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Evaluating the Effect of Global Positioning System (GPS) Satellite Clock Error via GPS Simulation

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Abstract. This study is aimed at evaluating the effect of Global Positioning System (GPS) satellite clock error using GPS simulation. Two conditions of tests are used; Case 1: All the GPS satellites have clock errors within the normal range of 0 to 7 ns, corresponding to pseudorange error range of 0 to 2.1 m; Case 2: One GPS satellite suffers from critical failure, resulting in clock error in the pseudorange of up to 1 km. It is found that increase of GPS satellite clock error causes increase of average positional error due to increase of pseudorange error in the GPS satellite signals, which results in increasing error in the coordinates computed by the GPS receiver. Varying average positional 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. For Case 1, in general, the highest average positional error values are observed for readings with the highest PDOP values, while the lowest average positional error values are observed for readings with the lowest PDOP values. For Case 2, no correlation is observed between the average positional error values and PDOP, indicating that the error generated is random.

1. Introduction

Fundamental to the operation of GNSS is the one-way ranging that depends on satellite clock predictability. Even though the clocks in GNSS satellites are very accurate, they drift slightly, resulting in small errors which affect GNSS accuracy. This drift can be in the order of 9 to 18 ns per day and introduces a slow ramp type error in the transmitted signal. This error is difficult to detect because its signature resembles the typical relative motion between a GNSS satellite and receiver. The GNSS control segment continually monitors the satellite clocks and corrects any drift that is found. However, these corrections are based on observations and may not indicate the clock's current state, leaving residual error in the range of up to 7 ns [1-5]. On occasion, the satellite clocks behave unpredictably and produce errors that grow significantly before the operators can spot it and mark it as unhealthy. For example, on 1 January 2004, the clock on GPS satellite SV-23 drifted for approximately 3 h by a pseudo range error rate of 70.6 m/s before the command centre marked it unhealthy, by which time the pseudo range error had grown from 0 to 285 km [6]. A similar clock failure occurred for GPS satellite SV-22 on 28 July 2001, where its clock drifted for 90 min, leading to pseudo range error of up to 200 km [7].

This study is aimed at evaluating the effect of Global Positioning System (GPS) satellite clock error on GPS performance. It will be conducted using GPS simulation, which will allow the tests to be held with various repeatable conditions, as defined by the authors. As the tests are conducted in controlled laboratory environments, they will not be inhibited by unintended signal interferences and obstructions [8-10]. In previous studies, GPS simulation was used to evaluate the vulnerabilities of GPS to radio frequency interference (RFI) [11, 12] and multipath [13, 14].

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2. Methodology

The apparatus used in the study are an Aeroflex GPSG-1000 GPS simulator [15], a notebook running GPS Diagnostics v1.05 [16] and a Garmin GPSmap 60CSx handheld GPS receiver [17]. The GPS receiver employs the GPS L1 coarse acquisition (C/A) signal, which is an unencrypted civilian GPS signal widely used by various GPS receivers. The signal has a fundamental frequency of 1,575.42 MHz and a code structure which modulates the signal over a 2 MHz bandwidth [2, 18, 19]. The study is conducted in STRIDE's mini-anechoic chamber [20] to avoid external interference signals and unintended multipath errors. The test setup employed is as shown in Fig. 1. Simulated GPS signals are generated using the GPS simulator and transmitted via the coupler. The following assumptions are made for the tests conducted:

- No ionospheric or troposheric delays
- Zero unintended clock and ephemeris error
- No obstructions or multipath
- No interference signals.

The tests are conducted for coordinated universal time (UTC) times of 0000, 0300, 0600 and 0900 for the following coordinates:

- N 2° 58', E 101° 48', 0 m (Kajang, Selangor, Malaysia)
- N 39° 45', W 105° 00', 0 m (Denver, Colorado, USA)
- S 16° 55', E 145° 46', 0 m (Cairns, Queensland, Australia)
- S 51° 37', W 69° 12', 0 m (Rio Gallegos, Argentina).

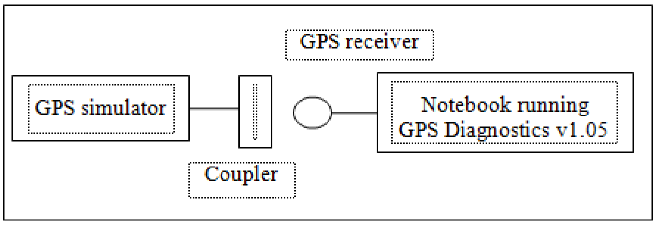

Figure 1. The test setup employed.

The almanac data for the periods is downloaded from the US Coast Guard's web site [21] and imported into the GPS simulator. The GPS signal power level is set at -130 dBm.

Trimble Planning [22] is used to estimate GPS satellite coverage at the test areas for the period of the study in terms of position dilution of precision (PDOP) (Table 1), which represents the effect of GPS satellite geometry on 3D positioning precision. A PDOP value of 1 is associated with an ideal arrangement of the satellite constellation. To ensure high-precision GPS positioning, a PDOP value of 5 or less is usually recommended. In practice, the actual PDOP value is usually much less than 5, with a typical average value in the neighbourhood of 2 [2, 18, 23].

The GPS simulator does not provide specific GPS satellite clock error simulation. However, it does allow for selection of pseudorange errors for the GPS satellites. For this study, GPS satellite clock error is simulated using the pseudorange error function, with 1 ns of clock error representing a pseudorange error of 0.3 m [1-5]. Two conditions of tests are used:

Table 1. PDOP of GPS coverage at the test areas for the period of the tests.

Location	Time	PDOP
Kajang	0000	1.33
	0300	1.46
	0600	1.24
	0900	1.72
Denver	0000	1.39
	0300	2.22
	0600	1.26
	0900	1.43
Cairns	0000	1.52
	0300	1.67
	0600	1.44
	0900	1.60
Rio Gallegos	0000	1.75
	0300	1.25
	0600	1.78
	0900	1.66

- **Case 1:** All the GPS satellites have clock errors within the normal range of 0 to 7 ns, corresponding to pseudorange error range of 0 to 2.1 m.
- **Case 2:** One GPS satellite, with the highest elevation (Table 2), suffers from critical failure, resulting in clock error in the pseudorange of up to 1 km (the maximum pseudorange error provided by the GPS simulator).

For each reading, the coordinates computed by the GPS receiver are recorded for a period of 15 min, and the values of average horizontal, vertical and overall errors are calculated.

Table 2. GPS satellites (SV) with the highest elevation at the start of each test period. These satellites are used to simulate critical failure that causes large clock error.

Location	Time	SV	Elevation	Azimuth
Kajang	0000	16	65.77	-133.38
	0300	3	86.43	-3.87
	0600	1	65.12	103.50
	0900	2	64.45	-37.06
Denver	0000	1	85.27	-35.07
	0300	29	76.79	-48.33
	0600	21	79.92	97.25
	0900	14	72.36	19.84
Cairns	0000	14	87.27	-163.54
	0300	31	63.11	119.28
	0600	11	57.69	-78.83
	0900	20	82.00	37.34
Rio Gallegos	0000	26	72.89	-107.89
	0300	24	73.81	-108.52
	0600	25	79.51	-125.26
	0900	21	63.00	-19.45

3 Results & Discussion

As observed in Fig. 2-9, increase of GPS satellite clock error causes increase of average positional error. This is due to increase of pseudorange error in the GPS satellite signals, which results in increasing error in the coordinates computed by the GPS receiver. It is observed that the maximum overall error caused by satellite clock error is in the range of 1.42 to 2.40 m for Case 1, and 929.36 to 1,393.98 m for Case 2. For Case 2, the overall errors caused are constrained by the limitation of the pseudorange error function (1 km) provided by the GPS simulator. In comparison, the critical failures suffered by GPS satellites SV-22 in 2001 and SV-23 in 2004 caused pseudorange errors of up to 200 and 285 km respectively [6, 7].

It is observed that for Case 1, for all the readings, the values of vertical error are larger than horizontal error, as GPS receivers can only track satellites above the horizon, resulting in the vertical solution being less precise than the horizontal solution [2, 18, 19]. For Case 2, vertical error is initially larger than horizontal error, but with increasing GPS satellite clock error, horizontal error becomes larger than vertical error. This is as the GPS satellite with simulated critical error has high elevation, causing horizontal error to increase at a higher rate as compared to vertical error. Critical failure simulation applied to GPS satellites with lower elevations would result in higher rate of vertical error increase and lower rate of horizontal error increase.

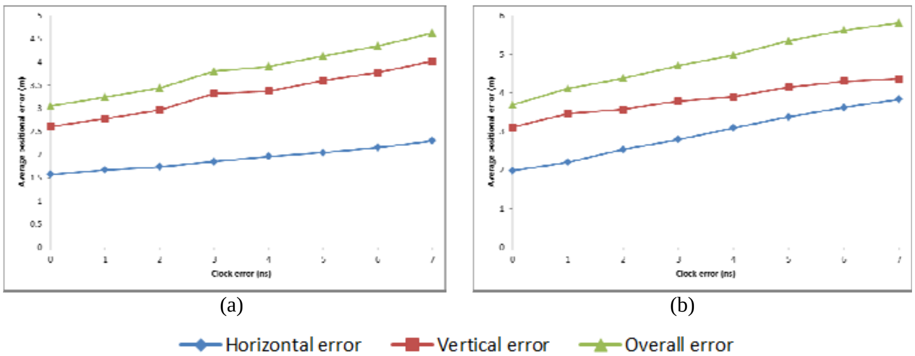

Figure 2: Recorded average positional error values for Case 1 at Kajang for periods of: (a) Lowest error: 0600 (b) Highest error: 0900.

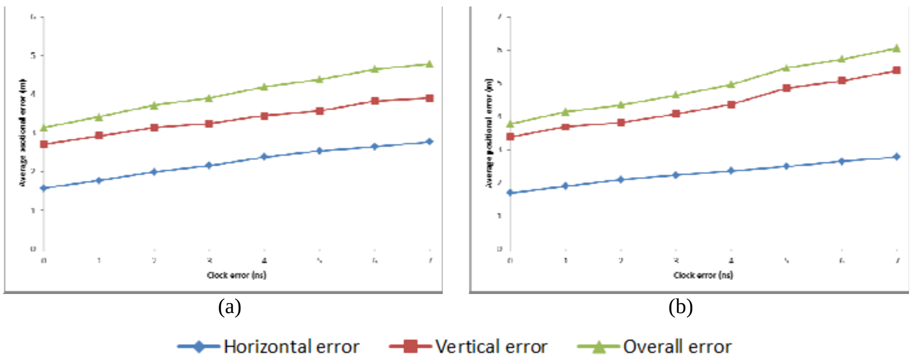

Figure 3: Recorded average positional error values for Case 1 at Denver for periods of: (a) Lowest error: 0600 (b) Highest error: 0300.

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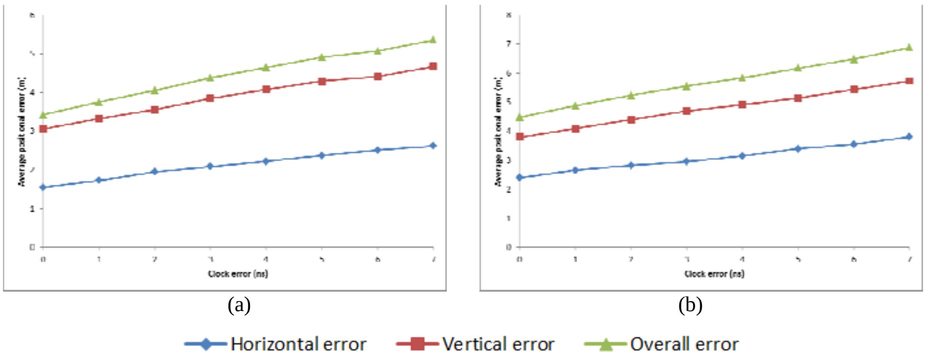

Figure 4: Recorded average positional error values for Case 1 at Cairns for periods of: (a) Lowest error: 0600 (b) Highest error: 0300.

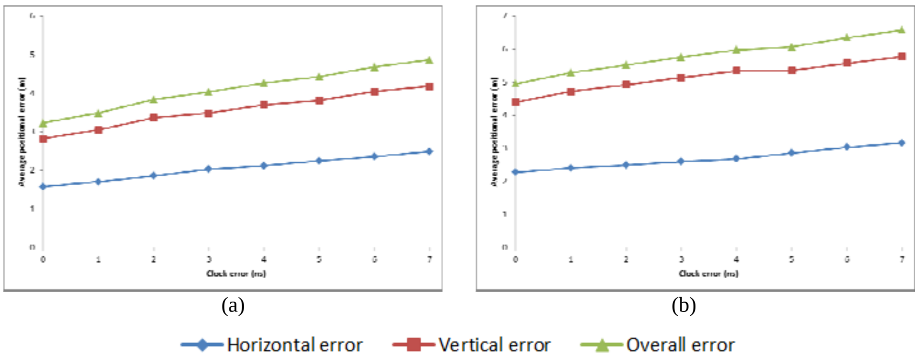

Figure 5: Recorded average positional error values for Case 1 at Rio Gallegos for periods of: (a) Lowest error: 0300 (b) Highest error: 0600.

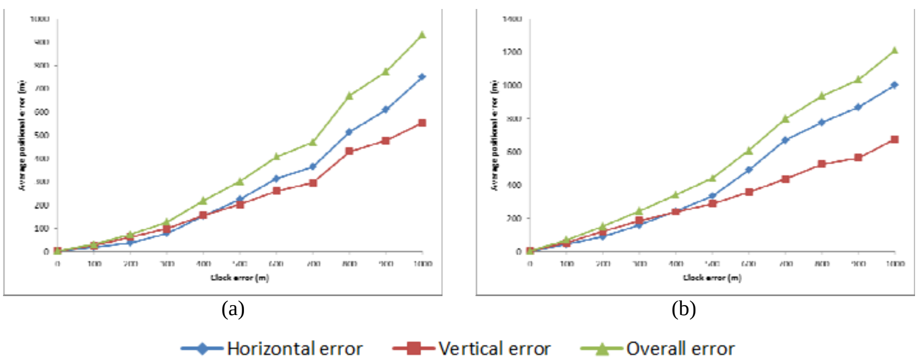

Figure 6: Recorded average positional error values for Case 2 at Kajang for periods of: (a) Lowest error: 0900 (b) Highest error: 0600.

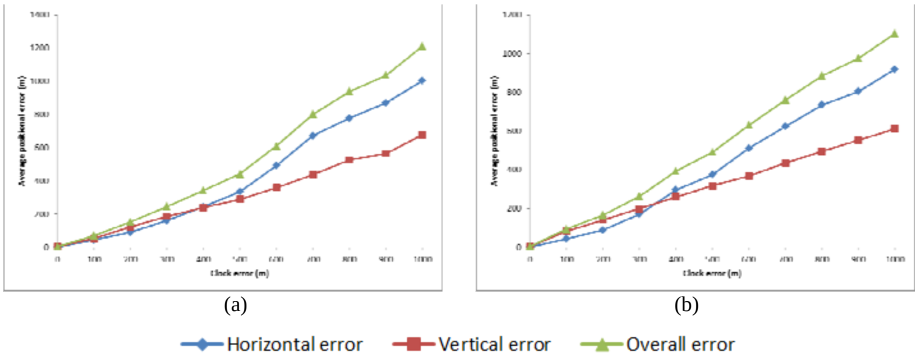

Figure 7: Recorded average positional error values for Case 2 at Denver for periods of: (a) Lowest error: 0600 (b) Highest error: 0000.

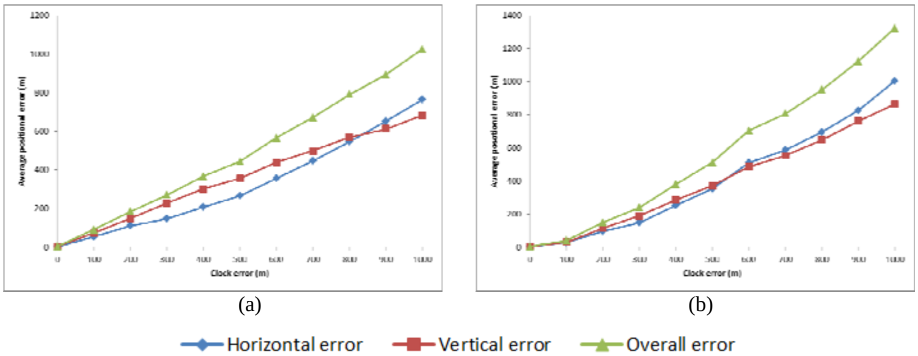

Figure 8: Recorded average positional error values for Case 2 at Cairns for periods of: (a) Lowest error: 0000 (b) Highest error: 0600.

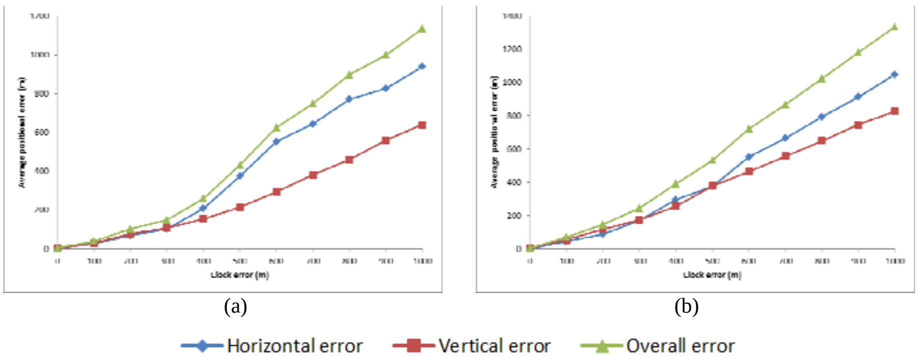

Figure 9: Recorded average positional error values for Case 1 at Rio Gallegos for periods of: (a) Lowest error: 0600 (b) Highest error: 0000.

Varying average positional 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, 18, 23]. For Case 1, in general, the highest average positional error values are observed for readings with the highest PDOP values (Kajang at 0900, Denver at 0300, Cairns at 0300 and Rio Gallegos at 0600), while the lowest average positional error values are observed for readings with the lowest PDOP values (Kajang at 0600, Denver at 0600, Cairns at 0600 and Rio Gallegos at 0300). For Case 2, no correlation is observed between the average positional error values and PDOP, indicating that the error generated is random.

The tests conducted in this study employed GPS signal power level of-130 dBm. Usage of lower GPS signal power levels would result in reduced carrier-to-noise density (C/N_0) levels, which is the ratio of received GPS signal power level to noise density. Lower C/N_0 levels would 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, higher rates of increase of positional error values [2,18, 19, 24]DOD, 2001; Kaplan & Hegarty, 2006; Petovello, 2009; USACE, 2011).

4. Conclusion

Based on the results of this study, it was found that increase of GPS satellite clock error caused increase of average positional error due to increase of pseudorange error in the GPS satellite signals, which resulted in increasing error in the coordinates computed by the GPS receiver. Varying average positional error patterns were 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. For Case 1 (all the GPS satellites have clock errors within the normal range of 0 to 7 ns), in general, the highest average positional error values were observed for readings with the highest PDOP values, while the lowest average positional error values were observed for readings with the lowest PDOP values. For Case 2 (one GPS satellite suffers from critical failure, resulting in clock error in the pseudorange of up to 1 km), no correlation was observed between the average positional error values and PDOP, indicating that the error generated was random.

References

[1] Olynik MC 2002 *Temporal Characteristics of GPS Error Sources and Their Impact on Relative Positioning*. Master's thesis (Alberta: The University of Calgary Calgary).
[2] Kaplan ED and Hegarty CJ 2002 *Understanding GPS: Principles and Applications.* (Massachusetts : Artech House, Norwood)
[3] Worley S, 2014 *GPS Errors & Estimating Your Receiver's Accuracy* Available online at: http://edu-observatory.org/gps/gps_accuracy.html (Last access date: 31 July 2014).
[4] Royal Academy of Engineering (RAE) 2011 *Global Navigation Space Systems: Reliance and Vulnerabilities* (London: Royal Academy of Engineering (RAE))
[5] Bidikar B, Rao GS, Ganesh L, and Kumar MS 2014 *Positioning* **5** 22-26
[6] Eastlack H 2004 *SVN-23/PRN-23 Integrity Failure of 1 January 2004*. (US Air Force, Washington, D.C.: Second Space Operations Squadron).
[7] Lavraks JW 2005 *An Overview of Civil GPS Monitoring* (Manassas, Virginia: Institute of Navigation (ION)).
[8] Aloi DN, Alsliety M and Akos DM 2011 *IEEE T. Instrum. Meas.* **56** 11-24.
[9] Kou Y and Zhang H 2011 *Inside GNSS* **6** 52-61
[10] Pozzobon O, Sarto C, Chiara AD, Pozzobon A, Gamba G, Crisci, M and Ioannides R 2013 *Inside GNSS* **8** 45-53.
[11] Dinesh, S, Mohd Faudzi, M. and Zainal Fitry 2012 MA *Defence. Sci. J.* **62** 338-347.
[12] Dinesh S, Mohd Faudzi M, Rafidah M, Nor Irza Shakhira B, Siti Robiah A, Shalini S, Aliah I, Lim BT, Zainal Fitry MA, Mohd Rizal AK and Mohd Hasrol Hisam, MY 2014 *ASM Sci. J.* **8**, 11-20.

[13] Dinesh S, Shalini S, Zainal Fitry MA and Siti Zainun A 2013 *Defence S&T Tech. Bull.* **6** 130-140.
[14] Dinesh S, Shalini S, Zainal Fitry MA, Siti Zainun A, Siti Robiah A, Mohd Idris I and Mohd Hasrol Hisam MY *Adv. Mil. Tech.* **9** 81-95.
[15] Aeroflex 2010 *Avionics GPSG-1000 GPS / Galileo Portable Positional Simulator* (Aeroflex Inc.: Plainview, New York).
[16] CNET 2004 *GPSDiag 1.0* Available online at: http://download.cnet.com/GPSDiag/3000-2130_4-4951103.html (Last access date: 31 January 2010).
[17] Garmin 2007 *GPSmap 60CSx Owner's Manual* (Olathe, Kansas: Garmin International Inc.).
[18] Department of Defence (DOD) 2001 *Global Positioning System Standard Positioning Service Performance Standard, Command, Control, Communications, and Intelligence* (Washington D.C.: Department of Defence (DOD))
[19] US Army Corps of Engineers (USACE) 2011 *Engineer Manual EM 1110-1-1003: NAVSTAR Global Positioning System Surveying* (Washington D.C., US Army Corps of Engineers (USACE)).
[20] Kamarulzaman M 2010 *Technical Specification for STRIDE's Mini-Anechoic Chamber* (Malaysia: Science & Technology Research Institute for Defence (STRIDE), Ministry of Defence).
[21] US Coast Guard (USCG) 2014 *GPS NANUs, Almanacs, & Ops Advisories* Available online at: http://www.navcen.uscg.gov/?pageName=gpsAlmanacs (Last access date: 31 July 2014).
[22] Trimble 2014 *Trimble's Planning Software* Available online at: http://www.trimble.com/planningsoftware.shtml (Last access date: 31 July 2014).
[23] Dinesh S, Wan Mustafa WH, Mohd Faudzi M, Kamarulzaman M, Hasniza H, Nor Irza Shakhira B, Siti Robiah A, Shalini S, Jamilah J, Aliah I, Lim BT, Zainal Fitry MA, Mohd Rizal AK, Azlina B and Mohd Hasrol HMY 2010 *Defence S&T Tech. Bull.* **3** 100-118.
[24] Petovello M *Inside GNSS* **4** 20-29.