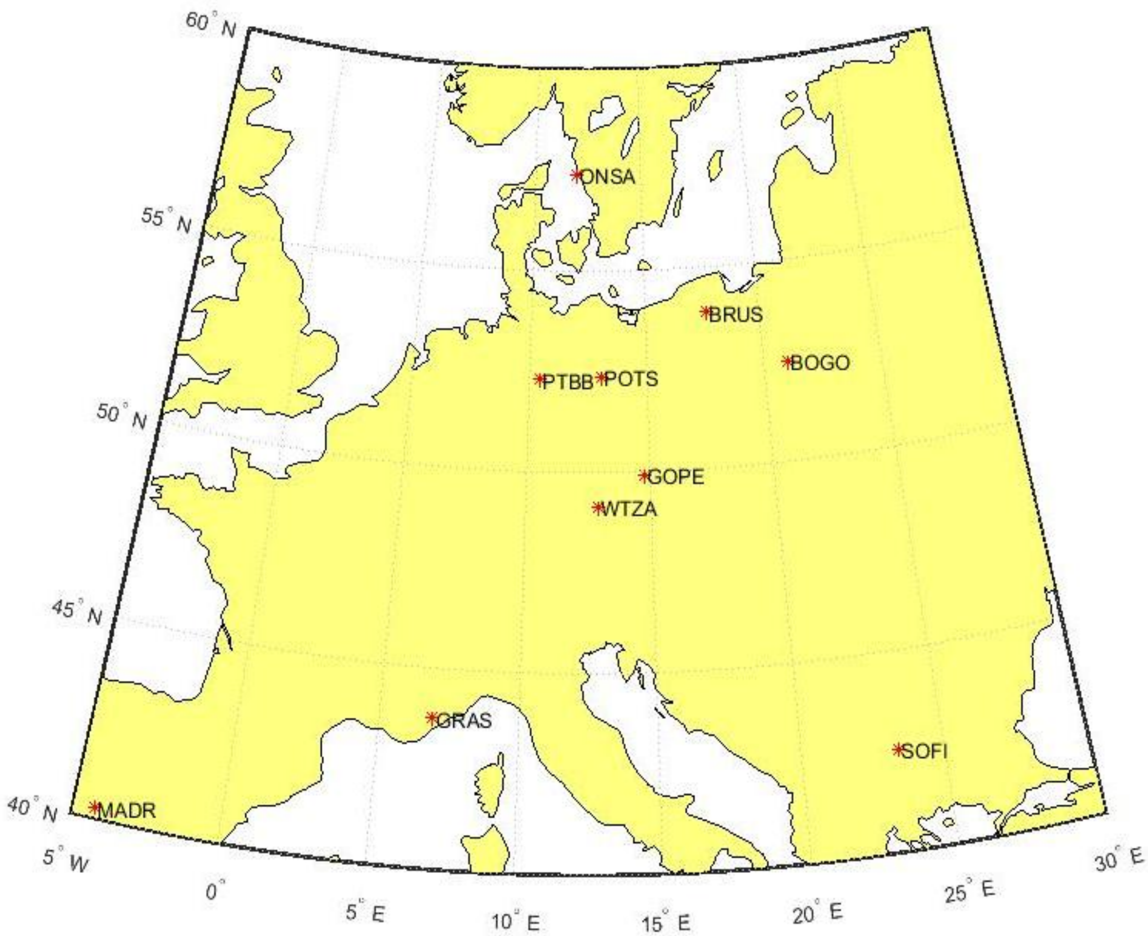

FIGURE 2: IGS Stations Locations.

Satellite	MSIBE		M_DCB		Satellite	MSIBE		M_DCB	
	MD (ns)	RMS	MD (ns)	RMS		MD (ns)	RMS	MD (ns)	RMS
G1	0.228	0.250	0.746	0.251	G17	0.087	0.125	0.038	0.138
G2	0.121	0.091	-0.073	0.087	G18	-0.136	0.113	-0.044	0.100
G3	0.004	0.078	0.194	0.066	G19	0.236	0.095	0.381	0.066
G4	0.169	0.092	0.003	0.123	G20	0.096	0.096	0.004	0.073
G5	-0.082	0.106	-0.236	0.111	G21	-0.208	0.109	-0.121	0.088
G6	-0.059	0.066	0.169	0.061	G22	-0.188	0.091	0.050	0.109
G7	-0.015	0.084	-0.233	0.085	G23	0.210	0.082	0.052	0.053
G8	-0.094	0.085	-0.271	0.085	G24	-0.168	0.086	-0.221	0.076
G9	0.011	0.074	0.038	0.088	G25	-0.091	0.122	-0.220	0.085
G10	-0.068	0.088	-0.343	0.095	G26	-0.302	0.089	-0.020	0.092
G11	0.211	0.090	0.202	0.063	G27	0.078	0.062	0.060	0.088
G12	0.029	0.059	0.049	0.051	G28	-0.177	0.080	-0.340	0.107
G13	0.296	0.080	0.140	0.062	G29	-0.195	0.128	-0.277	0.091
G14	-0.058	0.124	0.150	0.126	G30	0.057	0.077	0.020	0.074
G15	-0.055	0.101	-0.164	0.117	G31	0.018	0.099	0.057	0.138
G16	-0.057	0.069	0.096	0.084	G32	0.102	0.070	0.115	0.077
BOGO	0.139	0.077	0.065	0.080	POTS	0.120	0.073	0.237	0.094
BRUS	0.121	0.120	0.309	0.111	PTBB	0.083	0.082	0.201	0.095
GOPE	0.150	0.069	0.142	0.068	SOFI	-0.045	0.119	0.081	0.113
GRAS	0.085	0.125	0.370	0.131	WTZA	0.137	0.078	0.270	0.083
ONSA	0.140	0.093	0.178	0.103					

TABLE 1: The Mean Differences (MD) and RMS between satellites and receivers estimated from 1 to 31 January 2010 using multiple GPS stations (MSIBE and M_DCB minus CODE).

The RMS of all differences is lower than 0.3 ns [21]. Figure 4 shows the mean differences between receiver IB values estimated by MSIBE and those released by CODE, IGS, and JPL combined from 1-31 Jan 2010. The figure shows that the results of MSIBE are mostly close to those of CODE than IGS and JPL. By comparing the figure 4 with the corresponding chart published by [21], it is visibly appeared that all differences between MSIBE receivers' IBs results and between CODE, IGS and JPL are less than those from M_DCB except station GOPE almost equal.

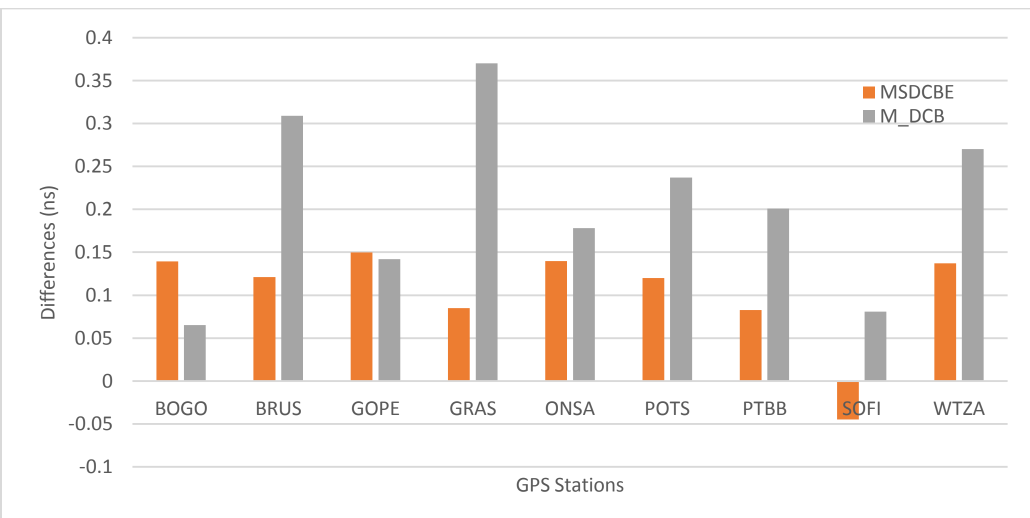

FIGURE 3: Mean difference between the receiver IB values of CODE and the computed values by each of MSIBE and M_DCB estimated from (1-31) Jan 2010.

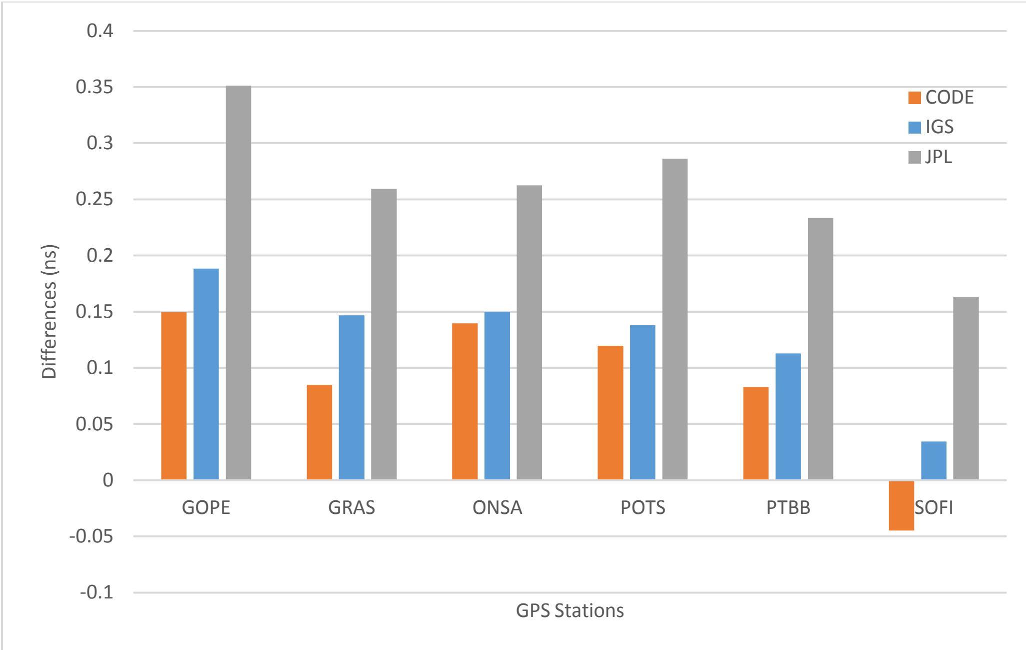

FIGURE 4: Mean differences between receiver IB values estimated by MSIBE and those released by CODE, JPL, and IGS combined from 1-31 Jan 2010.

4.2 Effect of Network Size Factor on IB Estimation

By using multi station IBs estimation, the number of stations used will appear as a factor influences IBs estimation. This test was done by comparing IBs computed by MSIBE of a network of three stations (GOPE, GRASand ONSA) and IBs of the same receivers but this time as a part of a network of nine stations (BOGO, BRUS, GOPE, GRAS, ONSA, PTBB, SOFI and WTZA). Figure 5 shows these results which demonstrate that using nine receivers gives more accurate IBs. Also, the satellites IBs differences (figure 6) almost improved but not like receivers IBs, because satellites IBs are small values compared with those of receivers.

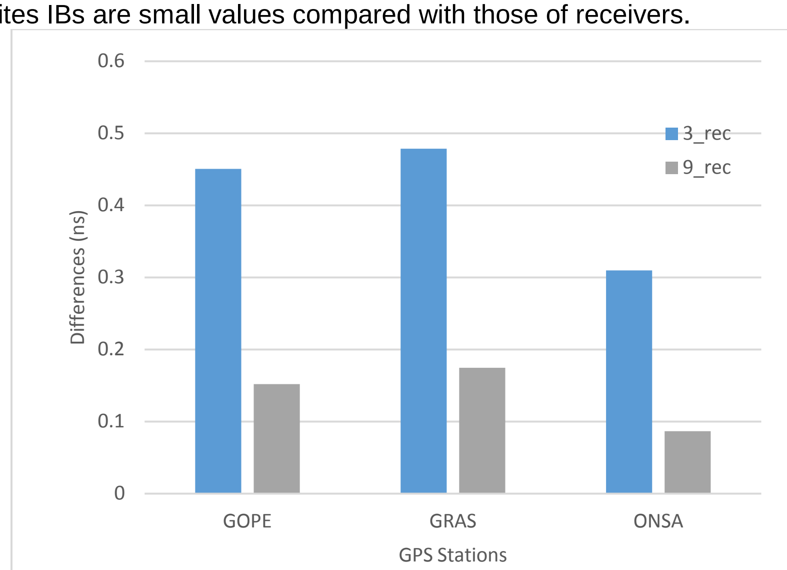

FIGURE 5: Mean difference between the receiver IB values of IGS and the computed values by MSIBE estimated from (1-5) Jan 2010.

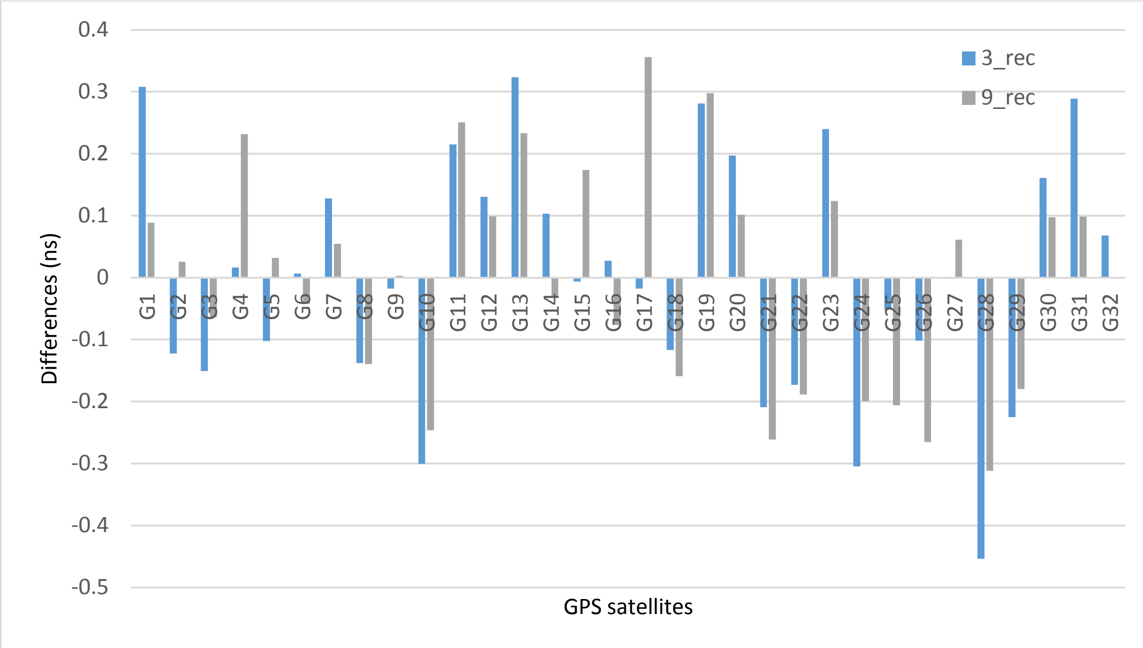

FIGURE 6: Mean difference between the satellites IB values of IGS and the computed values by MSIBE estimated from (1-5) Jan 2010.

4.3 Comparison of Multi-station from MSIBE and Single Station from ZDDCBE and M_DCB Test Results

In this section, the performance of multi station network against single station IB estimation will be evaluated. Table 2 shows the mean deference between the receiver IB values computed by IGS and the computed values by each of M_DCB, ZDDCBE and MSIBE estimated from 1-5 Jan 2010. Figure 7 shows these results graphically and figure 8 shows the mean differences computed from M_DCB, ZDDCBE and MSIBE for GPS satellites. The results show a significant difference between multi station networks against single station IB estimation. The maximum difference between receiver IB estimation using IGS and MSIBE is 0.1477 ns of MADR station, but it is 1.1866 ns and 0.7982 ns for M_DCB and ZDDCBE respectively.

IGS St.	Model	IB diff. (ns)	IGS St.	Model	IB diff. (ns)
GOPE	M_DCB	0.3847	ONSA	M_DCB	1.1866
	ZDDCBE	0.1724		ZDDCBE	0.7982
	MSIBE	0.004		MSIBE	-0.0310
GRAS	M_DCB	0.3379	PTBB	M_DCB	0.6692
	ZDDCBE	0.1466		ZDDCBE	0.3550
	MSIBE	0.066		MSIBE	-0.0578
MADR	M_DCB	0.3078	SOFI	M_DCB	0.6916
	ZDDCBE	0.3468		ZDDCBE	0.4650
	MSIBE	0.1477		MSIBE	-0.0149

TABLE 2: Mean difference between the receiver IB values computed by IGS and the computed values by using single station M_DCB, ZDDCBE and multi-station MSIBE estimated from 1-5 Jan. 2010.

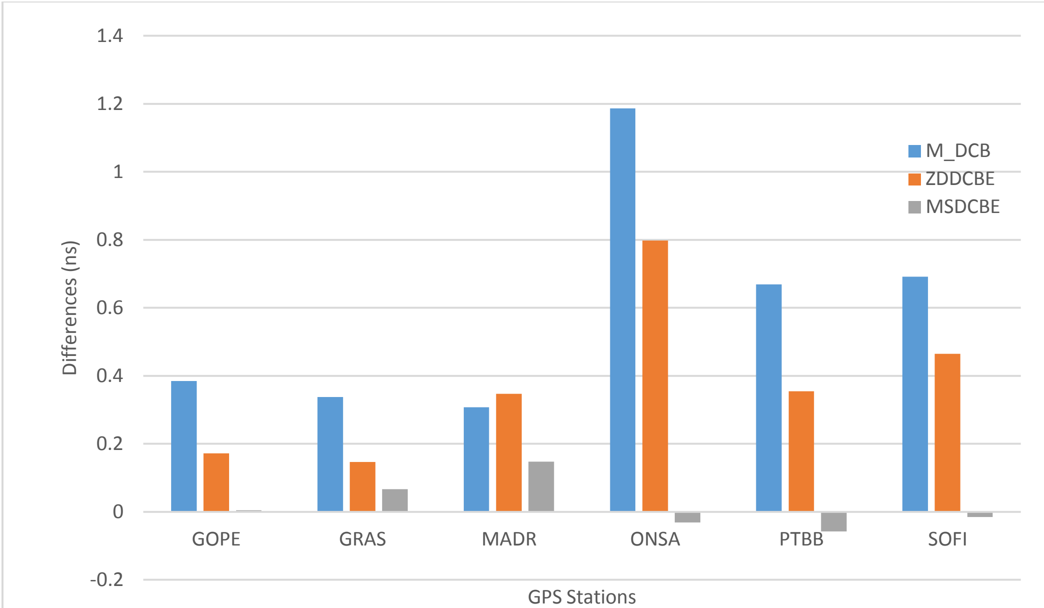

FIGURE 7: Mean difference between the receiver IB values of IGS and the computed values by each of M_DCB, ZDDCBE and MSIBE estimated from (1-5) Jan 2010.

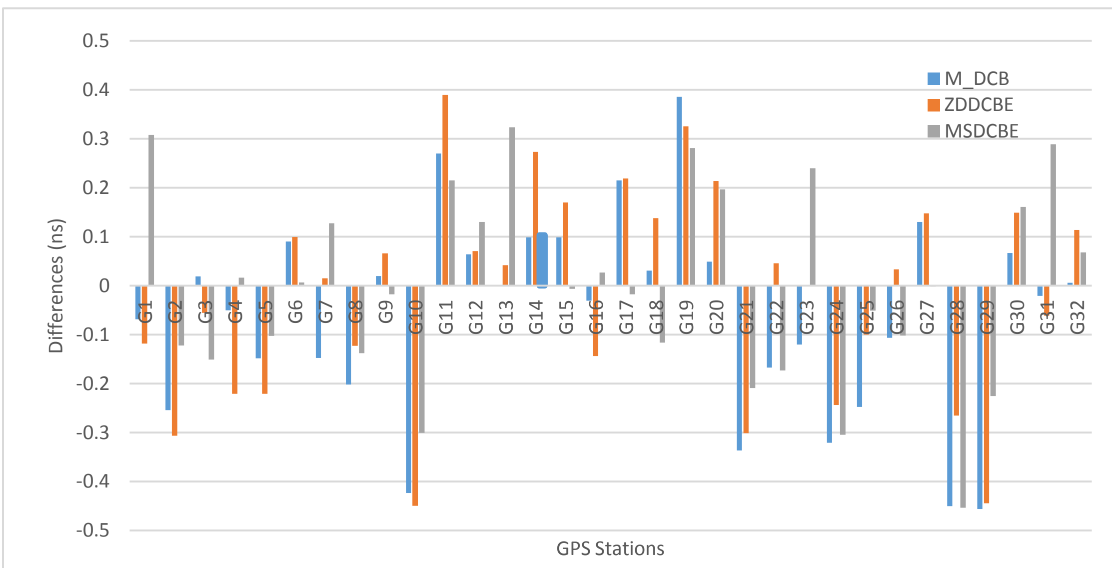

FIGURE 8: Mean difference between the satellites IB values of IGS and the computed values by M_DCB, ZDDCBE and MSIBE estimated from (1-5) Jan 2010.

5. CONCLUSIONS

The current study proposes a new MATLAB code called MSIBE able to calculate IBs of GPS satellites and receivers. This code was compared with two other codes and evaluated using IAAC data and from all the above, we can conclude that:

1) The estimated IBs results also affected and improved by using weight function according to satellite elevation angle observations. In addition, results show a good agreement with IGS, CODE and JPL results than using multi station estimation IB without weight function.

2) When using multi station IB estimation, number of input stations influences in IB results. However, it is recommended to enlarge the size of used network, but it needs high computer requirements and much more analysis time (only one station have more than 20,000 observation per a day).
3) The most effective factor in IBs estimation is using multi station network instead of single station that appeared from results which improved from 1.1866 ns and 0.7982 ns maximum IB mean differences for M_DCB and ZDDCBE single station analysis to 0.1477 ns for MSIBE. So, using multi station network IB estimation- if available- is strongly recommended.

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