Chapter 36
Analysis of Positioning Accuracy for COMPASS Based on Single/Multi Frequency Pseudo-Range

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Abstract Compass/Beidou satellite navigation system makes it possible for positioning using three frequencies for the first time. Single frequency pseudo-range measurement and multi-frequency combination pseudo-range measurement are introduced; single & dual frequency positioning accuracy of raw & smooth pseudo-range are analyzed; and the single point availability for different accuracy demands at Lintong station is counted. Results show that: the noise of the ionosphere free using triple-frequency combination is amplified as much as the one using dual frequency combination by eliminating only the first order ionosphere delay; and the amplification is 30 times by eliminating both the first and second order ionosphere delay; pseudo-range positioning errors less than 10 m takes up about 95 % for single & dual frequency pseudo-range; and the single point availability for 10, 15 and 20 m (both level and height errors) take up about 95, 99 and 100 % at the this station.

Keywords Beidou satellite navigation system · Multi-frequency combination pseudo-range measurement · Smooth pseudo-range positioning · Positioning accuracy · Availability

36.1 Introduction

Compass is a self-developed, independent satellite navigation system which is being implemented and independently run by China [1]. Its goal is providing positioning, navigation and timing (PNT) service, as well as short-message communication service, for most Asia–Pacific region users in 2012, and realizing global coverage around 2020.[1] After completion, it will provide users integrated

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[1] http://www.beidou.gov.

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services of PNT and short-message. The capacity of compatibility and interoperability enables it to take advantage of multi-system observation data, which will greatly improve observation redundant degree as well as navigation and positioning accuracy [2]. Now the service performance has become a great concern for system builders, related scholars and many future users.

In the early stage of the system construction, many researches has presented on the service performance of Compass based on simulation data. For example, Yang Xinchun analyzed the system's satellite visibility, DOP values and positioning accuracy in China mainland based on the Compass global constellation. And the XPL value provided in China mainland is studied using the Space-Based Augmentation System's (SBAS) integrity algorithm. Results show that the simulation meets the predetermined demand [3].

In the process of system-building, a number of studies are carried out based on measured data by scholars who show strong interests in Compass. Wu et al. has analyzed the ionosphere parameters correction accuracy using measured ionosphere model and positioning accuracy indicators. Results show that the ionosphere parameters correction accuracy is better than 65 % and GPS positioning accuracy (3-dimension) is improved 7.8–35.3 % in the Northern Hemisphere [4]. Chen et al. analyzed the pseudo-range quality and position accuracy with Compass constellation of seven satellites. Results show that multipath and observation noise is in the magnitude of 0.5–3 m, B1/B2 dual-frequency pseudo-range position accuracy is 15.92 m [5]; Professor Shi Chuang also carried out some studies based on the Compass constellation of eight satellites, Compass satellite observations experimental network (Beidou Experimental Tracking Stations, BETS) data and PANDA software. The results show that the radial accuracy of Compass satellite precise orbit determination is better than 10 cm, static precise point positioning accuracy is of centimeter level, baseline relative positioning is of a millimeter; dynamic pseudo-range differential positioning accuracy is of 2.0–4.0 m, and RTK positioning accuracy is of 5–10 cm, close to the current level of GPS [6]. At the same time, foreign scholar Oliver Montenbruck do some research using a small regional Compass monitoring network and its triple-frequency data in March of 2012 and results show that RMS of Overlap differences for Compass satellite precise orbit determination is about 1–10 m, that horizontal and vertical errors achieve 12 cm in single frequency single point positioning (PPP) and that baseline relative position error, north, east and up are 2, 4 and 9 mm, reaching the GPS dynamic positioning level [7].

Compass has owned the ability to provide regional service with the 16th Beidou navigation satellite launched on October 25, 2012 and other early launched satellites, and formal services will be opened early next year in most parts of the Asia–Pacific (see footnote 1). It transmits three frequency signals which are two open service signals B1 and B2, with their frequency 1561.098 and 1207.14 MHz, code rate 2.046 Mcps, and bandwidth 2.046 MHz and one authorized service signals B3, with its frequency 1268.52 MHz, code rate 10.23 Mcps, and bandwidth 10.23 MHz. Compass is the first tri-frequency satellite navigation system, will provide reliable and high-precision services for users, together with GPS, GLONASS, GALILEO [1].

This paper first introduces the Compass single-frequency measurement and muti-frequency combination measurement and its observation noise, and then analyzes the raw & smooth pseudo-range single & dual positioning accuracy based on the measured data and the reasons for precision changes; finally the single point availability is analyzed for different users in the region.

36.2 Combination Pseudo-Range Measurement

For civilian users, Compass provides three frequency signals. These signals can form a variety of measurements. As the ionosphere delay is one of the most important error sources of the satellite navigation and positioning, the combination of multi-frequency measurement generally used the ionosphere-free style. These styles include the following:

36.2.1 Single-Frequency Pseudo-Range Measurement

The form of Compass's three single-frequency pseudo-range measurements $P1$ is as follows:

$$P1 = \rho_0 + C(\Delta t - \Delta T) + \Delta I_i + \Delta D_{trop} + \delta_i \qquad (i = 1,2,3) \tag{36.1}$$

ρ_0 for the geometric distance to the satellite receiver. C for the speed of light, Δt for the receiver clock error, ΔT for the satellite clock error, ΔI_i for the ionosphere delay, ΔD_{trop} for the troposphere delay, δ_i for the pseudo-range measurements noise. Assumed that the pseudo-range measurements noise of each frequency data are white noise and independent to each other. The size of the noise is δ.

36.2.2 Dual-Frequency Combination Pseudo-Range Measurement

The general form of dual-frequency combination pseudo-range measurements of the Compass are as follows:

$$P2 = \alpha\rho_i + \beta\rho_j + C(\Delta t - \Delta T) + \Delta D_{trop} + \sqrt{\alpha^2 + \beta^2}\delta \qquad (i,j = 1,2,3; i \neq j) \tag{36.2}$$

$P2$ for the dual-frequency pseudo-range measurements, $\alpha = \frac{f_i^2}{f_i^2 - f_j^2}, \beta = \frac{-f_j^2}{f_i^2 - f_j^2}$, the noise is larger $\sqrt{\alpha^2 + \beta^2}$ times after combination.

36.2.3 Tri-frequency Combination Pseudo-Range Measurement

The tri-frequency pseudo-range measurements can eliminate the first-order ionosphere delay or the second-order ionosphere delay [8].

1. The combination to eliminate the first-order ionosphere delay of tri-frequency measurements is P3:

$$P3 = \alpha\rho_1 + \beta\rho_2 + \gamma\rho_3 + C(\Delta t - \Delta T) + \Delta D_{trop} + \sqrt{\alpha^2 + \beta^2 + \gamma^2}\delta \qquad (36.3)$$

While $\alpha = \frac{D_2 - D_1/f_1^2}{3D_2 - D_1^2}$, $\beta = \frac{D_2 - D_1/f_2^2}{3D_2 - D_1^2}$, $\gamma = \frac{D_2 - D_1/f_3^2}{3D_2 - D_1^2}$, $D_1 = \frac{1}{f_1^2} + \frac{1}{f_2^2} + \frac{1}{f_3^2}$, $D_2 = \frac{1}{f_1^4} + \frac{1}{f_2^4} + \frac{1}{f_3^4}$, the combination of noise amplification is larger $\sqrt{\alpha^2 + \beta^2 + \gamma^2}$ times.

2. The combination to eliminate the second-order ionosphere delay of tri-frequency measurements is P4:

$$P4 = \alpha\rho_1 + \beta\rho_2 + \gamma\rho_3 + C(\Delta t - \Delta T) + \Delta D_{trop} + \sqrt{\alpha^2 + \beta^2 + \gamma^2}\delta \qquad (36.4)$$

While $\alpha = \frac{f_1^3(f_2 - f_3)}{D}$, $\beta = \frac{f_2^3(f_3 - f_1)}{D}$, $\gamma = \frac{f_3^3(f_1 - f_2)}{D}$, $D = (f_1 - f_2)(f_2 - f_3)(f_1 - f_3)(f_1 + f_2 + f_3)$, The combination of noise amplification is larger $\sqrt{\alpha^2 + \beta^2 + \gamma^2}$ times.

36.2.4 Coefficients of Combination Pseudo-Range Measurement

The coefficients of various combine measurements for compass and noise magnification are shown in the following Table 36.1:

The table shows that the observation noise magnification of dual-frequency combination measurement of B1/B2 and B1/B3 is 2.90 times and 3.53 times. For tri-frequency combination measurement, the observation noise magnification is roughly equal to the dual-frequency combination measurements by eliminating only the first order ionosphere delay. While the first and second order ionosphere delay is eliminated, the magnification is 35.75 times. Usually the high order

Table 36.1 Coefficients of compass combined pseudo-range measurements

Measurements	α	β	γ	Noise magnification
$P2_{B1/B2}$	2.49	−1.49	/	2.90
$P2_{B1/B3}$	2.94	−1.94	/	3.53
P3	2.57	−1.23	−0.34	2.87
P4	9.10	20.06	−28.16	35.75

ionosphere delay is far less than 1 % of the total delay. The observation noise is largely magnified when using the combination of tri-frequency measurements to eliminate the ionosphere delay. It is always used in cycle slip detection and ambiguity resolution fixed. This article analyzes the single & dual positioning accuracy of the raw & smooth pseudo-range measurement.

36.3 Pseudo-Range Positioning Accuracy

36.3.1 Data Processing Strategy

This article analyzed the Compass positioning accuracy using the 3 days data of Lintong Station (CLIN) in the 254, 255, 256 day of year. Data acquisition equipment is developed by CLP 20. The troposphere corrections are based on model SAASTAMOINEN zenith and NELL projection function. The Klobuchar 8 parameters model is used for single frequency ionosphere delay correction, and combination of deionization layer is used for dual-frequency. The satellite clock error correction parameters stems from the navigation message relativistic corrections and the earth's rotation effect corrections are related to corresponding models. The cut-off angle of the data is 5°. Positioning results are validated according to GPS precise point positioning result.

36.3.2 Raw Pseudo-Range Positioning Accuracy

Single & dual frequency of raw pseudo-range positioning results are as follows:

Analysis found that for 10 m positioning accuracy, the percentage of B1, B3 single frequency and B1/B3 ionosphere combination pseudo-range were 98.98, 96.48 and 95.37 %. The variation of the positioning accuracy is basically consistent with the PDOP value. Overall the positioning results of B1 single frequency are better than those of B1/B3 dual-frequency and B3 single frequency. Analysis found that dual-frequency combination enlarges the multipath and noise, that the positioning error is greater than that in B1 single frequency positioning; the positioning error of B3 single frequency pseudo-range is greatly influenced by ionosphere delay. If the positioning results for the 12–14 h (BDT 4–6 h) are neglected; the proportion of the three-dimensional error better than 10 m is up to 99 %.

From the Fig. 36.1 we also can get that: single-frequency positioning errors of B3 single frequency is particularly evident around BDT 5 h, while dual-frequency positioning is not. Analysis found that this phenomenon is related to the correction accuracy of Compass Klobuchar 8 parameters model. The ionosphere correction

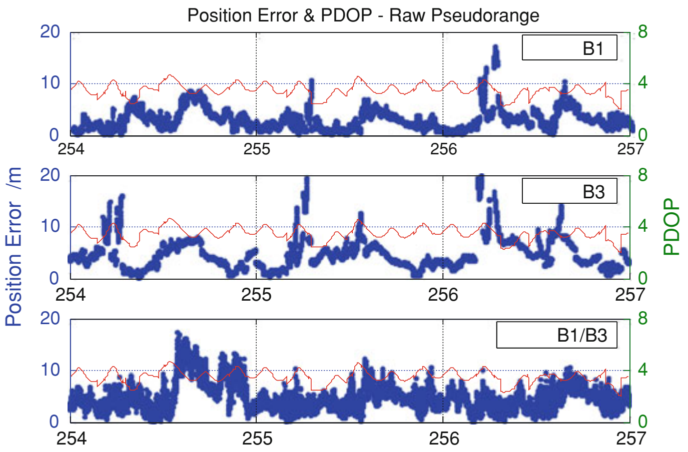

Fig. 36.1 Time serial of position error and PDOP value for raw pseudo-range

error of 1 TECU to the B3 frequency pseudo-range delay is about 25 cm. The impact is greater than the influence to B1 pseudo-range. And the ionosphere activity happens to be most intense around this time (around 14 h local time). The positioning error of single & dual frequency is large around BDT 15 h caused by poor constellation structure. This time the visible satellites number of CLIN station is 8, which C06 and C09 satellite over the southerly, C07 and C10 just entering the field of view in the south of the station. All GEO satellites are in the south of the station, the constellation structure presented "one-sided", and positioning error is large.

36.3.3 Smooth Pseudo-Range Positioning Analysis

Single & dual frequency smooth pseudo-range positioning results is as follows (Fig. 36.2):

The analysis found that the positioning accuracy using the smooth pseudo-range single & dual frequency is significantly improved. The positioning accuracy of dual-frequency is better than 10 m, most obviously improved. The proportion of the positioning accuracy for B1, B3 single frequency and B1/B3 combination pseudo-range better than 10 m is 98.74, 96.33 and 99.03 %.

The observation noise is greatly reduced of smooth pseudo-range, so the positioning accuracy of dual-frequency improved is better than single-frequency. The positioning error of single frequency is still large around BDT 5 h, proving that positioning errors are mainly due to ionosphere delay. Meanwhile, the positioning accuracy of smooth pseudo-range around BDT 15 h is not highly improved, which is an approval that constellation structure within this period is the reason for it.

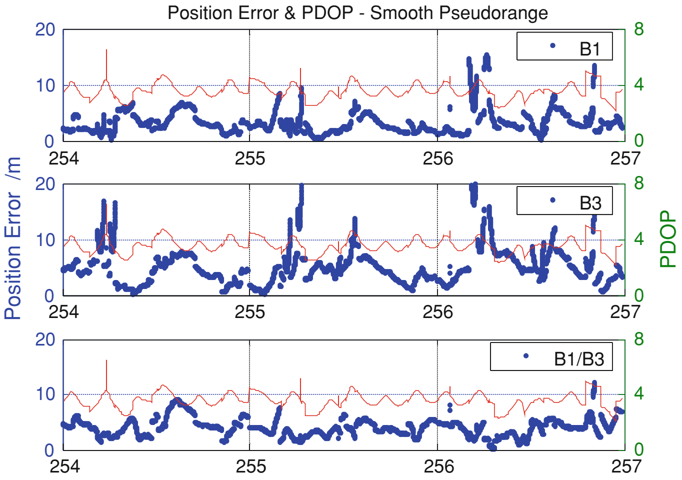

Fig. 36.2 Time serial of position error and PDOP value by smooth pseudo-range

36.4 Availability Analysis

Availability refers to the probability of the system that can provide the navigation service, which is one of the system's performance indicators [9]. It can be divided into instantaneous availability, single point availability and service area availability. Single point availability is available statistics of a point in different time [9]. Generally, analyzing availability is based on DOP values or positioning accuracy. In the section, it is analyzed through positioning accuracy.

Single point availability is calculated using the following formula:

$$P_{A,i} = \frac{\sum_{t=t_{start},inc=T}^{t_{end}} \{Bool(t) = True\}}{1 + \frac{t_{end} - t_{start}}{T}} \tag{36.5}$$

While, t_{start} and t_{end} for the start and end time of the test respectively; T for sampling interval; If positioning accuracy on t epoch meet the requirements then $Bool(t) = 1$, otherwise $Bool(t) = 0$.

Horizontal and vertical errors of the raw pseudo-range positioning in 3 days are as follows (Figs. 36.3 and 36.4):

Horizontal and vertical errors of the smooth pseudo-range positioning in 3 days are as follows (Figs. 36.5 and 36.6):

In order to analyze single point availability of the Compass system in CLIN station, it has divided accuracy demands into five levels, including 5, 8, 10, 15 and 20 m of both horizontal errors and vertical errors. The results are as follows: (Tables 36.2 and 36.3).

Results show that: for 10 m positioning accuracy demands, B1 single frequency raw pseudo-range, B1 frequency and B1/B3 dual-frequency smooth pseudo-range can reach 98 %. The availability for 10, 15 and 20 m is 95, 99 and 100 % of both

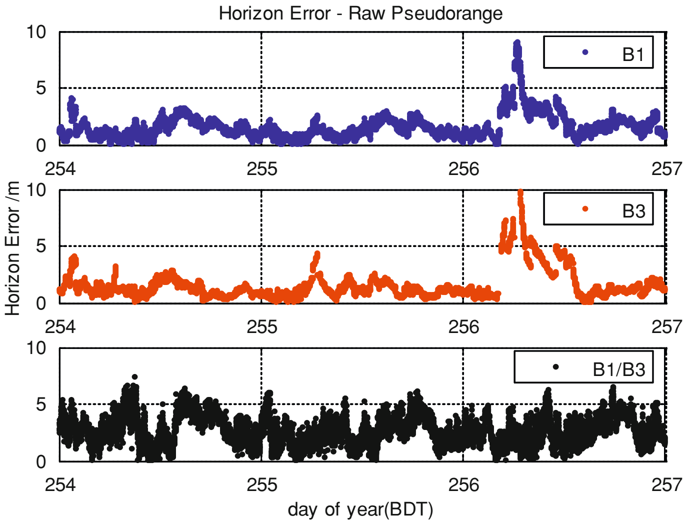

Fig. 36.3 Time serial of horizon error by raw pseudo-range

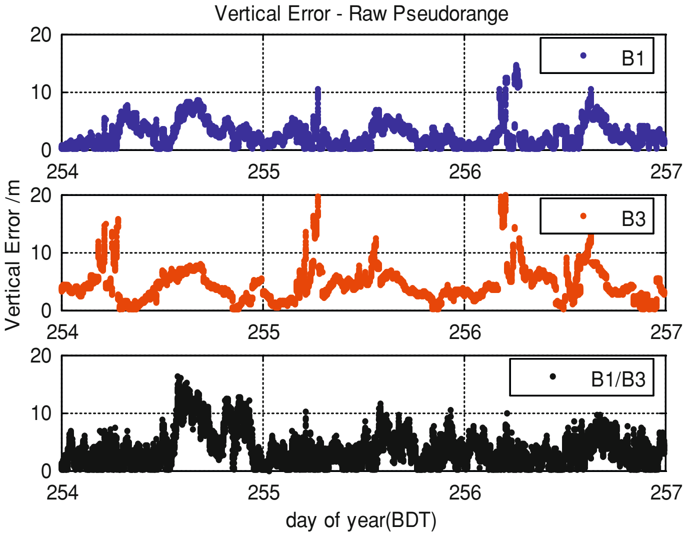

Fig. 36.4 Time serial of vertical error by raw pseudo-range

raw and smooth pseudo-range of single & dual frequency positioning. The B3 single-frequency is influenced largely by the ionosphere delay and the availability is slightly low.

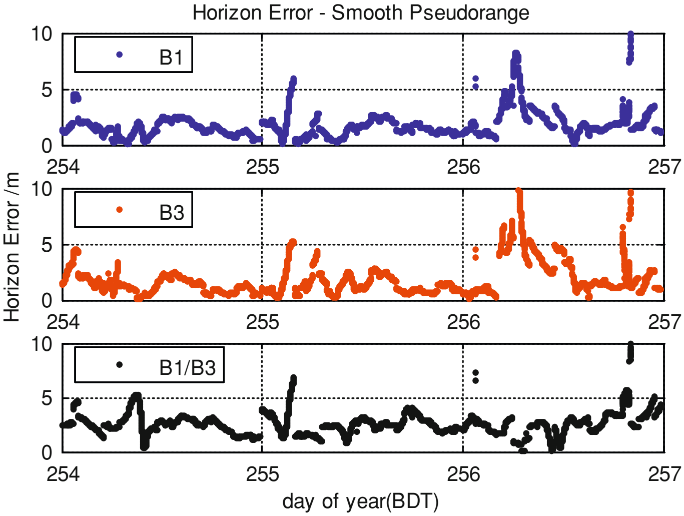

Fig. 36.5 Time serial of horizon error by smooth pseudo-range

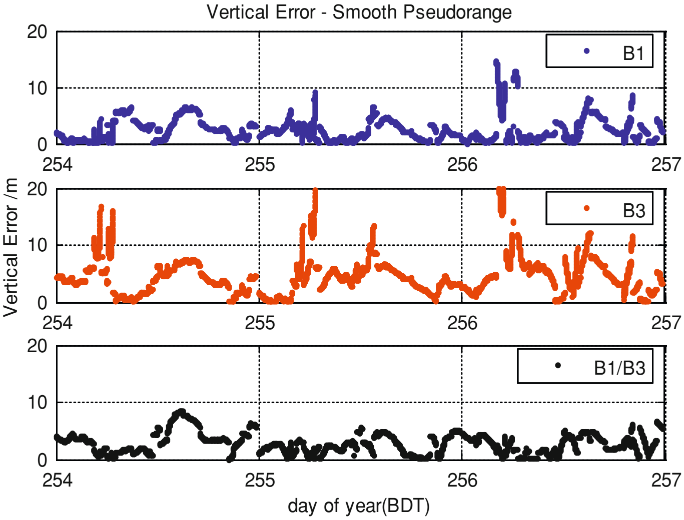

Fig. 36.6 Time serial of vertical error by smooth pseudo-range

Results also show that B3 single-frequency positioning vertical error is large. Also B1 single-frequency and B1/B3 dual-frequency positioning are affected by ionosphere delay in time BDT 4–6 h (local time 12–14 h). The single & dual

Table 36.2 Single point availability of different accuracy demands by raw pseudo-range (%)

H/V (m)	5	8	10	15	20
B1	84.07	97.08	98.90	99.64	100
B3	63.09	91.37	96.01	98.69	99.93
B1/B3	63.08	89.18	94.20	99.79	100

Table 36.3 Single point availability of different accuracy demands by smooth pseudo-range (%)

H/V (m)	5	8	10	15	20
B1	84.29	97.87	98.36	99.81	100
B3	60.99	91.57	95.62	98.82	99.93
B1/B3	78.54	97.43	99.78	100	100

frequency positioning vertical error is large around BDT 15 h by influence of constellation structure. Therefore, we suggested that users can avoid these two time periods for high accuracy requirements in Lintong region.

36.5 Conclusion

Compass is the first tri-frequency positioning satellite navigation system. This article first introduces the Compass's single-frequency pseudo-range measurement and multi-frequency pseudo-range measurements, then analyze the single & dual frequency positioning accuracy, finally analyze the single point availability in Lintong station for different accuracy requirements. Conclusions are as follows:

1. The noise of pseudo-range measurement increases up to 3 times when eliminating the first-order ionosphere delay. It is roughly equal to the accuracy of dual-frequency combination measurement. The noise of pseudo-range measurement increases 30 times when eliminating up to first-order and second-order ionosphere delay;
2. The proportion of the pseudo-range positioning accuracy of B1, B3 single frequency and B1/B3 dual-frequency better than 10 m: 98.98, 96.48 and 95.37 % for raw pseudo-range; 98.74, 96.33 and 99.03 % for smooth pseudo-range;
3. The positioning accuracy is slightly deteriorated in Lintong region around BDT 5 and 15 h by the influence of ionosphere delay and the constellation.
4. For the demands of 10, 15 and 20 m positioning accuracy, the single point availability of Lintong station are 95, 99 and 100 %. The B3 ingle-frequency positioning accuracy is influenced by the ionosphere delay and its availability is slightly lower.

This article is analyzed based on 4G +5I +2M Compass constellation. The results show that the single & dual frequency positioning can achieve high accuracy and high stability. The system performances will be better with full Compass area constellation of 5G +5I +4M.

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