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Publication details:
Proceedings of IGNSS2007

Event details:
IGNSS2007
Sydney, Australia

Publication Date:
2007

DOI:
https://doi.org/10.26190/unsworks/720

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ABSTRACT

GNSS receivers have been shown to be most vulnerable to CW interference. It affects the acquisition process of the signal and can also pass through the tracking loop filters to affect the received satellite signal quality. Carrier to noise density ratio (C/No) is an indicator of received signal quality to the receiver. Lower C/No means lower quality of the received signal. Galileo satellites will be soon in place operating together with GPS satellites. Considering the designer's intention of maintaining interoperability between different satellite navigation systems, it is reasonable to seek a quantified comparison between the different systems in terms of vulnerability to CW interference. In this paper, considering the signal structures, the characterization of the effect of CW interference on the C/No for GPS and Galileo is investigated and compared. It is shown that for the available Galileo signal (GIOVE-A BOC(1, 1) in the E1/L1 band), the worst spectral line happens far from the L1 frequency. A frequency was selected which is midway between the GPS and Galileo worst spectral lines, and for the same power of RFI, GPS is shown to be more vulnerable to interference. Also the probability of availability of one GPS satellite is compared with that of one Galileo satellite in terms of interference power and frequency. It is shown that these two systems can be considered as alternatives to each other in the presence of different RFI frequencies as their availability in the presence of CW RFI is different in terms of RFI frequency (L5, L2C, E5 and E6 are not considered).

KEYWORDS GPS, Galileo, Interference, C/No

1. INTRODUCTION

In recent years there has been a rapid growth in the utilization of GNSS across a diverse range of application areas. However, coupled to this expansion in use has been the expansion in awareness that GNSS is potentially vulnerable to sources of interference. This has caused particular concern in the domain of transportation, as indicated for example by the US Department of Transport's undertaking of a report entitled 'Vulnerability Assessment of the Transportation Infrastructure Relying on GPS' [1]. Whilst this report dealt specifically with the issue of GPS usage within the transport infrastructure of the US, there are vast numbers of other applications in which GPS is continuing to play a crucial role that are similarly vulnerable. Mobile communication networks require that the base-stations of their radio access networks be synchronized. [2, 3], and surveyors use GPS for an increasing portion of their work. The fact that Galileo shares a number of design commonalities with GPS means that the subject area remains equally valid for Galileo.

Galileo will however have some important differentiators between itself and GPS, such as multiple civil frequencies (also planned for GPS), integrity and encryption of some civil signals, which improve performance over current GNSS standards in terms of interference, performance monitoring and resistance to production of misleading information. Whilst these characteristics shall provide undoubted improvements, there remains scope to further improve the situation at ground level through the introduction of complementary techniques and developments in the user equipment. CW interference has serious adverse effects on the quality of the received GNSS signal [4]. It passes through the tracking loop filters when coincident with the signal code spectral line [5] and severely affects the correlator outputs [6, 7]. Interoperability and compatibility between different GNSS systems has become a hot topic recently. This means that receivers have to be capable of receiving different signals and cope with intersystem interference [8]. Many works have assessed the effect of different types of interference on Galileo [9, 10]. It is the objective of this paper to focus on CW interference, in order to compare the effect of CW interference on the quality of the received Galileo BOC(1,1) in the E1 band and GPS C/A signals in the L1 band (i.e. on the same carrier) using the same approach explained implicitly for GPS signal in [6]. In section 2 the signal structure for both systems is analysed. In section 3 using the 'Kai Borre software receiver' [11], the dependence of C/No on the loop updating rate (integrator).and the Doppler frequency is examined. Also, the effect of CW interference on the received signal quality for the two systems is analysed. In Section 4, the probability of GPS and Galileo satellite availability is investigated in the presence of CW RFI. This paper concludes in section 5.

2. STRUCTURE OF THE E1/L1 SIGNALS

2.1 GPS Signal Structure

All GPS satellites use the same frequency band and make use of the code division multiple access (CDMA) technique. Spread spectrum signals are transmitted including different ranging codes per signal, per frequency, and per satellite. The code is a Gold code with a relatively short 1-ms period (i.e., the PRN sequence repeats every 1 ms). Therefore, the C/A code (neglecting the navigation data) has a line spectrum with lines 1 kHz apart [4]. In the correlator which is a combination of a delay lock loop (DLL) and a phase lock loop (PLL), the carrier and code phase are tracked. The approach in [6] is to calculate the carrier to noise density ratio using the correlator output power resulting from each of the signal, interference and noise. For the special case when the interference is continuous wave (CW) with fixed carrier frequency, then in [4] and [12], it has been shown that its effect on C/No depends on the Doppler frequency of the satellite signal and also the duration of the integration and dump block used inside the loops.

2.2 Galileo Signal Structure

Similarly to the effect of interference on GPS, interference effects for the Galileo signal (BOC(1, 1) of El band) depend on its unique PRN code spectral line structure. Therefore the Galileo signal structure and tracking method as part of a receiver design should be first analysed.

GIOVE-A is the first and only prototype Galileo satellite launched. It started to transmit satellite signals modulated by the navigation message, the E1 carrier (which is the same as L1) and the Binary Offset Code -BOC (1, 1) spreading code on 12 January 2006. BOC (1, 1) can be regarded as the modulation product of PRN and square wave sub-carrier which has a same chipping rate as Pseudo Random Noise (PRN) (shown in Figure 1). The GIOVE-A E1 signal has two separate channels: a data channel (modulated with a 1.023Mchip/sec PRN, the B-code, with 4ms period and 250chip/sec navigation data) and a pilot channel (modulated with a 1.023Mchip/sec Primary PRN code, the C-code with 8ms period and a 125chip/sec secondary PRN code, the S-code with 200ms period. The signal generation scheme is shown in Figure 2. As the navigation data period is the same as one full length of 4ms of B-code, the maximum non-coherent integration time for the data channel will be 4ms. A similar situation exists on the pilot channel where the S-code has a code period of that of one full C-code length. Therefore, the S-code in the pilot channel can be treated in a similar way to the navigation data in the data channel. If the tracking loop update rate (integration time) for the pilot channel is chosen to be 8ms for the maximum non-coherent integration time, the S-code will be 'invisible' during the whole tracking process. Once the tracking loops for the pilot channel has successfully tracked the S-code, a coherent tracking process can be performed and therefore aid the data channel tracking. Based on this idea, the analysis of pilot channel tracking performance in the presence of interference becomes more important for a Galileo receiver design. Therefore the interference experiments on GIOVE-A in this paper were carried out on the pilot channel and where the GIOVE-A signal is mentioned, we refer to this signal.

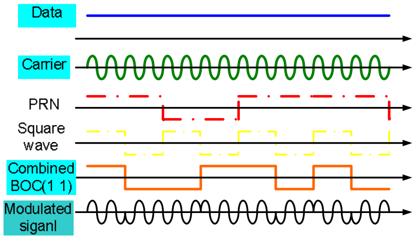


Figure 1. Galileo BOC(1,1) modulation scheme

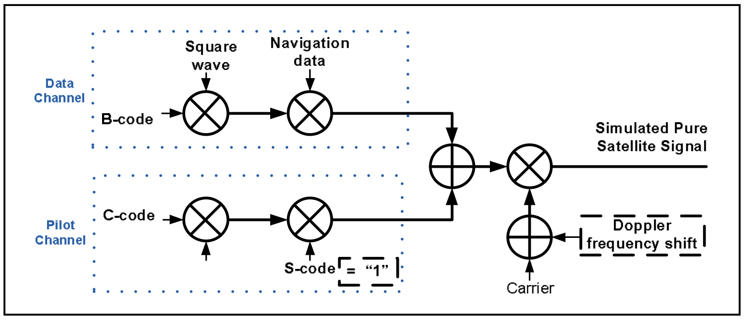


Figure 2. GIOVE-A Signal generation for E1 band BOC (1,1)

3. COMPARING THE EFFECT OF CW RFI ON GPS AND GALILEO SIGNALS

To investigate the effect of a specific type of interference on the received signal quality, tracking loop bandwidth, signal to noise ratio, and also the Doppler frequency of the received signal are the important parameters to be considered.

3.1 The Experiment Setup:

Data generation:

Based on the signal generation schemes of ICD (GIOVE-A) [13] and ICD (GPS)[14], each sampled Binary Phase-Shift Key (BPSK) signal modulates a carrier whose frequency changes linearly with time. The generation approaches for GPS and Galileo simulation signals are shown in Figure 3 and Figure 4 respectively. As the S-code of GIOVE-A is invisible when

8ms integration times are used, it can be regarded as the “navigation bits” for the pilot channel, similar in a way to the Galileo data channel and the GPS L1 signal. Therefore the effects of the S-code in the GIOVE-A pilot channel and the Navigation data for GPS are not included in the simulation data. The linear Doppler frequency shift applies only to the carrier frequency while the minor effect on code phase is neglected. Moreover as the changing Doppler frequency shift will determine how fast a CW RFI sweeps across the PRN spectral lines in the frequency domain, the Doppler frequency shift rate has to be slower when the spectral lines are close to each other, so overlapping between the RFI and each spectral lines is avoided (discussed later in 3.4). Therefore, in order to distinguish the interference effect on C/No, a simulated pure Galileo satellite signal should have a slower Doppler frequency changing rate (0.5Hz/Second and 1Hz/Second) for 10mins compared to two simulated pure GPS satellite signals (2Hz/Second and 3Hz/Second for 20minuts data). Finally, additive white noise and interference are added on to each of the pure satellite signals.

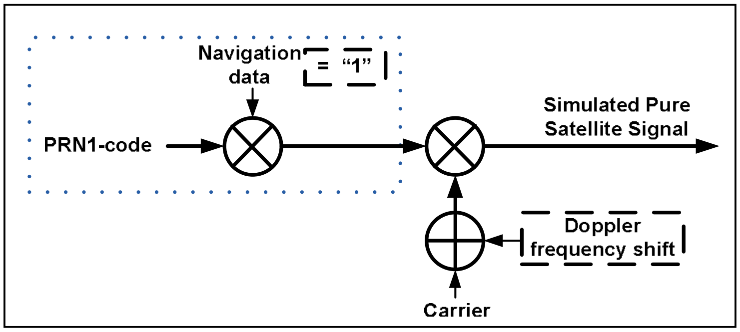


Figure3. GPS signal generation for L1 band C/A code

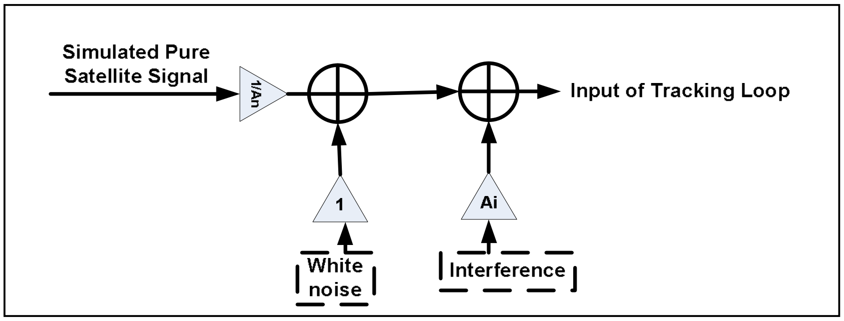


Figure 4. Galileo BOC(1,1) modulation scheme

Tracking Loop design:

For fair comparison, the tracking loops for both GPS and Galileo discussed in this paper are designed based on the ‘Kai Bore’ GPS software receiver [11] using a conventional Costas tracking loop method with similar tracking loop parameters. However, the conventional delay lock loop (DLL) for BOC (1, 1) is more sensitive to noise [15] because of the ambiguity property of the DLL for binary offset code. Therefore in order to avoid the possibility of false lock and lost lock, the noise power (proportional to $\sqrt{An}$, where An is the noise amplitude) for this experiment is set to be as low as only 4 times (6dB) higher than the pure satellite signals power (proportional to $\sqrt{As}$, where As is the pure signal amplitude).Also, the threats of acquisition ambiguity is eliminated during the acquisition process by always acquiring a signal whose C/No is higher than 50dBHz [15]. In this way, the effect of interference on both GPS and Galileo signals dominates the effects of noise. Although this is not a realistic situation, both of GPS and Galileo tracking loop hence be able to keep lock and only the effect of interference on both signals can be pronounced.

Besides noise level and interference level, the C/No computed from the Costas loop outputs of I-Prompt and Q-Prompt has to do with the phase error which relies on the tracking loop parameters (e.g. integration time: T, loop gain: G, and DLL discriminator early and late chip distance: d)[6]. So in order to have a fair tracking loop performance comparison by considering the different input of Doppler frequency acceleration , integration time for GPS and Galileo signal tracking simulation and their different auto-correlation function shapes, the different tracking loop parameters are chosen as shown in Table 1.

	GPS		Galileo		
Integration time T	8ms		64ms		8ms
Gain for DLL (Gd)	1		1.5		1
Gain for PLL (Gp)	0.9		1		0.5
data(Doppler change rate)	2Hz/Second	3Hz/Second	0.5Hz/Second	1Hz/Second	0.5Hz/Second
Average C/No without interference (6dB of signal to noise ratio)	60.3274dBHz	60.7227dBHz	50.7595dBHz	50.8010dBHz	54.6475dBHz
Early-Late distance (d)	0.35chip		0.1chip		
sampling frequency (Fs)	16367600Hz				
Intermediate frequency fIF)	4130400Hz				
* The C/No is obtained using C/No estimator [Eqs. (117), PP.392,Parkinson&Spilker Jr.,1996]					

Table 1. Tracking Loop setting for different data and their C/No

The settings in Table 1 are selected to maximize the possibility of keeping lock for both GPS and Galileo signals in the presence of varying frequency and power of CW RFI. The average C/No (in table1) is used to compare with the CNo values obtained from the Costas loop output when CW RFI is present, in order to isolate the effect of CW RFI when the satellite availability of possibility is compared in section 4.

3.2 Worst Spectral Line for GPS PRN1 and Galileo GIOVE-A:

According to the mathematical expression for C/No [6], the PRN spectrum line which has the highest power in the frequency domain will be most vulnerable to the same frequency of CW RFI. For convenience, that particular strong frequency component is known in this paper as the “worst line”. Different PRNs have different worst lines. In order to compare to the worst case in the environment of CW RFI for both GPS and Galileo receivers, the unique worst lines for both GPS PRN1 and Galileo GIOVE-A have been found. GPS PRN1 has a full length code period of 1ms, so the spectrum lines (neglecting the navigation data) are evenly 1KHz away from each other [4]. The GIOVE-A C-code has 8ms full length, so the Dirac lines of the pilot channel PRN spectrum are thus closer at 125Hz apart. By selecting an appropriate resolution in the frequency domain, each of the separate spectral lines for both PRN1 and the GIOVE-A pilot channel PRN can be clearly seen in Figure 5. The worst line is at 42127Hz for PRN1. The worst line is at 771770Hz for the GIOVE-A pilot channel C-code (with the second worst line at 603640Hz).

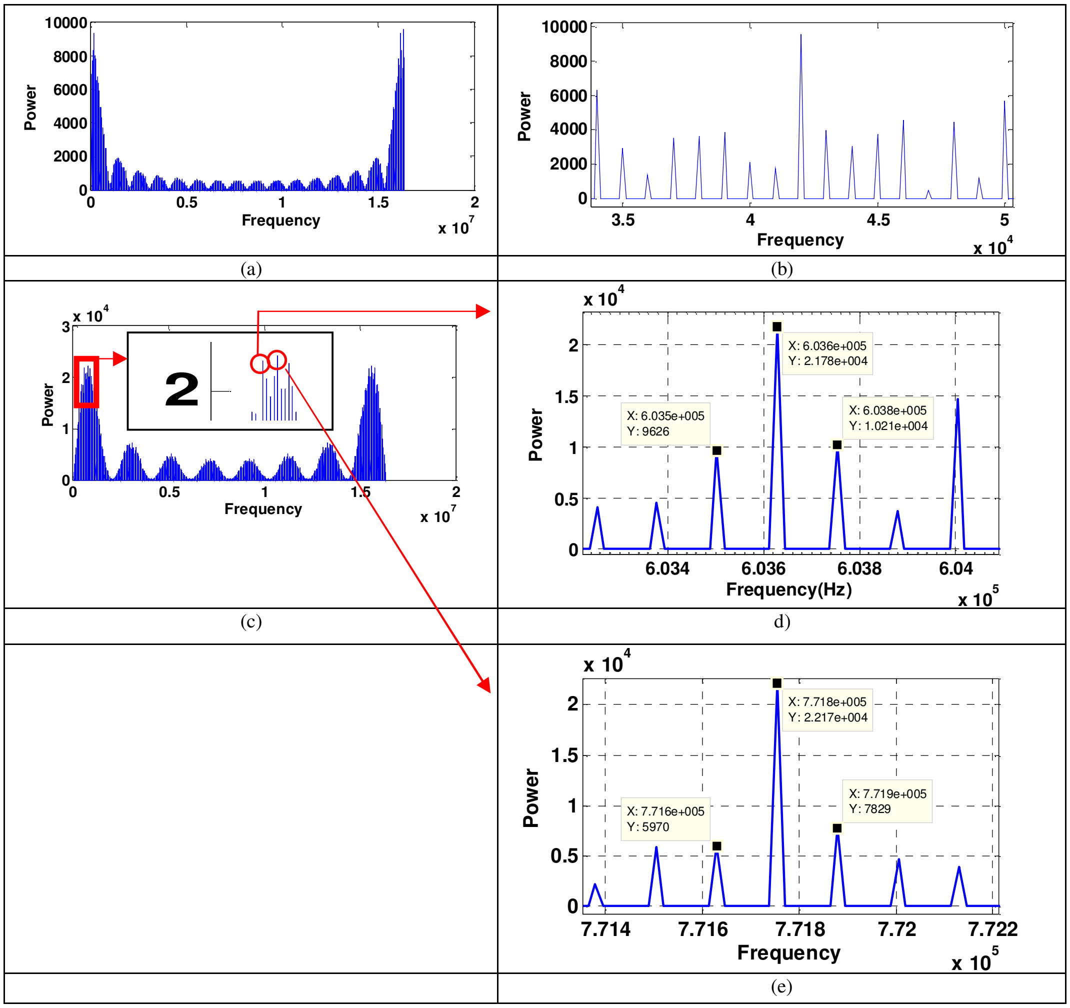


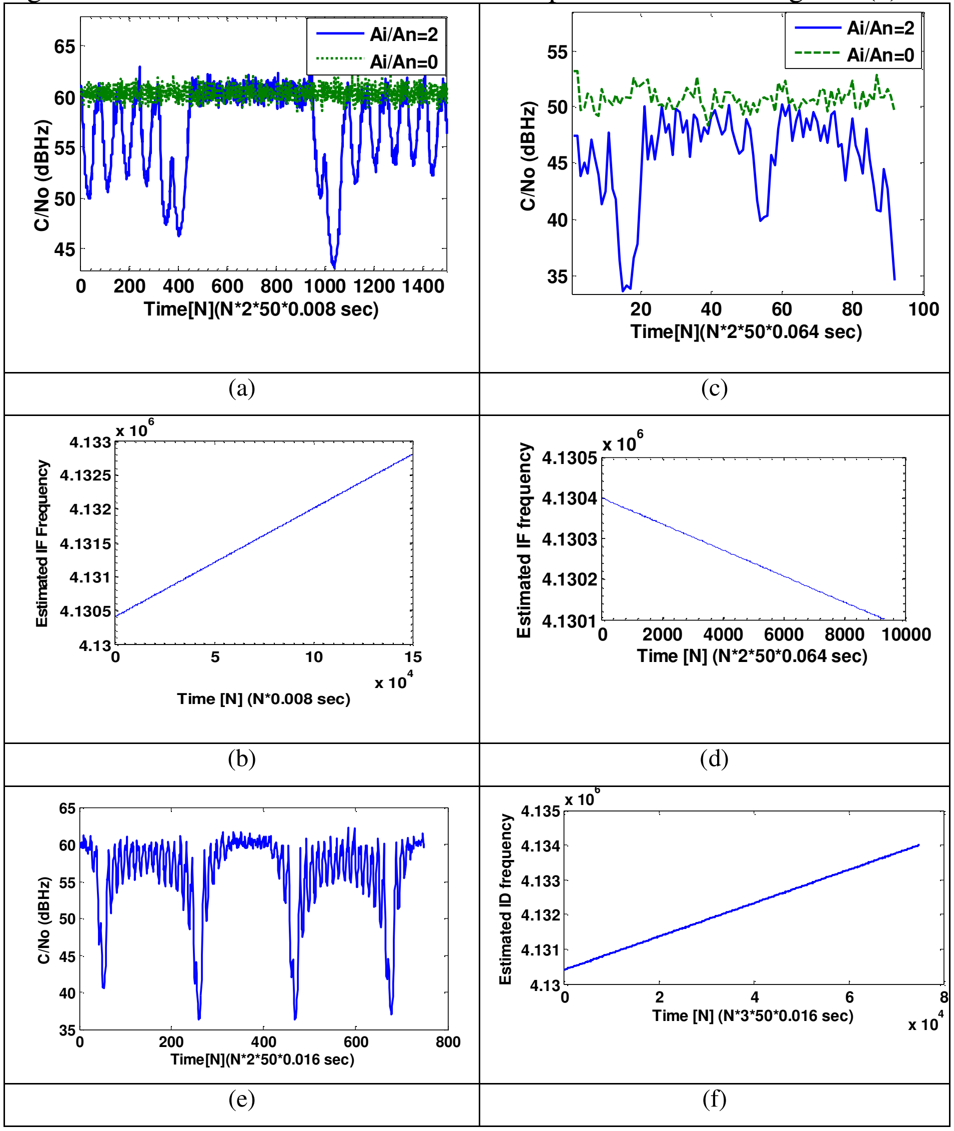
Figure 5. PRN spectrum and their worst lines
(GPS PRN1 spectrum (a) and its 42127Hz frequency component (b) ;
Galileo C-PRN (Square wave modulated with C-code) spectrum (c) and its 603640Hz frequency component (d) 771770Hz frequency component (e)

3.3 Doppler Frequency

One function of the Costas loop is to track and remove the carrier of the incoming signal to extract the navigation data [16]. When the carrier shifts with Doppler, the band centre of Costas loop will shift accordingly. Therefore, CW interference will be swept across different spectral lines in time [6]. The data used in the experiment is designed based on this idea as mentioned in part 3.1. Higher Doppler frequency and longer data length will cause more frequent coincidences to happen, while wider PRN code spectral line spacing will have fewer coincidences in the same time, but the effects are more pronounced.

Figure 6 is an example of C/No calculation using the narrow-to-wideband power ratio method [5]. The C/No for GPS PRN-1 and Galileo signal tracking output are estimated in the presence of CW RFI with a frequency close to their worst lines (which are at 42127Hz for GPS PRN-1 and 603640Hz for GIOVE-A C-code) respectively. Both signals were assumed to have the same environmental noise power (6dB higher than signal power) and for each the tracking loop update rate (integration time) is 8 times of each PRN code periods (discussed in 3.4. As can be seen in figure 6(b), the C/No for GPS PRN-1 is drawn with Doppler frequency (2Hz/Second) changing from 0Hz to 2.4KHz in 20min of data. The deep troughs in Figure

6(a) correspond to the coincidence of CW RFI with the code worst line and its neighbours. It clearly shows that two coincidences happen with about 1 kHz spacing which is determined by the PRN code period (1ms) and explained in [6]. However, the C-code of GIOVE-A has code period of 8ms and the coincidence of CW RFI with its Galileo signal will happen at 125Hz spacing. To draw a C/No for the pilot channel of GIOVE-A with about 2 deep troughs, a satellite signal has a Doppler frequency rate 4 times lower (0.5Hz/Second) and half the data length (10min) is required. The corresponding C/No result and its estimated carrier frequency are shown in Figure 6 (c & d). One interesting phenomenon shown in Figure 6(a) is that, there is a period of "no effect" of RFI with frequency close to the worst line of GPS PRN1. This "no effect" zone happens on the every other period between two coincidences. To clearly show this effect, another set of GPS PRN-1 data (with 3Hz/sec Doppler shift) is tracked using 16ms integration time. Its CNo and estimated carrier plot are shown in Figure6 (e) and (f).



(a) (c)

(b) (d)

(e) (f)

Figure 6. C/No computed from GPS PRN-1(a) ; its estimated Carrier (b)and GIOVE-A C channel (c) tracking results & its estimated Carrier (d); The CNo computed from GPS PRN-1signal (with a 3Hz/sec Doppler shift) tracking loop output with the presence a RFI closed to its worst line(T=16ms)(e); and its estimated Carrier (f).

3.4 Receiver Tracking Loop

Figure 7 is an example of two different integration periods on otherwise the same tracking loops using the same simulated GPS satellite signal. In these two cases, the level of noise has been intentionally kept low as well, so that the effect of interference is more pronounced. The big troughs in the figures occur at the time when coincidence between CW RFI (4.5 KHz away from band centre) and two of the spectral lines of GPS PRN-1 happens. The ripples in the figures have to do with the tracking loop update rate which here is the same as the integration and dump period. The width of each sinc function (around each trough) is inversely proportional to the integration period. The longer the integration time (T), the narrower will be the sinc function [6] and the deeper the trough. As can be seen from Figure 7, the main lobe of the symmetrical sinc functions has a width of 250Hz or 125Hz (=2*dF kHz, where dF is 1/T).

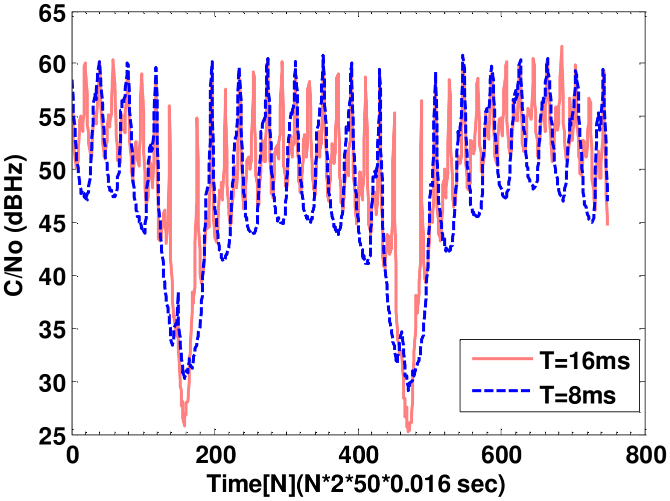
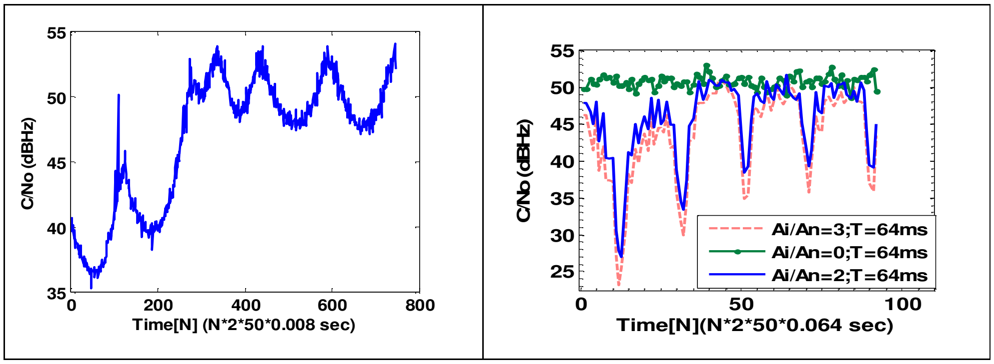


Figure 7 C/No of tracking results using different tracking update rate (T) for the same GPS data based on the same tracking loop

The same theory can also be applied to the Galileo GIOVE-A signal which has same power of noise and CW RFI (603640Hz away from band centre) compared to the GPS signal. On this data, the Doppler frequency changes from 0Hz to 600Hz in 10min. Because the C-code has a code period of 8ms, each sinc function should be 125Hz apart from its neighbours. Meanwhile, if the integration time (T) is also 8ms, each sinc function should have a width of 250Hz, so two neighbouring sinc functions will overlap each other. This situation is illustrated in Figure 8 (a). For a more obvious sinc function showing the effect of CW RFI , 64ms integration periods were used, as shown in Figure 8 (b).By comparing Figure8 (a) and (b), it is noticed that the troughs of which is using 8ms integration period are shorter and wider than that of using 64ms integration time. Another point to note in this figure is that the ratio of C/No decrease has to do with the power of each spectral line component in the frequency domain, as was also the case for GPS. The higher the power of the spectral line the more serious and the wider neighbourhood are affected in terms of C/No decrease when a coincidence happens. Moreover, by comparing the two graphs in Figure 8(a) and (b), the C/No shown in (b) is lower comparing to (a). That is also because the high Doppler frequency ramp (1Hz/sec) having a lower update rate for the same tracking loop would introduce higher phase error. A concern therefore arises from Figure 8(b) about how the C/No can be influenced by other different environment factors (e.g. noise power and interference power).



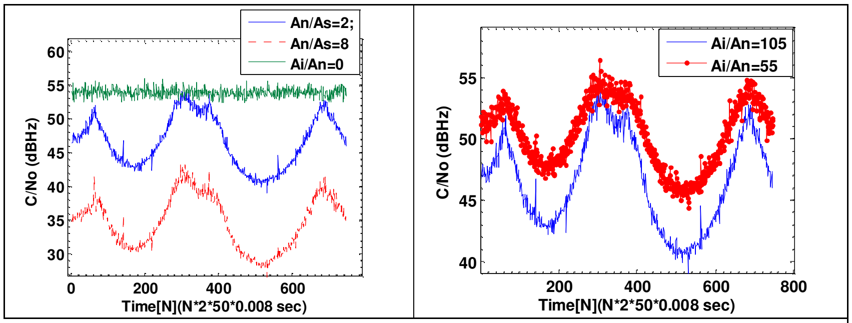
(a) (b)

Figure 8. C/No of tracking results using different tracking update rate (T) for the same GPS data based on the same tracking loop(a: T=8ms; b: T=64ms)

3.5 RFI Power

It is understandable that with a lower signal to noise ratio (S/N) of input signal, greater phase error can occur in the PLL thereby causing lower C/No. That is also shown in Figure 9 (a) where the same Costas loop is applied to the same Galileo signal in the presence of different environment factors (e.g. S/N and power of CW RFI).When there is no interference (green) added to the input signal, C/No is quite constant over the whole 10min tracking period. With the same S/N, when a constant power of CW RFI presents in the input signal, serious C/No attenuation (Blue) can happen when spectral lines coincide with the CW RFI. When an input signal with a fixed power of CW RFI (Ai=2) but varying S/N (As/An=2 (or S/N=-6dB) and As/An=8 (or -18dB)), the big troughs and their neighbourhoods remain a similar shape although the whole figure of C/No has "moved" down. This shows that it is only the CW RFI that determines the C/No "sinc shapes" which is consistent with the results derived in [17 and 18].

The "depth" of the main lobe of the sinc function is not only determined by the power of affected spectral lines but also the power of the additive CW RFI. Figure 8 (b) has shown the relationship between such a ratio of C/No "depth" and the power of CW RFI added with the same S/N(=-6db). In that case, when a 6dB stronger power of CW RFI(Blue) is added to the input signal, C/No decreases by about 6dB (compared to red). This is true only at the "peaks" of the main lobes, where coincidence between spectral lines and CW RFI happens. The influence of CW RFI also occurs away from those "peaks" due to ripples from the next "coincidence zone". In general, for the same frequency of CW RFI (10 KHz away from band centre), the stronger power of CW RFI has led to the lower C/No (blue).



(a) **(b)**

Figure 9. Same Costa loop applied to different environment: (a) different S/N : (b)

different power of CW RFI (about 10Khz away from band center) -using 10min pure satellite signal has 0.5Hz/sec doppler frequency shift .

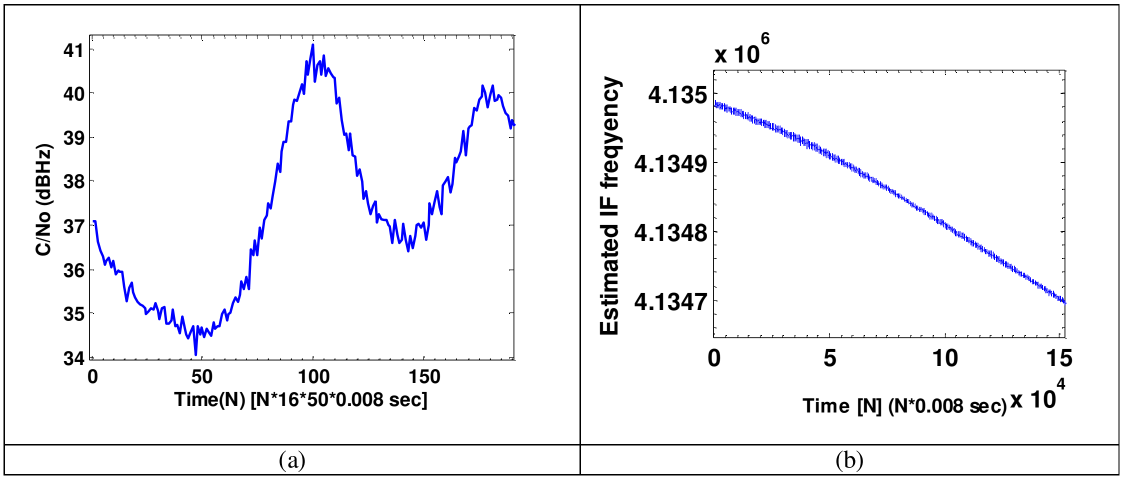
These effects of different power CW RFI on GIOVE-A are well matched to the theory described in [6], which characterizes the effect of CW RFI on GPS L1 C/A code. Therefore to provide interoperability between the two GNSS systems at the L1 frequency may require comparing the CW RFI effect on two systems, at a comparable CW RFI frequency. An experiment was carried out by adding a CW RFI whose frequency is 406950Hz, which is midway between the worst lines of GPS PRN-1(42127Hz) and Galileo GIOVE-A C-code (771770Hz). The interference to signal ratio (20log10(Ai/As)) changes from 6dB to 22.9 dB while each signal has a constant S/N (-6dB). The 20 min GPS signal has 3Hz/sec Doppler frequency change whereas the 10 min Galileo signal has 0.5hz/sec Doppler frequency change. Using the tracking loop settings described in 3.1 each of the computed C/No values exhibits 3 troughs over the total tracking period. For the sake of having the same power of CW RFI involved in the tracking loops and comparable shape of CNo troughs when the same power of CW RFI affects, both 8ms and 64ms integration periods are applied to the Galileo signal; while GPS has an integration period of 8ms. The minimum value of C/No for a particular power of CW RFI for each signal is compared to their average C/No in Table 1. Their corresponding differences are shown in Table 2. Those differences are the lowest “depth” of the sinc functions and only determined by the power of interference. So in this way the phase error caused by other factors (e.g. different Doppler frequency acceleration or tracking loop design settings) can be neglected. According to Table 2, the GIOVE-A pilot channel has a better tolerance to CW RFI than GPS PRN-1. The Galileo signal also has the best tolerance for 8ms integration times, because shorter integration time will lead to shorter but wider troughs as discussed in 3.4. This result is also helpful to the satellite availability analysis in part 4.2, where the experiment setup is the same as here.

20log10(Ai/As)	GIOVE-A(64ms)	GIOVE-A(8ms)	GPS PRN1(8ms)
6.0	-12.4	-5.4327	-19.1
15.5	-20.7	-11.7880	-27.4
20	-28.9	-16.1374	-31.8
22.9	-32.7	-18.7483	-35.1

Table 2 C/No decrease ratio for GPS PRN1 and Galileo GIOVE-A at the present of CW RFI frequency at 406950Hz

3.6 Real Galileo and GPS signals

The Real intermediate frequency (IF) GIOVE-A data was recording from time (UTC): 25 Apr 2007 - 02:08:38 by using the Nordnav Software receiver at SNAP lab of UNSW (an observing location of 33.5517°S, 151.1340°E). Figure 10 shows the real Galileo signal tracking results for the first 20 min of recorded data applying the same tracking loop (8ms of non-coherent type) which has introduced in this paper. The carrier tracking results (Figure10 (b)) shows that the Doppler frequency of the real signal was changing for about 300Hz per 20 min. The two troughs on this C/No results (in Figure 10(a)) illustrated a similar features that has discussed in 3.3 (Figure6(c)).



(a) (b)

Figure 10 (a)C/No and (b)Estimated carrier of recorded real GIOVE-A data

4. SATELLITE AVAILABILITY

The term “exclusive zone” was introduced in [12]. If there is a certain value of C/No that has been set as a threshold and regarded as the minimum signal quality that a GNSS receiver tracking loop can handle, those interference corrupted signals resulting in low C/No below the threshold, will be regarded as “unavailable”. Different satellite systems might have different C/No characteristics in a hybrid GPS/Galileo L1 receiver when the signal is exposed to the same CW RFI frequency and power level.

In order to analysis the system interoperability in terms of satellite availability due to the effect of CW RFI on two satellite signals, an experiment was designed. The method is indicated in Figure 11. First of all a mean value of vectors of C/No (Pink) are calculated when there is no interference present in the generated noisy satellite data ((S/N=-6dB) described in Table1). The mean values of C/No (light Blue) of GPS and Galileo signals are computed respectively. Hence each of the C/No thresholds (red) are set at a value with the same amount of margin (5 dB off in 4.1and 10dB off in 4.2) from that C/No mean value respectively.

The Galileo data used in this experiment has Doppler frequency changing at 0.5Hz/sec for 10min while the GPS data has a change of 3Hz/Sec for 20 min. As discussed in part 3.4 and 3.5, the width of the main lope of C/No sinc function is inverse proportional to integration time T and proportional to the value of the power of CW RFI. So in order to discard the effect of different integration time on two tracking loop, 8 times of integration time (T= 8ms for GPS and T=64ms for Galileo) compared to their PRN code periods is selected. The width of each symmetric sinc function main lobe will occupy 2/8 times of each interference affected zone area (which equals the distance between two sinc “peaks” in the time domain) aroused by the coincidence between CW RFI and each of the spectral lines. In other words, the width of the sinc function main lobe in this experiment will be only depend on the PRN code period and also the effect of CW RFI on each crossing spectral line. So that d1 and d2 is the threshold crossing period (in Figure 11). The satellite availability probability (Pa) is then obtain according Eq. 1

$$P_a = 1 - \frac{\sum_{N=1,2\ldots i} d_i}{D} \quad \text{(Eq 1)},$$

where N is the number of troughs crossed by the threshold.

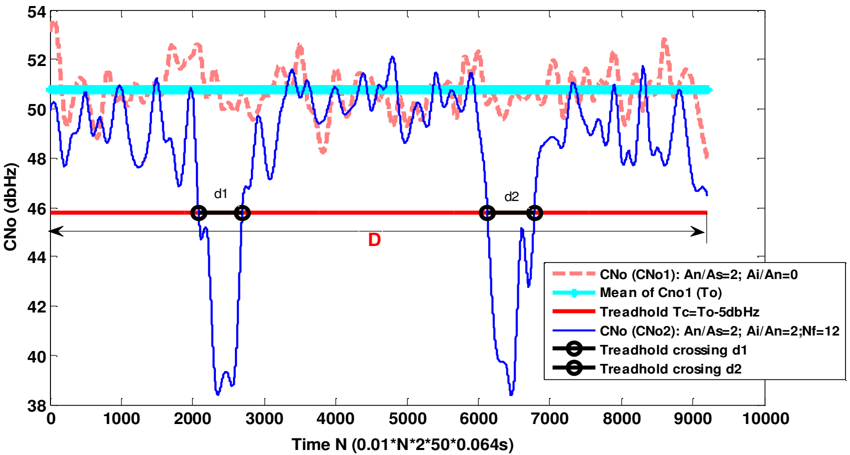


Figure 11. Experiment method illustration for satellite availability analysis.

Unfortunately, when concerning the same power of CW RFI that involves inside the tracking loop, there is no simple linear relationship between the integration time and the power of CW RFI that go through the loop filter. Although longer integration time should be expected to have higher power of spectral lines and thereby the signal is more affected by the same power of CW FRI, loop bandwidth is inversely proportional to the integration time. The longer of the integration time, the narrower loop bandwidth (also means the better CW RFI rejection property) the tracking loop should have. Therefore, tracking experiment with 8ms of integration time for Galileo signal is also carried out, for the simplicity of comparison with that for GPS signal, to ensure same power of CW RFI can go through the loop filter, although a trade-off has to make to having overlapping C/No sinc function on Galileo signal.

4.1 RFI Frequency

Based on the previously described experiment setup for satellite availability analysis, different frequency but same power CW RFI was added to each of the satellite signals before tracking. The frequency of CW RFI is changing from 0Hz to 771700Hz. As expected from the worst line theory, each of the lowest Pa for a satellite of GPS (PRN-1) and a satellite of Galileo signal exists at a CW RFI frequency close to their worst lines. But Galileo appears to be more seriously affected (Pa=0) by a CW RFI whose frequency is close to its second worst line when for a 64ms integration time. When the CW RFI comes close to the GIOVE-A C-code second worst line, the combined effect from three nearby lines are so strong that the signal quality drops dramatically. When the CW RFI comes close to 771770Hz, the combination of the worst line itself and its neighbour lines caused satellite probability of availability of about 0.5037 which is similar to when CW RFI frequency is close to the worst line of GPS-PRN-1.

However, Galileo also exhibits a less vulnerable character over a wider range of CW RFI frequencies than GPS does for a 64ms integration time. As can been seen for the Pa for GPS PRN1, Figure 12 (red) is almost always lower than that of Galileo GIOVE-A (blue) over the chosen frequency range. However, when 8ms integration time is utilized (Green), the wider C/No exclusive zone “pulls” down the Pa for GIOVE-A quickly when the C/No for GIOVE-A is lower than the thresholds. A crossing happens between GPS (8ms) and Galileo (8ms) almost right at the midway between the two worst lines. This implies that GPS and Galileo might be able to cooperate together in a hybrid GPS/Galileo L1 receiver with 8ms integration times for both Galileo/GPS tracking loops, as one compensate the other.

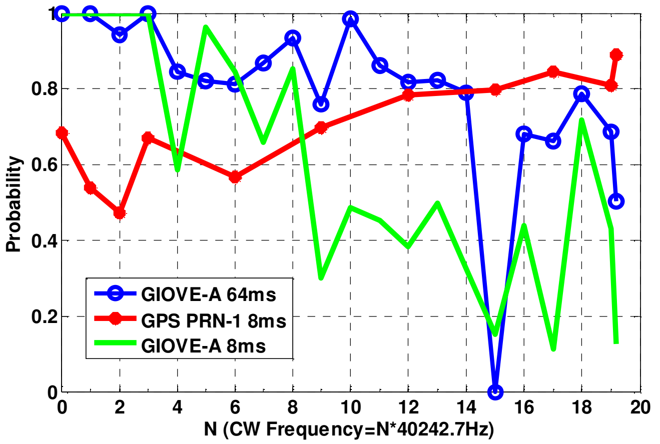


Figure 12. Pa of GPS and GIOVE-A availability with varying frequency of CW RFI

4.2 RFI Power

As expected according to the results in Table 2, GPS PRN-1 has lower satellite availability probability (comparing to that of 64ms integration time for Galileo signal) with an increasing power level of CW RFI until the tracking loop loses track (when 10log10 (Pi/Ps)>27dB in Figure 13, where Pi and Ps is power of interference and signal respectively) because of poor signal quality. In this experiment the setup of part 3.5 was used, with a frequency of 406950Hz CW RFI added onto both GPS and Galileo signals with a power level changing from 6dB to 27dB.

The Pa (Green) for Galileo (when 8ms of integration time is used) is the highest where the power of CW RFI is lower than 15dBHz. However, it drops dramatically when the wide C/No sinc function falls below the threshold, although its C/No is actually still the best among the three (shown in Table 2). Such a crossing between GPS (8ms) and Galileo (8ms) again shows a possibility of interoperability between GPS and Galileo signal on a hybrid GPS/Galileo L1 receiver when different power of CW RFI exists.

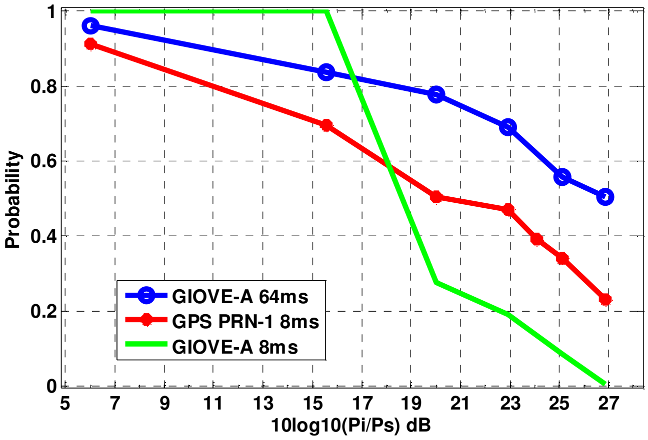


Figure 13 . Pa of GPS and GIOVE-A availability with varying power of 406950Hz CW RFI

5. CONCLUSIONS

In this paper, after looking at the structure of the GPS and Galileo signals, the effect of CW interference on these two signals is analysed. The difference of effects is first explained based on the difference between the two signal structures. Then the difference is investigated for different interference powers and frequencies. It is shown that the integration time which is a receiver parameter can affect the shape of C/No and is considered in the analyses. Worst spectral lines are evaluated for the both signals and the effect of CW RFI on a real Galileo signal collected by the NordNav RF front-end is examined. It is shown that for similar conditions, the drop in C/No in the presence of RFI located in the middle of the bandwidth is always larger than that of Galileo signal. Finally giving a definition of probability of availability of a satellite within its visible period, it is shown that a Galileo signal is more probable than GPS signal to be available in the presence of CW RFI close to L1 frequency and GPS signal is more probable to be available in the presence of interference which is far from L1 frequency (for the two particular codes selected). This means that these two systems can be considered as alternatives to each other in the presence of different RFI frequencies as their availability in the presence of CW RFI is different in terms of RFI frequency.

ACKNOWLEDGEMENTS

The authors acknowledge the support of the CRC for Spatial Information in funding this project (CRC-SI Project 1.1).

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