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Effect of Continuous Wave Interference on GNSS Receivers

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Abstract

The positioning performance of GNSS receivers is strongly influenced by radio interferences, especially continuous wave interference (CWI). Recent studies have modeled the effects of the interference and have shown that the effect of the interference is strongest where the frequency offset between CWI interference and the GNSS signal is a multiple of 1KHz. However, these studies have not yet modeled the effect of phase offset between CWI interference and signal which has a significant impact on the positioning performance. In this paper, we present the effect of CWI interference on positioning performance considering the role of both frequency and phase offset. In addition, theoretical and simulation results also show that CWI noise does not significantly affect the signal with some specific values of phase offset.

Keywords: GNSS, GNSS interference, CWI

1. Introduction

In recent years, GNSS based services have played an increasingly important role in many fields, ranging from civil to military applications [1]. However, due to transmission over a long distance, the energy received at the receiver is very weak (below ambient noise). As a result, the positioning performance of such receivers is strongly affected by intentional or accidental interference. Among RF interferences that affect on GNSS receivers, continuous wave interference (CWI) has the highest impact on GNSS signals [2]. CWI may come from harmonics of fixed broadcast stations, CWI usually comes from hand-held jammers. Studies on this topic are emerging in recent years. However, these studies focus primarily on either evaluating their influence on the signal to noise ratio and the positioning performance or studying the ideal case when the CWI is at a fixed frequency and zero in phase offset. The limitation of the first studies is that only evaluate the output at the receiver and consider the signal processing chain as a black-box. Because the signal to noise ratio depends mainly on the processing method of this unit, the results depend greatly on the receiver architecture used. Concerning the second study [4, 5, 6], the case of stationary CWI phase offset is very rare in practice due to the relative movement of the receiver and the interference source or the frequency shift at the transmitter source.

From the limitations pointed out, this paper presents the effect of CWI taking into account the interference phase on carrier to noise ratio of GNSS receiver.

2. Methodology

Amongst performance metrics to measure the effect of interference on GNSS receiver performance, the carrier to noise ratio (C/N0) is used because it is strictly related to the positioning performance [1,3]. This section presents the derivation of the signal to noise ratio in the case of CWI interference. Because the receiver processes the satellites separately, the effect of the CWI must be considered for each satellite. Therefore, without loss of generality, we only analyze the effect of this interference on a single satellite signal.

The signal at ADC output contains the interested GPS signal $s(nT_s)$ continuous wave interference $i(nT_s)$and ambient noise $\eta(nT_s)$. The ambient noise can be treated as Gaussian noise. Therefore, the received signal can be modelled as follows:

$$x(nT_s) = s(nT_s) + i(nT_s) + \eta(nT_s) \quad (1)$$

In (1), the components are defined as follows:

$$s(nT_s) = \sqrt{2P_s}D(nT_s + \tau)C(nT_s)\cos(2\pi f_{IF}T_s n + \phi_s)$$
$$i(nT_s) = \sqrt{2P_i}\cos(2\pi f_I T_s n + \phi_i) \quad (2)$$

$\eta(nT_s)$ is modelled as a Gaussian noise

where:

P_s is the signal power of satellite s received at the receiver.
f_{IF} is the intermediate frequency.
T_s is the sampling period.
Φ_s is the initial phase of GPS satellite s signal.
P_i is the signal power of CWI at the receiver.
Φ_i is the initial phase of CWI.

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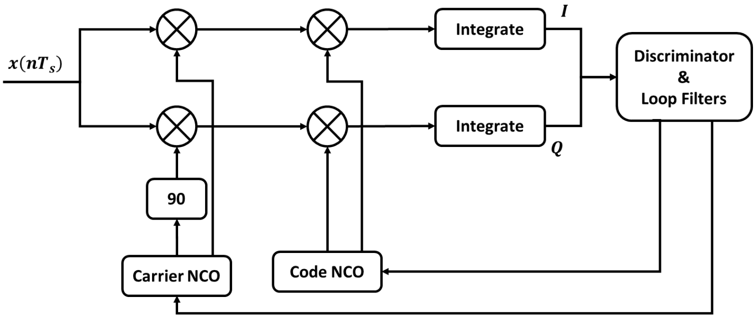

Fig 1. Tracking stage of GNSS Receivers

The received signal is passed through the tracking stage as shown in Fig. 1

The local carrier and code for the satellite *s* can be expressed as

$$IQ_{local}(n) = C(n)e^{j2\pi f_{IF}T_s n+\phi} \quad (3)$$

After integration and dump, GPS signal, interference and noise at m^{th} integration period time become:

$$IQ(m) = IQ_{sv}(m) + IQ_i(m) + IQ_n(m) \quad (4)$$

$$IQ_s(m) \approx A_s T_d F_s R_0(\tau_m) sinc(\Delta f_{IF}^m T_d) e^{j\Delta\Phi_s^m} \quad (5)$$

$$IQ_i(m) \approx \frac{1}{2} A_i F_s T_d C_M sinc\left(T_d \Delta f_i^{kM}\right) e^{j(\Delta\Phi_{i,m}+\pi T_d \Delta f_i^{kM})} \quad (6)$$

$$IQ_n(m) \approx n_{I,m} + jn_{Q,m} \quad (7)$$

where:

$A_s = \sqrt{2P_n}$.

T_d is the integration period.

F_s is the sampling frequency ($F_s = 1/T_s$).

R_0 denotes the cross-correlation function.

τ_m is the code phase difference between incoming and local signal at m^{th} integration period.

Δf_{IF}^m is the residual frequency offset at local signal at m^{th} integration period.

$sinc(x) = \sin(\pi x)/x$

$\Delta\Phi_s^m$ is the residual phase offset at local signal at m^{th} integration period.

$A_i = \sqrt{2P_i}$.

C_M is the M^{th} coefficient of Fourier transform of PRNn.

Δf_i^{kM} is the residual CWI frequency offset at local signal at m^{th} integration period

$\Delta\Phi_{i,m}$ is residual CWI phase at local signal at m^{th} integration period

n_I, n_Q is punctual noise

$N = F_s T_d$

We can remove the role of discriminator and loop filters by assuming that local carrier and code remain keeps align with the incoming signal without loss of generalization. Therefore, (5) and (6) are the same for every m^{th} integration period, they can be reduced as follows:

$$IQ_s \approx A_s T_d F_s R_0(\tau) sinc(\Delta f_{IF} T_d) e^{j\Delta\phi_s} \quad (8)$$

$$IQ_i \approx \frac{1}{2} A_i F_s T_d C_M sinc(T_d \Delta f_i) e^{j(\Delta\phi_i)} \quad (9)$$

To estimate the carrier to noise ratio, there are several techniques. However, [3] as shown that the estimators give similar results with similar results for the GNSS positioning signal. Therefore, we choose signal to noise variance technique to estimate ratio. In this technique, the carrier-to-noise ratio is estimated as follows:

$$\hat{\lambda}_C = \frac{\hat{P}_d}{\hat{P}_n} \quad (10)$$

where:

$$\hat{P}_d = \left[E\left(Re\left(IQ(m)\right)\right)\right]^2 \quad (11)$$

$$\hat{P}_{tot} = E(|IQ(m)|^2) \quad (12)$$

$$\hat{P}_n = \hat{P}_{tot} - \hat{P}_d \quad (13)$$

E(x) denotes the expectation of x.

In the presence of CWI, (11) and (13) can be expressed as follows:

$$\hat{P}_d = \left[E\left(Re\left(IQ(m)\right)\right)\right]^2 = \left|A_s T_d F_s R_0(\tau) sinc(\Delta f_{IF} T_d) + Re\left(\frac{1}{2} A_i F_s T_d C_M sinc(T_d \Delta f_i) e^{j\Delta\Phi_i}\right)\right|^2 \quad (14)$$

$$\hat{P}_{tot} = E(|IQ(m)|^2) = \left|A_s T_d F_s R_0(\tau) sinc(\Delta f_{IF} T_d) + \frac{1}{2} A_i F_s T_d C_M sinc(T_d \Delta f_i) e^{j\Delta\Phi_i}\right|^2 + P_n^2 \quad (15)$$

$$\hat{P}_n = \hat{P}_{tot} - \hat{P}_d = \left|Im\left(\frac{1}{2} A_i F_s T_d C_M sinc(T_d \Delta f_i) e^{j\Delta\Phi_i}\right)\right|^2 + P_n^2 \quad (16)$$

Therefore, the SNV estimator in the presence of CWI can be expressed as

$$\hat{\lambda}_C = \frac{\hat{P}_d}{\hat{P}_n} = \frac{\left|A_s T_d F_s R_0(\tau) sinc(\Delta f_{IF} T_d) + Re\left(\frac{1}{2} A_i F_s T_d C_M sinc(T_d \Delta f_i) e^{j\Delta\Phi_i}\right)\right|^2}{\left|Im\left(\frac{1}{2} A_i F_s T_d C_M sinc(T_d \Delta f_i) e^{j\Delta\Phi_i}\right)\right|^2 + P_n} \quad (17)$$

3. Results and Discussion

3.1. Effect of CWI on C/N_0

In [5, 8], the ratio is expressed as follows:

$$\frac{C}{N_0} = \frac{\left(A_s T_d R_0(\tau) sinc(\Delta f_C T_d)\right)^2}{L_n N_0 + \left(A_i T_d C_n^* sinc(T_d \Delta f_i)\right)^2} \quad (18)$$

Compared with (18), (17) shows the contribution of frequency and phase offset on signal to noise ratio. It is obvious that in (17) the role of phase offset is only shown when the $sinc(T_d \Delta f_i)$ is large enough. In other words, the role of phase difference is only significant when the frequency offset is a multiple of 1KHz.

Because the spectral characteristics of GPS L1 satellites are the same, without loss of generality, the PRN01 is used to visualize the effect of CWI.

As pointed out in section 2, considering a specific satellite will not affect the accuracy of the formula. The parameters for this illustration are selected as follows

Signal of interest (SOI): GPS L1CA PRN01, Power: -160dBW

Noise: Gaussian noise, Power -204 dBHz

Interference: CW interference, Power -140dBW, relative CWI frequency with SOI frequency vary in range from -4 kHz to 4 kHz.

Fig. 2 shows that the C/N0 is formed like the shape of $sinc(\Delta f_i T_d)$. Therefore, the attenuation of C/N0 occurs when the frequency offset is not only at a multiple of 1KHz but also at all the offset that satisfy multiple of 1/Td Hz. However, the metric has the biggest degradation at the peak of the main lobe. The result is consistent with the results of previous studies.

Clearly, through the figure, we can see that the signal to noise ratio is essentially the same for different phase deviation values. However, at the highest peak (when the deviation is a multiple of 1KHz), the signal to noise ratio is very different for different phase deviations.

This figure shows that although having the same power and frequency deviation, the effects of CWI interference are very different with different phase deviation values. Specifically, with the value of phase deviation of 5/6 rad, the signal to noise ratio is not lost as much as the phase deviation of 0 (Fig. 3).

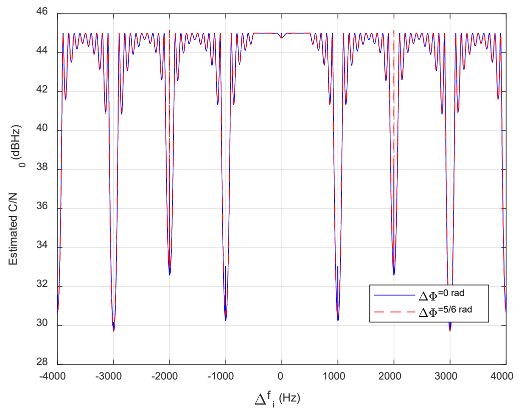

Fig. 2. The theorectical C/N_0 of the satellite PRN01 in the presence of CWI

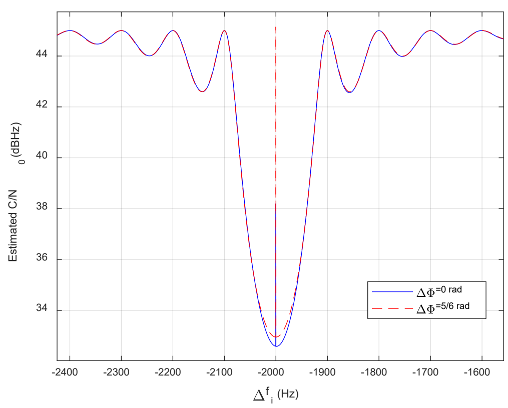

Fig. 3. The theorectical C/N_0 of the satellite PRN01 in the presence of CWI when the frequency offset is -2000 Hz.

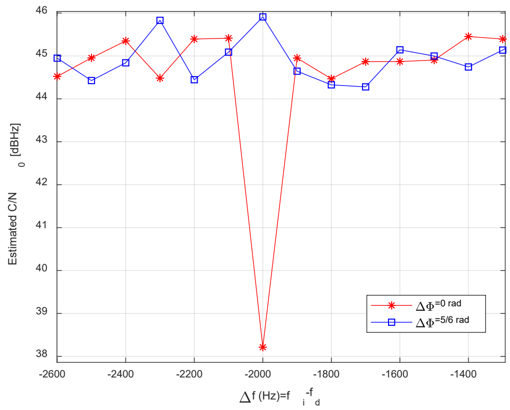

Fig 4. The estimated C/N0 in the simulation scenario

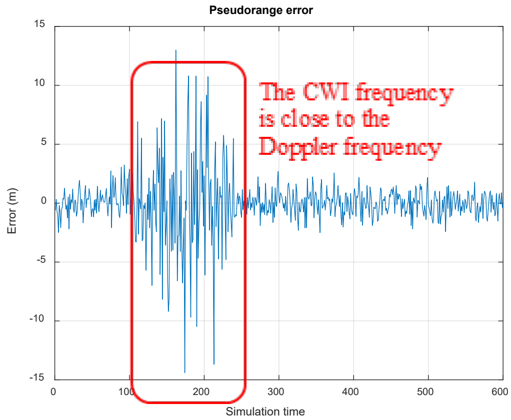

Fig 5. The effect of CWI on GNSS pseudorange error

To verify the 17, we used NAVISIM simulator to generate IF signal and CWI interference according to the above parameters [9].

Signal of interest (SOI): GPS L1CA PRN01, Power: -160dBW

Noise: Gaussian noise, Power -204 dBHz

Interference: CW interference, Power -140dBW

In the simulation, CWI frequency offset varies around 2 kHz with step 100 Hz. Moreover, to clarify the role of phase offset, two values of phase offset are selected (0 and 150 degrees) in this simulation. The simulation result is shown in Fig. 4.

Compared with the theoretical results in Fig. 3, Fig. 4 shows similar simulation results to the theoretical results. Specifically, the effect of different signal to noise ratios on different values of phase difference

3.2. Effect of CWI on GNSS Positioning Accuracy

The GNSS positioning error mostly depends on the pseudorange error of every satellite and dilution of precision (DOP). Because DOP error is caused by the relative position of the GPS satellites. Therefore, to assess the impact of CWI on GPS positioning accuracy, we only consider the impact of CWI on pseudorange error.

Since the distance error is highly dependent on the receiver architecture, it is difficult to theoretically analyze the role of CWI on the pseudorange error. Therefore, in this section, we evaluate the effect of CWI on the error by empirical analysis with our software-based GNSS receiver developed from the architecture proposed by Akos [11].

To illustrate the role of CWI, we used NAVISIM simulator to generate GPS signals but remove all errors except CWI. To avoid the loss of tracking, we choose a smaller power of CW interference with the parameters as follows:

Signal of interest (SOI): GPS signals, Power: -160dBW

Noise: Gaussian noise, Power -204 dBHz

Interference: CW interference, Power -150dBW

To show the impact of CWI, we choose the satellite PRN01 and a time interval when the CWI frequency is close to the satellite Doppler frequency.

This figure shows that the pseudorange error increases significantly when the CWI frequency is close to the Doppler frequency. This is consistent with the claims in this study and [10].

4. Conclusion

In this paper, we have presented a generalized formula for the effect of signal to noise ratio considering frequency deviation and phase deviation. The similarity between simulation and theoretical results shows the correctness of the generalized formula. In addition, the theoretical and simulation results also show that the effect of the phase difference of the CWI on the signal is greatest when the frequency deviation is a multiple of 1kHz.

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