Assessment of GPS L1/Galileo E1 Interference Monitoring System for the Airport Environment

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1 BIOGRAPHY
Oscar Isoz graduated as a Master of Science in Electrical Engineering at Luleå University of technology in 2009. He is now a PhD student there and his research focuses is detection and localization of GNSS interference.

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ABSTRACT
How does the GPS L1 spectrum look like at a commercial airport? How frequently do radio frequency interference (RFI) incidents occur? To answer this, the GPS L1/Galileo E1 band was monitored at two different airports for an extended period of time. The monitor stations continuously recorded the noise level using the automatic gain control (AGC) in the frontend. Also, the raw intermediate frequency (IF) signal was recorded at regular intervals as well as when the AGC level dropped below a certain threshold.

In this paper the analysis of long-term measurements of the spectrum and AGC level at Luleå Airport outside Luleå, Sweden, and Kaohsiung International Airport in Kaohsiung City, Taiwan, is presented. The results shows that RFI incidents did occur at both airports, although more frequent at Kaohsiung International Airport. The measurements also show that the AGC level is useful in systems monitoring the RFI environment. Importantly, the measured data could be utilized for analyses toward the future introduction of GBAS for civil aviation authorities.

2 INTRODUCTION
GNSS (Global Navigational Satellite Systems) is used more and more in our society, but there are some locations where the reliability is more critical than elsewhere. The question is. Are there any potential interferers in those areas and if so, how frequent are they? In this paper this question is assessed by analysing the results of a GPS L1/Galileo E1 interference monitoring campaign that took place at two airports during the summer of 2011.

There are a number of cases where GNSS interference has been detected and localized. One well known case occurred in Moss Landing, CA, US in 2001 [Vincent et al., 2003]. This interference was caused by the preamplifier in an active TV antenna that had unintentional transmissions in the GPS L1 band creating a GNSS “denied” area with a radius of up to 3 km (the US Coast Guard also wrote an official warning about these antennas in [US, 2003]). A more recent incident occurred at Newark Airport, NY, US in Jan 2010, where one of the GBAS (ground based augmentation system) GNSS receivers were occasionally jammed, the investigation revealed that the jamming most likely came from a truck on the nearby highway where the trucker that had a low power GNSS jammer (possibly to make it hard for the trucking company to see how and where he drove) [Logan, 2010]. These two cases shows
two potential threats to the use of GNSS - intentional and unintentional interference.

Jammers are illegal in most countries but can be bought online for a low cost and it is possible that they will be more frequent in the future. The reason is that number of areas where individuals are monitored using GNSS are expanding. In some countries people can be sentenced to carry a GPS transponder so that the police can be sure that the convicts are where they are supposed to be (i.e. at work or at home). More and more companies are installing GPS transponders in their vehicles and there are also GPS based road toll systems available [AG, 2008]. All this increases the potential criminal benefit of owning a GNSS jammer and therefore the need to assess potential threat so that appropriate actions can be taken. This paper will present the results of a GPS L1/Galileo E1 interference monitoring campaign that took place at two airports during the summer of 2011.

It has previously been shown that the automatic gain control (AGC) can be used to measure the interference [Bastide et al., 2003] and that wideband interference can be localized using multiple independent frontends [Isoz et al., 2010].

A number of systems has been proposed that is capable of monitor an area for GNSS interference. One such example was the GPS anomaly event monitor presented in [van Graas et al., 2008], which is capable of monitor the environment for a wide array of GNSS anomalies. Other examples are the crowd-sourcing idea presented by L.Scott where cellphones with GNSS receivers would be used as sensors [Logan, 2010] and the generalized GPS interference detection and localization (GIDL) system developed by K.Gromov [Gromov et al., 2000] that used multiple front ends that shared a common clock source.

The scope of the work presented here is only to monitor the GNSS spectrum for changes in the power level that can indicate the presence of a jammer using a low cost system.

3 SYSTEM DESIGN

The monitoring station was built around a SiGe 4120 frontend. Using a USB interface it is possible to record both intermediate frequency (IF) data and automatic gain control (AGC) data. Each airport had a station that consisted of a laptop, a frontend capable of sampling a 8 MHz wide band centered around the GPS L1 frequency at a rate of 16.3676 MHz and a Novatel antenna were deployed. A laptop runs software which records both the IF data as well as information about the AGC from the frontend. The IF data is temporarily stored in a circular buffer whereas the AGC data is continuously saved to disk. In order to have the system as sensitive as possible while reduce the number of false alarms the AGC trigger levels was set manually after an initial period of AGC recordings.

When an anomaly occurs, the last 40 seconds and the following 10 seconds of IF data is saved to disk in a times-tamped file. If no RFI is detected 60 seconds of IF data is saved after four hours. When the system has recorded an anomaly IF file, it waits for five minutes before it is ready to record a new IF file while continuing to record AGC samples. The reason for this is to avoid to filling the drive on the computer with IF data if the interference continues to trigger the system over an extended period of time. Using a software defined GPS receiver (SDR) it was then possible to see how the interference could affect the various parts of a GPS receiver. It was also possible to calculate the spectrum of the recorded IF data and therefore get some insight in how the interference behaved in the frequency domain.

3.1 Hardware

In order for a receiver with a multi bit analog to digital converter (ADC) to extract maximum amount of information from the received signal the analog gain has to be adjusted to the received signal strength. For a signal that can be considered to be Gaussian white noise the maximum amount of information can be extracted when the gain of the frontend is adjusted so that the histogram of the samples have a Gaussian shape. Therefore the AGC reading is effected by everything before it in the receiver chain and changes in AGC value might not always indicate a change in the spectrum. One event could be if the gain of the low noise amplifier (LNA) in the antenna changes due to variations in temperature or supply voltage.

The idea behind the experiment presented in this paper is that in order for something to be considered interference it has to affect the GNSS receivers so that it will be harder for them to acquire and or track satellites. The AGC can be designed in many different ways and there are both analog and digital implementations [Ward, 2007]. Therefore it is not feasible to give theoretical predictions of how the AGC or a specific receiver behaves for a certain type of interference, unless the exact design is known.

3.2 Characterization of the AGC

Before the system was deployed a number of tests were done in the lab in order to verify the functionality of the AGC. The first test was to see if there are any differences between individual frontends and how they react to various levels of white noise.

![Figure 1. Setup to determine the individual differences between different frontends](image)

This experiment was done using a signal generator that was connected directly to the device under test (DUT) via a DC-block, Fig. 1. For practical reasons the white noise (AWGN) signal was simulated using a 256 QAM signal with random data and a symbol rate of 50 Msps, gen-
erating a 50 MHz wide AWGN like signal and the shape of the signal was verified using a spectrum analyzer. The results can be seen in Fig. [2].

It is clear that there are differences between the frontends and that each frontend has an active region of about 40dB. It should be noted that the graph shows the power generated by the signal generator and not the power at the antenna connector of the frontend.

![Figure 2. Differences in AGC value between different frontends](image)

A second experiment were done to measure how sensitive the frontend was to added continuous wave (CW) signal and AWGN interference. To make sure that the receiver worked within its intended range and did not receive any unwanted interference a Novatel 702-GG antenna located inside an anechoic chamber was used as a white noise generator. The antenna was powered using a DC power supply using a bias-T and was connected to the frontend via a 2:1 splitter. The other port of the splitter was connected to a signal generator capable of generating both carrier and wideband signals at the GPS L1 frequency. A DC block was placed on the input of the frontend to prevent it from sending DC to the signal generator. The setup can be seen in Fig. [3].

But are the results from the SiGe valid for other receivers as well? To answer this two other receivers were connected to the setup used in the second experiment and their version of AGC messages was recorded. It is clear that the SiGe responds similar to what the Novatel and Ublox receivers when the receivers are exposed to wideband and narrowband RFI. How the change in AGC corresponds to changes in the receiver performance has not been tested.

4 DEPLOYMENT

Since the AGC level varies between different installations only AGC data was recorded until the daily variations could be determined. When the typical AGC levels was known for either site two thresholds could be set one low threshold that triggered the system when the ACG dropped for only one sample (0.02s) and one slightly higher that triggered the system once the AGC had been low for at-least five samples (0.1sec) The AGC threshold had to be adjusted so it would be sensitive enough to capture any interference while not trigger too many times.

4.1 Luleå Airport - Sweden, ESPA or LLA

The first location where the system was deployed was at Luleå Airport outside Luleå in northern Sweden. The coordinates of the airport are 65°32’57” north latitude and 22°07’24” east WGS 84. It is a rather small airport with about 12900 landings and takeoffs and 900 k passengers in 2010. The location is about 7 km from the city and about 13 km from Luleå University of Technology. The system was deployed in a building that is located outside the secure area but close to the main entrance to the airport, the antenna is approximately 130 m from the nearest airplane gate as can be seen in Fig. [5].

Unfortunately it has only clear line of sight to a small portion of the runway from the antenna, the rest of the view is blocked by buildings that are slightly higher than the antenna. The area between the main road to the airport and the antenna consists mainly of fairly tall pine trees where only the trunks are blocking the view.

A potential concern was a radio tower was located 10 m from the antenna. To determine if the tower had any ef-
fect on the system three datasets was taken, first one at the university, then a second with the antenna on the ground in front of the tower and finally when the system had been deployed. When the three datasets was compared there was no significant change in neither spectrum or AGC level, it was then concluded that the radio tower did not have any significant effect on the monitor system. After the initial installation the system was started and ran autonomously. The computer was connected to a broadband connection and all transfer of data and control of the system was therefore done remotely.

4.2 Kaohsiung International Airport - Taiwan, RCKH or KHH

The other location where the system was deployed at Kaohsiung International Airport in Kaohsiung City, Taiwan. The coordinates of the airport are 22° 34’ 37” North latitude and 120° 21’ 1” East longitude. It is an air transportation hub in southern Taiwan and is surrounded by several roads with heavy traffic. The total aircraft movements in 2010 were 41 309 and the number of passengers was 4000k.

The system was deployed inside the airport restricted area and close to the main runway of the airport. The NovAtel 701 antenna was installed on top of a four story building approximately 500 meters from the runway Fig. 8. It is clear line of sight to the runway from the antenna at Kaohsiung International Airport Fig. 9 and also almost clear line of sight to the provincial highway no 17 and the container yard on the other side of the road as shown in Fig. 10.

Figure 5. Location of the station at Luleå airport

Figure 6. View towards the main entrance to Luleå airport

Figure 7. View towards the runway at Luleå Airport

Figure 8. Location of the station at Kaohsiung international airport

Figure 9. View from the antenna towards the terminal and runway at Kaohsiung international airport

Figure 10. View from the antenna towards one of the major roads around Kaohsiung international airport
The system was started and ran autonomously after the initial setup was done. Also all transfer of data and control of the software could be done remotely using a broadband connection.

5 RESULTS
All AGC data that was collected at the stations until the 20th of Sept will be shown. Each individual plot shows the recorded AGC data for a month, in order to show multiple days of data in the same plot the values for each day have been shifted upwards by 0.2 times the day of month when the data was recorded. Both systems experienced a number of interrupts in the data collection (shown as gaps).

5.1 Luleå Airport - Sweden
Data presented here was collected between 16th May and 20th September 2011 and the results are presented in Fig. 11, 12, 13, 14 and 15. During this period only one major interrupt occurred, which can be seen in Fig. 12. This was caused by lack of available space on the hard drive in the laptop. There are some minor interrupts that were caused by scheduled software upgrades. At Luleå airport no severe interference was observed until early September.

In Fig. 14 and in Fig. 12 it can be seen that the AGC becomes higher than normal for some time, this was probably caused by loss of power to the antenna. It is known that the airport would upgrade some of the equipment in the building where the station was located during the summer. Another thing that can be seen in the figure is that the AGC varies slightly over the duration of the day and that the variation is not constant between different days. The exact reason for this has not been found and is under investigation.

5.2 Kaohsiung International Airport - Taiwan
Data presented here was collected between 1st of August and 20th September 2011 Fig. 16 and Fig. 17. Fig 16 shows the collected AGC data at Kaohsiung International Airport from Aug. 1st to 31st and Fig. 17 shows the AGC from 1st to 20th September. Note that several AGC data interruptions occurred due to the scheduled system maintenance. In comparison with the collected AGC data at Luleå airport, there are several noticeable variations of the AGC data collected at KHH in each day.

Importantly, several significant interferences are observed during the initial calibration phase. Unfortunately, RFI record trigger scheme was not activated so that the system did not collect any IF data during these events. The fluctuation in AGC results in further investigation. Fig. 18 shows an example of the significant RFI at KHH on Aug. 9th, 2011. The figure is zoomed in around 1300 h in Fig.
By studying the AGC values some features can be identified:

- The AGC patterns are similar and asymmetrical.
- The duration of each interference event is about 240 seconds and the AGC voltages dropped and raised back to the nominal value gradually.
- The power of the interference drops significantly for a short period of time, this could indicate that line of sight to the interference is temporarily blocked by something.

Note that KHH is and surrounded by several major roads and that it has heavy traffic nearby.

Fig. 20 shows the antenna surrounding the area at a specific azimuth. There is a building (i.e. line-of-sight obstruction) at the roof between the antenna and the feeder road of National Highway No. 1. As a result, the signal transmitted from the highway is blocked for 47 degrees in azimuth. Especially, the National Highway No. 1 branch is a feeder road only for the trucks to the Kaohsiung harbor, where many trucks routinely pass by especially during the working hours. Fig. 21 shows the orientation of the antenna location, the feeder road, and the obstacle. As a result, the path way is blocked for a length of 540 meters. In addition, the speed limitation of the National Highway No. 1 branch is less than 50 km/h (i.e., 13.6 m/s). Under the speed limitation, the potential interferer would be blocked from line of sight during a period of 40 seconds. This coincides with the features of the interference events on August 9th, 2011, which can be seen by studying Fig. 19. Given this it is plausible that the interference came from the road, although this is just one theory and it is not possible to say conclusively if it is the correct one.
5.3 Spectrum
After the systems were deployed a number of the IF files from each site was processed using a MATLAB based software defined GPS receiver in order to verify that there was no continuous interference on the sites.

5.4 AGC Sample Statistics at Luleå and Kaohsiung Airports
Each system triggered a number of times during the measurement campaign. Two triggers was used, one that reacted when the AGC went below a certain value for 0.02 sec or more Tab. 2, 4 and one higher that reacted when the AGC went below a higher threshold for at least 0.1 second Tab. 1, 3. Each of these triggers will be presented in a separate table and histogram will be shown for the triggers that caused the AGC to go low for at least 0.1sec. If Tab. 4 is compared to eg Fig. 19 it is clear that although the max duration of the interference was about 50 s the total time when the station received interference was closer to 130 s. The reason for this discrepancy is that the received signal level fluctuates and passes the trigger threshold a number of times, although the fluctuations can be seen as an increase in the number of triggers.

<table>
<thead>
<tr>
<th>LLA</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>Aug</th>
<th>Sept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Duration(s)</td>
<td>0.205</td>
<td>0</td>
<td>4.98</td>
<td>0.205</td>
<td>83.6</td>
</tr>
<tr>
<td>Min Duration(s)</td>
<td>0.205</td>
<td>0</td>
<td>0.102</td>
<td>0.205</td>
<td>0.102</td>
</tr>
<tr>
<td>Median Duration(s)</td>
<td>0.205</td>
<td>0</td>
<td>0.102</td>
<td>0.133</td>
<td>0.235</td>
</tr>
<tr>
<td>Mean Duration(s)</td>
<td>0.205</td>
<td>0</td>
<td>0.265</td>
<td>0.143</td>
<td>2.84</td>
</tr>
<tr>
<td>Total number of triggers below threshold</td>
<td>1</td>
<td>0</td>
<td>108</td>
<td>4</td>
<td>90</td>
</tr>
<tr>
<td>Average number of triggers/day</td>
<td>0.09</td>
<td>0</td>
<td>3.50</td>
<td>0.33</td>
<td>4.79</td>
</tr>
</tbody>
</table>

Table 1. Collected AGC Sample Statistics, triggers at least 0.1 s below the high threshold at LLA

<table>
<thead>
<tr>
<th>LLA</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>Aug</th>
<th>Sept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Duration(s)</td>
<td>0.061</td>
<td>0.020</td>
<td>4.18</td>
<td>0.061</td>
<td>47.3</td>
</tr>
<tr>
<td>Min Duration(s)</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>Median Duration(s)</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>Mean Duration(s)</td>
<td>0.022</td>
<td>0.020</td>
<td>0.072</td>
<td>0.023</td>
<td>0.574</td>
</tr>
<tr>
<td>Total number of triggers below threshold</td>
<td>45</td>
<td>32</td>
<td>194</td>
<td>66</td>
<td>251</td>
</tr>
<tr>
<td>Average number of triggers/day</td>
<td>3.90</td>
<td>1.07</td>
<td>6.28</td>
<td>2.13</td>
<td>13.1</td>
</tr>
</tbody>
</table>

Table 2. Collected AGC Sample Statistics, triggers at least 0.02 s below the high threshold at LLA

One thing that should be noted about Fig. 23 and Fig. 26.
is that the AGC and the IF files can only be automatically aligned to within one second due to limitations in how the files are named.

5.5 Analysis of one interference detection at LLA
On the 19th of September the system at LLA was triggered. Analysis of the AGC data revealed that the system received higher than normal signal levels for about 35 seconds. Unfortunately the system was configured so that it only recorded 10 s of IF data after it was triggered so it is not possible to analyse the full duration of the incident. Fig 24 shows that the RFI was a narrowband source that was not very stable in its frequency. This signals were observed a number of times at both airports. The approximate time the AGC was triggered is marked in the spectrogram with a black line, it can be seen that the spectrum has some dark horizontal lines, when the spectrum is looked at from another direction it can be seen that there is an significant increase in the power of the signal around 7500 kHz It can also be seen that the spectrum is compressed about 40 seconds in to the file (the darker horizontal line).

5.6 Analysis of one interference detection at KHH
An RFI detection that had similar characteristics as those described in the section where only AGC data was recorded occurred on the 11th of Sept at KHH. In the AGC plot Fig. 25 it can be seen that in this case the AGC first dropped then went back up before it went down. In this case the interference caused the AGC to only drop during about 2 s. But as can be seen in Fig. 26 the interference is strong enough to cause the C/N0 to drop to around 30 and causing loss of lock in the SDR used here. When the spectrogram is observed it is clear that there is some narrowband interference that initially has a low enough power so that it does not initially affect the AGC although a minor change in AGC can be seen around sample 250 in Fig. 25.

It can be seen in Fig. 25 that the received signal power increased during at least 10 s. In Fig. 26 it can be seen that both the C/N0 value ans well as the correlator output was impacted significantly.

5.7 AGC as a RFI monitor
Since no receiver was in parallel to the AGC collection it is impossible to say if the AGC failed to detect anything that could have caused a receiver tracking issues. But what can be clear is that the AGC triggered at many times when it was no visible change in the spectrum and sometimes the changes in AGC did correspond to a very short drop in the strength of the tracking results. It is also clear that it was not overly sensitive to narrowband RFI, although this was expected since a narrow band CW tone does not add much energy to the spectrum and GNSS signals are resilient versus narrowband interference due to the use of code division multiple access (CDMA) coding.

6 CONCLUSIONS AND FUTURE WORK
In this paper a low-cost GPS L1 RFI monitor system has been presented. Currently, the system has been deployed at Luleä Airport in Sweden and Kaohsiung International Airport in Taiwan to monitor the GPS L1 band in the area around the two airports. As a result, a number of RFI incidents of varying durations were observed at both airports. Especially incidents at KHH seem to correspond to traffic flow/hours. The experiment results show the effectiveness

<table>
<thead>
<tr>
<th>KHH</th>
<th>Aug</th>
<th>Sept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Duration(s)</td>
<td>51.3</td>
<td>1.74</td>
</tr>
<tr>
<td>Min Duration(s)</td>
<td>0.102</td>
<td>0.102</td>
</tr>
<tr>
<td>Median Duration(s)</td>
<td>0.163</td>
<td>0.143</td>
</tr>
<tr>
<td>Mean Duration(s)</td>
<td>0.394</td>
<td>0.285</td>
</tr>
<tr>
<td>Total number of triggers below threshold</td>
<td>3628</td>
<td>20</td>
</tr>
<tr>
<td>Average number of triggers/day</td>
<td>117</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Table 3. Collected AGC Sample Statistics from KHH, triggers at least 0.1 s below the high threshold at KHH

<table>
<thead>
<tr>
<th>KHH</th>
<th>Aug</th>
<th>Sept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Duration(s)</td>
<td>42.9</td>
<td>0.775</td>
</tr>
<tr>
<td>Min Duration(s)</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>Median Duration(s)</td>
<td>0.041</td>
<td>0.020</td>
</tr>
<tr>
<td>Mean Duration(s)</td>
<td>0.109</td>
<td>0.048</td>
</tr>
<tr>
<td>Total number of triggers below threshold</td>
<td>13306</td>
<td>123</td>
</tr>
<tr>
<td>Average number of triggers/day</td>
<td>431</td>
<td>6.46</td>
</tr>
</tbody>
</table>

Table 4. Collected AGC Sample Statistics from KHH, triggers at least 0.02 s below the low threshold at KHH

Figure 22. AGC data on the 19th September from LLA
Figure 23. A summary of how the SDR code was affected by the interference on the 19th September at LLA.

Figure 24. Spectrogram over the analyzed IF file from LLA, the approximate time for AGC detection is marked by the black line.

Figure 25. AGC data on the 11th September from KHH.
Figure 26. A summary of how the SDR code was affected by the interference on the 11th September at KHH

Figure 27. Spectrogram over the analyzed IF file from KHH, the approximate time for AGC detection is marked by the black line
7 ACKNOWLEDGMENTS
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REFERENCES


