Effects of Radio Frequency Interference on GNSS Receiver Output

Masters Thesis
Peter F. de Bakker

Delft University of Technology
Faculty of Aerospace Engineering

Supervisors:
J. Samson - ESTEC
P. Joosten - TUDelft
B.A.C. Ambrosius - TUDelft
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Summary

Interference has a significant influence on the tracking of GNSS satellite signals by a GNSS receiver. This can range from a degradation of the performance to a total prohibition of satellite signal acquisition and/or tracking.

Any signals transmitted in or near the GNSS frequency bands will interfere with the reception of the GNSS signals. Different types of interference are: unintentional interference of other systems using the same frequency bands, intentional interference also known as jamming and naturally occurring interference. Interference can be described by a number of properties such as: the type of interference (e.g. noise or continuous wave), the interference centre frequency, the interference bandwidth, the interference power and the interference behaviour in the time domain (pulsed or continuous). Several effects of interference can be detected on the output of a GNSS receiver. Used for this study were: loss of receiver tracking, decrease of the effective carrier-to-noise ratio \( (C/N_0) \), increase of the noise on the pseudo range measurements and increase of the noise on the phase measurements.

To investigate the influence of radio frequency interference on GNSS receivers, tests were performed in the navigation laboratory at ESA/ESTEC in Noordwijk, the Netherlands. Here both GNSS signals and interfering signals can be produced at radio frequencies with dedicated hardware simulators. Both GPS signals and Galileo signals were used during the tests. Several types of interfering signals were used such as Gaussian White Noise (GWN) and Amplitude Modulated signals (AM). The interference was moved through the frequency band of the GNSS signal under investigation and several interference parameters were varied such as interference power and bandwidth to investigate the influence of these parameters on the receiver performance. For the tests three different dual frequency GPS receivers were used as well as the Galileo Experimental Test Receiver (GETR). During these tests the receivers were logging among others the effective \( C/N_0 \), the pseudo range measurements and the phase measurements. Also some field measurements were investigated taken at Turin, Italy.

The simulator test results showed that GNSS receivers can take up to five minutes to measure a stable \( C/N_0 \) after RFI is added to the GNSS signals. Comparison of the GPS simulator test results and the Galileo simulator test results showed that the jamming threshold for both systems is comparable for RFI at the centre frequency of the signal main lobe. The results showed that the lowest \( C/N_0 \) was measured for RFI at the centre frequency of main lobe of the signal. For all signals with a single main lobe at the signal centre frequency, the highest noise on the pseudo range measurements was found for interference halfway between the centre frequency of the signal and the side of the main lobe. The results showed that AM narrow band interference has a strong influence on the noise part of the \( C/N_0 \) measurements made by the GETR. Comparison of the simulator test results to theoretical relations for \( C/N_0 \) and noise on pseudo range measurements showed that the influence of the interference centre frequency on the receiver performance can accurately be predicted. However, the theory considered for this study cannot be used to predict actual values for \( C/N_0 \) and pseudo range noise. Comparison of the simulator test results to field measurements made at Turin, Italy, showed that the simulator tests can be very useful for a first analysis of field measurements. However, they could not be used to explain all the measured results.

From the results some important conclusions were reached. The jamming threshold for GPS and Galileo are comparable. Theory and formulae can predict the
influence of changing certain interference parameters on receiver output very well, but absolute values cannot be predicted as easily because of the strong dependence on the actual receiver. The simulator test results can be a useful tool to predict receiver performance in known interference environments or to determine an interference mask that safeguards receiver performance. The tests have shown that interference detection and identification solely on receiver output is limited to determining the severity of the impact of the interference. Interference parameters will be nearly impossible to determine.

Based on this study it is recommended that the simulator test results be compared to more field measurements to validate the test results and the comparison method. It is expected that these comparisons will be complicated by other sources influencing the receiver output, such as multi-path and receiving antenna gain. Some methods are suggested to overcome these complications. However, the suggested methods have not been tested during this study. It is also recommended that the occurrence of cycle slips as a result of interference should be investigated further. Finally it is recommended that more tests should be performed with pulsed interference as opposed to continuous interference. Pulsed interference is commonly encountered during field measurements.
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I would like to thank Simon Johns for all his help in the navigation laboratory at ESTEC. Further, I would like to thank Andrzej Baranski, Alberto Garcia-Rodriguez and all the other people of the radio navigation section at ESTEC for their help and interest in the project. I would like to thank Jean-Luc Gerner for his role in the realization of this project. Special thanks are due Jaron Samson for his dedication to this project and his excellent supervision.

I would like to thank Massimiliano Spelat and Martin Hollreiser for the great cooperation during the Galileo interference tests. I also would like to thank Jean-Marie Sleewaegen for his help in explaining some of the test results.

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On a personal level I would like to thank Frans van der Lee for his help. Finally, I would like to thank Hans & Janny de Bakker and Vicki Erasmus for their great support throughout this project.
## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM</td>
<td>Amplitude Modulation</td>
</tr>
<tr>
<td>BOC</td>
<td>Binary Offset Carrier</td>
</tr>
<tr>
<td>C/N&lt;sub&gt;0&lt;/sub&gt;</td>
<td>Carrier-to-Noise ratio (also signal-to-noise ratio)</td>
</tr>
<tr>
<td>E1</td>
<td>Galileo frequency band shared with GPS L1 centred at 1575.42 MHz</td>
</tr>
<tr>
<td>E5a-D</td>
<td>Galileo E5a data signal centred at 1176.45 MHz</td>
</tr>
<tr>
<td>E5a-P</td>
<td>Galileo E5a pilot signal centred at 1176.45 MHz</td>
</tr>
<tr>
<td>E5b-D</td>
<td>Galileo E5b data signal centred at 1207.14 MHz</td>
</tr>
<tr>
<td>E5b-P</td>
<td>Galileo E5b pilot signal centred at 1207.14 MHz</td>
</tr>
<tr>
<td>E6A</td>
<td>Galileo E6A data signal centred at 1278.75 MHz</td>
</tr>
<tr>
<td>E6BC-D</td>
<td>Galileo E6BC data signal centred at 1278.75 MHz (also E6B)</td>
</tr>
<tr>
<td>E6BC-P</td>
<td>Galileo E6BC pilot signal centred at 1278.75 MHz (also E6C)</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>ESTEC</td>
<td>European Space Research and Technology Centre</td>
</tr>
<tr>
<td>f</td>
<td>Frequency</td>
</tr>
<tr>
<td>Galileo</td>
<td>European Global Navigation Satellite System</td>
</tr>
<tr>
<td>GETR</td>
<td>Galileo Experimental Test Receiver</td>
</tr>
<tr>
<td>GLONASS</td>
<td>(Russian) Global Navigation Satellite System</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
</tr>
<tr>
<td>GPS</td>
<td>(American) Global Positioning System</td>
</tr>
<tr>
<td>GSTB-V2</td>
<td>Galileo System Test Bed version 2</td>
</tr>
<tr>
<td>GSVF-2</td>
<td>Galileo Signal Validation Facility version 2</td>
</tr>
<tr>
<td>GWN</td>
<td>Gaussian White Noise</td>
</tr>
<tr>
<td>H&lt;sub&gt;r&lt;/sub&gt;</td>
<td>Receiver transfer function</td>
</tr>
<tr>
<td>IGS</td>
<td>International GNSS Service</td>
</tr>
<tr>
<td>INRIM</td>
<td>(Italian) National Institute of Metrological Research</td>
</tr>
<tr>
<td>ITU</td>
<td>International Telecommunication Union</td>
</tr>
<tr>
<td>J/S</td>
<td>Jammer-to-Signal power ratio</td>
</tr>
<tr>
<td>L1 C/A</td>
<td>GPS L1 Coarse Acquisition signal centred at 1575.42 MHz</td>
</tr>
<tr>
<td>L1A</td>
<td>Galileo L1A data signal centred at 1575.42 MHz</td>
</tr>
<tr>
<td>L1BC-D</td>
<td>Galileo L1BC data signal centred at 1575.42 MHz (also L1B)</td>
</tr>
<tr>
<td>L1BC-P</td>
<td>Galileo L1BC pilot signal centred at 1575.42 MHz (also L1C)</td>
</tr>
<tr>
<td>L2</td>
<td>GPS L2 carrier centred at 1227.6 MHz</td>
</tr>
<tr>
<td>L5</td>
<td>GPS L5 carrier centred at 1176.45 MHz</td>
</tr>
<tr>
<td>LNA</td>
<td>Low Noise Amplifier</td>
</tr>
<tr>
<td>PR</td>
<td>Pseudo Range</td>
</tr>
<tr>
<td>PRN</td>
<td>Pseudo Random Noise</td>
</tr>
<tr>
<td>Q</td>
<td>Jamming resistance quality factor</td>
</tr>
<tr>
<td>R&lt;sub&gt;c&lt;/sub&gt;</td>
<td>Spreading code rate</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency (Interference)</td>
</tr>
<tr>
<td>RFI</td>
<td>Radio Frequency Interference</td>
</tr>
<tr>
<td>SBAS</td>
<td>Satellite Based Augmentation System</td>
</tr>
<tr>
<td>SD</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>S&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Interference power spectral density</td>
</tr>
<tr>
<td>S&lt;sub&gt;S&lt;/sub&gt;</td>
<td>Signal power spectral density</td>
</tr>
</tbody>
</table>
1 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. On these waves a code is modulated, which can be used by the receiver to determine the range to the satellite that transmits the signal. When four or more satellites are tracked, these ranges can be used to calculate the position of the receiver. For a more accurate position solution receivers can also track the phase of the signal carrier waves directly instead of only the modulated code. The accuracy of the position solution depends on among others the accuracy of the used measurements.

The number of systems that make use of the radio magnetic spectrum has increased a lot over the last decades and the number of users increases daily. This development has crowded the radio frequency spectrum significantly. When two systems use the same frequencies or frequencies close to each other, this can cause interfere for both systems. These two systems can both be navigation systems such as GPS and Galileo, but interference of completely different systems can also be encountered and can even be much more severe.

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 [Kaplan & Hegarty, 2006].

An entirely different approach is not to mitigate interference but to just make the user aware of any interference. This gives the user the opportunity to decide whether to rely on the position solution or not and at the same time gives the user some knowledge about his environment. Some easy ways to detect RFI are to use either a spectrum analyzer or a (military) receiver that directly measures the interference-to-noise ratio. However, in many situations this equipment is unavailable. It is the purpose of this study to investigate the possibilities of detecting RFI without using dedicated hardware. It was decided to limit the study to stationary receivers. This makes it possible to separate RFI effects from other effects that result from movement of the receiver.

Another consideration for this study was that though many interference tests have been performed with GPS receivers, the Galileo system has not yet been tested in the same manner. This leads to the following research questions:
1. What are the effects of RFI on GNSS receiver output?
2. How does the Galileo system compare to GPS when considering RFI?
3. How does the theory on GNSS and RFI compare to GNSS and RFI test results?
4. How do simulated GNSS and RFI test results compare to GNSS and RFI field measurements?
5. Is it possible to detect RFI on GNSS receivers by only studying the receiver output?

To answer these questions a study was performed to assess the effects of interference on the output of stationary GNSS receivers. This study was performed at ESA/ESTEC in Noordwijk, the Netherlands and in cooperation with the Technical University of Delft, the Netherlands. A large part of the study consisted of tests performed with GNSS receivers, GNSS hardware simulators and a RFI generator in the navigation laboratory at ESTEC. The receivers were logging data which was then used to determine the receiver performance under different RFI conditions. The results of these tests can be useful for several reasons:

- They give information on the impact of interference on different GNSS systems and receivers answering research questions 1 and 2.
- They can be used to evaluate the theory on the influence of interference on GNSS receivers answering research question 3.
- They can be used to predict the performance of a receiver in a location with known levels of interference answering research question 4.
- They can be used to detect and estimate interference that is present during receiver operations answering research question 5.
- They can be used to determine requirements for the environment of locations for permanent receivers (e.g. Galileo Sensor Stations).
- They can be used to define RFI tests that can form part of standard receiver testing.

The test results were also compared to both theoretical relations and field measurements. The comparison of simulator tests to theoretical relations showed that although the used theory can predict the impact of changing some RFI parameters, it is not specific enough to predict actual receiver performance. The comparison of simulator test results to field measurements showed that although useful the test results cannot explain all field measurements. This has to do with the fact the exact characteristics of RFI encountered at field measurements is generally not known.

This introduction will be concluded with an overview of the different chapters of this thesis.

Chapter 2 gives an introduction to the subject of interference. First the Galileo signals will be introduced, then a definition of RFI will be provided followed by an overview of important RFI parameters and commonly encountered sources of interference in the GNSS signal bands. Then the expected effects of RFI on GNSS receiver output will be discussed with special attention for the measured carrier-to-noise ratio (C/N₀) and the noise on the pseudo range and phase measurements. Finally, some attention will be paid to antenna gain and ground reflection multi-path.

Chapter 3 discusses the tests performed for this study. This will start with a discussion of the tests needed to reach the objectives of this study as well as the
reasons why these tests are necessary. This will be followed with an overview of the tests that were performed. Finally an introduction to the used hardware will be given and the used measurement set-ups will be discussed.

In chapter 4 the results of the tests will be discussed. First some early results that had a big impact on all subsequent tests, and in particular test durations, will be discussed. This will be followed by an overview of the results from the tests with simulated GPS signals and an overview of the results from the tests with simulated Galileo signals. A comparison will be made between the different GNSS signals and also between the simulator test results and the theoretical predictions. Finally some field measurements taken at Turin, Italy will be discussed and compared to the simulator test results.

In chapter 5 the conclusions that were reached during this study are discussed. These conclusions regard the quality of the different Global Navigation Satellite Systems and receivers and the usefulness of the simulator test results.

Chapter 6 contains some recommendations for future studies in this field. These recommendations could be used to further validate the results of this study and expand the applicability of these results.

This thesis also contains a large number of Appendices which hold further information about the used hardware and test procedures as well as additional test results that were not included in the main body of the thesis to increase the readability.
2 Theory

In this chapter the theoretical foundations of this study are described. Paragraph 2.1 gives an introduction to the GNSS signals that were used during this study, with special attention to the power spectra. Paragraph 2.2 starts with a definition of radio frequency interference and goes on to introduce several important interference parameters and common sources of interference. Paragraph 2.3 identifies and discusses the expected effects of interference on GNSS receiver output. Paragraph 2.4 deals with the signal-to-noise ratio measured by GNSS receivers as well as several important processes that influence the measured value. The jamming resistance quality factor is introduced and it will be explained how this factor can be used to predict the measured C/N₀ in the presence of RFI. Paragraph 2.5 briefly discusses antenna gain and ground reflection multi-path and paragraph 2.6 discusses the noise on pseudo range and phase measurements as well as how this data can be extracted from the pseudo range and phase measurements. Also some comments on cycle slips will be made.

2.1 GNSS Signals Power Spectra

This paragraph will introduce the GNSS signals that were used during this study. First some remarks about the GPS signals are made and then the Galileo signals will be introduced, with special attention to the signal power spectra. For a list of GNSS signals with their centre frequency and received power on Earth see Appendix A.

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. The military signals can only be used to their full extent by a receiver with access to the encryption code. There are some possibilities to track the code without the encryption code available (semi-codeless tracking), but this does reduce the C/N₀ values. With the modernization of GPS there will be more civil signals available, but these were not considered for this study.

There are 6 Galileo signals on 3 carrier waves. 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. 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 [Dellago et al., 2003]. The pilot channel can be tracked with a lower C/N₀ than the corresponding data channel.

Figure 2-1 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 centre frequency just like the traditional GPS signals. The bandwidth of this main lobe is twice the spreading code rate. Figure 2-1 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 centred at a distance equal to the subcarrier frequency from the centre frequency of the signal. Figure 2-1 shows the BOC modulated signals with the subcarrier frequency and spreading code rate as multiples of 1.023 MHz between brackets [12].

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 2-1. 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.

![Figure 2-1: Galileo signal power spectra](image)

**2.2 Radio frequency interference**

“RF signals from any undesired source that are received by a GNSS receiver are considered interference.” [Kaplan & Hegarty, 2006]

Table 2-1 shows the parts of the radio magnetic spectrum used by the Global Navigation Satellite Systems [12; 13; 14; 15]. For a list of the transmitted signals and received signal strength on Earth see Appendix A.
### Table 2-1: GNSS frequencies and bandwidths

<table>
<thead>
<tr>
<th>Signal</th>
<th>Frequency (MHz)</th>
<th>Bandwidth (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS L1</td>
<td>1575.42</td>
<td>40</td>
</tr>
<tr>
<td>GPS L2</td>
<td>1227.60</td>
<td>40</td>
</tr>
<tr>
<td>GPS L5</td>
<td>1176.45</td>
<td>24</td>
</tr>
<tr>
<td>GLONASS L1</td>
<td>1602.56-1615.50</td>
<td>10</td>
</tr>
<tr>
<td>GLONASS L2</td>
<td>1240.00-1269.00</td>
<td>10</td>
</tr>
<tr>
<td>Galileo L1</td>
<td>1575.42</td>
<td>40.92</td>
</tr>
<tr>
<td>Galileo E6</td>
<td>1278.75</td>
<td>40.92</td>
</tr>
<tr>
<td>Galileo E5</td>
<td>1191.795</td>
<td>92.07</td>
</tr>
<tr>
<td>Galileo E5A</td>
<td>1176.45</td>
<td>N/A</td>
</tr>
<tr>
<td>Galileo E5B</td>
<td>1207.14</td>
<td>N/A</td>
</tr>
</tbody>
</table>

1. GLONASS uses frequency division multiple access. The centre 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.

Any signals that are transmitted in or near the GNSS frequency band(s) will at least partially pass through the frequency filters used in GNSS equipment. This means that these signals are considered interference for the purposes of this study.

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 centre frequency.

Another way to categorize interference is by the source of the interference. Interference can be either intentional or unintentional. GPS and GLONASS are designed as military systems and so should take into account intentional interference, known as jamming, from a hostile transmitter. Even the Galileo system which is primarily designed as a civilian system can meet intentional interference (e.g. terrorist activity). This is especially important for safety of life applications. However most of the interference that can be measured in a peaceful environment is unintentional interference. This can be either another system using the same frequency band or natural occurrences of interference.

It has been assumed that during the measurements on ‘live’ GNSS signals that have been performed for this study only unintentional interference was measured. However this assumption does not limit the applicability of the simulator test results to unintentional interference. In fact, the interference that was used for the tests resembles jamming more closely than it does unintentional interference. A list of unintentional interferers that can be expected in or near the GNSS bands has been put in Table 2-2 [Kaplan & Hegarty, 2006; 1].

### Table 2-2: Unintentional interferers on GNSS systems

<table>
<thead>
<tr>
<th>Interferer</th>
<th>Frequencies (MHz)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GNSS</td>
<td>All GNSS frequencies</td>
<td>It is important to notice that Global Navigation Satellite Systems interfere with themselves (intrasystem interference) and each other (intersystem interference) if they share the same frequency bands such as GPS and Galileo. Several studies into this type of interference, e.g. [Wallner et al., 2005], show results that would be nearly undetectable in field measurements.</td>
</tr>
<tr>
<td>Pseudolites</td>
<td>All GNSS frequencies</td>
<td>These are ground based transmitters of navigation signals. The signals of these pseudolites are very similar to GNSS signals and can be a lot stronger depending on the distance between the transmitter and the receiver.</td>
</tr>
<tr>
<td>DME</td>
<td>960-1164</td>
<td>Distance Measuring Equipment is used for aircraft navigation and can often be found near airfields. The signals are pulsed and the bandwidth depends on the number of aircrafts that make use of it.</td>
</tr>
<tr>
<td>TACAN</td>
<td>960-1164</td>
<td>Tactical Air Navigation is a system that uses DME, but also gives bearing information. The signals are pulsed.</td>
</tr>
<tr>
<td>ADS</td>
<td>960-1164</td>
<td>Automatic Dependent Surveillance is a system that airplanes use. It transmits information on among others the airplane position and altitude.</td>
</tr>
<tr>
<td>Link 16</td>
<td>960-1164</td>
<td>Link 16 is a military communication system that makes use of pulsed signals.</td>
</tr>
<tr>
<td>RADAR</td>
<td>960-1164 1215-1240</td>
<td>RADAR uses pulsed signals.</td>
</tr>
<tr>
<td>Space borne sensors</td>
<td>1215-1240</td>
<td>Ocean surface measurements</td>
</tr>
<tr>
<td>Amateur radio</td>
<td>1240-1300</td>
<td>Amateur radio is permitted in this part of the frequency spectrum by the ITU as long as it does not cause harmful interference to other services</td>
</tr>
<tr>
<td>Mobile communications</td>
<td>1350-1400</td>
<td></td>
</tr>
<tr>
<td>Satellite communications</td>
<td>1535-1559</td>
<td>Space-to-Earth (downlink)</td>
</tr>
<tr>
<td>MSS</td>
<td>1610-1660.5</td>
<td>Mobile Satellite Service in Earth-to-space direction (uplink)</td>
</tr>
</tbody>
</table>
2.3 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 2.4.

3. Increase of noise on the pseudo range measurements
   Interference can increase the error on the pseudo range measurements. This error consists of a bias and noise. The total error can be determined if the actual range to the satellite is known. The noise on the pseudo range measurements can also be determined without knowledge of the actual range. The method used to determine the noise on the pseudo range during this study is discussed in paragraph 2.6.

4. Increase of noise on the phase measurements
   For GNSS receivers that also take phase measurements the noise on these measurements can be used in much the same way as the noise on the pseudo range. One complication is that the noise on the phase measurements is in the same order of magnitude as the clock noise (see paragraph 2.6).

5. Increase of cycle slips in the phase measurements
   When there is severe noise on the phase measurements, this can cause the receiver to ‘skip a beat’ on the phase measurements. When this happens the phase measurement increases instantaneously with a multiple of \( 2\pi \).

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.
2.4 RFI and signal-to-noise ratio

The C/N<sub>0</sub> is accurately described as the signal power to noise power density ratio. The C/N<sub>0</sub> 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/N<sub>0</sub> should be used instead. This value uses a white noise power density that is equivalent to the actual noise plus interference. Kaplan & Hegarty [2006] provide the following method to determine the effective C/N<sub>0</sub> (to use these expressions all values should be entered as ratios not in decibels):

\[
(C/N_0)_{\text{eff}} = \frac{1}{\frac{1}{C/N_0} + \frac{J/S}{QR_c}}
\]

where \((C/N_0)_{\text{eff}}\) is the effective signal to noise ratio in 1 Hz, C/N<sub>0</sub> is the unjammed signal to noise ratio in 1 Hz, J/S is the jammer-to-signal ratio, R<sub>c</sub> 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:

\[
Q = \frac{\int_{-\infty}^{\infty} |H_R(f)|^2 S_S(f) df}{R_c \int_{-\infty}^{\infty} |H_R(f)|^2 S_I(f)S_S(f) df}
\]

where \(H_R\) is the receiver transfer function, \(S_S(f)\) is the power spectral density of the signal normalized over the entire spectrum, \(S_I\) 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 one. If it assumed that there is no filtering within the signal band, (2-2) can be simplified to use for in-band interference:

\[
Q \approx \frac{1}{R_c \int_{-\infty}^{\infty} S_I(f)S_S(f) df}
\]

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:

\[
Q \approx \frac{1}{R_c \int_{f-\beta/2}^{f+\beta/2} S_I(f) df}
\]
where \( f_i \) is the interference centre frequency and \( \beta_i \) 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 \( C/N_0 \) is known and \( (C/N_0)_{\text{eff}} \) is measured (2-1) can be used as follows:

\[
\frac{J/S}{Q} = R \left( \frac{1}{(C/N_0)_{\text{eff}}} - \frac{1}{C/N_0} \right) \tag{2-5}
\]

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 \( C/N_0 \). 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 \( C/N_0 \) is that RFI is not the only factor influencing the \( C/N_0 \). To prevent false alarms it is important to know what other sources can influence the signal-to-noise ratio. Table 2-3 lists the factors that influence the received signal power with the dynamic power range within which they are expected to behave [Misra & Enge, 2001].

<table>
<thead>
<tr>
<th>Table 2-3: Factors influencing the ( C/N_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Variations in satellite transmitted power</td>
</tr>
<tr>
<td>Variations in the free-space propagation loss</td>
</tr>
<tr>
<td>Varying satellite antenna gain with nadir angle</td>
</tr>
<tr>
<td>Variations in atmospheric losses</td>
</tr>
<tr>
<td>Foliage attenuation</td>
</tr>
<tr>
<td>Multi-path</td>
</tr>
<tr>
<td>Varying receiving antenna gain with satellite elevation</td>
</tr>
</tbody>
</table>
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. The receiving antenna gain and ground reflection multi-path are discussed in paragraph 2.5.

### 2.5 Antenna gain and ground reflection multi-path

From paragraph 2.4 it became clear that receiving antenna gain and multi-path needed some attention because of their strong influence on the signal-to-noise ratio. It is important to make a distinction between the antenna gain specifications, which often come from measurements in an anechoic chamber, and the effective antenna gain in a real situation where multi-path from especially the ground (plate) cannot be separated from the gain. A simple multi-path model describes discrete reflected signals with delay, amplitude and carrier phase different from the direct signal [Kaplan & Hegarty, 2006]. When a reflected signal arrives at the antenna in phase with the direct signal, it will increase the received signal power and $C/N_0$. When a reflected signal arrives at the antenna out of phase with the direct signal, it will decrease the $C/N_0$.

Figure 2-2 shows how the effective antenna gain can differ from the specified antenna gain as a result of one ground reflection multi-path ray (see Appendix B). The resulting antenna gain pattern varies much more with the elevation angle than the specified antenna gain. This means that the measured signal-to-noise ratio can change significantly when satellite elevation changes and this makes it more difficult to detect interference by looking at the signal-to-noise ratio.

![Figure 2-2: Specified and effective antenna gain](image)
2.6 Noise on pseudo range and phase measurements

This paragraph deals with the noise on the pseudo range and phase measurements and describes how the noise can be determined from the measurements.

2.6.1 Measuring the pseudo range error

Three different techniques to determine the error or noise on the pseudo range measurements will be discussed in this paragraph:

1. The measured pseudo ranges can be compared to truth data. When using a GNSS simulator, the simulator can determine the simulated range from the satellites to the receiver. When measuring ‘live’ GNSS signals with an antenna, the actual range from the satellites to the receiver can be determined with the International GNSS Service (IGS) data [2]. For this approach it is important that the position of the receiver is determined with a precision that is an order of magnitude better than the precision of the pseudo range measurements.

2. The phase measurements can be subtracted from the pseudo range measurements (code minus phase). This leaves the error on the phase measurements and the error on the pseudo range measurements. Because the error on the phase measurements is one order smaller than the error on the pseudo range measurements it can be neglected, leaving only the error on the pseudo range measurements. Any cycle-slips in the phase measurements should first be removed. They can be detected by searching instantaneous increases of the phase measurements equal to a multiple of $2\pi$ or equal to the wavelength of the carrier wave when the phase measurements are expressed as a distance.

3. By assuming that the high frequent component of the pseudo range measurements is equivalent to the noise component of the pseudo range error, the noise on the pseudo range can be determined by differentiation of the pseudo range measurements. Experience showed that in the third derivative of the pseudo range measurements (in MATLAB the derivative was calculated by taking the difference between every two successive measurement values) all low frequent variations disappeared. After normalization the standard deviation of the third derivative can be used as a measure for the noise on the pseudo range measurements. The normalization factor can be calculated in the following manner [Samson, 2003]:

Let $PR(i)$ be the pseudo range measurement at time $= i$ consisting of the measurement without noise $a(i)$ and the noise on the measurement $n(i)$:

$$ PR(i) = a(i) + n(i) $$

The first, second and third time derivative of the pseudo range measurements is calculated with MATLAB as follows:

$$ \frac{dPR(i)}{dt} = PR(i + 1) - PR(i) $$
\[
\frac{d^2 PR(i)}{dt^2} = PR(i + 2) - 2PR(i + 1) + PR(i)
\]
\[
\frac{d^3 PR(i)}{dt^3} = PR(i + 3) - 3PR(i + 2) + 3PR(i + 1) - PR(i)
\]

Assuming that \(a(i)\) has no high frequent component, the last equation becomes:
\[
\frac{d^3 PR(i)}{dt^3} = n(i + 3) - 3n(i + 2) + 3n(i + 1) - n(i)
\]

If the standard deviation (SD) of \(n(i)\) is equal to \(s\), then the standard deviation of the third derivative of the pseudo range measurements is:
\[
SD\left(\frac{d^3 PR(i)}{dt^3}\right) = \sqrt{s^2 + 9s^2 + 9s^2 + s^2} = \sqrt{20}s
\]

This gives the normalization factor of \(1/\sqrt{20}\)

For this study the code minus phase measurements and the third derivative of the pseudo range measurements were used. Both methods are easily implemented and don’t use information that is not already available in the receiver output. The third derivative method was the primary method to measure the noise on the pseudo range measurements, because of its high resistance to receiver anomalies and automatic exclusion of any measurement biases. The code minus phase method was used to check the third derivative method and also gave some interesting information on the biases.

2.6.2 Measuring the phase noise and cycle slips

To determine the noise on the phase measurements (thermal noise) the third derivative of the phase measurements can be used similar to the noise on the pseudo range measurements [Samson, 2003]. However, there are two complicating factors:

1. The receiver clock noise is of the same order of magnitude as the thermal noise. This means that the third derivative method will not separate the clock noise from the thermal noise. To separate the receiver clock noise from the thermal noise on the phase measurements, the fact that the clock noise will be the same on all the tracked satellites and carrier frequencies can be used. If enough carriers are tracked, the mean noise of all carriers at a certain epoch will be close to the value of the clock noise at this epoch. By calculating this mean value at each epoch, the clock noise can be determined and separated from the thermal noise.

2. There could be cycle slips present in the phase measurements. Cycle slips can be detected by searching for a sudden increase of the phase measurements equal to a multiple of \(2\pi\) or the wave length of the carrier wave when the phase measurements are expressed as a distance. When cycle slips are detected they can be removed from the phase measurements in able to determine the phase noise. Cycle slips themselves can also be another indication of interference on the GNSS signals.
3 Tests performed and experimental setup

This chapter will discuss the tests that were performed for this study and the reasons why these tests were chosen. The instruments and measurement setups that were used to perform these tests will also be discussed. Chapter 2 introduced the theory on the effects of RFI on receiver performance and gave some formulae that can be used to predict the quantitative effects of RFI on GNSS receiver output. However it is also noted that these effects strongly depend on a number of receiver parameters in a way that is not easily predicted. Also these effects have not yet been measured in detail for the Galileo system.

Therefore it was important for this study to include extensive tests that chart the effects of RFI on receiver performance. To exclude the influence of sources other than RFI on the performance of the receivers, such as multi-path or atmospheric effects, these tests could only be performed in a controlled environment. For this reason GNSS hardware simulators were used for the tests. These simulators will be introduced briefly in paragraph 3.1. The tests that were performed with these simulators are explained in paragraph 3.2 for the GPS system and in paragraph 3.3 for the Galileo system.

Finally, a comparison was made to see how the simulator test results correspond to a real interference situation. Measurements were taken in Turin, Italy where strong interference was reported. Because the test environment was no longer controlled, a spectrum analyzer was used to measure the interference that was present at the time of the GNSS measurements. The tests that were performed in this fashion are explained in paragraph 3.4.

3.1 Hardware

In this paragraph a short introduction to the used hardware will be given. More detailed information can be found in the Appendices and References.

3.1.1 GNSS signal generators

The signal generators used in this study are radio frequency hardware simulators. The signals that are produced simulate actual signals as they could come from an antenna receiving GNSS signals.

1. GSVF-2: Galileo Signal Validation Facility. This unit has been designed for the signal evaluation phase of the Galileo development track [Harris et al., 2006]. It can produce Galileo System Test Bed (GSTB-V2) L1, E5 and E6 signals as well as some other test signals in the same bands. The simulator also simulates a Low Noise Amplifier (LNA) and so the signals can directly be inserted in the front-end of a compatible GNSS receiver (in this case the GETR see below). This unit is controlled by the graphical user interface, which makes it possible to change, among others, the user environment and satellite orbits. For this study a geostationary satellite orbit in combination with a stationary user was simulated.

2. Spirent GNSS hardware simulator: This unit, in short called the Spirent Rack, can produce GPS L1, L2 and L5 signals as well as GLONASS signals. For this study only GPS L1 and L2 were used. This unit is controlled by the SimGen software [3], which makes it possible to create scenarios that simulate, among others, changing user environment and satellite orbits. For
this study the actual satellite orbits as per Jan 2005 were used in combination with a stationary user. This simulator does not simulate an LNA and so an LNA has to be added to the measurement setup. Integrated in the Spirent rack is an interference generator (see point 3).

3. Agilent interference generator: This unit is integrated in the Spirent Rack and is controlled by the SimGen software. This means scenarios can be used that change the interference settings during the measurements [4].

3.1.2 GNSS receivers

1. GETR: Galileo Experimental Test Receiver [Simsky et al., 2005]. This receiver has 7 Galileo channels which search for a specific satellite Pseudo Random Noise (PRN) number as well as 8 GPS channels that automatically track any available GPS satellite.

2. Septentrio PolaRx2 GNSS receiver: This receiver has 48 channels and supports GPS L1 and L2 as well as GLONASS and Satellite Based Augmentation System (SBAS) signals [5].

3. Javad Legacy GPS GLONASS receiver: This receiver can track GPS signals as well as GLONASS signals [6].

4. Novatel OEM4-G2 GPS receiver enclosed in a ProPak-G2: This receiver has 24 channels and supports GPS L1 and L2 as well as SBAS signals [7].

3.1.3 Miscellaneous

1. Antenna: The Space Engineering Galileo antenna that was used for the measurements has 10 dB gain role-off from 90 to 0 degrees of elevation [8].

2. Cables: All the cables used in the measurement setups are calibrated cables that have small losses. The short cables that were used inside the navigation laboratory have losses smaller that 1dB. Only the longer cables connecting the antennae on the roof of the navigation laboratory have greater losses.

3. GPS Networking Inc. GPS Amplified splitters: Depending on the setup a 2-way or 4-way splitter was used to connect the different receivers and a spectrum analyzer to the same signal input. One of the RF outputs of the splitter passes Direct Current (DC) from the connected GPS receiver through the splitter to the antenna or signal generator. The other RF outputs are DC blocked. The splitters have the high isolation option which has a gain of 4.5 dB [9].

3.2 Simulated GPS measurements

The purpose of these tests was to show the effects of RFI on receiver performance as well as to show how these effects depend on frequency offset and interference-to-signal power for certain interference types. Frequency offset here is the difference between the centre frequency of the interference and the centre frequency of the GNSS signals. This setting was changed from -20MHz to +20MHz around both the GPS L1 and L2 frequency. The interference-to-signal power is the total interference power with respect to the total GNSS signal power. The interference-to-signal power was used rather than the absolute interference and signal power under the assumption that this would make the results more generally applicable. To check the validity of
this assumption, the influence of the absolute signal power was also investigated with some tests.

For these tests three receivers were used to see what the differences between these receivers are and to see if general results could be obtained:

1. Septentrio PolaRx2
2. Javad Legacy
3. Novatel OEM4

Two types of interference were used:

1. White Gaussian Noise with 1MHz bandwidth
2. Continuous wave interference

3.2.1 GPS simulation setup

This paragraph describes the test setup that was used for the tests with the simulated GPS signals and the procedures that were used. The most important parts of this setup are the Spirent rack that produces the GPS signals and interference and the GPS receivers. The setup and procedures are described in greater detail with the help of Figure 3-1. A step by step list of actions, a link budget and the used receiver settings can be found in Appendix C.

The GPS L1/L2 component of the Spirent rack as well as the interference generator is routed through the signal combiner of the Spirent rack to the calibrated RF1 out port. None of the other Spirent components generate signals during these tests. The signal power is increased by the Low Noise Amplifier with 28dB before the signal enters the four way splitter to make sure the signal power is comparable to a setup where a
receiver is connected to a real antenna. From the splitter the signal goes to three different GPS receivers and one spectrum analyzer.

The GPS receivers track the simulated signals during the tests and log among others the pseudo range measurements, the phase measurements and the carrier-to-noise ratio measurements with a frequency of 1Hz. The spectrum analyzer is used to monitor the tests.

3.3 Simulated Galileo measurements

For these tests the Galileo Experimental Test Receiver was used. The general idea of these tests is the same as that of the simulated GPS measurements. The exact tests were decided upon after discussions with the User and Ground Receiver Management of the Galileo Project, because of their interest in the results and their expertise with respect to the receiver and simulator. Measurements were performed on the Galileo E1, E5 and E6 bands with changing frequency offset and interference-to-signal power for certain interference types. Three types of interference were used:

1. White Gaussian Noise with 1MHz bandwidth
2. White Gaussian Noise with 100kHz bandwidth
3. Amplitude Modulated narrow band interference

3.3.1 Galileo simulation setup

This paragraph describes the test setup that was used for the tests with the simulated Galileo signals and the procedures that were used. The most important parts of this setup are the GSVF-2 that produces the GSTB-V2 signals, the interference generator that is incorporated in the Spirent rack and the GETR. The setup and procedures are described in greater detail with the help of Figure 3-2. A step by step list of actions, a link budget and the used receiver settings can be found in Appendix D.

The GPS L1/L2 component of the Spirent rack has a direct connection to the GETR (cable 4). When the test starts, this connection makes it possible for the GETR to synchronize with the Spirent clock. When this has happened the GETR will put a time stamp on all the measurements that corresponds to the scenario that is run by the Spirent software. This allows for easy and accurate interpretation of the measurements by linking the measurements to specific interference conditions. After synchronization the Auxiliary In port of the GETR is switched off, to make sure that the GPS signals will not influence the test results.
The GSVF-2 generates the GSTB-V2 signals and these are directly provided to the GETR via cable 2. When the interference generator produces interference this is routed through the signal combiner of the Spirent rack to the calibrated RF1 out port. None of the other Spirent components are connected to the signal combiner, which means that cable 1 only carries the desired interference to the GSVF-2 Interference In port. The GSVF-2 combines this with the GSTB-V2 signals and transmits the combined signal on the RF OUT port. Between the Interference In port and the RF OUT port of the GSVF-2 is approximately 13 dB of attenuation, which is taken into account in the interference scenario. As a result cable 2 carries the desired interference signals on top of the GSTB-V2 signals.

The GSVF-2 transmits the same signals on the RF Monitor port as on the RF OUT port with approximately 10 dB more power. This port is connected to a Spectrum Analyzer to monitor the interference during the tests.

The GETR tracks the GSTB-V2 signals during the tests and logs among others the pseudo range and carrier-to-noise ratio with a frequency of 1Hz.

### 3.4 Giove-A interference measurements

For this part of the study data that was collected as part of a different measurement campaign in Turin, Italy [Samson & Baranski, 2006] has been analyzed. Unlike the tests in the navigation lab, these measurements were not performed under a controlled environment. However, the use of a spectrum analyzer provided information on the occurring interference during the measurements. To increase the chances of measuring interference with a significant impact on the receivers, the receivers and spectrum analyzer were left collecting data for long time spans. A consequence of this approach was that the update rate of the spectrum analyzer measurements could not be set below 1 second. This provided a problem, because, with an update rate of 1 second, continuous interference could not be distinguished from pulsed interference.
To solve this problem the measurements were first analyzed and any interference with enough power to significantly influence the receivers was identified. At the frequencies at which this interference appeared more measurements were taken to determine the interference characteristics in the time domain, by using a very high update rate. This method works under the assumption that the same interference sources are received over the course of the measurements (several days).

For these measurements the GETR and a spectrum analyzer were connected to the Space engineering Galileo antenna. For a link budget and the used receiver settings of the measurement setup see Appendix E. The results of these measurements are compared to the simulator test results in paragraph 4.5, which also illustrates how the simulator tests can be used for an interference analysis.
4 Presentation of results

The measurement campaign performed for this research has produced a lot of results in the form of plots. Most of these can be found in the Appendices. In this chapter only those plots have been included that are necessary to explain the results or improve the discussion thereof.

Paragraph 4.1 shows that, to get a correct and reliable C/N₀ measurement under certain RFI conditions, these conditions had to be maintained for several minutes. In paragraph 4.2 the influence of the absolute signal power on the C/N₀ measurements is investigated for constant J/S. Paragraph 4.3 shows the results of the simulated GPS signal measurements for the three different GPS receivers that were used during this study. Paragraph 4.4 shows the results of the simulated Galileo signal measurements and compares them to the GPS results. Paragraph 4.5 deals with the field measurements made in Turin, Italy. These results are then compared to the simulator test results.

4.1 Interference time span length

During the tests with the simulated GNSS signals, the performance of the receivers was determined for a large number of RFI configurations. For every configuration 100 measurement samples were taken. For the C/N₀ values that appear in the results the mean of these 100 samples was taken. This implies that the standard deviation (SD) of these values is 10% of the SD of the 100 measurement samples themselves. For the values of the noise on code and phase measurements the SD of the 100 measurement samples was taken. Although the SD is a biased estimator it can be considered to be unbiased for 100 samples [10]. The SD of the values that appear in the results is smaller than 10% of the SD of the 100 measurement samples.

During the tests the receivers were logging data with a frequency of 1 Hz. For the GPS receivers, tracking about 10 simulated satellites at once, this meant that 100 samples could be collected in 10 seconds. For the GETR, tracking just one simulated satellite, this took 100 seconds. However the measurement time had to be increased because of the behaviour of the PolaRx 2 and the GETR when RFI was added. Figure 4-1 shows the C/N₀ measurements of the PolaRx 2 when RFI is added to the GPS L1 signal. As can be seen, the C/N₀ value does not decrease instantaneous to the lower value, but instead decreases with a delay and can take several minutes to reach a constant value again. This effect is also visible when removing the RFI, so both measurement time with RFI and time in between RFI time spans was increased to 5 minutes.

Figure 4-2 shows the C/N₀ measurements of the GETR when RFI is added to the GSVF-2 E6BC-Pilot (E6BC-P) signal. The GETR measures the noise only at the beginning of each acquisition which will lead to incorrect C/N₀ values when interference is added. One GETR channel was left tracking a PRN number that was not simulated by the GSVF-2 and so could never be acquired. This meant that every time the channel restarted acquisition the noise measurement was corrected. This can take up to 80 seconds. With the 100 seconds measurement time the interference time span was set at 4 minutes. The time in between interference time spans was set at 2 minutes. The C/N₀ measurements for the L1A, E6A and E5AltBOC signals could not be corrected. The GETR can only track the E5AltBOC signal on one channel and the
L1A and E6A signals generated by the GSVF-2 are not unique for each satellite. Therefore, the GETR could not have a channel constantly trying to acquire these signals.

![Figure 4-1: PolaRx 2 C/N₀ vs. time](image1)

![Figure 4-2: GETR C/N₀ vs. time](image2)


4.2 Absolute signal power

As mentioned in chapter 3, the results of this study will be presented with the signal-to-noise ratio and the jammer-to-signal ratio rather than the absolute signal power and interference power. The aim was to make the results of this study more generally applicable and less dependant on the precise measurement setup. However, to check how the results would change when e.g. a different LNA was used, the influence of the absolute signal power had to be investigated.

Figure 4-3 shows how the C/N₀ measured by the PolaRx-2 receiver depends on the signal strength when the J/S ratio is kept constant for 1 MHz Gaussian White Noise (GWN) interference on the centre frequency of the GPS L1 signal. Test results for the other receivers can be found in Appendix F. The upper line in Figure 4-3 shows the measured C/N₀ without interference. The figure shows that for high J/S levels and high signal power the lines are almost horizontal. This means that the J/S level alone is enough to predict the measured C/N₀. The absolute signal level is not important. However, for lower J/S levels and/or lower signal power the measured C/N₀ depends not only on the J/S level, but also on the absolute signal power. Special note should be made of the combination of low signal power and low J/S levels. For these conditions the lines are very close together and a small increase in the J/S ratio will not have a significant effect on the measured C/N₀.

Equation (2-1) was used to determine the jamming resistance quality factor Q from the measurements. The least squares method gave a Q of 2.35. The dotted lines in Figure 4-3 show the effective C/N₀ that can be calculated with equation (2-1), the unjammed C/N₀ and this value of Q. The figure shows that all residuals are very small. This means that with a single value for the jamming resistance quality factor the effective C/N₀ values measured by the receiver can accurately be predicted for
different levels of the signal power and the jammer-to-signal ratio. This in turn means that a meaningful comparison can be made between the test results shown in paragraph 4.3 and 4.4 and measurements made with a different signal power. The value for Q coming from the measurements is not equal to the value that can be calculated with equation (2-4), which is 1.23. This difference indicates that either the receiver does filter within the 1 MHz around the signal centre frequency or that there is some other factor that is not taken into account in equation (2-2).

4.3 Simulated GPS signal measurements

This paragraph will discuss the GPS simulator test results. More GPS simulator test results can be found in Appendix F.

Figure 4-4 shows the GPS L1 C/A code jamming thresholds for the 3 receivers when 1MHz Gaussian white noise is added. The jamming threshold here is defined as the jammer-to-signal ratio for which the receiver looses tracking. The vertical axis shows the level of the interference compared to the level of the signal and the horizontal axis shows the frequency of the interference compared to the L1 centre frequency. The differences between the receivers are due to many different receiver properties, but special note should be made of the filtering in the receivers, the tracking threshold and the C/N$_0$ mask. The tracking threshold is the lowest C/N$_0$ value for which a receiver is able to track a signal. However most receivers will not output measurements if the C/N$_0$ is below a certain value called the C/N$_0$ mask. For the PolaRx 2 this value was 19 dB-Hz, for the OEM4 this value was 20 dB-Hz and for the LEGACY this value was 27 dB-Hz.

![Figure 4-4: Jamming threshold GPS-L1 C/A code](image)

Figure 4-5 shows for which frequency and power of the RFI the SD of the noise on the pseudo range measurements equals 0.15 m for the different receivers. The differences between the receivers are largely due to receiver filtering, the code loop noise bandwidth or the smoothing interval (which unfortunately could not be switched...
off for all receivers), the correlator spacing and the predetection integration time [Kaplan & Hegarty, 2006; Betz, 2000]. For comparison: the SD of the noise on the PR measurements without RFI was 0.015 m for the PolaRx 2, 0.074 m for the OEM4 and 0.067 m for the LEGACY receiver.

![Graph](image.png)

**Figure 4-5: Noise on PR = 0.15 m GPS-L1 C/A code**

### 4.4 Simulated Galileo signal measurements

This paragraph will discuss the Galileo simulator test results. More Galileo simulator test results can be found in Appendix G.

Figure 4-6 shows the jamming thresholds of the GETR for all 3 Galileo signals on the L1 band (the addition of P or D to the signal corresponds to the Pilot or Data component of the signal) as well as the jamming threshold of the PolaRx 2 receiver for the GPS L1 C/A code when 1MHz GWN is added. The vertical axis shows the level of the interference compared to the level of the composite signal and the horizontal axis shows the frequency of the interference compared to the L1 centre frequency. The interference level with respect to the Galileo component signals (as opposed to the composite signal) is up to 6 dB higher depending on the signal for all results in this paper. It can be seen that each Galileo L1 signal is most vulnerable to interference in the main lobes of the signal and that the tolerable interference levels for the GETR are in the same order of magnitude as for the PolaRx 2. Furthermore it can be seen that the PolaRx 2 receiver tolerates more interference at the sides of the GPS L1 band without loosing C/A code tracking than does the GETR without loosing e.g. L1BC-Pilot tracking. This is related to the receiver front-end bandwidth. The GETR front-end bandwidth is 40 MHz, which is much greater than the front-end bandwidth of most GPS receivers. But comparison of the simulator test results to theoretical values also shows that the GETR is more vulnerable to RFI at the sides of the L1 band, than theory predicts. Similar results are later shown for the E6BC-Pilot signal.
Figure 4-7 shows the jamming thresholds for the E6 signals and Figure 4-8 shows the jamming thresholds for the E5a and E5b signals. The RFI frequencies are given relative to the appropriate signal centre frequency. It can be seen that the E5b signal does not completely correspond to the mirrored E5a signal, which is unexpected. This could be a result of an asymmetry in the input filter or the generated signal or the receiver does not perform exactly the same processing for both signals.
Figure 4-8: Jamming threshold E5

Figure 4-9 shows the measured C/N₀ of the tests with band limited Gaussian white noise (bandwidth 1MHz) on the E6BC-Pilot signal. Every coloured square in the figure corresponds to one measurement time span of 5 minutes. The horizontal position of the square corresponds to the centre frequency of the interferer with respect to the centre frequency of the signal and the vertical position corresponds to the interference level with respect to the composite signal level. The colour of the square corresponds to the measured C/N₀ which can be read from the colour bar to the right of the figure. At the sides of the figure the squares are spaced further apart, because fewer measurements were taken. The missing squares for high jammer-to-signal power indicate that the receiver was unable to track signals with this interference present. The C/N₀ is most sensitive to interference at the centre frequency of the E6BC-P signal and follows the power spectrum of the signal quite closely.

Figure 4-10 shows the theoretical C/N₀ values for the same interference settings as Figure 4-8 calculated with equation (2-1) and equation (2-4) and using the measured unjammed C/N₀ and tracking threshold values. It can be seen that close to the E6 centre frequency the theory is quite close to the test results. However, when the RFI is farther removed from the E6 centre frequency or the RFI is in between the E6 lobes, the C/N₀ of the GETR decreases more than the theoretical values. It should be noted that the presence of the other E6 signals was not taken into account for the theoretical predictions.
Figure 4-9: E6BC-P C/N₀ 1 MHz GWN

Figure 4-10: Theoretical E6BC-P C/N₀ 1 MHz GWN

Figure 4-11 is essentially the same as Figure 4-9 only now the colour of the squares corresponds to the SD of the noise on the PR measurements. It can be seen that for a certain J/S the pseudo range measurements are noisiest when the interference has 2.5 MHz offset from the centre frequency of the signal. These results fit the theory given in [Betz, 2000]. A certain value of the C/N₀ apparently does not always give the same value for the noise on the PR. Instead it depends on the centre frequency of the RFI that is present on the signal. This dependency is shown more clearly in Figure 4-12 for the E5a-P signal.
Effects of Radio Frequency Interference on GNSS Receiver Output

Figure 4-11: E6BC-P noise on PR 1 MHz GWN

Figure 4-12: Noise on the PR vs. the C/N₀ on the E5a-P signal

Figure 4-12 shows similar results as those shown in Figure 4-9 and Figure 4-11 in an alternative way. Every measurement of 5 minutes is now represented by a coloured dot. The colour of the dots corresponds to the centre frequency of the RFI with respect to the E5a centre frequency. On the axes the measured C/N₀ and noise on the pseudo range are shown. The RFI power is no longer explicitly shown, but when comparing dots with same colour (i.e. the same RFI centre frequency) lower C/N₀ values and higher values of the noise on the pseudo range correspond to higher RFI power. The
blue line in Figure 4-12 shows the theoretical relation between the C/N₀ and the noise on the PR considering only white noise interference with infinite bandwidth [Kaplan & Hegarty, 2006]. It can be seen that the degradation of the C/N₀ due to RFI close to the centre frequency of the E5a signal (blue dots) does not correspond to the degradation of the PR measurements that could be expected from the infinite bandwidth white noise theory. Also RFI with a centre frequency offset 8 or 13 MHz with respect to E5a can degrade the PR measurements more than would be expected from the C/N₀ value. This shows that interference monitoring based solely on measured C/N₀ can be misleading, because it does not accurately predict the receiver performance.

Tests were also performed with GWN with 100 kHz bandwidth. Figure 4-13 shows the C/N₀ measurements of these tests for the L1BC-P signal and Figure 4-14 shows the noise on the PR. As mentioned before the C/N₀ measurements closely follow the spectrum of the signal which is very clear in Figure 4-13. Whenever the RFI is in one of the lobes of the signal the C/N₀ drops more than when the RFI is in between the lobes. What also can be seen in Figure 4-13 and Figure 4-14 is that they are not symmetrical. Apparently the GETR could tolerate more interference when centred at +10 MHz than when centred at -10 MHz with respect to the L1 centre frequency. This behaviour again could be a result of an asymmetry in the input filter or the generated signal.

![Figure 4-13: L1BC1-P C/N₀ 100 kHz GWN](image)
Also some tests were performed with narrow band interference with amplitude modulation (modulation depth 100%, modulation frequency 10 Hz). For these tests only one jammer-to-signal ratio was used and the centre frequency of the interference was swept through part of the appropriate signal band as before. Again the GETR was also searching for a satellite signal which was not generated to continuously update the noise measurements. The blue line in Figure 4-15 shows the results of these tests for the E5a-P signal, but the results of the E5a-D signal were very similar. The C/N₀ term used by the GETR in the C/N₀ computation for both the Pilot and Data channel is based on the noise power in 1 ms [11]. When this test was repeated without the updated noise measurements the effect was not visible (the red line in Figure 4-15). This proved that the effect originates from the noise measurements and not the signal strength measurement and also explains why it was visible on both the Pilot and Data channel.
4.5 GIOVE-A interference measurements

RFI measurements with a spectrum analyser were made at INRIM in Turin, Italy after reports of decreased performance of a GETR tracking the GIOVE-A L1 signals. Figure 4-16 shows the results of these measurements in the frequency domain. More measurements in the time domain showed that all the RFI was of a pulsed nature except for the 3 MHz wide interference centred at -18 MHz with respect to the L1 centre frequency [Samson & Baranski, 2006]. The RFI amplitude before it enters the antenna is about -110 dBW with a resolution bandwidth of 200 kHz.
To compare the INRIM results to the simulator test results some steps of approximation have to be taken:

The RFI in the simulator tests was band limited Gaussian white noise, but the RFI measured at INRIM was not. However, if we look at the theory used for this study, equations (2-1) and (2-3), it is only the spectrum of the RFI that is important. For this comparison it was assumed that as long as the RFI spectrum resembles band limited GWN, the impact on the receiver will be similar.

The RFI bandwidth at INRIM is greater than the RFI bandwidth used for the simulator tests. So only the worst 1 MHz of the INRIM interference was considered. This RFI is then centred at -17 MHz with respect to the L1 centre frequency and the power is -103 dBW taking into account the resolution bandwidth of 200 kHz.

The unjammed C/N₀ received from the GIOVE-A satellite is lower than the unjammed C/N₀ measured during the simulator tests. However, equation (2-1) can be used to determine Q from the simulator test results. Equation (2-1) can then be used to predict the effective C/N₀ for different values of the unjammed C/N₀. In this specific case the J/S is so large that the effective C/N₀ is expected to be the same for both values of the unjammed C/N₀.

The J/S has to be determined for the INRIM measurements. Assuming that all RFI enters the antenna with 0 degrees of elevation, an antenna gain roll-off of 10 dB and the nominal signal strength of the GIOVE-A satellite of -152 dBW, the J/S can be determined and is equal to 39 dB for the worst 1 MHz RFI bandwidth or 44 dB for the entire 3 MHz RFI bandwidth.

Table 4-1 shows the comparison of the INRIM measurement results to both the simulator test results and theoretical predictions using equation (2-1) and (2-4) for the L1BC-D signal.

### Table 4-1: Comparison of INRIM results to simulator test results and theoretical predictions for the L1BC-D signal

<table>
<thead>
<tr>
<th></th>
<th>RFI frequency (MHz)</th>
<th>RFI bandwidth (MHz)</th>
<th>J/S (dB)</th>
<th>C/N₀ No RFI (dB-Hz)</th>
<th>C/N₀ Effective (dB-Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GETR at INRIM</td>
<td>-18</td>
<td>3</td>
<td>44</td>
<td>45</td>
<td>35</td>
</tr>
<tr>
<td>GETR simulator tests</td>
<td>-17</td>
<td>1</td>
<td>39</td>
<td>52</td>
<td>35</td>
</tr>
<tr>
<td>Band limited Gaussian white noise theory</td>
<td>-18</td>
<td>3</td>
<td>44</td>
<td>45</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>-17</td>
<td>1</td>
<td>39</td>
<td>45</td>
<td>42</td>
</tr>
</tbody>
</table>

The theoretical values show that approximation step 2 used for the comparison of the results is allowed. Step 1 and 3 are based directly on the theory and step 4 is based on technical specifications and knowledge of the RFI source.

The INRIM results are very close to the simulator test results, but there is a big difference between the measurements taken with the GETR and the theoretical values. As mentioned before, the C/N₀ values for L1BC measured with the GETR are decreased more than theory predicts for RFI at the sides of the L1 band.
For the L1A signal the INRIM results fit less well to the simulator test results. At INRIM the C/N$_0$ of the L1A signal was less degraded than in the simulator tests when the same RFI was applied. The unexpected L1A C/N$_0$ values at INRIM could not be explained without exact knowledge of the interference and/or further testing with the simulator.
5 Conclusions

This chapter will try to answer the research questions posed in the introduction of this thesis as well as draw some additional conclusions. These research questions are:

1. What are the effects of RFI on GNSS receiver output?
2. How does the Galileo system compare to GPS when considering RFI?
3. How does the theory on GNSS and RFI compare to GNSS and RFI test results?
4. How do simulated GNSS and RFI test results compare to GNSS and RFI field measurements?
5. Is it possible to detect RFI on GNSS receivers by only studying the receiver output?

ad 1. The effects of RFI on GNSS receiver output

During this study the following effects of RFI on GNSS receivers were identified:

1. Loss of receiver tracking
2. Decrease of the measured C/N0
3. Increase in the noise on the pseudo range measurements
4. Increase in the noise on the phase measurements
5. Increase of cycle slips in the phase measurements

With respect to these effects some important conclusions can be drawn based on the simulator test results. A receiver will lose tracking first for RFI at the centre frequency of the main lobe of the signal and the C/N0 will also decrease most for RFI at the centre frequency of the main lobe. However, the noise on the pseudo range will increase most for RFI halfway between the centre frequency of the main lobe of the signal and the side of the main lobe. This means that the C/N0 and noise on the pseudo range are not directly linked and that a certain value for the C/N0 cannot simply be translated to a value for the noise on the pseudo range.

ad 2. The Quality of the Different GNSS Systems and Receivers

The results show that the jamming threshold of the GETR when tracking GSVF-2 signals is comparable to that of the GPS receivers when tracking simulated GPS signals. One noticeable difference is that the GPS receivers are less vulnerable to RFI at the sides of the GPS L1 band than the GETR is. This is related to the GETR front-end bandwidth which is greater than the front-end bandwidth of most GPS receivers.

The noisiest pseudo range measurements for all Galileo signals with a single main lobe at the signal centre frequency were found halfway between the centre frequency of the signal and the side of the main lobe. This is in accordance with earlier finding for the tracking of GPS signals [Betz, 2000].

ad 3. Simulator test results compared to RFI theory

Equations (2-1) to (2-4) showed that the decrease of the measured C/N0 of a GNSS receiver as a result of RFI is related to the overlap of the RFI and the GNSS signal in the frequency spectrum. This relation was also clearly visible in the simulator test results. Also the expected sensitivity of the pseudo range measurements to RFI halfway between the centre frequency of the main lobe and the side of the main lobe
of GNSS signals [Betz, 2000] was clearly found in the simulator test results. However, comparison of the simulator test results to theoretical values also showed that for RFI outside the main lobe(s) of a signal, the $C/N_0$ of the GETR decreases more than the theoretical predictions. It is concluded that although the theory gives a good impression of the influence of certain RFI parameters, the behaviour of a specific receiver is rather more complex and is not easily predicted.

ad 4. Simulator test results compared to field measurements

In paragraph 4.5 the steps of approximation necessary for a comparison of the simulator test results to field measurements were discussed. These had to do with the signal and interference power and with the interference type and properties. The simulator tests investigating the influence of the absolute signal power showed that a difference in received signal power can easily be compensated for. A difference in the type of interference cannot so easily be overcome. The test results from the field measurements made in Turin, Italy showed a decreased $C/N_0$ for the L1BC-Data in line with the expected values based on the simulator tests. However, the $C/N_0$ measured for the L1A signal deviated from the expected values and this difference could not be explained without further tests with the interference type encountered during the field measurements. Even very extensive RFI simulator tests cannot test every possible RFI scenario, so there will always be discrepancies between simulator tests and field measurements. However, RFI simulator tests can still be a very useful tool to explain or predict GNSS receiver performance under certain RFI conditions.

ad 5. Interference Detection on GNSS Receiver Output

The field measurements take at Turin, Italy showed that RFI can have a very strong impact on GNSS receiver output. This impact can easily be detected and, as long as it can be separated from other sources that influence the receiver output, such as multi-path, can be used as an indicator that there is RFI present on the GNSS signals.

When trying to detect RFI in this way it is important to know that tracking the $C/N_0$ measurements is not enough to determine the performance of the receiver. The simulator test results show that the noise on the pseudo range measurements cannot be derived from the $C/N_0$ measurements when the centre frequency of the RFI is unknown. If no spectrum analyzer is used during measurements the frequency of any interference is generally not known. Therefore receiver performance cannot be predicted when only the $C/N_0$ is monitored. Another problem with RFI detection by using the $C/N_0$ was shown in Figure 4-1 and Figure 4-2, which showed that the $C/N_0$ measurements do not instantaneously show the correct value when RFI enters the receiver.

Directly monitoring the receiver performance by looking at the noise on the pseudo range in addition to monitoring the $C/N_0$ measurements is a possible alternative, but still no direct knowledge of the interference will be known, only the severity of the impact.

Additional conclusions

As already mentioned in the introduction, the test results from this study can also be useful when defining requirements for the environment of locations for permanent receivers or when defining standard receiver tests.
Requirements for site Acceptance

The results from this study can be used to determine the continuous interference that can be allowed on a site before it should be rejected as a possible location for permanent receivers (e.g. Galileo Sensor Stations). If some requirement is determined (e.g. the minimal C/N$_0$ that should be received from a satellite with a certain elevation) an interference mask can be derived from e.g. Figure 4-9 or Figure 4-13.

Regarding this requirement the following should be noted. Using the C/N$_0$ which is closely related to the power spectrum of the signal does not necessarily safeguard receiver performance. A better way would be to determine a requirement for the noise on the pseudo range and derive an interference mask from this value using e.g. Figure 4-11 or Figure 4-14.

Standard Receiver Testing

When allowed interference conditions have clearly been determined, the tests performed for this study can be repeated for any receiver that is a candidate for such a permanent ground station. This way it could easily be determined whether or not the receiver performance under these conditions is acceptable.
6 Recommendations

Applicability of the Results

One application of the results of this study has been demonstrated with the field measurements taken in Turin, Italy. However, the relation between RFI and receiver performance in field measurements is complicated by some factors that were already mentioned in chapter 2.

The measured carrier-to-noise ratio is influenced by multi-path, the antenna gain pattern, atmospheric effects, etc. This makes it more difficult to detect interference, but there are some ways to overcome these difficulties. If a stationary antenna is considered, the effects of multi-path and antenna gain are mostly dependent on the satellite elevation and azimuth angle and so become quite predictable once measured. This makes it possible to separate these effects from the effects of interference. Another important distinction is that multi-path will influence the tracking of each satellite signal individually, but interference entering the antenna will influence the tracking of all satellite signals simultaneously. This distinction can also be used to separate these effects in the receiver output.

The noise on the pseudo-range measurements is also influenced by more effects than just RFI such as multi-path and atmospheric effects. Multi-path can be removed from PR measurements by subtracting the Pilot measurements from the Data measurements.

It is recommended that the results of this study are compared to more field measurements to validate the results, using the proposed methods to separate the effects of RFI from other sources influencing the receiver performance.

Pulsed Interference

For this study only continuous RFI was considered and the results are not applicable to pulsed RFI. Very strong pulsed RFI is often encountered during RFI measurements, but with a very low duty-cycle and little impact on the receiver. Also, blanking can be used to reduce the impact of pulsed RFI, but not to reduce the impact of continuous RFI. It is recommended that more tests be performed to investigate the influence of pulsed interference and other types of modulated signals on GNSS receivers.

Cycle Slips

During this study an increase of cycle-slips in the phase measurements was identified as a possible effect of RFI on receiver output. However, due to time limitations this effect was not studied in detail. It is therefore recommended that the relation between cycle-slips and RFI should be investigated further.
References

References to papers and books were made with the author(s) and year of publication. Documents that could not be referenced in this manner have been referenced with a number.


Samson, J., CALC_PHASE_NOISE.m, Part of Tango, ESA internal software, 2003.

Samson, J., Baranski, A. Interference at INRIM in L1, E5 and E6, ESA internal document, July 2006.


## 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 [12; 13; 14; 15].

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

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

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 centre frequencies of the GLONASS signals are separated by 0.5625 MHz on L1 and 0.4375 MHz on L2 [15].
3. Minimum received power with a 3dBi gain linearly polarized antenna for a satellite with a minimum of 5 degrees elevation [13; 14; 15].
4. Minimum received power with a 0dBi gain ideally matched antenna for a satellite with a minimum of 10 degrees elevation [12].
Appendix B: Simple ground reflection Multi-path model

This appendix will illustrate how the antenna gain will change from the specified values, when it is placed on a reflective surface. This will be done with a simplified multi-path model. Only one multi-path ray will be modelled and the polarization of the waves will not be considered.

Suppose an antenna is placed at height \( h \) from an endless flat surface. Suppose also that a GNSS satellite has an elevation angle \( \alpha \) and is so far away that the carrier waves reaching the antenna can be considered to be parallel (see Figure B-1).

![Figure B-1: Ground reflection multi-path](image)

From Figure B-1 it is clear that the carrier reaching the antenna after reflecting from the surface has travelled a longer distance than the carrier that reaches the antenna directly. The difference consists of 2 parts: the first part before the carrier reaches the surface \( x_1 \) and the second part after it reflects from the surface \( x_2 \). The lengths of \( x_1 \) and \( x_2 \) can be determined from the height \( h \) and the elevation angle \( \alpha \) as follows:

\[
\sin(\alpha) = \frac{h}{x_2}
\]

\[
x_2 = \frac{h}{\sin(\alpha)}
\]

and

\[
\cos(\pi - 2\alpha) = \frac{x_1}{x_2}
\]

\[
x_1 = x_2 \cdot \cos(\pi - 2\alpha)
\]

This difference in distance causes the carriers to have a phase difference when they arrive at the antenna:

\[
\phi = 2\pi \frac{x_1 + x_2}{\lambda}
\]
where $\phi$ is the phase difference and $\lambda$ is the wavelength of the carrier.

Depending on the phase difference the carriers will either enhance each other or cancel each other out. If the difference in distance is equal to half the wavelength of the carrier the waves are in anti-phase. If the reflectivity of the surface is 100%, the waves could theoretically cancel each other out completely. However in practice this is not likely because the reflectivity will be lower than 100%, the reflecting carrier will arrive with a negative elevation angle and the polarization of the reflected wave will have changed. Due to the gain role off of the antenna and the polarization of the antenna the reflecting carrier will be received with a lower power then the line of sight carrier. The effective antenna gain including the multi-path ray and not considering the polarization will be:

$$G_{\text{eff}} = G_\alpha + 10 \log \left( 1 + r \cos(\phi) 10^{\frac{G_\alpha - G_\alpha}{10}} \right)$$

where $G_{\text{eff}}$ is the effective gain $G_\alpha$ is the gain for elevation angle $\alpha$ $G_{-\alpha}$ is the gain for elevation angle $-\alpha$ which is the elevation angle of the multi-path ray and $r$ is reflectivity of the surface.

If we take the antenna gain from the specifications of the AeroAntenna AT2775-42 GPS L1 L2 antenna and use the following values:

- $h = 1.87$ m (height of the antenna mounted on the roof at ESTEC)
- $\lambda = 0.19$ m (wavelength of GPS L1)
- $r = 0.5$ (the reflected signal will be -3 dB)

The effective antenna gain can be calculated for any elevation angle. The resulting difference between the specified antenna gain and the effective value is shown in Figure B-2.

![Antenna gain vs elevation](image)

*Figure B-2: Specified and effective antenna gain*
Appendix C: GPS simulator tests – procedures, link budget and receiver settings

These are the procedures that were used for the GPS simulator tests:

1. Prepare the interference file for the SimGen scenario with dedicated software tool. The interference file is an ASCII file that lists all RFI generator commands with time from scenario start. A software tool was created in the MATLAB development environment to create these files automatically.
2. Connect the all three GPS receivers to the Spirent Rack with the antenna splitter as shown in Figure C-1.
3. Load the interference scenario in SimGen.
4. Reset the almanac, ephemerides last known position and last measured time on all receivers. GNSS receivers store and use the last known constellation information, position and time in order to acquire satellite tracking faster. When using a simulator this stored information is usually incorrect (especially the time) and it can take the receiver very long to adept. By resetting this information the receiver will make a full satellite search and will start tracking within a few minutes.
5. Check and change the receiver settings (see below). Some receivers will reset the receiver settings along with the constellation information, position and time. For these receivers the settings have to be changed after point 4.
6. Start the Spirent Rack with SimGen and wait until the receivers are tracking the GPS signals.
7. Start the data logging with the receivers.
8. Wait until the interference scenario has finished.
9. Stop the data logging with the receivers.
10. Stop the simulator and the receivers.

Figure C-1: GPS simulation setup
Table C-1 shows the link budget for the GPS simulations. The used signal power is comparable to the signal power that can be received with a GPS antenna. The minimum RFI power used during the simulations is 2.3 dB more than the signal power. This RFI power has very little impact on the receiver. The maximum power was chosen close to the jamming threshold which was determined during some explorative tests. This value was different for each test.

<table>
<thead>
<tr>
<th>Table C-1: GPS simulation link budget</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>L1 C/A signal power</td>
</tr>
<tr>
<td>Min. RFI power</td>
</tr>
<tr>
<td>Max. RFI power</td>
</tr>
<tr>
<td>-------------------------------------</td>
</tr>
<tr>
<td>Spirent combiner output</td>
</tr>
<tr>
<td>28 dB</td>
</tr>
<tr>
<td>Low Noise Amplifier gain</td>
</tr>
<tr>
<td>Low Noise Amplifier output</td>
</tr>
<tr>
<td>GPS splitter gain</td>
</tr>
<tr>
<td>GPS splitter output</td>
</tr>
<tr>
<td>Cable losses</td>
</tr>
<tr>
<td>Receiver input</td>
</tr>
<tr>
<td>Jammer-to-signal ratio</td>
</tr>
</tbody>
</table>

1. The signal power of the other GPS signals is relative to the GPS L1 C/A signal power as defined in [13; 14]
2. The jamming threshold was determined before each simulator test and was then used as the maximum value

Table C-2, Table C-3 and Table C-4 show the settings used for the Septentrio PolaRx 2, the Javad Legacy and the Novatel OEM4 receiver respectively. Table C-5 shows the most important settings that were used for the GPS simulator and those setting that deviate from the default settings.

<table>
<thead>
<tr>
<th>Table C-2: Septentrio PolaRx2 info and settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firmware version</td>
</tr>
<tr>
<td>Measurement interval</td>
</tr>
<tr>
<td>Elevation mask</td>
</tr>
<tr>
<td>Smoothing interval</td>
</tr>
<tr>
<td>Measurement fit</td>
</tr>
<tr>
<td>Tracking sensitivity</td>
</tr>
</tbody>
</table>
### Table C-3: Javad Legacy info and settings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firmware version</td>
<td>2.3</td>
</tr>
<tr>
<td>Recording interval</td>
<td>1 s</td>
</tr>
<tr>
<td>Terminal elevation mask</td>
<td>0 degrees</td>
</tr>
<tr>
<td>Elevation mask for log file</td>
<td>0 degrees</td>
</tr>
<tr>
<td>Code smoothing interval</td>
<td>0 s</td>
</tr>
<tr>
<td>Anti-interference</td>
<td>Off</td>
</tr>
<tr>
<td>C/N₀ mask</td>
<td>27 dB-Hz</td>
</tr>
</tbody>
</table>

### Table C-4: Novatel OEM4 info and settings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firmware version</td>
<td>2.210</td>
</tr>
<tr>
<td>Measurement interval</td>
<td>1 s</td>
</tr>
<tr>
<td>Elevation cut-off angle</td>
<td>0 degrees</td>
</tr>
<tr>
<td>Code smoothing interval L1</td>
<td>2 s</td>
</tr>
<tr>
<td>Code smoothing interval L2</td>
<td>5 s</td>
</tr>
<tr>
<td>C/N₀ mask</td>
<td>20 dB-Hz</td>
</tr>
</tbody>
</table>

### Table C-5: Spirent GNSS simulator information and settings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firmware version</td>
<td>V2.252 SR01</td>
</tr>
<tr>
<td>Signal types</td>
<td>GPS L1, GPS L2, Interference</td>
</tr>
<tr>
<td>Signal sources – general</td>
<td>Disabled, Disabled, Fixed</td>
</tr>
<tr>
<td>Diverge ephemeris</td>
<td>Disabled</td>
</tr>
<tr>
<td>Diverge clock</td>
<td>Disabled</td>
</tr>
<tr>
<td>Signal strength</td>
<td>Fixed</td>
</tr>
<tr>
<td>Signal sources – Earth obscuration</td>
<td>0 degrees, Earth tangent</td>
</tr>
<tr>
<td>Angle</td>
<td>0 degrees</td>
</tr>
<tr>
<td>Type</td>
<td>Earth tangent</td>
</tr>
<tr>
<td>Signal sources – motion – orbits</td>
<td>Jan 01 2005</td>
</tr>
<tr>
<td>Load Yuma</td>
<td>Jan 01 2005</td>
</tr>
<tr>
<td>Signal sources – signal control – signal power</td>
<td>1.5 dB</td>
</tr>
<tr>
<td>Global offset</td>
<td>1.5 dB</td>
</tr>
<tr>
<td>Atmosphere – general</td>
<td>Disabled</td>
</tr>
<tr>
<td>Tropospheric model</td>
<td>Disabled</td>
</tr>
<tr>
<td>Ionospheric model</td>
<td>Disabled</td>
</tr>
<tr>
<td>Vehicle</td>
<td>Static</td>
</tr>
<tr>
<td>Antenna pattern</td>
<td>Disabled</td>
</tr>
<tr>
<td>Multipath</td>
<td>Disabled</td>
</tr>
</tbody>
</table>
Appendix D: Galileo simulator tests – procedures, link budget and receiver settings

These are the procedures that were used for the Galileo simulator tests:

1. Prepare the interference file for the SimGen scenario with dedicated software tool. The interference file is an ASCII file that lists all RFI generator commands with time from scenario start. A software tool was created in the MATLAB development environment to create these files automatically.
2. Connect the GETR to the Spirent Rack and GSVF-2 as shown in Figure D-1.
3. Make sure the AUX IN port of the GETR is switched ON.
4. Load the interference scenario in SimGen.
5. Load the geostationary settings in GSVF-2 graphical user interface (GUI).
6. Reset the NVRAM of the GETR. The GETR stores and uses the last known constellation information, position and time in order to acquire satellite tracking faster. When using a simulator this stored information is usually incorrect (especially the time) and it can take the receiver very long to adept. By resetting the NVRAM the receiver will make a full satellite search and will start tracking within a few minutes.
7. Change the GETR settings (see below). When the NVRAM is reset, the receiver settings are back to the factory defaults.
8. Set the GETR channels to the Galileo signals under investigation and for each signal also tune one channel to a PRN number that will not be simulated.
9. Start the Spirent Rack with SimGen and wait until the automatic GPS channels of the GETR have locked on to the simulated GPS signals and the GETR has synchronized with the Spirent Rack.
10. Switch the AUX IN port of the GETR OFF.
11. Start the GSVF-2 simulation of the Galileo signals.
12. Start the GETR channels tracking the GSVF-2 signals as well as the channels tracking the satellite PRNs that are not simulated.
13. Start the data logging with the GETR.
14. Wait until the interference scenario has finished.
15. Stop the data logging with the GETR.
16. Stop both simulators and the GETR.
Table D-1 shows the link budget for the Galileo simulations. The used signal power is comparable to the signal power that the GETR receives when attached to the Space Engineering Galileo antenna (see Appendix E). The minimum RFI power used during the simulations is equal to the signal power. This RFI power has very little impact on the receiver. The maximum power was chosen close to the jamming threshold which was determined during some explorative tests. This value was different for each test.

**Table D-1: Galileo simulation link budget**

<table>
<thead>
<tr>
<th></th>
<th>Signal power</th>
<th>Min. RFI power</th>
<th>Max. RFI power$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spirent combiner output</td>
<td>-111 dBW</td>
<td>-111 dBW</td>
<td>-48 dBW</td>
</tr>
<tr>
<td>GSVF-2 RFI attenuation</td>
<td>-13 dB</td>
<td>-13 dB</td>
<td>-13 dB</td>
</tr>
<tr>
<td>GSVF-2 RF output</td>
<td>-124 dBW</td>
<td>-124 dBW</td>
<td>-61 dBW</td>
</tr>
<tr>
<td>Cable losses</td>
<td>-1 dB</td>
<td>-1 dB</td>
<td>-1 dB</td>
</tr>
<tr>
<td>GETR input</td>
<td>-125 dBW</td>
<td>-125 dBW</td>
<td>-62 dBW</td>
</tr>
<tr>
<td>Jammer-to-signal ratio</td>
<td>0 dB</td>
<td>0 dB</td>
<td>63 dB</td>
</tr>
</tbody>
</table>

$^1$ The jamming threshold was determined before each simulator test and was then used as the maximum value
Table D-2 shows the used settings and firmware version of the GETR. Table D-3 shows the most important settings that were used for the GSVF-2 and those setting that deviate from the default settings. For the settings of the Spirent GNSS simulator information and settings see Table C-5.

### Table D-2: GETR info and settings

<table>
<thead>
<tr>
<th>Setting</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firmware version</td>
<td>3.1</td>
</tr>
<tr>
<td>PLL bandwidth</td>
<td>10 Hz</td>
</tr>
<tr>
<td>DLL bandwidth</td>
<td>1 Hz</td>
</tr>
<tr>
<td>Max PLL predetection time</td>
<td>10 ms</td>
</tr>
<tr>
<td>Max DLL predetection time</td>
<td>100 ms</td>
</tr>
<tr>
<td>Tracking C/N₀ threshold</td>
<td>1 dB-Hz</td>
</tr>
<tr>
<td>BOC side peak detection</td>
<td>Enable</td>
</tr>
<tr>
<td>PPS source</td>
<td>GPS</td>
</tr>
<tr>
<td>Blanking</td>
<td>Off</td>
</tr>
</tbody>
</table>

### Table D-3: GSVF-2 simulator information and settings

<table>
<thead>
<tr>
<th>Setting</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firmware version</td>
<td>V1.1.3</td>
</tr>
<tr>
<td>Signal types – GSTB-V2</td>
<td>L1, E5a, E5b, E6</td>
</tr>
<tr>
<td>Signal path model</td>
<td>Disabled</td>
</tr>
<tr>
<td>Fixed received C/N₀</td>
<td>60 dB-Hz</td>
</tr>
<tr>
<td>LNA gain</td>
<td>18 dB</td>
</tr>
<tr>
<td>Satellite orbit</td>
<td>Geostationary</td>
</tr>
<tr>
<td>Signal propagation</td>
<td>Disabled</td>
</tr>
<tr>
<td>Tropospheric model</td>
<td>Disabled</td>
</tr>
<tr>
<td>Ionospheric model</td>
<td>Disabled</td>
</tr>
<tr>
<td>Multipath model</td>
<td>Disabled</td>
</tr>
<tr>
<td>User motion</td>
<td>Stationary</td>
</tr>
</tbody>
</table>
Appendix E: Giove-A RFI measurements – link budget and receiver settings

Table E-1 shows the link budget for the Giove-A measurements made at Turin, Italy. The RFI power was measured; for the Giove-A signal power the Galileo SIS ICD was consulted [12]. Table E-2 shows the used settings and firmware version of the GETR.

### Table E-1: Giove-A measurement link budget

<table>
<thead>
<tr>
<th></th>
<th>Signal power</th>
<th>RFI power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Received signal strength</td>
<td>-152 dBW</td>
<td>-98 dBW</td>
</tr>
<tr>
<td>Antenna gain, LNA gain and cable losses¹</td>
<td>27 dB</td>
<td>17 dB</td>
</tr>
<tr>
<td>GETR input</td>
<td>-125 dBW</td>
<td>-81 dBW</td>
</tr>
<tr>
<td>Jammer-to-signal ratio</td>
<td></td>
<td>44 dB</td>
</tr>
</tbody>
</table>

¹. The Space Engineering antenna has a gain rolloff of 10 dB. The RFI is assumed to enter with 0 degrees of elevation while the Giove-A signals are assumed to enter with more 40 degrees of elevation.

### Table E-2: GETR info and settings

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Firmware version</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>PLL bandwidth</td>
<td>10 Hz</td>
<td></td>
</tr>
<tr>
<td>DLL bandwidth</td>
<td>1 Hz</td>
<td></td>
</tr>
<tr>
<td>Max PLL predetection time</td>
<td>10 ms</td>
<td></td>
</tr>
<tr>
<td>Max DLL predetection time</td>
<td>100 ms</td>
<td></td>
</tr>
<tr>
<td>Tracking C/N₀ threshold</td>
<td>1 dB-Hz</td>
<td></td>
</tr>
<tr>
<td>BOC side peak detection</td>
<td>Enable</td>
<td></td>
</tr>
<tr>
<td>PPS source</td>
<td>GPS</td>
<td></td>
</tr>
<tr>
<td>Blanking</td>
<td>On</td>
<td></td>
</tr>
</tbody>
</table>
Appendix F: GPS simulator test results

The following results of the GPS simulator tests with 1 MHz GWN interference are included in this appendix:

Septentrio PolaRx 2

Figure F-1: PolaRx 2 C/N₀ vs. signal power for constant J/S.................................A12
Figure F-2: PolaRx 2 GPS L1 C/N₀..................................................................A12
Figure F-3: PolaRx 2 GPS L1 PR noise...........................................................A13
Figure F-4: PolaRx 2 GPS L1 phase noise.........................................................A13
Figure F-5: PolaRx 2 GPS L2 C/N₀..................................................................A14
Figure F-6: PolaRx 2 GPS L2 phase noise........................................................A14

Javad Legacy

Figure F-7: Legacy C/N₀ vs. signal power for constant J/S.................................A15
Figure F-8: Legacy GPS L1 C/N₀....................................................................A15
Figure F-9: Legacy GPS L1 PR noise.................................................................A16
Figure F-10: Legacy GPS L1 phase noise........................................................A16
Figure F-11: Legacy GPS L2 C/N₀..................................................................A17
Figure F-12: Legacy GPS L2 PR noise.................................................................A17

Novatel OEM4

Figure F-13: OEM4 C/N₀ vs. signal power for constant J/S...............................A18
Figure F-14: OEM4 GPS L1 C/N₀.................................................................A18
Figure F-15: OEM4 GPS L1 PR noise............................................................A19
Figure F-16: OEM4 GPS L1 phase noise.........................................................A19
Figure F-17: OEM4 GPS L2 C/N₀.................................................................A20
Figure F-18: OEM4 GPS L2 phase noise........................................................A20
Figure F-1: PolaRx 2 C/N₀ vs. signal power for constant J/S

Figure F-2: PolaRx 2 GPS L1 C/N₀
Figure F-3: PolaRx 2 GPS L1 PR noise

Figure F-4: PolaRx 2 GPS L1 phase noise
Effects of Radio Frequency Interference on GNSS Receiver Output

Figure F-5: PolaRx 2 GPS L2 C/N₀

Figure F-6: PolaRx 2 GPS L2 phase noise
Effects of Radio Frequency Interference on GNSS Receiver Output

Figure F-7: Legacy C/N₀ vs. signal power for constant J/S

Figure F-8: Legacy GPS L1 C/N₀
Figure F-9: Legacy GPS L1 PR noise

Figure F-10: Legacy GPS L1 phase noise
Effects of Radio Frequency Interference on GNSS Receiver Output

Figure F-11: Legacy GPS L2 C/N₀

Figure F-12: Legacy GPS L2 PR noise
Figure F-13: OEM4 C/N₀ vs. signal power for constant J/S

Figure F-14: OEM4 GPS L1 C/N₀
Figure F-15: OEM4 GPS L1 PR noise

Figure F-16: OEM4 GPS L1 phase noise
Figure F-17: OEM4 GPS L2 C/N₀

Figure F-18: OEM4 GPS L2 phase noise
Appendix G: Galileo simulator test results

The following results of the Galileo simulator tests with GWN interference are included in this appendix:

**RFI Bandwidth 1MHz**  Galileo E5

Figure G-1: E5a-P C/N₀ 1 MHz GWN ................................................................. A23
Figure G-2: E5a-P PR noise 1 MHz GWN .......................................................... A23
Figure G-3: E5a-D C/N₀ 1 MHz GWN ............................................................... A24
Figure G-4: E5a-D PR noise 1 MHz GWN ......................................................... A24
Figure G-5: E5b-P C/N₀ 1 MHz GWN ............................................................... A25
Figure G-6: E5b-P PR noise 1 MHz GWN ........................................................... A25
Figure G-7: E5b-D C/N₀ 1 MHz GWN ............................................................... A26
Figure G-8: E5b-D PR noise 1 MHz GWN ......................................................... A26
Figure G-9: E5AltBOC C/N₀ 1 MHz GWN ......................................................... A27
Figure G-10: E5AltBOC PR noise 1 MHz GWN ................................................. A27

**RFI Bandwidth 1MHz**  Galileo E6

Figure G-11: E6BC-P C/N₀ 1 MHz GWN ........................................................... A28
Figure G-12: E6BC-P PR noise 1 MHz GWN ...................................................... A28
Figure G-13: E6BC-D C/N₀ 1 MHz GWN ........................................................... A29
Figure G-14: E6BC-D PR noise 1 MHz GWN ...................................................... A29
Figure G-15: E6A-D C/N₀ 1 MHz GWN ............................................................. A30
Figure G-16: E6A-D PR noise 1 MHz GWN ....................................................... A30

**RFI Bandwidth 1MHz**  Galileo L1

Figure G-17: L1BC-P C/N₀ 1 MHz GWN ............................................................. A31
Figure G-18: L1BC-P PR noise 1 MHz GWN ...................................................... A31
Figure G-19: L1BC-D C/N₀ 1 MHz GWN ........................................................... A32
Figure G-20: L1BC-D PR noise 1 MHz GWN ...................................................... A32
Figure G-21: L1A-D C/N₀ 1 MHz GWN .............................................................. A33
Figure G-22: L1A-D PR noise 1 MHz GWN ....................................................... A33

**RFI Bandwidth 100kHz**  Galileo E5

Figure G-23: E5a-P C/N₀ 100 kHz GWN ............................................................. A34
Figure G-24: E5a-P PR noise 100 kHz GWN ..................................................... A34
Figure G-25: E5a-D C/N₀ 100 kHz GWN .......................................................... A35
Figure G-26: E5a-D PR noise 100 kHz GWN ..................................................... A35
Figure G-27: E5b-P C/N₀ 100 kHz GWN ........................................................... A36
Figure G-28: E5b-P PR noise 100 kHz GWN .................................................... A36
Figure G-29: E5b-D C/N₀ 100 kHz GWN .......................................................... A37
Figure G-30: E5b-D PR noise 100 kHz GWN .................................................... A37
Figure G-31: E5AltBOC-P C/N₀ 100 kHz GWN ............................................... A38
Figure G-32: E5AltBOC PR noise 100 kHz GWN ............................................. A38
RFI Bandwidth 100kHz  
Galileo E6

Figure G-33: E6BC-P C/N₀ 100 kHz GWN ......................................................... A39
Figure G-34: E6BC-P PR noise 100 kHz GWN ............................................... A39
Figure G-35: E6BC-D C/N₀ 100 kHz GWN ...................................................... A40
Figure G-36: E6BC-D PR noise 100 kHz GWN ................................................. A40
Figure G-37: E6A-D C/N₀ 100 kHz GWN ......................................................... A41
Figure G-38: E6A-D PR noise 100 kHz GWN .................................................... A41

RFI Bandwidth 100kHz  
Galileo L1

Figure G-39: L1BC-P C/N₀ 100 kHz GWN ......................................................... A42
Figure G-40: L1BC-P PR noise 100 kHz GWN .................................................. A42
Figure G-41: L1BC-D C/N₀ 100 kHz GWN ...................................................... A43
Figure G-42: L1BC-D PR noise 100 kHz GWN ................................................. A43
Figure G-43: L1A-D C/N₀ 100 kHz GWN .......................................................... A44
Figure G-44: L1A-D PR noise 100 kHz GWN .................................................... A44
Effects of Radio Frequency Interference on GNSS Receiver Output

Figure G-1: E5a-P C/N₀ 1 MHz GWN

Figure G-2: E5a-P PR noise 1 MHz GWN
Effects of Radio Frequency Interference on GNSS Receiver Output

Figure G-3: E5a-D C/N₀ 1 MHz GWN

Figure G-4: E5a-D PR noise 1 MHz GWN
Effects of Radio Frequency Interference on GNSS Receiver Output

Figure G-5: E5b-P C/N₀ 1 MHz GWN

Figure G-6: E5b-P PR noise 1 MHz GWN
Figure G-7: E5b-D C/N₀ 1 MHz GWN

Figure G-8: E5b-D PR noise 1 MHz GWN
Figure G-9: E5AltBOC C/N₀ 1 MHz GWN

Figure G-10: E5AltBOC PR noise 1 MHz GWN
Figure G-11: E6BC-P C/N₀ 1 MHz GWN

Figure G-12: E6BC-P PR noise 1 MHz GWN
Figure G-13: E6BC-D C/N₀ 1 MHz GWN

Figure G-14: E6BC-D PR noise 1 MHz GWN
Figure G-15: E6A-D C/N₀ 1 MHz GWN

Figure G-16: E6A-D PR noise 1 MHz GWN
Figure G-17: L1BC-P C/N₀ 1 MHz GWN

Figure G-18: L1BC-P PR noise 1 MHz GWN
Figure G-19: L1BC-D C/N₀ 1 MHz GWN

Figure G-20: L1BC-D PR noise 1 MHz GWN
Figure G-21: L1A-D C/N₀ 1 MHz GWN

Figure G-22: L1A-D PR noise 1 MHz GWN
Effects of Radio Frequency Interference on GNSS Receiver Output

Figure G-23: E5a-P C/N₀ 100 kHz GWN

Figure G-24: E5a-P PR noise 100 kHz GWN
Figure G-25: E5a-D C/N₀ 100 kHz GWN

Figure G-26: E5a-D PR noise 100 kHz GWN
Figure G-27: E5b-P C/Nₜ 100 kHz GWN

Figure G-28: E5b-P PR noise 100 kHz GWN
Effects of Radio Frequency Interference on GNSS Receiver Output

Figure G-29: E5b-D $C/N_0$ 100 kHz GWN

Figure G-30: E5b-D PR noise 100 kHz GWN
Figure G-31: E5AltBOC-P $C/\!N_0$ 100 kHz GWN

Figure G-32: E5AltBOC PR noise 100 kHz GWN
Effects of Radio Frequency Interference on GNSS Receiver Output

Figure G-33: E6BC-P C/N₀ 100 kHz GWN

Figure G-34: E6BC-P PR noise 100 kHz GWN
Effects of Radio Frequency Interference on GNSS Receiver Output

Figure G-35: E6BC-D C/N₀ 100 kHz GWN

Figure G-36: E6BC-D PR noise 100 kHz GWN
Effects of Radio Frequency Interference on GNSS Receiver Output

Figure G-37: E6A-D C/N₀ 100 kHz GWN

Figure G-38: E6A-D PR noise 100 kHz GWN
Figure G-39: L1BC-P C/N₀ 100 kHz GWN

Figure G-40: L1BC-P PR noise 100 kHz GWN
Effects of Radio Frequency Interference on GNSS Receiver Output

Figure G-41: L1BC-D $C/N_0$ 100 kHz GWN

Figure G-42: L1BC-D PR noise 100 kHz GWN
Effects of Radio Frequency Interference on GNSS Receiver Output

Figure G-43: L1A-D C/N₀ 100 kHz GWN

Figure G-44: L1A-D PR noise 100 kHz GWN