Chapter 46
GPS/GLONASS/COMPASS Combined Positioning Based on CNMC

Zhang Yize, Chen Junping, Wu Bin, Wang Jiexian, Yang Sainan and Duan Bingbing

Abstract GLONASS and COMPASS system have become important part of GNSS system in the past few years. With the construction and improvement of these systems, multi-system combined solutions will greatly improve the accuracy in GNSS positioning. The current research of multi-system positioning mainly focuses on the combination of GPS and GLONASS systems, while the data of COMPASS has not combined with other systems. This paper focuses on the GPS/GLONASS/COMPASS multi-system combined positioning. Experiments using the data of GPS/GLONASS/COMPASS capable stations were conducted for positioning. Results show that the accuracy of triple-system positioning is better than that of single or combination of two systems. To reduce the noise of the pseudorange, a real-time algorithm called CNMC is applied. The smoothed GNSS pseudorange is then used for combined positioning. Results show that this method can improve the reliability of the estimated parameters and improve the positioning precision by about 30–60 %, depending on the precision of the satellite orbits and clocks. A station differential strategy is proposed to reduce the effect of orbits and clocks, which is proved to dramatically improve positioning precision.

Keywords Multi-system positioning · Code noise and multipath correction (CNMC) · Multipath effect · Station differencing

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46.1 Introduction

As GPS, GLONASS, Galileo and COMPASS have become the four mainly global positioning systems in the past few decades, the inter-compatibility and inter-operation among these systems have become big issues. Traditional multi-system application mainly focuses on GPS/GLONASS combined positioning. Results show that the combined system positioning precision is better than single system both in pseudorange and phase [1–3]. The COMPASS system has put into operation and starts to provide official service by the year 2012 [4]. According to the design of the COMPASS system, the positioning accuracy is 25 m horizontally and 30 m vertically in 2012, and the service coverage area is regional (mainly in Asia). By the year of 2020, the global COMPASS system will be in full operation with positioning accuracy of within 10 m [5]. A lot of study on COMASS positioning performance has been discussed in recent few years [6–9]. However, the COMPASS combined positioning with GPS or GLONASS, or even a triple-system combined positioning is rarely discussed so far. Based on this background, we study the GPS/GLONASS/COMPASS combined positioning in this paper.

The COMPASS Navigation Satellite System (CNSS), also named Beidou-2, is China's second-generation satellite navigation system, which is capable to provide positioning, navigation and timing (PNT) service to users on a continuous worldwide basis. Unlike the other systems, COMPASS utilizes the Geostationary Orbit (GEO) and Inclined Geosynchronous Satellite Orbit (IGSO) satellites for a better regional service [6]. However, the constellation of GEO satellites makes the multipath effect on them much more serious than that of IGSO or MEO satellites [8]. Many algorithms have been discussed to correct the multipath effect [7, 8, 10]. Results demonstrate that these methods are able to correct multipath effect in different level. In this paper, we use a method called Code Noise and Multipath Correction (CNMC) to estimate the multipath effect and make the pseudorange smoother. Then the smoothed GNSS pseudorange can be used for multi-system GNSS positioning.

However, the smooth level of the pseudorange data greatly depends on the precision of satellite orbits and clocks, which is usually up to meter-magnitude for navigation ephemeris. For COMPASS system, it is worse than GPS and GLONASS. To eliminate this error, a station differencing strategy is used here.

The paper is organized as following: a brief introduction is given in Sect. 46.1; Sect. 46.2 focuses on the multi-system GNSS positioning model; Sect. 46.3 introduces the algorithm of CNMC, the station differencing strategy is also discussed in this part; Experiments and results on CNMC are listed and discussed. Section 46.4 gives the conclusions.

46.2 GPS/GLONASS/COMPASS Combined Positioning

Considering the multipath effect, we start with the GNSS pseudorange and carrier phase observation equations expressed in meters as follows:

$$\begin{cases} P_1 = \rho - c \cdot \delta^j + c \cdot \delta_i + \delta_{trop} + \frac{1}{f_1^2}\delta_{iono} + Mp_1 + \varepsilon_{p1} \\ P_2 = \rho - c \cdot \delta^j + c \cdot \delta_i + \delta_{trop} + \frac{1}{f_2^2}\delta_{iono} + Mp_2 + \varepsilon_{p2} \\ L_1 = \rho - c \cdot \delta^j + c \cdot \delta_i + \delta_{trop} - \frac{1}{f_1^2}\delta_{iono} + M\phi_1 + amb_1 + \varepsilon_{\phi 1} \\ L_2 = \rho - c \cdot \delta^j + c \cdot \delta_i + \delta_{trop} - \frac{1}{f_2^2}\delta_{iono} + M\phi_2 + amb_2 + \varepsilon_{\phi 2} \end{cases} \quad (46.1)$$

where P_1, P_2, L_1 and L_2 are the pseudorange and carrier phase observations in each band, ρ is the geometric distance between the satellite and receiver, δ^j and δ_i mean the clock corrections in satellite and receiver, δ_{trop} and δ_{iono} are the tropspheric and ionospheric delays, $Mp_1, Mp_2, M\phi_1$ and $M\phi_2$ are the multipath effects in pseudorange and carrier phase, f_1, f_2 is the frequency, ε_{p1}, ε_{p2}, $\varepsilon_{\phi 1}$ and $\varepsilon_{\phi 2}$ are the observation noise.

To eliminate the ionospheric delay, the Ionospheric-Free (IF) combined is applied, so the expression of pseudorange in Eq. (46.1) can be rewritten as:

$$P_{IF} = \rho - c \cdot \delta^j + c \cdot \delta_i + \delta_{trop} + Mp_{IF} + \varepsilon_{pIF} \quad (46.2)$$

In GPS/GLONASS/COMPASS combined positioning, the system time offset should be taken into account [2, 3], so the receiver clock parameter δ_i is different for different system. We conduct a field experiment in Shanghai using Trimble NET R9 receiver, which can receive triple-system GNSS data. Then the multi-system GNSS observations are used for kinematic positioning. In the positioning processing, only the coordinate of the receiver and the receiver clocks in different systems are estimated.

The kinematic pseudorange positioning statistics for different combinations are listed in Table 46.1. DOP value is a very important factor to specify GNSS geometry effects on user positioning accuracy [9]. We compare the DOP value for each system and combined triple-system in Fig. 46.1. Due to the constellation of GEO and IGSO satellites, the mean DOP value of COMPASS is much bigger than that of GPS or GLONASS, and that is why the RMS of single COMPASS positioning is worse in horizontal than the other two systems. However, any kind of combination of different systems improves the positioning accuracy, especially for a GPS/GLONASS/COMPASS combination. We can also see from Fig. 46.1 that the DOP value is somehow more stable for COMPASS, which is due to the fact that the GEO and IGSO satellites, visible for the regional area most of the time, are the main contributor to the current COMPASS constellation. Both for GPS and COMPASS, there are sometime DOP value jumps, which is because the missing data for one satellite at that epoch indicating bad quality of data.

Table 46.1 Kinematic pseudorange positioning precision for different GNSS combination

Combination	RMS			
	N/m	E/m	U/m	3-D/m
G	1.374	3.884	3.532	5.427
R	1.970	3.773	5.018	6.580
C	7.585	3.045	7.265	10.935
R + C	3.299	1.605	3.196	4.865
G + R	3.625	2.852	4.753	4.754
G + C	3.116	0.819	2.513	4.086
G + R + C	2.317	1.003	1.976	3.206

C stands for COMPASS, *G* for GPS, *R* for GLONASS

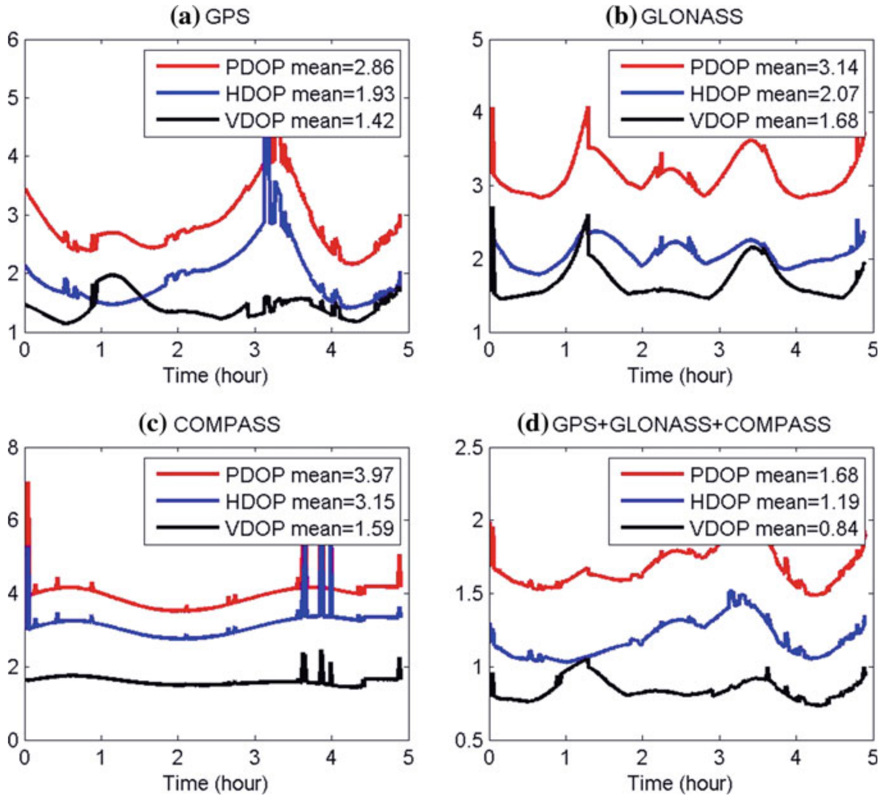

Fig. 46.1 The DOP value for different systems of a GNSS station in Shanghai (DOY 350, 2012)

46.3 Carrier Phase Smoothed Pseudo-range

To smooth the pseudorange with carrier phase, algorithm such as Hatch Filter [11], RNXSMT [12] or CNMC [8] are usually applied. Hatch Filter uses the epoch-differenced IF (Ionospheric-Free) combination phase to smooth IF combination pseudorange. This algorithm is simple and easy to realize. However, it doesn't take the multipath effect into account. In other words, it considers the epoch-differenced multipath effects as the same value for the pseudorange and phase observations. Hatch Filter is a real-time algorithm, which is widely used when the multipath effect is small enough and can be neglected. However, the multipath effect in pseudorange is much more serious for COMPASS system, especially for GEO and IGSO satellites. The RNXSMT algorithm is a post-processing method, which is not suitable for real-time positioning. In this part, we adopt the CNMC algorithm for real-time COMPASS combined positioning.

46.3.1 CNMC Algorithm

The theory and details on CNMC can be found in relevant bibliography [8]. We only give the formulas here.

Taking the L1 band for example, the multipath effect in pseudorange for dual-frequency observations in Eq. (46.1) can be written as follows:

$$\begin{cases} Mp_1 = P_1 - L_1 - 2\frac{f_2^2}{f_1^2 - f_2^2}(L_1 - L_2) - CAmb_1 \\ Mp_2 = P_2 - L_2 - 2\frac{f_1^2}{f_1^2 - f_2^2}(L_1 - L_2) - CAmb_2 \end{cases} \tag{46.3}$$

where $CAmb_1$ and $CAmb_2$ is the combined ambiguities.

$CAmb_1$ and $CAmb_2$ can be get from a real-time formula. Take L1 band as example, if no cycle slip happens in an observation arc, it can express as follows:

$$CAmb_1(t_n) = \frac{n-1}{n} CAmb_1(t_{n-1}) + \frac{1}{n}[P_1(t_n) - L_1(t_n) - 2\frac{f_2^2}{f_1^2 - f_2^2}(L_1(t_n) - L_2(t_{n-1}))] \tag{46.4}$$

From Eqs. (46.3) and (46.4), the multipath effect can be estimated in a real-time way. At the first epoch, the multipath effect is initialized as zero. With the increase of the arc, the combined ambiguity will be more and more precise. At the same time, the multipath effect could be derived more precisely. However, when a cycle slip happens, a new initialization will be restarted. So the effectiveness of this algorithm is subject to the data quality [8].

Having known the multipath effect in pseudorange, it can be added to the raw pseudorange observation to get "cleaned" pseudorange. In some way, the CNMC is a carrier phase smoothed pseudorange method in fact.

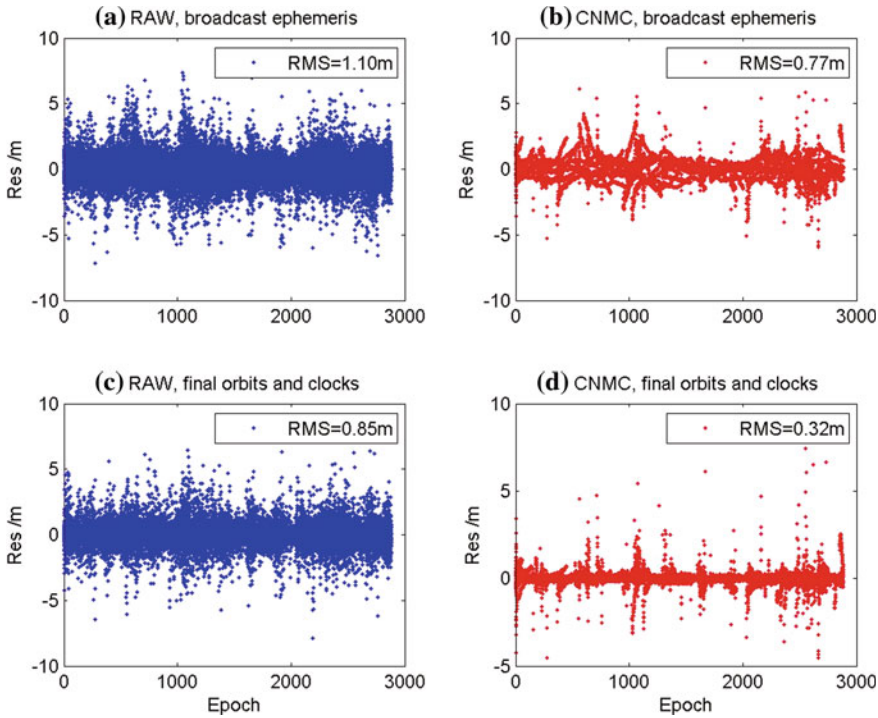

Fig. 46.2 The residuals of GPS observations for raw and smoothed pseudorange using different products (SHAO, DOY 298, 2012)

Here we use the GPS data of the IGS station at Shanghai (SHAO) to verify the CNMC algorithm. The broadcast ephemeris and IGS final orbits with satellite clocks are respectively applied. Figure 46.2 shows the effect of CNMC algorithm. From (a) and (b) in Fig. 46.2 we can see that the quality of the smoothed pseudorange is improved by 30 % compared with the raw data. This improvement can reach up to 62 % using IGS final products. It indicates that CNMC reduces the noise of pseudorange and make it smoother. However, the smooth level greatly depends on the precision of the satellite orbits and clocks.

46.3.2 *CNMC Application and Improvement Based on Station Differencing*

As it is discussed and concluded above, the CNMC algorithm greatly depends on the data quality and the precision of satellite orbits and clocks. However, for real-time users, it is hard to get the final precise products, especially for satellite clocks. Station differencing method, which could reduce the impact of satellite orbits and clocks, could be used in combination with the CNMC algorithm.

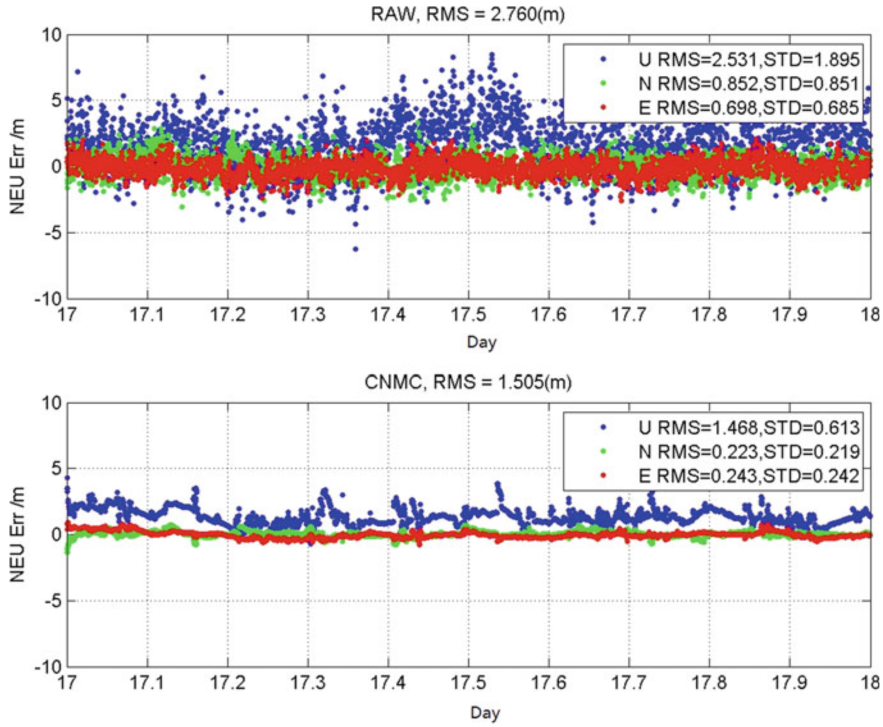

Fig. 46.3 The GPS/COMPASS combined positioning error of different strategies; *Upper* using RAW observations; *Lower* using smoothed observations

Data of two stations in Shanghai, parting 1,000 m in between, is used. Both stations are capable to receive mixed GPS and COMPASS data. We use two strategies in data analysis: (1) Station differencing without data smoothing (2) Station differencing with data smoothing using CNMC algorithm. The GPS/COMPASS kinematic positioning results for these two strategies are shown in Fig. 46.3. From the figure we can see that CNMC algorithm makes the positioning error smoother and the precision is improved by 45.5 %, which proves that CNMC algorithm is effective in station differencing.

Using the CNMC algorithm, multipath effect in P1 and P2 can be estimated in real-time. Here we list the multipath of 2 GEO, 2 IGSO and 2 MEO satellites, which is available in Fig. 46.4. It can be seen from the figure that the multipath effect can be more than 1 m for most satellites. Multipath of GEO satellites (C03 and C04) is smaller and more stable than that of IGSO and MEO satellites. For IGSO and MEO satellites, multipath is much serious in the periods of arising and descending.

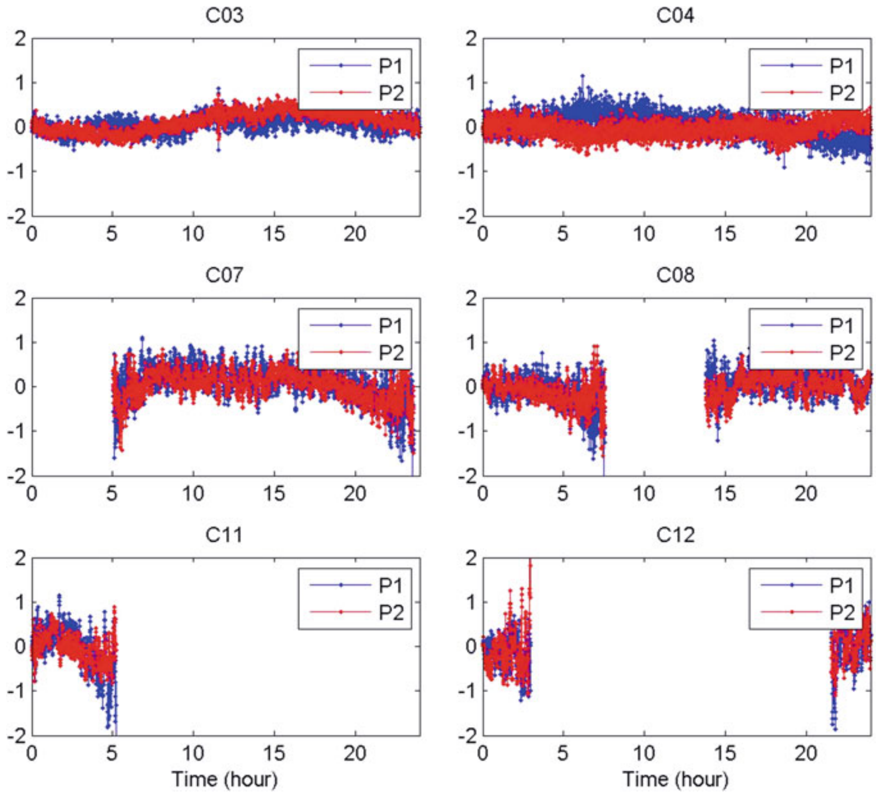

Fig. 46.4 The multipath (in meters) of different COMPASS satellites

The accuracy of user positioning could be further improved by adding the equivalent satellite clock corrections, which are differential information for authorize users [9]. It is a strategy that fixes station coordinates and calculates the user range error caused by satellite orbits, clocks and other errors and these information is sent to authorize users via GEOs. The equivalent satellite clock correction is normally derived using pseudorange observations, thus its quality depends on pseudorange. Figure 46.5 shows the equivalent satellite clock correction for three COMPASS satellites using raw and smoothed COMPASS data. From the figure we can see that after removing multipath effects using the CNMC algorithm, the noise of the equivalent satellite clock correction is much smaller and more stable. This indicates that the CNMC algorithm can be used in wide area difference system.

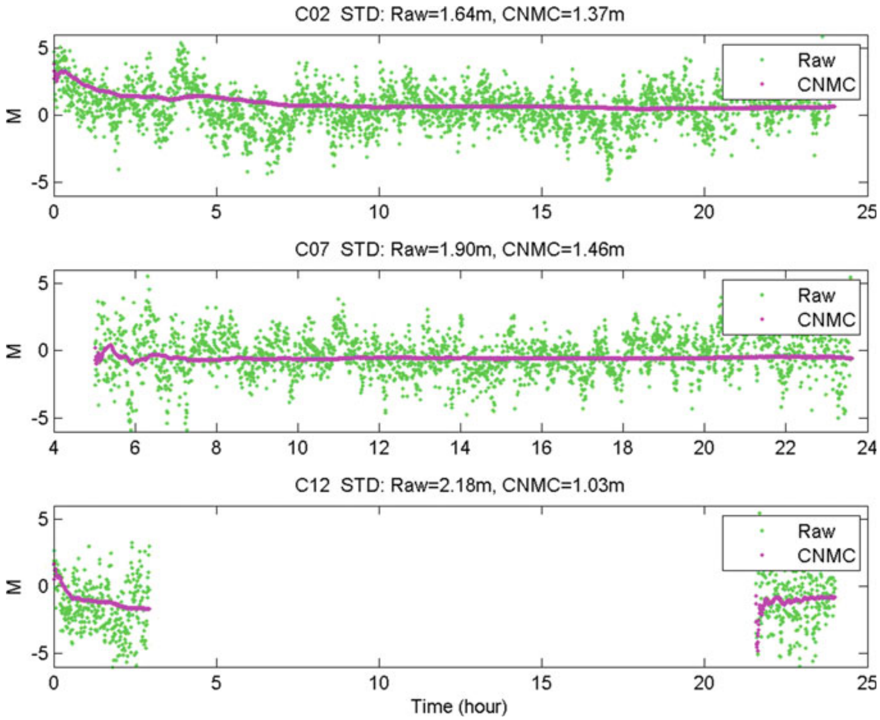

Fig. 46.5 Multipath effect on equivalent satellite clock corrections

46.4 Conclusions

In this paper, we discuss the positioning model of multi-system GNSS positioning, an example of combined GPS/GLONASS/COMPASS positioning proves that the accuracy of triple-system positioning is better than that of single or double system. The CNMC algorithm of eliminating multipath effect and smoothing the pseudorange is discussed. We found that the effective of the CNMC algorithm greatly depends on the precision of satellite orbits and clocks. The station differenced strategy is used to further eliminate the error caused by satellite. The CNMC algorithm also improves the precision of the estimation of equivalent satellite clock corrections.

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