1-GPS

Introduction

Global Navigation Satellite Systems (GNSS) such as GPS, Galileo and GLONASS make use of radio magnetic waves. These waves are transmitted by satellite antennae and received by users ranging from backpackers and car navigation systems to airplanes and satellites in low earth orbits.
Radio Frequency Interference (RFI) can significantly decrease the performance of GNSS receivers or even completely prohibit the acquisition or tracking of satellites. For a GNSS receiver degraded performance can result in among others less accurate range and phase measurements leading to a less accurate position solution. Because modern GNSS applications demand increasingly high accuracy, this makes the subject of interference very important.
The subject of RFI is especially relevant for users of the GPS L2 and L5 bands and the Galileo E5 and E6 bands. The International Telecommunication Union (ITU) has not allocated these bands to satellite navigation exclusively, unlike the shared GPS L1/Galileo E1 band. As a result, more sources of interference can be expected in these bands.
There are several ways to limit the influence of RFI on receiver performance. These include but are not limited to frequency excision to negate narrow band interference and blanking to negate pulsed interference (these methods suppress energy peaks in either the frequency or time domain), but also smart ranging code design and smart antenna design [1].

1-1 GNSS Signals Power Spectra

The GPS is poised to play a critical role offering commercial opportunities in wireless communications as a result of the Federal Communications Commission's E-911 directive and the expansion of location-based mobile-commerce services (LBS). Successful E-911/LBS products and services will require solutions with features that can implement GPS in mobile phones with low cost, low power consumption, reasonable accuracy, high sensitivity and jamming.
Jamming immunity is a measure of the receiver's ability to provide GPS performance despite the presence of interfering signals anywhere else in the frequency spectrum. The ability of a GPS receiver to resist unwanted frequencies is a key measure of its performance. Applications involving cellular handsets provide a guaranteed source of potential jammers namely the cellular frequencies themselves. Traditionally GPS offers one signal for civil use and several encrypted military signals. The civil signal is called the GPS L1 Coarse Acquisition code (C/A) and can be tracked by any receiver. On the L1 carrier the L1A and L1BC signals are modulated. Of these the L1BC signal consists of a pilot and data component. The E6 carrier similarly holds the E6A and E6BC signals, with the E6BC signal consisting of a pilot and data component. On the E5 carrier the E5a and E5b signals are modulated both of which have a pilot and data component. All of these signals can be tracked by a receiver and for all those signals consisting of a pilot and data component the pilot and data channels can be tracked separately. Alternatively the E5a and E5b signals together can be tracked as one large bandwidth signal [2]. The pilot signal component (or pilot tone) is a ranging code without data modulation. A pilot channel has been allocated to each carrier frequency to improve the tracking performance [3]. The pilot channel can be tracked with a lower C/N_0 than the corresponding data channel. Figure 1-1 shows the spectra of the different Galileo signals. The E6BC signal and the E5a and E5b signals when generated separately are modulated with Binary Phase Shift Keying (BPSK). This modulation type creates a main lobe at the signal center frequency just like the traditional GPS signals. The bandwidth of this main lobe is twice the spreading code rate. Figure 1-1 shows the BPSK modulated signals with the spreading code rates as multiples of 1.023 MHz between brackets. The E6A, L1A and L1BC signals as well as the E5 signal when alternatively generated as one large bandwidth signal are modulated with a Binary Offset Carrier (BOC). This modulation type creates two main lobes with a bandwidth equal to twice the

spreading code rate centered at a distance equal to the subcarrier frequency from the center frequency of the signal. Figure 1-1 shows the BOC modulated signals with the subcarrier frequency and spreading code rate as multiples of 1.023 MHz between brackets [2].
When a BOC modulated signal and a BPSK modulated signal share a frequency band, the main lobes of both signals are separated by the subcarrier frequency of the BOC modulation. This can be seen in the E6 band in Figure 1-1. An advantage of this approach is that both signals create less interference for each other. The modulation structure of the L1A and L1BC signals is quite complex because they share the frequency band with the GPS L1 signals. Another advantage of a BOC modulation is the high multi-path tolerance.

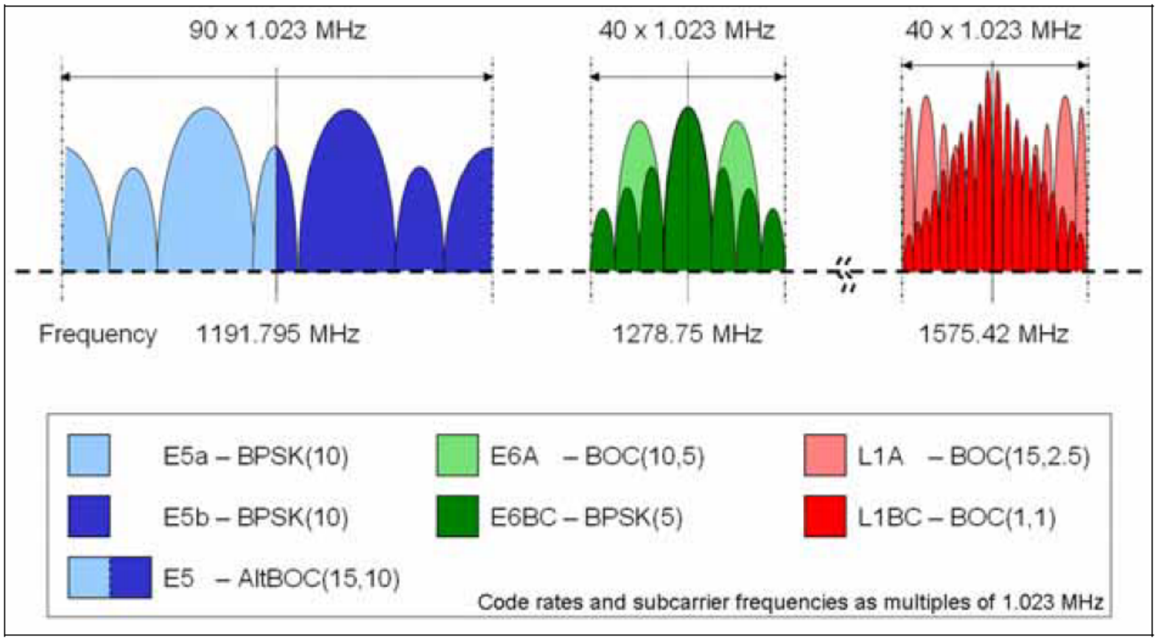

Figure1-1: Galileo signal power spectra

1.2 Radio frequency interference

“RF signals from any undesired source that are received by a GNSS receiver are considered interference.” [1]
Table 1-1 shows the parts of the radio magnetic spectrum used by the Global Navigation Satellite Systems [2; 4; 5; 6]. For a list of the transmitted signals and received signal strength on Earth see Appendix A.

Table 1-1: GNSS frequencies and bandwidths

Signal	Frequency (MHz)	Bandwidth (MHz)
GPS L1	1575.42	40
GPS L2	1227.60	40
GPS L5	1176.45	24
GLONASS L1	1602.56-1615.50[1]	10
GLONASS L2	1240.00-1269.00[1]	10
Galileo L1	1575.42	40.92
Galileo E6	1278.75	40.92
Galileo E5	1191.795	92.07[2]
Galileo E5A	1176.45	N/A[3]
Galileo E5B	1207.14	N/A[3]

1. GLONASS uses frequency division multiple access. The center frequencies of the GLONASS signals are separated by 0.5625 MHz on L1 and 0.4375 MHz on L2.
2. The theoretical bandwidth of Galileo E5 is 92.07 MHz, but only 54 MHz has been used for this study, because of limitations of the Giove-A satellite, the GETR and the GSVF-2 simulator (see chapter 3).
3. The bandwidth of the Galileo E5a and E5b are not specified separately.

Interference can be characterized by a number of properties:

1. Interference type
   Interference can be divided into several different types:
   a. Continuous wave, this is a single tone which appears as a vertical line in an amplitude versus frequency diagram
   b. Amplitude, frequency or phase modulated signals. For these signals the amplitude, the frequency or the phase of the carrier is changed over time to modulate a code onto a carrier. This will spread the signal over a larger part of the frequency spectrum. Another form of code modulation is pulse modulation (see point 5).
   c. Noise, this is the sum of random transmissions of radio frequency signals. If the amplitude is spread according to a Gaussian distribution it is called Gaussian noise. If in combination with this the frequency spectrum is flat it is called Gaussian white noise. When intentionally produced this type of interference can be seen as an increase in the noise floor in (part) of the frequency spectrum.
2. Centre frequency Depending on where the interference appears in the frequency domain (relative to the frequency band of interest, i.e. the GNSS frequency bands) it is either called in band, near band or out of band interference. This study focuses on in band interference which means that the interfering signal is transmitted within the designated frequency band for the GNSS signal in question.
3. Bandwidth
   Interference can also be characterized by the bandwidth of the interfering signal. It is then called either wideband or narrowband interference depending on the bandwidth of the interfering signal in comparison to the bandwidth of the GNSS signal. Wideband interference can have very different effects on

Receiver performance than narrowband interference. However the border between wide band and narrowband is not very strict especially since it depends on the GNSS signal that is considered.

4. Power
Because of GNSS signal design, GNSS systems work with very low signal power. As a consequence many interfering signals have much higher power. The power of the interference is often expressed as interference-to-signal power or jammer-to-signal power (J/S) in decibels.

5. Time domain
Interference can either be continuous or pulsed in the time domain. Some parameters used to describe pulsed interference are:

a. Pulse width (PW), this is the time length of one pulse in seconds.
b. Pulse repetition frequency (PRF), this is the number of pulses per second.
c. Duty cycle (DC), this is the percentage of the time that the pulses are transmitted. It can be calculated with:

$$DC = \frac{PRF \cdot PW}{1s}$$

Pulsed interference often has duty cycles in the order of 5% or smaller. This significantly decreases the impact on receiver performance compared to continuous interference with the same power and center frequency.

Another way to categorize interference is by the source of the interference. Interference can be either intentional or unintentional.

1.3 The effects of RFI on GNSS receiver output

Several effects of interference on GNSS receiver output were identified for this study and will be discussed in this paragraph. The possibilities to use these effects as indicators to detect interference on receiver output will also be discussed.

1. Loss of receiver tracking
   When subjected to very strong interference a GNSS receiver can lose tracking of all satellite signals. The obvious disadvantage of using this effect as an indicator of interference is that it cannot be used for interference that is severe enough to significantly decrease the receiver performance, but not severe enough to make the receiver lose lock of the satellite signals.
2. Decrease of measured signal strength
   Another indicator is the received GNSS signal strength that many GNSS receivers measure. Most receivers and all of the ones used for this study use the signal-to-noise ratio (C/N_0) in decibels per Hertz (dB-Hz) for these measurements. The signal-to-noise ratio gives information on the signal power compared to the noise power density. The relation between the measured C/N_0 and RFI as well as the possibility to use the C/N_0 to detect RFI will be discussed in paragraph 1.4.

For a user of a GNSS receiver the relevance of the first mentioned effect of RFI is obvious. If the receiver is unable to track satellites it cannot calculate its position. When the receiver is able to track satellites, most users will be interested in the accuracy of the position solution rather than e.g. the noise on the pseudo range measurements. However, the accuracy of the position solution depends among others on the pseudo range measurements and/or the phase measurements. When RFI causes more noise on the pseudo range and phase measurements or cycle-slips on the phase measurements, the accuracy of the position solution will decrease.

1.4 RFI and signal-to-noise ratio

The C/N0 is accurately described as the signal power to noise power density ratio. The C/N0 gives a good measure for the quality of a received signal as long as the noise has a flat spectrum over the entire frequency band (white noise) and can indeed be described by a scalar value (the noise power density). When there is also RFI the effective C/N0 should be used instead. This value uses a white noise power density that is equivalent to the actual noise plus interference [1].

Provide the following method to determine the effective C/N0 (to use these expressions all values should be entered as ratios not in decibels):

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$$(C/N_0)_{eff} = \frac{1}{\frac{1}{C/N_0} + \frac{J/S}{QR_c}} \qquad \textbf{(2-1)}$$

where (C/N0)eff is the effective signal to noise ratio in 1 Hz, C/N0 is the unjammed signal to noise ratio in 1 Hz, J/S is the jammer-to-signal ratio, Rc is the spreading code rate of the signal in chips per second and Q is the dimensionless jamming resistance quality factor. Factor Q can be determined with the following expression:

$$Q = \frac{\int_{-\infty}^{\infty} |H_R(f)|^2 S_S(f)df}{R_c \int_{-\infty}^{\infty} |H_R(f)|^2 S_i(f) S_S(f)df} \qquad \textbf{(2-2)}$$

Where HR is the receiver transfer function, SS(f) is the power spectral density of the signal normalized over the entire spectrum, Si is the interference power spectral density normalized over the entire spectrum and f is the frequency. The receiver transfer function is the filter transfer function normalized to have a maximum of value of one. If it assumed that there is no filtering within the signal band, (2-2) can be simplified to use for in-band interference:

$$Q \cong \frac{1}{R_c \int_{-\infty}^{\infty} S_i(f) S_S(f)df} \qquad \textbf{(2-3)}$$

When band limited white noise interference is considered (which was used during the simulator tests), the interference spectrum is flat for part of the frequency band and is zero everywhere else. Equation (2-3) can then be simplified further to:

$$Q \cong \frac{1}{\frac{R_c}{\beta_i} \int_{f_i-\beta_i/2}^{f_i+\beta_i/2} S_S(f)\,df} \qquad \textbf{(2-4)}$$

where fi is the interference center frequency and βi is the interference bandwidth. Notice that the signal is now only integrated over the interference bandwidth.

In paragraph 2.3 the possibility to use the signal-to-noise ratio as an indicator of interference was mentioned. Suppose the unjammed C/N0 is known and (C/N0)eff is measured (2-1) can be used as follows:

$$\frac{J/S}{Q} = R_c\left(\frac{1}{(C/N_0)_{eff}} - \frac{1}{C/N_0}\right) \qquad \textbf{(2-5)}$$

to determine the factor J/S over Q. This factor then gives information on the severity of the impact of the interference on the measured C/N0. The jammer parameters such as bandwidth and centre frequency cannot be determined in this way because there are too many variables.

Another important difficulty when trying to detect RFI by using the measured C/N0 is that RFI is not the only factor influencing the C/N0. To prevent false alarms it is important to know what other sources can influence the signal-to-noise ratio. Table 1-2 lists the factors that influence the received signal power with the dynamic power range within which they are expected to behave [7].

Table 1-2: Factors influencing the C/N_0

	Range	Notes
Variations in satellite transmitted power	6dB	New GPS satellites transmit up to 6dB more power than the minimum requirement. This very slowly decreases during the satellite's life.
Variations in the free-space propagation loss	2dB	When the elevation angle of a GNSS satellite decreases, the distance to the receiver increases. When the distance increases so does the propagation loss.
Varying satellite antenna gain with nadir angle	3dB	The transmitting antennae of GPS satellites are designed to negate the effects of increasing propagation loss with decreasing elevation angle.
Variations in atmospheric losses	2dB	Atmospheric losses are difficult to predict, but they are usually no greater than 2dB.
Foliage attenuation	N/A	Tree leaves in the line of sight from the receiver to the satellite can decrease the received power. If the receiver site is chosen with care this is easily prevented.
Multi-path	N/A	Depending on the phase difference between the line of sight signal and the reflected signal, multi-path can either decrease or increase the received signal power. The effects can be very strong.
Varying receiving antenna gain with satellite elevation	15dB	GNSS antennae can have up to 15dB gain roll-off from the zenith to the horizon.

Of these factors the satellite power changes very slowly and predictably, the free-space propagation loss is compensated for by the satellite antenna gain with a very predictable result and foliage attenuation is easily prevented. The most important factors that remain are the atmospheric losses, multi-path and the receiving antenna gain.
There are many models that describe the influence of the atmosphere on the propagation of GNSS signals. The influence is greatest when the satellite has a low elevation and when the atmosphere is warmed up by the sun, because this makes the path of the signal through the atmosphere longer. For satellites with elevation angles above 40 degrees the losses are in the order of 0.3 dB.

1.5 Analyze the effect of modulated signals

Another aim of this chapter is to analyze the effect of modulated signals such as amplitude modulated (AM) and frequency modulated (FM) signal sources on the GPS spectrum during the acquisition process. Interference signals cause distortion in the GPS signal resulting in an incorrect or no correlation peak during acquisition.
Radio Frequency Interference (RFI) is a major source for potential degradation of GPS accuracy and reliability. Other sources of error which degrade GPS accuracy and make RFI mitigation harder include satellite and user motions which introduce Doppler effects, slow power fluctuations (due to changes in effective antenna gain and path loss) and fast power changes (due to multipath fading, blockage and shadowing). Doppler fluctuations make it difficult to distinguish between user motion and receiver clock drift. Power fluctuations make it difficult to determine the thresholds for acquisition and tracking whereas atmospheric errors introduce range and range rate errors [8].
The US E-911 directive requires that emergency call locations be identified within a 1-sigma accuracy of 50 meters [9]. This is a problem for mobile phones since their locations are not fixed. To meet this Requirement, GPS can be interfaced with mobile phones. These mobile phones use frequency modulated (FM) Signals for communications. The incorporation of GPS into a cellular handset means that a jammer will be operating nearby at the cellular frequency, about 1800 MHz in GSM systems [10]. A high jammer power level can cause the generation of unwanted mixing products (spurs) if the level exceeds the linear range of the circuit blocks. An out-of-band jammer mixes with spectral components to create spurs in the same frequency band as the desired signal. If the power levels are high enough, the resulting spurs may possibly exceed the linear range of the circuit, resulting in the receiver's inability to retain GPS signal lock. Table1-3 provides a summary of the handset frequencies and power levels that will manifest themselves as out-of-band jammers. There is a possibility of these signals interfering with GPS signals and causing problems for acquisition. Care must be taken to isolate the mobile signals from GPS to avoid interference and jamming of the GPS signals [10].

Table 1-3: Mobile operating frequencies and power levels

GPS Jamming Frequencies in a Handset		
Cellular Standard	**Transmit Freq (MHz)**	**Max. Handset output power**
GSM	880-913 and 1710-1785	+33 dBm
IS-95	824-849	+23 dBm
PCS	1850-1910	+24 dBm

High order harmonics of amplitude modulated (AM) and FM radio broadcast transmitters emissions fall close to the
GPS L1 frequency which can potentially cause interference. With an AM broadcast, the harmonic order is very high (985) and the likelihood of RFI is minimal [11]. For an FM broadcast, the harmonic order is lower (15 to 18) and the maximum effective isotropic radiated power (EIRP) is higher (50 to 60 dBW). Analog TV broadcast maximum EIRP limits are higher than for FM, while harmonic orders are lower (2 to 9 for RFI signals within 2 MHz of GPS L1) and will cause more interference [11].
A GPS receiver is designed to take care of most of interference signals. The antenna and RF front-end filters are designed to take care of spurious signals. The antenna gain pattern is chosen to reduce the effect of multipath signals reflected from the ground. The predetection bandwidth of the GPS receiver also plays an important role in reducing the out-of-band interference signals [12]. The predicted amplitude of the induced perturbation depends on the relative amplitude of the jammer and the received GPS signal (the frequency offset between the jammer and the nearest C/A code line and on the weight of that spectrum line) [13].
The objective of this work is to analyze the modulated signal interference in GPS acquisition. The types of modulated signals analyzed are AM and FM signals. The signal strength of the interference signal is varied from 0 dB to +40 dB relative to signal strength of GPS signals. Adaptive predetection integration was carried out to determine whether the interference effects could be suppressed. Adaptive predetection integration in GPS acquisition can be used to reduce continuous wave and broadband noise interference [14]. During adaptive integration, different coherent and non-coherent integration periods were tested. The detection of interference signal by acquisition process is advantageous since it allows avoiding false locks and possibility of generating erroneous measurements by the tracking process. This also helps in avoiding waste of a GPS signal simulator along with an interference signal generator is used to generate various interference scenarios.

1-5-1AM Interference

An AM signal is a continuous wave signal whose amplitude varies as a function of the modulating signal.AM is used widely for radio communications [15]. The AM signal was tested with the carrier frequency kept at the GPS L1 frequency and the modulating signal was varied from 1 Hz to 50 KHz. The modulation depth of the AM signal was varied from 10% to 100%. The modulation depth determines the amount of modulation present in the signal. The interference frequency is at the GPS L1 frequency and is difficult to isolate using filters. The correlation process spreads the interference signal over the predetection integration bandwidth and decreases the signal power to reduce the effect of the interference signal [16].

1-5-2 FM Interference

An FM signal is a continuous wave signal whose frequency varies as a function of the modulating signal [15].
FM signals are used for radio broadcasts in the 88-108 MHz frequency range and for cellular transmission at various frequencies listed in Table1-3. The signal level of these FM signals is very high and the high order harmonics of FM signals in the GPS frequency band will have considerable power as compared to GPS signal levels. This will result in interference from the FM signal that needs to be mitigated. The GPS L1 frequency was used as the carrier frequency for the FM signals analyzed. The modulating frequencies were varied from 1 to 50 Hz with frequency deviation varying from 10 KHz to 20 MHz. The interference power levels were varied from 0 to +40 dB relative to GPS signal power.

1-5-3CONCLUSIONS

AM signals were found to be more damaging than FM signals. An AM signal of 20 dB more than the GPS signal will prevent successful acquisition for the cases studied. An AM signal with a modulation frequency beyond 1 KHz and a modulation depth above 50% induces large interference for the different AM signals studied. A coherent integration time below 5 ms is not sufficient to obtain a proper signal peak even for 0 dB relative interference power. Coherent integration of 10 ms with a non-coherent integration factor of 2 provides better interference tolerance compared to 20 ms coherent integration.

The acquisition process can tolerate up to +30 dB relative FM interference for the cases studied. An FM signal with a frequency deviation below 100 KHz and a modulating signal below 10 KHz were found to be more damaging among various signals considered. A coherent integration time of 10 ms or longer and a non-coherent integration factor of 3 or more provides better tolerance to FM signals. The GPS acquisition process has more tolerance to FM signals than AM signals and hence FM could be used for communication devices when operating in close proximity with GPS.

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Appendix A: GNSS signals and received signal strength

Table A-1 gives an overview of the different GNSS signals and the received signal strength on Earth as defined in the appropriate system ICDs [2; 4; 5; 6].

Table A-1: GNSS signals and received signal strength on Earth

GNSS system	Signal	Centre frequency main lobe(s) (MHz)	Bandwidth main lobe(s) (MHz)	User received signal power (dBW)
GPS	L1 C/A	1575.42	2.046	-160[3]
	L1 P	1575.42	20.46	-163[3]
	L2 C/A	1226.60	2.046	-166[3]
	L2 P	1227.60	20.46	-166[3]
	L5	1176.45	20.46	-157.9[3]
Galileo	L1A	1560.075 1590.765[1]	5.115	-157[4]
	L1BC-P	1574.397 1576.443[1]	2.046	-160[4]
	L1BC-D	1574.397 1576.443[1]	2.046	-160[4]
	E5a-P	1176.45	20.46	-158[4]
	E5a-D	1176.45	20.46	-158[4]
	E5b-P	1207.14	20.46	-158[4]
	E5b-D	1207.14	20.46	-158[4]
	E5AltBoc P	1176.45 1207.14[1]	20.46	-155[4]
	E6A	1268.52 1288.98[1]	10.23	-155[4]
	E6BC-P	1278.75	10.23	-158[4]
	E6BC-D	1278.75	10.23	-158[4]
GLONASS	L1 standard accuracy	1602.56- 1615.50[2]	1.022	-161[3]
	L1 high accuracy	1602.56- 1615.50[2]	10.22	-161[3]
	L2 standard accuracy	1240.00- 1269.00[2]	1.022	-167[3]
	L2 high accuracy	1240.00- 1269.00[2]	10.22	-167[3]

1. Signals with a binary offset carrier modulation have two large lobes separated by the binary offset frequency.
2. GLONASS uses frequency division multiple access. The center frequencies of the GLONASS signals are separated by 0.5625 MHz on L1 and 0.4375 MHz on L2 [6].
3. Minimum received power with a 3dBi gain linearly polarized antenna for a satellite with a minimum of 5 degrees elevation [4; 5; 6].
4. Minimum received power with a 0dBi gain ideally matched antenna for a satellite with a minimum of 10 degrees elevation [2]