Chapter 29
GPS/GLONASS System Bias Estimation and Application in GPS/GLONASS Combined Positioning

Junping Chen, Pei Xiao, Yize Zhang and Bin Wu

Abstract Multi-GNSS data analysis has become a new challenge with the development of satellite navigation systems. System bias is the key issue in Multi-GNSS data analysis, which has no recommended models within IGS community. We introduce the integrated data analysis model developed at the GNSS data analysis center of Shanghai Astronomical Observatory (SHAO). Based on the routine GNSS data analysis at SHAO over 14 months, we analyze the precise GPS/GLONASS system bias product in detail. Results show: (1) system bias shows similarity for same type of receivers, while obvious difference are observed for different type of receivers; (2) variation of system bias shows same pattern for all stations, which indicates that the long-term variation of system bias is caused by the system time offset; (3) system bias is influenced also by type of antenna type. A model is derived to separate hardware delay difference (HDD) between GPS/GLONASS observations at the same receiver and the so-called inter-frequency bias (IFB). Analysis of the HDD and IFB time series shows that both terms are affected by the change of receiver type, antenna type, firmware series, cable type and length. Applying the system bias into PPP positioning, precision of GLONASS-only solution is improved by 55 % and precision of GPS/GLONASS combined solution is improved by 30 %.

Keywords GNSS · SHA · Analysis center · Inter system bias (ISB) · IFB

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J. Sun et al. (eds.), *China Satellite Navigation Conference (CSNC) 2013 Proceedings*, Lecture Notes in Electrical Engineering 244, DOI: 10.1007/978-3-642-37404-3_29,
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29.1 Introduction

Coordinate and time reference frame are both the key parameters of satellite navigation system. As to time reference frame, GPS is based on GPST, GLONASS is based on GLONASST. As to coordinate reference, GPS adopts WGS-84, GLONASS adopts PZ-90. There are differences in framework accuracy and scale for different navigation systems [1–4].

As navigation system develops and updates, multi-system fusion has become the tendency of the development. In certain environment, such as urban canyon and ravines, single system can't provide service because of limited satellite conditions. Besides, satellite constellation has periodic regression relative to the Earth, the relative relationship of navigation satellites–Earth–Sun also has regression of different period. The periodic regression of these relative relationships will add relevant periodic errors into parameters such as coordinates and receiver clock offset [5]. So multi-mode observation increases the number of available satellites. Meanwhile, the data fusion can reduce the influence of the periodic regression of satellite constellation, to improve the precision of station-relative parameters (e.g. coordinate, troposphere) and other public parameters (e.g. ERP) [6].

High-precision integrated processing of multi-mode data is the guarantee of multi-system fusion. Multi-system integrated data processing need taking into consideration of various system bias parameters. As to GPS/GLONASS integrated processing, the inter-system bias (ISB) of GPS and GLONASS system includes system's time difference TO and different system's hardware delay bias difference in receiver (ΔDCB). Among them, system's time difference is the difference between system times; ΔDCB is the hardware delay difference in receiver, it includes inter-frequency bias (IFB) of GLONASS satellite, which is because GLONASS system is based on frequency division multiple access (FDMA). Nowadays, IGS has not published integrated product and its processing standard. This article introduces GPS/GLONASS integrated data processing model; analyses and discusses the characteristics of ISB and IFB parameter, which is based on the 14 months routine results of global GNSS network provided by the GNSS data analysis center at SHAO (SHA). By introducing bias parameters to multi-mode positioning, the parameter resolution precision can be greatly improved.

29.2 GPS/GLONASS Integrated Data Processing Unified Model

Observation function of receiver i to GPS satellite j can be written as:

$$\begin{aligned} P_{\mathrm{i}}^{\mathrm{j}} &= \rho_{\mathrm{i}}^{\mathrm{j}} + \mathrm{c} \cdot \left(dt_i - dt^j\right) + DCB_i^j - I_i^j + T_i^j + \varsigma_i^j \\ \mathrm{L}_{\mathrm{i}}^{\mathrm{j}} &= \rho_{\mathrm{i}}^{\mathrm{j}} + \mathrm{c} \cdot \left(dt_i - dt^j\right) + DPB_i^j + \lambda \cdot N_i^j - I_i^j + T_i^j + \varepsilon_i^j \end{aligned} \tag{29.1}$$

P_i^j, L_i^j are respectively the pseudorange and carrier phase observation; ρ_i^j is geometrical distance; c is light speed, λ is wavelength; dt_i is receiver clock offset, dt^j is satellite clock offset; DCB_i^j and DPB_i^j are pseudorange and carrier phase bias (including both receiver and satellite); N_i^j is ambiguity, I_i^j is the ionospheric delay error, T_i^j is the tropospheric delay error, ς_i^j is other error corrections (including relativistic effect, tide, PCO, PCV, phase unwrapping and so on), ε_i^j is residual. In practical application, I_i^j could be ignored by forming the ionosphere-free combination using dual-frequency pseudo-range and carrier phase observations.

The pseudorange observation in (29.1) provides reference to clock offset parameters. The pseudorange bias DCB_i^j (such as P1-P2, P1-C1) will be absorbed by clock offset $c \cdot (dt_i - dt^j)$. Nowadays, the carrier phase bias DCB_i^j is not included in GPS data processing, it will be combined with other parameters (mainly ambiguity). Then (29.1) can be rewritten as:

$$\begin{aligned} P_{\mathrm{i}}^{\mathrm{j}} &= \rho_{\mathrm{i}}^{\mathrm{j}} + \mathrm{c} \cdot \left(\overline{d}t_i - \overline{d}t^j\right) - I_i^j + T_i^j + \varsigma_i^j \\ \mathrm{L}_{\mathrm{i}}^{\mathrm{j}} &= \rho_{\mathrm{i}}^{\mathrm{j}} + \mathrm{c} \cdot \left(\overline{d}t_i - \overline{d}t^j\right) + \lambda \cdot \overline{N}_i^j - I_i^j + T_i^j + \varepsilon_i^j \end{aligned} \tag{29.2}$$

where:

$$\begin{aligned} c \cdot \left(\overline{d}t_i - \overline{d}t^j\right) &= c \cdot \left(dt_i - dt^j\right) + DCB_i^j \\ \lambda \cdot \overline{N}_i^j &= \lambda \cdot N_i^j + DPB_i^j - DCB_i^j \end{aligned} \tag{29.3}$$

Nowadays, IGS clock offset product reference is based on P1/P2 ionosphere-free combination. Under that basis, the DCB_i^j of P1/P2 ionosphere-free combination in (29.3) will be absorbed by clock offset parameter. Other observations need parameters provided by IGS to correct DCB_i^j.

Expend (29.2) to GPS/GLONASS dual-mode observation, observation function of receiver i to GPS satellite k and GLONASS satellite j can be written as :

$$\begin{aligned} \mathrm{L}_{\mathrm{i}}^{kG} &= \rho_{\mathrm{i}}^{kG} + \mathrm{c} \cdot \left(\overline{d}t_i - \overline{d}t^k\right)^G - I_i^{kG} + T_i^{kG} + \lambda^G \cdot \overline{N}_i^{kG} + \varsigma_i^k \\ \mathrm{L}_{\mathrm{i}}^{\mathrm{j}R} &= \rho_{\mathrm{i}}^{\mathrm{j}R} + \mathrm{c} \cdot \left(\overline{d}t_i - \overline{d}t^j\right)^G + ISB_i^{jk} + \lambda^R \cdot \overline{N}_i^{jR} - I_i^{jR} + T_i^{jR} + \varepsilon_i^j \end{aligned} \tag{29.4}$$

where:

$$\begin{aligned} ISB_i^{jk} &= \mathrm{c} \cdot \left(\overline{d}t_i - \overline{d}t^j\right)^R - \mathrm{c} \cdot \left(\overline{d}t_i - \overline{d}t^k\right)^G \\ &= TO + \Delta DCB_i^{j,k} \end{aligned} \tag{29.5}$$

In (29.4), the superscript R represents GLONASS, G represents GPS; ISB_i^{jk} is inter-system bias on station i between GPS satellite k and GLONASS satellite j (including system time difference *TO* and pseudorange delay bias in satellites and receiver $\Delta DCB_i^{j,k}$, which includes inter-frequency bias IFB_i^j). Definitions of other parameters are the same with (29.1) and (29.2). *TO* in (29.5) is defined as a one-day constant for all stations. $\Delta DCB_i^{j,k}$ is mainly because of GPS and GLONASS systems' different frequencies, which can be written as ΔDCB_{sys}. $\Delta DCB_i^{j,k}$ is also slightly effected by GLONASS satellites' different frequencies IFB_i^j, IFB_i^j is various to different receivers and different frequencies.

Formula (29.4) is the universal observation function of multi-system integrated data processing, it also applies to the combined observation of GPS and other satellite system. By defining inter-system bias ISB_i^{jk}, estimating $c \cdot \left(\overline{d}t_i - \overline{d}t^j\right)^G$ and unifing GLONASS clock offset to GPS time system, we can realize the integrate of multi-system's time reference. ρ_i^j Contains satellite orbit and receiver coordinates, restrain station coordinates to ITRF reference, then we can realize the unification of multi-system's space reference. As to users, adopting these orbit and clock offset and all kinds of bias parameters under the same time and space reference can unifies different systems' observation to the same satellite system, thus simplify the users' application and promote positioning precision.

In (29.4), calculating $\overline{d}t_i$ and $\overline{d}t^j$ at the same time is rank deficient, the general method is fixing one reference clock (usually the station with an external high-precision atomic clock, fixing the clock offset by GPS pseudorange process). ISB_i^{jk} contains TO, ΔDCB_{sys}, and IFB_i^j, IFB_i^jcan be absorbed in $\lambda^R \cdot \overline{N}_i^{jR}$ while TO and ΔDCB_{sys} have correlations with clock offset. Considering these correlations above, there are two solutions: weight ISB_i^{jk} to reduce the influence on correlation; add zero mean condition to all the ISB_i^{jk} in one station (IGS AC Mail 643). Different solutions cause the inconformity of GLONASS clock offset reference between IGS analysis centers [7].

29.3 GPS/GLONASS Inter-System Bias

Based on the multi-system integrated data processing modal above, Shanghai Astronomical Observatory developed integrated Geodetic Platform Of SHAO (iGPOS) and established GNSS data analysis center (SHA) [8].

Figure 29.1 shows the IGS network processed in the GNSS routine of SHA, among them about 70 stations can provide GPS/GLONASS combined observations. Figure 29.2 compares several analysis centers' orbit precision (from 2011.7 to 2012.8). The precision of GPS orbits of SHA is 1.5 cm and the precision of GLONASS orbits is 3.2 cm, which is about the precision of other IGS analysis centers.

SHA adopts the strategy that EMR and GFZ uses to deal with ISB: set the ISB of each receiver to each GLONASS frequency as a one-day constant. Figure 29.3 shows the GPS/GLONASS ISBs of station BRMU (BERMUDA, UK) from 2011181 to 2012240. In this figure, different color represents different GLONASS satellite frequency. In this period ISBs are between 50 and 70 m, the difference of

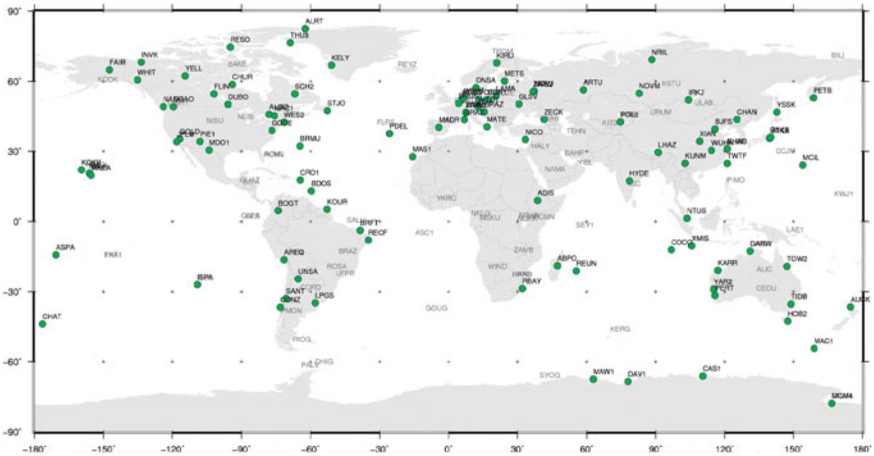

Fig. 29.1 IGS network processed in the GNSS routine of SHA

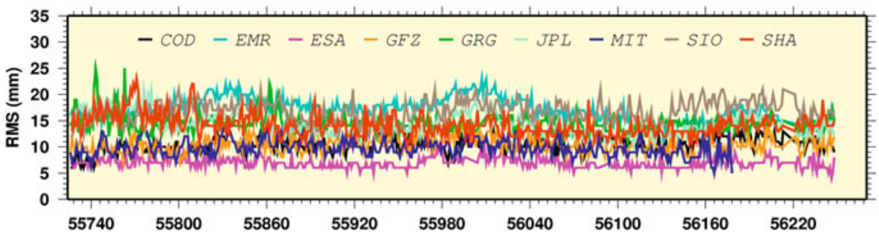

Fig. 29.2 Comparison of IGS analysis centers' orbit precision. Results in mm

adjacent day is less than 3 ns. Difference of different GLONASS frequency is less than 5 m (the minus channel number is −7, the max is 6). IFB's order of magnitude is obviously lower than ISB. Besides, on 2011271 BRMU's antenna type changed from TRM29659.0 to JAVRINGANT_DM, this change reflected to ISB obviously (about 10 m). It can be concluded that the type of antenna has influence on ISB.

Figure 29.4 shows the ISB series of 26 LEICA receivers. Different color represents different antenna type. It can be seen that the ISB of stations with LEICA antenna (LEIAT504GG and LEIAR25.R3), Topcon antenna (TPSCR3_GGD), Allen Osborne antenna (AOAD/M_T and AOAD/M_B) and Javad antenna (JAVRINGANT_DM) only have little difference less than 5 m. Meanwhile Ashtech and AOAD/M_TA_NGS antenna (this kind of antenna adopts Ashtech low noise amplifier technology [9]) and Trimble antenna (TRM29659.00) have obviously bigger difference. However, the difference between different antenna types is relatively less than the difference between receiver types.

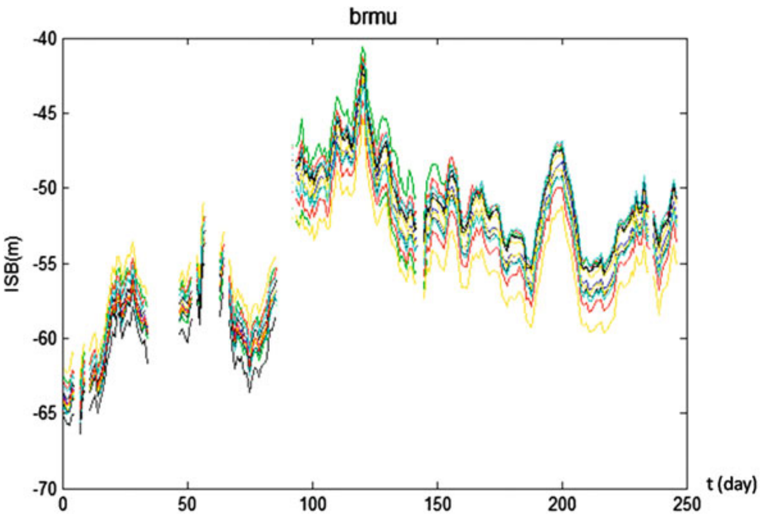

Fig. 29.3 ISBs of different GLONASS satellites on station BRMU (2011.06.30–2012.8.30)

As mentioned, *ISB* includes 3 parts: system time difference *TO*, GPS and GLONASS systems' hardware delay bias difference ΔDCB_{sys}, and GLONASS satellites' inter-frequency bias IFB_i^j. As it shows in Fig. 29.4, ISB's long-term changing tendency is consistent for the same type receivers, it mainly reflects the long-term changes of *TO* and ΔDCB_{sys}. Taking one frequency as reference frequency (such as channel 0) can reduce hardware delay bias difference in station and system time difference:

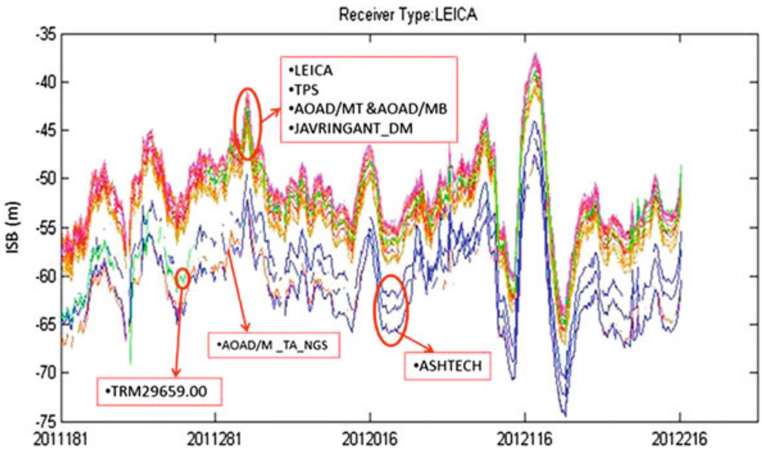

Fig. 29.4 ISB series of 26 LEICA receivers (2011.06.30–2012.8.30)

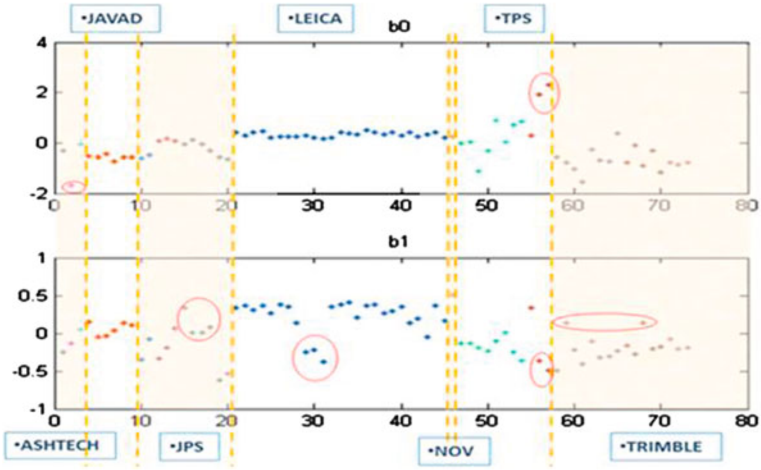

Fig. 29.5 $b0$, $b1$ of all the 74 stations

$$
\begin{aligned}
ISB_i^m - ISB_i^n &= \left(TO + \Delta DCB_i^{m,G}\right) - \left(TO + \Delta DCB_i^{m,G}\right) \\
&= \left(TO + \Delta DCB_{sys} + IFB_i^m\right) - \left(TO + \Delta DCB_{sys} + IFB_i^n\right) \\
&= IFB_i^{m,n}
\end{aligned}
\quad (29.6)
$$

IFB has linear relationship with the channel number [10, 11], so (29.6) can be rewritten as:

$$ISB_i^m - ISB_i^n = IFB_i^{m,n} = b0 + b1 \cdot (f^m - f^n) \quad (29.7)$$

In (29.7), f^m, f^n are GLONASS satellites' channel numble, $b0$, $b1$ are the fitting coefficients.

Take channel 0 as reference frequency, subtract its ISB from other satellite's. By means of the least square fit according to formula (29.7), we obtain $b0$, $b1$ for each station on each day. By using 14 months ISB data, which is provided by Shanghai Observatory GNSS Analysis Center (SHA), we get all the $b0$, $b1$ of 74 stations (shown in Fig. 29.5). There are 7 receiver types in total, it is shown that $b0$, $b1$ values of the same type receivers are consistent, and $b0$, $b1$ of different receivers vary widely. Antenna type's influence on $b0$, $b1$ is also obvious, the 11 stations with Ashtech antenna has been marked by red circles in Fig. 29.5, $b0$, $b1$ of these stations have obvious difference.

29.4 Application of ISB in GPS/GLONASS Combined Positioning

Introducing ISB to positioning can improve the accuracy and validity of positioning, especially when the valid satellite number is less [12]. ISB can be corrected directly, then GPS and GLONASS can be seen as a single system.

GPS/GLONASS combined positioning function is:

$$\begin{aligned}
\mathrm{P}_{\mathrm{i}}^{kG} &= \rho_{\mathrm{i}}^{kG} + \mathrm{c}\cdot\overline{d}t_i - I_i^{kG} + T_i^{kG} + \varsigma_i^k \\
\mathrm{P}_{\mathrm{i}}^{\mathrm{j}R} &= \rho_{\mathrm{i}}^{\mathrm{j}R} + \mathrm{c}\cdot\overline{d}t_i + ISB - I_i^{jR} + T_i^{jR} + \varepsilon_i^j \\
\mathrm{L}_{\mathrm{i}}^{\mathrm{j}G} &= \rho_{\mathrm{i}}^{kG} + \mathrm{c}\cdot\overline{d}t_i + \lambda^G\cdot\overline{N}_i^{kG} - I_i^{kG} + T_i^{kG} + \varsigma_i^k \\
\mathrm{L}_{\mathrm{i}}^{\mathrm{j}R} &= \rho_{\mathrm{i}}^{\mathrm{j}R} + \mathrm{c}\cdot\overline{d}t_i + ISB + \lambda^R\cdot\overline{N}_i^{jR} - I_i^{jR} + T_i^{jR} + \varepsilon_i^j
\end{aligned} \tag{29.8}$$

The parameters in formula (29.8) are the same with formula (29.4), GPS/GLONASS satellite clock offset adopts SHA's precision product, ISB can be obtained by using the model above mentioned. To the station with known ISB, there are only 6 parameters (coordinates, receiver clock offset and troposphere parameter) to be estimated. To the station with unknown ISB, we can give ISB an initial value according to the receiver type and antenna type, use the IFB model above to correct ISB, we only need another parameter (ISB of channel 0), then we can reduce the number of parameters and promote positioning precision.

29.4.1 Pseudorange Positioning

We choose 4 stations' data (pots, casl, chur, aspa) on doy 120 to doy 126, 2012, the interval is 30 s. These stations are installed with different manufacturers' receivers, the receiver and antenna information of these stations is in Table 29.1.

Tests are conducted by using pseudorange observations in 2 strategies: GONASS only and GPS/GLONASS combined positioning. Every strategy is applied in 3 scenarios:

1. Without consideration of GLONASS IFB;
2. Introduce GLONASS IFB from SHA;
3. Introduce GLONASS IFB modle of the corresponding receiver; estimate a one-day parameter: ISB of frequency-0.

The coordinates precision and increase rate are shown in Tables 29.2 and 29.3.

It can be seen from the statistics in Tables 29.2 and 29.3 that without considering GLONASS IFB obtains the lowest precision, while directly using ISB provided by SHA obtains the highest precision. The two ways to introduce IFB both greatly improve the positioning precision, coordinate precision increases up to

Table 29.1 Station information

Station	Receiver type	Antenna type
pots	JAVAD TRE_G3TH DELTA	JAV_RINGANT_G3T
cas1	LEICA GRX1200GGPRO	AOAD/M_T
chur	TPS NET-G3A	ASH701945E_M
aspa	TRIMBLE NETR5	TRM55971.00

Table 29.2 GLONASS pseudorange positioning coordinates precision and increase rate

Station	Without IFB RMS (m)	IFB model		ISB from SHA	
		RMS (m)	Increase rate (%)	RMS (m)	Increase rate (%)
chur	7.60	5.84	23.19	3.40	55.28
aspa	4.29	3.60	16.09	3.30	22.99
cas1	2.99	1.90	36.29	1.77	40.87
pots	2.39	2.29	4.11	1.89	20.79

Table 29.3 GPS/GLONASS combined pseudorange positioning coordinates precision and increase rate

Station	Without IFB RMS (m)	IFB model		ISB from SHA	
		RMS (m)	Increase rate (%)	RMS (m)	提高率 (%)
chur	2.99	2.42	19.17	1.89	36.75
aspa	2.62	2.41	8.18	2.31	11.85
cas1	2.34	1.75	25.12	1.65	29.56
pots	1.74	1.71	1.43	1.58	9.08

55 %. Precision of combined positioning is up to 4 times better than of GLONASS single system (chur, from 7.60 to 1.89 m).

29.4.2 Carrier Phase Positioning

We make a test of Kinematic PPP with the carrier phase observation data at the station CHUR on 2012 doy 318. This test is applied in 4 scenarios:

1. GPS PPP
2. GLONASS PPP
3. Combined GPS/CLONASS PPP
4. Based on the third strategy, introduce the inter-system hardware delay bias IFB, which is provided by Shanghai Observatory GNSS Analysis Center.

All of these four strategies obtain satisfactory final positioning results. Figure 29.6 shows the positioning error and its components in X, Y, Z directions on the first 50 epochs. It can be seen that the convergence speeds of these four strategies are all

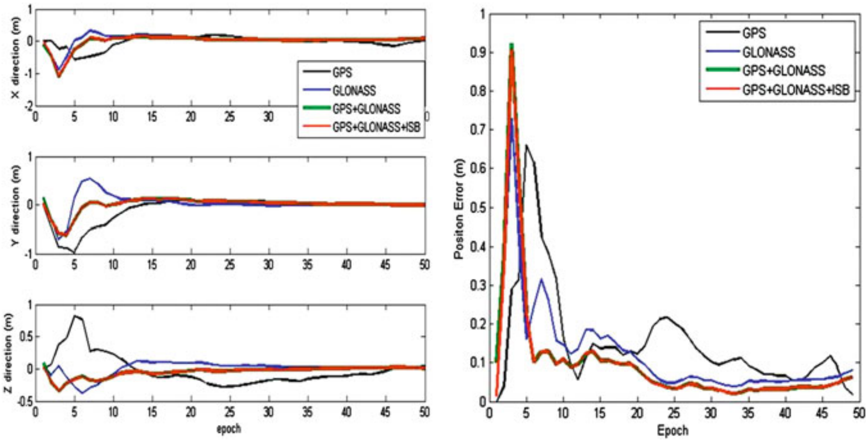

Fig. 29.6 Kinematic carrier phase PPP results on station CHUR

fast, among them the convergence of combined GPS/GLONASS PPP is faster than single system PPP. Introducing ISB only has little effect on the first several epochs. The results of strategy (29.3) and (29.4) are almost the same, this is because in strategy (29.3), the ISB values have been absorbed by ambiguities, although it gets good precision and fast convergence speed, its ambiguities are not accurate.

29.5 Conclusion

As navigation system develops and updates, multi-system fusion has become the tendency of the development. Multi-mode can solve the issues of coverage and system bias that may exist in single system. In certain environment, such as urban canyon and ravines, single system could not provide service because of limited satellite conditions. We introduce the integrated data analysis model by GNSS data analysis center of Shanghai Astronomical Observatory (SHAO). Based on the routine GNSS data analysis at SHAO over 14 months, we analyze the precise GPS/GLONASS system bias product in detail and put forward a model of inter-frequency bias (IFB). Results show: (1) ISBs have similarity in receivers of the same type, while obvious difference are observed in receivers of different type; (2) variation of ISBs shows same pattern for all stations, which indicates that the long-term variation of ISB is caused by the system time offset; (3) ISB is influenced also by antenna type. Applying ISB into pseudorange positioning, precision of GLONASS-only solution is improved by 55 % and precision of GPS/GLONASS combined solution is improved by 30 %. Applying ISB into PPP, there is no obvious effect on coordinates, this is because in PPP, ISB can be absorbed by ambiguity.

Acknowledgments This paper is supported by the 100 Talents Programme of The Chinese Academy of Sciences, the National High Technology Research and Development Program of China (Grant No. 2013AA122402), and the National Natural Science Foundation of China (NSFC) (Grant No. 40974018 and 11273046).

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