Chapter 32
Analysis of Ranging and Positioning Performance Influenced by Signal Coherence Parameters

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Abstract Multi-band, multi-service and multi-modulation are new trends of GNSS development. Since novel modulation types like BOC/MBOC and multiplex techniques of navigation signals have been utilized, the composite navigation performance is indeed improved. With increased modulated signals broadcasting on single frequency in satellite, Signal coherence parameter has become one of the most important monitoring parameter. For satellite navigation system, the coherence of phases between pseudo-random codes and between carriers are the prerequisite for realization to pseudo-random code ranging and carrier phase ranging, and they are also two of the main factors affecting on the satellite signal system. This paper discusses how the coherence of phases between pseudo-random codes, between carriers and between carrier and code affect pseudo-random range measurement, carrier phase range measurement and carrier phase smoothing pseudo range process. Furthermore, the relationship between code minus carrier and code phase carrier phase coherence is discussed. Then, the positioning error and code minus carrier measurement is given by the simulation of carrier phase smoothing pseudo range process. In the end, we test code minus carrier parameter and code phase carrier phase coherence parameter using the system built by ourselves.

Keywords Carrier phase · Code phase · Carrier code coherence · CMC (code minus carrier) · Signal quality monitoring

32.1 Introduction

GNSS (Global Navigation Satellite System) signal quality monitoring and evaluation is one significant part in navigation system design and operation as it can

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Table 32.1 List of signal quality monitoring parameters

Classification	Parameters
Frequency	Power spectrum, stray in-band, stray out-of-band, phase noise
Modulation	Constellation, vector graph phase error, magnitude error, error vector magnitude, IQ offset, peak to average envelope ratio
Correlation	Correlation peak, S curve, correlation loss, T offset, signal power, eye diagram, group delay
Ranging	Code phase coherence, IQ quadrature, code phase carrier phase coherence
Time	Ranging code, navigation data, signal voltage distribution histogram

support the signal design and gordian technique in-orbit test verification. Though the navigation signal monitoring and evaluation is mainly a comprehensive measurement of satellite navigation system own performance, it is related to the user application performance [1, 2]. Frequently used monitoring parameters are listed in Table 32.1.

The system performance requirement from users can be separated into four areas—precision, integrity, consistency and availability [3], in which the precision is the foundation of other performance requirements. In the signal monitoring system, signal coherence is of great value since and its inner connection to the navigation performance needs to be studied (Fig. 32.1).

This paper analysed the relationship between signal coherence parameter and ranging precision based on a software receiver and tests is performed using signals from different navigation systems.

32.2 Theory Analysis

32.2.1 Code Coherence Parameter

In modernized system, satellite multiplex efficiency has been enhanced as several signals are broadcast from one satellite frequency band. Ideally, different signals from the same satellite should keep in synchronization. Thus, the phase offset between different codes is defined as code coherence. Now presume that one satellite broadcasts m synchronized signals, and the number k signal in the number i satellite has a phase offset δ_{ck} following the normal distribution as $\delta_{\mathrm{ck}} \sim \mathrm{N}(\mu_{\mathrm{k}}, \sigma_{\mathrm{k}}^2)$. Then the code coherence between k2 signal and k1 signal is $\varepsilon_{c_{k1,k2}}^{(i)} = \delta_{ck2} - \delta_{ck1}$. Assuming that different δ_{ck} are mutual independent, therefore the code coherence parameter is normal distributed as $\varepsilon \sim \mathrm{N}(\mu_{\mathrm{k2}} - \mu_{\mathrm{k1}}, \sigma_{\mathrm{k1}}^2 + \sigma_{\mathrm{k2}}^2)$. We believe $\mu_{\mathrm{k}} = 0$ in general situations.

When the error parts from satellite to receiver measurements is mutual independent, the user ranging error of k1 signal will increase $\sigma_{\mathrm{k1}}^2 - \sigma_{\mathrm{k2}}^2$ compared to k2 signal. Meanwhile, the pseudo range will shift

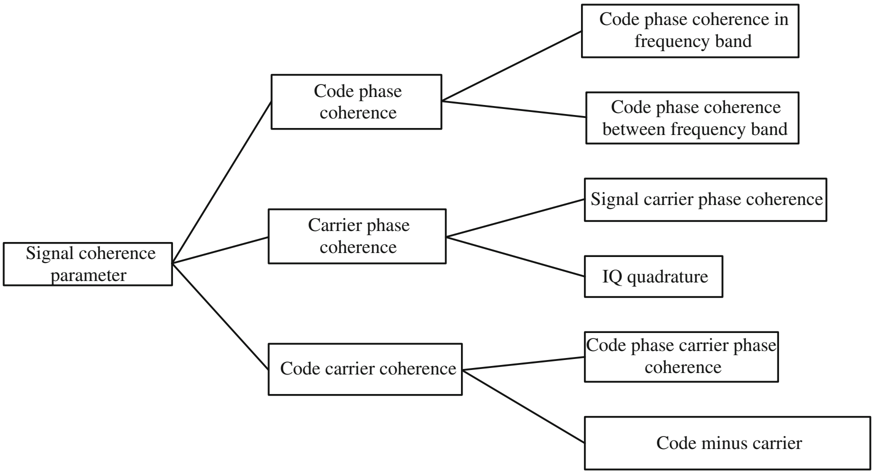


Fig. 32.1 Classification of signal coherence parameter

$$\delta_R = c(\mu_{k2} - \mu_{k1}) \tag{32.1}$$

However, this range offset will be included in the clock error if receiver uses same signal from each satellite in positioning operation. Inversely, the range offset will not be absorbed in clock error if the receiver uses different signals from different satellites, as they have unequal distribution in different satellites.

32.2.2 Code Carrier Coherence Parameter

In high-precision positioning applications, carrier phase smoothing pseudo range technique is often involved to improve measurement precision. Code carrier coherence parameter implies the coherence between code phase and carrier phase [4–6].

Assume the pseudo range measurement of GNSS receiver is ρ and the carrier phase measurement is Φ, and they can be expressed as,

$$\rho(t) = \begin{cases} r(t) + c[\delta t_u(t) - \delta t^s(t-\tau)] \\ + I(t) + T(t) + \varepsilon_\rho(t) \end{cases} \tag{32.2}$$

$$\Phi(t) = \lambda\phi(t) = \begin{cases} r(t) + c[\delta t_u(t) - \delta t^s(t-\tau)] \\ - I(t) + T(t) + \lambda N + \varepsilon_\phi(t) \end{cases} \tag{32.3}$$

in which, r represents the distance between satellite and receiver, I represents the Ionosphere error, T represents the Troposphere error, N represents the carrier phase ambiguity, $\delta t_u(t) - \delta t^s(t-\tau)$ represents clock error of satellite and receiver, c represents light speed, λ represents the wavelength of carrier, ε_ρ(t) represents the measurement error of code caused by receiver and multipath, $\varepsilon_\Phi(t)$ represents the measurement error of carrier caused by receiver and multipath. Code carrier coherence parameter consists of two items according to the calculation methods, and they are code minus carrier and code phase carrier phase coherence.

Code minus carrier measurement is defined as

$$\delta_{CMC}(t) = \rho(t) - \Phi(t) \tag{32.4}$$

Code phase carrier phase coherence is defined as [2]

$$\delta_{cc} = \left|\frac{f_{code}}{f_{code0}} - \frac{f_{carrier}}{f_{carrier0}}\right| = \left|\frac{\Delta f_{code}}{f_{code0}} - \frac{\Delta f_{carrier}}{f_{carrier0}}\right| \tag{32.5}$$

This comes from the requirement of WAAS (Wide Area Augmentation System) from the USA authority. Δf represents the anomalous variation of code or carrier frequency. To do the differential of code minus carrier,

$$d\frac{\delta_{CMC}}{dt} = \frac{\frac{d\rho}{\lambda} * 360 - d\Phi}{dt} = \frac{\frac{dc_p}{\lambda} * c * 360 - d\phi}{dt} \tag{32.6}$$

c_p represents the code phase measurement, φ represents the carrier phase measurements with unknown phase ambiguity. Further analysis shows,

$$\begin{aligned} d\frac{\delta_{CMC}}{dt} &= \frac{\frac{dc_p}{\lambda} * c * 360 \; - \; d\phi}{dt} \\ &= \frac{[(f_{code} + \Delta f_{code} - f_{code})dt/f_{code0}] * f_{carrier0} - (f_{carrier} + \Delta f_{carrier} - f_{carrier})dt}{dt/360} \\ &= 360 * f_{carrier0}\left(\frac{\Delta f_{code}}{f_{code0}} - \frac{\Delta f_{carrier}}{f_{carrier0}}\right) \\ &= 360 * f_{carrier0}\delta_{cc} \end{aligned} \tag{32.7}$$

Accordingly, the differential of code minus carrier equals code phase carrier phase coherence times a constant. The code minus carrier measurement represents the difference between code and carrier ranging results, while the code phase carrier phase coherence represents the variance ratio of ranging results. Moreover, they differ in calculation methods. Code minus carrier measurement is calculated using results from information processing level and code phase carrier phase coherence measurement is calculated using results from signal processing level.

One real-time application of carrier phase smoothing pseudo range can be expressed as

$$\overline{\rho(t_i)} = \frac{1}{i}\rho(t_i) + \frac{i-1}{i}\left[\overline{\rho(t_{i-1})} - \Delta\Phi(t_{i-1}, t_i)\right] \tag{32.8}$$

An afterwards application of carrier phase smoothing pseudo range can be expressed as

$$\overline{\rho(t_i)} = \overline{\rho(t_1)} + \Delta\Phi(t_i, t_1) \tag{32.9}$$

In which, $\overline{\rho(t_i)}$ represents the smoothed pseudo range in i epoch, $\overline{\rho(t_1)}$ represents the smoothed pseudo range in start epoch.

$$\overline{\rho(t_1)} = \frac{1}{M}\sum_{i=1}^{M}[\rho(t_1)]_i \tag{32.10}$$

And M is a preset constant.

It can be proved that the results of real-time carrier phase smoothing pseudo range could be represented by code minus carrier measurement from several epochs as shown in Eq. 32.11.

$$\overline{\rho(t_i)} = \frac{1}{i}\sum_{j=1}^{i}\delta_{CMC}(t_j) + \Phi(t_i) \tag{32.11}$$

Similarly, we have the results of afterwards carrier phase smoothing pseudo range could be represented by code minus carrier measurement from several epochs as shown in Eq. 32.12.

$$\overline{\rho(t_i)} = \sum_{j=1}^{k}\frac{1}{k}\delta_{cc}(t_j) + \Phi(t_i) \tag{32.12}$$

It shows that the results of carrier phase smoothing pseudo range uses the code minus carrier measurement from several epochs to estimate the pseudo range.

The carrier phase measurement can provide more accurate ranging results under a stable condition, thus improve the precision of carrier phase smoothing pseudo range than the pure pseudo range measurement. In the calculation, the carrier phase ambiguity is cancelled out by carrier phase differentiation and only carrier cycle jump should be taken into consideration, which makes it easier to use. Consequently, the code carrier coherence becomes the precondition to improve the precision of carrier smoothing pseudo range. If there is an abnormal phase error happens, the code minus carrier measurement will be affected and introduces a ranging error into positioning results [7].

Assume the code minus carrier measurement varies near the theoretical value, and the standard error is σ_{CMC} angle. Thus the precision of real-time carrier phase smoothing pseudo range is,

$$\sigma = \frac{c}{360f}\frac{\sigma_{CMC}}{\sqrt{L}} \tag{32.13}$$

And the precision of afterwards carrier phase smoothing pseudo range is

$$\sigma = \frac{c}{360 \cdot f}\frac{\sigma_{CMC}}{\sqrt{k}} \tag{32.14}$$

In which, t represents the smoothing length, c represents light speed, f represents carrier frequency, L represents epoch number per smooth period. The simulation of relationship between carrier phase smoothing pseudo range and code minus carrier is shown in Figs. 32.2, 32.3 and 32.4. A section data of 2000s containing pseudo range and carrier phase from GPS L1 receiver is utilized in the simulation calculating code minus carrier in the carrier phase smoothing pseudo range. Multipath error, ionosphere error and other errors are included in the pseudo range and carrier phase. Assuming the variance of code multipath error is 0.3 m; the variance of carrier multipath error is 0.002 m, the variance of code ionosphere error is 1 m and the variance of other error is 4 m. Moreover, an inherent error of code minus carrier is added, which has an expectation of 1 m and a standard error of 20 m.

From the simulation results we can derive that the average error of code minus carrier measurement caused by signal will greatly influence the carrier smoothing pseudo range results by accumulation of each epoch results. Specifically, the bias of code minus carrier can be accumulated during the smoothing process which lead to an increasing error in the pseudo range.

The standard error of code minus carrier measurement has a slightly influence on the precision of smoothing results because carrier phase smoothing process significantly decrease the variance of pseudo range. And the variance of code minus carrier measurement is mainly affected by the variance of carrier phase.

32.2.3 Carrier Phase Coherence

Traditional IQ quadrature parameter represents the imperfection of carrier phase difference between in-phase and quadrature-phase signal. Consequently, it will affect the ranging precision and positioning accuracy. As for modernized signal, more than two signals are modulated on the carrier, therefore the IQ quadrature

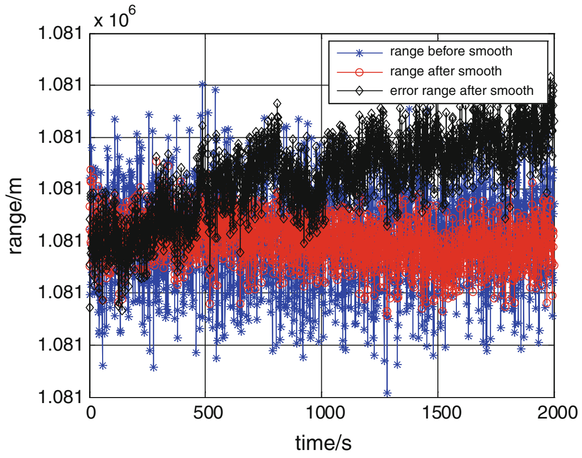


Fig. 32.2 Simulation results of carrier smooth pseudo-range

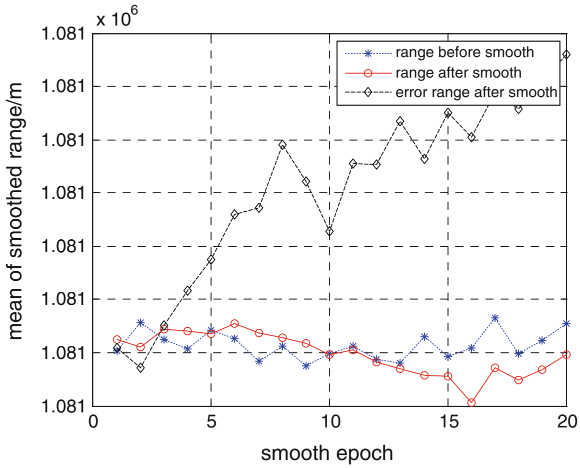


Fig. 32.3 Expectation of pseudo-range after smoothing

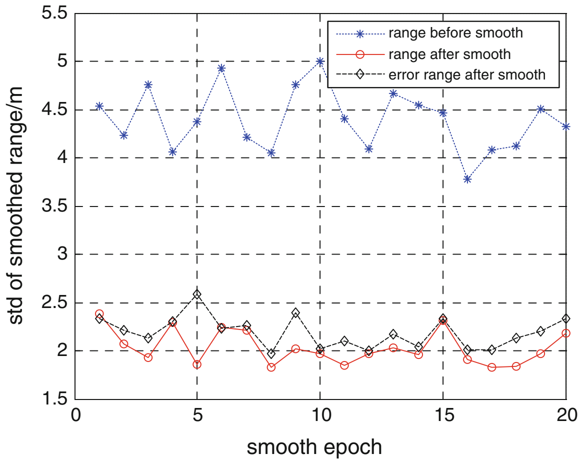


Fig. 32.4 Standard error of pseudo-range after smoothing

parameter can be redefined here as signal carrier phase coherence measurement. The deterioration of carrier phase coherence affect range measurement in a way similar to the code phase coherence.

32.2.4 Test Results

To fully exploit the flexibility of software and high gain signal, a high-gain antenna with software receiver system was adopted to monitor the signal quality from different satellites. The structure of it is shown in Fig. 32.5.

The results of GPS code phase carrier phase coherence is shown in Figs. 32.6 and 32.7.

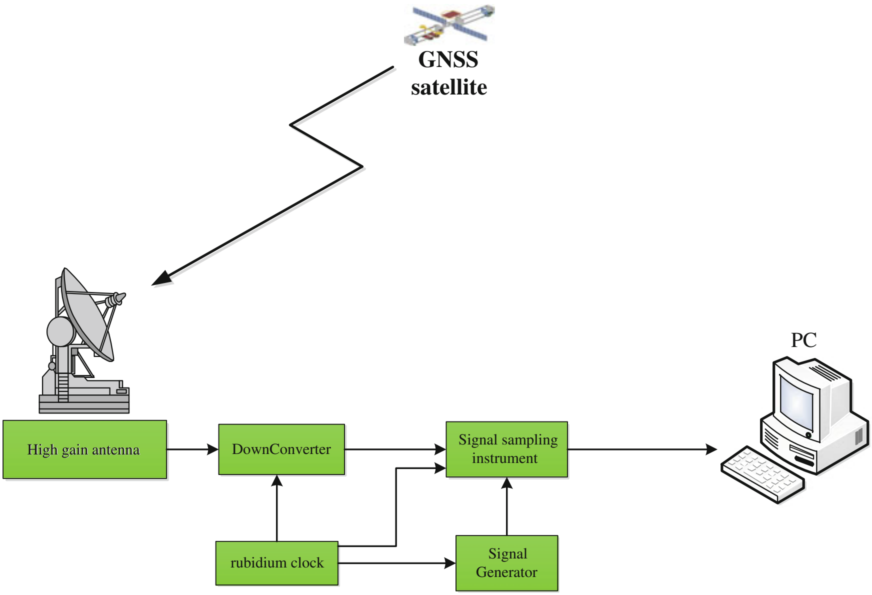
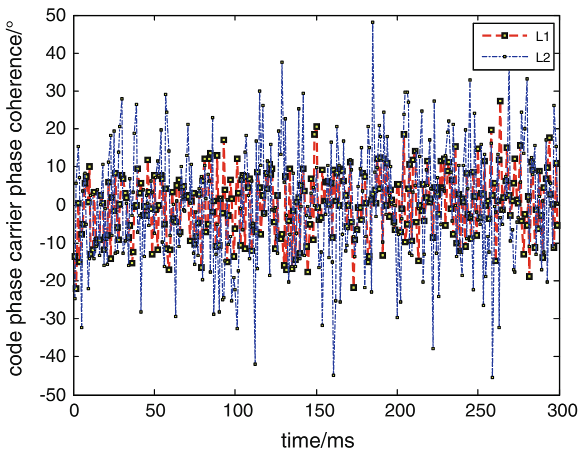


Fig. 32.5 Structure of test system

Fig. 32.6 Results of GPS code carrier coherence parameter



It can be concluded that the code phase carrier phase coherence possesses a feature like white noise with a zero mean. The result of code minus carrier measurement after cleaning ionosphere error is shown in Fig. 32.8.

The results of code minus carrier measurement reply the multipath error and measurement precision of receiver, and its fresh frequency is much slower than the code phase carrier phase coherence. Due to the huge difference between code minus carrier and code carrier coherence parameter in time scale, the linearity is

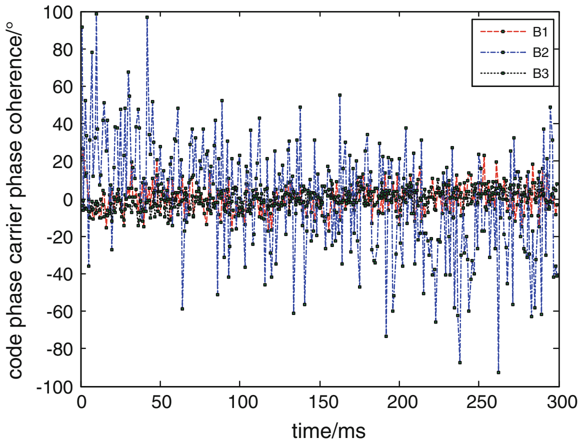


Fig. 32.7 Results of Beidou code carrier coherence parameter

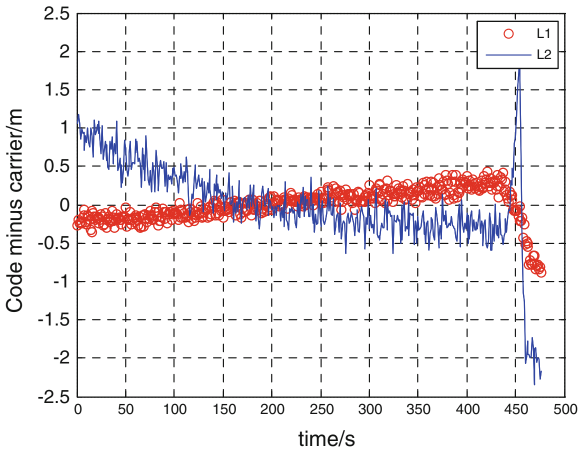


Fig. 32.8 Results of GPS CMC parameter

not verified here. However, it can be seen that the variation of code minus carrier tend to have a zero mean randomness.

32.3 Conclusion

Signal coherence parameter has a direct influence on the code phase ranging and carrier phase ranging and is one of the most important monitoring parameter. This paper discusses how the coherence of phases between pseudo-random codes and carriers affect pseudo-random range measurement and carrier phase range measurement.

The results of carrier phase smoothing pseudo range uses the code minus carrier measurement from several epochs to estimate the pseudo range. Therefore an abnormal phase error will affect the code minus carrier measurement and introduce a ranging error into positioning results.

Equations show that the differential of code minus carrier has a linear relation of code phase carrier phase coherence. The code minus carrier measurement represents the difference between code and carrier ranging results, while the code phase carrier phase coherence represents the variance ratio of ranging results.

Then, the positioning error and code minus carrier measurement is given by the simulation of carrier phase smoothing pseudo range process. The simulation result shows that the bias of code minus carrier can cause an increasing error of smoothed pseudo range.

In the end, we test code minus carrier parameter and code phase carrier phase coherence parameter using the system built by ourselves. The result shows that code phase carrier phase coherence's feature is similar to white noise and has high precision in time domain. Code minus carrier measurement has a larger time scale than code phase carrier phase coherence and directly linked to the multipath error and noise of receiver.

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