A Comprehensive Study of the Effects of Linear Chirp Jamming on GNSS Receivers Under High-Dynamic Scenarios

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Abstract— **Despite the significant advances in signal processing methods used nowadays, Global Navigation Satellite Systems (GNSS) receivers still experience substantial challenges, such as signal jamming, which remains a crucial source of degradation of the receiver performance. The presence of jamming signal influences the acquisition and tracking modules inside the receiver leading to loss-of-lock of the GNSS satellite signals. Consequently, GNSS receivers cannot provide reliable position, velocity and time services. The aim of this paper is to comprehensively explore the effects of linear chirp jamming on commercial receivers under high-dynamic scenarios. Moreover, the paper investigates the advantages of using combined GPS/GLONASS receivers under jamming conditions in comparison to using GPS-only receivers. In this paper, a SPIRENT GSS6700 Multi-GNSS Simulator controlled by Spirent SimGEN™ software is used to provide realistic controlled simulation scenarios. The linear chirp jamming signals are created using an Agilent interference signal generator (ISG) unit. Both commercial NovAtel ProPak-G2 Plus and NovAtel OEMV receivers are used to conduct these tests. The results show different behaviors of the various receivers in response to the applied jamming signals. The Carrier-to-Noise (C/N_0), the Dilution of Precision (DOP), and the navigation solution accuracy are used as measures to assess the performance of the receivers under study. Results show that the NovAtel OEMV receiver outperforms the NovAtel ProPak-G2 Plus receiver. Moreover, it is revealed that multi-constellation receivers achieved higher resistance for signal jamming effects than GPS only receivers.**

Keywords— GNSS, Interference, Jamming, Receivers;

I. Introduction

The Global Navigation Satellite Systems (GNSS) such as the Global Positioning System (GPS), GLONASS, and GALILEO are satellite-based navigation systems that can provide positioning, navigation and timing (PNT) solutions to a large number of applications [1]. A typical example of the GNSS systems is the GPS which consists of about 30 satellites employed into six orbital planes and orbiting the Earth at an altitude of approximately 20,200 kilometers. Theses satellites consistently transmit Radio Frequency (RF) signals carrying important navigation message towards receivers near or on the Earth's surface. Due to traveling such long distances, the GPS signals reach the receiver antenna at very low power levels normally ranging between -160 to -130 dBm [2,3]. These very weak signals are, hence, vulnerable to and easily affected by unintentional and intentional signal interference. The deliberate form of signal interference, commonly known as signal jamming, is caused by the broadcast of malicious signals in the same frequency band of the target signal with the aim of stopping GPS receivers in the area from performing accurate signal tracking [4]. In other words, GPS jammers take advantage of the main weakness of GPS signals, which is their very low power level to prevent the accomplishment of good positioning solution. Depending on the band of interest (or bandwidth of the inserted malicious signal), jamming signals are usually categorized as narrowband and wideband signals. One important type of jamming signals, which is discussed in this paper, is the linear chirp jamming [5-7].

The impact of signal jamming on GPS receivers and its consequences has been investigated in several studies [4]. As an example, the impact of low-cost commercial jammers on GPS receivers was discussed in [6]. The research shows that jamming signals can significantly degrade the GPS receiver performance according to the introduced jamming to signal ratio (JSR). One significant effect of signal jamming on the GPS receiver is the degradation of measurements accuracy and interrupting the receiver ability to acquire the satellite signals. Furthermore, high JSRs jamming signals can lead to total loss of lock on the satellite signals which in turn cause a complete denial of GPS services [8]. Despite having some sort of anti-jamming abilities due to the spread spectrum nature of the system, commercial GPS receiver's performance can be harshly degraded if the receiver's anti-jamming capability is beaten [9]. Thus, there is an obvious need for more investigation of the effects of jamming on commercial receivers.

The main goal of this paper is to explore the effects of linear chirp jamming on the performance of commercial GNSS receivers. This paper also investigates the benefits of using combined GPS/GLONASS receivers compared to the GPS-only receivers under jamming scenarios. Therefore, the paper in fact provides a thorough analysis of the benefits of combined GPS and GLONASS in terms of degradation of signal power, and positioning solution availability and accuracy. The rest of this paper is organized as follows. Section II provides a detailed overview of the effects of signal jamming on GNSS receivers. The experiment setup and selected test trajectories are described in section III. Section IV then provides a full explanation of results and obtained receiver performance. The final section concludes the paper findings and provides an insight into the planned future work.

II. Background

GNSS receivers use external RF signals transmitted by GNSS satellites form very high elevations to provide the user with a position, navigational, and time solution. Nonetheless, the power levels of these received GNSS signals nearby or at the Earth's surface are very low normally ranging between -160 dBm to -130 dBm; which is below the noise floor of a GNSS receiver. This fact makes those signals susceptible to signal interference and jamming effects. Signal jamming is defined as the process of emitting RF signals on or close to the GNSS signal bandwidth at relatively high-power levels to prevent the receiver from locking to the satellite signals. Signal jamming is considered as one of the toughest sources of signal interference to GNSS receivers [10] and, indeed, represents the most challenging issue facing the growing demand of countless GNSS based services such as personal privacy devices (PPDs) [11,12]. PPDs are becoming more widespread which makes the signal jammers a more significant hazard on everyday life needs for many consumers [13].

Several studies have been investigating the effects of signal interference in general, and signal jamming, on the functionality of GNSS receivers [8,14]. For instance, the impact of signal interference on GNSS receivers are discussed in [15]. Amongst these are loss-of-lock of one or more of the satellite signals; drop in the carrier-to-noise-ratio (C/N_0) levels; increase of noise on the pseudorange and carrier phase measurements, and the increase in the number of cycle slips on the carrier phase measurements. Signal jamming can significantly destroy the accuracy of the obtained positioning solution which could, in turn, cause a complete loss-of-lock to the satellite signals. Furthermore, it has been revealed that a receiver's front-end could be saturated entirely by broadband additive white Gaussian noise (AWGN) signals, high power narrowband signals, or pulsed signals [16].

The effects of signal jamming on the GPS signal acquisition and tracking processes have been explored in some other papers [17,18]. For example, it was reported in [19] that the broadband noise comes in second place due to the resultant damage it could cause during the GPS signal acquisition. Furthermore, applying relatively high-power jamming signals can lead to loss-of-tracking to the satellite signals; thus, the receiver will need to re-apply signal reacquisition process(s).

The impact of GNSS signal jamming on GPS and Galileo receivers in terms of the drop in Carrier-to-Noise ratio (C/N_0) levels is investigated in [4]. The GNSS signals and interfering signals were logged using a National Instruments (NI) RF signal analyzer (NI PXI-5663) then processed using some commercial receivers and software-based GNSS receivers. It was shown that the commercial receivers demonstrated better performance than software receivers under jamming conditions.

III. Experiment work

In this research, the SPIRENT GSS6700 signal simulator is used to generate a controlled realistic aircraft trajectory with high-dynamics. The Agilent interference signal generator (ISG) is used to produce the desired jamming signal. Both signals are merged through a GSS8366 combiner. This hardware system is controlled using the SimGen™ simulation software. This software package allows the simulation of many jamming scenarios such as Continuous Wave interference (CWI), Amplitude Modulation (AM) interference, Frequency Modulation (FM) interference and Linear Chirp interference. This simulation system can also simulate atmospheric effects, multipath environments, and terrain obscurations. Additionally, it can simulate diverse platforms including, but not limited to, land vehicles, ships and aircrafts [20]. The output RF signal from the GSS8366 is fed into a Low Noise Amplifier (LNA) to compensate for the signal attenuation resulting from the use of an antenna splitter to supply the multiple receivers under test. After that, the output of the LNA is connected to a 1-to-4 antenna splitter which feeds the signal to a NovAtel OEMV receiver and a NovAtel ProPak-G2 Plus receiver. Figure 1 shows the complete system setup, which was implemented in the Navigation and Instrumentation laboratory at the Royal Military College of Canada.

Figure 1: Experiment Hardware Setup

To evaluate the performance of the receivers under dynamic scenarios, an aircraft platform was chosen for trajectory simulation. The selected trajectory starts with the aircraft taking off from the territory of Nunavut, Canada. The simulated altitude changed between zero and 2,500 meters above the ground. During this, various dynamic behaviors were inserted such as acceleration and deceleration and soft and sharp turns. The total length of the trajectory was about 15 minutes. The trajectory velocity profile is shown in Figure 2.

The jammer was turned on after 5 minutes of the beginning of the trajectory with an initial power of -100 dBm. Then, the power level was gradually incremented by a step of 5 dB every 40 seconds until it reaches its maximum at -70 dBm. Then, the power level was decremented every 40 seconds again by a step of 5 dB until it is back to the initial value of -100 dBm. At that point, the jammer was turned off as shown in Figure 3. This simulated scenario runs four times. The first two are used as a reference where the jammer is disabled throughout the whole trajectory. Only GPS constellation is enabled in the first one; however, both GPS and GLONASS are enabled in the second. The other two trajectories are collected in the presence of a linear chirp jamming signal. Once again, the first of these two latter trajectories incorporated a GPS only scenario while the second was GPS/GLONASS scenario.

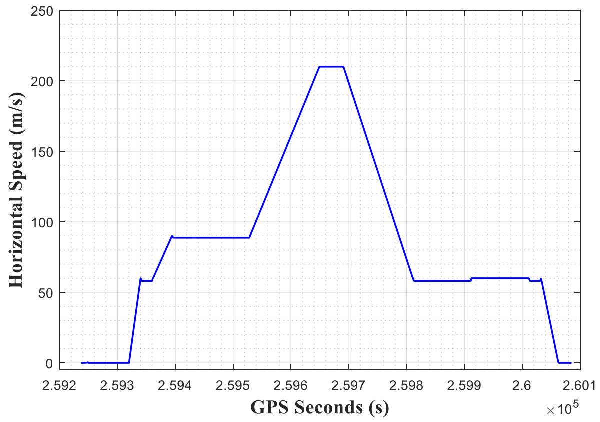


Figure 2: Trajectory Velocity Profile

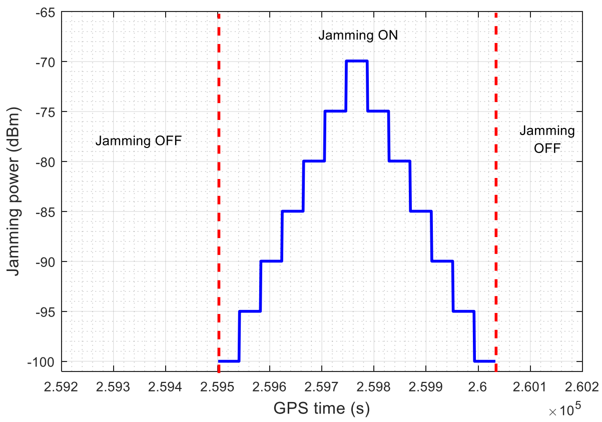


Figure 3: Jamming Profile

IV. RESULTS

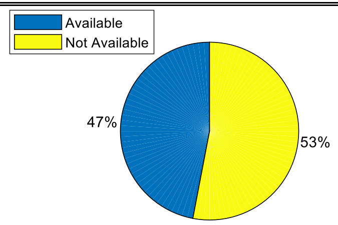
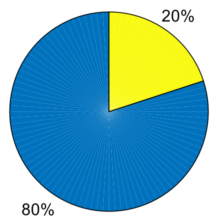
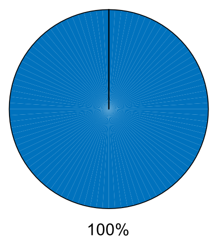
In this section, we show the results obtained using both commercial NovAtel ProPak-G2 Plus and NovAtel SPAN-SE receivers under the jamming test described above. Different metrics are used in this section to gain comprehensive analysis on the effects of linear chirp jamming on the GPS only and combined GPS/GLONASS systems. These are solution availability, signal strength, satellite availability, Dilution of Precision (DOP) and position and velocity accuracy.

In this analysis, three scenarios are considered. In the first and second scenarios, only GPS constellation is enabled, and the RF signal is collected using NovAtel ProPak-G2 Plus, and NovAtel OEMV receivers, respectively. In the third scenario, both GPS and GLONASS constellations are activated, and the RF signal is collected using only NovAtel OEMV receiver. In all three scenarios, the jamming signal is enabled according to the jamming profile shown in Figure 3. A total of ten GPS and seven GLONASS satellites were visible through the experiment time. Each of the next subsections discusses one of the used evaluation metrics in detail.

1) Navigation Solution Availability

Table 1 shows the percentage at which the navigation solution was available throughout the whole trajectory for each scenario. The percentage of the navigation solution availability of Scenarios 1, 2 and 3 are 47%, 80%, and 100%, respectively. This clearly demonstrates that the NovAtel OEMV outperformed the NovAtel ProPak-G2 Plus by 33%. It also shows that combining the GPS/GLONASS constellations lead to the solution is always available, obviously because the jamming signal is centered at the GPS L1 frequency, and hence, GLONASS is barely affected.

Table 1: Navigation Solution Availability Percentile

Scenario	Solution Availability
1	
2	
3	

2) Average C/N$_0$ Ratio

Figure 4 illustrates the average C/N$_0$ ratio of all visible GPS and GLONASS satellites. The grey shaded portion between the two vertical magenta lines is the period when the jammer is turned “ON.” At the start of the experiment, the average C/N_0 was around 47 dB-Hz. After the jammer was turned “ON,” however, the average C/N_0 significantly decreased until both receivers in scenario 1 and 2 lost all GPS satellites. However, in scenario 3 the presence of GLONASS constellation significantly improved the receiver’s performance and helped in maintaining a good average C/N_0 throughout the whole trajectory.

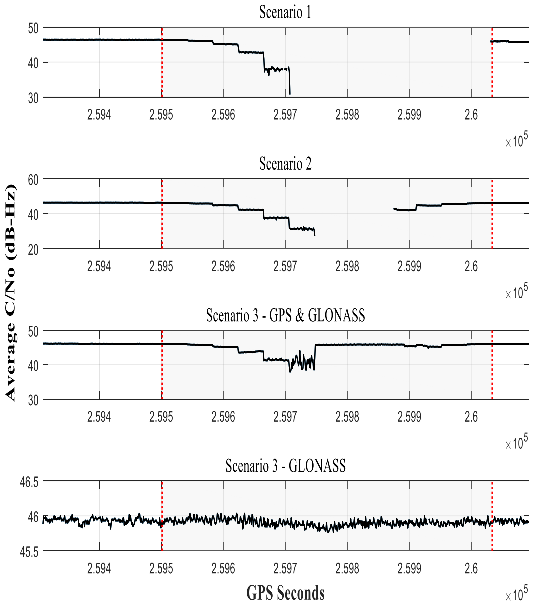


Figure 4: Average C/N_0 for all scenarios

3) Minimum Number of Visible Satellites

Figure 5 shows the minimum number of visible satellites in the three scenarios at different values of the jamming power. As shown, the NovAtel ProPak-G2 Plus started losing lock of GPS satellites when jamming power was about -85 dBm. However, the NovAtel OEMV receiver lost lock of the GPS satellites starting from -80 dBm. It can also be seen that at the jamming power of -70 dBm, only GLONASS satellites are visible.

4) Dilution of Precision

Figure 6 shows the time series analysis of GDOP values for the three scenarios. When the jammer was turned “ON,” it is evident that NovAtel OEMV preserved better GDOP values over the NovAtel ProPak-G2 Plus in scenarios 1 and 2. Moreover, a visible improvement in PDOP values was observed when combining GLONASS in the solution in comparison to the GPS-only case. Similar results can be seen in Figure 7 for TDOP, which also reflects a noticeable improvement in DOP values as a result of incorporating GLONASS constellation in the solution.

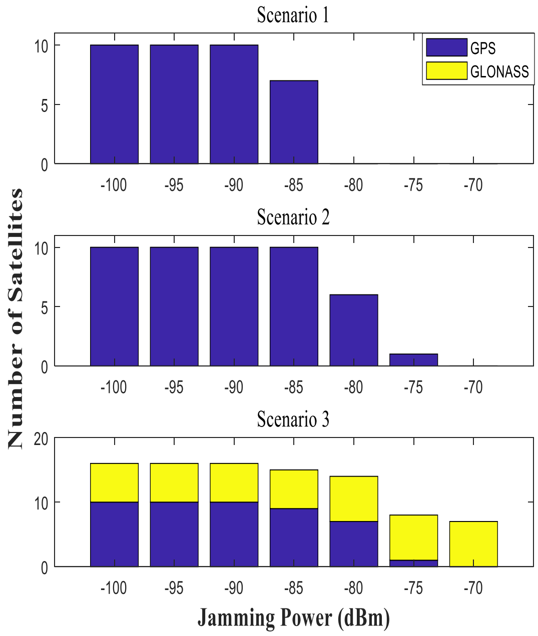


Figure 5: Minimum Number of Visible Satellites at Different Values of Jamming Power.

5) Position and Velocity Accuracy

Figure 8 and Figure 9, respectively, show the horizontal and Up position errors for the three scenarios during the jamming period. Figure 10 shows the horizontal speed error for the three scenarios as compared to the reference trajectory which is obtained from the SPIRENT Simulator. It is clear from these figures that incorporating GLONASS constellation caused a slight improvement in both position and velocity accuracies. Furthermore, it is noticed that the NovAtel OEMV outperforms the NovAtel ProPak-G2 Plus in terms of position and velocity accuracies.

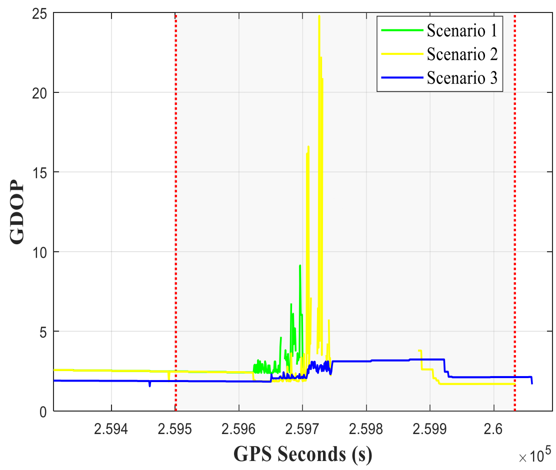


Figure 6: Time Series GDOP Values

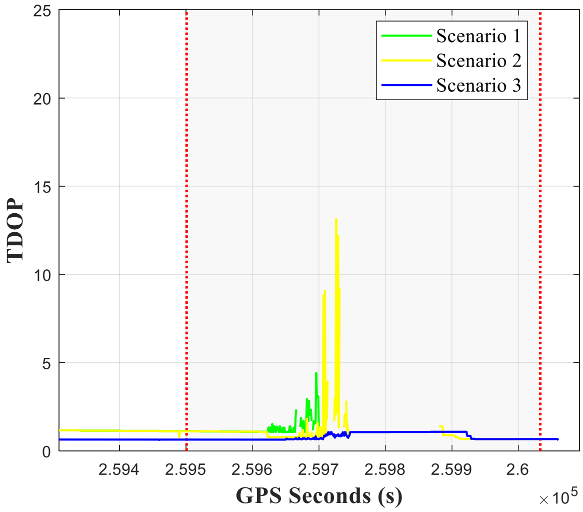


Figure 7: Time Series TDOP Values

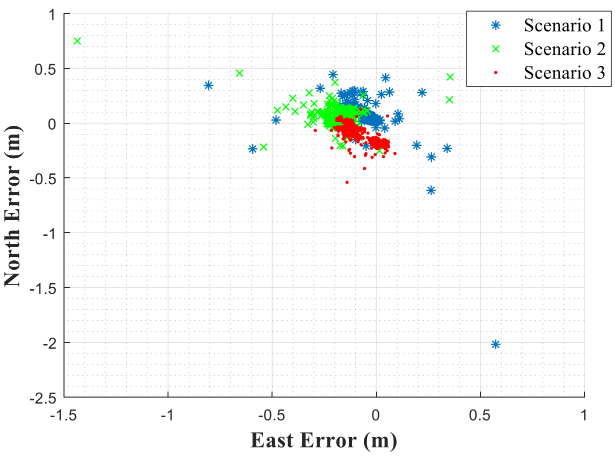


Figure 8: Horizontal Position Error

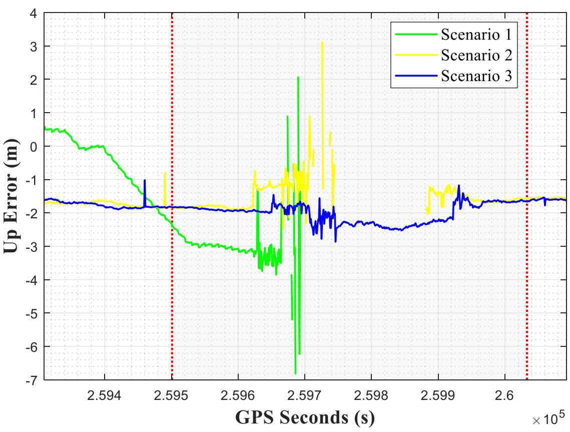


Figure 9: Up Position Error

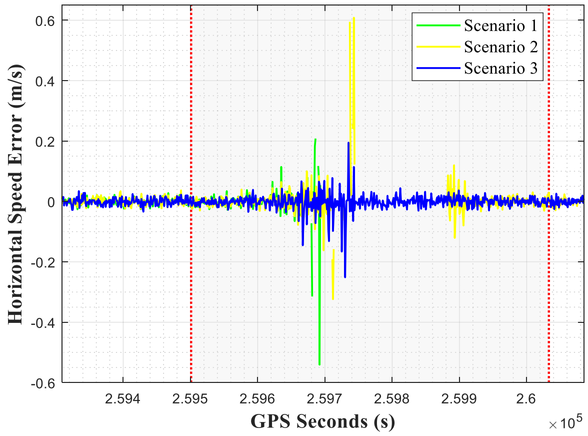


Figure 10: Horizontal Speed Error

V. Conclusion

GNSS receivers are is increasingly threatened by signal interference and jamming. This, accordingly, imposes significant threats to services that rely on the GNSS position, velocity, and time solutions. Several studies in the literature have already investigated some of the aspects associated with signal jamming effects including, but not limited to, type of jamming signals, and effects on received signal power and measurements accuracy. This paper comprehensively investigates the impact of linear chirp jamming signals on the performance of commercial GNSS receivers under high-dynamic scenarios. Furthermore, the performance of GPS-only receivers versus combined GPS/GLONASS receivers is explored under jamming conditions. Two receivers by NovAtel are used to verify the findings of this study. In addition, a few high-dynamic scenarios are created using Spirent SimGEN™ with the GSS6700 Multi-GNSS Simulator. An Agilent Interference Signal Generator (ISG) unit is used to produce the simulated jamming signals. various responses are noted for the receivers under test which were described using the Dilution of Precision (DOP), the Carrier-to-Noise (C/N_0) measures, and position and velocity accuracy. The NovAtel OEMV receiver proves to outperform NovAtel ProPak-G2 Plus receiver. Moreover, it is evident that dual-constellation receivers maintained higher resistance against jamming signal than GPS only receivers. As a future work expectation, we still see a room for further investigation of the implemented setup using more evaluation metrics.

References

[1] M. Tamazin, M. Karaim, and A. Noureldin, GNSSs, Signals, and Receivers, In: R. B. Rustamov, ed. Multifunctional Operation and Application of GPS. Rijeka: Intech, pp. 119-139, 2018.

[2] E. D. Kaplan and C. J. Hegarty, Understanding GPS: Principles and Applications: Artech house, 2005.

[3] M. Karaim, M. Elsheikh and A. Noureldin, GNSS Error Sources, In: R. B. Rustamov, ed. Multifunctional Operation and Application of GPS. Rijeka: Intech, pp. 69-85, 2018.

[4] Y. Chen, Y. Chien and H. Tsao, "Chirp-Like Jamming Mitigation for GPS Receivers Using Wavelet-Packet-Transform-Assisted Adaptive Filters," International Computer Symposium (ICS), Chiayi, pp. 458-461, 2016.

[5] Y. Chien, C. Chen, P. Chen, and H. Tsao, "Impact of Jamming Excisor on the Tracking Loops For GPS Receivers", SICE Annual Conference (SICE) 2014 Proceedings of the, pp. 383-388, 2014.

[6] D. Borio, C. O'Driscoll, and J. Fortuny, "GNSS Jammers: Effects and Countermeasures," in ESA Workshop on Satellite Navigation Technologies and European Workshop on GNSS Signals and Signal Processing, Noordwijk, 2012.

[7] M. M. E. Moussa, A. Osman, M. Tamazin, M. Korenberg, and A. Noureldin, "Enhanced GPS Narrowband Jamming Detection Using High-Resolution Spectral Estimation," GPS Solutions, pp. 1-11, 2016.

[8] R. Bauernfeind, T. Kraus, A. S. Ayaz, D. Dötterböck, and B. Eissfeller, "Analysis, Detection and Mitigation of In-Car GNSS Jammer Interference in Intelligent Transport Systems," in Deutscher Luft-und Raumfahrtkongress, Berlin, 2012.

[9] Y.-R. Chien, "Design of GPS Anti-Jamming Systems Using Adaptive Notch Filters," IEEE Systems Journal, vol. PP, no. 99, pp. 1-10, Oct. 2013.

[10] A. Rugamer, I. Lukcin, G. Rohmer, and J. Thielecke, "GNSS Interference Detection Using a Compressed Sensing Analog to Information Converter Approach", Proceedings of the ITM of The Institute of Navigation, San Diego, California, pp. 843-855, January 2013.

[11] M. Jones, "The Civilian Battlefield: Protecting GNSS Receivers From Interference and Jamming," Inside GNSS, Apr. 2011.

[12] M. J. Marcus, "Growing consumer interest in jamming: spectrum policy implications [Spectrum Policy and Regulatory Issues]," IEEE wireless communications, p. 4, Feb. 2014.

[13] D. Borio, C. O'Driscoll, and J. Fortuny, "Jammer impact on Galileo and GPS receivers," in International Conference on Localization and GNSS, Turin, 2013.

[14] R. H. Mitch, R.C. Dougherty, M.L. Psiaki, S.P. Powell, B.W. O'Hanlon, "Signal Characteristics of Civil GPS Jammers," GPS world, January 2012.

[15] P. F. El Bakkar, "Effects of Radio Frequency Interference on GNSS Receiver Output", Master Thesis, Delft University of Technology, January 2006.

[16] M. Moussa, "High Resolution Jamming Detection in Global Navigation Satellite Systems," Ph.D. Thesis, Electrical and Computer Engineering, Queen's University, May 2015.

[17] D. Borio, "A statistical theory for GNSS signal acquisition," Ph.D. thesis, Politecnico Di Torino, Torino, 2008.

[18] M. Abdizadeh, "GNSS signal acquisition in the presence of narrowband interference," Ph.D. Thesis, Geomatics Engineering, University of Calgary, Calgary, 2013.

[19] S. M. Deshpande, "Study of Interference Effects on GPS Signal Acquisition," Ph.D. Thesis, Geomatics Engineering, University of Calgary, Calgary, 2004.

[20] MS3008 Datasheet, "SPIRENT SIMGEN Software Suite Datasheet and Specification," Issue 9-00, July 2015.