Evaluation of the Effect of Radio Frequency Interference (RFI) on the Accuracy of the Global Positioning System (GPS) L1 C/A Signal via GPS Simulation

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ABSTRACT

In this study, Global Positioning System (GPS) simulation is employed to study the effect of radio frequency interference (RFI) on the accuracy of two handheld GPS receivers; Garmin GPSmap 60CSx (evaluated GPS receiver) and Garmin GPSmap 60CS (reference GPS receiver). Both GPS receivers employ the GPS L1 coarse acquisition (C/A) signal. The results of this study demonstrate that interference signals that are insufficient to jam GPS receivers can still cause significant reduction in GPS accuracy. With increasing interference signal power level, probable error values increase due to decreasing carrier-to-noise density ($C/N_0$) levels for GPS satellites tracked by the receiver. Varying probable error patterns are observed for readings taken at different locations and times. This is due to the GPS satellite constellation being dynamic, causing varying GPS satellite geometry over location and time, resulting in GPS accuracy being location / time dependent. In general, the highest probable error values are observed for readings with the highest position dilution of precision (PDOP) values, and vice versa.

Keywords: Global Positioning System (GPS) simulation; radio frequency interference (RFI); probable error; carrier-to noise-density ($C/N_0$); position dilution of precision (PDOP).

INTRODUCTION

There is a steady growth in the entrenchment of Global Navigation Satellite Systems (GNSS) in current and upcoming markets, having penetrated various consumer products, such as cell phones, personal navigation devices (PNDs), cameras and assimilation with radio-frequency identification (RFID) tags, for various applications, including navigation, surveying, timing reference and location based services (LBS). While the Global Positioning System (GPS), operated by the US Air Force (USAF), is the primarily used GNSS system worldwide, the upcoming Galileo and Compass systems, and the imminent conversion of Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) signals from frequency division multiple access (FDMA) to code division multiple access (CDMA) look set to make multi-satellite GNSS configurations the positioning, navigation & timing (PNT) standard for the future.

However, many GNSS users are still not fully aware of the vulnerabilities of GNSS systems to various error parameters, such as ionospheric and tropospheric delays, satellite clock, ephemeris and multipath errors, satellite positioning and geometry, and signal interferences and obstructions. These error parameters can severely affect the accuracy of GNSS readings, and in a number of cases, disrupt GNSS signals [1-8].

One particular vulnerability that has received significant attention is jamming. Jamming is defined as the broadcasting of a strong signal that overrides or obscures the signal being jammed [9-11]. Since GNSS satellites, powered by photocells, are approximately 20,200 km above the Earth surface, GNSS signals that reach the Earth have very low power levels (approximately -160 to -130 dBm), rendering
them highly susceptible to jamming [5, 6, 12-16]. For example, a simple 1 W battery-powered jammer can block the reception of GNSS signals approximately within a radius of 35 km from the jammer [14]. Given the various incidents of intentional and unintentional jamming of GNSS signals, including military GNSS signals [12, 17-20], the development of various GNSS anti-jamming technologies has received significant attention [15, 21-27]. In addition, many current GNSS receiver evaluations concentrate on radio frequency interference (RFI) operability [29-35].

In order to study the effect of RFI on the GPS L1 coarse acquisition (C/A) signal, the Science & Technology Research Institute for Defence (STRIDE) conducted a series of tests specifically aimed at evaluating the minimum interference signal power levels required to jam various GPS receivers [36, 37]. However, interference signals with power levels below the minimum jamming threshold could still severely distort GPS accuracy, rendering it useless for applications requiring high precision. To this end, Dinesh et al. [38] studied the effect of RFI on GPS accuracy. The study was conducted via field evaluations using live GPS signals. However, such field evaluations are subject to various error parameters which are uncontrollable by users.

The ideal GPS receiver evaluation methodology would be using a GPS simulator, which can be used to generate multi-satellite GPS configurations, transmit GPS signals which simulate real world scenarios, and adjust the various error parameters. This would allow for the evaluations of GPS receiver performance under various repeatable conditions, as defined by users. As the evaluations are conducted in controlled laboratory environments, they will not be inhibited by unwanted signal interferences and obstructions [39-42].

In this study, GPS simulation is employed to study the effect of RFI on the accuracy of two handheld GPS receivers; Garmin GPSmap 60CSx [43] (evaluated GPS receiver) and Garmin GPSmap 60CS [44] (reference GPS receiver). Both GPS receivers employ the GPS L1 C/A signal.

**METHODOLOGY**

The apparatus used in the study were an Aeroflex GPSG-1000 GPS simulator [45], an Advantest U3751 spectrum analyser [46], an IFR 2023B signal generator [47], a Hyperlog 60180 directional antenna [48], and a notebook running GPS Diagnostics v1.05 [49]. The study was conducted in the STRIDE semi-anechoic chamber [50] using the test setup shown in Figure 1. The following assumptions were made for the tests:

i) No ionospheric or tropospheric delays
ii) Zero clock and ephemeris error
iii) No multipath fading or unintended obstructions
iv) No unintended interference signals.
The date of simulation was set at 10 January 2012. The almanac data for the period was downloaded from the US Coast Guard's web site [51], and imported into the GPS simulator. The GPS signal power level was set at -131dBm, which is the highest value permitted by the GPS simulator. For each GPS receiver, the test procedure was conducted for coordinated universal time (UTC) times of 0000, 0300, 0600 and 0900 for the following coordinates:

i) N 2° 58’ E 101° 48’ (Kajang, Selangor, Malaysia)
ii) N 39° 45’ W 105° 00’ (Denver, Colorado, USA)
iii) S 16° 55’ E 145° 46’ (Cairns, Queensland, Australia)
iv) S 51° 37’ W 69° 12’ (Rio Gallegos, Argentina).

The Trimble Planning software [52] was used to estimate GPS satellite coverage at the test areas for the period of the tests (Figure 2).
Figure 2: Position dilution of precision (PDOP) of GPS coverage at the test areas for the period of the tests: (a) Kajang (b) Denver (c) Cairns (d) Rio Gallegos.
(Source: Screen captures from the Trimble Planning software)

Once a location fix was obtained with the GPS receiver, the values of horizontal probable error (HPE), vertical probable error (VPE) and estimate probable error (EPE) were recorded. The interference signal used was an FM signal with carrier frequency of 1,575.42 MHz (the fundamental frequency of the GPS L1 C/A signal), peak deviation of 1 MHz and information frequency of 5 kHz. Interference signal transmission was started at power level of -140 dBm. The power level was increased by increments of 3 dBm, and the corresponding values of HPE, VPE and EPE were recorded.

RESULTS & DISCUSSION

Prior to transmission of interference signals, the evaluated GPS receiver recorded lower probable error values as compared to the reference GPS receiver (Table 1). This occurred as the evaluated GPS receiver has higher receiver sensitivity, and hence, is able to obtain lower PDOP values. In addition, it has lower receiver noise, reducing the value of its user equivalent ranging error (UERE), which is the total expected magnitude of position errors due to measurement uncertainties from the various error components for a particular receiver.

<table>
<thead>
<tr>
<th>Location</th>
<th>UTC time</th>
<th>Evaluate GPS receiver</th>
<th>Reference GPS receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>HPE</td>
<td>VPE</td>
</tr>
<tr>
<td>Kajang</td>
<td>0000</td>
<td>2.9</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>0300</td>
<td>2.7</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>0600</td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>0900</td>
<td>1.9</td>
<td>4.9</td>
</tr>
<tr>
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<td>3.2</td>
</tr>
<tr>
<td></td>
<td>0300</td>
<td>2.5</td>
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<td>11.6</td>
</tr>
<tr>
<td></td>
<td>0900</td>
<td>2.9</td>
<td>3.9</td>
</tr>
<tr>
<td>Rio</td>
<td>0000</td>
<td>2.4</td>
<td>4</td>
</tr>
</tbody>
</table>

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For all the readings, the values of VPE are larger than HPE, as GPS receivers can only track satellites above the horizon, resulting in GPS height solution being less precise than the horizontal solution [38, 53-55]. The difference between VPE and HPE values is significantly larger for the reference GPS receiver as compared to the evaluated GPS receiver. The reference GPS receiver, having lower receiver sensitivity, has much better horizontal component accuracy as compared to the vertical component. For the GPS evaluated receiver, with higher receiver sensitivity, while the horizontal component accuracy is still larger, the difference with the vertical component is much smaller. During the jamming tests, at some points, depending on GPS coverage, the horizontal component accuracy became lower than the vertical component.

As observed in Figures 3 - 14, with increasing interference signal power level, probable error values increase due to decreasing carrier-to-noise density \((C/N_0)\) levels for GPS satellites tracked by the receiver, which is the ratio of received GPS signal power level to noise density. Lower \(C/N_0\) levels result in increased data bit error rate when extracting navigation data from GPS signals, and hence, increased carrier and code tracking loop jitter. This, in turn, results in more noisy range measurements and thus, less precise positioning [2, 38, 53, 54, 56].

<table>
<thead>
<tr>
<th>Time</th>
<th>0000</th>
<th>0300</th>
<th>0600</th>
<th>0900</th>
</tr>
</thead>
<tbody>
<tr>
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<td>6.6</td>
<td>9.6</td>
<td>11.7</td>
<td>11.8</td>
</tr>
<tr>
<td>HPE</td>
<td>3.1</td>
<td>3.2</td>
<td>4.5</td>
<td>4.8</td>
</tr>
<tr>
<td>VPE</td>
<td>2.8</td>
<td>4.6</td>
<td>5.4</td>
<td>5.4</td>
</tr>
</tbody>
</table>

![Figure 3: Recorded probable error values for the evaluated GPS receiver at Kajang for UTC times of: (a) 0000  (b) 0300  (c) 0600  (d) 0900.](image-url)
Figure 4: Recorded probable error values for the reference GPS receiver at Kajang for UTC times of: (a) 0000  (b) 0300  (c) 0600  (d) 0900.

Figure 5: Recorded probable error values for the evaluated GPS receiver at Denver for UTC times of: (a) 0000  (b) 0300  (c) 0600  (d) 0900.
Figure 6: Recorded probable error values for the reference GPS receiver at Denver for UTC times of: (a) 0000  (b) 0300  (c) 0600  (d) 0900.

Figure 7: Recorded probable error values for the evaluated GPS receiver at Cairns for UTC times of: (a) 0000  (b) 0300  (c) 0600  (d) 0900.
Figure 8: Recorded probable error values for the reference GPS receiver at Cairns for UTC times of: (a) 0000  (b) 0300  (c) 0600  (d) 0900.

Figure 9: Recorded probable error values for the evaluated GPS receiver at Rio Gallegos for UTC times of: (a) 0000  (b) 0300  (c) 0600  (d) 0900.
Figure 10: Recorded probable error values for the reference GPS receiver at Rio Gallegos for UTC times of: (a) 0000 (b) 0300 (c) 0600 (d) 0900.

Figure 11: Comparison of recorded EPE values of varying times at Kajang for the (a) evaluated and (b) reference GPS receivers.
Figure 12: Comparison of recorded EPE values of varying times at Denver for the (a) evaluated and (b) reference GPS receivers.

(a)                                                                                   (b)

Figure 13: Comparison of recorded EPE values of varying times at Cairns for the (a) evaluated and (b) reference GPS receivers.

(a)                                                                                   (b)

Figure 14: Comparison of recorded EPE values of varying times at Rio Gallegos for the (a) evaluated and (b) reference GPS receivers.

The probable errors of the evaluated GPS receiver increased to values that are significantly higher than then reference GPS receiver. This occurred as the evaluated GPS receiver requires higher interference signal power levels to be jammed as compared to the reference GPS receiver. The interference signal power levels that are just slightly lower than the evaluated GPS receiver’s jamming threshold cause significant degradation of accuracy.

Varying probable error patterns are observed for the each of the readings. This is due to the GPS satellite constellation being dynamic, causing varying GPS satellite geometry over location and time, resulting in GPS accuracy being location / time dependent [2, 38, 53-55]. In general, the highest probable error values were observed for readings with the highest PDOP values (Kajang at 0300, Denver at 0600, Cairns at 0000 and Rio Gallegos at 0300), while the lowest probable error values were observed for readings with the lowest PDOP values (Kajang at 0900, Denver at 0300, Cairns at 0300 and Rio Gallegos at 0600).

It is observed that the interference signal power levels required to affect the location fixes of the GPS receivers are significantly high as compared to the GPS signal power level. The noise-like C/A code structure, which modulates the L1 signal over a 2 MHz bandwidth, allows for the signal to be received at low levels of interferences. The P(Y) code (restricted to the US military) has a more robust...
structure, modulating the L1 and L2 signals over 20 MHz bandwidths, and has better resistance to interference.
The tests conducted in this study employed GPS signal power level of -131 dBm. Usage of lower GPS signal power levels would result in reduced $C/N_0$ levels and hence, higher rates of increase of probable error values. In addition, the minimum interference signal power levels required to jam the GPS receivers would also be lower.

CONCLUSION
The results of this study have demonstrated that interference signals that are insufficient to jam GPS receivers can still cause significant reduction in GPS accuracy. With increasing interference signal power level, probable error values increase due to decreasing $C/N_0$ levels for GPS satellites tracked by the receiver. Varying probable error patterns are observed for readings taken at different locations and times. This is due to the GPS satellite constellation being dynamic, causing varying GPS satellite geometry over location and time, resulting in GPS accuracy being location / time dependent. In general, the highest probable error values were observed for readings with the highest PDOP values, and vice versa.

This study has highlighted the relative ease to conduct GNSS jamming. Low power level interference signals, from intentional or unintentional sources, can cause the disruption of GNSS signals. Given the increasing dependence on GNSS for PNT applications, GNSS disruptions could prove to be problematic, if not disastrous. Hence, GNSS vulnerability mitigations steps should be given emphasis, including navigation / positioning / timing backups, making full use of ongoing GNSS modernisation programs, increased ability to identify and locate GNSS jammers, integrity monitoring and augmentation, and anti-jamming technologies.

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REFERENCES


