IEICE TRANS. COMMUN., VOL.E103–B, NO.1 JANUARY 2020

PAPER

Unbiased Interference Suppression Method Based on Spectrum Compensation

Jian WU[†], ***Member***, **Xiaomei TANG**[†a)], **Zengjun LIU**[†], **Baiyu LI**[†], ***and*** **Feixue WANG**[†], ***Nonmembers***

SUMMARY The major weakness of global navigation satellite system receivers is their vulnerability to intentional and unintentional interference. Frequency domain interference suppression (FDIS) technology is one of the most useful countermeasures. The pseudo-range measurement is unbiased after FDIS filtering given an ideal analog channel. However, with the influence of the analog modules used in RF front-end, the amplitude response and phase response of the channel equivalent filter are non-ideal, which bias the pseudo-range measurement after FDIS filtering and the bias varies along with the frequency of the interference. This paper proposes an unbiased interference suppression method based on signal estimation and spectrum compensation. The core idea is to use the parameters calculated from the tracking loop to estimate and reconstruct the desired signal. The estimated signal is filtered by the equivalent filter of actual channel, then it is used for compensating the spectrum loss caused by the FDIS method in the frequency domain. Simulations show that the proposed algorithm can reduce the pseudo-range measurement bias significantly, even for channels with asymmetrical group delay and multiple interference sources at any location.
key words: *GNSS receiver, pseudo-rang measurement, interference suppression, non-ideal channel, spectrum compensation*

1. Introduction

The Global Navigation Satellite System (GNSS) is being widely used in many fields for precise positioning. However, the navigation signal received by GNSS receivers on the ground is very weak (typically −20 dB below the noise floor), thus it is easily affected by intentional and unintentional interference. In order to improve the receiver usability in interference environment, several anti-interference methods have been proposed, which can be classified into the following groups: adaptive time-domain processing [1], frequency-domain filtering [2], time-frequency domain filtering [3], spatial filtering [4], and spatial-time adaptive processing [5]. Among them, the frequency domain interference suppression (FDIS) algorithm is one of the most widely used interference suppression methods due to its simple implementation and effective interference suppression [2], [6], [7]. The basic principle is to design a notch filter in the frequency domain to achieve interference suppression. If the RF front-end channel equivalent filter is an ideal filter, that is, the amplitude-frequency response is constant and the phase-frequency response is linear, the FDIS filter will not cause pseudo-range measurement bias [7]. However, those equivalent front-end receivers are not ideal in practice, as they suffer from variable amplitude-frequency response and nonlinear phase-frequency response [8]. Besides, different interference frequencies will lead to different pseudo-range measurement bias [9].

There are two main ways to conquer the pseudo-range calculation bias. The first way, channel calibration, offsets the non-ideal characteristics of the channel in the analog domain or digital domain, which is usually achieved by analog group delay equalization technology [10] and digital calibration technology [11], [12]. However, the former has poor accuracy and small adaptation range, while the later imposes a large computational burden and is not feasible in practice. The second way is to compensate the spectrum loss of the desired signal. In [13], the mirror frequency amplitude compensation (MFAC) method is proposed to double the amplitude of the symmetry position to the notch frequency. It can be considered as using the symmetry spectrum to compensate the signal spectrum loss. Nevertheless, there are two shortcomings in the MFAC method: first, it is only suitable for channels that have symmetrical group delay, which is hard to achieve in most GNSS receivers. Due to the use of analog devices in GNSS receiver, the channel group delay response is mostly asymmetric and nonlinear [14]. Second, the spectrum loss cannot be compensated by the MFAC method if another interference exists at the symmetrical position.

This paper proposes an interference suppression algorithm based on spectrum compensation. The procedure of this algorithm is to estimate the received signal using the parameters measured by tracking loop, and then the estimated signal is filtered by the real channel equivalent filter. The channel characteristics can be kept stably for a long time, therefore, the filter parameters can be measured in advance and stored in the receiver [15], [16]. The filtered signal is used to compensate the spectrum loss of the received signal. After compensation, the received signal can be processed free of bias.

This paper is organized as follows. Section 2 introduces the model of no-ideal channel filter and the model of pseudo-range measurement bias, respectively. The method proposed in this paper is discussed in detail in Sect. 3. Section 4 validates the effectiveness of the algorithm through simulation experiments. Section 5 summarizes this paper.

Manuscript received February 15, 2019.
Manuscript revised May 28, 2019.
Manuscript publicized July 16, 2019.
[†]The authors are with National University of Defense Technology, Changsha, China.
a) E-mail: txm_nnc@126.com
DOI: 10.1587/transcom.2019EBP3046

2. Signal Model

2.1 Signal Processing Model

The signal received by a GNSS receiver is a composite signal of the navigation signal and the interference. In a traditional GNSS receiver, the signal is first passed through the Radio frequency (RF) front-end unit for amplifying, filtering, and down converting processing. The output of RF front-end is a base band signal, which can be expressed as

$$r(t) = s(t) \otimes h(t) + I(t) + n(t) \tag{1}$$

where $s(t)$ is the desired signal, $I(t)$ is the interference signal, $n(t)$ is additional white Gaussian noise with a constant power spectral density equal to $N_0/2$ dBW/Hz. $h(t)$ is the equivalent filter of the RF front-end.

The desired signal $s(t)$ can be represented as

$$s(t) = A \cdot D(t)c(t-\tau)e^{j2\pi f_d t + j\phi_0} \tag{2}$$

where A, $D(\cdot)$, $c(\cdot)$, τ, f_d, and ϕ_0 are the signal amplitude, navigation bit, the pseudo-random noise (PRN) code, the time delay, the Doppler frequency, and carrier phase, respectively. In this paper, the correlation process is realized within one data bit, therefore the navigation bit is considered as the constant 1.

The FDIS filter $h_I(t)$ is then used for interference suppression. The desired signal after the FDIS filtering can be written as $s_{out}(t)$ in time domain and $S_{out}(f)$ in frequency domain:

$$\begin{aligned} s_{out}(t) &= r(t) \otimes h_I(t) \\ &\approx s(t) \otimes h(t) \otimes h_I(t) \end{aligned} \tag{3}$$

And

$$S_{out}(f) = S(f) \cdot H(f) \cdot H_I(f) \tag{4}$$

where $\otimes$ denotes convolution operator. $H(f)$ and $H_I(f)$ are the frequency responses of $h(t)$ and $h_I(t)$, respectively. $S(f)$ is the spectrum of the desired signal $s(t)$. Note that the interference is considered to be completely suppressed in (3) and (4). For the sake of simplicity, the noise part is also not considered.

2.2 Model of Non-Ideal Channel Filter

The transfer function $H(f)$ of the equivalent filter of the RF front-end can be expressed as [14]

$$H(f) = A(f)e^{j(\phi(f) - 2\pi f \tau_0)} \tag{5}$$

where $A(f)$ and $\phi(f)$ represent the amplitude frequency response and phase frequency response of non-ideal part, respectively. τ_0 is the group delay of ideal part, which can be considered as a priori known information and is set to zero in this paper.

The group delay response of the non-ideal part $\tau_g(f)$ is defined as

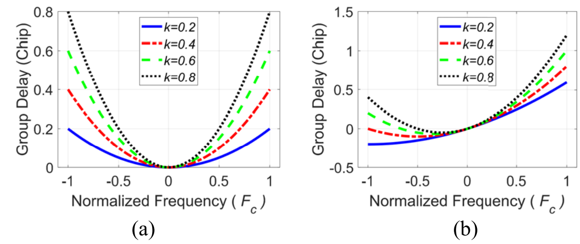

Fig. 1 Group delay with different κ. (a) Results of symmetrical quadratic curve group delay, (b) results of asymmetrical quadratic curve group delay with $\mu = 0.4$.

$$\tau_g(f) = -\frac{1}{2\pi}\frac{d\phi(f)}{df} \tag{6}$$

Typically, if $\tau_g(f) = 0$ and the amplitude frequency response is a constant, the channel is considered ideal. Otherwise, the channel is non-ideal, which will lead to a distortion of the auto-correlation function (ACF) of the signal and cause the pseudo-range measurement bias. Amplitude-frequency response has little influence on the pseudo-range measurement [17], which is ignored in this paper. Only group delay response is discussed.

The group delay of the non-ideal channel may be symmetric or asymmetric [10]. Most of the symmetric group delay response performance as quadratic curve group delay, which can be modeled as $\tau_g(f) = \kappa(f/B_n)^2$, where κ reflects the degree of distortion, B_n is the bandwidth of the front-end filter. Figure 1(a) shows the symmetric quadratic curve group delay with different κ. However, the general form of the group delay in GNSS receiver is asymmetric [14]. The asymmetric quadratic curve group delay response can be modeled as $\tau_g(f) = \kappa(f/B_n)^2 + \mu \cdot f/B_n$, where μ and κ reflect the degrees of distortion of the first-order part and second-order part. Figure 1(b) shows the asymmetric quadratic curve group delay with different κ, and $\mu = 0.4$. The horizontal axis is defined as the frequency offset normalized by code frequency F_c relative to the code center frequency, and the vertical axis is defined as the group delay with the unit of chip.

2.3 Principle of the FDIS Method

The FDIS algorithm is processing in frequency domain by nulling the interference frequency bins, whose schematic procedure is shown in Fig. 2. The signal is first transformed into frequency domain, and then the FDIS filter is employed to suppress the spectrum of the interference. Note that the frequencies of interference need to be detected before suppression, whereas the detection methods are beyond the scope of this work, we regard the interference is already detected here. Finally, the suppressed signal is transformed back to time domain for signal tracking process.

Assuming the frequency and bandwidth of the interference are f_I and B_I, respectively, the frequency-domain response of the FDIS can be written as

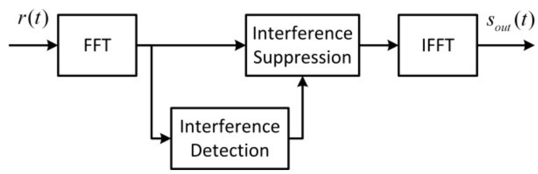

Fig. 2 The schematic of FDIS algorithm.

$$H_I(f) = \begin{cases} 0, & |f - f_I| < B_I/2 \\ 1, & others \end{cases} \tag{7}$$

Using the FDIS filtering method, the interference is removed completely. However, the spectrum of the desired signal is also suppressed at the same frequency bins.

2.4 Model of Pseudo-Range Measurement Bias

If there is no interference signal, the group delay of the non-ideal channel will lead to a constant pseudo-range measurement bias [13], which can be expressed as

$$\varepsilon_0 = \frac{\int_{-b}^{b} G(f,d) \cdot \sin(\phi(f))df}{2\pi \int_{-b}^{b} f \cdot G(f,d) \cdot \cos(\phi(f))df} \tag{8}$$

where $G(f,d) = S(f) \cdot \sin(\pi f d)$, d is correlation space. b is the front-end filter bandwidth normalized by the code frequency F_c. The bias is only related with the group delay of the non-ideal channel, which can be measured accurately and can be considered as a prior known parameter. In the tracking loop, the true pseudo-range τ and ε_0 cannot be separated, so the two parameters are usually considered as a whole.

If interference is present, the pseudo-range bias after FDIS filter can be expressed as [13]

$$\varepsilon = \frac{\int_{-b}^{b} G(f,d) \cdot H_I(f) \cdot \sin(\phi(f))df}{2\pi \int_{-b}^{b} f \cdot G(f,d) \cdot H_I(f) \cdot \cos(\phi(f))df} \tag{9}$$

The bias model in (9) denotes the total pseudo-range bias, which contains the constant bias ε_0 and the unfixed value $\Delta\tau$ introduced by the FDIS method. The bias introduced by the FDIS is given as

$$\Delta\tau = \varepsilon - \varepsilon_0 \tag{10}$$

From (10), it can be found that $\Delta\tau$ is related with interference parameters. Different interferences may lead to different pseudo-range biases.

Figure 3 illustrates the numerous simulation results of $\Delta\tau$ in (10). The bandwidth of the interference in the simulation is $0.1F_c$. Figure 3(a) shows the pseudo-range bias versus different frequencies of the interference for symmetric quadratic curve group delay. It can be found that interference frequency will cause a fluctuation on the pseudo-range bias. Additionally, the tracking bias at the mirror frequency will have the same values. However, the pseudo-range bias is not symmetry for asymmetric quadratic curve group delay as shown in Fig. 3(b). In Fig. 3, the horizontal axis is defined as the frequency offset of the interference normalized by code frequency F_c with respect to the code center frequency, and the vertical axis is defined as the pseudo-range bias with the unit of chip.

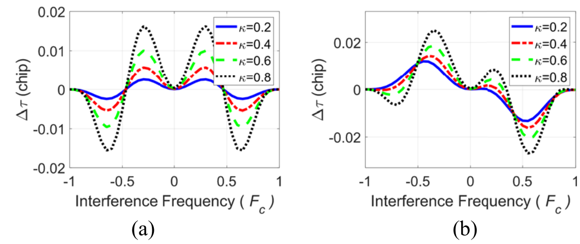

Fig. 3 Pseudo-range bias $\Delta\tau$ versus interference frequency with different κ. (a) For symmetric group delay, (b) for asymmetric group delay with $\mu = 0.2$.

3. Proposed Method

From the above discussions, it can be found that the main reason for pseudo-range measurement bias is the energy loss of the received signal caused by the FDIS method under non-ideal channel. Therefore, an unbiased interference suppression algorithm is proposed based on spectrum compensation in this paper. The key points of this algorithm are estimating the received signal and compensating signal spectrum loss.

3.1 Reconstruction of the Desired Signal

From (2), it can be found that in order to reconstruct the received signal, several parameters are needed, i.e. the code phase τ, the signal amplitude A, Doppler frequency f_d, the carrier phase ϕ, and the equivalent filter $h(t)$. Among them, $h(t)$ can be considered as a priori known parameter, which is stored in the receiver.

In GNSS receiver, the code phase can be estimated by the code tracking module. Doppler frequency and carrier phase can be estimated by the carrier tracking module [18]. Carrier-to-noise ratio (C/N_0) is another important parameter estimated in GNSS receiver, which is defined as the ratio of the power of the signal C to the noise power N_0 in a 1 Hz bandwidth. The amplitude of the signal can be estimated by $\hat{A} = \sqrt{2 \cdot C/N_0 \cdot N_0}$, where C/N_0 and N_0 can be estimated separately. The reconstructed signal after filtered by $h(t)$ can be expressed as

$$\begin{aligned} s'(t) &= \hat{A}c(t - (\hat{\tau} - \varepsilon_0))e^{-j(2\pi \hat{f}_d t + \hat{\phi})} \otimes h(t) \\ &= \alpha A c(t - \tau - \Delta\tau)e^{-j(2\pi f_d t + \phi_0)}e^{-j(2\pi \Delta f_d + \Delta\phi)} \otimes h(t) \end{aligned} \tag{11}$$

where $\hat{A}$, $\hat{\tau}$, $\hat{f}_d$, and $\hat{\phi}$ are the estimates of the amplitude A, code delay τ, Doppler frequency f_d, and carrier phase ϕ, respectively. $\alpha = \hat{A}/A$ denotes the ratio between the estimated amplitude and the real amplitude. $\Delta f_d = \hat{f}_d - f_d$ denotes the

Doppler frequency estimation error. $\Delta\phi = \hat{\phi} - \phi_0$ denotes the carrier phase estimation error. $\Delta\tau = \hat{\tau} - \tau - \varepsilon_0$ denotes the code phase estimation bias induced by the FDIS method. The constant pseudo-range bias ε_0 should be deducted from the code phase estimate $\hat{\tau}$ to make the local replica signal after the channel equivalent filter $s'(t)$ has the same delay with the received signal $s_{out}(t)$ to be compensated. When the signal is tracked, the carrier of the signal can be wiped-off effectively and has little effect on code tracking, so the influence of Doppler frequency and carrier phase estimated error is not considered in latter analysis without loss of generality.

The reconstructed signal in frequency domain can be expressed as

$$\begin{aligned} S'(f) &= \alpha S(f) H(f) e^{j2\pi f \Delta\tau} \\ &= \alpha S(f) e^{j\phi(f)} e^{j2\pi f \Delta\tau} \end{aligned} \tag{12}$$

Then the reconstructed signal is used to compensate for the signal spectrum loss due to interference suppression filter. The spectrum after compensation is given as

$$\begin{aligned} S_{aft}(f) &= S_{out}(f) + S'(f) \cdot (1 - H_I(f)) \\ &= S(f) \cdot H_I(f) \cdot e^{j\phi(f)} \\ &\quad + \alpha S(f) \cdot (1 - H_I(f)) \cdot e^{j(\phi(f) + 2\pi f \Delta\tau)} \end{aligned} \tag{13}$$

where $S_{aft}(f)$ consists of two parts, the first part is the spectrum without compensation and the second part is the compensation part.

Replace $S_{out}(f)$ by $S_{aft}(f)$ as the input of correlation unit and tracking loop, and the pseudo-range measurement bias can be rewritten as

$$\varepsilon_{after} = \frac{\Delta_1}{\Delta_2} \tag{14}$$

where Δ_1 and Δ_2 can be expressed as follows.

$$\begin{aligned} \Delta_1 = &\int_{-b}^{b} G(f, d) \cdot H_I(f) \cdot \sin(\phi(f)) df \\ &+ \alpha \cdot \int_{-b}^{b} G(f, d) (1 - H_I(f)) \cdot \sin(2\pi f \Delta\tau + \phi(f)) df \end{aligned} \tag{15}$$

where the main difference between the first term and the second term is that $\phi(f)$ and $H_I(f)$ are replaced by $\phi(f) + 2\pi f \Delta\tau$ and $1 - H_I(f)$, respectively. It is the same as that in (16).

$$\begin{aligned} \Delta_2 = &\int_{-b}^{b} G(f, d) \cdot H_I(f) \cdot 2\pi f \cos(\phi(f)) df \\ &+ \alpha \cdot \int_{-b}^{b} G(f, d) (1 - H_I(f)) \cdot 2\pi f \cos(2\pi f \Delta\tau + \phi(f)) df \end{aligned} \tag{16}$$

After compensation, the pseudo-range bias introduced by FDIS can be represented as

$$\Delta\tau_{after} = \varepsilon_{after} - \varepsilon_0 \tag{17}$$

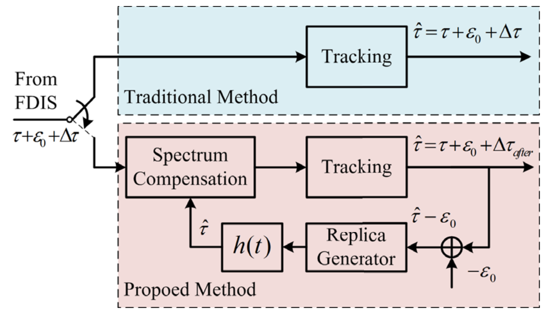

Fig. 4 Pseudo-range estimation principle scheme.

From (17), it can be found that if the signal is estimated accurately, the pseudo-range bias will be a constant value $\varepsilon_{after} = \varepsilon_0$, therefore, $\Delta\tau_{after} = 0$. Otherwise, $\Delta\tau_{after} \neq 0$, which means the bias introduced by the FDIS method is not eliminated completely.

3.2 Pseudo-Range Estimation Model

The pseudo-range estimation principle scheme is shown in Fig. 4. The time delay of the signal after FDIS contains three terms: the true value τ, the constant bias ε_0, and the unfixed bias $\Delta\tau$. The main purpose of a signal tracking loop is to estimate the pseudo-range of the received signal, and the output of the code tracking loop is the pseudo-range estimation $\hat{\tau}$. When using the traditional method, the pseudo-range estimate is the same with that of the input signal, which contains the unwanted bias term $\Delta\tau$.

The proposed method is used after the signal is tracked. The GNSS receiver first uses the traditional method to achieve signal initial tracking, and then switches to the proposed method to achieve unbiased estimation. The initial code phase for signal reconstruction is $\hat{\tau} - \varepsilon_0$, after filtered by $h(t)$, the signal is delayed by ε_0, therefore, the time delay of the signal for spectrum compensation is $\hat{\tau}$. The bias term $\Delta\tau$ in the output of the traditional method is the initial error term when reconstructing the local replica signal. The proposed method can be considered as a special case of an output feedback control system. After using the proposed method, the bias $\Delta\tau$ becomes $\Delta\tau_{after}$, which can be reduced significantly and becomes approximately zero after several loop processings.

It must be noted that the proposed method cannot improve the interference suppression ability and can work well only after the signal is tracked using the traditional method. Therefore, the theoretical limitation of the interference bandwidth that can be compensated by the proposed method is depended on the interference suppression performance of the GNSS receiver.

3.3 Analysis of the Influence of the Estimation Error

The code phase and the amplitude estimation results are the two most important parameters that have influence on the performance of the proposed method.

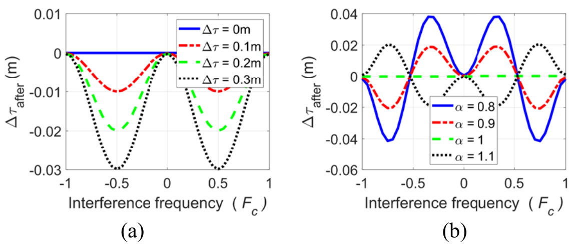

Fig. 5 Simulation results for symmetric quadratic curve group delay, (a) pseudo-range bias versus interference frequency with different $\Delta\tau$, (b) pseudo-range bias versus interference frequency with different α.

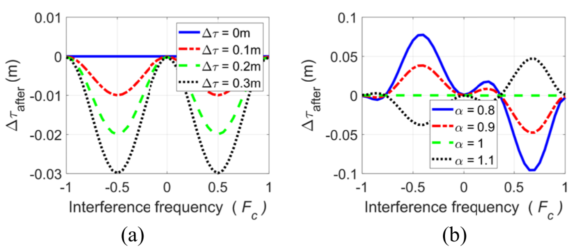

Fig. 6 Simulation results for asymmetric quadratic curve group delay, (a) pseudo-range bias versus interference frequency with different $\delta\tau$, (b) pseudo-range bias versus interference frequency with different α.

In this part, the effect of the parameter estimation error is analyzed by numerical simulation of the GPS L1 C/A code. The code frequency is 1.023 MHz and the bandwidth of the interference is $0.1F_c$. The simulation results of the pseudo-range bias $\Delta\tau_{after}$ in (17) are illustrated in Fig. 5 and Fig. 6.

Figure 5 shows the pseudo-range bias $\Delta\tau_{after}$ with different initial code phase estimation error $\Delta\tau$ and amplitude estimation error α for symmetric quadratic curve group delay. As shown in Fig. 5(a), the larger the code delay estimation error, the larger the pseudo-range bias after spectrum compensation. For the case that the code delay estimation error is 0.3 m, the maximum pseudo-range bias is about 0.03 m with interference frequency of about $0.5F_c$. From Fig. 5(b), it can be found that there is a close relationship between the reduction of the pseudo-range measurement deviation and the amplitude estimation error. Raising the accuracy of the amplitude estimates will decrease the pseudo-range bias. It also shows that the pseudo-range bias will be in the opposite if the estimated amplitude is larger than the true value.

Figure 6 shows the pseudo-range measurement bias $\Delta\tau_{after}$ for asymmetric quadratic curve group delay. As shown in Fig. 6(a), the code phase error has the same impact on the pseudo-range bias with that in Fig. 5(a), which means that the impact of code phase error is independent of channel characteristics. The same conclusions can be drawn from Fig. 6(b) with that in Fig. 5(b). The horizontal axis in Fig. 5 and Fig. 6 have the same definition as in Fig. 3, and the vertical axis is defined as pseudo-range bias with the unit of meters.

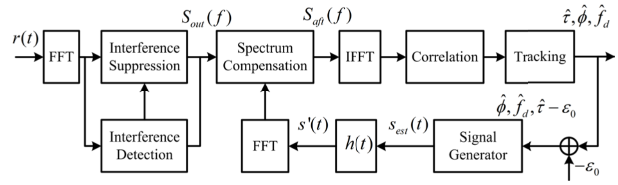

Fig. 7 Flowchart of the proposed method.

3.4 The Procedure of the Proposed Method

The flowchart of the proposed algorithm is shown in Fig. 7 with the following steps.

1) Transform the base band signal $r(t)$ into frequency domain. Then interference detection method is used to detect the frequency bins of the interference.
2) Employ the FDIS method in frequency domain by nulling the interference spectrum lines, and the desired signal after interference suppression is $S_{out}(f)$ as given in (4).
3) Reconstruct the desired signal, which can be expressed as $s_{est}(t) = \hat{A}c(t-(\hat{\tau}-\varepsilon_0))e^{-j(2\pi\hat{f}_d t+\hat{\phi})}$. The amplitude $\hat{A}$ is estimated by the parameter C/N_0, $\hat{\tau}$ is estimated by the code tracking loop, $\hat{f}_d$ and $\hat{\phi}$ are estimated by the carrier tracking loop.
4) Filter the reconstructed signal by the channel equivalent filter $h(t)$, which is measured as a priori knowledge and stored in the receiver. The filtered signal $s'(t)$ can be obtained from (11).
5) Transform the filtered signal $s'(t)$ into the frequency domain $S'(f)$ to compensate the spectrum loss of the desired signal. The spectrum of the compensated signal is $S_{aft}(f)$ as shown in (13).
6) Transform the compensated signal $S_{aft}(f)$ back into the time domain. The signal strength of the compensated signal is still below the noise floor, and the correlation process is used to de-spread the signal before the tracking loop. After that, the tracking loop is used for code delay and carrier phase estimating.

4. Simulation Results

In order to verify the proposed algorithm, the pseudo-range measurement of the proposed method is compared with the FDIS and the MFAC methods. The GNSS signal and interference are simulated numerically using MATLAB. The simulation model is shown in Fig. 8. Specifically, the digital baseband GPS L1 C/A signal, the interference, and the white Gaussian noise are separately generated, and these three components are combined together afterward. After being filtered by a channel equivalent filter, the combined signal is processed by a GNSS software receiver. In the simulation, we set $F_c = 1.023\,MHz$, $f_d = 0\,Hz$, $f_s = 5\,MHz$, and $B_n = 2.5\,MHz$. The simulating data length is 200 s and the correlation time is 1 ms. The C/N_0 is 40 dBHz, which

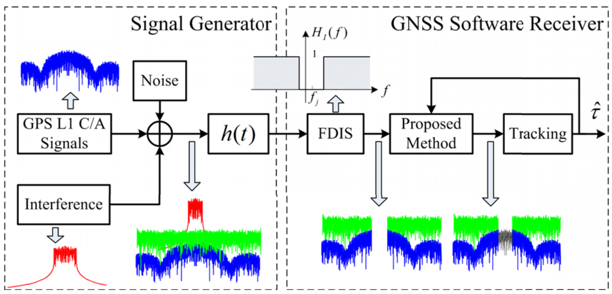

Fig. 8 Flowchart of the simulation model.

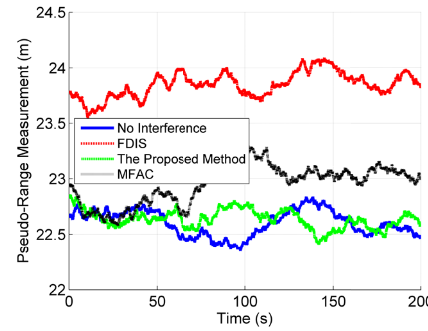

Fig. 9 Pseudo-range measurement with $f_j = 0.3F_c$.

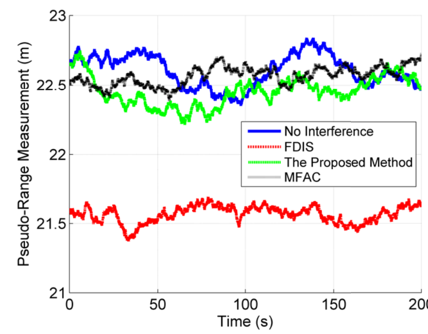

Fig. 10 Pseudo-range measurement with $f_j = 0.7F_c$.

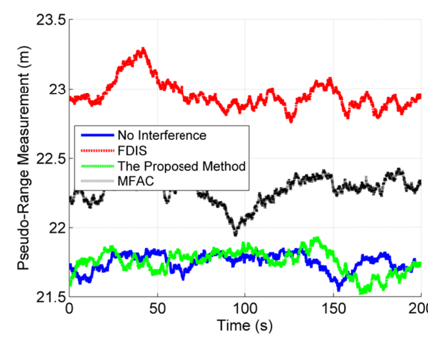

Fig. 11 Pseudo-range measurement with $f_j = 0.3F_c$.

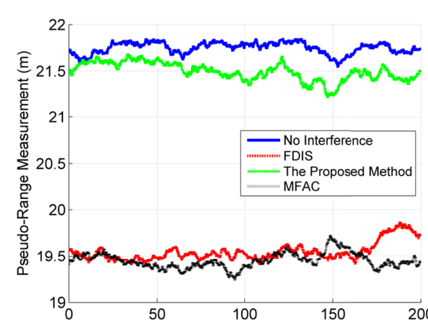

Fig. 12 Pseudo-range measurement with $f_j = 0.7F_c$.

is equivalent to signal-to-noise ratio at about −24 dB. The interferences used in this section are narrowband Gaussian interference with bandwidth of $0.1F_c$ and interference-to-noise ratio of 50 dB. The ideal band stop filter in frequency domain is used in FDIS module. In addition, the time delay of the simulated signal is set to be zero, so that the pseudo-range measured by the receiver is the pseudo-range measurement error. Furthermore, the correlation space used in the code tracking loop is 0.5 chips, and the bandwidth of the loop filter is 0.1 Hz.

Note that if the interference is present but without interference suppression, the desired signal cannot be captured and tracked by the receiver, and the pseudo-range cannot be calculated neither. This case is not considered in this simulation.

4.1 Simulation A

The purpose of simulation A is to compare the pseudo-range measurement with different methods. In this part, two kinds of group delay are simulated, i.e. symmetric quadratic curve group delay and asymmetrical quadratic group delay. Only a single interference is considered and the interference bandwidth is $0.1F_c$.

Figure 9 and Fig. 10 show the pseudo-range measurement for symmetric group delay. The interference frequency used in these two figures are $0.3F_c$ and $0.7F_c$, respectively. As shown in these two figures, the pseudo-range measurement is biased after the FIDS compared with that without interference when the channel is not ideal. The proposed method and the MFAC method can both reduce the pseudo-range bias. The experimental results are consistent with the theoretical analysis. It must be noted that the pseudo-range measurement bias takes non-zero values even when the interference is absent as shown in the Fig. 9 and Fig. 10, this is because the channel is non-ideal in this simulation, and will induce a constant pseudo-range measurement bias as discussed in (8).

Figure 11 and Fig. 12 show the results of pseudo-range measurement bias when the channel is non-ideal with asymmetric group delay. Since the MAFC method is only suitable to symmetrical group delay, it will not achieve unbiased pseudo-range measurement under this condition. However, the method proposed in this paper can still reduce most of the bias value of the pseudo-range measurement.

4.2 Simulation B

The simulation scenario is that the received signal contains

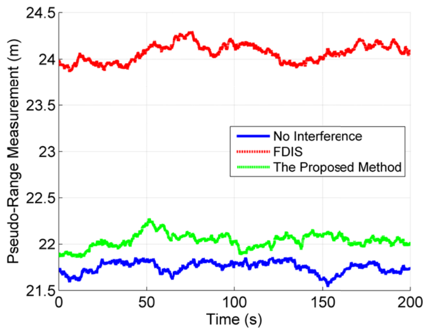

Fig. 13 Pseudo-range measurement with $f_j = \pm 0.3F_c$.

Table 1 Pseudo-range bias with non-ideal group delay.

Group Delay	$f_j\ (F_c)$	$\varepsilon_0\,(m)$	$\varepsilon\ (m)$	$\varepsilon_{after}\ (m)$	Reduction ratio (%)
Symmetric group delay	0.3	22.6246	23.8425	22.6488	98
	0.7	22.6246	21.5718	22.4571	84
Asymmetric group delay	0.3	21.7115	22.9710	21.7498	97
	0.7	21.7115	19.5223	21.4891	90
	0.3/-0.3	21.7115	24.0641	21.9995	88

two interference signals at symmetrical positions beside the center frequency of the desired signal. The frequencies of the interferences are $0.3F_c$ and $-0.3F_c$, respectively. The asymmetric quadratic curve group delay is simulated in this part. The simulation results are shown in Fig. 13.

Table 1 shows the mean values of pseudo-range bias in different simulations, which is calculated within the simulation time. In this table, ε_0, ε, and ε_{after} are the pseudo-range biases without interference, after the FDIS but without the proposed method, and after the proposed method, respectively. The reduction ratio in the table is calculated by $|(\varepsilon - \varepsilon_{after})/(\varepsilon - \varepsilon_0)|$, where, $\varepsilon - \varepsilon_{after}$ means the bias reduction with and without using the proposed method, $(\varepsilon - \varepsilon_0)$ is the bias induced by the FDIS without using the proposed method. In these simulated cases, the pseudo-range bias is reduced significantly using the proposed method compared with the traditional FDIS without any compensation.

5. Conclusion

The FDIS method will bias the pseudo-range measurement if the front-end channel of the GNSS receiver is non-ideal. In order to solve this problem, an unbiased interference suppression algorithm based on spectrum compensation is proposed in this paper. The main idea of the proposed method is to estimate the received signal by using the parameters calculated by the tracking loop and to compensate the spectrum loss of the desired signal. The simulation results support the validity and effectiveness of the method proposed in this paper. From our theoretical analysis and simulations, the pseudo-rang bias can be reduced significantly compared with the traditional methods under both symmetrical and asymmetrical group delay in the presence of interference.

Acknowledgments

This work has been supported in part by the National Natural Science Foundation of China under grant no. 61601485.

References

[1] Y.-R. Chien, “Design of GPS anti-jamming systems using adaptive notch filters,” IEEE Syst. J., vol.9, no.2, pp.451–460, 2015.
[2] N. Varshney and R.C. Jain, “An adaptive notch filter for narrow band interference removal,” 2013 National Conference on Communications (NCC), New Delhi, India, Feb. 2013.
[3] M.J. Rezaei, M.R. Mosavi, and M. Abedi, “New GPS anti-jamming system based on multiple short-time Fourier transform,” IET Radar, Sonar & Navigation, vol.10, no.4, pp.807–815, 2016.
[4] C. Fernández-Prades, J. Arribas, and P. Closas, “Robust GNSS receivers by array signal processing: Theory and implementation,” Proc. IEEE, vol.104, no.6, pp.1207–1220, 2016.
[5] S. Daneshmand, A.J. Jahromi, A. Broumandan, and G. Lachapelle, “GNSS space-time interference mitigation and attitude determination in the presence of interference signals,” Sensors, vol.15, no.6, pp.12180–12204, 2015.
[6] W. Yang, C. Zhang, X. Jin, Z. Jin, and T. Yuan, “Adaptive median threshold algorithm used in FDIS of DSSS receivers,” J. Syst. Eng. Electron., vol.24, no.1, pp.11–18, 2013.
[7] T. Zhang, X. Zhang, and M. Lu, “Effect of frequency domain anti-jamming filter on satellite navigation signal tracking performance,” China Satellite Navigation Conference (CSNC) 2013 Proceedings, Lecture Notes in Electrical Engineering, vol.243, pp.507–516, 2013.
[8] M. Soellner, R. Kohl, W. Luetke, et al., “The impact of linear and non-linear signal distortions on Galileo code tracking accuracy,” Proc. 15th International Technical Mettings of the Satellite Division of the Institute of Navigation (ION GPS 2002), pp.1270–1285, Portland, OR, Sept. 2002.
[9] G.A. McGraw, C. McDowell, R.S.Y. Yong, and D.W. Glessner, “Assessment of GPS anti-jarm system pseudorange and carrier phase measurement error effects,” Proc. 18th Iternational Technical Meeting of the Satellite Division of the Institute of Navigation, pp.603–617, Long Beach, CA, 2005.
[10] M. Gerken, “All pass transfer functions with prescribed group delay,” Proc. ICASSP’94. IEEE International Conference on Acoustics, Speech, and Signal Processing, vol.3, pp.III/577–III/580, Adelaide, SA, 1994.
[11] “Group delay compensation using IFFT filters,” US Patent: 0195502, 2006.
[12] “Signal receiver with group delay and amplitude distortion compensation,” US Patent: 8837654, 2014.
[13] G. Fan, X. Tang, J. Nie, Y. Huang, and G. Sun, “A zeros bias frequency-domain interference suppressor for GNSS receivers,” IEICE Trans. Commun., vol.E99-B, no.9, pp.2081–2086, Sept. 2016.
[14] J.M. Betz, “Effect of linear time-invariant distortions on RNSS code tracking accuracy,” Proc. 15th International Technical Meeting of the Satellite Division of the Institute of Navigation, pp.1636–1647, Portland, Oregon, 2002.
[15] S. Di, G.H. Zhang, and K.M. Feng, “Introduction and analysis of methods of measuring the group delay of frequency-translating devices,” J. Astronautic Metrology and Measurement, vol.27, no.1, pp.1–5, 2007.
[16] X. Zhu, Y. Li, S. Yong, and Z. Zhuang, “A novel definition and measurement method of group delay and its applications,” IEEE Trans. Instrum. Meas., vol.56, no.1, pp.229–233, 2009.
[17] T. Felhauer, “On the impact of RF front-end group delay variations on GLONASS pseudorange accuracy,” Proc. 10th International

Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 1997), pp.1527–1532, 1997.

[18] E.D. Kaplan and C.J. Hegarty, Understanding GPS: Principles and Applications, 2nd ed., Artech House, Boston, MA, USA, 2006.

Jian Wu received the B.S. and M.E. degrees from the Department of Electronic Science of National University of Defense Technology in 2012 and 2014, respectively. He is now a Ph.D candidate in Information and Communication Engineering at National University of Defense Technology. His main interests include GNSS signal processing and interference suppression technology.

Xiaomei Tang received the Ph.D. degree from NUDT in 2010. She is an associate researcher in the Department of Electronic Science at National University of Defense Technology. Her main interests include GNSS signal processing and GNSS/INS integration system.

Zengjun Liu received the Ph.D. degree from NUDT in 2014. He is an associate researcher in the Department of Electronic Science at National University of Defense Technology. His main interests include precision position and data processing of GNSS receiver.

Baiyu Li received the Ph.D. degree from NUDT in 2011. He is an associate researcher in the Department of Electronic Science at National University of Defense Technology. His main interests include GNSS signal processing and RF front-end of GNSS receiver.

Feixue Wang is a professor in the College of Electronic Science, National University of Defense Technology. He received M.S. and Ph.D. degrees from National University of Defense Technology. His main interests include algorithm design and performance analyses of GNSSs, ASIC, communication, and information systems.