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Evaluation of the Effect of Commonly Used Materials on Multipath Propagation of Global Positioning System (GPS) Signals via GPS Simulation

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Abstract:

In this study, Global Positioning System (GPS) simulation is employed to study the effect of five commonly used materials (aluminium, glass, wood, polyvinyl chloride (PVC) and ceramic) on multipath propagation of GPS signals. Based on the results of this study, it is found that multipath signals from panels made of the materials cause increase in probable error values due to errors in the GPS receiver's pseudorange measurements. The probable errors decrease with increasing distances of the panels from the GPS receiver due to decrease of strength of multipath signals. It is observed that aluminium causes the highest amount of the multipath, resulting in the highest probable errors. This is followed by glass, ceramic, PVC and wood.

Keywords:

Global Positioning System (GPS) simulation, multipath, probable errors, pseudorange measurements, dielectric constant.

1. 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

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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) appear 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 and ephemeris errors, satellite positioning and geometry, radio frequency interference (RFI) and spoofing, and obstructions and multipath. These error parameters can severely affect the accuracy of GNSS readings, and in a number of cases, even disrupt GNSS signals [1-4].

Multipath refers to the distortion of direct line-of-sight (LOS) GNSS satellite signals by localised reflected / diffracted signals, caused by objects such as trees, buildings, etc. As the multipath signals travel additional distances, they are delayed relative to the LOS signals, resulting in pseudorange measurements to the GNSS satellites being severely degraded. The multipath signals' paths are dependent on the reflecting surfaces and satellites' positions. As the satellites move with time, the multipath effect is also a variable of time. Multipath error is dependent on the architecture of GNSS receiver, in terms of the different ways the receivers deal with the signals [5-7].

Yi et al. [8] studied the effect of five commonly used materials (aluminium, glass, wood, polyvinyl chloride (PVC) and ceramic) on multipath propagation of GPS signals. 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 GNSS receiver evaluation methodology would be using a GNSS simulator, which can be used to generate multi-satellite GNSS configurations, transmit GNSS signals that simulate real world scenarios, and adjust the various error parameters. This would allow for the evaluations of GNSS 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 [9-11].

As part of the 10th Malaysian Plan (RMK10) project entitled *Evaluation of the Effect of Radio Frequency Interference (RFI) on Global Positioning System (GPS) Signals via GPS Simulation* (January 2011 – May 2012), the Science & Technology Research Institute for Defence (STRIDE) employed GPS simulation to study the effect of RFI on GPS signals [12, 13]. In addition, Dinesh et al. [14] used GPS simulation to study the effect of various scenarios of multipath on GPS accuracy, while Dinesh et al. [15] demonstrated the repeatability of multipath for every two GPS satellite passes of approximately 23 h 56 min.

In this study, GPS simulation is employed to study the effect the five materials (aluminium, glass, wood, PVC and ceramic) on multipath propagation of GPS signals. The study is conducted based on important characteristics of GPS signal obstruction and multipath [5-7]:

i) Physical obstructions prevent certain GPS signals from reaching the GPS receiver, causing a reduction in number of visible GPS satellites
ii) Multipath signals that are reflected off physical obstructions have lower power levels as compared to unaffected GPS signals

iii) The effects of GPS signal obstruction and multipath can be correlated with GPS satellite elevation, with the effects being at a maximum during low elevations and improving for higher elevations.

2. Methodology

The apparatus used in the study are an Aeroflex GPSG-1000 GPS simulator [16], a notebook running GPS Diagnostics v1.05 [17], and a Garmin GPSmap 60CSx handheld GPS receiver [18], which employs the GPS L1 coarse acquisition (C/A) signal. It is conducted in STRIDE's semi-anechoic chamber [19] 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:

i) No ionospheric or tropospheric delays
ii) Zero clock and ephemeris error
iii) No unintended obstructions or multipath
iv) No interference signals.

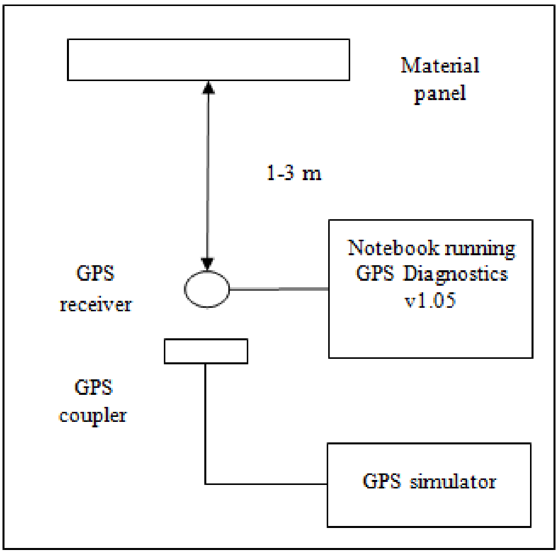


Fig. 1 The test setup employed

The date, coordinates and GPS signal power level of simulation are set at 2 January 2014, N 2° 58', E 101° 48' (Kajang, Selangor) and –130 dBm respectively. The almanac data for the period is downloaded from the US Coast Guard's web site [20], and imported into the GPS simulator. The test procedure is conducted for coordinated universal time (UTC) times of 0000, 0600, 1200 and 1800.

Trimble Planning [21] is used to estimate GPS satellite coverage at the test area for the periods of the study in terms of position dilution of precision (PDOP) (Fig. 2), 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 [1, 22, 23]. The GPS satellites visible at the start of each test period are shown in Tab. 1.

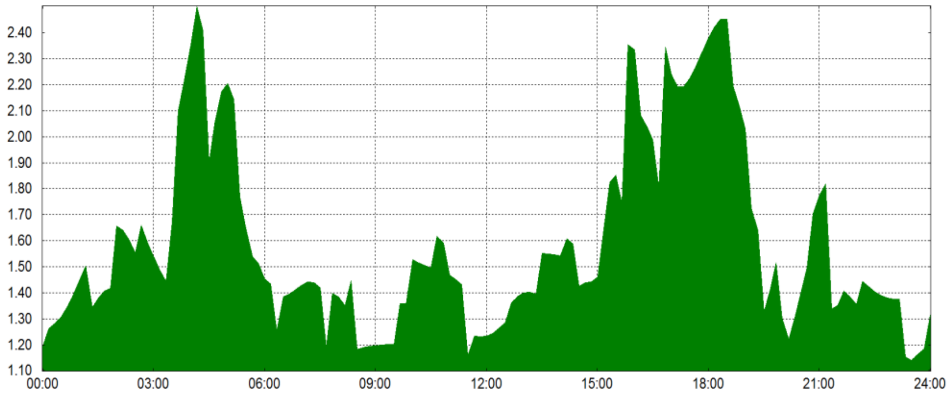


Fig. 2 PDOP of GPS coverage at the test area for the period of the tests. The x-axis is UTC time while the y-axis is PDOP
(Source: Screen capture from Trimble Planning)

The tests are initially conducted for non-multipath conditions, with the panel removed. Two conditions of GPS coverage are used; the full range of available GPS satellites, and only the six GPS satellites with the highest elevation at the start of each test period (assuming that the remaining GPS satellites are blocked by physical obstructions). The tests are then conducted for the panels (dimensions of 1 × 1 m) made of aluminium, glass, wood, PVC and ceramic, placed at distances of 1, 2 and 3 m from the GPS receiver. For each reading, values of horizontal probable error (HPE), vertical probable error (VPE) and estimate probable error (EPE) are recorded for a period of 15 min.

3. Results and Discussion

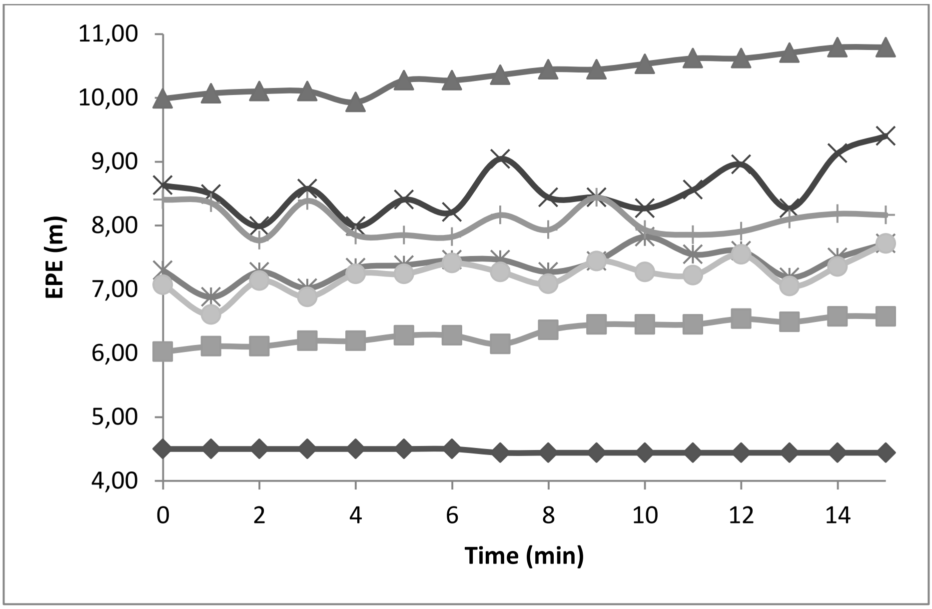
As observed in Figs. 3-5, and Tab. 2, the decrease in number of visible satellites due to physical obstructions cause increase in probable error values. This is due to decreasing carrier-to-noise density (C/N_0) levels for GPS satellites tracked by the receiver, which is the ratio of received GPS signal 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, 22, 24].

Tab. 1 GPS satellites (SV) visible at the start of each test period. The satellites that are in bold have the highest elevations for each period and were selected for multipath simulation

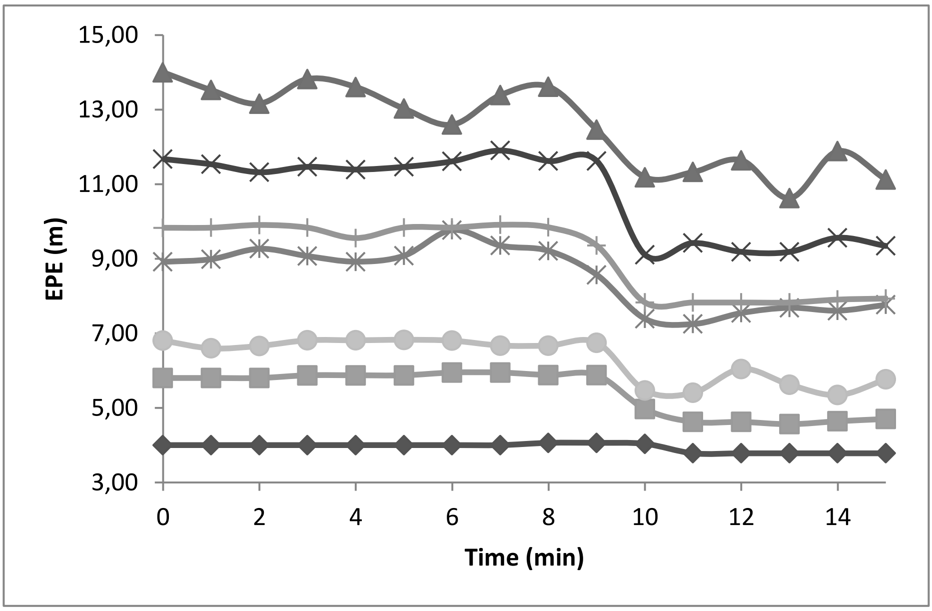
UTC Time	Number of satellites	SV	Elevation (°)	Azimuth (°)	Time	Number of satellites	SV	Elevation (°)	Azimuth (°)
0000	10	1	20.40	29.71	1200	8	12	22.83	79.16
		4	**46.18**	**-127.29**			**14**	**28.38**	**-39.18**
		7	**56.35**	**172.64**			**18**	**48.54**	**35.22**
		8	**77.39**	**-89.24**			**21**	**63.86**	**-174.23**
		9	**70.60**	**-99.64**			**22**	**33.61**	**-9.052**
		10	17.68	-162.87			**25**	**41.30**	**120.75**
		13	14.07	164.49			29	10.06	153.49
		17	27.77	-39.70			**31**	**42.78**	**-132.36**
		20	**34.32**	**89.32**			-	-	-
		28	**34.40**	**3.26**			-	-	-
		-	-	-			-	-	-
0600	10	**2**	**29.23**	**31.01**	1800	11	**3**	**80.28**	**147.05**
		4	12.65	74.75			**6**	**62.09**	**64.76**
		5	**38.94**	**-2.79**			11	20.17	-162.85
		12	**41.80**	**-110.78**			14	13.12	136.39
		15	**48.17**	**-164.04**			**16**	**36.77**	**-0.59**
		17	13.42	136.86			**19**	**52.49**	**179.45**
		24	13.19	-157.53			20	32.95	-99.79
		25	**20.37**	**-72.77**			23	30.88	-26.64
		26	**65.24**	**119.38**			**27**	**68.54**	**91.14**
		29	12.92	-29.85			31	14.44	67.41
		-	-	-			**32**	**46.54**	**-141.25**

Tab. 2 Recorded average probable error values

Time	Number of visible satellites	Panel	Probable error (m)								
			1 m			2 m			3 m		
			HPE	VPE	EPE	HPE	VPE	EPE	HPE	VPE	EPE
0000	10	-	2.60	3.60	4.47	2.60	3.60	4.47	2.60	3.60	4.47
	6	-	3.18	5.48	6.33	3.18	5.48	6.33	3.18	5.48	6.33
	6	Aluminium	5.31	8.91	10.38	4.21	6.62	7.84	3.66	5.96	6.99
	6	Glass	4.46	7.29	8.55	3.71	6.01	7.06	3.41	5.73	6.67
	6	PVC	3.91	6.25	7.37	4.08	6.41	7.60	3.24	5.48	6.37
	6	Wood	3.79	6.14	7.22	3.26	5.48	6.38	3.19	5.48	6.34
	6	Ceramic	4.33	6.81	8.07	3.69	6.02	7.06	3.32	5.57	6.48
0600	10	-	2.44	3.03	3.89	2.44	3.03	3.89	2.44	3.03	3.89
	6	-	3.58	4.27	5.57	3.58	4.27	5.57	3.58	4.27	5.57
	6	Aluminium	8.45	9.94	13.06	5.92	6.64	8.90	5.33	6.19	8.17
	6	Glass	7.03	8.07	10.71	5.48	6.31	8.36	5.24	5.98	7.95
	6	PVC	5.63	6.48	8.58	4.96	5.65	7.52	4.66	5.82	7.46
	6	Wood	4.05	4.84	6.31	3.68	4.28	5.64	3.66	4.28	5.63
	6	Ceramic	5.89	6.69	8.92	5.31	6.11	8.09	5.09	5.81	7.72
1200	8	-	2.83	4.16	5.03	2.83	4.16	5.03	2.83	4.16	5.03
	6	-	2.93	4.38	5.27	2.93	4.38	5.27	2.93	4.38	5.27
	6	Aluminium	6.04	8.16	10.15	4.39	5.97	7.41	3.35	5.2	6.19
	6	Glass	4.63	6.68	8.13	3.51	5.34	6.39	3.23	4.73	5.73
	6	PVC	3.75	5.77	6.88	3.17	4.72	5.69	3.02	4.45	5.38
	6	Wood	3.42	5.01	6.07	2.93	4.43	5.31	2.93	4.42	5.30
	6	Ceramic	4.28	5.94	7.32	3.38	5.04	6.07	3.04	4.50	5.43
1800	11	-	2.57	3.21	4.11	2.57	3.21	4.11	2.57	3.21	4.11
	6	-	2.93	4.36	5.25	2.93	4.36	5.25	2.93	4.36	5.25
	6	Aluminium	6.94	7.78	10.43	5.31	6.34	8.27	3.54	5.21	6.30
	6	Glass	5.08	6.67	8.38	4.67	5.66	7.34	3.3	4.87	5.88
	6	PVC	4.11	5.74	7.06	3.06	4.71	5.62	2.94	4.4	5.29
	6	Wood	3.42	5.24	6.26	2.94	4.42	5.31	2.93	4.39	5.28
	6	Ceramic	4.43	6.11	7.55	3.72	5.33	6.50	3.23	4.91	5.88


11,00
10,00
9,00
8,00
7,00
6,00
5,00
4,00
EPE (m)
0
2
4
6
8
10
12
14
Time (min)

(a)


15,00
13,00
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9,00
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EPE (m)
0
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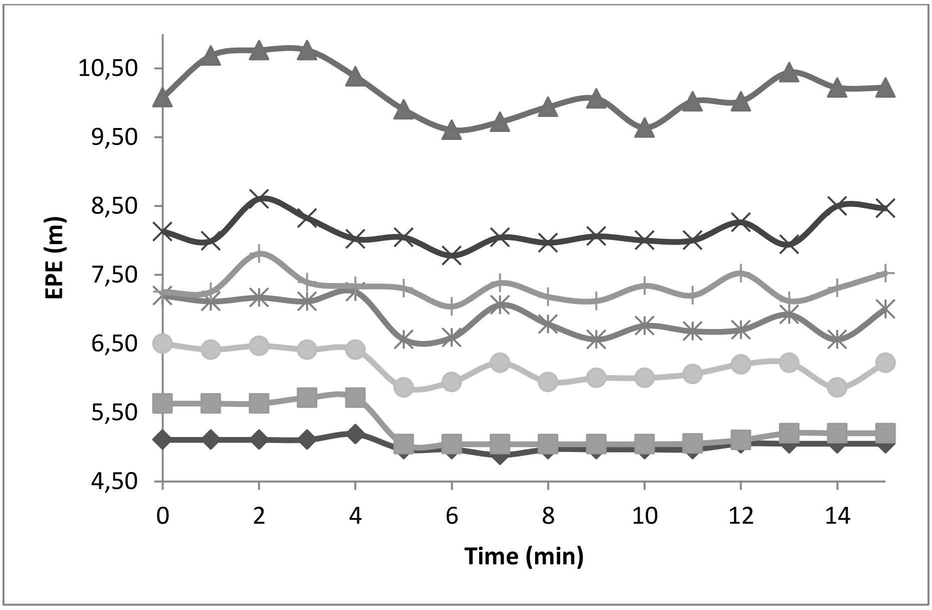
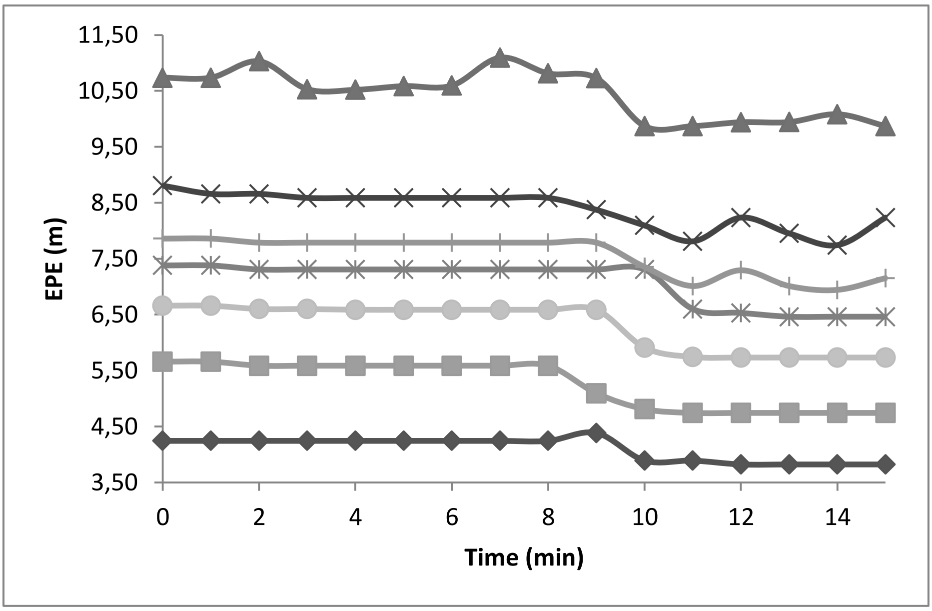
14
Time (min)

(b)

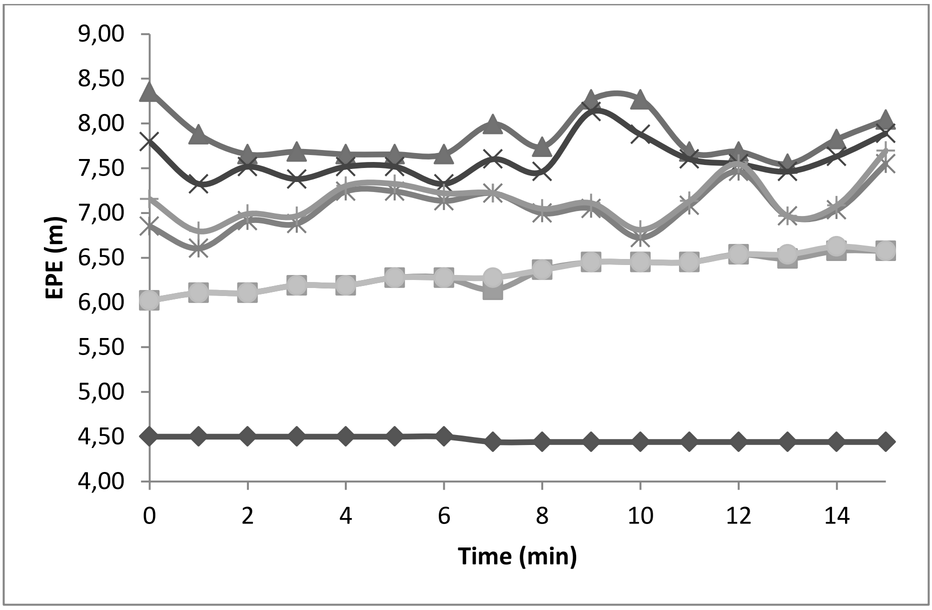


(c)



(d)

Fig. 3 Recorded EPE values for the panels placed at 1 m at UTC times of: (a) 0000, (b) 0600, (c) 1200, (d) 1800


9,00
8,50
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6,50
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EPE (m)
0
2
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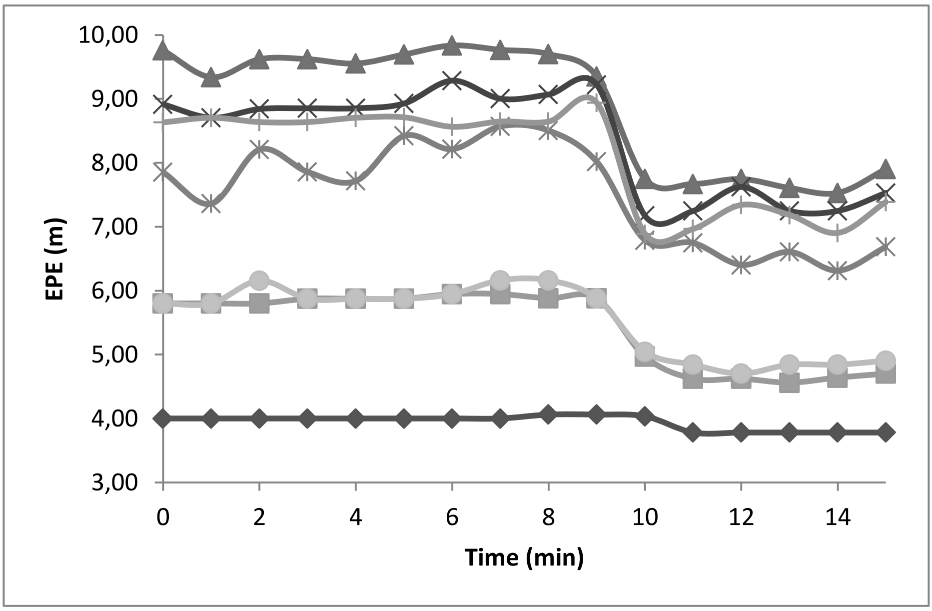
10
12
14
Time (min)

(a)


10,00
9,00
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7,00
6,00
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EPE (m)
0
2
4
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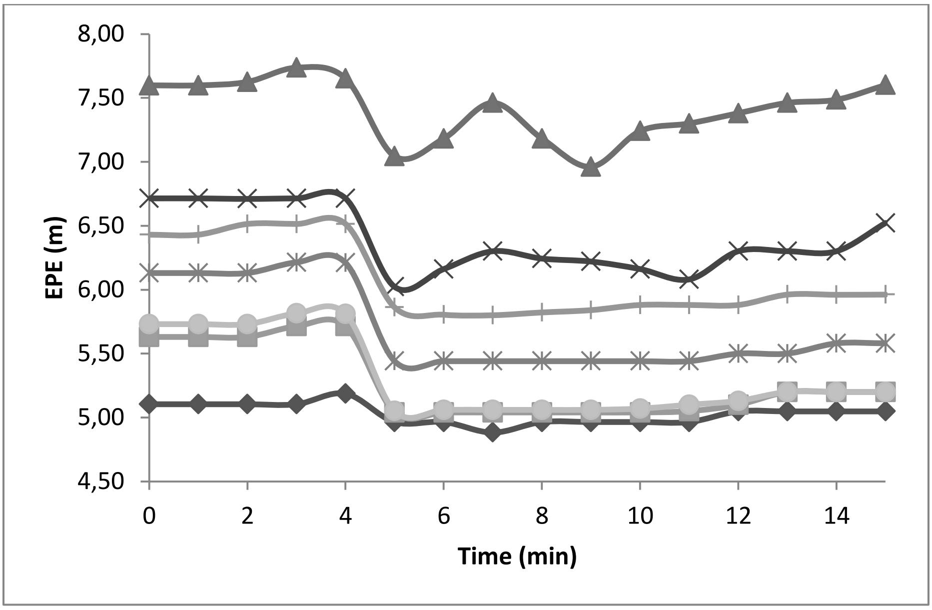
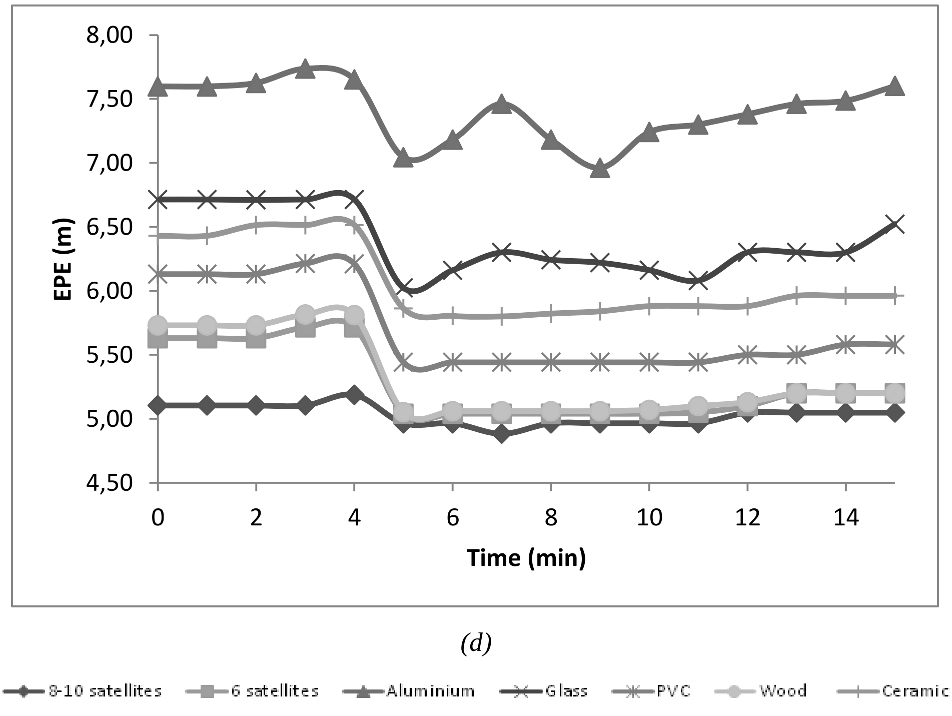
8
10
12
14
Time (min)

(b)

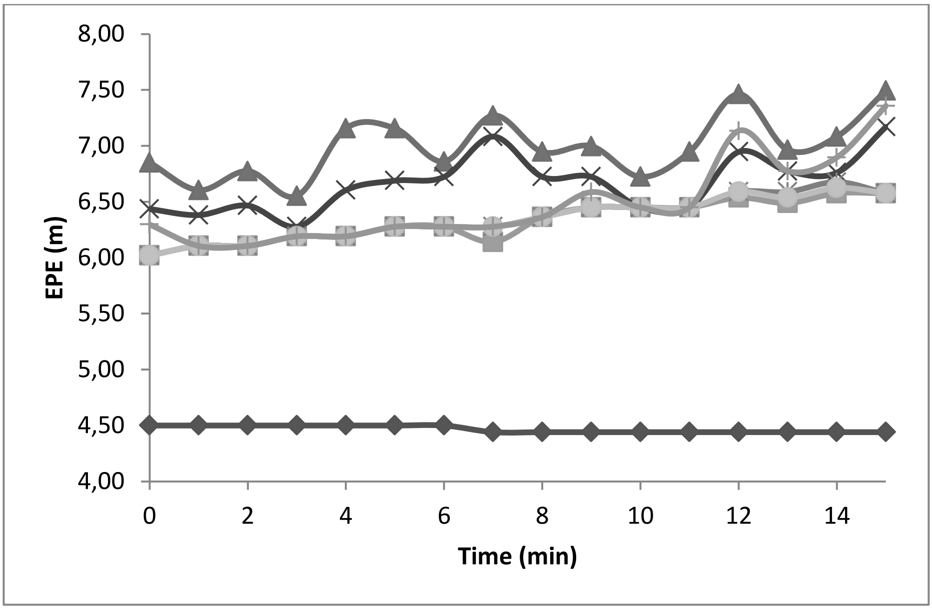


(c)

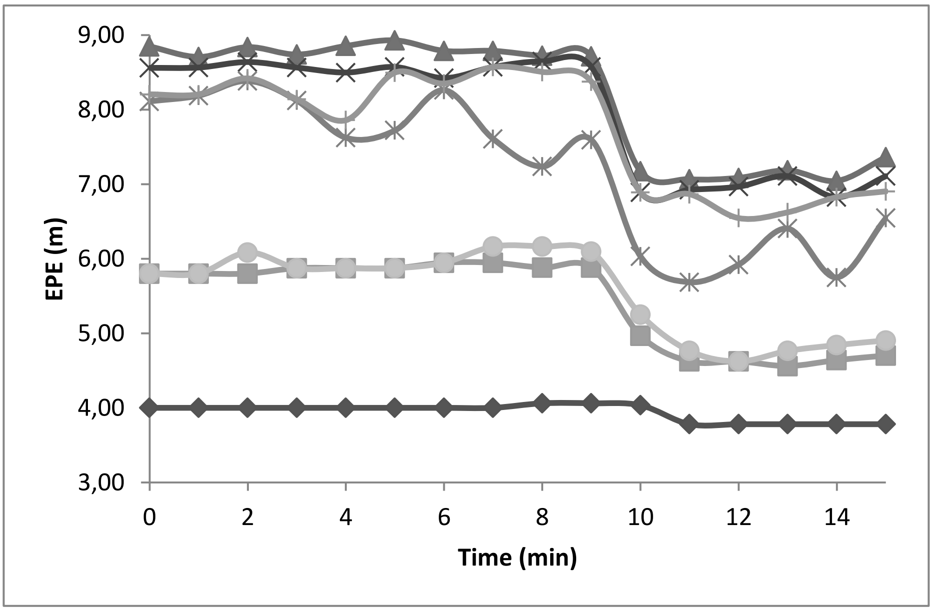


(d)

Fig. 4 Recorded EPE values for the panels placed at 2 m at UTC times of: (a) 0000, (b) 0600, (c) 1200, (d) 1800


8,00
7,50
7,00
6,50
6,00
5,50
5,00
4,50
4,00
EPE (m)
0
2
4
6
8
10
12
14
Time (min)

(a)


9,00
8,00
7,00
6,00
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EPE (m)
0
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8
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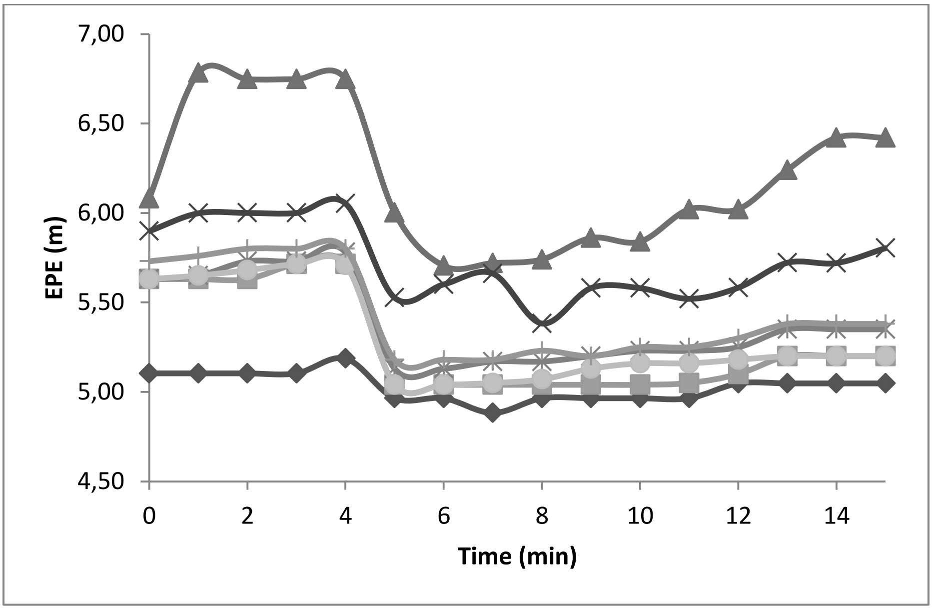
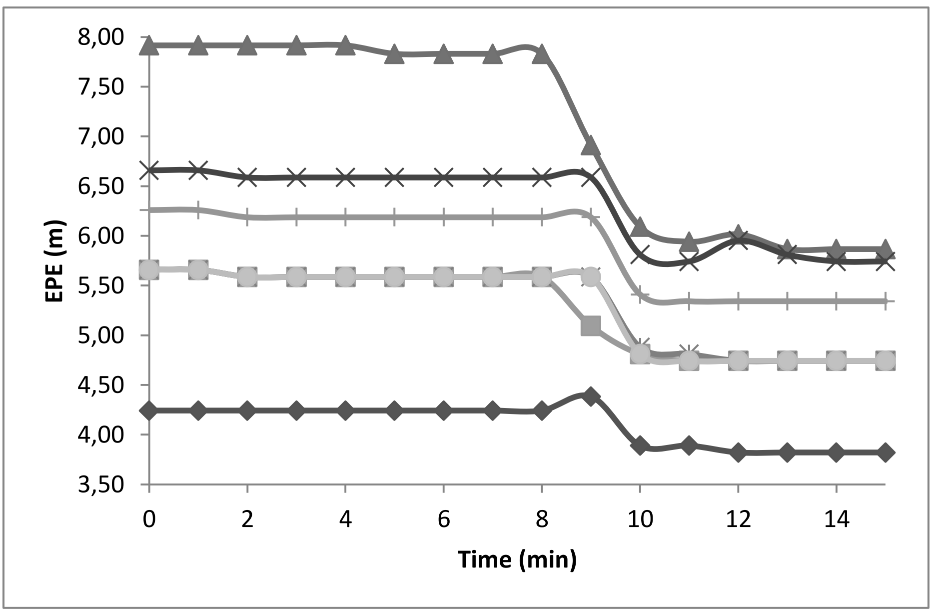
12
14
Time (min)

(b)



(c)



(d)

8-10 satellites — 6 satellites — Aluminium — Glass — PVC — Wood — Ceramic

Fig. 5 Recorded EPE values for the panels placed at 3 m at UTC times of: (a) 0000, (b) 0600, (c) 1200, (d) 1800

The multipath signals from the panels cause further increase in probable errors as the GPS receiver is tracking signals composed of the direct and multipath components. As the receiver cannot distinguish between the two components, it tracks composite signals, with the multipath component causing errors in pseudorange measurements. The probable errors decrease with increasing distances of the panels from the GPS receiver due to decrease of strength of multipath signals.

It is observed that aluminium causes the highest amount of multipath, resulting in the highest probable errors. This is followed by glass, ceramic, PVC and wood. These results are consistent with the findings obtained in Yi et al. [8]. Metal materials, such as, in the case of this study, aluminium, cause total reflection of GPS signals and hence, higher multipath. For non-metal materials, the multipath effect is dependent on the dielectric constant, which indicates the polarisation of the material. Materials with higher dielectric constants cause higher multipath, and vice-versa.

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 vertical (height) solution being less precise than the horizontal solution [1, 22, 23]. The reduction in number of visible satellites due to the introduction of physical obstructions causes increase in the differences between HPE and VPE values (Tab. 3), due to the removal of satellites above the horizon, while overhead satellites are maintained.

Varying probable error patterns are observed for each of the readings. This is due to the GPS satellite constellation being dynamic, causing changing GPS satellite geometry over time, resulting in GPS accuracy being time dependent [1, 22, 23]. Dinesh et al. [24] demonstrated that multipath is highly repeatable as it is approximately the same when the GPS satellites are in the same positions with respect to the earth at every two orbital passes (approximately 23 h 56 min). This repeatability can be used to build a history of multipath occurrences over time, which can then be used to generate multipath corrections for stationary sites.

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 C/N_0 levels and hence, higher rates of increase of probable error values.

4. Conclusion

Based on the results of this study, it was found that the multipath signals from the panels caused increase in probable error values, due to errors in the GPS receiver's pseudorange measurements. The probable errors decreased with increasing distances of the panels from the GPS receiver due to decrease of strength of the multipath signals. It is observed that aluminium caused the highest amount of multipath, resulting in the highest probable errors. This is followed by glass, ceramic, PVC and wood.

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Tab. 3 Differences between average recorded HPE and VPE values for the readings taken

UTC Time	Number of visible satellites	Panel	Difference between average HPE and VPE values (m)		
			1 m	2 m	3 m
0000	10	–	1.00	1.00	1.00
	6	–	2.30	2.30	2.30
	6	Aluminium	3.60	2.41	2.30
	6	Glass	2.83	2.30	2.32
	6	PVC	2.34	2.33	2.24
	6	Wood	2.35	2.22	2.29
	6	Ceramic	2.48	2.33	2.25
0600	10	–	0.59	0.59	0.59
	6	–	0.69	0.69	0.69
	6	Aluminium	1.49	0.72	0.86
	6	Glass	1.04	0.83	0.74
	6	PVC	0.85	0.69	1.16
	6	Wood	0.79	0.6	0.62
	6	Ceramic	0.80	0.8	0.72
1200	8	–	1.33	1.33	1.33
	6	–	1.45	1.45	1.45
	6	Aluminium	2.12	1.58	1.85
	6	Glass	2.05	1.83	1.5
	6	PVC	2.02	1.55	1.43
	6	Wood	1.59	1.5	1.49
	6	Ceramic	1.66	1.66	1.46
1800	11	–	0.64	0.64	0.64
	6	–	1.43	1.43	1.43
	6	Aluminium	0.84	1.03	1.67
	6	Glass	1.59	0.99	1.57
	6	PVC	1.63	1.65	1.46
	6	Wood	1.82	1.48	1.46
	6	Ceramic	1.68	1.61	1.68

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