Exclusion zones for GNSS signals when reconfiguring receiver hardware in the presence of narrowband RFI

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Abstract

Narrowband interference can severely degrade the performance of GPS receivers. Detecting the presence of interference and then characterizing it can lead to its removal. Receivers can be reconfigured to focus on other signals or satellites that are less vulnerable to that interference at that moment. Using hardware reconfigurability of FPGA receivers and characterizing the effect of narrowband interference on the GNSS signal quality lead us to a new RFI mitigation technique in which the highest quality and less vulnerable signal can be chosen at each moment. In the previous work [1], the post processing capability of a software GPS receiver, has been used to detect and characterize the CW interference. This is achieved by passing the GPS signal and the interference through the correlator. Then, using the conventional definition of C/No as the squared mean of the correlator output divided by its variance, the actual C/No for each satellite is calculated. In this work, first the "Exclusion zone" for each satellite signal has been defined and then by using some experiments the effects of different parameters like signal power, jamming power and the environmental noise power on the Exclusion zone have been analyzed. By monitoring the Doppler frequency of each satellite and using the actual C/No of each satellite using the traditional definition of C/No and actual data from a software GPS receiver, the decision to reconfigure the receiver to other signal can be made.

Keywords: GPS receiver, Interference, Hardware Reconfiguration, C/No, Exclusion zone

1. Introduction

Radio frequency interference (RFI) is amongst the most disruptive events in the operation of a GPS receiver. It affects the operation of the automatic gain control (AGC) and low noise amplifier (LNA) in the RF front-end [1] and depending on how much of it passes through these primary modules, it can also affect the carrier and code tracking loops [2, 3] which results in deterioration of all the GPS observables or in complete loss of lock in severe cases. Continuous-wave (CW) interference has been shown to have effects on the GPS C/A code signal [4], which relate to the characteristics of the frequency spectrum of the code. To make the receiver less vulnerable to interference, there are different approaches. Interference sources can be detected, localized and switched off [5, 6]. The interference can be suppressed in the receiver [7] or the receiver can switch to other signals and/or satellites which are less affected by interference as the different RFI has a different effect on different signals [8]. The last approach is the one on which this paper is focused. GPS satellites currently transmit on several frequencies to civilians. In the near future, there will be three GPS signals (L1, L2C, L5) and three Galileo signals, each of which has a different specification, requiring different baseband processing hardware in the receiver. A generic GPS receiver has 12 channels (each dedicated to a single received satellite signal). To cater for each of the 6 different signals, one solution is to have 72 different hardware channels available. An alternate solution is to reconfigure the hardware only to use the channels it requires. In this paper, first the effect of CW on the receiver for the C/A L1 signal is studied in section 2. An Exclusion zone for each satellite in the presence of CW interference is defined in section 3 and also the setup for the experiment to characterize this quantity. In section 4, a series of experiments is introduced to analyse the effect of different signal, interference and environmental parameters on the value of Exclusion zone. Section 5 concludes the paper.

2. When to Reconfigure the Receiver

Not all types of interference require the receiver to reconfigure. Because of the specific structure of the C/A code CDMA signal, a GPS receiver is inherently immune against some types of interference and vulnerable to others. To answer the question as to when to reconfigure the receiver, we need to know how interference affects each channel in the receiver. The observables of the receiver affected by RFI have often been used to detect and characterize the interference. In [9], using a statistical approach, it was shown that correlator output power among the other observables shows consistent performance under varying levels as well as types of interference. This quantity in the receiver is used to calculate the carrier to noise density ratio C/N_0. Because of this consistent behaviour, C/N_0 is usually considered to be an indicator of received GPS signal quality. In [2], this parameter was characterized in terms of front-end bandwidth, discriminator design and other receiver characteristics. This characterization used the conventional definition of C/N_0 as the squared mean of the correlator output divided by its variance. In [3], as a special case, assuming the interference to be CW constant amplitude signal, another expression is derived for C/N_0 which is consistent with the previous results (**Eq. 1**). Figure 1 shows the received GPS signal plus the environmental noise and also interference passing through the correlator.

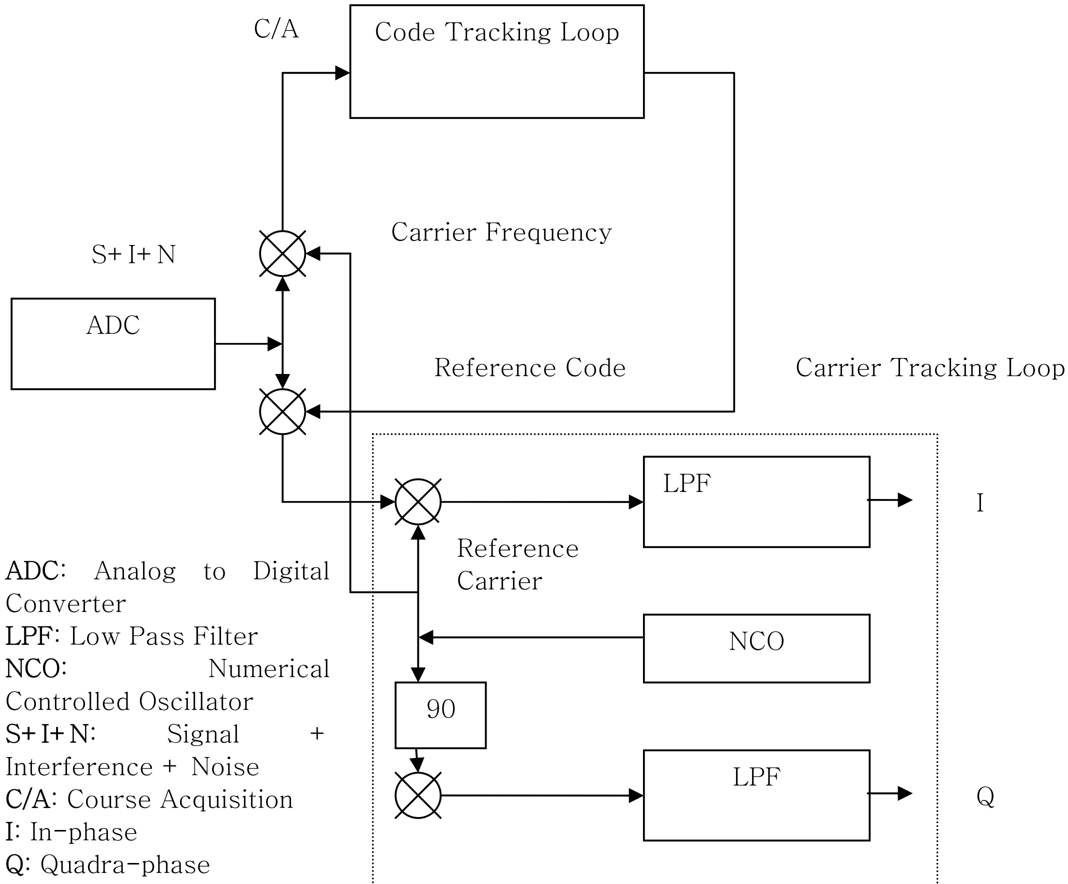


Figure 1 Correlator (Code and Carrier Tracking Loops)

Eq. 1 shows the mathematical expression for the C/N_0 in the output of the correlator.

$$\text{C/No} = \frac{(\mathrm{T_d} R_0(\tau).\mathrm{sinc}(\Delta f_c T_d))^2}{L_n N_0 + J(\mathrm{T_d}.\mathrm{C_j}.\mathrm{sinc}(\mathrm{T_d}.\Delta \mathrm{f_i}))^2} \qquad \textbf{Eq. 1}$$

where:

N_0 is the thermal noise power,
L_n is the processing gain in the noise,
T_d is the integration duration time,
τ is the signal-reference code phase difference in code chips,
$\hat{f}_c$ is the estimate of carrier frequency.

$$\Delta f_c = \mathrm{f_c} - \hat{f}_c$$

$$\Delta f_i = \mathrm{f_i} - \mathrm{f_c}$$

J is the interference power,
C_j is the j^{th} spectral line coefficient
$R_0(\tau)$ is the cross correlation of the received C/A code and the receiver replica of the same code.

In Figure 2, for example, using Eq. 1 and assuming a specific environmental noise power, the C/N_0 is drawn for satellite 1 with Doppler frequency changing from 0 kHz to 10 kHz and CW interference at 100 kHz away from the band centre at 1.57542 GHz (in the normal situation, Doppler frequency changes from around -6 kHz to +6 kHz. The deep troughs in this graph (Figure 2) correspond to the coincidence of CW RFI with the code spectral lines. It is clear from the picture that this happens at 1 kHz spacing. As expected and will be explained in the section 5, there are different values for different lines. This difference comes from the difference between the coefficients of different lines in the code spectrum. The other point which is noticeable in this graph is the sinc functions occurring around each trough. The width of each sinc function is related to the integration period, as can be seen in the Eq. 1. The longer the integration period, the narrower will be the sinc functions [6].

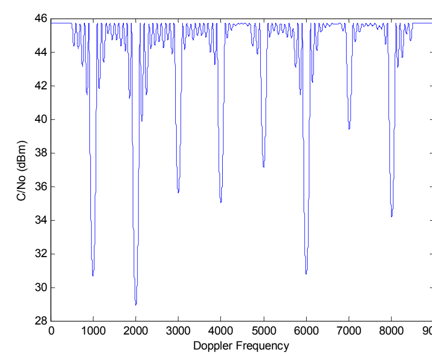


Figure 2 C/N_0 calculated using the mathematical expression for satellite 1 with Doppler frequency changing from 0 kHz to 10 kHz and CW interference at 14 kHz away from the band center at 1.57542 GHz.

In [10], using a software receiver and using the I and Q sample data, C/N_0 has been calculated and proved to show the same behaviour in the presence of CW RFI. The point that is noticeable in Figure 2 is that depending on the Doppler frequency of the received signal, C/N_0 is affected differently and for some Doppler frequencies C/N_0 is not affected at all. So this argument shows for example that having the C/N_0 more than a specific threshold can be a good tool to decide about the reconfiguration of the receiver.

3. Exclusion zone for Each Satellite Signal

Figure 3 shows the variation of the Doppler frequency for different satellites for 24 hours for a specific almanac file in the presence of narrowband CW interference. Gaps in the plots indicate where an interferer in L_1 frequency will cause these signals to be "lost". Depending on satellite number, signal power, strength of the interference and the background noise power, the width of this gap changes. Instead of losing lock, we can set a threshold for the C/No which is a good indication of the signal quality. For any value of C/No less than this threshold, that specific signal will be taken out of the operating channels and the hardware will be reconfigured to switch to another signal or satellite. We call the zones that are achieved through this algorithm "Exclusion zone". This is the frequency region in which the interference "knocks out" that satellite at L1 and the L1 pseudorange for that satellite should be "excised" from the solution. In the reconfigurable receiver, this could mean excising the L1 channel for that satellite.

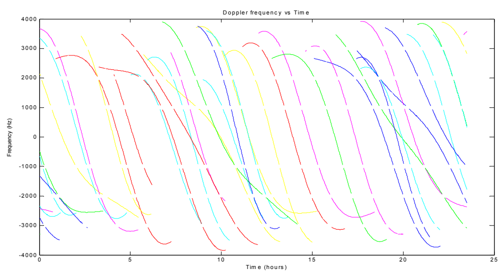


Figure 3 Variation of doppler frequency for the visible satellites in 24 hours

4. Experiment Hardware Setup

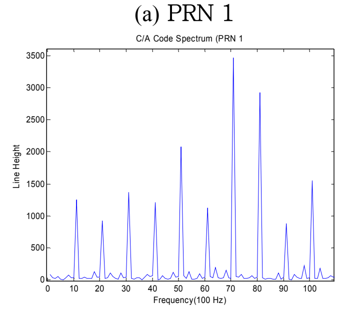
To characterize the effect of the above mentioned signal, interference and environment, the single channel signal generation capability of Spirent 4760 GPS signal generator was used to generate a PRN 1 signal with specific Doppler frequency. A Ronde and Shwarz SM300 9 KHz - 3 GHz was used with TG1010 Programmable 10 MHz DDS Thurlby Thandar function generator to generate a CW narrowband RFI which sweeps a frequency range of 10 kHz in 20 minutes in the L_1 band. This signal and interference are added through a signal combiner and fed to a NordNav software GPS receiver. In Figure 4 a picture of this setup is shown.

Figure 4 NordNav software receiver and the RF signal generators to generate swept CW RFI

5. Experiments

Three experiments were carried out using this setup to investigate the effect of signal power, background noise power and the interference power on the size of the Exclusion zone defined in section 3. In the first experiment, it was found that different C/A code spectral lines have different effects on the signal quality and consequently different effects on the Exclusion zone of that signal. If we look at the C/A code spectrum, because of the specification of the code which is periodic with a period of 1 ms, in the frequency spectrum there are spectral lines which are 1 kHz away from each other. The height of these lines depends on how the PRN is generated and changes from one line to the next. It also changes from PRN to PRN. In figure 5 , the first ten spectral lines for PRN 1 and 2 are shown. It can be seen that the lines have different heights and orresponding lines from the two PRNs do not necessarily have the same height.

(a) PRN 1



(b) PRN 2

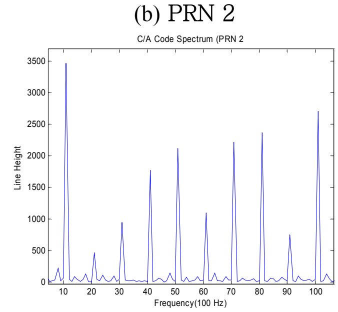


Figure 5 The spectrum of the first 10 lines
(a) PRN 1 (b) PRN2

In [Balaei 2006] it was shown that different attenuations in C/No result when the RFI coincides with each of these lines. Here in this experiment it is shown that this also leads to different values for the Exclusion zones. A CW interference generated by a Ronde and Shwarz RF signal generator was moved across the frequency range of 10 kHz with central frequency 1.5743 GHz. This central frequency was the reading of the signal generator and is not necessarily the same as the frequency the receiver would expect as the signal generator is not synchronized with either the GPS signal generator or the NordNav software GPS receiver. A single channel signal from the Spirent simulator (PRN 1) is generated at a specified Doppler frequency. These two signals are then combined in a signal combiner and fed into NordNav software GPS receiver. Based on the algorithm explained in [Balaei 2006], the frequency of the RFI was determined. In Figure 6, the the difference between the estimated C/N_0 and the theoretically calculated value is shown across the whole bandwidth.

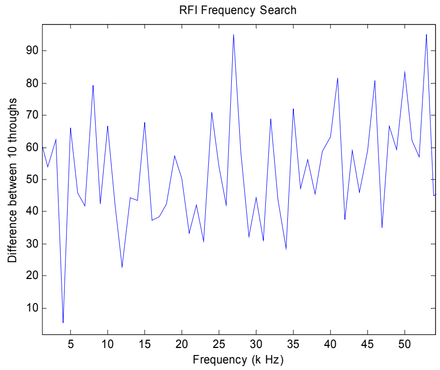


Figure 6 The difference between the estimated C/N_0 and the theoretically calculated value

In Figure 6, the difference between the estimated C/N_0 and the theoretically calculated one is shown. This difference has been calculated in the first 1000 kHz from the band center. This is in fact the difference between the 10 trough values of resulted from Eq. 1 and the values of troughs of a “10 trough searching window” (which can be generated by using the I and Q samples from the receiver) over the whole bandwidth of the C/A code spectrum [6]. It is clearly seen that sweeping the CW RFI started 4 kHz away from L_1. This is consistent with the fact that we put the RFI in 10 kHz away from L_1 and then moved it 10 k Hz around that frequency (from 4k Hz to 14 k Hz). Now that the exact position of the RFI has been calculated, the second step is to find the Exclusion zone for each of the lines. In Figure 7 this quantity is shown in terms of the C/No calculated theoretically Eq. 1. Obviously the higher the line, the greater the effect of the interference, and the lower will be the C/No.

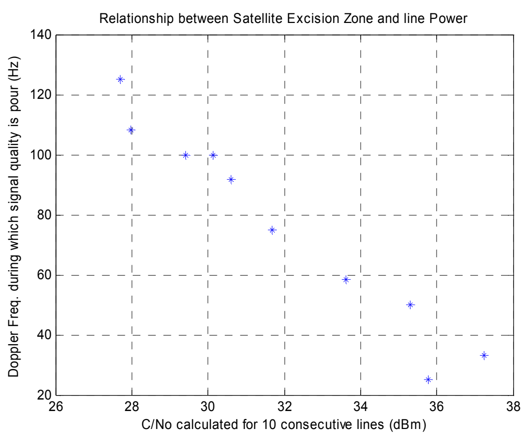


Figure 7 Relation between satellite Exclusion zone and the C/No calculated theoretically

In Figure 7, it can be seen that there is a linear relationship between the Exclusion zone of different C/A code spectral lines and the C/No which is calculated theoretically as the result of those lines. Now that the frequency of the RFI is known, in the following three experiments the Exclusion zone is characterized for just the two lines circled (7 and 8 kHz away from the band center) in Figure 8.

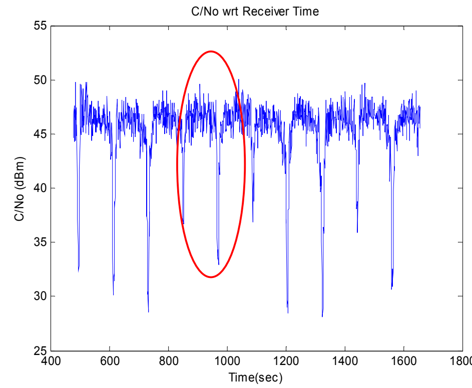


Figure 8 C/No calculated using the I and Q samples

Figure 9 Wide-band RFI generator

To do these experiments, the same hardware setup is used plus a wideband noise which is added to the signal through the signal combiner. The wideband noise is generated by three amplifiers givng 81dB gain and an L_1 filter. This is passed through a programmable attenuator to control the amount of noise going into the receiver. The wideband generator circuit is shown in Figure 9. Instead of 10 kHz, the interference is moved only 2 kHz in 4 minutes (which guarantees one 1kHz line in 2 minutes). The first experiment has signal and CW RFI power levels constant. This experiment used two wideband noise powers. It has been shown [11] that AGC level in the RF front end is a good indicator of the receiver input power. This fact is confirmed Figure 10 where the behaviour of the AGC level in the NordNav receiver has been characterized with respect to the power level of input wideband noise.

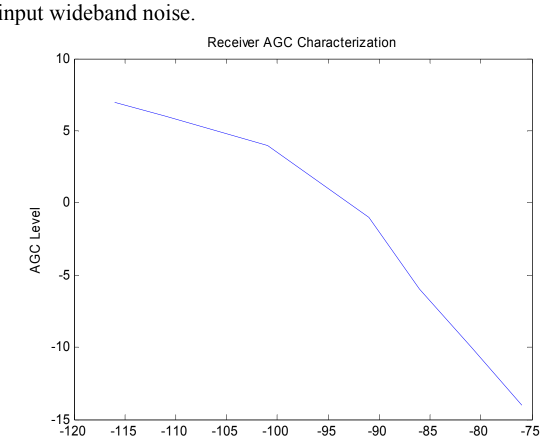


Figure 10 Receiver AGC level versus the input wideband noise power level

AGC level is optimized to get the highest signal to noise ratio from the input signal after quantization [4]. The lower the input power, the higher the AGC gain. The first part of this experiment has been done for two different wideband power levels {what are they? Explain why only two}. In Figure 11 the AGC level of the receiver is shown for the two cases. In the higher input power case, AGC has constant level 6 whereas in low power case it changes between 6 and 8.

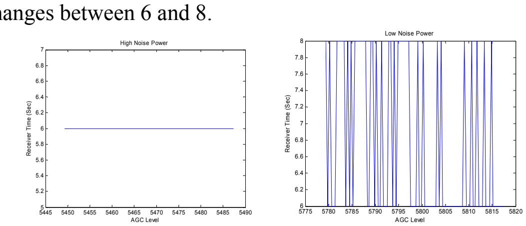


Figure 11 Receiver AGC level for each of the scenarios

The C/No for the high and low wideband noise power input is shown in Figure 12. The threshold for the Exclusion zone has been chosen at 40 dBm in these experiments (for different receivers different threshold can be used). The Exclusion zone for these two cases has been summarized in Table 1. For the lower power input, neither of the lines drops below the threshold whereas for the higher input power, the signal quality drops off the threshold for a zone of width 16 Hz.

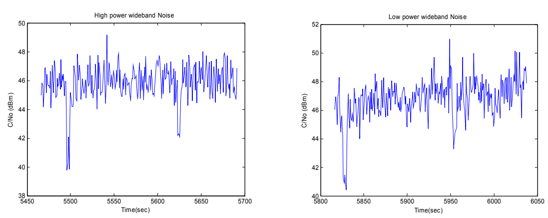


Figure 12 C/No wrt time for two levels of wideband noise (-110 dBm and -108 dBm)

Table 1 Exclusion zones for two different wideband noise powers for two consecutive C/A code spectral lines

Noise Power / Exclusion zone	-110 dBm	-108 dBm
Line 1	0 Hz	16 Hz
Line 2	0 Hz	0 Hz

To get a feeling of the effect of input wideband noise power on the C/No, in Table 2, the average of C/No when the RFI doesn't line up with the code C/A spectral line and also the minimum C/No when it does has been shown.

Table 2C/No for two different widebend noise power and two different relative situation of RFI wrt the signal

Noise Power/ C/No	-110 dBm	-108 dBm
Coincidence	40.38 dBm	39.75 dBm
Non-Coincidence	46.75 dBm	45.97 dBm

Table 2 indicates the effect of input wideband noise power on the C/No. The experiment is shown for when the RFI doesn't line up with the code C/A spectral line and also the minimum C/No when it coincides has been shown.

Table 3C/No for two different widebend noise power and two different relative situation of RFI wrt the signal

Noise Power/ C/No	-110 dBm	-108 dBm
Non coincidence	40.38 dBm	39.75 dBm
Coincidence	46.75 dBm	45.97 dBm

In the second experiment, the wideband noise power and the signal power were kept constant. The experiment is performed for four different RFI powers (Table 4).

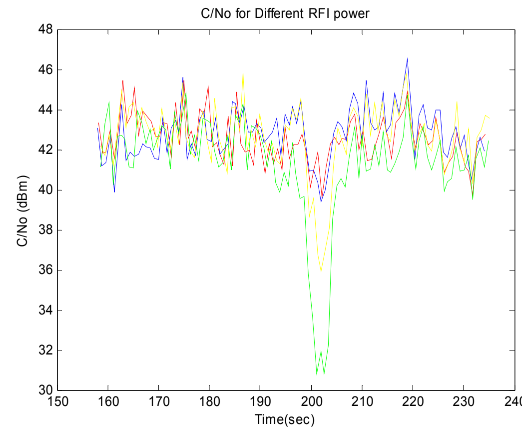


Figure 13 C/No for four different power of RFI (green, yellow, blue and red for -82,-85,-88, -91 dBm correspondingly)

In Figure 13, the effect of these four power levels of RFI is shown on the C/No. It is obvious that where the RFI lines up with the C/A code spectral line, the higher power has the more serious effect. The other thing that can be seen from Figure 13 is that unlike the previous experiment, where the RFI doesn't line up with the C/A code line, the power of RFI doesn't have any effect on the C/No. In Table 4, it can be seen that the Exclusion zone for the two lines is increased with the power of RFI. This is to be expected, as the depth of the trough is greater for greater RFI power, and the width is also greater. Also of note is that both Figure 7 and Figure 13 are consistent with Eq. 1.

Table 4 Exclusion zones for four different RFI powers for two consecutive C/A code spectral lines

RFI Power/ Exclusion zone	-82dBm	-85dBm	-88dBm	-91dBm
Line 1	94 Hz	87 Hz	22 Hz	0 Hz
Line 2	101 Hz	116 Hz	14 Hz	7 Hz

In the last experiment, the wideband noise power and the RFI power are kept constant. This experiment is done for two different signal powers. The C/No is shown in Figure 14 for the two cases. As it is expected from Eq. 1, the signal power also affects the C/No regardless of whether the RFI lines up with the code line or not.

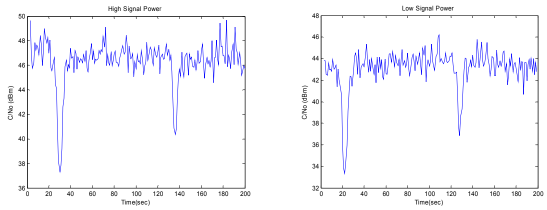


Figure 14 C/No for two different signal power

In Table 5, the Exclusion zone for the two cases are shown. For higher signal powers we have smaller Exclusion zones and for the taller line this value is also higher.

Table 5 Exclusion zone for two different Signal power for two consecutive C/A code spectral lines

RFI Power/ Exclusion zone	15dB (level offset)	20dB(level offset)
Line 1	60 Hz	40 Hz
Line 2	40 Hz	0 Hz

Conclusion

In this paper the concept of reconfiguration of GPS receiver hardware in the presence of CW interference is studied. An “Exclusion zone” for each signal and satellite is defined to be the frequency area in which the signal can’t be used by the receiver. This area was shown to be related to the frequency of the interference and the Doppler frequency of the satellite signal. By using three experiments the effects of the environmental noise power, RFI power and the receiver satellite signal power on the Exclusion zone of each signal are characterized. It is shown that different lines within a signal and corresponding lines in two different signals do not necessarily have the same Exclusion zones. Wideband noise was also found to have an effect on the C/No and consequently on the Exclusion zone of each signal.

Acknowledgement

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