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Positioning performance of SBAS and PPP technology from the Australia and New Zealand SBAS test-bed

Eldar Rubinov
FrontierSI
erubinov@frontiersi.com.au

Chris Marshall
FrontierSI
cmarshall@frontiersi.com.au

Lachlan Ng
FrontierSI
lng@frontiersi.com.au

Ahmad Ridhwanuddin Tengku
FrontierSI
atengku@frontiersi.com.au

ABSTRACT

This paper describes the positioning performance results from the Australia and New Zealand Satellite Based Augmentation System (SBAS) test-bed. The two year test-bed ran from January 2016 to January 2018 and transmitted three positioning services - L1 SBAS, Dual Frequency Multi Constellation (DFMC) SBAS and Precise Point Positioning (PPP). The L1 SBAS is a standard service that is available in other parts of the world and can be used with most commercially available GNSS receivers. DFMC on the other hand was not yet a published standard, which meant that it was not openly available and special hardware was needed to access it. The test-bed presented the world's first opportunity to test DFMC, which was expected to provide improvement over L1 SBAS in a number of areas.

A testing campaign was carried out on all three services using a variety of receivers and antennas from consumer-grade to geodetic in order to test a typical performance of each service in different environments. This paper describes the testing campaign in detail and presents the results obtained. It was found that in good testing environments, L1 SBAS and DFMC are capable of achieving sub-metre instantaneous positioning and PPP is capable of decimetre-level positioning after a period of convergence of 40-60 minutes. It was also found that the quality of positioning is highly dependent on the quality of the receiver and antenna hardware.

KEYWORDS: *SBAS, DFMC, PPP.*

1 INTRODUCTION

Satellite Based Augmentation System (SBAS) is a correction service that can improve standalone Global Navigation Satellite System (GNSS) positioning in a number of ways including accuracy, integrity and availability. The service works by computing corrections to the satellite orbits and clocks from a set of ground based reference stations, uploading the corrections to a geostationary satellite (GEO) via an uplink station, and disseminating the corrections to users (Enge et al., 1996). This process is shown graphically in Figure 1.

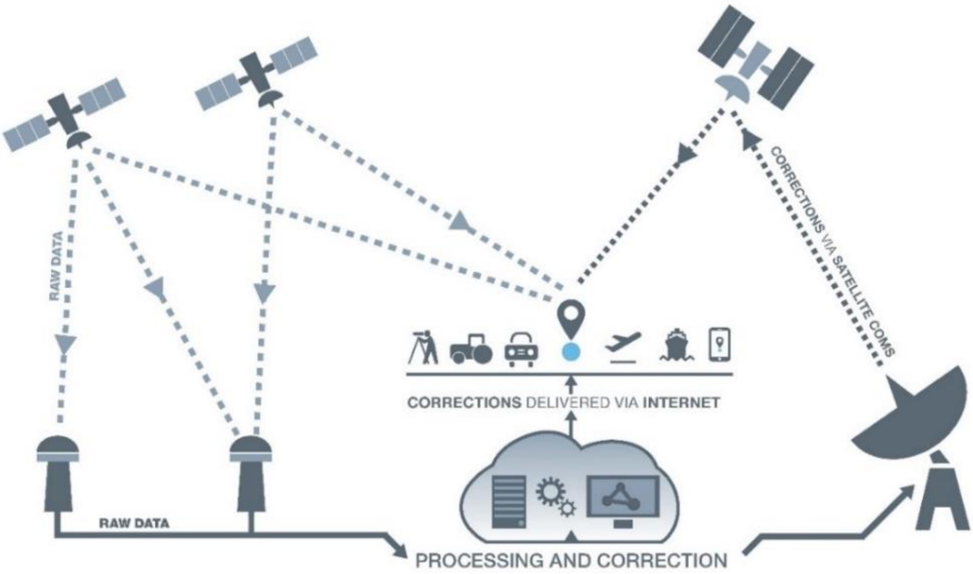

Figure 1: SBAS test-bed configuration (Dawson, 2018).

Originally designed to improve vertical guidance for safer aviation, SBAS has also been used for many non-aviation applications since its inception (Gakstatter, 2015). Currently SBAS is implemented in several regions around the world including Wide Area Augmentation System (WAAS) in North America, European Geostationary Navigation Overlay Service (EGNOS) in Europe, GPS-Aided GEO Augmented Navigation (GAGAN) in India and Multi-functional Satellite Augmentation System (MSAS) in Japan. A number of other countries and regions are also in various stages of developing their own SBAS services including Russia, China, South Korea, Nigeria and South America.

Between January 2017 and January 2019, the Australian and New Zealand (Aus-NZ) governments ran a two year test-bed to examine the benefits of SBAS technology to the region. The SBAS signals were transmitted using PRN122 from the Inmarsat 4F1 satellite positioned at 143.5º East in a geostationary orbit. Lockheed Martin uplink station at Uralla, NSW was used to uplink the SBAS messages to the satellite. GMV provided the server infrastructure to compute the SBAS corrections (Barrios et al., 2017; Barrios et al., 2018). Throughout the course of the test-bed, three different signals were evaluated:

- **L1 SBAS:** L1 SBAS signal is the single frequency service broadcast across other regions of the world by existing systems such as WAAS, EGNOS, MSAS and GAGAN. This signal provides sub-metre horizontal accuracy in real-time.

- **Dual Frequency Multi-Constellation (DFMC):** DFMC SBAS is the second generation SBAS technology where two different frequencies and two (or more) constellations are used. In the case of the Aus-NZ test-bed, L1/L2 GPS and E1/E5a Galileo signals were used to make use of all available satellites. This signal also provides sub-metre horizontal accuracy in real-time.

- **Precise Point Positioning (PPP):** the PPP signal provides users with decimetre-level horizontal accuracy after a period of solution convergence, which is typically 40-60 minutes. In the Aus-NZ test-bed the PPP corrections were transmitted within the L1 SBAS and DFMC messages.

The L1 SBAS signal was first broadcast in June 2017, followed by DFMC and PPP from October 2017 through to January 2019. After the completion of the test-bed all three signals remained active with a view to extend the test-bed service until the ground infrastructure for a fully operational safety-of-life SBAS is constructed.

The signals were available via a satellite broadcast from the Inmarsat 4F1 geostationary satellite as well as through the internet via a standard protocols such as SISNeT (Signal in Space through the Internet) and RTCM (Radio Technical Commission for Maritime Services). In case of RTCM, only the PPP service was available. While, SBAS is based primarily on a space-based communications link, the added internet capability was useful to test various parameters such as the effect of latency on the final positioning accuracy.

FrontierSI was responsible for coordinating 27 projects across 10 different industry sectors testing SBAS technology (Mitchell et al., 2019) as well as overseeing an economic benefits study of the value that the technology would bring to the economies of both countries (EY, 2019). Apart from these various projects, FrontierSI also carried out a testing campaign to evaluate the performance of the various commercially available consumer and mid-range GNSS receivers that would be typically used with SBAS service. This paper details the results of FrontierSI's testing.

2 OVERVIEW OF THE SBAS TEST-BED POSITIONING SERVICES

This section describes the three test-bed signals including signal standards, coverage area, compatible equipment and more.

2.1 Single Frequency L1 SBAS

L1 SBAS signal is the single frequency service currently available in other regions of the world based on the Radio Technical Commission for Aeronautics (RTCA) DO-229D Minimum Operational Performance Standards (MOPS) for Global Positioning System Airborne Equipment (RTCA, 2006). This signal provides sub-metre horizontal positioning in real-time and is available on virtually all GNSS-capable devices, from consumer to professional. The signal is transmitted over the region covering Australia and New Zealand (see Figure 2).

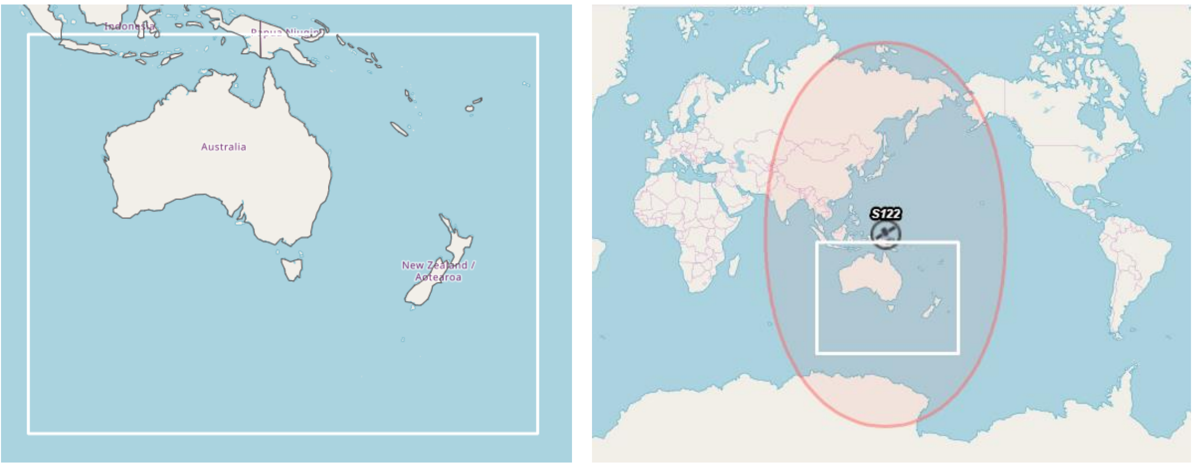

Figure 2: L1 SBAS (left) and DFMC (right) coverage areas.

2.2 Dual Frequency Multi Constellation SBAS

DFMC is a second generation SBAS service which uses dual frequency observations and the ionospheric-free pseudorange and carrier phase linear combination, which effectively removes the effects of the ionosphere on the solution. At the start of the SBAS test-bed in January 2017, the MOPS for DFMC were not finalised and hence the service was based on the latest draft at the time, which was WG62 GAL GPS SBAS MOPS v0.3.8_10 (DFMC, 2017). The future DFMC standard assumes GPS L1/L5 and Galileo E1/E5$_a$, however due to the fact that there were only 12 GPS and 14 Galileo satellites broadcasting on the L5 and E5$_a$ frequencies at the start of the test-bed, it was decided to use GPS L1/L2P GPS and Galileo E1/E5$_a$ to make use of all available GPS and Galileo satellites. DFMC was transmitted from June 2017. The GPS signals were changed to L1/L5 at the completion of the test-bed in March 2019. The service coverage area for DFMC corresponds to the footprint of the Inmarsat 4F1 satellite and is shown in Figure 2.

At the start of the test-bed there were no commercial off-the-shelf (COTS) receivers that could decode the DFMC messages. To counter that, a special equipment configuration was used, which included a dual-frequency GNSS receiver and an RF front-end connected to a GNSS antenna through a signal splitter, as well as a tablet to combine both GNSS and SBAS measurements and compute positions. Half-way through the test-bed, GMV produced a handheld receiver called magicUT that was able to decode and provide positioning services using all three test-bed signals. Figure 3 shows the original equipment configuration and the new magicUT receiver.

Figure 3: Original SBAS equipment configuration (left) and magicUT receiver (right).

Aus-NZ test-bed was one of the first places in the world to test the DFMC service along with Japan who also carried out various tests of the service around the same time (Kitamura et al., 2018; Kitamura and Sakai, 2019).

2.1 Precise Point Positioning

The PPP is a high-precision positioning technique which uses dual-frequency phase and code observations to compute centimetre to decimetre level positioning using precise orbits and clock information. In the Aus-NZ test-bed the PPP messages were transmitted within the L1

SBAS and DFMC messages in effect providing a combined SBAS and PPP solution and it was up to the user to extract the relevant messages based on the application. This combined approach has an advantage in a sense that no separate channel is necessary to transmit PPP data, however the disadvantage is that there is a limit on the amount of information that could be transmitted, which directly relates to the number of spare bits in the SBAS messages. This also has an impact on the accuracy of the resultant PPP solution, which is typically 5-20cm in each direction (Mezzera et al., 2018).

The PPP messages were transmitted in a proprietary GMV format, which meant that the same equipment constraints for DFMC were also true for PPP. Additionally, PPP was also transmitted in RTCM format, but this was only available via the internet.

3 GNSS RECEIVER AND ANTENNA HARDWARE

GNSS receiver and antenna hardware varies significantly depending on the application. For the purpose of the testing, equipment was subdivided into three categories which were consumer-grade, mid-range and professional. Table 1 shows these three categories including approximate price range and applications where these devices are often used.

Table 1: Equipment classifications.

Equipment	**Description**
Consumer	< $100 - consumer applications, mobile phones, IoT, trackers, etc.
Mid-range	$100-$3,000 - GIS, mapping, automotive, forestry, robotics, etc.
Professional	> $3,000 - geodesy, surveying, scientific applications

A number of receivers and antennas were used in the testing described in this report and these are introduced below. Three consumer-grade receivers were used including Quectel L76-L, SkyTraq V838 and U-blox M8N. These are shown in Figure 4.

Quectel L76-L SkyTraq V838 U-blox M8N

Figure 4: Consumer receivers used for testing.

Three mid-range receivers were used in the testing, including EoS Arrow Gold, Juniper Systems Geode and GMV magicUT. The magicUT receiver is a prototype receiver developed by GMV especially for the Aus-NZ SBAS test-bed, whilst the other two are COTS receivers targeted at the mid-range mapping market. These receivers can only track the SBAS L1 signal, whereas the magicUT receiver can track and decode all three test-bed services – L1 SBAS, DFMC and PPP.

A single professional (geodetic) receiver was used during the testing which was Septentrio AsteRx-U. The mid-range and professional receivers are shown in Figure 5.

EOS Arrow Gold Juniper Systems Geode GMV MagicUT Septentrio AsteRx-U

Figure 5: Mid-range and professional receivers used for testing.

Antennas also play a key role in tracking and decoding the various satellite navigation signals. Antennas can be subdivided into similar categories to match the receiver categories. Small patch antennas are typically used with consumer-grade devices, compact geodetic antennas are typically used with mid-range devices and professional geodetic antennas are used with geodetic receivers. Four different antennas were used during the testing including a consumer-grade patch antenna, mid-range Tallysman TW7972, and geodetic-grade Topcon G3-1A and Tallysman VP6000. These are shown Figure 6.

Patch Antenna Tallysman TW7972 Topcon G3-A1 Tallysman VP6000

Figure 6: Antennas used for testing.

4 TESTING METHODOLOGY

The testing described in this paper was part of a larger testing campaign carried out by FrontierSI, which included static tests, kinematic (driving) tests as well as forestry tests under dense canopy. Due to size restrictions only the static testing results are included in this publication. Four static tests were carried out as part of the testing campaign each focussing on a different aspect of the SBAS test-bed. These tests are described in this section.

The first test consisted of testing performance of the consumer and mid-range receivers with L1 SBAS service. Static tests were conducted on a surveyed control point in an open-sky environment. In each case, three receivers were connected to the Topcon G3-1A antenna through a signal splitter and three 24-hour datasets were collected on each receiver. The resulted coordinates were compared to the truth in terms of accuracy and precision.

In the second test the impact of an antenna and a ground plane (GP) on L1 SBAS positioning performance of a consumer-grade and a geodetic receiver were examined. A Septentrio AsteRx-U and U-blox M8N receivers were connected to a single antenna via a signal splitter and five different antenna combinations were tested, including a patch, patch with GP, Tallysman TW7972, Tallysman TW7972 with GP and a Topcon G3-1A. Due to a large number of antenna combinations the tests were limited to 4 hours.

The third test looked at comparing the performance of L1 SBAS and DFMC services using the same hardware. Two magicUT receivers were connected to a Tallysman VP6000 antenna via a signal splitter, one configured to receive L1 SBAS and the other DFMC signal corrections. Three 24-hour datasets were collected and performance analysed.

The fourth test looked at the performance of PPP using all three communication methods – GEO broadcast, SISNT and RTCM. SISNeT provides the same message as one received from the GEO, the only difference is that it is received via the internet, so the latency with which the messages are received would be different. RTCM on the other hand provides a different set of messages based on the RTCM standard. In this test, three magicUT receivers were connected to a Tallysman VP6000 antenna through a signal splitter each connected to a PPP service. Three datasets were collected, and the performance was measured, not only in terms of accuracy and precision, but also in terms of convergence time. The position deemed to be converged when the horizontal error was less than 0.1m and vertical error less than 0.3m for a period of at least 10 minutes.

5 RESULTS

The results of all four tests are presented in this section. The results are presented in terms of mean, standard deviation and root mean square (RMS) error. RMS is a useful quantity that gives a combined measure of the positioning performance, whereas mean and standard deviation can help to isolate whether the cause of the error is due to a system bias or random noise.

5.1 Test 1 – Static test of consumer and mid-range equipment

The positioning errors for consumer-grade and mid-range receivers from all three 24-hour sessions are presented in Tables 2 and 3. The results are also presented graphically in Figures 7 to 10. As the results were similar from day-to-day, only a single 24-hour session is presented.

Table 2: Positioning errors for consumer-grade receivers.

Receiver	Horizontal Error (m)			Vertical Error (m)		
	Mean	St Dev	RMS	Mean	St Dev	RMS
Quectel	0.54	2.05	2.13	-2.42	3.31	4.11
SkyTraq	0.49	0.62	0.80	0.47	1.40	1.50
U-blox	0.22	1.09	1.12	0.32	1.71	1.74

Table 3: Positioning errors for mid-range receivers.

Receiver	Horizontal Error (m)			Vertical Error (m)		
	Mean	St Dev	RMS	Mean	St Dev	RMS
Arrow Gold	0.23	0.37	0.44	0.21	0.43	0.49
Geode	0.24	0.41	0.47	0.48	0.56	0.74
magicUT	0.15	0.47	0.49	0.04	0.72	0.73

Quectel and SkyTraq devices failed to provide an epoch-by-epoch output in static mode. This is potentially due to the fact that these consumer-grade devices are designed for kinematic applications and if the position of the antenna does not change, it simply uses the previously recorded position. In SkyTraq's example, the receiver would keep the same position for 30-60 seconds before providing a new coordinate.

The results provide an interesting insight into the performance of the various receivers. Quectel has provided the worst positioning performance with a horizontal RMS of ~2.1m. From Figure 7 it can also be seen that the resolution of the coordinate output was limited, which made the positioning output to appear in a gridded pattern. SkyTraq provided the best results with an RMS of ~0.8m followed by U-blox with ~1.1m, although SkyTraq failed to provide an independent epoch-by-epoch output in static mode.

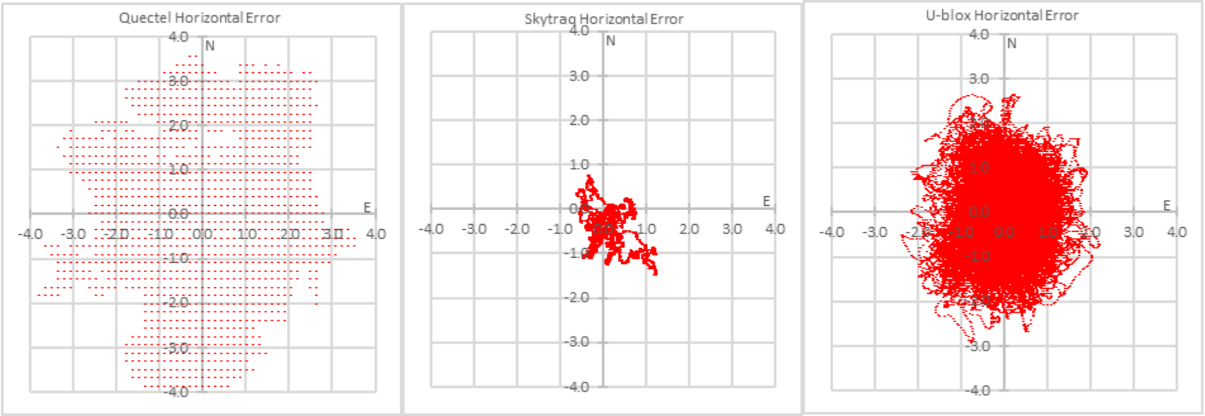

Figure 7: Horizontal errors for consumer-grade receivers.

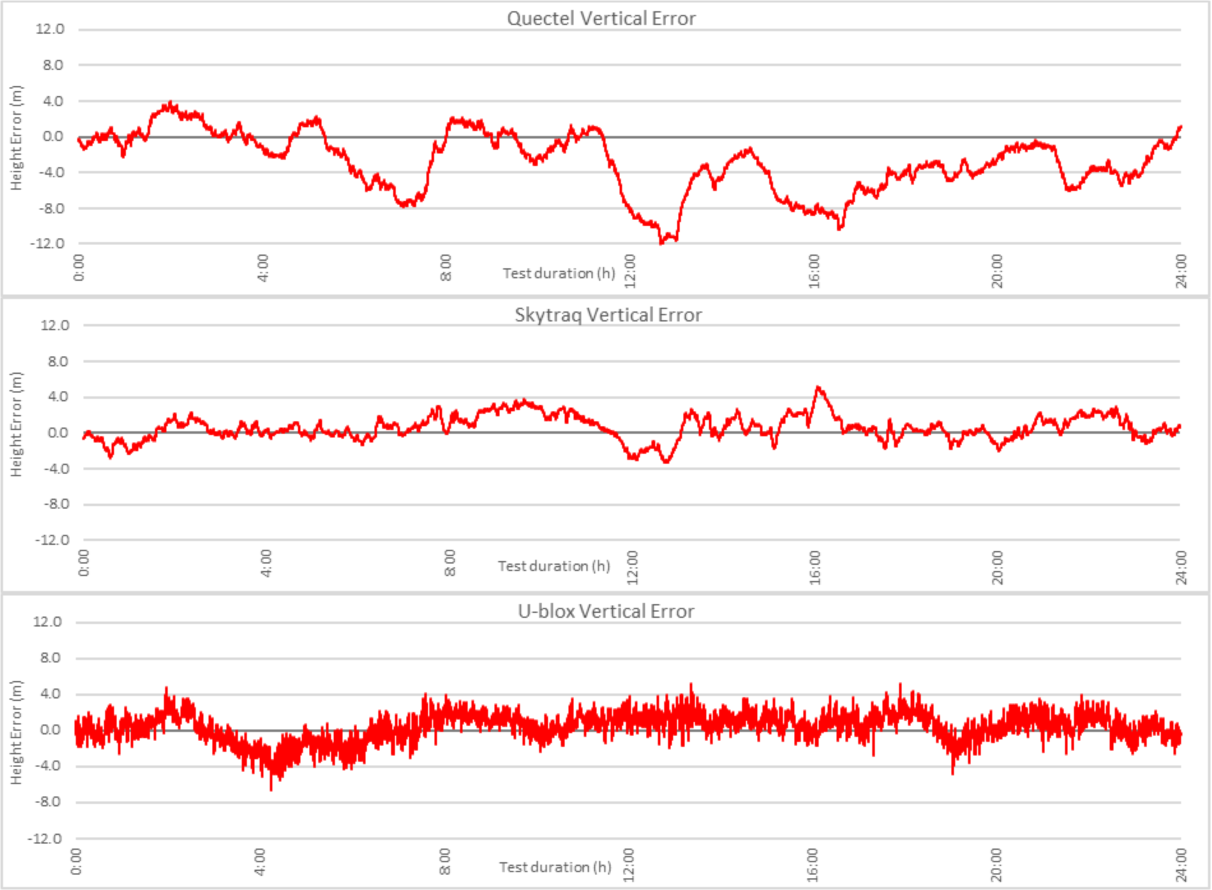

Figure 8: Vertical errors for consumer-grade receivers.

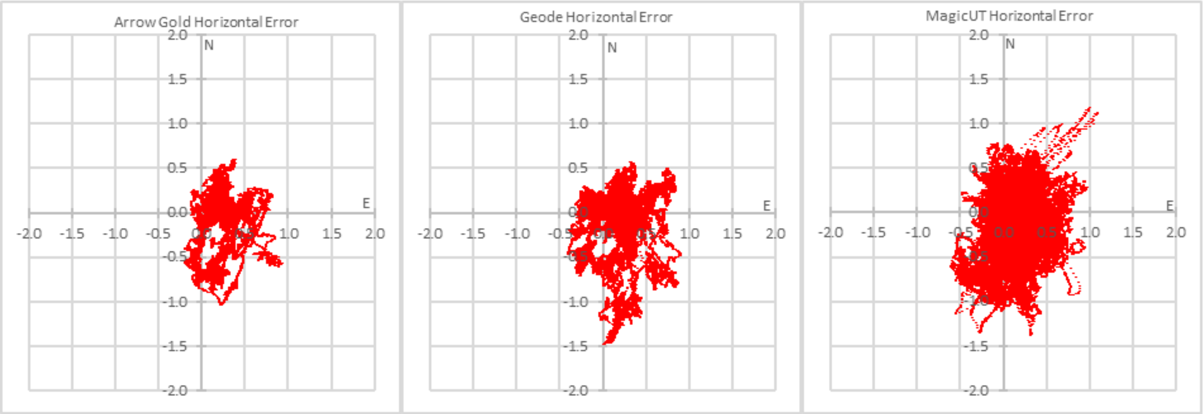

Figure 9: Horizontal errors for mid-range receivers.

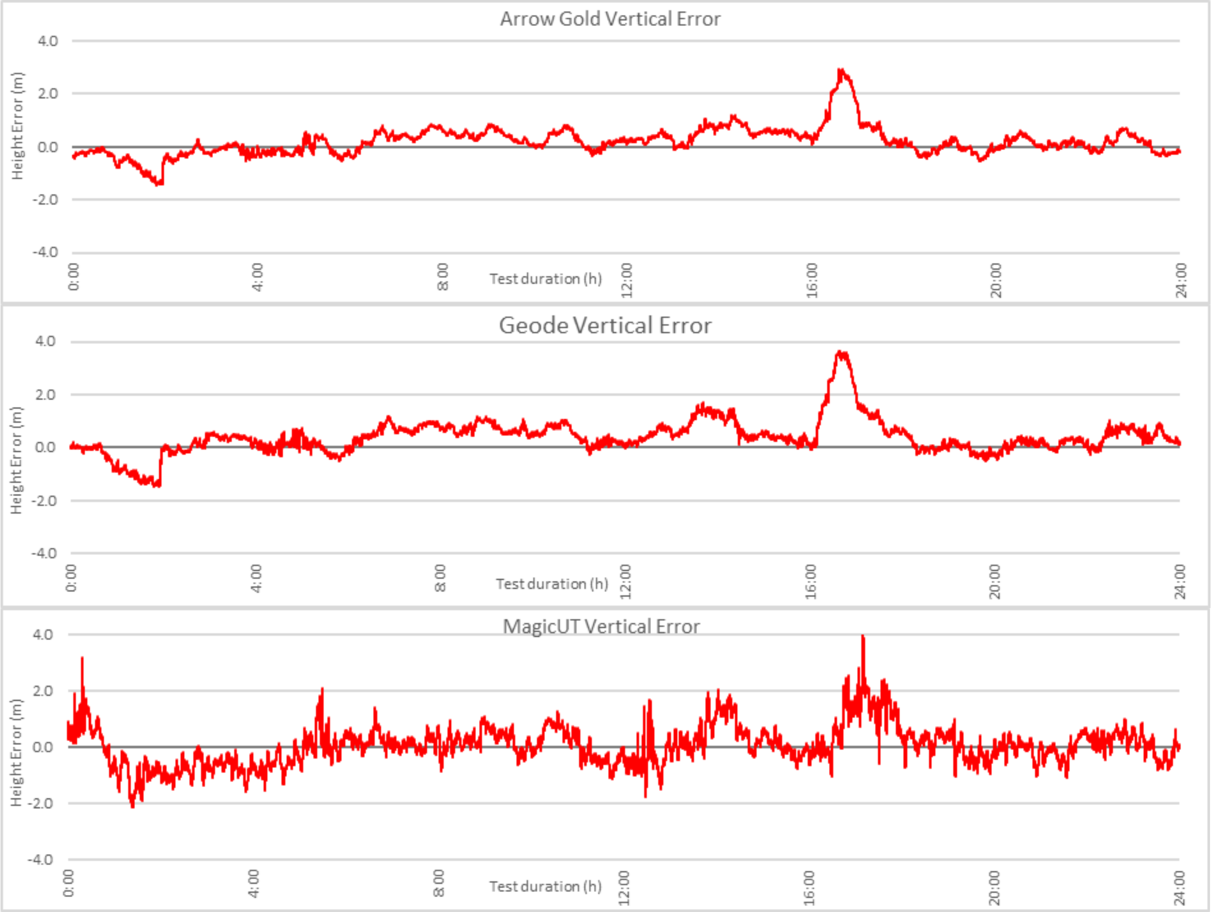

Figure 10: Vertical errors for mid-range receivers.

Mid-range receivers provided a much better performance compared to the consumer-grade receivers with all three receivers providing sub 0.5m horizontally and sub-metre vertically. Interestingly both Geode and Arrow Gold provided similar vertical positioning pattern to each other (Figure 8), potentially due to the fact that both receivers are based on a Hemisphere GNSS board.

Test 2 – Antenna static test

Tables 4 and 5 and Figures 11 and 12 provide positioning results for Septentrio and U-blox receivers with different antennas. The purpose of the test was to examine what impact the various antennas have on consumer-grade and geodetic receivers, and whether a ground plane can help improve the positioning performance.

Table 4: Antenna testing results with Septentrio receiver.

Antenna Setup	Septentrio Horizontal Error (m)			Septentrio Vertical Error (m)		
	Mean	**St Dev**	**RMS**	**Mean**	**St Dev**	**RMS**
Topcon G3-A1	0.22	0.27	0.35	0.48	0.27	0.53
TW7972 with GP	0.37	0.33	0.50	0.99	0.26	1.02
TW7972	0.86	0.39	0.95	0.21	0.75	0.77
Patch with GP	0.37	0.45	0.58	1.53	0.43	1.59
Patch	0.99	0.47	1.09	0.81	0.87	1.18

Table 5: Antenna testing results with U-blox receiver.

Antenna Setup	U-blox Horizontal Error (m)			U-blox Vertical Error (m)		
	Mean	**St Dev**	**RMS**	**Mean**	**St Dev**	**RMS**
Topcon G3-A1	0.21	0.72	0.75	0.45	1.18	1.26
TW7972 with GP	0.11	0.99	1.00	1.89	1.67	2.52
TW7972	0.79	0.84	1.15	0.97	1.53	1.81
Patch with GP	0.25	1.42	1.44	1.90	1.70	2.55
Patch	0.47	1.24	1.33	1.96	2.48	3.16

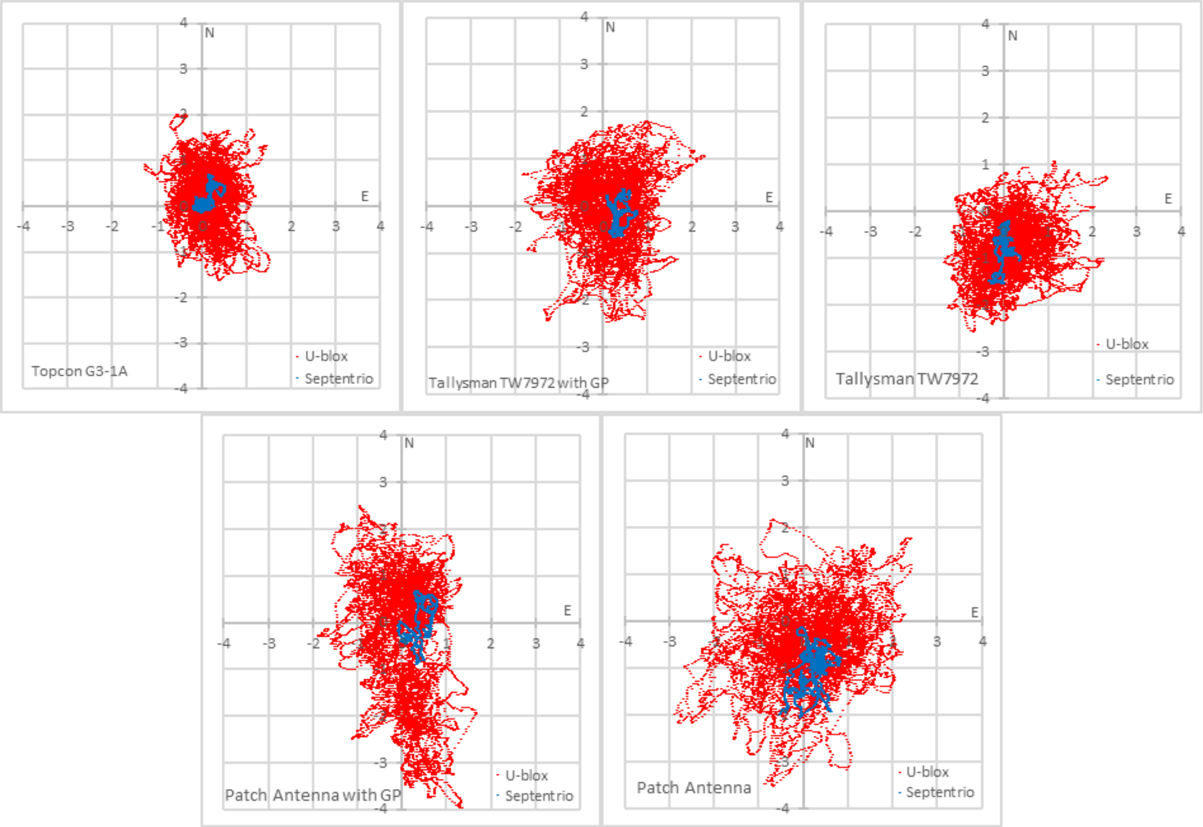

Figure 11: Horizontal positioning with different antennas.

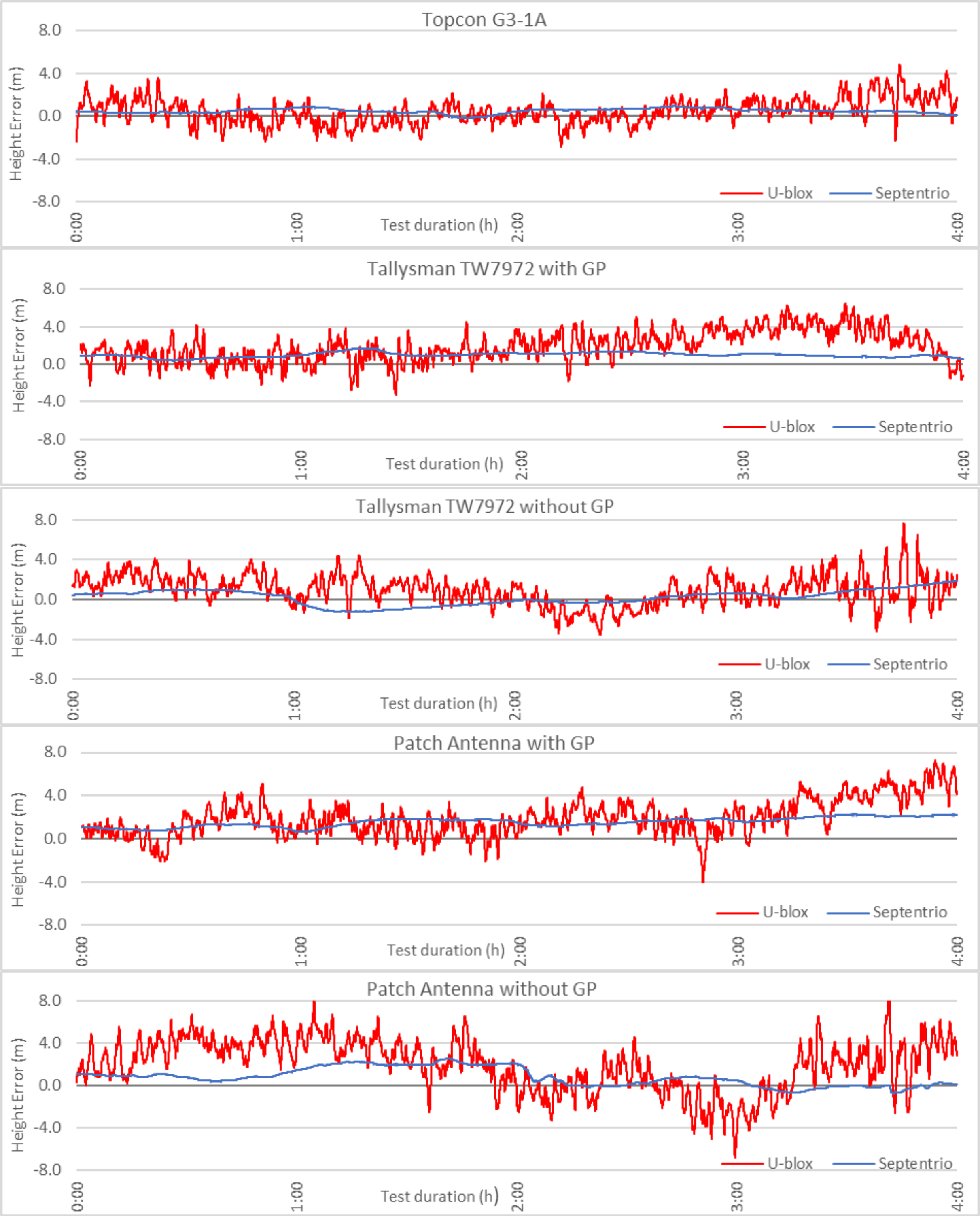

Figure 12: Vertical positioning with different antennas.

From the results above it is clear that the quality of antenna has a significant impact on positioning. In both Septentrio and U-blox receivers the resultant positioning quality has decreased gradually from a geodetic antenna to a patch antenna. In Septentrio receiver the horizontal RMS degraded from 0.35m to 1.09m and in U-blox receiver from 0.75 to 1.44m.

However, the patterns were different for each receiver. With the Septentrio receiver, both the Tallysman TW7972 and patch antenna with ground planes provided very similar results (0.50m and 0.58m RMS), and when the ground plane was removed the error for both has doubled (0.95m and 1.09m RMS). In the U-blox receiver, this was not the case. Both TW7972 and patch antennas provided similar results with and without ground planes.

The vertical results showed more variation as expected and in general it highlighted the fact that a four hour dataset is not sufficient to provide conclusive results. Longer data series are needed to provide a clearer picture on the antenna behaviour.

Test 3 – Static test of L1 SBAS vs DFMC

Table 6 and Figures 13 and 14 show the results of SBAS L1 and DFMC testing. From the results it can be seen that DFMC has provided a much tighter solution horizontally with the RMS of 0.38m compared to 0.70m from the L1 SBAS service. Furthermore, the improvement was mainly in the mean, whereas the standard deviation was similar for both. This shows that the use of ionospheric-free linear combination is effective in reducing the bias of the mean on the resultant solution. Vertically both services provided RMS of 0.83m, however Figure 14 shows that the DFMC solution was less noisy, which is also highlighted by smaller standard deviation even though the mean was further from zero.

Table 6: Mid-range receiver L1 SBAS vs DFMC static results.

SBAS Service	**Horizontal Error (m)**			**Vertical Error (m)**		
	Mean	**St Dev**	**RMS**	**Mean**	**St Dev**	**RMS**
SBAS L1	0.50	0.50	0.70	-0.31	0.77	0.83
DFMC	0.07	0.38	0.38	-0.66	0.51	0.83

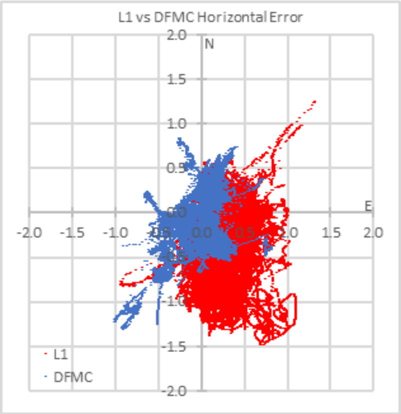

Figure 13: L1 SBAS vs DFMC horizontal results.

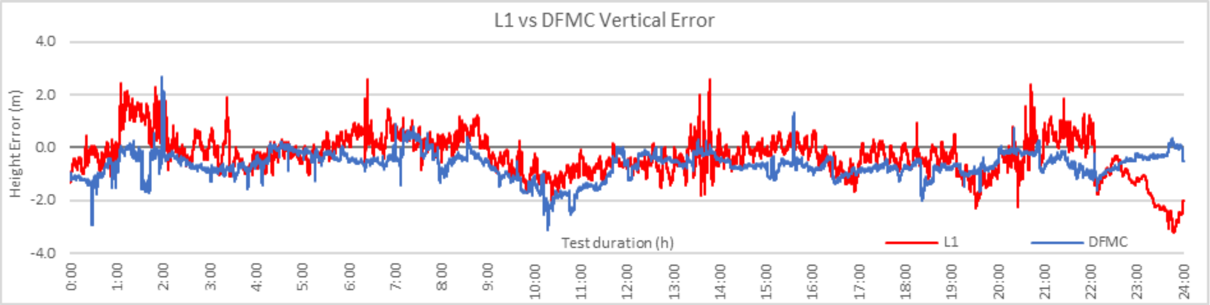

Figure 14: L1 SBAS vs DFMC vertical results.

Test 4 – Static PPP results

In this test the different service delivery mechanisms – GEO, SISNeT and RTCM, were examined on their effect on the resulting positioning performance of a PPP solution. Apart from the accuracy statistics, convergence time was also measured. Table 7 shows the statistics for PPP testing, and Figures 15 and 16 show the plots of horizontal and vertical positioning. The horizontal position graphs show the positions after convergence.

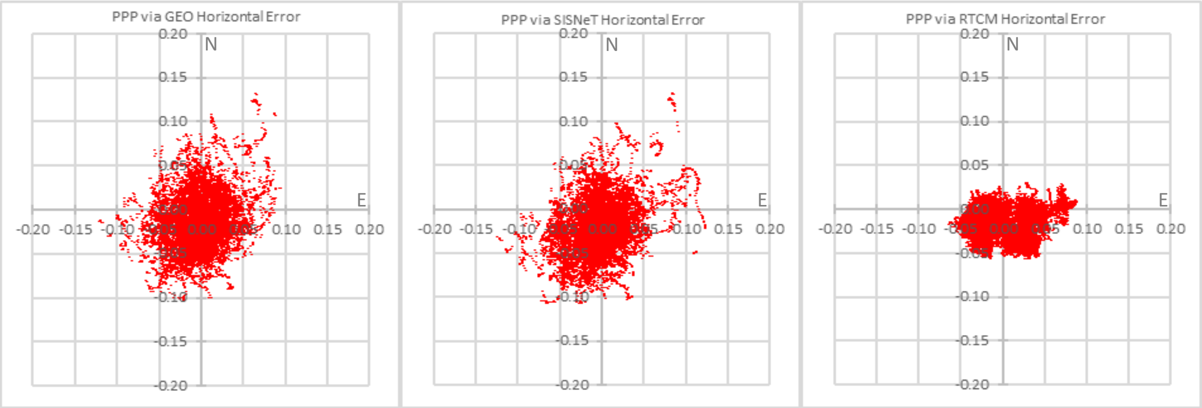

Figure 15: PPP horizontal errors from GEO (right), SISNeT (centre) and RTCM (right).

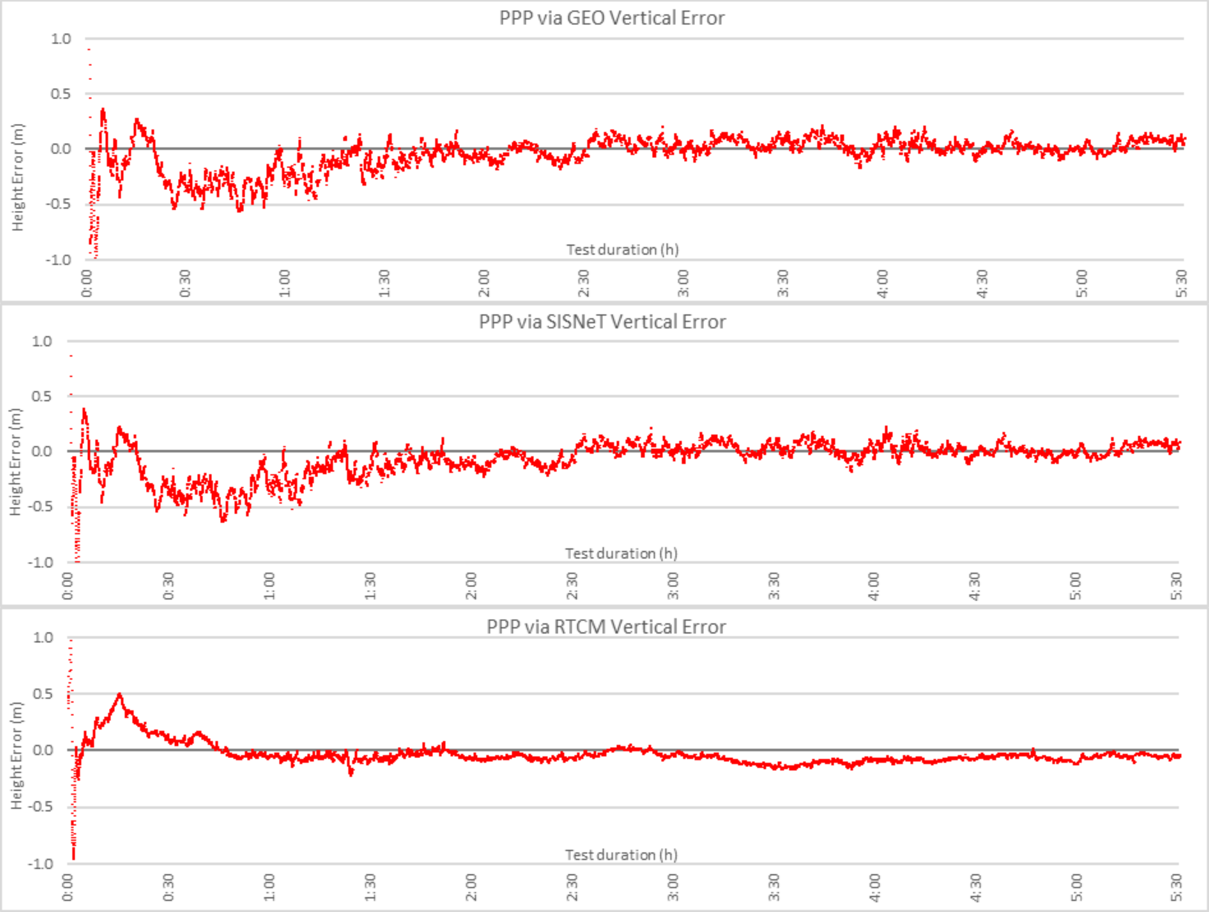

Figure 16: PPP vertical errors from GEO (top), SISNeT (centre) and RTCM (bottom).

Table 7: PPP testing results.

PPP Service	Horizontal Difference (m)			Vertical Difference (m)			Convergence Time (min)
	Mean	St Dev	RMS	Mean	St Dev	RMS	
PPP via GEO	0.015	0.038	0.041	0.022	0.071	0.074	72
PPP via SISNeT	0.020	0.042	0.047	-0.003	0.085	0.086	83
PPP via RTCM	0.016	0.033	0.037	-0.051	0.051	0.072	29

From Table 7 it follows that all three solutions have provided similar results at ~4cm horizontal and 7-8cm vertical RMS figures. The big difference was in convergence time where the RTCM method was a clear winner with 29 minutes compared to 72 and 83 minutes of GEO and SISNeT. This was the expected result, as RTCM provides a much more complete set of messages compared to the other two methods. Figure 15 also shows that horizontally the RTCM solution is less noisy compared to both GEO and SISNeT solutions.

6 CONCLUDING REMARKS

This paper presented results from the Aus-NZ SBAS test-bed which ran from January 2016 to January 2018. Three separate services were evaluated in the testing, which were L1 SBAS, DFMC and PPP. It was shown that both L1 SBAS and DFMC are capable of providing sub-metre instantaneous horizontal positioning and PPP is capable of providing decimetre-level horizontal positioning after a convergence period of 40-60 minutes. It was also shown that the quality of positioning is highly dependent on the quality of the receiver and antenna hardware.

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