SBAS TEST-BED DEMONSTRATION PROJECT

PROJECT SUMMARY AND TECHNICAL RESULTS

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1. Introduction

1.1. Project Objectives

In 2017, the Cooperative Research Centre for Spatial Information (CRCSI) (now FrontierSI) was contracted by Geoscience Australia (GA) and Land Information New Zealand (LINZ) to run a Satellite Based Augmentation System (SBAS) test-bed with two main objectives:

- to coordinate and undertake user testing of SBAS in Australia and New Zealand in selected industry sectors, and
- to conduct an economic benefit study of the SBAS technology.

This report details the projects selected and focusses on the work carried out and resultant technical results. This report also details the technical testing separately carried out by FrontierSI staff on various types of GNSS equipment in different environments. The economic benefit study was conducted by Ernst and Young (EY) in conjunction with FrontierSI and is detailed in a separate report (EY, 2019).

1.2. Project Background

In late 2016, GA was awarded $12 million in funding to implement a test-bed to evaluate SBAS technology, including two new signals. In early 2017, New Zealand formally joined the trial, contributing an additional $2 million, with LINZ representing the various NZ government departments.

Throughout the course of the test-bed, three different signals were tested across the Australian and New Zealand region:

- SBAS Legacy L1: the SBAS L1 signal is the single frequency service broadcast across other regions of the world by existing systems such as Europe's European Geostationary Navigation Overlay Service (EGNOS) and USA's Wide Area Augmentation System (WAAS). Figure 1 demonstrates current SBAS L1 capability and system development world-wide. This signal provides sub-metre horizontal accuracy in real-time.
- SBAS Dual Frequency Multi-Constellation (DFMC): DFMC SBAS is the second generation SBAS technology where two different frequencies and two or more GNSS constellations are used. In the case of the Australia and New Zealand 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. This signal was broadcast for the first time on the SBAS testbed.
- Precise Point Positioning (PPP): the PPP signal provides users with decimetre-level horizontal accuracy in near real-time in clear sky conditions after an initial period of convergence, which is typically 30-40 minutes.

For the Aus-NZ SBAS testbed, the SBAS L1 signal was first broadcast in June 2017, followed by DFMC SBAS and PPP being broadcast from October 2017 through to July 2019. The area covered is shown in Figure 1.

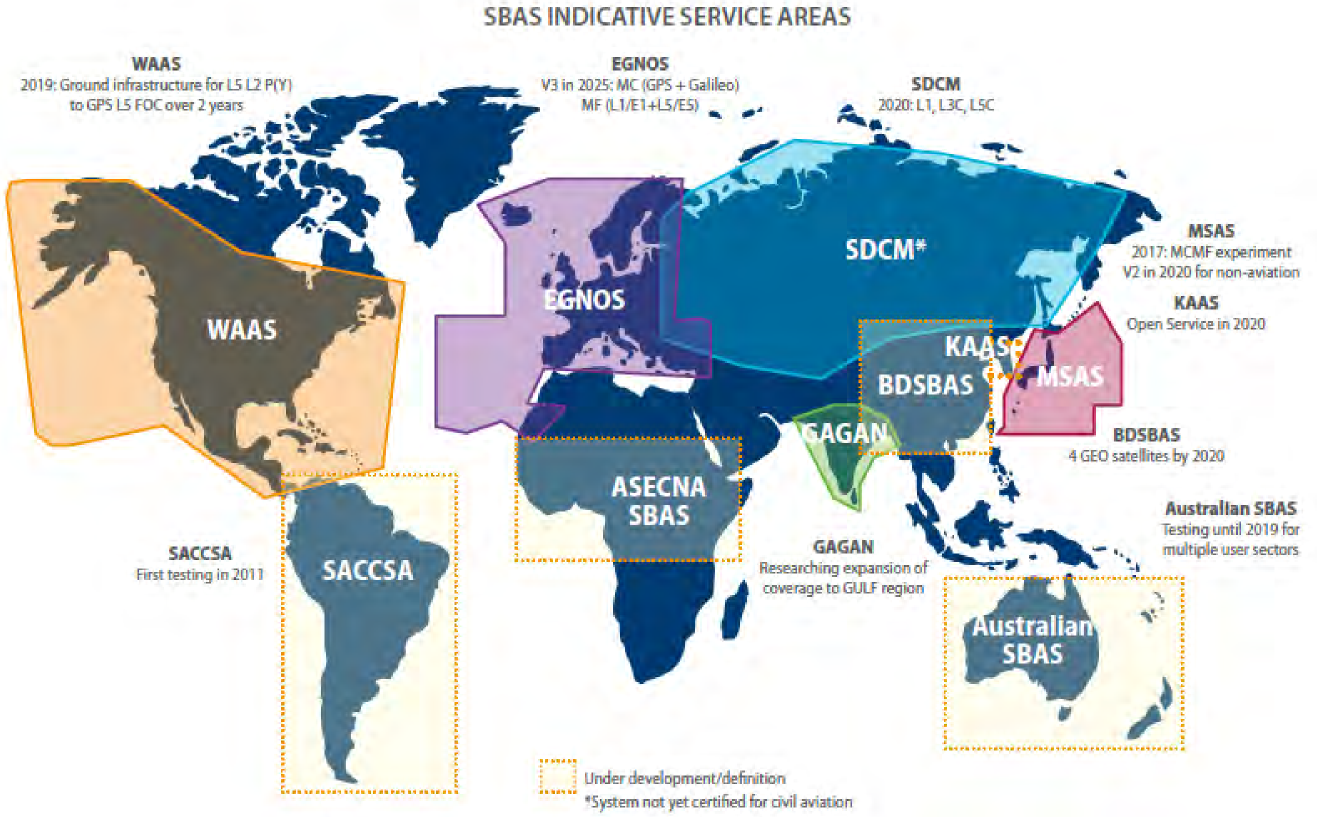

Figure 1. Regions where SBAS is either operational or in development worldwide (GSA, 2018).

An SBAS involves use of the following infrastructure which has been provided by the following organisations for the purposes of the Aus-NZ test-bed:

- Global Navigation Satellite Systems (GNSS): GPS and Galileo satellite constellations have been used
- Communication satellite(s): a geostationary communications satellite broadcasts the SBAS message over a region. In many existing systems world-wide more than one satellite is used. For the purposes of the test-bed, Inmarsat's 4F1 satellite was used.
- Uplink station: the uplink station provides the correction message to the communication satellite(s). For the test-bed, Lockheed Martin's uplink station based in Uralla, NSW was used.
- Ground reference stations: for the test-bed a sub-set of existing reference stations operated by GA across Australia and LINZ in New Zealand were used for the trial. Approximately 50 stations were utilised.
- Ground Master station: the master station collects the raw data from the reference stations and computes SBAS corrections, which are then sent to the satellite via the uplink station. GMV's magicSBAS and magicPPP products have been used for this purpose during the test-bed.

Figure 2 shows the infrastructure required for an SBAS and Figure 3 shows the Lockheed Martin uplink station and GMV SBAS and PPP servers at Uralla.

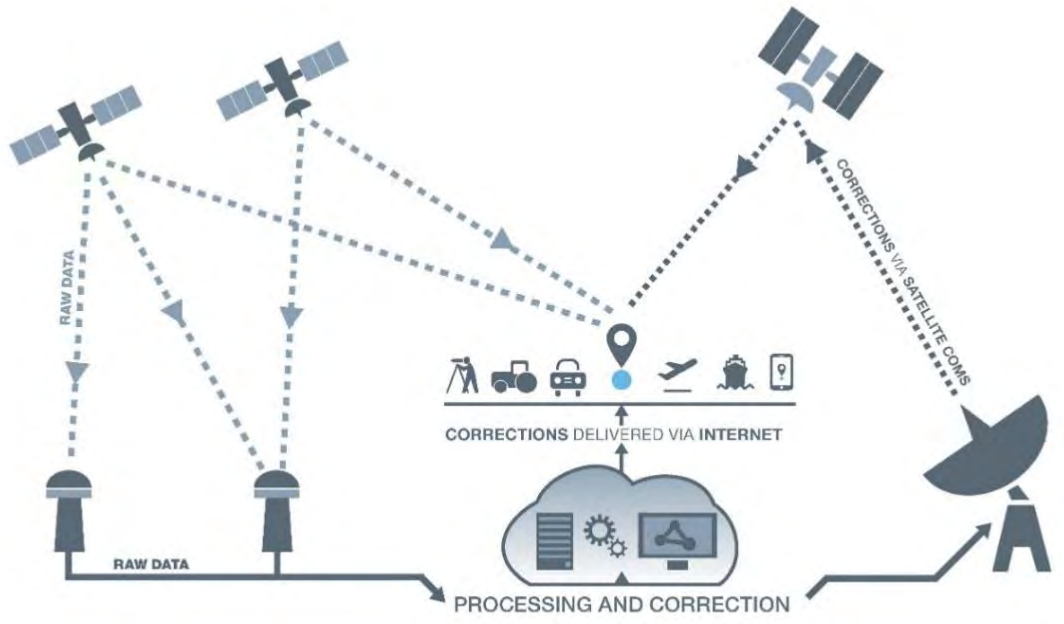

Figure 2. SBAS test-bed configuration (credit: Geoscience Australia).

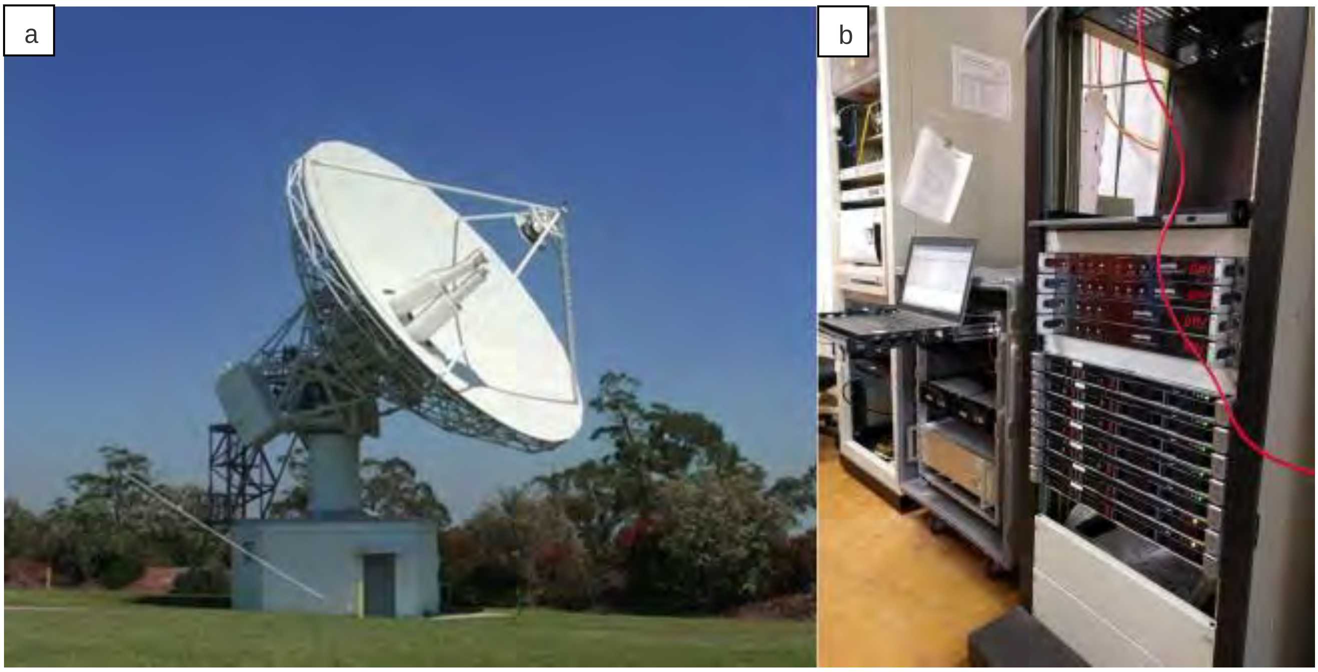

Figure 3. Lockheed Martin uplink station (a), GMV SBAS and PPP servers at Uralla (b) (credit: GMV).

2. Project Selection Process

This section details how projects were selected from the two Expression of Interest (EOI) calls through to proposal acceptance from the Steering Group (SG). The SG consisted of key representatives involved in the project from FrontierSI, GA and LINZ. Projects were sought from ten industry sectors which were: agriculture, aviation, construction, consumer, maritime, rail, resources, road, spatial and utilities. Table 1 highlights examples of where different applications for the SBAS technology were considered in these sectors.

Table 1. Industry sectors and examples where the SBAS technology may be used.

Sector	Example uses
Agriculture	Precision machinery monitoring, spray applications, fertilising, top dressing and yield mapping.
Aviation	Drone applications (including beyond Line-of-Sight), precision landing and navigation for aircraft landing (Performance Based Navigation) and data (e.g. image/LiDAR) acquisition.
Construction	Building Information Modelling (BIM), precision guidance and drone applications.
Maritime	Boat tracking, navigation, under-keel clearance, cable protection zones/exclusion areas and compliance of fisheries/parks.
Utilities	Drone asset management and inspection and electrical network synchronisation.
Spatial	Underground services, people movement and pedestrian navigation, enhanced search and rescue and mapping.
Resources	Resource supply chain, exploration and mine operations tracking.
Rail	Management systems, rail line mapping and integrity monitoring, vehicle tracking.
Road	Connected and Autonomous Vehicle tracking, asset and road furniture management, traffic flow monitoring, tolling (off-road), truck/fleet management, and Advanced Driver Advisory systems.
Consumer	Mobile workforce management and tracking, sport and well-being tracking, personal use mapping, and mobile integration (such as ride-sharing applications)

In April 2017, FrontierSI (then the CRCSI) opened an EOI call for SBAS test-bed demonstrator projects. The call requested that interested organisations provide some detail on projects that could be conducted that can use the SBAS technology to solve interesting problems in particular industry sectors. The EOI requested that organisations work together collaboratively on projects such that at least one industry participant was involved in the project.

In total, 72 EOIs were received. Through this first EOI call, several sector gaps were identified. Consequently, FrontierSI ran a second call for EOIs in specific sectors which closed in September 2017. Twenty three EOIs were received for the second call. In total, 95 EOIs were received. From each EOI call, the project ideas were evaluated against project criteria and a methodology developed by the SG. If an EOI was successful, the lead organisation was invited to submit a proposal which detailed their proposed project in more detail. These proposals were then reviewed by the SG, refined and consequently approved or further details on the project were sought. In some instances, projects detailed in a proposal were not approved by the SG and did not become a demonstrator project. Twenty seven SBAS test-bed demonstrator projects were selected. The first projects commenced in October 2017, in conjunction with the full operational capability of the test-bed.

3. Project details

Across the 10 industry sectors, 27 Demonstrator Projects were selected. This section details further information on each project, including the lead organisation, sub-sector (if applicable), SBAS signals tested and test sites used. Further information on all organisations involved and approximate project timelines are included in Appendix A.

3.1. Agriculture

Seven projects were carried out in the agriculture sector. These are detailed in Table 2.

Table 2. Agriculture SBAS projects.

Lead organisation	Sub-sector	Project title	SBAS signals tested	Key test areas	
				Country	Specific region
CQUniversity Australia	Livestock	Increased accuracy in on-animal spatio-temporal monitoring for livestock sensing applications	SBAS L1	Australia, New Zealand	Rockhampton, QLD, Australia South Island, New Zealand
Venture Southland	Forestry	Real-time SBAS-assisted production forestry management and planning	SBAS L1, DFMC, PPP	New Zealand	Southland region, South Island, New Zealand
Forestry Corporation of NSW	Forestry	Operational use of SBAS in production forests	SBAS L1, DFMC	Australia	Bathurst and Coffs Harbour NSW, Australia
Kondinin Group	Broadacre	Identifying and quantifying the economic and environmental benefits of SBAS technology to Australian grain production.	SBAS L1, DFMC, PPP	Australia	VIC (south-west region) and QLD Australia
Corrigin Farm Improvement Group (CFIG)	Broadacre	Putting SBAS into the hands of farmers	SBAS L1, PPP	Australia	Corrigin, WA, Australia
Page Bloomer Associates Ltd	Horticulture	Appropriate precision for horticultural farm management	SBAS L1, DFMC, PPP	New Zealand	North Island, New Zealand
Plant and Food Research	Horticulture (viticulture)	Geospatial resolution in vineyards	SBAS L1, DFMC, PPP	Australia, New Zealand	Marlborough, New Zealand, and Orange, NSW, Australia

3.2. Aviation

Two projects were carried out in the aviation sector. Table 3 details the aviation SBAS projects.

Table 3. Aviation SBAS projects.

Lead organisation	Project title	SBAS signals tested	Key test areas	
			Country	Specific region
Airways New Zealand	SBAS navigation benefits for New Zealand aviation system	SBAS L1, DFMC	New Zealand	Not Applicable
Airservices Australia	SBAS benefits for Australian aviation	SBAS L1, DFMC	Australia	Not Applicable

3.3. Construction

One SBAS project was carried out in the construction sector. Project details are shown in Table 4.

Table 4. Construction SBAS project.

Lead organisation	Project title	SBAS signals tested	Key test areas	
			Country	Specific region
Position Partners	Fit for purpose, high-accuracy, spaced based augmentation services applied to precision guidance, remotely piloted and safety systems for construction and utilities industries in Australia and New Zealand	SBAS L1, DFMC, PPP	Australia	VIC, NSW and QLD, Australia

3.4. Consumer

Two SBAS projects were carried out in the consumer sector. These are detailed in Table 5.

Table 5. Consumer SBAS projects.

Lead organisation	Project title	SBAS signals tested	Key test areas	
			Country	Specific region
Queensland University of Technology (QUT)	Exploring opportunities for a special needs routing platform with SBAS	SBAS L1, DFMC, PPP	Australia	Brisbane, Gold Coast, QLD, Australia
Australia Post	Autonomous last-mile parcel delivery	SBAS L1, DFMC	Australia	Brisbane, QLD Sydney, NSW

3.5. Maritime

Three SBAS projects were conducted in the maritime sector. Details are shown in Table 6.

Table 6. Maritime SBAS projects.

Lead organisation	Project title	SBAS signals tested	Key test areas	
			Country	Specific region
Acoustic Imaging Pty Ltd	Marine pilotage, navigation & offshore survey enhancement project	SBAS L1, DFMC, PPP	Australia	Sydney, NSW, Australia
Maritime Industry Australia Ltd (MIAL)	A comprehensive maritime assessment on the impact of an operational SBAS and the potential business critical applications	SBAS L1, DFMC, PPP	Australia, New Zealand	Various routes around Australia and New Zealand
Identec Solutions	SBAS testing for terminal process automation	SBAS L1, DFMC, PPP	Australia	Sydney, NSW and Melbourne, VIC, Australia

3.6. Rail

One project was conducted in the rail sector. Details are shown in Table 7.

Table 7. Rail SBAS project.

Lead organisation	Project title	SBAS signals tested	Key test areas	
			Country	Specific region
Position Partners	SMART rail (Satellite Management Assisting Rail Transport)	SBAS L1, DFMC, PPP	Australia	TAS, Australia

3.7. Resource

Two projects were carried out in the resource sector. Details are shown in Table 8.

Table 8. Resource SBAS projects.

Lead organisation	Project title	SBAS signals tested	Key test areas	
			Country	Specific region
QUT	Demonstration of SBAS signals for improved surface mine operation safety and productivity	SBAS L1, DFMC, PPP	Australia	Brisbane, Middlemount, QLD, Australia)
Curtin University	Positional improvements for digital mines	SBAS L1, DFMC, PPP	Australia	WA, Australia

3.8. Road

Four projects were conducted in the road sector. These are detailed in Table 9.

Table 9. Road SBAS projects.

Lead organisation	Project title	SBAS signals tested	Key test areas	
			Country	Specific region
VicRoads	VicRoads road safety action plan 2016-2020 highly automated driving with SBAS trial	SBAS L1, DFMC, PPP	Australia	Melbourne, VIC, Australia
Ministry of Transport New Zealand	National heavy vehicle differential pricing trials project	SBAS L1, DFMC, PPP	New Zealand	North Island, New Zealand
Transport for NSW	SBAS for connected vehicles: the potential road safety and efficiency gains through the use of an Australian SBAS	SBAS L1, DFMC, PPP	Australia	Sydney, Wollongong, NSW, Australia
HERE Technologies	Technology demonstrator of augmented differential positioning using SBAS Technology integrated with HERE true SLI and LiDAR road reality capture platform for highly automated driving	SBAS L1, DFMC, PPP	Australia	NSW, Australia

3.9. Spatial

Four projects were carried out in the spatial sector. Details for these projects are shown in Table 10

Table 10. Spatial SBAS projects.

Lead organisation	Project title	SBAS signals tested	Key test areas	
			Country	Specific region
NSW DFSI – Spatial Services	Assessing dual-frequency multi-constellation SBAS and SBAS-aided precise point positioning for survey applications	SBAS L1, DFMC, PPP	Australia	NSW, Australia
University of Otago	SBAS applications for low accuracy rural cadastral surveys	SBAS L1, DFMC, PPP	New Zealand	Dunedin, South Island, New Zealand
Royal Melbourne Institute of Technology (RMIT)	Assessing dual-frequency multi-constellation SBAS and SBAS-aided precise point positioning for survey and/or mapping applications in Victoria	SBAS L1, DFMC, PPP	Australia	VIC, Australia
University of Tasmania	Precision and accuracy of Unmanned Aerial System (UAS) positioning with SBAS, DFMC and PPP – application in precision agriculture	SBAS L1, DFMC, PPP	Australia	TAS, Australia

3.10. Utilities

One project was carried out in the utilities sector. Details are provided in Table 11.

Table 11. Utility SBAS project.

Lead organisation	Project title	SBAS signals tested	Key test areas	
			Country	Specific region
Orbica	Improving Australasia's field to office asset data lifecycle	PPP	New Zealand	Christchurch, South Island, New Zealand

4. Test Equipment

There were two types of equipment used throughout the project – the SBAS kit and the MagicUT. This equipment is explained in further detail in this section.

4.1. SBAS Kit

At the outset of the test-bed, available commercial receivers could not be configured to receive DFMC or PPP signals, so a specific hardware setup was assembled to provide the level of flexibility required by the Demonstrator Projects. Data collection conducted in early Demonstrator Projects primarily utilised the equipment configuration outlined in Table 12, hereafter referred to as the SBAS Kit.

Table 12. SBAS Kit Hardware.

• Septentrio AsteRx-U receiver • SRX-10 software defined radio front-end • Tallysman VP600 GNSS Antenna • Passive signal splitter (1 x 4)	• USB Hub • Winmate Linux Tablet running GMV PPP software and SRX-10 Launcher • Power, Antenna, USB Cables • Rechargeable Lead-Acid Battery

The components listed in Table 12 were connected as described in Figure 4 (note: USB hub not shown). Routing the antenna through a passive signal splitter allowed identical satellite observations to be received at the front-end and the receiver simultaneously, enabling separate processing of the signal by each component. The SRX-10 software defined radio front-end paired with software on the tablet was used to decode and store the SBAS messages received during testing, while the receiver recorded the raw satellite observations at the same time. Logging both the SBAS messages and raw satellite observations during testing enabled rigorous statistical analysis during the test period, as well as providing some resilience against system errors and aiding in troubleshooting the source of any issues.

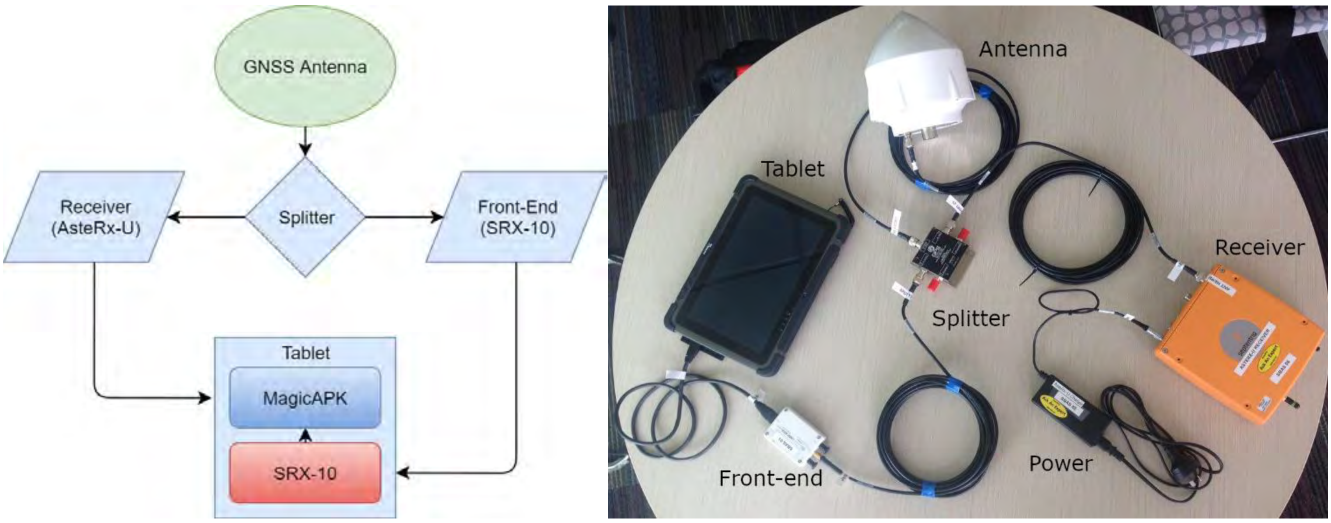

Figure 4. SBAS Kit component setup.

The SBAS Kit was housed either in a modified 45 litre box, or in a GNSS backpack for field testing, as shown in Figure 5. The SBAS Kit provided robust high-quality positioning data, but had the disadvantage of many different parts and was not a suitable form factor for Demonstrator Projects with space and weight limitations (e.g. UAS, livestock).

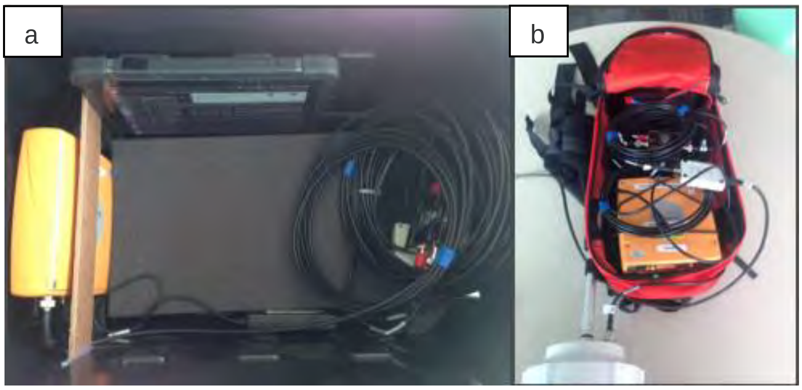

Figure 5. SBAS kit in a box (a), and in a backpack (b).

4.2. MagicUT

Special hardware known as MagicUT was developed by GMV for use in the test-bed in order to access DFMC and PPP signals. The MagicUT was a portable and easy-to-use android device capable of receiving, monitoring and logging all the SBAS signals without the need for any external devices apart from the antenna. The android system allowed for easy configuration and management of the device, with applications pre-loaded to allow setup and collection of data. The in-built screen allowed real-time monitoring of system performance and could be configured to display a wide range of statistics. Test configurations using the MagicUT required an external antenna but did not need external data storage nor power sources, unless the test period lasted longer than the MagicUT battery allowed. The MagicUT is a prototype receiver and does not carry the same level of development as many commercial products. Some typical equipment setups and the android interface of can be observed in Figure 6.

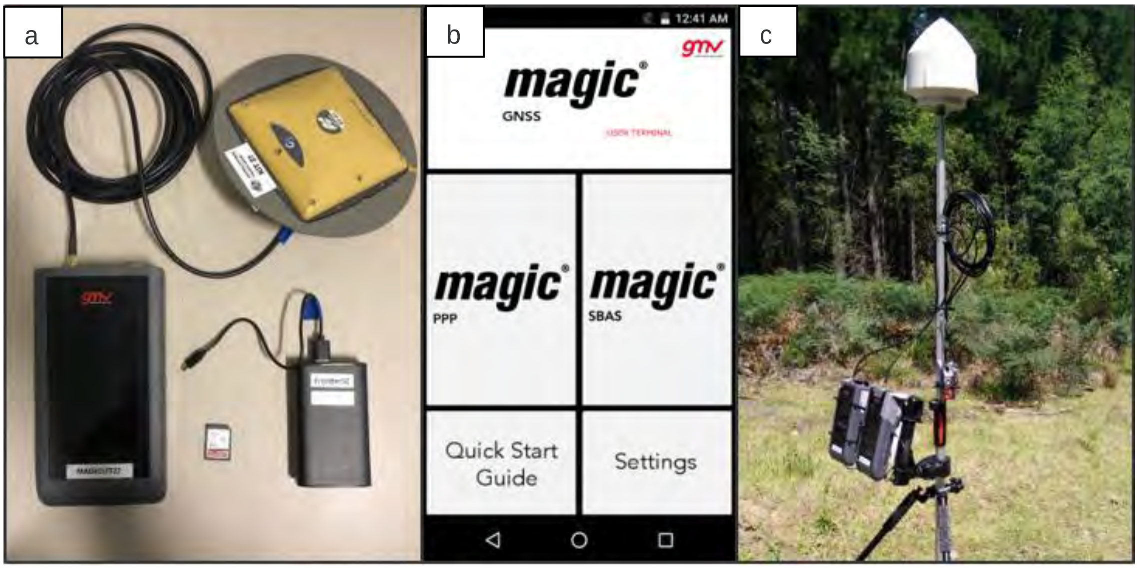

Figure 6. MagicUT components (a), start-up screen (b), and two MagicUTs on a pole during testing (c).

4.3. Equipment and testing environment

Collecting positioning data using each of the SBAS signals across a wide array of conditions allowed the FrontierSI team to develop a more holistic understanding of the expected performance of the signals when applied to each particular use case. By examining 27 demonstrator projects, a performance baseline for each industry sector was developed to assist in modelling any potential economic benefits that may accrue due to activities in each sector. Each project team was given the opportunity to determine appropriate test equipment to suit their expertise and the use case/applications within their industry sectors. Each project had a unique set of requirements for positioning accuracy, integrity and availability, coupled with challenges such as the harsh environments at mine-sites, or limited payload capability.

The test setups varied significantly depending on the project, whether mounted on the bridge of a ship, train locomotive or a cattle collar. Each project having distinct test cases, environment, and equipment required individual test methodologies to be developed to evaluate the potential uses within each industry sector. Data was collected by a range of receivers and antennas across the 27 Demonstrator projects, representing consumer-grade (<$100), mid-range ($100-3,000), and professional (>$3,000). These receivers were tested in a breadth of environments, from ideal open-sky GNSS conditions to heavily obstructed areas such as urban canyons and plantation forests. A summary of the classifications used for equipment, and for test enviroments can be found in Table 13 and Table 14.

Table 13. Equipment classifications.

Equipment	Description
Consumer	< $100 - consumer grade chips, mobile phones, IoT, trackers, etc.
Mid-range	$100-$3,000 - GIS, mapping, forestry, robotics etc.
Professional	> $3,000 - geodetic, surveying, high-precision applications

Table 14. Environment classifications.

Environment	Description
Open sky	No obstructions, highest accuracy results expected
Light Obstruction	1-storey buildings and some trees, no significant obstructions
Partial Obstruction	2-3 storey buildings, medium-level tree canopy, undulating terrain, open mine pits
Moderate Obstruction	Dense forest, container port (cranes), construction sites (machinery/equipment)
Significant Obstruction	Urban canyon, dense plantation forest, other significant obstructions

5. Project Challenges

As expected in any technology demonstration project, a variety of technical hardware and software challenges were experienced throughout the test-bed project, which are summarised in this section. The challenges included:

- New signals – two out of the three signals (DFMC and PPP) were new signals, which meant that standard off-the-shelf receivers could not decode them. A new specific set of hardware was needed to utilise these signals. Existing commercial receivers that could be SBAS-enabled to receive SBAS L1 data often required a firmware upgrade in order to access the test-bed SBAS L1 signal.
- Hardware availability - initially, a limited number of SBAS kits were available when all signals came online (October 2017), which meant only some projects could conduct testing (discussed earlier in Section 4.1). The MagicUTs were available for use by projects only at a later stage. MagicUTs had less limitations and solved some of the issues experienced with the SBAS kit.
- Hardware - the SBAS kit contained many parts, which made it complicated and cumbersome to use and with several points of failure, such as the front-end and a USB splitter. A number of these devices broke and required replacement. The tablets also experienced problems with overheating as well as other issues with the touch screens. A number of tablets had to be sent back to the manufacturer for repairs.
- DFMC – DFMC is a brand new signal. At the start of the test-bed it did not show the expected performance, and the service continued improving as the test-bed progressed and by the end of the test-bed met performance expectations. The improvement in performance over time resulting from the new signal also introduced challenges as new versions of software continued to arrive. Thus, some projects had to recompute their results a number of times to align with the latest version of software.
- MagicUT certification – this was potentially the biggest challenge. The certification of the magicUT took a lot longer than originally planned and this introduced many problems with timing for many projects. Resultant delays in certification delayed many projects which meant a complete shift in the overall testing timetable. There were flow-on effects as some project teams had commenced work with employees, others had to fit within strict timelines. The sector that was most impacted was the agriculture sector, since tests were planned against growing seasons for various activities and due to delays, some of those could not be carried out.
- Signal outages – there were a number of unplanned signal outages/disruptions throughout the test-bed, which had an impact on various projects as testing could not be conducted during those times. The outages varied in duration from a few hours, a number of days up to as long as a month. The testbed was often taken offline with little or no notice.
- Equipment logistics – distributing equipment between Australia and New Zealand proved to be a complicated process. Each set of equipment required special customs documents called carnets to be issued, but even with the carnet, the courier companies proved to be unable to deliver it. The first shipment sat at New Zealand customs for 3 weeks, before it was returned. Often equipment was hand-delivered to New Zealand to ensure project testing could proceed.
- Varied experience of project teams – between the 27 projects, there was a varied level of positioning knowledge, know-how, and experience. Some had very little or no experience with GNSS equipment and data processing. Whilst the FrontierSI technical team provided as much technical support as possible, the number of projects and compressed timing of testing meant that some projects had trouble with either data collection or processing and this was not realised until results were reviewed later in the project.

- Project timeframe – the test-bed was a relatively short project (signals were available for testing from October 2017 to January 2019). The 27 Demonstrator Projects needed to conduct testing during this period. Many of the issues described above meant that flexibility was required by project teams as to when testing occurred. This sometimes had flow-on effects to other projects due to the limitations on available hardware.

6. Project Testing Overview

This section presents an overview of the testing conducted by all projects in the industry sectors as well as testing carried out by FrontierSI. The test results shown throughout this section have been aggregated by sector and are indicative of the type of equipment and test environment applicable to that sector. Testing across all sectors concentrated on the positioning accuracy of the SBAS testbed, except for the aviation sector where both accuracy and integrity were examined.

This section summarises projects by sector and presents aggregated positioning results for the sector. The results are combined from multiple projects in the sector and present expected performance at a 95% Confidence Interval (CI) for that sector, i.e. in the typical sector environment using similar hardware. Some projects did not achieve satisfactory results for a number of reasons (e.g. immaturity of the service or inexperience of the project team) and as such they were left out of the computation process, in order to not to bias the results.

6.1. Agriculture

The projects included in this sector were CQUniversity Australia, Venture Southland, Forestry Corporation of NSW, Kondinin Group, CFIG, Plant and Food Research and Page Bloomer. Aggregated results for the sector are presented in Table 15, followed by short descriptions of each project.

The Agriculture sector is considered different to other sectors in that there are a high number of candidate applications, and a large number of projects were conducted to enable adequate representation of the wide range of environments. Generally, the agricultural environment has mostly clear open sky with a very few obstructions. The exception is forestry, which by definition has dense tree canopy and presents a very challenging environment for any GNSS positioning. The results shown in Table 15 refer to an open sky environment with mid-range to professional equipment.

Table 15. Aggregated positioning results for the Agriculture sector.

Agriculture Sector		
Signal	Expected horizontal performance at 95% CI (m)	Expected vertical performance at 95% CI (m)
SBAS L1	0.50	1.05
DFMC	0.63	1.34
PPP	0.20	0.48

6.1.1. CQUniversity Australia

The Demonstrator Project with CQUniversity Australia aimed to examine how the SBAS L1 signals can be used to facilitate the development of key livestock management applications such as virtual fencing, which could provide significant production efficiency gains for the livestock sector (see Figure 7). Numerous off- and on-animal tests were conducted throughout the trial to provide an overall picture of the likely value of SBAS to livestock applications.

Initially, testing was planned to be done on both cattle and sheep, but in the end only cattle testing was possible due to the large form factor of the receiver. Most of the testing was carried out in Rockhampton, QLD between January and August 2018, with static testing completed in New Zealand (South Island) in January 2019.

Figure 7. Example simulating a moving virtual fence (credit: CQUniversity Australia).

6.1.2. Venture Southland

This project focussed on evaluating the SBAS technology and techniques for use by on-the-ground forestry technicians to assist forestry management activities and building of roads. All three SBAS signals were tested during the project.

Three field trials were conducted to test applications where the SBAS signals could be useful for small scale production forestry. The testing was undertaken in Southland, New Zealand during the second half of 2018. Typical forestry conditions from around the test region are displayed in Figure 8.

Figure 8. Range of forest conditions including un-thinned forest area (a), thinned forest area (b), partially obstructed forest road (c) (credit: Venture Southland).

6.1.3. Forestry Corporation of NSW

Forestry Corporation of NSW tested the availability and accuracy of SBAS signals under a range of hardwood and softwood canopy environments at Orara and Sunny Corner State Forests, NSW in the second half of 2018. The project compared the performance of SBAS receivers to standard GNSS along surveyed transects at both hardwood and softwood forest sites. The SBAS L1 and DFMC service coverage and reliability in forest environments was tested to see if the SBAS signals could provide improved performance over standalone GNSS under typical forestry management conditions. The testing was carried out in environments as shown in Figure 9.

Figure 9. Softwood forest test environment (a) and forestry harvesting equipment (b) (credit: Forestry NSW).

6.1.4. Kondinin Group

The Kondinin Group tested SBAS L1, DFMC and PPP technology in various broadacre farming operations including seeding, spraying, spreading, autonomous machinery operation and harvesting. The main focus of the project was investigating whether PPP could provide sufficient pass-to-pass accuracy for Controlled Traffic Farming (CTF) operations, where pass-to-pass referred to a repeatable relative accuracy of positioning during a 15 minute period. The testing was done in Victoria and Queensland in the second half of 2018 in a mostly open sky environment and involved collecting data on various machinery types depicted in Figure 10.

Figure 10. Agricultural machinery used in the testing including John Deere 9330 (a), Swarmfarm Generation Indigo 65hp autonomous tractor (b), Goldacres CropCruiser Evolution 6036 (c) and John Deere 8370R (d) (credit: Kondinin Group).

6.1.5. Corrigin Farm Improvement Group

The project performed tests at 10 farms throughout the Corrigin region in Western Australia between May and September 2018 using a variety of GNSS receivers and a phone app that was developed specifically for this project. A typical test setup is shown in Figure 11. Measurements were taken from SBAS L1, DFMC and PPP capable equipment installed on the grower's machinery whilst the grower was performing routine activities (e.g. seeding, spreading), to determine indicative performance for these tasks. The testing was done in a predominantly open sky environment.

Figure 11. Case Magnum 180 tractor used in the testing (a), antenna setup on the tractor (b) (credit: CFIG).

6.1.6. Plant and Food Research

In this demonstrator project, the New Zealand Institute for Plant and Food Research Limited worked with UNSW to evaluate the benefits of the SBAS L1, DFMC and PPP in vineyard environments. Signal performance was tested in a variety of vineyard tests conducted in March 2018 in the Marlborough region of New Zealand and around Orange, NSW, Australia. The testing aimed to determine if any of the SBAS signals could be used to distinguish between rows in a vineyard and if particular plants, or even bunches of grapes could be identified. The testing conducted in vineyards was often an open sky environment provided the antenna was placed above the vines. Typical vineyard test environments observed during testing are shown in Figure 12.

Figure 12. SBAS testing in vineyards (credit: Plant and Food Research).

6.1.7. Page Bloomer

The Page Bloomer project focussed on testing the SBAS technology for use in farming environments in New Zealand, comparing it against various commercial systems currently available. SBAS L1 and PPP signals were evaluated in testing conducted between April and August 2018 in Hastings, Gisborne and Nelson in New Zealand in a mix of vegetable farms and orchards. This testing was primarily conducted in open farm landscapes, with some measurements occurring close to vegetation and under canopy. Figure 13 shows one of the test courses and an orchard where testing occurred.

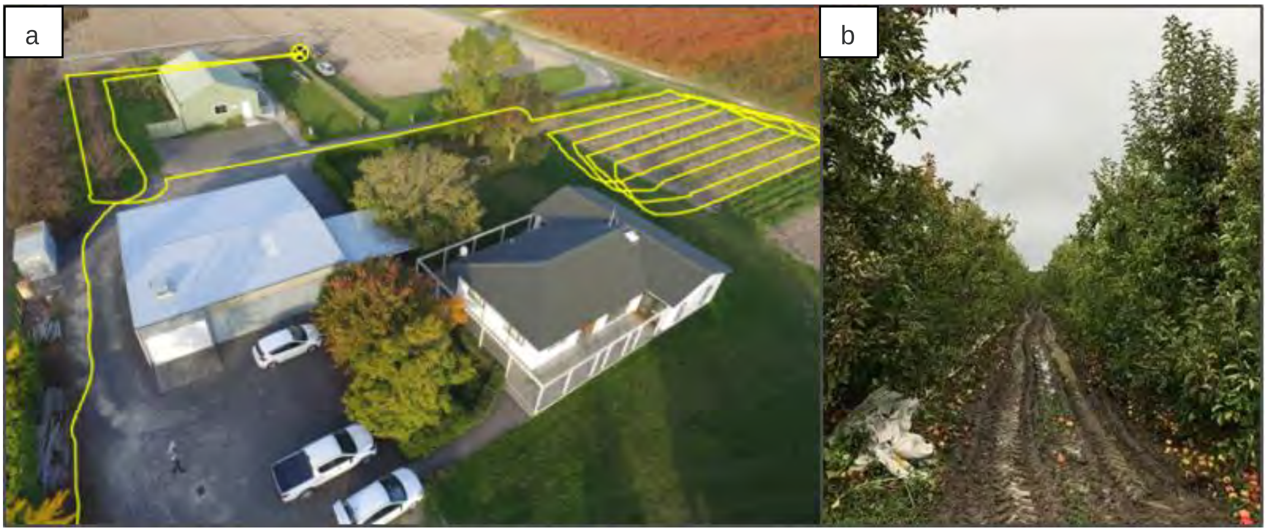

Figure 13. View of the kinematic test course (a), Motueka Orchard in Nelson (b) (credit: Page Bloomer).

6.2. Aviation

Two projects were carried out in the aviation sector with the civil aviation authorities in Australia and New Zealand respectively. The shared aim of the projects was to test the suitability of SBAS for precision approaches with vertical guidance in the region and whether the signal could deliver the required performance for International Civil Aviation Organisation (ICAO) requirements. Table 16 shows the aggregated results for the aviation sector followed by descriptions of the projects. For aviation, integrity information is of most importance, and as such only SBAS L1 and DFMC were examined in both projects. Professional grade equipment was used in the aviation sector.

Table 16. Aggregated positioning results for the Agriculture sector.

Aviation Sector		
Signal	Expected horizontal performance at 95% CI (m)	Expected vertical performance at 95% CI (m)
SBAS L1	0.69	1.33
DFMC	0.59	1.10
PPP	Not tested	Not tested

6.2.1. Airservices Australia

The Airservices Australia project tested both SBAS L1 and DFMC to quantify the improvements in a number of key aviation parameters such as accuracy, availability, continuity and integrity. Two different tests were carried out which enabled analysis of SBAS performance in a variety of environments and operational conditions. Firstly, two aviation receivers were installed at static locations in Darwin (NT) and rural NSW and recorded raw data including key aviation parameters. Secondly, SBAS equipment was installed in an aircraft that flew across Australia and collected SBAS information during the second half of 2018. Figure 14 shows the setup of the SBAS equipment on the test aircraft. The flights analysed covered WA, SA, NT NSW, ACT and QLD.

Additionally, a series of precision approaches with vertical guidance were flown into airfields in Mt Hotham, Benalla, Wagga Wagga and Canberra. In all cases the approaches were successful and the feedback from pilots was that SBAS was safer, eliminated guesswork, could save fuel and avoid missed approaches, and freed up some capacity for the pilots to deal with other things.

Figure 14. SBAS equipment setup in the cabin (a), antenna mounting position on test aircraft (b), close-up of installed antenna (c) (credit: Airservices Australia).

6.2.2. Airways New Zealand

The Airways New Zealand project was similar to the Airservices in scope and was aimed at testing SBAS L1 and DFMC services across New Zealand. Specific emphasis was placed on two types of operations:

- Helicopter Emergency Medical Services where the availability of SBAS can provide guidance to heliports in poor weather and allow the helicopters fly at higher altitudes without the risk of inflight icing.
- Regional aerodromes where poor weather conditions, coupled with constraints of existing instrument approach procedures, lead to flight diversions and cancellations.

SBAS equipment was installed on a helicopter and a flight inspection aircraft to conduct testing around aerodromes in New Zealand. In total, data was recorded around 16 aerodromes in the first half of 2018. The testing was conducted in open sky under various weather conditions.

In general, it was found that the accuracy of SBAS was sufficient to carry out precision approaches with vertical guidance, and as a result the project team recommended the deployment of a certified SBAS L1 system in New Zealand.

6.3. Consumer

Two projects were carried out in the consumer sector. Australia Post examined autonomous delivery robots and QUT looked at the use of SBAS in a navigation system for visually impaired people. The aggregated results from the sector are shown in Table 17 followed by short descriptions of the projects. Mostly consumer-grade devices were used in this sector and as such PPP was not tested by either project as PPP was not be available on devices of this type at least at the time of testing. The testing varied from urban, to suburban to open sky depending on the location of the testing.

Table 17. Positioning results for the Consumer sector.

Consumer Sector		
Signal	Expected horizontal performance at 95% CI (m)	Expected vertical performance at 95% CI (m)
SBAS L1	2.09	3.98
DFMC	3.00	5.80
PPP	Not tested	Not tested

6.3.1. Australia Post

Australia Post conducted SBAS testing on an automonous delivery robot which was part of a current set of trials testing parcel delivery in urban environments. The vehicle used travelled autonomously on footpaths using a combination of scanning, positioning and other navigation equipment. This project explored how SBAS L1 could be used to improve the standalone GNSS accuracy of the robot. Testing was conducted in suburbs around Brisbane and in Sydney between June and October 2018. The test environment varied from open sky, to underneath tree canopies and adjacent to buildings. An image of the delivery robot during Australia Post’s wider trials is shown in Figure 15.

Figure 15. Australia Post autonomous delivery robot (credit: Australia Post).

6.3.2. Queensland University of Technology

This QUT project aimed to test the feasibility of an SBAS driven special needs routing platform that could provide detailed information for a safe journey to people with disabilities or visual impairment. To test this, the project team undertook walks in different locations and environments around Brisbane and Surfers Paradise, ranging from open areas, to densely built up areas with high rise corridors, and mapped the SBAS location data to the actual walking path determined through a stereo vision-based system. The testing occurred in the first half of 2018.

Figure 16. Stereo vision camera (a), SBAS kit in portable backpack (b), example route taken by the project team (c) (credit: QUT).

6.4. Construction

A single project was carried out in Construction sector by Position Partners and UNSW which tested a variety of applications in the sector, many of which were aimed at improving safety. Indicative testing results from the construction sector are given in Table 18 followed by description of the project. Generally, mid-range to professional equipment is used in the sector and the environment is challenging due to many obstructions such as buildings and machinery.

Table 18. Positioning results for the Construction sector.

Construction Sector		
Signal	Expected horizontal performance at 95% CI (m)	Expected vertical performance at 95% CI (m)
SBAS L1	1.14	2.16
DFMC	1.77	2.29
PPP	0.65	1.15

6.4.1. Position Partners

This project tested the positioning performance of SBAS L1, DFMC and PPP signals in construction applications, specifically for personnel and machinery tracking, UAS for inspections and other safety applications. Efficiency and productivity in the civil construction industry stand to be improved through the use of SBAS in congested construction zones.

Four test scenarios were conducted between July and November 2018 across sites in Queensland, New South Wales and Victoria. Initial bench tests were used to assess the various hardware and software configurations and establish a baseline of expected positioning performance. The images from UAS testing, Plant Testing, and of the portable equipment setup are shown in Figure 17.

Figure 17. DJI M20 UAS (a), Backpack with MagicUT receivers (b), machinery and personnel on site (c) (credit: Position Partners).

6.5. Maritime

Three projects were carried out in the maritime sector which included Maritime Industry Association Limited (MIAL), Acoustic Imaging and Identec Solutions. Aggregated results for the sector are shown in Table 19 followed by short descriptions of the projects. Professional equipment is used in the maritime sector and the environment is open sky anywhere offshore with obstructions in harbours and container ports. Maritime is a perfect environment for PPP, since there are no overhead obstructions offshore and the receivers on ships always remain powered, which means they only need to converge once (upon installation).

Table 19. Positioning results for the Maritime sector.

Maritime Sector		
Signal	Expected horizontal performance at 95% CI (m)	Expected vertical performance at 95% CI (m)
SBAS L1	0.91	1.93
DFMC	1.38	3.77
PPP	0.10	0.22

6.5.1. Acoustic Imaging

The aim of the Acoustic Imaging project was to demonstrate how SBAS L1 and PPP could be applied to the port and harbour maritime sector in Australia and New Zealand. Ports and harbours are under constant change from meteorological, oceanographic, geophysical and anthropogenic factors resulting in frequent revision of the Electronic Navigation Charts (ENCs). ENCs are the result of a hydrographic survey which incorporates high resolution underwater acoustic echosounders to generate detailed bathymetry maps. Professional maritime pilots use ENCs to navigate large vessels in and around the harbour. The ENC is displayed on a Portable Pilotage Unit (PPU) and the location of the vessel is tracked relative to background features displayed in the PPU.

The project looked at whether the SBAS signals could assist the hydrographic survey activities (i.e. the generation of ENCs) or the pilotage activities (i.e. the usage of ENCs). The project was conducted in Sydney Harbour with some testing done at the start of 2018 and remainder of testing at the start of 2019. Figure 18 shows the survey vessel used as well as the hydrographic and pilotage equipment.

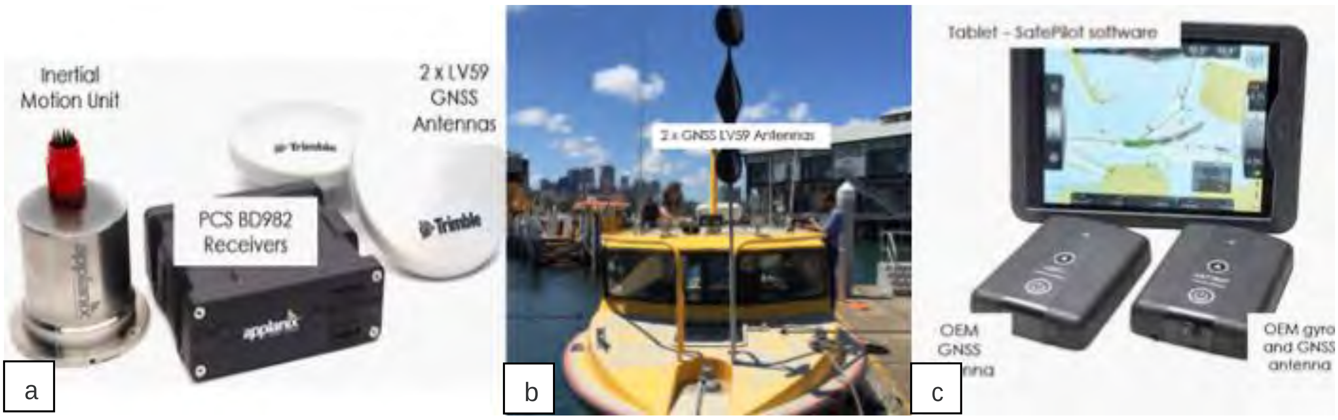

Figure 18. Hydrographic survey equipment (a), survey vessel with SBAS equipment (b), pilotage equipment (c) (credit: Acoustic Imaging).

6.5.2. MIAL

The MIAL project investigated significant potential benefits that SBAS L1, DFMC and PPP positioning can bring for the maritime industry. The project mainly focussed on Close Quarters Position and Under Keel Clearance (UKC). Of these application areas, MIAL selected vessels and voyages to participate in the test-bed and delivered the broadest possible range of industry specific scenarios across both Australia and New Zealand. In total, 16 vessels participated in the test-bed (see Figure 19) between November 2017 and May 2018, including a voyage to Antarctica.

Figure 19. Some of the vessels that participated in the MIAL SBAS voyages (credit: MIAL).

6.5.3. Identec Solutions

Identec Solutions investigated the use of SBAS L1, DFMC and PPP positioning in container port terminals. A container terminal primarily serves as a transfer hub for import, export and transhipment containers between road and vessel transports. As a container enters the yard via either a vessel or road transport its movement through the yard must be tracked so that the yard inventory remains accurate and operations are efficient. Typically, differential GNSS (DGNSS) is used to track the movement of containers in the port. A local base station is setup and each piece of machinery, i.e. crane and straddle carrier, acts like a rover. The project aimed to investigate whether SBAS signals can provide an alternative solution to DGNSS. Testing was conducted in Melbourne and Sydney port terminals in the second half of 2018. Figure 20 shows a rubber tyred gantry crane and typical container port in Lyttelton, New Zealand.

Figure 20. A rubber tyre gantry crane (a), typical container port (b) (credit: Identec Positioning).

6.6. Rail

A single project was carried out in the rail sector with Position Partners and TasRail which looked at train control management and performance of SBAS in challenging terrain including what's known as virtual tunnels. The results from the project are given in Table 20 followed by a description of the project. Professional equipment is used in the rail sector and the environment can change from open sky to highly obstructed depending on the terrain.

Table 20. Positioning results for the Rail sector.

Rail Sector		
Signal	Expected horizontal performance at 95% CI (m)	Expected vertical performance at 95% CI (m)
SBAS L1	0.55	0.63
DFMC	1.34	3.39
PPP	0.27	0.57

6.6.1. Position Partners and TasRail

Increasingly, GNSS and SBAS are becoming key contributors to the deployment of modernised train-control systems around the world. These modernised train control and management systems promise to reduce the costs associated with maintaining ground infrastructure while improving train safety and operational efficiency. Rail freight operators such as TasRail in Tasmania have embraced and integrated GPS technology within their train control and management systems, however, satellite availability and positional integrity have come into question because of the challenging environmental and topographical conditions found along many sections of Tasmania's rail network. For example, 'virtual tunnels' can occur when rail lines cut through steeply sloping terrain that are also covered overhead by a thick vegetation canopy, resulting in GNSS signal blackspots.

The project focussed on mounting an SBAS Kit capable of L1, DFMC and PPP positioning on a locomotive and transiting the entire TasRail network to investigate the advantages of SBAS technology for train control and management. Testing was conducted with two trains across six rail lines around Tasmania between April and June 2018 aiming to better understand how SBAS will affect positioning quality in areas with poor sky visibility or virtual tunnels. Figure 21 shows the train and the equipment setup on the locomotive.

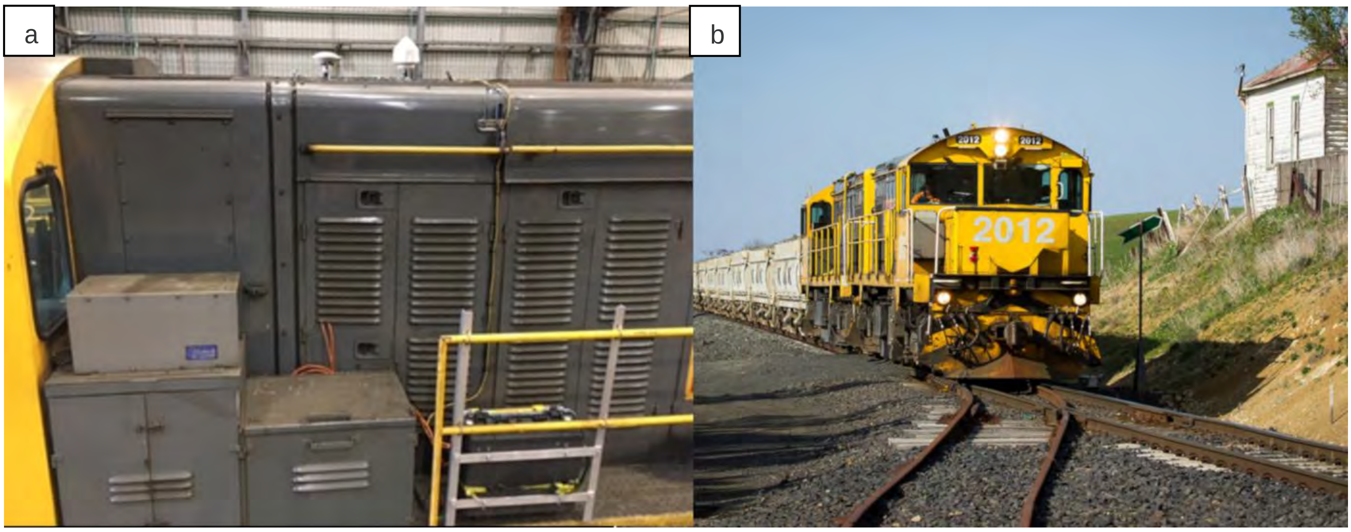

Figure 21. SBAS equipment setup on the locomotive (a) and the train in transit (b) (credit: TasRail).

6.7. Resources

Two projects were carried out in the Resources sector, both in the open pit mining scenarios. Queensland University of Technology (QUT) and Wenco Mining Systems (Wenco) have examined improved surface mine operation safety and productivity, whilst Curtin University and Roy Hill investigated positioning improvements that SBAS could offer for digital mines. The aggregated results of the testing are shown in Table 21 below followed by short descriptions of the projects. The equipment used in the mining environment ranges from consumer-grade devices for vehicle tracking to mid-range and professional for various other activities. Environment in an open cut mines can vary depending on the proximity to the mine wall and surrounding machinery.

Table 21. Positioning results for the Resources sector.

Resource Sector		
Signal	Expected horizontal performance at 95% CI (m)	Expected vertical performance at 95% CI (m)
SBAS L1	0.87	2.67
DFMC	0.58	2.01
PPP	0.20	0.71

6.7.1. QUT and Wenco

The QUT and Wenco project investigated the potential benefits that SBAS L1, DFMC and PPP could bring to safety of vehicle navigation and increases in productivity in an open cut mining environment. Most of the testing was carried out at the Middlemount coal mine in Queensland with some vehicle interaction tests also done in Brisbane in the second half of 2018. The project demonstrated the use of SBAS services for Vehicle-to-Anything (V2X) safety operation by conducting analysis of warnings between two vehicles on multiple collision scenarios.

Figure 22. Haul truck (a) and the SBAS antenna placement on the truck (b) (credit: Wenco).

6.7.2. Curtin and Roy Hill

The focus of the Curtin and Roy Hill project was to determine the improvements SBAS L1, DFMC and PPP can bring to existing mine technologies, specifically in areas of:

- Improving the accuracy of the representation of ore bodies using Augmented Reality (AR) systems.
- Reducing the reliance on physical survey pegs by seeking precise real-time positioning of the drill hole using SBAS technologies, i.e. 'digital pegging'.
- Continuous positioning for autonomous activities to ensure availability and reduce operational downtime.

The testing was conducted at the Roy Hill mine in Western Australia during the second half of 2018. Figure 23 below shows some of the testing that has been carried out.

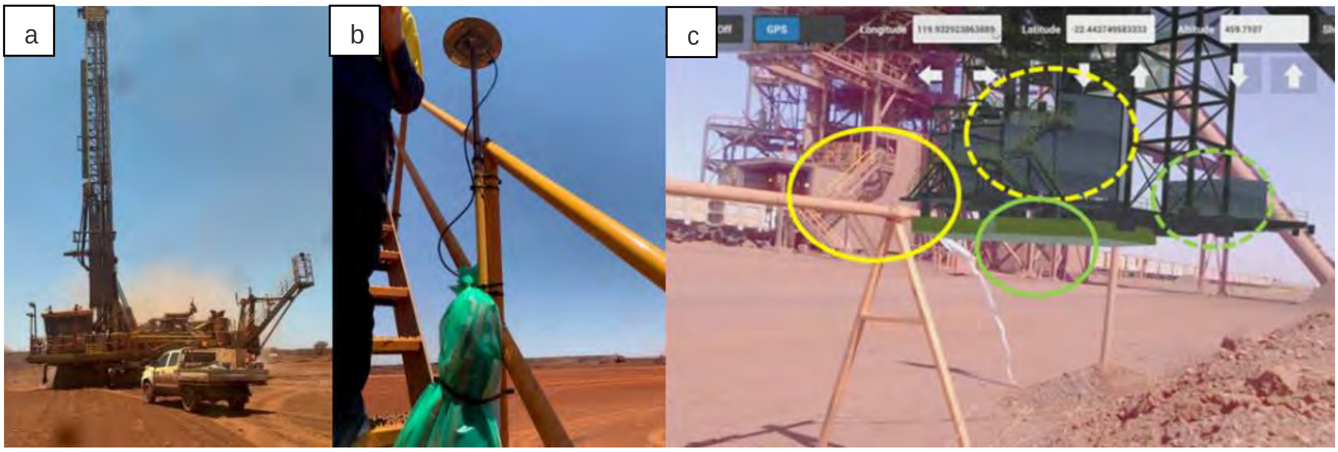

Figure 23. Drill machine used for autonomous operation test (a), antenna position on drill machine (b), AR application test (c) (credit: Roy Hill).

6.8. Road

Four projects have been carried out in the road sector including VicRoads, which looked at the Connected and Automated Vehicles (CAV) applications; New Zealand Ministry of Transport (MoT), which examined electronic Road User Charge (eRUC) applications; Curtin and Transport for NSW, which investigated Cooperative Intelligent Transport Systems (C-ITS) applications; and HERE Technologies, which looked at the production of High Definition (HD) maps. The aggregated results for the road sector are shown in Table 22 below followed by description of each project. The equipment in the sector varies from consumer-grade devices for various tracking applications to mid-range equipment where better accuracy is required. The road sector presents the most challenging scenario for GNSS as the environment changes rapidly and there are many obstructions especially in built-up and vegetated areas due to trees and buildings.

Table 22. Positioning results for the Road sector.

Road Sector		
Signal	Expected horizontal performance at 95% CI (m)	Expected vertical performance at 95% CI (m)
SBAS L1	1.08	3.02
DFMC	1.97	3.13
PPP	0.62	1.04

6.8.1. VicRoads

The VicRoads trial looked at using SBAS technologies for the CAV applications, in particular Highly Automated Driving (HAD). The trial used the Bosch HAD vehicle driving various routes in urban and rural environments to test whether SBAS L1, DFMC and PPP services would provide satisfactory level of positioning to support CAV applications. Currently, Bosch uses an expensive GNSS receiver in Real-Time Kinematic (RTK) mode coupled with Inertial Motion Unit (IMU) to provide the vehicle with centimetre-level positioning. Testing was carried out in metropolitan Melbourne between October 2017 and March 2018. Figure 24 shows the Bosch HAD vehicle.

Figure 24. Bosch HAD vehicle (credit: Bosch).

6.8.2. Ministry of Transport New Zealand

The New Zealand MoT project investigated whether accuracy improvements provided by the SBAS L1, DFMC and PPP signals could potentially reduce the cost of distance-based electronic road pricing and if it could enable more sophisticated forms of transport pricing, e.g. lane-based pricing, congestion pricing, national network pricing etc. The current eRUC system requires a combination of technologies to measure distance and identify vehicle location. Further consideration would need to be given to whether the accuracy improvements through SBAS could make it appropriate to use only two sources of information (SBAS and internal gyroscope), removing the need to access information from internal vehicle mechanisms (vehicle odometer) or use external sensors (external hubodometer). The testing was done in the Northern Island of New Zealand in the second half of 2018.

6.8.3. Curtin and Transport for NSW

The Curtin and Transport for NSW project focused on the C-ITS aspects of connected and automated vehicles and in particular road safety and network efficiency. In the road safety scenario Vehicle-to-Vehicle (V2V) communications were trialled to test whether it is possible to place a vehicle in a lane accurately and reliably using the SBAS L1, DFMC and PPP signals. The aim was to see whether the system could issue alerts if two vehicles are in close proximity and at the same time not issue any false alerts. In the network efficiency trial it was investigated whether the SBAS signals can improve network efficiency through the use of vehicle priority, with special attention given to heavy vehicles and buses. The testing was carried out in varied environments including urban, suburban and rural areas around Sydney and Wollongong between May and June 2018. Figure 25 shows some test routes.

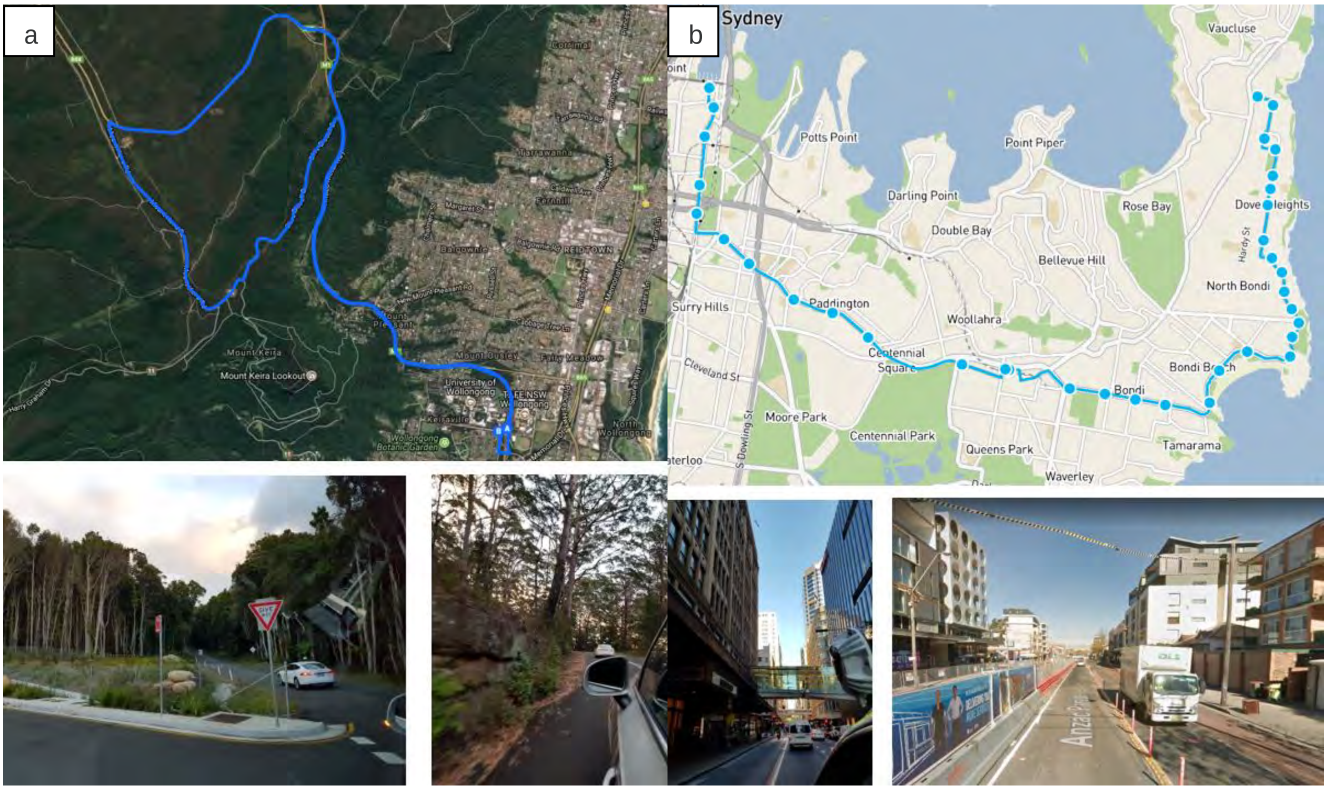

Figure 25. Examples route and photos of Wollongong rural area (a), and Sydney urban area (b) (credit: Curtin University).

6.8.4. HERE Technologies

The HERE Technologies project focussed on integrating PPP positioning into the HERE True street level imagery and Light Detection and Ranging (LiDAR) road data Reality Capture platform for highly automated driving. The main goal was to evaluate the accuracy of the SBAS signals in comparison to the HERE True results and determine any benefit of incorporating SBAS technology into the HERE Reality Capture Platform. Data was collected from areas of Sydney and rural New South Wales to test the accuracy of SBAS and HERE True signals in urban environments and over varied terrain. Ground control points in each working area were used to compare both SBAS and Here True systems positioning performance. Figure 26 shows the HERE True vehicle and the testing locations throughout NSW.

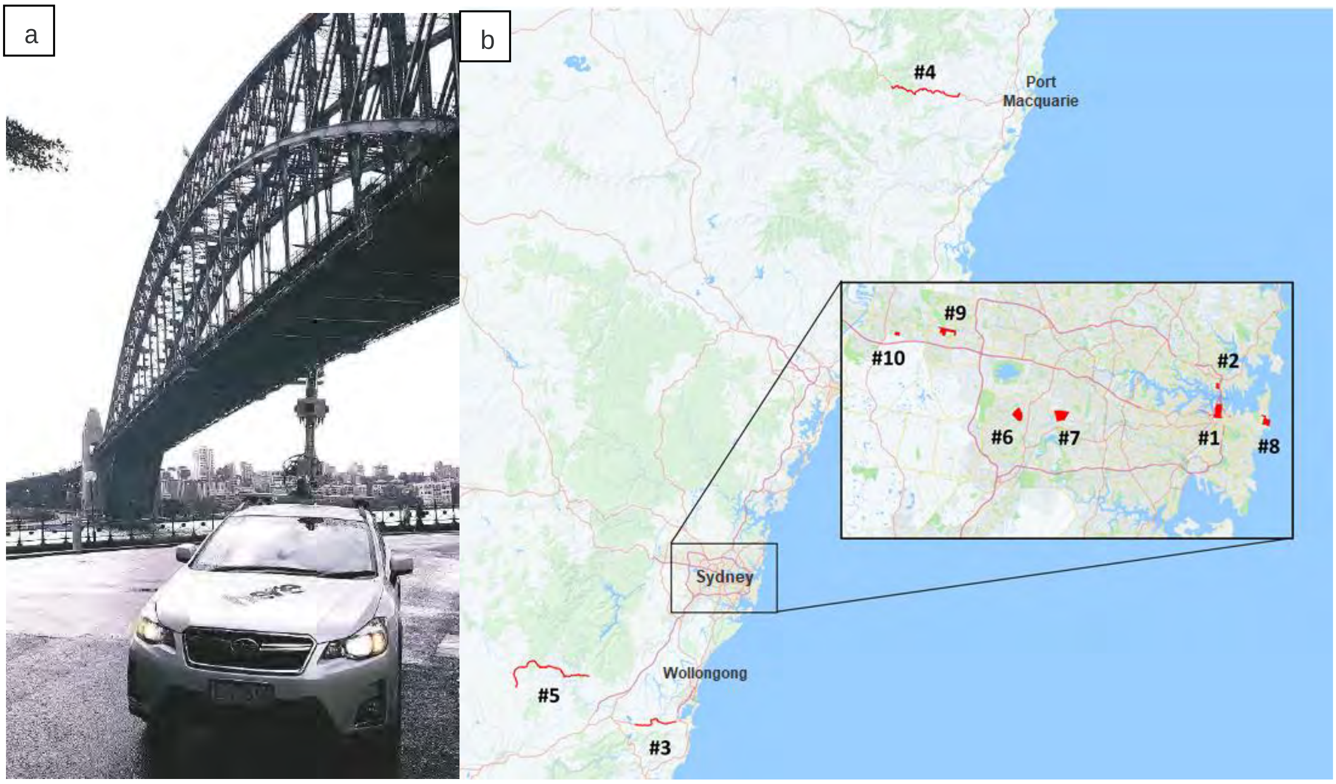

Figure 26. HERE True vehicle (a), testing locations around NSW (b).

6.9. Spatial

Four projects were carried out in the spatial sector including Department of Finance, Services and Innovation (DFSI) Spatial Services NSW, University of Otago, University of Tasmania (UTas) and Royal Melbourne Institute of Technology (RMIT). Both DFSI and RMIT examined the general accuracy achievable with SBAS and PPP services, University of Otago looked at SBAS being used for carrying out Class C cadastral surveys in New Zealand, and UTas tested UAS positioning in agriculture. Aggregated results for the sector are presented in Table 23 with short descriptions of the projects to follow. Equipment used in Spatial sector varies from mid-range to professional.

Table 23. Positioning results for the Spatial sector.

Spatial Sector		
Signal	Expected horizontal performance at 95% CI (m)	Expected vertical performance at 95% CI (m)
SBAS L1	0.87	1.36
DFMC	0.95	1.47
PPP	0.12	0.22

6.9.1. DFSI - Spatial Services

The objective of this project was to quantify the positioning quality achievable via SBAS L1, DFMC and PPP in a practical scenario to evaluate the potential benefits of SBAS technology for the surveying and spatial profession. This benefit applies particularly to remote locations with intermittent or non-existent mobile phone coverage which cannot leverage existing RTK or network NRTK positioning without a reliable connection. Testing was carried out around Lucknow, NSW in November and December 2017.

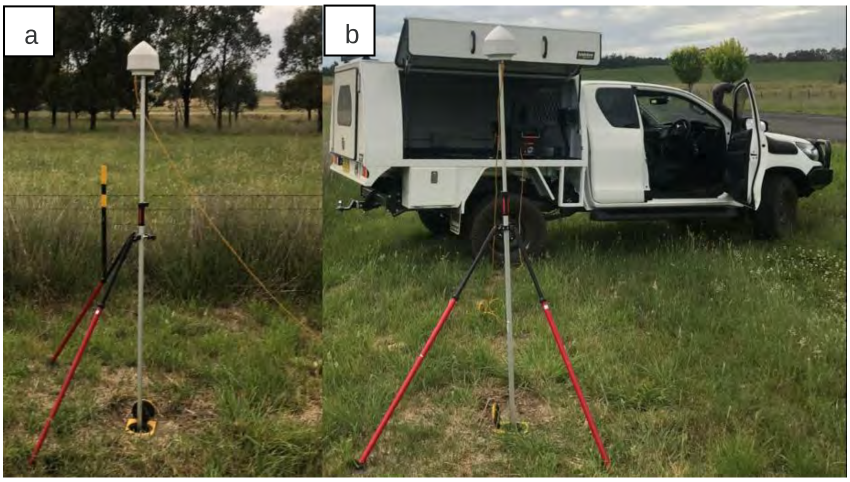

Figure 27. Recording sessions over a permanent mark (a), SBAS kit in nearby vehicle (b) (credit: DFSI).

6.9.2. University of Otago

The University of Otago test-bed project aimed to evaluate the effectiveness of using the SBAS L1, DFMC and PPP signals to conduct low accuracy rural surveys (referred to as Class C surveys in New Zealand, there is no Australian equivalent term). A demonstrated horizontal accuracy level of around 0.6 metres is required for the SBAS positioning service to meet the specified accuracy for Class C surveys.

Testing took place at four rural survey sites near Dunedin, New Zealand in December 2017. The sites exhibited a range of environmental and topographic conditions typical of Class C surveys across the country. These environments included a "best-case" site with few obstructions to the sky view, steep grassland-country typical of New Zealand South Island, including an area that was both heavily vegetated and steep. Figure 28 shows conditions at three of these sites.

Figure 28. Rural survey sites near Dunedin, New Zealand. Open terrain (a), steep terrain (b), vegetated terrain (c) (credit: University of Otago).

6.9.3. RMIT

The high precision surveying community has a strong demand for instantaneous cm-level positioning accuracy to support various applications (e.g. cadastral surveying, deformation monitoring, engineering set out). The RMIT project tested the suitability of SBAS L1, DFMC and PPP signals for the surveying community, by doing four tests around Victoria in Castlemaine, Queenscliff, and Bundoora between January and April 2018. These tests aimed to compare the absolute positioning accuracy provided by each signal compared to a post-processed ground truth in a static environment. Some images of the test equipment and sites can be viewed in Figure 29.

Figure 29. Tests carried out during the RMIT project: Open area (a), partially obstructed area (b) (credit: RMIT).

6.9.4. University of Tasmania

The UTas project looked at UAS positioning using SBAS L1, DFMC and PPP services, with a case study in the agricultural sector. The project was carried out in collaboration with industry partners Australian UAV and the Tasmanian Institute of Agriculture. The two primary aims of the project were firstly to test if the new SBAS receivers were able to accurately log the position of a UAS during flight, and secondly to test if this position could be used to create accurate orthomosaics from the captured imagery. To achieve these aims an experimental system was set up on a UAS that allowed the position of the antenna to be logged during flight by two receivers collecting SBAS solutions as well as a conventional dual frequency post-processed kinematic system. Additionally, there was a multispectral camera to collect imagery, much like it would if set up as a precision agriculture mapping system. Figure 30 shows the photo of the UAS on the ground and in flight.

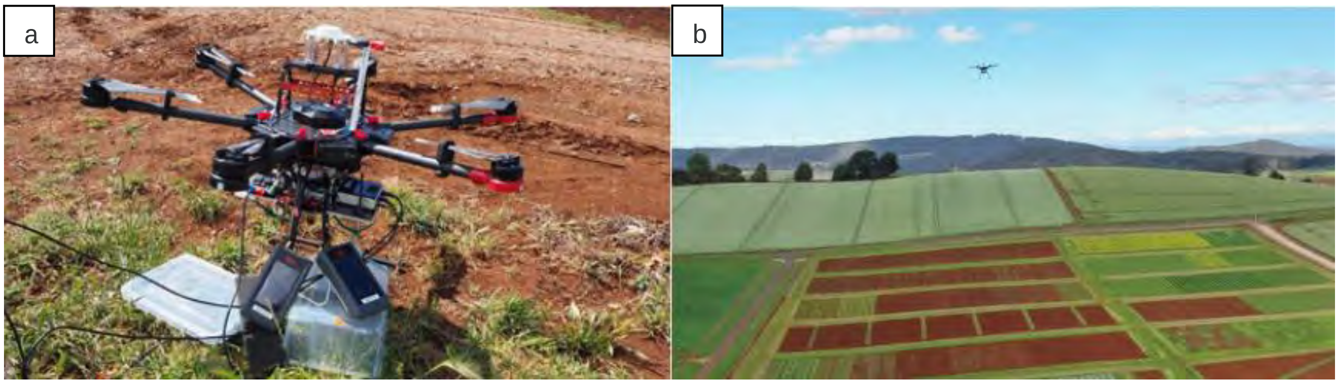

Figure 30. UAS testing during the UTas project: MagicUTs attached to UAS (a), UAS in flight (b) (credit: UTas).

6.10. Utilities

A single project was carried out in the utilities sector by Orbica and Reveal Infrastructure in Christchurch New Zealand. The project looked at improving the lifecycle of data collection using PPP services. The results from the project are presented in Table 24 followed by the description of the project. Mid-range to professional equipment is used in the Utilities sector and the environment varies depending on location.

Table 24. Positioning results for the Utilities sector.

Utilities Sector		
Signal	Expected horizontal performance at 95% CI (m)	Expected vertical performance at 95% CI (m)
SBAS L1	N/A	N/A
DFMC	N/A	N/A
PPP	0.39	0.76

6.10.1. Orbica and Reveal Infrastructure

The project aimed to test whether PPP technology would allow asset management data to be collected and processed on site in a timeframe that did not disrupt site works and to an accuracy that made it safe to rely on to excavate. This project also aimed to test and demonstrate that PPP technology can enable the democratisation of the collection, fixing and sharing of asset data, improving its reliability, which will lead to a reduction in costs and risks for central and local governments, asset owners and the Utilities industry. While this project focussed primarily on the use cases within the Water sector, there are a number of potential further applications for the PPP signals in the wider utilities sector which were not examined due to project scope and time constraints. This demonstrator project was completed between October 2017 to August 2018 in Christchurch, New Zealand. Figure 31 shows some examples of the testing carried out.

Figure 31. SBAS testing in various environments around Christchurch: open sky conditions at geodetic marker (a), partially obstructed environment (b), obstructed urban environment (c) (credit: Orbica).

6.11. FrontierSI Testing

In addition to the 27 projects in the nominated industry sectors, FrontierSI has also carried out some performance evaluation of the SBAS services. The testing included:

- Static testing of a number of consumer and mid-range devices with L1 SBAS, DFMC and PPP services
- Kinematic testing (car drive) of L1 SBAS, DFMC and PPP services
- Forestry testing of L1 SBAS

All the results from that testing are included in the FrontierSI Technical report which can be found in Appendix C.

7. Media Coverage

The SBAS test-bed has received a lot of media attention during the two year time period. A number of ministerial events were held including:

- CQUniversity event in Rockhampton on 9 November 2017
- VicRoads event in Melbourne on 13 December 2017
- Airservices Australia event in Canberra on 16 March 2018
- Kondinin event in Emerald, Queensland on 19 March 2019

Figure 32 shows photos from two such events.

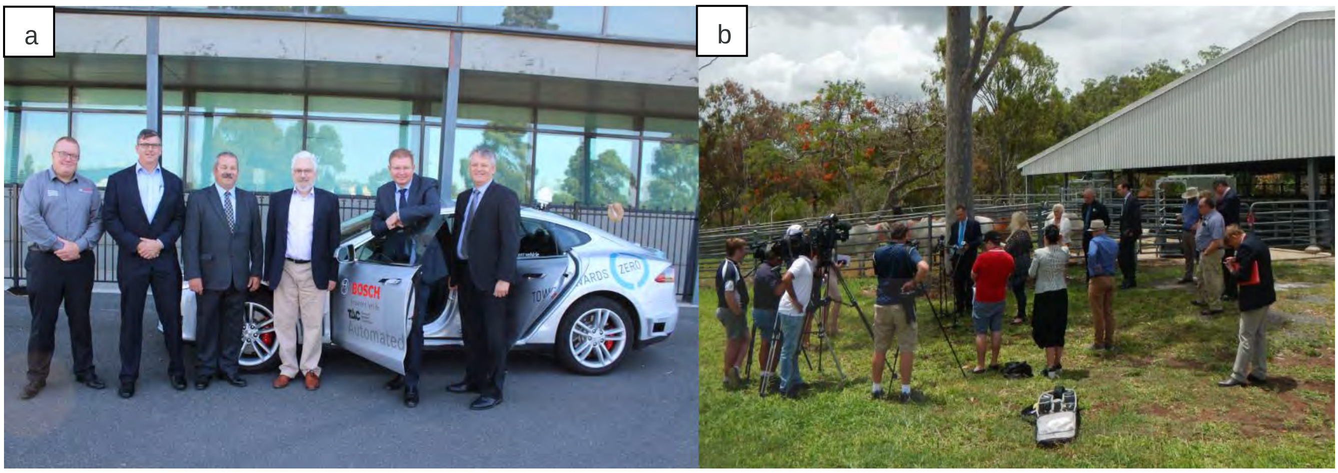

Figure 32. Vicroads project media event (a), Minister Canavan speaking to the media at the CQU test launch (b).

In the course of the project there were 176 media articles appearing in-print, online and televised about the SBAS test-bed project. These articles ranged from coverage about specific projects, to broader industry gains the precise positioning technology will allow. Project partners, along with Geoscience Australia, Land Information New Zealand and other government departments assisted with the preparation of materials to ensure the consumer benefits of an operational SBAS could be understood by a general audience.

The full list of SBAS Test-bed coverage in the media can be found in Appendix B.

8. Discussion

The testing campaign that was carried out during the two-year SBAS testbed was substantial and covered many different sectors and scenarios. Generally, it was found that under good observing conditions all three signals performed as expected, i.e. sub-metre instantaneous horizontal positioning for SBAS L1 and DFMC and decimetre-level horizontal positioning for PPP after a convergence period of 30-40 minutes. The vertical positioning error was approximately twice the magnitude of that for horizontal positioning. However, it was also noted that the positioning performance was affected by several factors:

- The observing environment can change from open sky to medium and severe obstruction limiting the number of GNSS satellites that could be observed. Obstructions can also block the correction signal from the SBAS satellite. The most common types of obstructions include buildings, trees, machinery (on construction and mining sites).
- Receiver and antenna hardware play a paramount role in the resulting positioning performance. It was found that in consumer-grade devices, there is little improvement in positioning performance with SBAS over standalone GNSS, whereas if upgraded to mid-range equipment (typically costing between $2,000-3,000AUD) the accuracy improvements were significant.

As such, the positioning performance can vary from sector-to-sector depending on the environment and the equipment that is applicable to each sector. Various signals are also more applicable to different sectors. For example, aviation was only interested in the SBAS services (not PPP) due to the integrity component, whereas maritime presents an ideal environment for PPP due to the fact that the receiver is usually always powered on, and hence the issue of convergence is readily overcome. The consumer sector is presently only interested in the SBAS L1 signal, because it is readily available on all consumer grade GNSS boards, including those in mobile phones.

It is also worth noting that during the beginning of the testbed, DFMC did not initially show improved results, being the first live implementation of that signal in the world. However, as the test-bed progressed, the performance improved significantly and reached that of SBAS L1 and in certain cases showed an improvement over SBAS L1.

8.1. Sector findings discussion

Apart from the general findings described above, sector-specific findings are discussed below.

- Aviation – both SBAS L1 and DFMC have met the ICAO guidelines for precision approaches with vertical guidance. DFMC showed slight improvement over SBAS L1 in positioning performance as well as protection levels, which is a key measure of integrity in aviation.

- Road – from the testing in the road sector it was shown that all three SBAS signals are sufficiently accurate to pinpoint the car to the correct lane, hence can provide direct benefit for eRUC applications. However, it also became clear that the road environment changes rapidly and as such provides challenging conditions for any satellite-based positioning solution. As such, using SBAS or PPP on their own will not be possible to enable CAV applications. A combination of different absolute and relative positioning technologies will be needed for that purpose.

- Agriculture – testing in the agriculture sector focussed on three separate areas – cattle tracking, machine guidance and forestry. Each of these application areas is quite different in terms of observing environment and equipment. In the cattle tracking environment, SBAS has shown promise in improving GNSS accuracy to sub-metre, which can lead to new applications such as forage front virtual fencing, or in other terms a virtual fence that moves slowly with time allowing the cattle to utilise the complete pasture and reduce wastage significantly. The challenge remains to develop SBAS and PPP-enabled hardware in a small enough form factor and long battery life that can be used on cattle and sheep. In the machine guidance scenario, PPP showed promise by achieving sub-decimetre pass-to-pass accuracy, however the convergence time still poses a problem and the challenge remains to reduce it to a few minutes instead of tens of minutes. SBAS solutions can be used for low-precision manual tasks such as spraying. Finally, forestry testing showed the potential of SBAS positioning to achieve sub-metre accuracy using mid-range hardware even under very dense canopy.

- Maritime is an important sector for both SBAS and PPP positioning. PPP can be used for many high-precision tasks in the industry, since convergence is not an issue (as the receiver is always on). SBAS also has a role due to the integrity component, however the "integrity" for maritime operations as defined by the International Maritime Organisation (IMO) is different to the ICAO definition. EGNOS testing in Europe suggests that SBAS is capable satisfying the IMO requirements (Segura et al., 2019).

- Rail – from the testing conducted in the rail sector it can be concluded that SBAS can have significant potential to be used in train control systems as well as providing better positioning in difficult environments. It also has potential in safety applications, tracking rail workers in real-time.

- Construction – whilst many applications in the construction sector require centimetre accuracy (which cannot be provided by SBAS or PPP), SBAS showed potential in the field of personnel and machinery tracking on construction sites. Another application that was not explicitly tested in this sector (but was tested in the Resource sector) is Augmented Reality (AR) applications, such as visualising 3D objects on a tablet or a helmet.

- Resources – both SBAS and PPP have shown potential in a number of areas in the open pit mining environment. Applications such as anti-collision systems, digital pegging, AR applications, accurate haul truck movement monitoring all stand to benefit from SBAS and PPP services. The most significant challenge at the moment is the antenna placement on the mine vehicles.

- Spatial – applications within the spatial sector are very wide ranging and there are many areas where SBAS and PPP can offer substantial benefit, especially in areas such as UAS mapping, GIS data collection and any other application where decimetre to sub-metre horizontal positioning accuracy is sufficient.

- Consumer – the consumer sector also has a very wide-ranging set of potential application areas, however only two were tested – delivery robots and navigation for visually impaired people. Both of these applications showed promise and there is scope to do more work in these areas. The biggest challenge in this sector is the consumer-grade hardware which has been shown to offer very little improvement from SBAS positioning. Better quality receivers and antennas are needed in order to fully capitalise on many applications in this sector. One potential area of further research is the PPP positioning on mobile phones. This can only be achieved on models with dual-frequency GNSS chipsets, which are starting to come onto the market.

- Utilities – only a single project was carried out in this sector, which did not illustrate the full potential of SBAS and PPP positioning. Asset management, especially of above-ground assets is one area where both SBAS and PPP can offer benefits to the sector.

9. Conclusion

This report summarises the technical side of the work carried out by FrontierSI during the course of the SBAS test-bed from January 2017 to January 2019. FrontierSI managed 27 projects testing SBAS technology across 10 industry sectors including aviation, road, rail, maritime, agriculture, construction, resource, utilities, spatial and consumer in Australia and New Zealand. Three different signals were broadcast including L1 Legacy SBAS, DFMC and PPP. The SBAS L1 signal was available for testing from June 2017, and both DFMC and PPP were available from October 2017.

It was shown that under good observing conditions all three signals achieved the expected performance which is sub-metre horizontal positioning for SBAS L1 and DFMC and decimetre-level horizontal positioning for PPP after a period of convergence, which is typically 30-40 minutes. The vertical accuracy was roughly twice that possible in the horizontal plane. It was also noted that the performance of the signals is highly dependent on two key factors, which are the observing environment, specifically the level of obstruction, and the quality of GNSS receiver and antenna hardware.

In all industry sectors the testing concentrated on the positioning accuracy apart from aviation, where both accuracy and integrity were examined. It was found that the performance of SBAS L1 and DFMC was sufficient to meet the ICAO standards for precision approaches with vertical guidance.

10. Recommendations

A variety of follow-on research & development (R&D) projects could be conducted, with the aim to promote and increase awareness of SBAS and its various applications (only some of which are known). Projects have been identified by the current SBAS test-bed team from discussions with industry, initial EOI project submissions and through industry knowledge gained from the SBAS test-bed project. The projects would not need to be restricted to the ten industry sectors identified for the SBAS test-bed.

These projects could be performed with a group of organisations, CRCs or manufacturers. The projects could run for up to a year and start at various times from July 2019. Ideally 3-5 projects would be run each year.

The industry projects would be selected upon identification of which sectors have higher awareness needs, or more difficult challenges to solve. The projects would target these specific areas to ensure any barriers to adoption are overcome, or perceived technical difficulties are assessed .

Some areas for industry projects include:

- Development of an industrial collar or ear tag for advanced high precision virtual fencing applications
- Automation applications in mining
- UAS delivery applications
- Augmented reality applications in construction and utilities sectors
- SBAS and PPP positioning in advanced train control systems
- Robust positioning for automated vehicles in difficult environments
- SBAS-aided navigation systems for people with visual impairment

As well as the industry projects that could be used to increase uptake of the technology, there is scope for R&D related projects to learn more about technical performance of the technology. Some areas for research projects include:

- SBAS and PPP positioning on a mobile phones
- Assessment of commercial equipment with SBAS and PPP positioning
- DFMC receiver development
- IoT in agriculture (2-way communications)
- Search and rescue applications (2-way communications)
- SBAS and PPP positioning comparison to QZSS services
- Understanding the ionospheric effect on SBAS L1 and DFMC in various parts of Australia
- Developing integrity measures for non-aeronautical applications for both SBAS and PPP
- Interoperability of DFMC and PPP with other positioning systems such as QZSS
- Site selection for SBAS reference stations
- Interference analysis on SBAS and PPP positioning

11. References

Ernst & Young (2019). SBAS Test-bed Demonstrator Trial: Economic Benefits Report.

European Global Navigation Satellite Systems Agency (GSA), (2018). *GNSS User Technology Report Issue 2*.

Segura D.I., J.M. Juan, H. Jia, A.R. Garcia, M.T. Alonso, F.J.P. Garcia, J. Sanz, J.A.L. Salcedo, M.L. Martinez (2019). Assessment of EGNOS Availability, Continuity and Coverage for maritime applications. Proceedings of European Navigation Conference, Warsaw, 9-12 April 2019.

Appendix A Final SBAS Project List

All details available on the SBAS projects is compiled and shown within Table 25.

Table 25. SBAS Test-bed Projects – Detailed Information.

No	Lead organisation	Sector	Sub-category	Project title	Country	Specific Region	Signals tested	Project Participants	Project start	Project end
1	CQUniversity Australia	Agriculture	Livestock	Increased accuracy in on-animal spatio-temporal monitoring for livestock sensing applications	Both	QLD (Rockhampton) and NZ	L1	•CQUniversity Australia •Dairy NZ	11-Sep-17	31-Jan-19
2	Venture Southland	Agriculture	Forestry	Real-time SBAS-assisted production forestry management and planning	NZ	NZ (Southland)	All	•Venture Southland •Southwood Export Ltd •University of Otago	14-Feb-18	15-Dec-18
3	Forestry Corporation of NSW	Agriculture	Forestry	Operational use of SBAS in production forests	Australia	NSW (Orara East State Forest, North Coast and Bathurst)	L1, DFMC	•Forestry Corporation of NSW	01-Jul-18	05-Dec-18
4	Kondinin Group	Agriculture	Broadacre	Identifying and quantifying the economic and environmental benefits of SBAS technology to Australian grain production	Australia	VIC (SW area) and QLD (tractor test)	All	•Kondinin Group •Precision Agriculture •Grains Research and Development Corporation	01-Mar-18	15-Dec-18
5	CFIG	Agriculture	Broadacre	Putting SBAS into the hands of farmers	Australia	WA (Corrigin)	All	•Corrigin Farm Improvement Group •ThinkSpatial •UNE •Wheatbelt Science	26-Feb-18	15-Dec-18

No	Lead organisation	Sector	Sub-category	Project title	Country	Specific Region	Signals tested	Project Participants	Project start	Project end
6	Page Bloomer Associates Ltd	Agriculture	Horticulture	Appropriate precision for horticultural farm management	NZ	Levin, Hawke's Bay, Auckland	L1, PPP	•Page Bloomer Associates Ltd •LandWISE Inc •GPS Control Systems Ltd •Forest Value Recovery •Hectare Group Ltd	01-Apr-18	30-Sep-18
7	Plant and Food Research	Agriculture	Viticulture	Geospatial resolution in vineyards	Both	NZ (Hawke's Bay and Marlborough) and NSW (Orange area)	All	•Plant and Food Research •UNSW •SeeSaw Wines •Whitehaven Wines	26-Feb-18	31-Jul-18
8	Airways New Zealand	Aviation	Aviation	SBAS navigation benefits for New Zealand aviation system	NZ	NZ (all)	L1, DFMC	•Airways New Zealand •Aeropath New Zealand •Auckland Rescue Helicopter Trust •IQ Aviation •Helicopters Otago Ltd (Trading name Heliotago)	22-Dec-17	31-Jul-18
9	Airservices Australia	Aviation	Aviation	SBAS benefits for Australian aviation	Australia	ACT (Canberra), NT (Darwin) and around Australia	L1, DFMC	•Airservices Australia •ASTRA •The University of Melbourne	22-Dec-17	31-Jul-18

No	Lead organisation	Sector	Sub-category	Project title	Country	Specific Region	Signals tested	Project Participants	Project start	Project end
10	Position Partners	Construction		Fit for purpose, high-accuracy, space based augmentation services applied to precision guidance, remotely piloted and safety systems for construction and utilities industries in Australia and New Zealand	Australia	VIC, NSW, QLD	All	•Position Partners (Australia/NZ) •University of New South Wales (UNSW)	01-Nov-17	28-Dec-18
11	QUT	Consumer		Exploring opportunities for a special needs routing platform with SBAS	Australia	QLD (Brisbane, Gold Coast)	All	•Queensland University of Technology •Locatrix Communications •Vision Australia •Gold Coast City Council	01-Nov-17	21-Feb-19
12	Australia Post	Consumer		Autonomous last-mile parcel delivery	Australia	QLD (Brisbane), NSW (Sydney)	L1	•Australia Post •Marathon Robotics	19-Mar-18	15-Dec-18
13	Acoustic Imaging Pty Ltd	Maritime		Marine pilotage, navigation & offshore survey enhancement project	Australia	NSW (Sydney)	L1, PPP	•Acoustic Imaging Pty Ltd •Port Authority of NSW	03-Nov-17	31-Jan-19

No	Lead organisation	Sector	Sub-category	Project title	Country	Specific Region	Signals tested	Project Participants	Project start	Project end
14	MIAL	Maritime		A comprehensive maritime assessment on the impact of an operational SBAS and the potential business critical applications	Both	Various	All	•Maritime Industry Australia Ltd •Various MIAL members and connections for testing	08-Nov-17	31-Jul-18
15	Identec Solutions	Maritime		SBAS Testing for Terminal Process Automation	Australia	NSW (Sydney), VIC (Melbourne)	All	•Identec Solutions Australia and New Zealand Pty Ltd •DP World Australia Ltd •RMIT	15-Apr-18	31-Jan-19
16	Position Partners	Rail		SMART Rail (Satellite Management Assisting Rail Transport)	Australia	Tasmania	All	•Position Partners •Institute of Railway Technology at Monash University •Tasmanian Railway Pty Ltd	05-Feb-18	30-Jul-18
17	QUT	Resources		Demonstration of SBAS signals for improved surface mine operation safety and productivity	Australia	QLD (Brisbane, Middlemount)	All	•Queensland University of Technology •Wenco International Mining Systems Ltd	01-Nov-17	31-Jan-19
18	Curtin University	Resources		Positional improvements for digital mines	Australia	WA	All	•Curtin University •Roy Hill	21-May-18	15-Jan-19

No	Lead organisation	Sector	Sub-category	Project title	Country	Specific Region	Signals tested	Project Participants	Project start	Project end
19	VicRoads	Road	CAV/ITS	VicRoads road safety action plan 2016 – 2020 Highly Automated Driving with SBAS trial	Australia	VIC (Melbourne)	All	•VicRoads •Robert Bosch (Australia) Pty Ltd •Transport Accident Commission •RMIT	18-Sep-17	29-Jun-18
20	Ministry of Transport New Zealand	Road		National heavy vehicle differential pricing trials project	NZ	NZ (all)	All	•Ministry of Transport •New Zealand Transport Agency •Beca	01-Dec-17	21-Dec-18
21	Transport for NSW	Road	CAV/ITS	SBAS for connected vehicles: the potential road safety and efficiency gains through the use of an Australian Satellite-Based Augmentation System	Australia	NSW (Sydney, Wollongong)	All	•Curtin University •Transport for NSW •Roads and Maritime Services •UNSW	01-Feb-18	31-Oct-18
22	Here Technology Pty Ltd	Road		Technology Demonstrator of Augmented Differential Positioning using the FrontierSI LINZ GA SBAS Technology integrated with HERE True SLI & LiDAR Road Reality Capture Platform for Highly Automated Driving	Australia	Various	All	•HERE Technology	01-Jan-18	09-Nov-18
23	Department of Finance, Services and Innovation - Spatial Services	Spatial		Assessing dual-frequency multi-constellation SBAS and SBAS-aided Precise Point Positioning for surveying applications	Australia	NSW	All	•Department Finance, Services and Innovation - Spatial Services	18-Sep-17	29-Jun-18

No	Lead organisation	Sector	Sub-category	Project title	Country	Specific Region	Signals tested	Project Participants	Project start	Project end
24	University of Otago	Spatial		SBAS applications for low accuracy rural cadastral surveys	NZ	NZ (Dunedin)	All	•University of Otago •Trimble New Zealand Solutions	01-Nov-17	15-Jun-18
25	RMIT	Spatial		Assessing dual-frequency multi-constellation SBAS and SBAS-aided Precise Point Positioning for survey and/or mapping applications in Victoria	Australia	VIC	All	•RMIT •Department of Environment Land Water and Planning	01-Jan-18	05-Jan-19
26	University of Tasmania	Spatial	UAS	Precision and accuracy of Unmanned Aircraft System (UAS) positioning with SBAS, DFMC and PPP – application in precision agriculture	Australia	TAS	All	•University of Tasmania •Tasmanian Institute for Agriculture •Australian UAV	05-Mar-18	21-Dec-18
27	Orbica	Utilities		Improving Australasia's field to office asset data lifecycle	NZ	NZ (Christchurch)	PPP	•Orbica Limited, New Zealand •Reveal Infrastructure Limited •Enable Networks Ltd	18-Sep-17	31-Jul-18

Appendix B Media coverage

SBAS Media Coverage		
Date	Source	Article Name
8/05/2019	spaceconnectonline.com.au	Geoscience Australia seeks EOIs for super accurate GPS services
6/05/2019	CIO Australia	Government ups the ante on securing Australia with satellites
17/04/2019	Computerworld Australia	Location, location, location: How Australia is getting precise about positioning
24/04/2019	NZCity	Global positioning system is our best navigation network, but this may change in five years
22/04/2019	Farming ahead	Free-to-air high precision GPS tested to 10cm
19/04/2019	Seven Local News Rockhampton	Self-driving tractor successfully trialled in Emerald will be available to farmers nationwide ...
19/04/2019	graincentral.com	Satellite technology to boost the future of farming
31/01/2019	Infrastructuremagazine.com.au	Cybersecurity experts sought for satellite spatial program
30/01/2019	Spatialsource.com.au	Expert input sought on SBAS cybersecurity strategy
21/01/2019	Australiancybersecuritymagazine.com.au	Cyber Security Strategy – Satellite -Based Augmentation System (SBAS)
18/01/2019	Computerworld New Zealand	Geoscience Australia works to secure positioning infrastructure from hackers
18/01/2019	Computerworld Australia	Geoscience Australia works to secure positioning infrastructure from hackers
18/01/2019	ARN	Geoscience Australia seeks guidance on satellite cyber security
7/01/2019	Createdigital.org.au	Meet one engineer sharpening the focus of our satellite positioning systems
11/12/2018	Spatialsource.com.au	SBAS construction site safety trial holds promise
22/10/2018	RMIT University	Better GPS opens new opportunities for industry
15/10/2018	defenceconnect	To infinity and beyond: On Point with Karl Rodrigues, Australian Space Agency
20/09/2018	Insidegnss.com	Lockheed Martin's SBAS Research Project in Thailand to Study Ionospheric Disturbance on Signals

6/09/2018	Business Acumen Queensland	Satellite technology lifts safety and efficiency in our skies
15/08/2018	Spatialsource.com.au	Q&A with Peter Woodgate
26/07/2018	Australian Flying	Regional SBAS Trials prove Successful
23/07/2018	PSNews	Airservices spreads wings with satellite system
23/07/2018	Daily Advertiser, Wagga Wagga	Satellite trial gets launch at airport
20/07/2018	Daily Advertiser, Wagga Wagga	New satellite trial boosts Wagga Airport safety and efficiency
20/07/2018	The Australian	Satellite-based augmentation system a step close
16/07/2018	Flight Safety Australia	Precisely to the point; the promise of satellite-based augmentation
5/07/2018	Whatech.com	Budget boosts precise location services
3/07/2018	Insidegnss.com	Australia Funds 4-year GNSS Plan, New Space Agency
14/06/2018	Reseller News	NZ shipping trial delivers leap in GPS accuracy
13/06/2018	Spatialsource.com.au	Ultra precise 3D mapping cars hit Australian roads
12/06/2018	Geospatial World	Mapping cars hit Australian roads fitted with world-first satellite positioning technology
25/05/2018	Space & Satellite AU newsletter	Geoscience Australia preparing to procure two satellite payloads for positioning capability
25/05/2018	Farm Weekly	Putting SBAS into the hands of WA farmers
16/05/2018	WA Today	The new space age is here
16/05/2018	Sydney Morning Herald	The new space age is here
16/05/2018	Weekly Times	Federal Budget invests in GPS agricultural technology
15/05/2018	Spatial Source e-newsletter	Canberra to host space agency from July 1
10/05/2018	Fully Loaded ATN	BUDGET GPS FUNDING LIFT AS MOBILE SCHEME ENDS
10/05/2018	Geospatial World	Australia allocates funds for National Positioning Infrastructure, Digital Earth Australia and SBAS in the federal budget
10/05/2018	Flight Safety	Budget funding for SBAS
10/05/2018	Science meets Business	Why can't my Uber find me?
10/05/2018	The Australian	GPS funding 'game-changer' for Royal Flying Doctor Service
10/05/2018	Mashable Australia	Why Australia is spending millions to make GPS signals more accurate

9/05/2018	Spatial Source e-newsletter	$260 million for GNSS and imagery
1/05/2018	Know How magazine	Why can't my Uber find me?
30/04/2018	Spatial Source e-newsletter	SBAS precision to support rural pilots
27/04/2018	Open Gov Asia	Geoscience Australia conducts aviation trial on satellite-based augmentation system
27/04/2018	Infrastructure	Satellite technology tested at Sydney port
24/04/2018	The National	New satellite system to make aviation safer
19/04/2018	Infrastructure	Satellite positioning technology guides new trial
19/04/2018	Coffs Coast Advocate	Airport tracking is heading for the stars
18/04/2018	Spatial Source e-newsletter	Four future trends from Locate '18
18/04/2018	IT News	Airservices trials precise plane guidance into regional airports
17/04/2018	Manufacturers' Monthly	Australia's new aviation trial looks to benefit from satellite technology
17/04/2018	Airline Ratings	NEW SATELLITE SYSTEM TO MAKE AVIATION SAFER
17/04/2018	Australian Aviation	Aviation trials with SBAS technology to kick off in June
16/04/2018	4-Traders	Airservices Australia : Satellite technology pinpoints regional pilots in new aviation trial
16/04/2018	Public Now	Satellite Technology Pinpoints Regional Pilots In New Aviation Trial
13/04/2018	WhaTech	Pinpointing pipe locations, with satellites
13/04/2018	The Australian	Satellite system heralded for its safety benefits
4/04/2018	Infrastructure e-newsletter	Satellite positioning trial hints at the future of our roads
29/03/2018	Get Business	SBAS test bed provides positioning by land, sea, and air to within 10cm
28/03/2018	IMOVE CRC news	SBAS test bed provides positioning by land, sea, and air to within 10cm
27/03/2018	Spatial Source e-newsletter	Megaliner in Sydney SBAS trial
26/03/2018	Public Now	Smooth Sailing For Satellite Positioning Technology Trial
26/03/2018	Royal Caribbean blog	Royal Caribbean helping to test new satellite system
9/03/2018	Flight Safety Australia 2017 Collectors' Edition	Navigating till the cows come home

1/03/2018	Infrastructure magazine	SATELLITE POSITIONING TRIAL HINTS AT THE FUTURE OF OUR ROADS
23/02/2018	Position Partners	Position Partners focussed on R&D in 2018
7/02/2018	Scoop NZ	NZ tech firm tests ground-breaking satellite technology
1/02/2018	Utility Magazine	Satellite technology to enable advanced asset location
14/12/2017	ITWire	VicRoads uses satellite positioning tech in automated driving tests
14/12/2017	Public. (website)	VicRoads On The Highway To Innovation
14/12/2017	Car Advice (online)	World-first satellite tech being tested in Melbourne
28/11/2017	4-traders website	Australian Government : World first for Australian maritime industry
28/11/2017	Public. Website	World First For Australian Maritime Industry
24/11/2017	Computerworld New Zealand	Sat nav systems get super-accurate
23/11/2017	WhaTech Channel	Get centimetre accurate positioning – on your smartphone
22/11/2017	Voxy.co.nz	New Zealand industries trial advanced GPS technologies
22/11/2017	LINZ website	New Zealand industries trial advanced GPS technologies
17/11/2017	TV: Seven Mackay, Mackay, Seven News Mackay, Rob Brough	No further details available
17/11/2017	7 News Central Queensland	No further details available
15/11/2017	Satnews Daily	Satellite-Based Augmentation System Trial Launched by Australia
15/11/2017	W3 Live News/Australasian Transport News	New satellite positioning system to have freight use
15/11/2017	W3 Live News/Computerworld New Zealand	ANZ project to improve satellite navigation launches
14/11/2017	Australasian Transport News	New satellite positioning system to have freight use
14/11/2017	NZ Herald online edition	Juha Saarinen: How to keep hands-free cars on the road
14/11/2017	Inside GNSS	Industry Trial of Australian SBAS Officially Launched
14/11/2017	Computerworld New Zealand	ANZ project to improve satellite navigation launches
13/11/2017	Computerworld from IDG	Trial of ultra-precise location tech launches

13/11/2017	Spatial Source e-newsletter	Australia launches regional SBAS positioning trial
13/11/2017	ITWire	The Australian Government has launched a GeoScience-led trial of what is claimed as "world-first" satellite positioning technology.
12/11/2017	Government News	Government announces 'world first' satellite positioning system
10/11/2017	Australian Aviation	Cattle farmers kick off two-year Australia/New Zealand SBAS trial
10/11/2017	The Morning Bulletin	CQU first to trail 'world-first' satellite positioning
10/11/2017	Daily Cargo News	Guidance from the heavens to the seas: new satellite positioning tech trial underway
9/11/2017	4-traders	Geoscience Australia : Industry trial of Australian Satellite-Based Augmentation System officially launched
9/11/2017	4-traders	Australian Government : launches trial of world-first satellite positioning technology
9/11/2017	The Morning Bulletin	Canavan lashes out at Palaszczuk's 'dog act' Adani move
9/11/2017	Whitsunday Times	Launch of world-first satellite technology in Rocky
8/11/2017	CQUniversity website	CQUni among first to join trial of new satellite positioning technology
25/09/2017	Executive Biz	Lockheed Satellite-Based Augmentation System Testbed Begins DFMC Signal Transmission
22/09/2017	Inside GNSS	Lockheed Martin's Second-Generation SBAS Testbed Achieves Another Milestone
17/08/2017	The Armidale Express	New Satellite Based Augmentation System technology set to revolutionise Australian industries
17/08/2017	The Guyra Argus	New Satellite Based Augmentation System technology set to revolutionise Australian industries
30/06/2017	Position magazine (June/July 2017)	Details of SBAS testbed revealed
21/06/2017	Science Meets Business	Navigating the future of GPS
20/06/2017	TimeBase	Driverless Cars Being Considered in Parliamentary Inquiry
1/05/2017	Knowhow magazine	Navigating GPS's future
1/05/2017	International Astronautical Federation (IAF) E-newsletter	New research to improve positioning in Australia and New Zealand
20/04/2017	Spatial Source e-newsletter	The precise positioning program, explained

19/04/2017	Safety Solutions	Positioning technology boosts safety in resources industry
18/04/2017	Unconventional Oil & Gas (no longer exists)	New positioning technology for resources industry
12/04/2017	Utility online magazine	New positioning technology testing for utility industry
12/04/2017	Stock Journal	Ag tests new precision tech
12/04/2017	Farm Online	Ag tests new precision tech
12/04/2017	ITWire	Positioning technology trials for spatial industry
11/04/2017	Air Cargo Asia Pacific	SBAS trial in Australia needs aviation participants
11/04/2017	Lloyds List Australia	FREE: New positioning technology to be tested
11/04/2017	WNIPT	Trial of new positioning technology for resources industry
10/04/2017	GA website	Trial of positioning technology across nine industries
3/04/2017	Spatial Source e-newsletter	Novel projects sought for satellite positioning testbed
31/03/2017	Voxy.co.nz	Expressions of Interest for SBAS trial
31/03/2017		Novel projects sought for satellite positioning testbed
30/03/2017	CIO	Joint Australia NZ research project to improve GPS accuracy
30/03/2017	PC World	Joint Australia NZ research project to improve GPS accuracy
24/03/2017	All Daily News (link no longer available)	Key partners meet to progress SBAS test-bed project
23/03/2017	Get Farming	Key partners meet to progress SBAS test-bed project
22/03/2017	GA website	Key partners meet to progress SBAS test-bed project
22/03/2017	Foreign Affairs NZ website	Key partners meet to progress SBAS test-bed project
13/03/2017	WhaTech	Joint Australia NZ research project to improve GPS accuracy
13/03/2017	Critical Comms	Satellite signal research to boost positioning
8/03/2017	Smart Highways	NZ and Australia in new location trial
7/03/2017	C4ISRNET	GPS + Galileo = better navigation
6/03/2017	InnovationAus.com	Our tech treaty with the Kiwis
28/02/2017	Logi News (Spanish?)	Australia desplegará un sistema de aumentación que ofrecerá servicios innovadores al sector transporte
27/02/2017	Air Traffic Management.net	Collaborative 2nd-gen SBAS research launches

22/02/2017	Spatial Source e-newsletter	New Zealand joins Australia to develop precise satellite positioning
22/02/2017	ATC Network	Geoscience Australia and Lockheed Martin Begin Collaborative Research Project For Second-Generation Satellite-Based Augmentation System (SBAS)
20/02/2017	Computerworld New Zealand	New satnav technology promises 10 centimetre accuracy
20/02/2017	Lab + Life Scientist-Labonline website	Trans-Tasman science treaty formed
20/02/2017	WNIPT	Research collaboration will lead to more accurate positioning services in Australia and New Zealand
19/02/2017	ZDNet	NZ government contributes AU$2m to join Geoscience Australia's positioning project
17/02/2017	Logistics & Material Handling	Australia, NZ collaborate on positioning research worth $73bn
17/02/2017	Jane's Airport 360 website	Australian project researches potential benefits from second-generation SBAS
17/02/2017	Live News.co.nz	New Zealand to participate in Australasian satellite positioning trial programme
17/02/2017	Foreign Affairs NZ website	Australia and New Zealand align on positioning
17/02/2017	CRCSI	Research Collaboration Leads to More Accurate Positioning
17/02/2017	Inside GNSS	Geoscience Australia, New Zealand, Lockheed Martin all Part of Second-Generation SBAS Research Project
17/02/2017	PM's website	Science and innovation treaty with New Zealand creates new opportunities
16/02/2017	M2M Zone	Lockheed Martin leads Australian project to improve satellite positioning accuracy
15/02/2017	Aviation Week Network	GMV has started two-year collaborative project with Geoscience Australia (GA) and the Australia and New Zealand Cooperative Research Center for Spatial Information (CRCSI)
15/02/2017	ITS International	Australian new generation satellite positioning augmentation system kicks off
14/02/2017	MyInforms.com	GEOSCIENCE AUSTRALIA PARTNERS WITH LOCKHEED, INMARSAT, GMV TO DEMO 2ND-GEN SATELLITE-BASED NAVIGATION TESTBED
14/02/2017	IConnect007 website	Geoscience Australia and Lockheed Martin Begin Collaborative Research Project For Second-Generation SBAS

14/02/2017	Air & Cosmos International	Geoscience Australia, Lockheed Martin collaborate on GNSS enhancements
14/02/2017	Executive Biz	Geoscience Australia Partners With Lockheed, Inmarsat, GMV to Demo 2nd-Gen Satellite-based Navigation Testbed
14/02/2017	GMV website	AUSTRALIAN NEW GENERATION SATELLITE POSITIONING AUGMENTATION SYSTEM KICKS OFF
13/02/2017	Newsdog	Lockheed Martin, Inmarsat, GMV join Geoscience Australia's positioning project
13/02/2017	ZDNet	Lockheed Martin, Inmarsat, GMV join Geoscience Australia's positioning project
13/02/2017	Defence Aerospace.com website	Geoscience Australia and Lockheed Martin Begin Collaborative Research Project for Second-Generation Satellite-Based Augmentation System (SBAS)
13/02/2017	GPS World	Geoscience Australia, Lockheed collaborate on multi-GNSS SBAS research
10/02/2017	Spatial Source e-newsletter	Global tech companies join Australia for national positioning project
10/02/2017	Geoconnexion website	Geoscience Australia and Lockheed Martin Begin Collaborative Research
10/02/2017	Technology Decisions	Major tech companies join Australian positioning trial
10/02/2017	Foreign Affairs NZ website	Technology companies join Australian national positioning project
10/02/2017	GA website	Technology companies join Australian national positioning project
9/02/2017	Lockheed website	Geoscience Australia and Lockheed Martin Begin Collaborative Research Project For Second-Generation Satellite-Based Augmentation System (SBAS)
1/02/2017	Position magazine (February/March 2017)	$12 million boost for positioning technology in Australia
19/01/2017	ITS International	Australia launches positioning technology trials
18/01/2017	Australasian Transport News	SATELLITE POSITIONING TECH GAINS $12M BOOST
17/01/2017	OpenGov Asia	Australian government investing $12 million to test Satellite Based Augmentation Systems
17/01/2017	GA website	Geoscience Australia A/CEO statement on funding for national positioning project
17/01/2017	GPS World	Australia to invest $12 million to test SBAS positioning technology

17/01/2017	IT News	Govt invests in trial to improve GPS accuracy for Australia
17/01/2017	GIM International e-newsletter	Million-dollar Boost for Positioning Technology in Australia
17/01/2017	Spatial Source e-newsletter	$12 million boost to Australian positioning technology
1/01/2017	Business Acumen online magazine (no published date)	Govt spends $12m on 'positioning' technology

Appendix C FrontierSI Technical Report

SBAS TEST-BED DEMONSTRATION PROJECT

TECHNICAL REPORT - FRONTIERSI SBAS TESTING CAMPAIGN

Christopher Marshall, Lachlan Ng and Eldar Rubinov

FrontierSI

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List of Acronyms

Aus-NZ	Australia and New Zealand
CORS	Continuously Operating Reference Station
COTS	Commercial off-the-shelf
DFMC	Dual Frequency Multi Constellation
GDA	Geocentric Datum of Australia
GEO	Geostationary satellite
GNSS	Global Navigation Satellite System
IMU	Inertial Motion Unit
IoT	Internet of Things
MGA	Map Grid of Australia
NMEA	National Marine Electronics Association
POI	Point of interest
PPP	Precise Point Positioning
RINEX	Receiver INdependent Exchange
RMS	Root Mean Square
RTCM	Radio Technical Commission for Maritime Services
SBAS	Satellite Based Augmentation System
SISNeT	Signal in Space through the Internet

List of Definitions

Term	Description
Absolute positioning	Absolute positioning refers to the method of positioning using a single GNSS receiver. The position is determined using only the measurements made on that receiver. It is the opposite to the relative positioning for which the receiver position is determined relative to another receiver whose position is known.
Accuracy	Closeness of a measured position to the true position. It is commonly quantified using the mean of measured positions over a specified period of time. Accuracy levels have been defined as follows: • Centimetre-level: 0-10cm • Decimetre-level: 10-30cm • Sub-metre level: 30cm-1m • Metre-level: 1-10 m
Availability	The percentage of time the system is usable for positioning within a given period. This can be affected both by issues with the provision of signals and by the receiver environment.
Precision	Refers to the spread of repeatedly measured positions around their mean. It is commonly quantified using the standard deviation.
Test-bed	A test-bed is a platform for conducting rigorous, transparent, and replicable testing of new technologies. The use of SBAS test-beds is a well-established method for reducing risk by evaluating technical performance and assessing costs and benefits for an operational SBAS.

1 Introduction

A 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. This process is shown graphically in Figure 1.

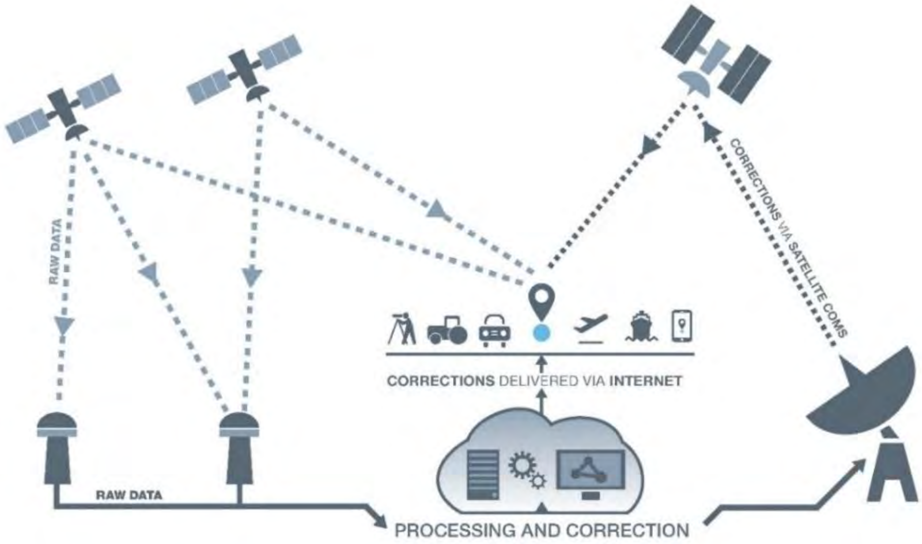

Figure 1. SBAS test-bed configuration (credit: Geoscience Australia).

Since its inception as an aviation technology designed to improve landing safety, SBAS has since found use in many non-aviation applications. Currently SBAS is implemented in several regions around the world including North America, Europe, India and Japan.

Between January 2017 and January 2019, the Australian and New Zealand governments ran a two year (SBAS) test-bed to test SBAS technology in the region. Throughout the course of the test-bed, three different signals were evaluated:

- SBAS Legacy L1: the SBAS L1 signal is the single frequency service currently available in other regions of the world. 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 Australia and New Zealand 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 in near real-time in clear sky conditions after an initial period of solution convergence, which is typically 30-40 minutes.

The SBAS L1 signal was first broadcast in June 2017, followed by DFMC SBAS and PPP from October 2017 through to January 2019. The signals were available from the Inmarsat 4F1 geostationary satellite as well as from 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 (FrontierSI, 2019) as well as overseeing an economic benefits study of the value that the technology would bring to the economy of both countries (EY, 2019).

Aside from these industry projects, FrontierSI also carried out specific testing to evaluate the performance of the currently commercially available consumer and mid-range GNSS receivers. The testing carried out by FrontierSI is complementary to that done by the demonstrator projects. The purpose of this report is to detail the results of FrontierSI's testing of a selection of GNSS receivers across a range of different environments.

Three testing campaigns with a number of tests in each were carried out as part of the program. The first campaign was aimed at testing static accuracy of a number GNSS receivers and antennas with SBAS L1, DFMC and PPP. The second campaign investigated kinematic performance by driving a car through a range of road environments, examining SBAS L1, DFMC and PPP performance. The third test looked at SBAS L1 accuracy in a selection of typical forestry environments.

2 Equipment and observation environment

Positioning performance of any satellite based navigation system depends on two key factors, which are observation environment and the quality of GNSS receiver and antenna hardware. Both of these are explained and categorised in this section.

2.1 GNSS receiver and antenna hardware

GNSS hardware varies significantly depending on the application. For the purpose of the testing, equipment was broken 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, forestry, robotics etc.
Professional	> $3,000 - geodetic, surveying, high-precision applications

A number of receivers and antennas were used in the testing described in this report and these are introduced below. Four consumer-grade receivers were used including Antenova M20050, Quectel L76-L, SkyTraq V838 and U-blox M8N. These are shown in Figure 2.

Antenova M20050 | Quectel L76-L | SkyTraq V838 | U-blox M8N

Figure 2. Consumer receivers used for testing.

Four mid-range receivers were used in the testing including EoS Arrow Gold, ComNav G100, Juniper Systems Geode and GMV magicUT. The magicUT receiver is a prototype receiver developed by GMV for the Aus-NZ SBAS test-bed, whilst the other three are commercial off-the-shelf (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 services – SBAS L1, DFMC and PPP. The mid-range receivers are shown in Figure 3.

EOS Arrow Gold | ComNav G100 | Juniper Geode | GMV MagicUT

Figure 3. Mid-range receivers used for testing.

A single professional (geodetic) receiver was used in the testing which was the Septentrio AsteRx-U. This receiver is shown in Figure 4.

Figure 4. Septentrio AsteRx-U receiver used for testing.

Apart from the receivers, antennas also play a key role in tracking and decoding the various satellite navigation signals. Antennas can be broken into similar categories to match the receiver categories. Typically, Small patch antennas are used with consumer-grade devices, compact geodetic antennas are used with mid-range devices and professional geodetic antennas are used with geodetic receivers. Four different antennas were used during the testing including a generic patch antenna, Tallysman TW7972, Topcon G3-1A and Tallysman VP6000. These are shown Figure 5.

Patch Antenna | Tallysman TW7972 | Topcon G3-A1 | Tallysman VP6000

Figure 5. Antennas used for testing.

2.2 Observation Environment

Positioning environments can vary from open sky to a highly obstructed one with poor visibility of the satellites. Common obstructions include buildings, bridges, trees, varying topography as well as site-specific obstructions such as cranes and machinery on construction sites and container ports. As such, five levels of observation environment were considered, which are summarised in Table 2.

Table 2. Observation environment classifications.

Environment	Description
Open sky	No obstructions, highest accuracy results expected
Light Obstruction	1-storey buildings and some trees, no significant obstructions
Partial Obstruction	2-3 storey buildings, medium-level tree canopy, undulating terrain, open pits walls, etc.
Moderate Obstruction	Dense forest, container port (cranes), construction sites (machinery/equipment), etc.
Significant Obstruction	Urban canyon, other significant obstructions

3 Testing campaign descriptions

Three separate testing campaigns were carried out which tested the various aspects on the Aus-NZ SBAS test-bed including receiver and antenna performance of the various commercial equipment currently available as well as the performance of different signals under different environments. These tests are described in detail below.

3.1 Static testing of SBAS L1, DFMC and PPP

A static testing campaign was carried out to examine the performance of various receivers, antennas and signals in a static mode under open sky conditions. These tests were designed to gauge the best positioning performance that could be obtained in a particular configuration under ideal conditions. A number of different tests were carried out which are listed below:

- Static testing of consumer-grade and mid-range receivers with SBAS L1 service
- Static testing of various antennas with SBAS L1 service
- Static test of SBAS L1 and DFMC services using magicUT
- Static test of the PPP service via GEO, SISNeT and RTCM using magicUT

3.2 Kinematic testing of SBAS L1, DFMC and PPP

Three separate kinematic runs were carried out by driving a test vehicle around Melbourne through a series of different environments while recording SBAS L1, DFMC and PPP signals. The logged data was used to perform the following tests:

- Kinematic testing of SBAS L1 service using mid-range receivers
- Kinematic testing of DFMC service using mid-range and professional receivers
- Kinematic testing of PPP service using mid-range receivers

3.3 Kinematic forestry testing of SBAS L1 and PPP

The forestry testing was undertaken to test the accuracy of SBAS L1 and PPP under the dense canopy common to forestry environments. DFMC testing was not attempted due to time constrains. Both standalone GNSS and SBAS-augmented positioning are currently used for a range of activities associated with commercial forest management around the world. The Aus-NZ test-bed has presented the opportunity to provide sub-metre positional accuracy on COTS devices in harsh GNSS signal conditions where forestry personnel operate. A test-bed project has been conducted by Forestry Corporation NSW, to determine whether receivers currently available were suitable for use in the forestry industry. However, these tests provided inconclusive results and prompted further testing by FrontierSI described in this report. The test methodology was developed in consultation with forestry experts to best align with the real-world forestry practice.

The testing was carried out using MagicUT and Geode receivers in SBAS L1 and PPP modes in December 2018 across varied plantation and native forest environments at Neerim plantation, Victoria. This report describes the methodology, results, and analysis of these tests in terms of kinematic performance.

4 Testing methodology

This section describes the methodology of the various testing campaigns in detail, including the equipment used, the signals tested and data processing methodology.

4.1 Static testing with SBAS L1, DFMC and PPP

Four static tests in two separate locations were completed as part of the static testing campaign. The tests were aimed at investigating the performance of different receivers, antennas and signals in an ideal open sky observing environment. These tests are described in detail below.

4.1.1 Static testing of consumer and mid-range equipment with SBAS L1 service

Prior to conducting the receiver tests, a separate static GNSS session was undertaken to establish the ground truth of the control point for use as a reference. This involved a 24 hour observation session using the magicUT receiver. The data was logged in a Receiver Independent Exchange (RINEX) format and was processed using the Geoscience Australia's AUSPOS[1] online processing service. Figure 6 shows the antenna setup and testing location.

The static consumer and mid-range grade receiver tests were each conducted at a control point and compared to the post-processed ground truth. A Topcon G3-A1 antenna on tribrach was mounted to a chimney on a single storey residential roof in Doncaster East, Victoria. On both occasions, the receivers were connected to the antenna via 4-way signal splitter to ensure each device experienced identical satellite conditions during the tests. Each receiver was configured to log data simultaneously at a frequency of 1Hz using Septentrio RxTools Data Link software.

Figure 6. Antenna location for the static receiver testing.

For the consumer receiver sessions each receiver was individually connected to a tablet via a USB hub as shown in Figure 7. Each receiver logged data and received power via USB connection while connected to the antenna via

[1] AUSPOS - http://www.ga.gov.au/bin/gps.pl

the signal splitter. Prior to testing, the Antenova and Quectel receivers required the SBAS correction function to be toggled on through commands in their proprietary software. Additionally, the Antenova, Quectel and SkyTraq receivers also required commands to disable a navigation speed or position pinning threshold, which, if enabled, would cause the receiver to repeatedly log the same position while the receiver was stationary. After configuration and ensuring each receiver was receiving an SBAS positioning signal, the coordinates were logged in a standard National Marine Electronics Association (NMEA) output through the Data Link software. Three independent 24 hour sessions were logged to ensure test repeatability. During the consumer test the Antenova receiver lost SBAS fix after the first 24-hour session, so the subsequent sessions have been omitted from the analysis.

Figure 7. Consumer-grade receiver setup for static testing.

For the mid-range receiver sessions, the receivers were connected to the tablet via Bluetooth for data logging in Data Link, with the exception of the MagicUT which logged data internally. The receivers were configured internally through their proprietary software prior to testing. Each receiver was connected to the antenna via a passive splitter, ensuring the same observing conditions. Like the consumer tests, three independent sessions of 24-hours duration were logged to separate files for each receiver. The testing setup is shown in Figure 8.

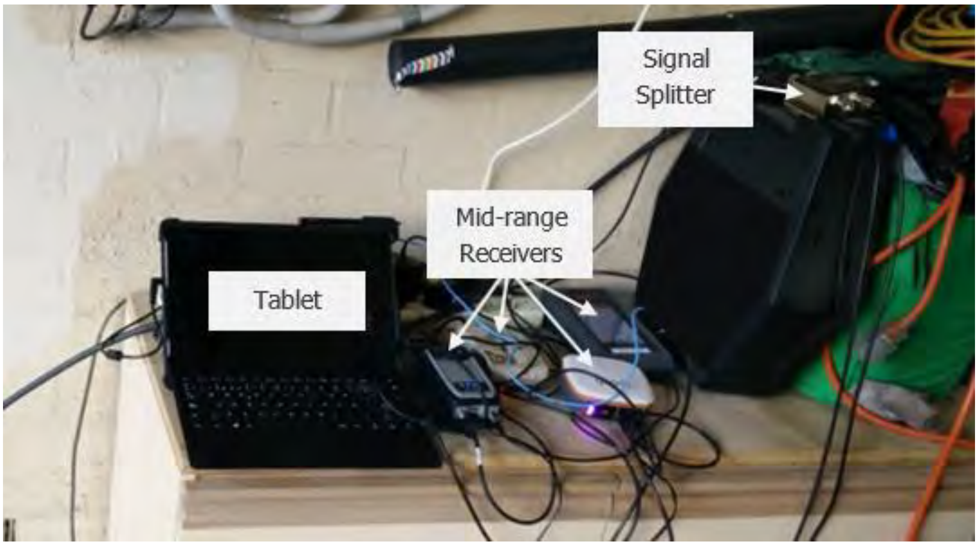

Figure 8. Mid-range receiver setup for static testing.

4.1.2 Static antenna testing with SBAS L1

The static antenna tests were carried out at a control point located on a residential rooftop in Maribyrnong, Victoria. The tribrach with antenna adapter was securely mounted and levelled on a control point allowing the antennas to be easily swapped between sessions without moving from the measured position. Two receivers, Septentrio AsteRx-U and U-blox M8N, were connected to each antenna setup via 4-way signal splitter and logged data at 1Hz. For each antenna test the receivers were configured to log coordinate data with SBAS L1 corrections for a period of four hours, and then the test was repeated without SBAS corrections (i.e. standalone mode). The purpose of the tests was two-fold. Firstly, it aimed to investigate how various antennas affect the positioning quality, and secondly to quantify the impact SBAS L1 corrections have on consumer and professional receivers.

Three different antennas were tested including a patch antenna (consumer), Tallysman TW7972 (mid-range) and Topcon G3-1A (professional). Additionally, patch and Tallysman TW7972 were tested in two modes, with a ground plane (GP) and without, to quantify the effect a GP can have on the positioning quality. As such, five separate antenna configurations were tested. Four of these are shown in Figure 9.

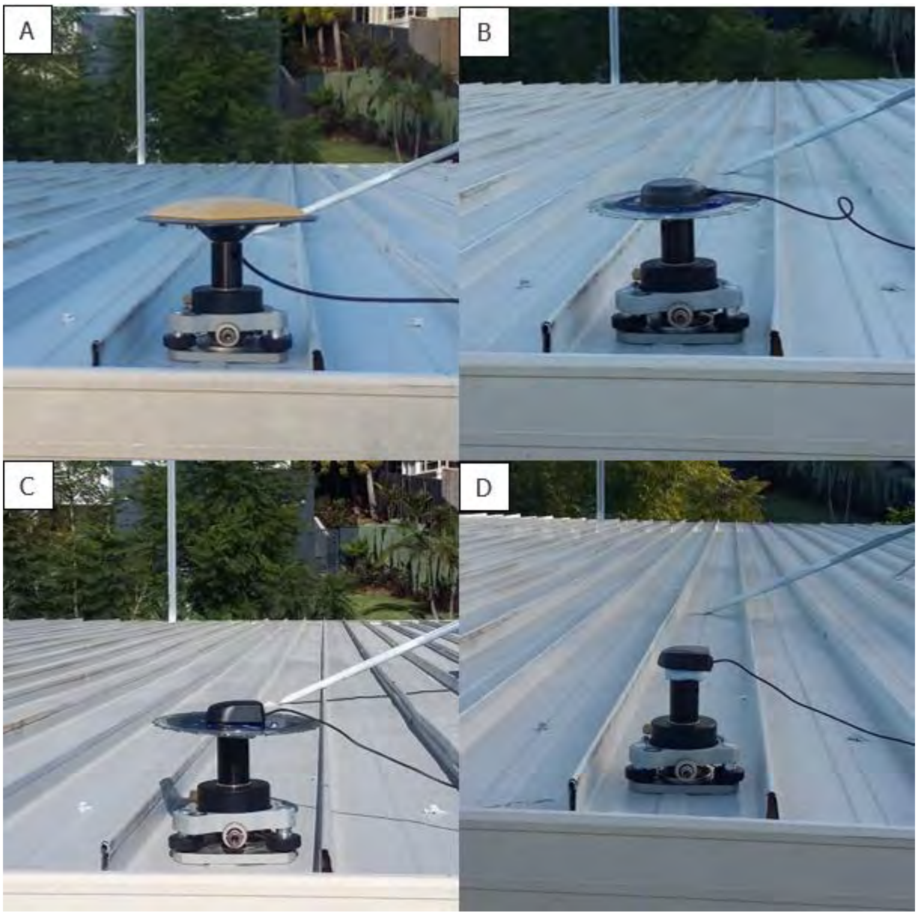

Figure 9. Various antenna configurations including Topcon G3-1A (A), Tallysman TW7972 with GP (B), patch with GP (C) and patch without GP.

4.1.3 Static SBAS L1 vs DFMC test

A single 24-hour static SBAS L1 vs DFMC test was carried out over the same control point as the consumer and mid-range grade receiver test, utilising the same antenna setup in Doncaster East, Victoria. Two magicUT receivers were connected to the antenna via 4-way signal splitter. The first magicUT was configured to log positions with SBAS L1 corrections and the second was configured to log positions using DFMC. Both receivers logged data at a frequency of 1Hz for 24 hours. The purpose of the test was to compare how DFMC compares to SBAS L1 in terms of accuracy and availability.

4.1.4 Static PPP test via GEO, SISNeT and RTCM

The static PPP test was conducted at the residential rooftop control point in Maribyrnong, Victoria. A tribrach was securely mounted and levelled to hold a Topcon G3-A1 antenna, which was connected to three magicUTs via a 4-way signal splitter. The first magicUT was setup to receive PPP corrections via GEO, the second to receive PPP via SISNeT and the third to use PPP via the RTCM. The receivers positioning with PPP via SISNeT and RTCM were connected to the local internet connection to enable the reception of PPP corrections. Once set up, the receivers were simultaneously initialised for logging for approximately 5.5 hours. The PPP data was then compared to the ground truth determined through post-processing the raw observations of one of the static sessions.

Corrections received via SISNeT are the same as those transmitted via the GEO, except they are received through the internet. In that sense, the only difference is the latency with which the signals are received, which for GEO corrections is typically 5-6 seconds, whereas for SISNeT is around 1 second. RTCM on the other hand provides a different set of messages, based on the RTCM standard.. With the GEO broadcast, the PPP corrections are tacked onto the SBAS corrections, hence there is some limitation to the amount of data that can be fit into the message. With the RTCM PPP corrections there is no such limitation, and hence it is expected that PPP via RTCM would perform better than that via GEO or SISNeT,

Apart from accuracy and availability, a key parameter for any PPP solution is the convergence time. For the purposes of the testing, the solution was deemed to have converged when the horizontal error was less than 0.2m and vertical error was less than 0.3m for at least 10 minutes.

4.2 Kinematic testing with SBAS L1, DFMC and PPP

The kinematic testing campaign was separated into three separate tests that ran simultaneously. The first test focused on SBAS L1 service with mid-range receivers including the Arrow Gold, ComNav G100, Geode and magicUT. All receivers were connected to a Tallysman VP6000 antenna through a 4-way signal splitter. The second test focused on DFMC positioning with three different receiver configurations including:

- Septentrio AsteRx-U with DFMC via GEO
- magicUT with DFMC via GEO
- magicUT with DFMC via SISNeT

All three receivers were connected to a second Tallysman VP6000 antenna via a 4-way signal splitter. The purpose of this test was two-fold. Firstly, to compare the performance of DFMC positioning on different receivers, and secondly to compare the performance of DFMC positioning from two correction sources, GEO and SISNeT.

Finally, the third test looked at the performance of PPP in a kinematic environment. A single magicUT receiver was configured in PPP mode via GEO and was connected to the second Tallysman VP6000 antenna through the remaining port on the signal splitter. Figure 10 and Figure 11 show the receiver and antenna setup for the kinematic tests.

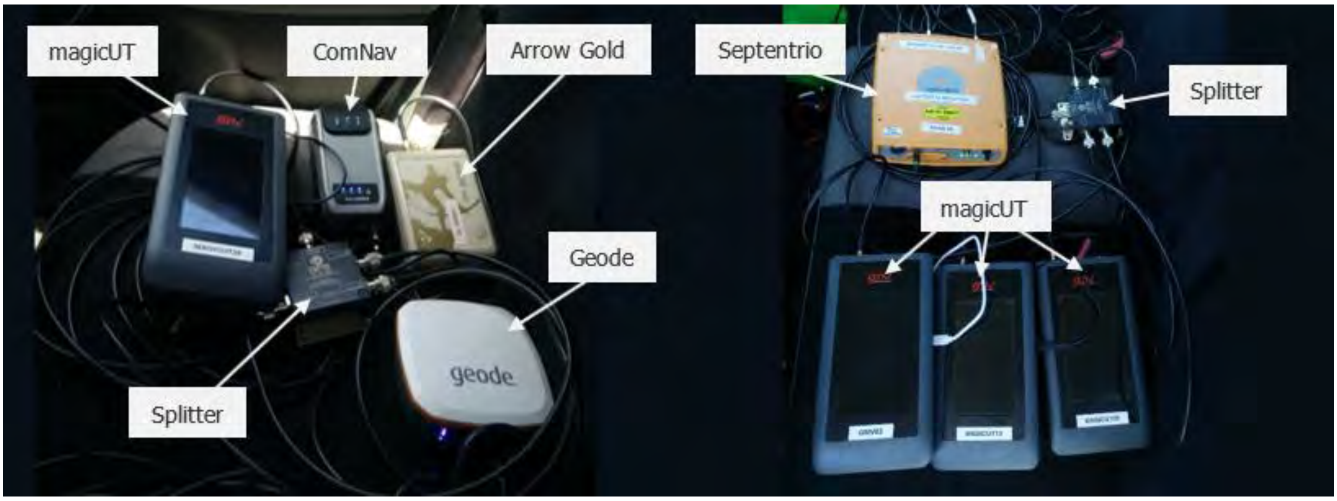

Figure 10. Hardware setup for kinematic test 1 (left), and tests 2 and 3 (right).

Figure 11. Antenna setup on the vehicle for kinematic tests 1, 2 and 3.

The kinematic tests used the receivers to log the position of the vehicle when driving through metropolitan Melbourne for approximately two hours (see Figure 12). The route included a range of observing conditions designated by letters A through to E on Figure 12 and Figure 13, which refer to the following environments, classified as per Table 2:

A. Urban canyon (significant obstructions).
B. Inner suburbs (moderate obstructions).
C. Vegetated suburbs (partial to moderate obstructions).
D. Freeway (open sky).
E. Outer suburbs (open sky to moderate obstructions).

Prior to starting the drive the vehicle was stopped for approximately 30 minutes to allow the PPP receiver to converge. The route was driven on three separate occasions, providing a total of three sets of kinematic data for each test.

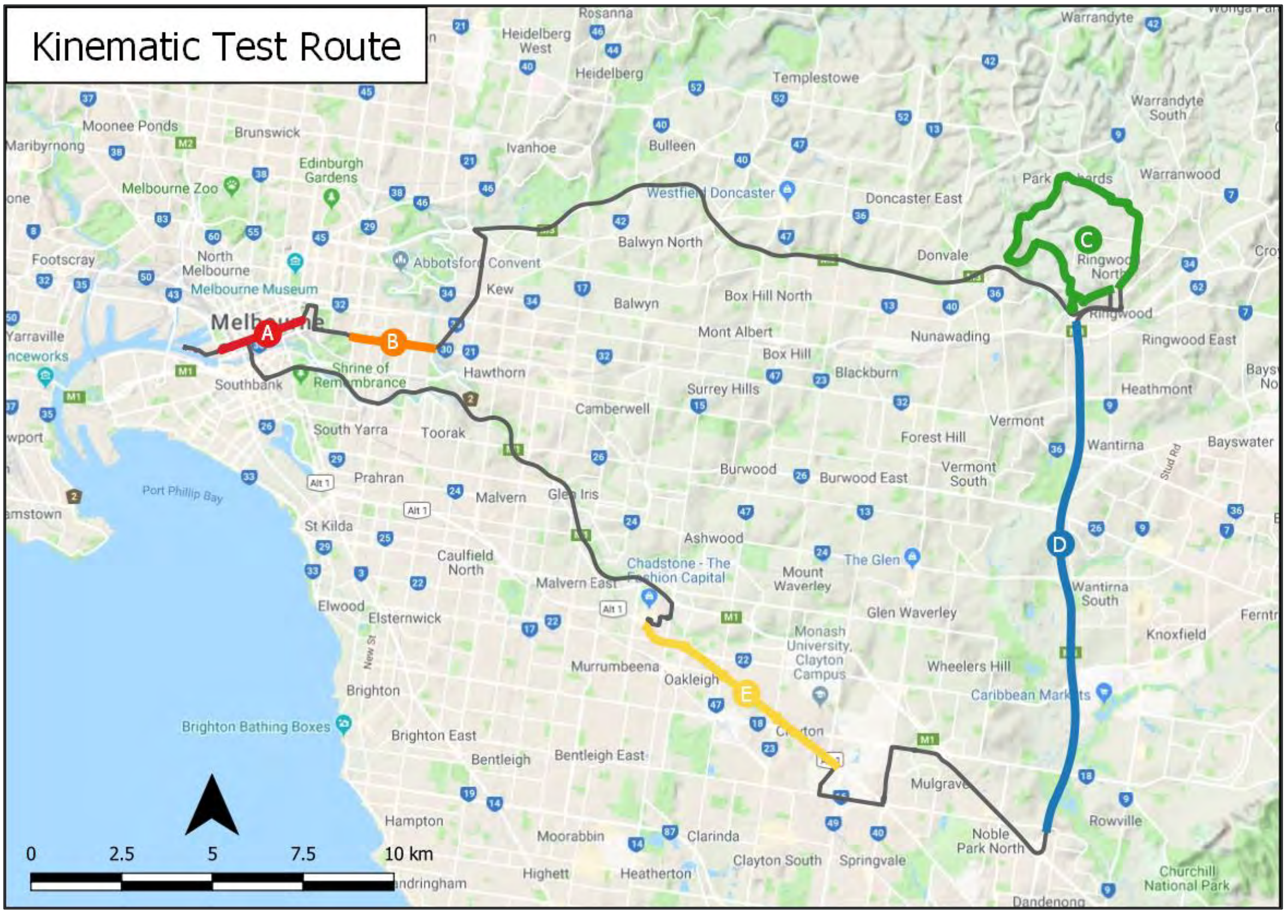

Figure 12. Kinematic test route.

Figure 13. Images of various environments during kinematic test (A) urban canyon, (B) inner suburbs, (C) vegetated suburbs, (D) open freeway, (E) outer suburbs (credit: Google street view).

4.3 Forestry testing with SBAS L1 and PPP

The SBAS receiver forestry tests aimed to imitate the typical scenario where foresters walk along under dense canopy and need to have accurate and instantaneous positioning. Since it would be almost impossible to get accurate reference position for a kinematic test under canopy, linear tracks of 100m length were established with five pegs along each track roughly at 20m intervals. These points were measured accurately by a land survey traverse using a total station and were used as a ground truth for subsequent SBAS measurements. Three tracks were established in different forestry environments including unthinned pine plantation, thinned pine plantation and native forest. Thinning operations remove every fifth row of trees, resulting in improved GNSS conditions. Pine plantation rows oriented east-west were desirable to emulate the worst-case positioning scenario, since the SBAS satellite (oriented approximately north) would be obstructed by the forest canopy for the majority of the test duration. Figure 14 and Figure 15 show the unthinned, thinned and native forest tracks and the established control points.

Figure 14. Thinned forest track and control points.

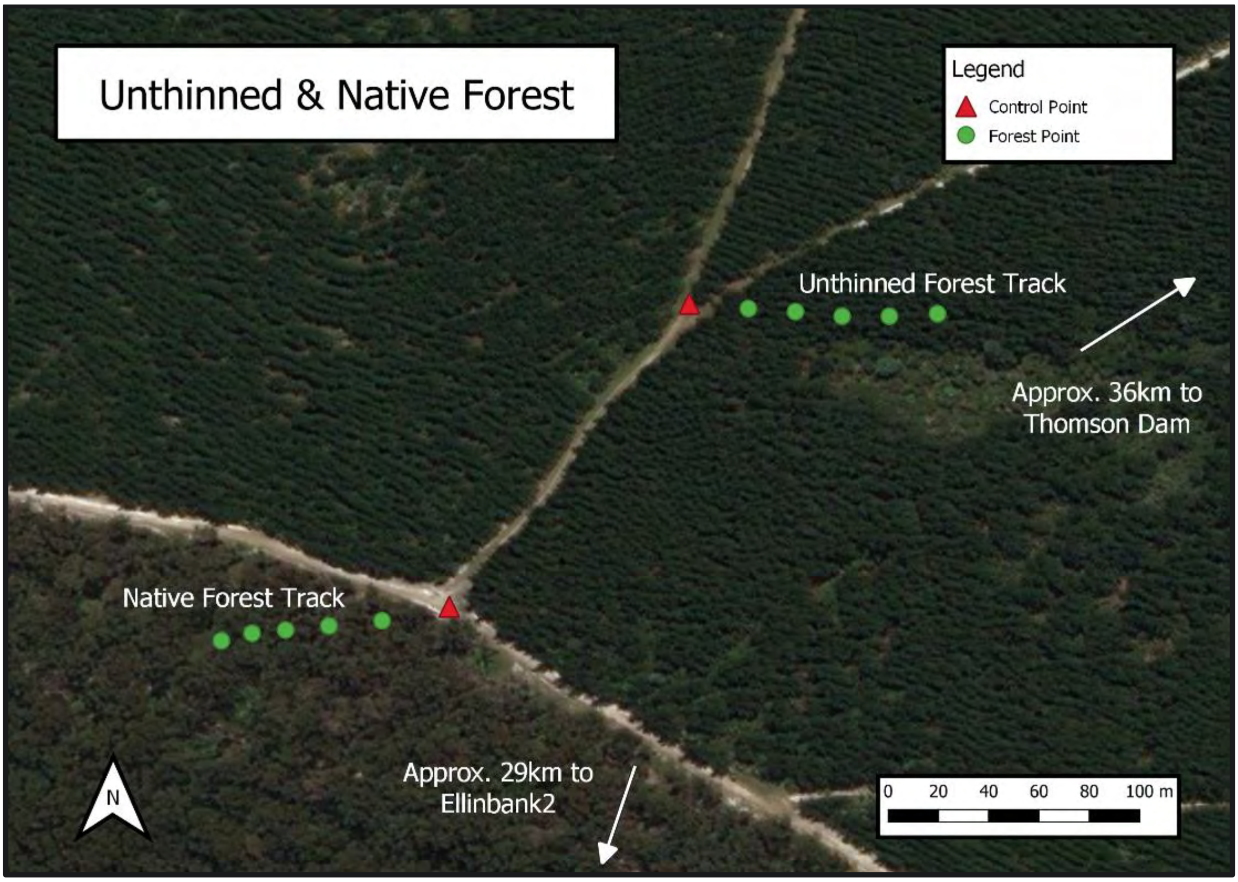

Figure 15. Unthinned and native forest tracks and control points.

Prior to conducting the receiver tests, a total station survey was undertaken in each forest environment to establish the ground truth position of the five forest-track control points along each linear track. The control survey involved a two-hour static GNSS session over two control points located along a road with moderately clear overhead conditions. Two magicUTs recorded data simultaneously with Leica AS10 antennas on tripods. These static control points were placed so that their baseline was approximately perpendicular to the control points along the forest track. The raw observations from the static survey were processed relative to the Ellinbank2 and Thomson Dam reference stations from the Victorian Continuously Operating Reference Station (CORS) network GPSnet[2] using Effigis EZSurv post-processing software.

The tests were conducted using two magicUT receivers, one in SBAS L1 and one in PPP mode connected to a single Tallysman VP6000 antenna on a survey pole logging data internally. The tests were repeated using the Geode receiver mounted to the survey pole, logging data to an Android phone. The testing involved traversing each forest track, stopping and levelling the pole over the control points using a bipod and recording a point of interest (POI) for each peg. Each POI comprised of a single measurement, no averaging over a number of epochs was done, in order to simulate the accuracy that would be achieved by walking through the forest. For the magicUTs test, 30 minute initialisation time was needed to allow the PPP solution to converge. Figure 16 shows the equipment used for the testing.

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[2] GPSnet - http://gnss.vicpos.com.au/

Figure 16. Forestry testing using magicUTs (left) and the Geode (right).

Each track was walked three times in both directions giving a total of six measurements over each point for each receiver. Due to time restrictions, the native forest track was only traversed using the Geode receiver.

5 Results

Results of all the testing campaigns are presented in this section. In all cases, whether static or kinematic, the measurements were compared to the ground truth and the differences computed. In the case of the static experiments, the ground truth was a single point and in case of kinematic tests, the ground truth was a reference trajectory. The results have been quantified in terms of three metrics – accuracy, precision and availability. The accuracy is measure of closeness of a measured position to the truth and quantified by the mean of the observation differences. Precision is a measure of the spread of the observations and is typically quantified by a standard deviation or sigma. The outliers were removed from the dataset at a 3-sigma level, i.e. any measurement that was more than three standard deviations away from the mean was considered an outlier and removed from the dataset. The mean and standard deviation of the differences were calculated to quantify each receiver's accuracy and precision respectively.

Another useful figure that is commonly used in measurement sciences to denote the quality of the measurement is the Root Mean Square (RMS), which is computed using:

$$x_{rms} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + \cdots + x_n^2\right)}$$

RMS is a useful quantity as it gives a combined measure of accuracy and precision in a single figure.

Finally, the availability of the dataset was computed as the number of actual measurements from the number of available measurements rom each given dataset, after the removal of outliers.

Whilst the ComNav G100 receiver was configured to receive SBAS corrections in consultation with manufacturer; after analysing the results it was found that the receiver was not applying those corrections correctly. As such, the positioning performance was at the level of a standalone receiver. After discussions with the manufacturer it was concluded, that more development work in needed in order for this receiver to be fully functional with the Aus-NZ SBAS signal. As such, all ComNav results have been excluded from the analysis.

5.1 Static testing results

Results of the four static tests are described in this section. The signal availability for all tests was 100%, which was expected for a static receiver in an open sky environment. As such, the availability is not reported for individual tests in this section.

5.1.1 Static testing of consumer and mid-range equipment results

Table 3 and Table 4 give the mean, standard deviation and RMS of horizontal and vertical differences for the consumer-grade receiver testing. The tables show the results for each of the three individual experiments as well as the combined overall figures. Antenova results are only shown for the first experiment as the receiver failed to output data for any future tests.

Table 3. Consumer receiver static results.

Receiver	Session	Horizontal Difference (m)			Height Difference (m)		
		Mean	St Dev	RMS	Mean	St Dev	RMS
Antenova	1	1.15	2.36	2.62	0.31	3.63	3.64
Quectel	1	0.83	1.89	2.07	-2.35	3.00	3.81
	2	0.45	1.91	1.97	-2.65	3.10	4.07
	3	0.34	2.34	2.37	-2.25	3.85	4.46
Quectel	Average	0.54	2.05	2.13	-2.42	3.31	4.11
SkyTraq	1	0.60	0.92	1.10	0.20	1.67	1.69
	2	0.44	0.58	0.72	0.63	1.34	1.48
	3	0.43	0.37	0.57	0.58	1.19	1.33
SkyTraq	Average	0.49	0.62	0.80	0.47	1.40	1.50
u-Blox	1	0.38	1.30	1.36	0.19	1.96	1.97
	2	0.08	0.99	1.00	0.42	1.54	1.60
	3	0.20	0.98	1.00	0.34	1.61	1.65
u-Blox	Average	0.22	1.09	1.12	0.32	1.71	1.74

Table 4. Mid-range receiver static results.

Receiver	Session	Horizontal Difference (m)			Height Difference (m)		
		Mean	St Dev	RMS	Mean	St Dev	RMS
Arrow Gold	1	0.24	0.38	0.45	0.24	0.39	0.46
	2	0.21	0.37	0.43	0.12	0.41	0.43
	3	0.23	0.37	0.44	0.29	0.50	0.58
Arrow Gold	Average	0.23	0.37	0.44	0.21	0.43	0.49
Geode	1	0.27	0.45	0.52	0.50	0.58	0.77
	2	0.21	0.40	0.45	0.40	0.52	0.66
	3	0.24	0.38	0.44	0.55	0.59	0.80
Geode	Average	0.24	0.41	0.47	0.48	0.56	0.74
magicUT	1	0.12	0.47	0.48	0.13	0.77	0.78
	2	0.21	0.45	0.50	0.04	0.68	0.68
	3	0.13	0.48	0.50	-0.05	0.72	0.72
magicUT	Average	0.15	0.47	0.49	0.04	0.72	0.73

Figures Figure 17 to Figure 19 show the horizontal errors for the consumer-grade receivers. Note that the axes are different for each receiver as the performances varied significantly from one device to another. Also, the full data series are shown in the graphs; i.e. no outliers have been removed in order to provide the full picture of the positioning.

Figures Figure 17 to Figure 19 provide an interesting insight into the performance of positioning quality of consumer devices. Firstly, it can be seen that Quectel and Antenova appear to have a rounding problem, which only allows them to achieve to a certain level of precision and makes the results appear in a grid pattern. SkyTraq and U-blox do not have this problem, and logged a sufficient number of decimal places in the coordinate output. Looking closely at SkyTraq and U-blox plots it can be seen that SkyTraq appears to be more precise, but has an offset of the mean (i.e. not centred around zero), whereas U-blox appears more accurate, but the spread of the points is much wider. This is also reflected by the respective mean and standard deviation figures in Table 3.

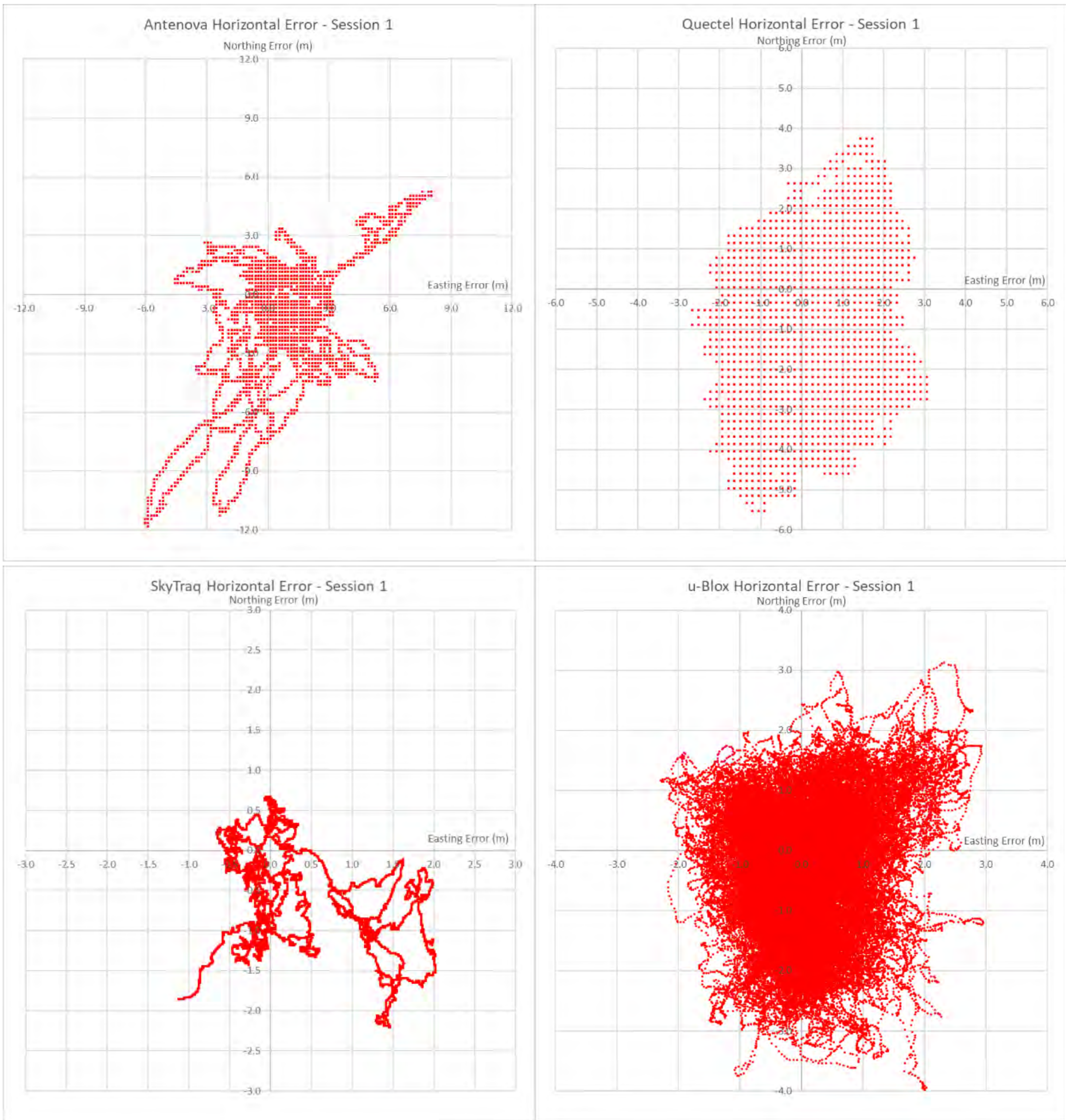

Figure 17. Consumer test 1 horizontal coordinate differences for Antenova, Quectel, SkyTraq and U-blox receivers.

It is also apparent that the SkyTraq appears to have recorded significantly less measurements than the U-blox. Through examining the coordinate output , it was found that the SkyTraq appears to bin the outputs by time; i.e. instead of providing an individual solution every second, it would provide the same solution for 30-60 seconds at a time. This problem was discovered during the testing, however after discussion with the manufacturer, no immediate solution seemed possible. The same problem was also present in Quectel and Antenova devices, which meant that only U-blox was able to provide an independent coordinate solution on a second-by-second basis. One potential explanation is that these consumer-grade devices are targeted at kinematic applications, i.e. only providing coordinate output when the device is moving. This assumption was not able to be verified during this testing campaign.

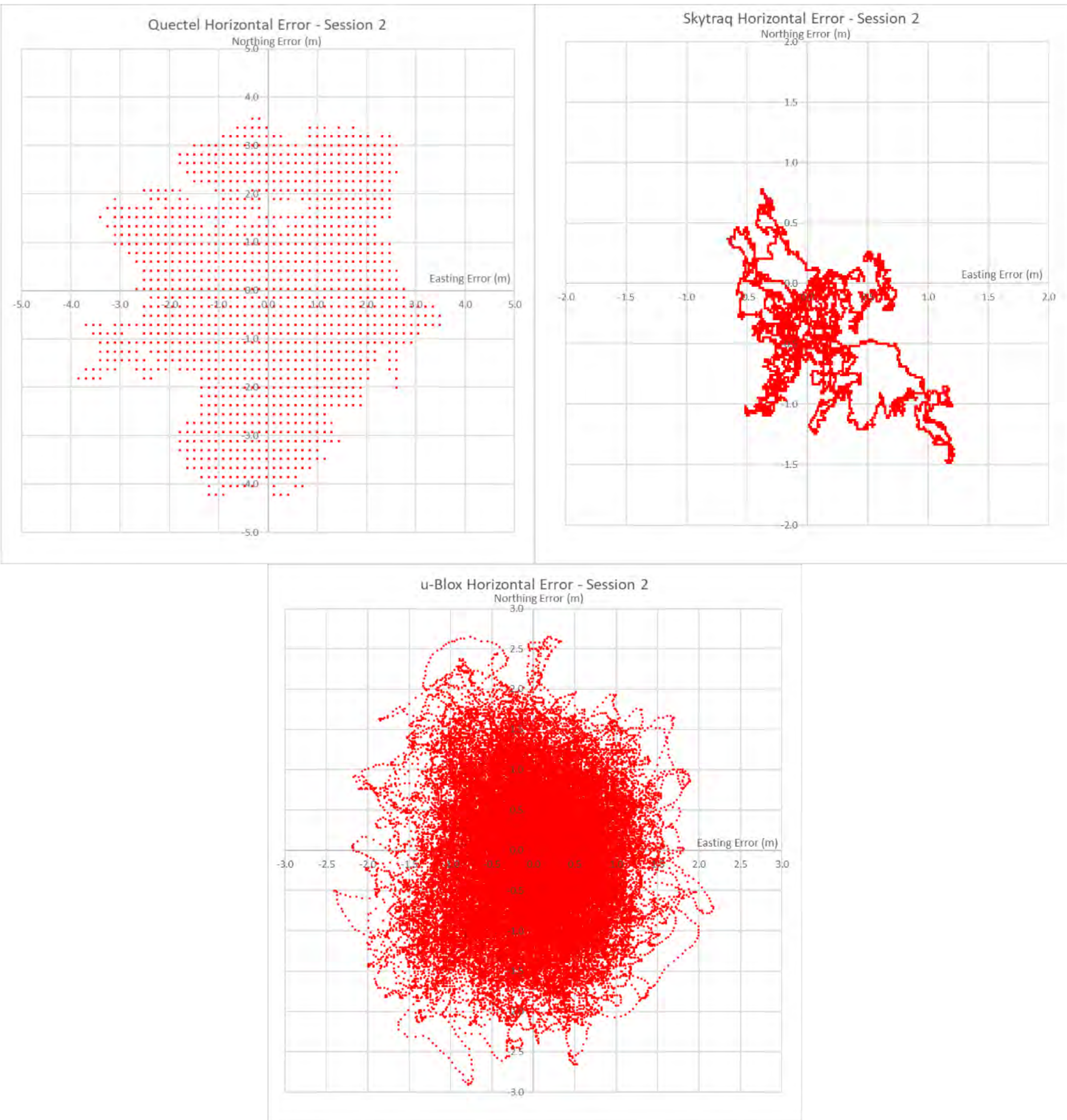

Figure 18. Consumer test 2 horizontal plots for Quectel, SkyTraq and U-blox receivers.

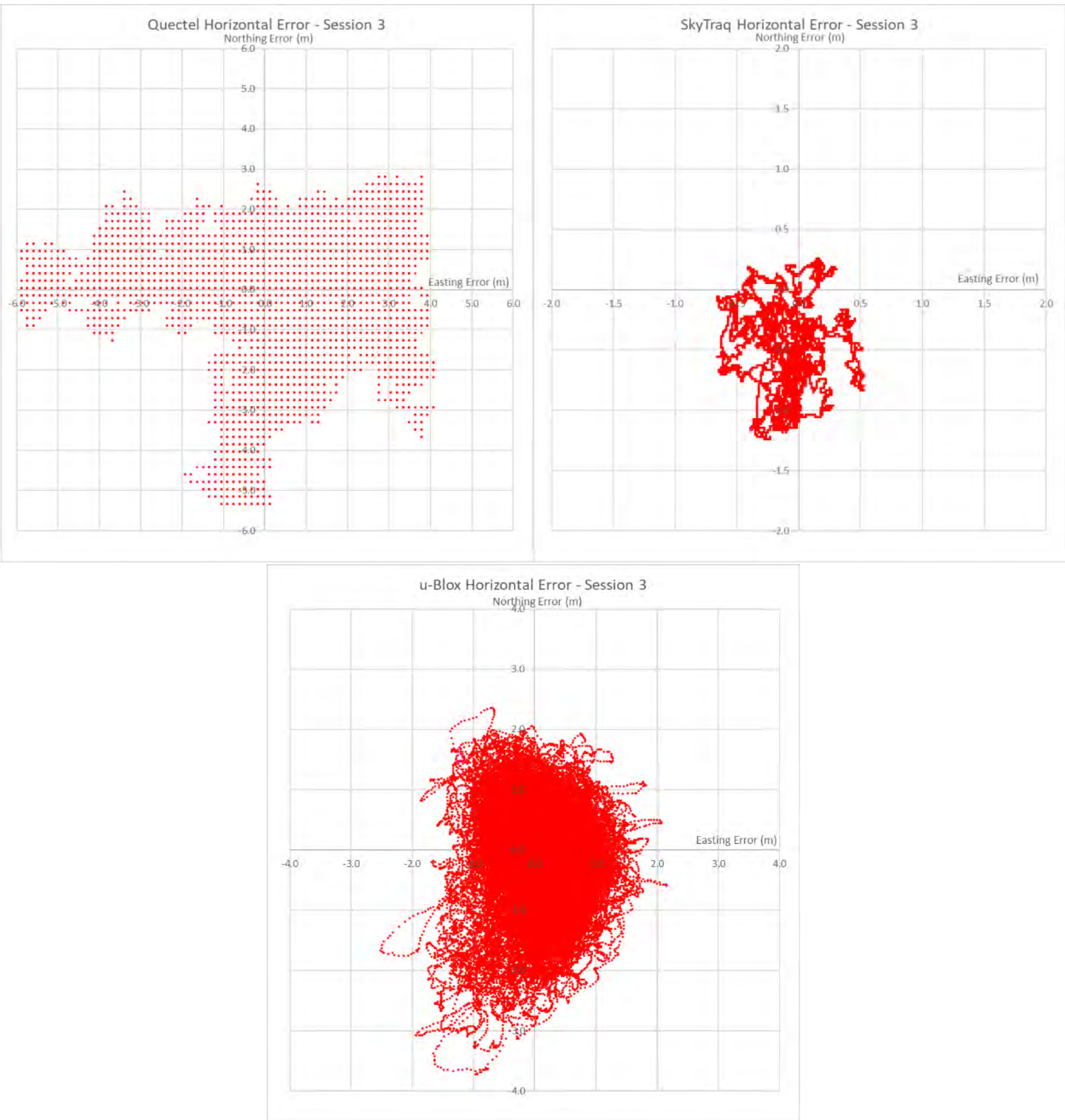

Figure 19. Consumer test 3 horizontal plots for Quectel, SkyTraq and U-blox receivers.

From the results in Table 3 and Figure 17 to Figure 19 it can be concluded that SkyTraq has provided the best performance with SBAS L1 positioning with an average RMS of 0.79m, but it failed to provide an independent coordinate output on an second-by-second basis. U-blox was the only device that able to provide an independent output, but the spread of the results was larger with an average RMS of 1.12m.

Figure 20 to Figure 22 show the graphs for vertical positioning for the consumer devices.

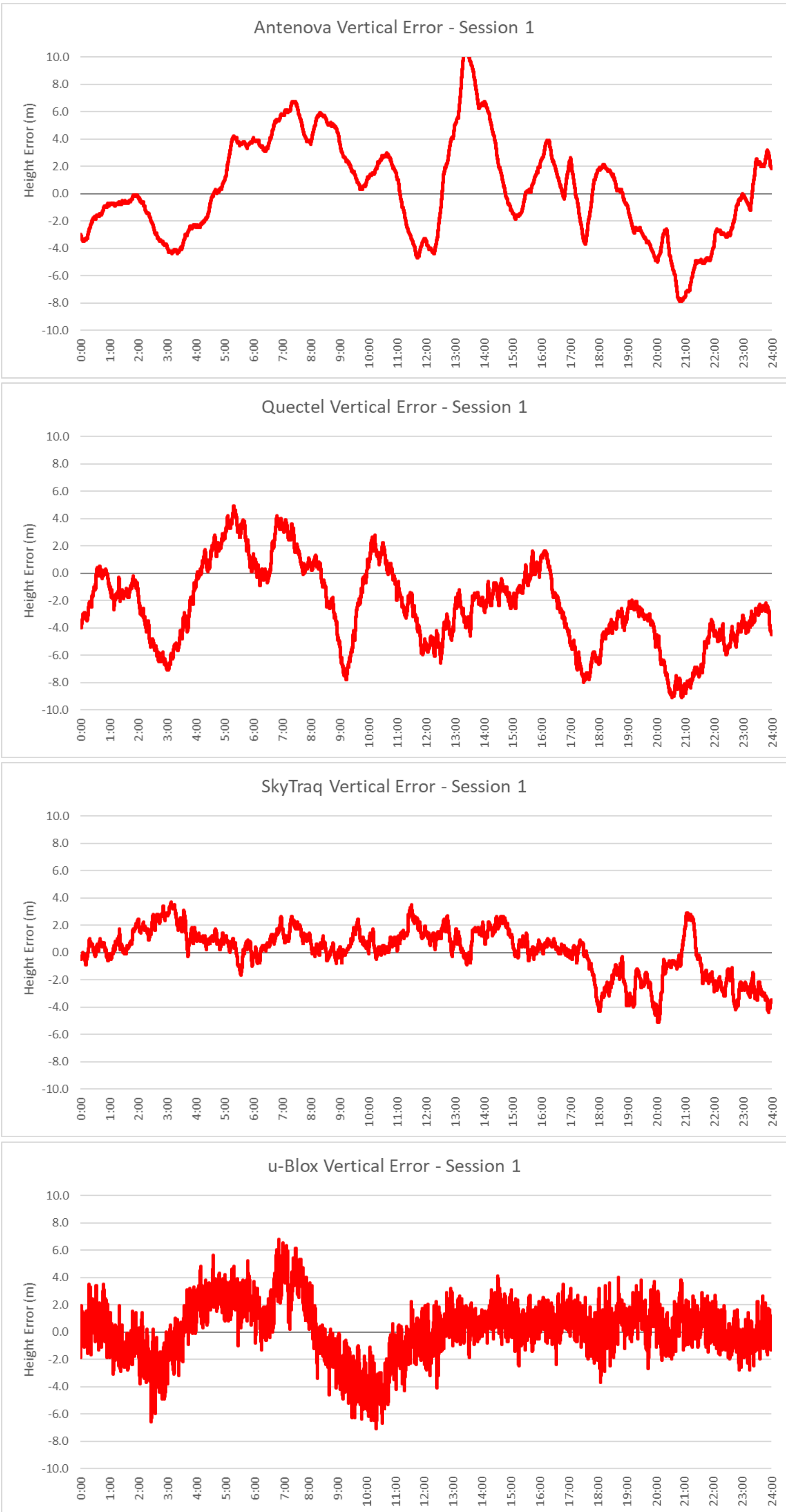

Figure 20. Consumer test 1 vertical plots for Antenova, Quectel, SkyTraq and U-blox receivers.

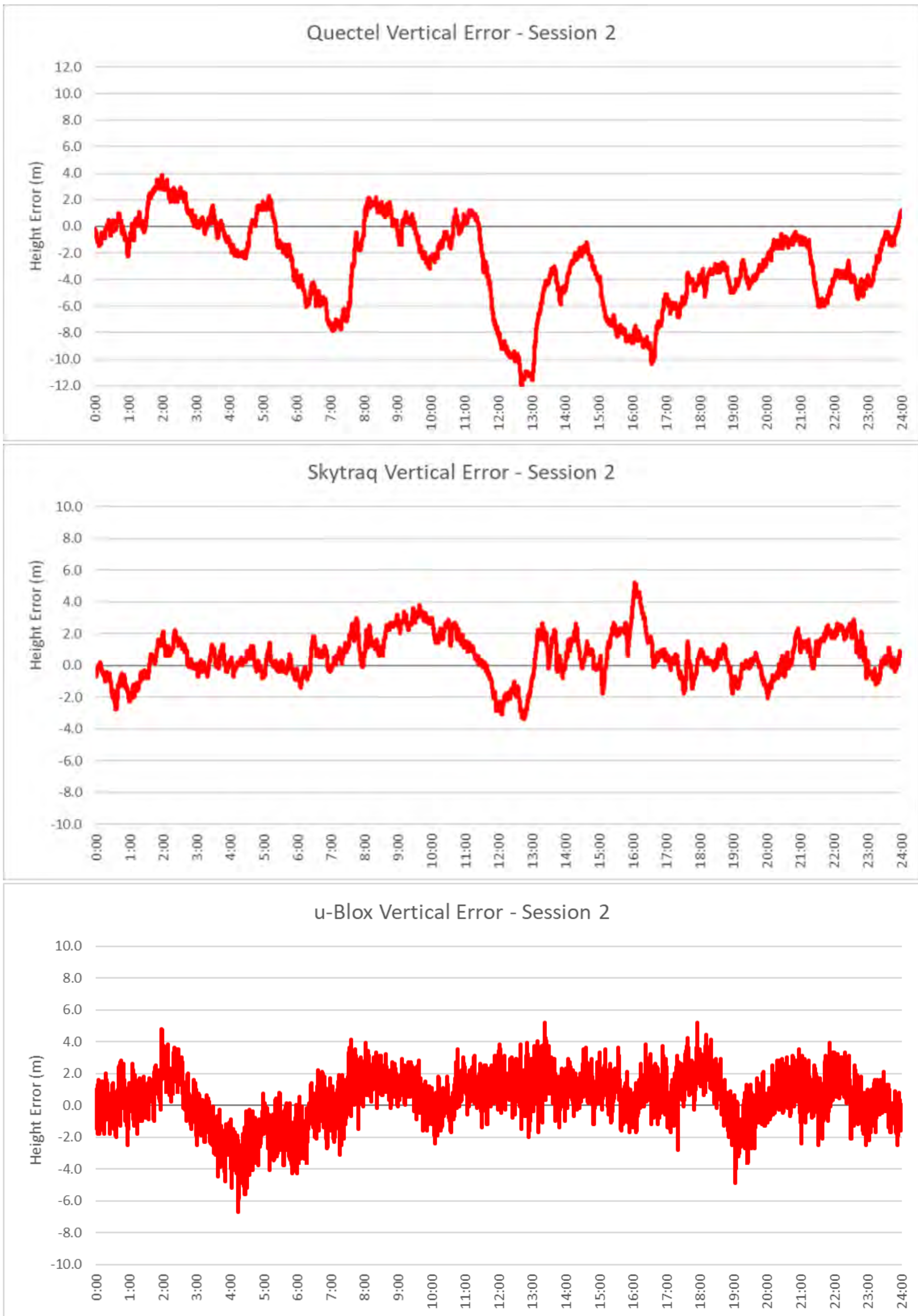

Figure 21. Consumer test 2 vertical plots for Quectel, SkyTraq and U-blox receivers.

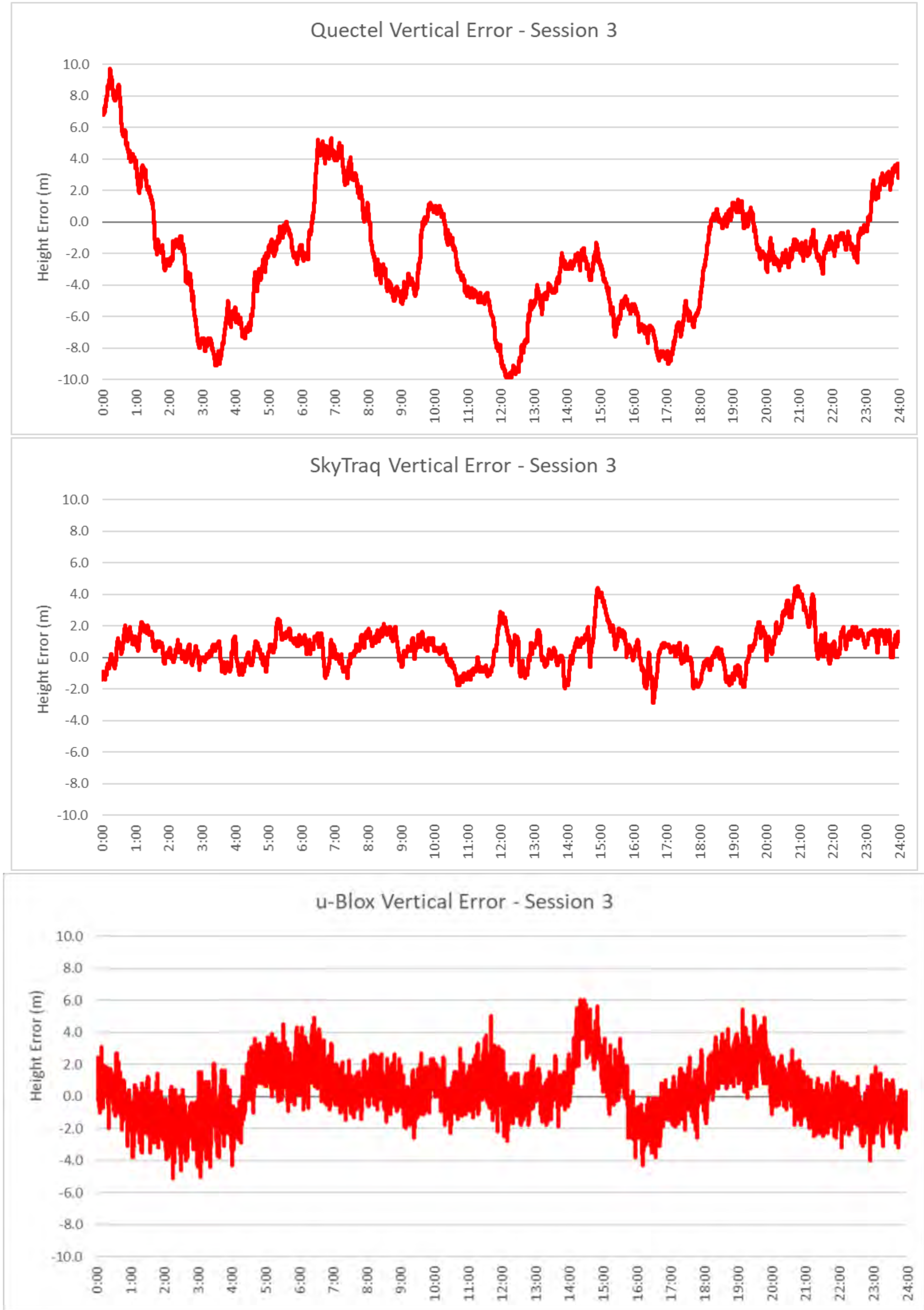

Figure 22. Consumer test 3 vertical plots for Quectel, SkyTraq and U-blox receivers.

The vertical results reflect the picture seen in the horizontal scenario. Quectel and Antenova have the worst performance with the vertical RMS of 4.05m and 3.64m respectively. SkyTraq has the best performance with the RMS of 1.41m, followed by U-blox with 1.70m. U-blox time-series appear much noisier than the SkyTraq due to the binning that is applied to the coordinates by the SkyTraq receiver.

Figure 23 to Figure 25 show corresponding horizontal plots for the mid-range receivers.

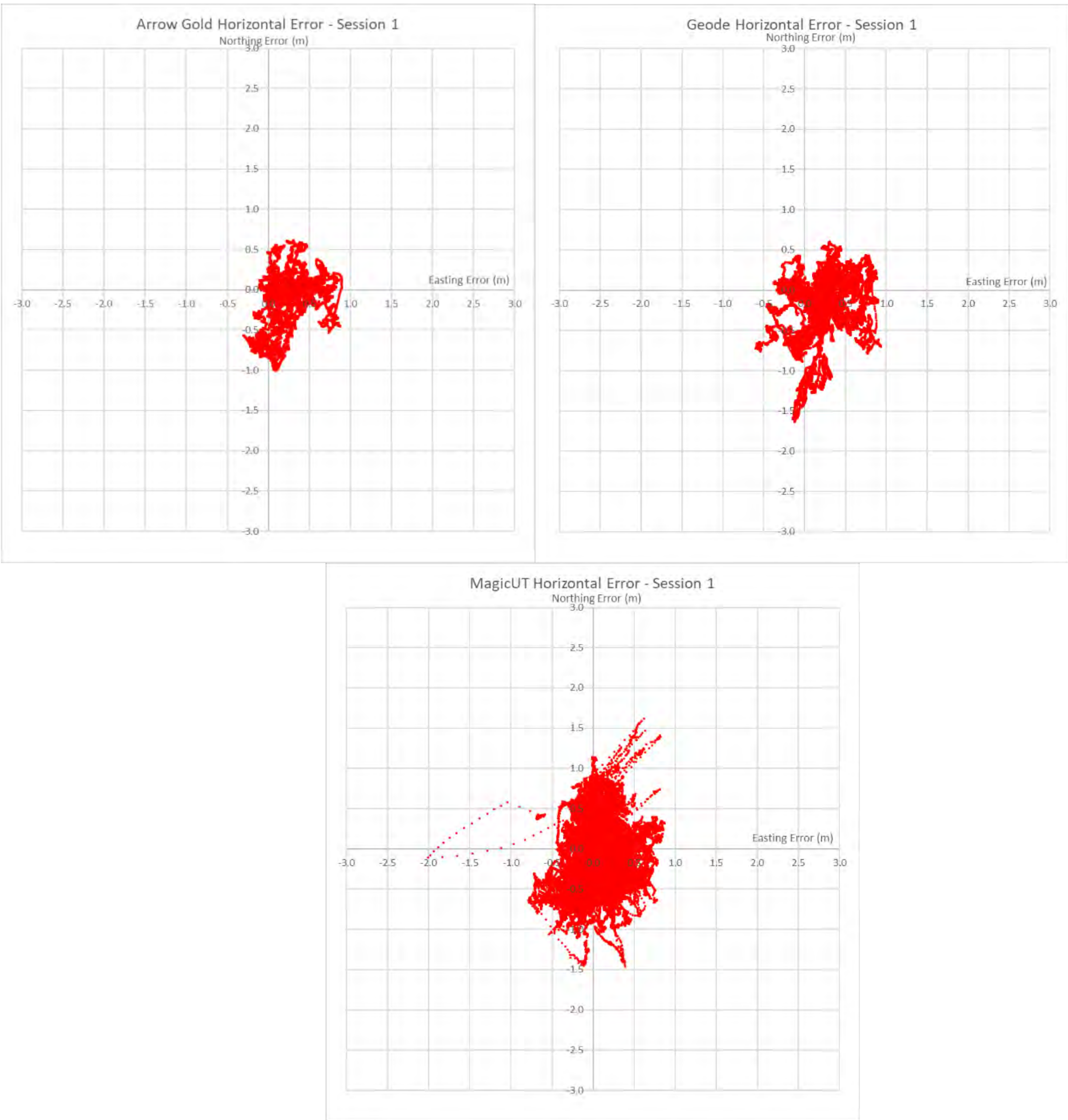

Figure 23. Mid-range test 1 horizontal plots for Arrow Gold, Geode and magicUT receivers.

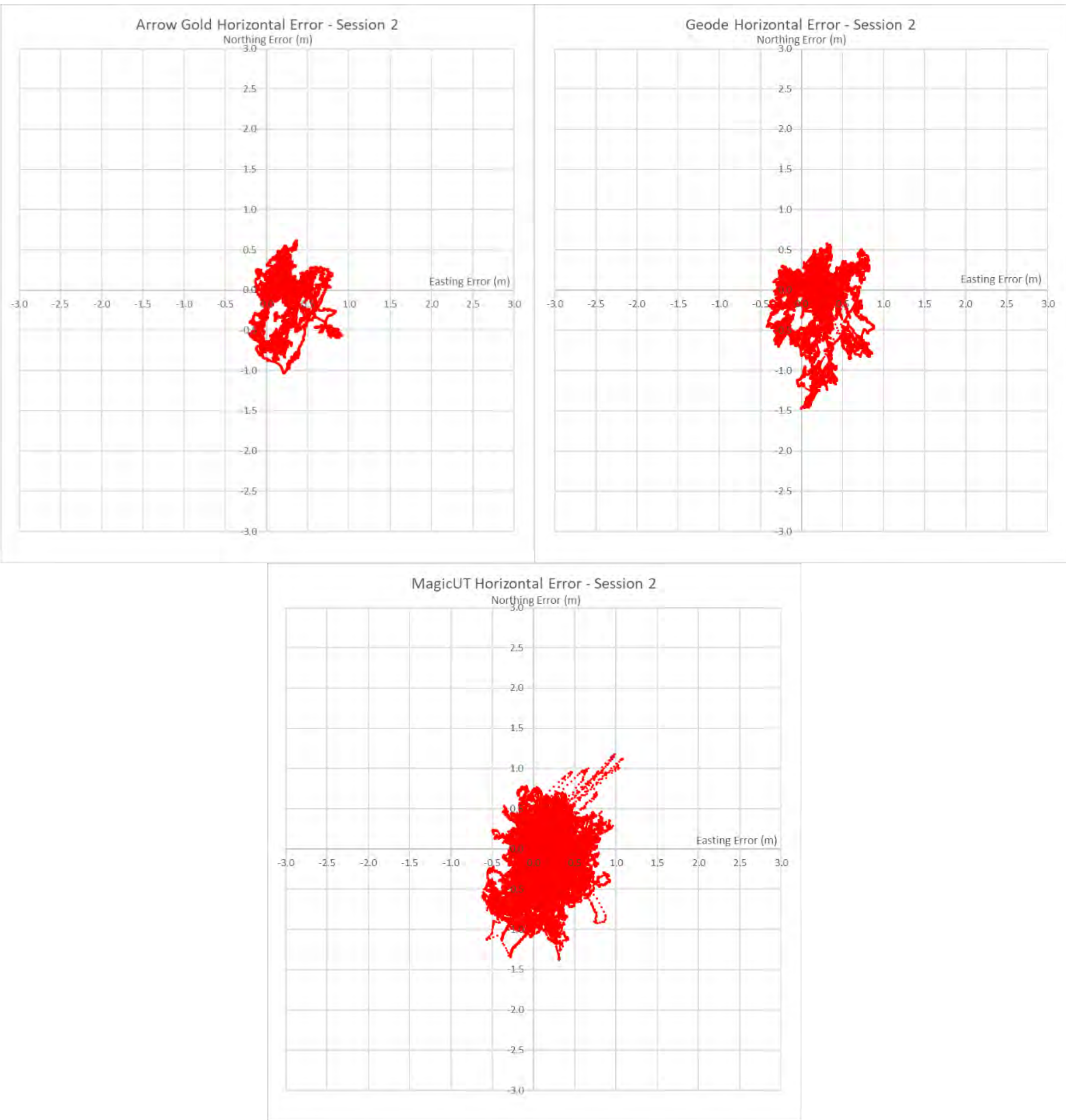

Figure 24. Mid-range test 2 horizontal plots for Arrow Gold, Geode and magicUT receivers.

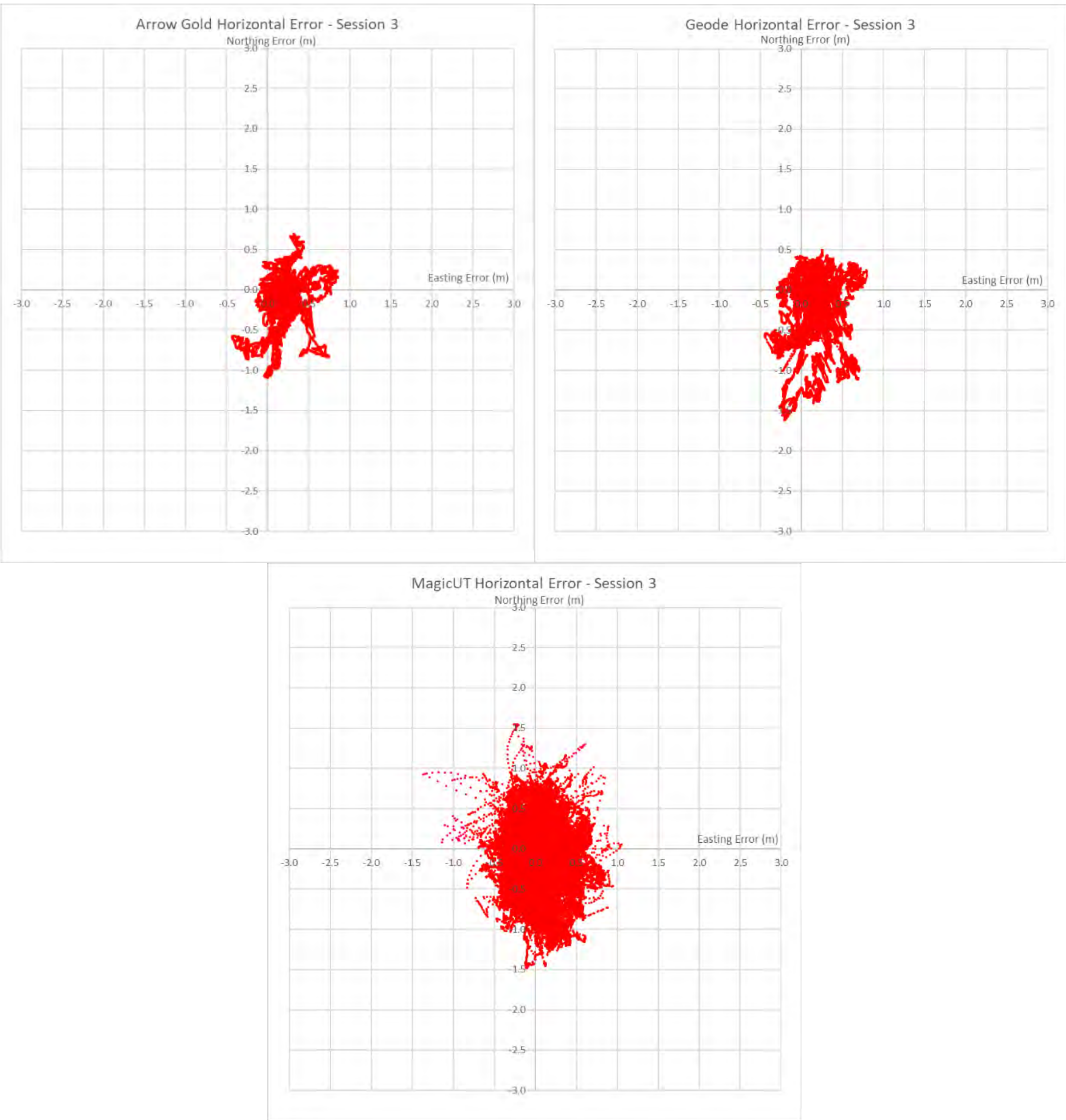

Figure 25. Mid-range test 3 horizontal plots for Arrow Gold, Geode and magicUT receivers.

It can be seen that the performance of the mid-range devices with SBAS L1 positioning is improved significantly when compared to the consumer devices, both in terms of accuracy and precision. The Arrow Gold and the Geode have produced almost identical results with RMS values of 0.43m and 0.44m for each device. This is potentially due to the fact that both devices are based on the same Hemisphere GNSS board. The magicUT had very similar performance of 0.49m RMS. This shows that mid-range devices are capable of providing horizontal positioning at ~0.5m level with SBAS L1 positioning.

Figure 26 to Figure 28 show the vertical time series for the mid-range devices.

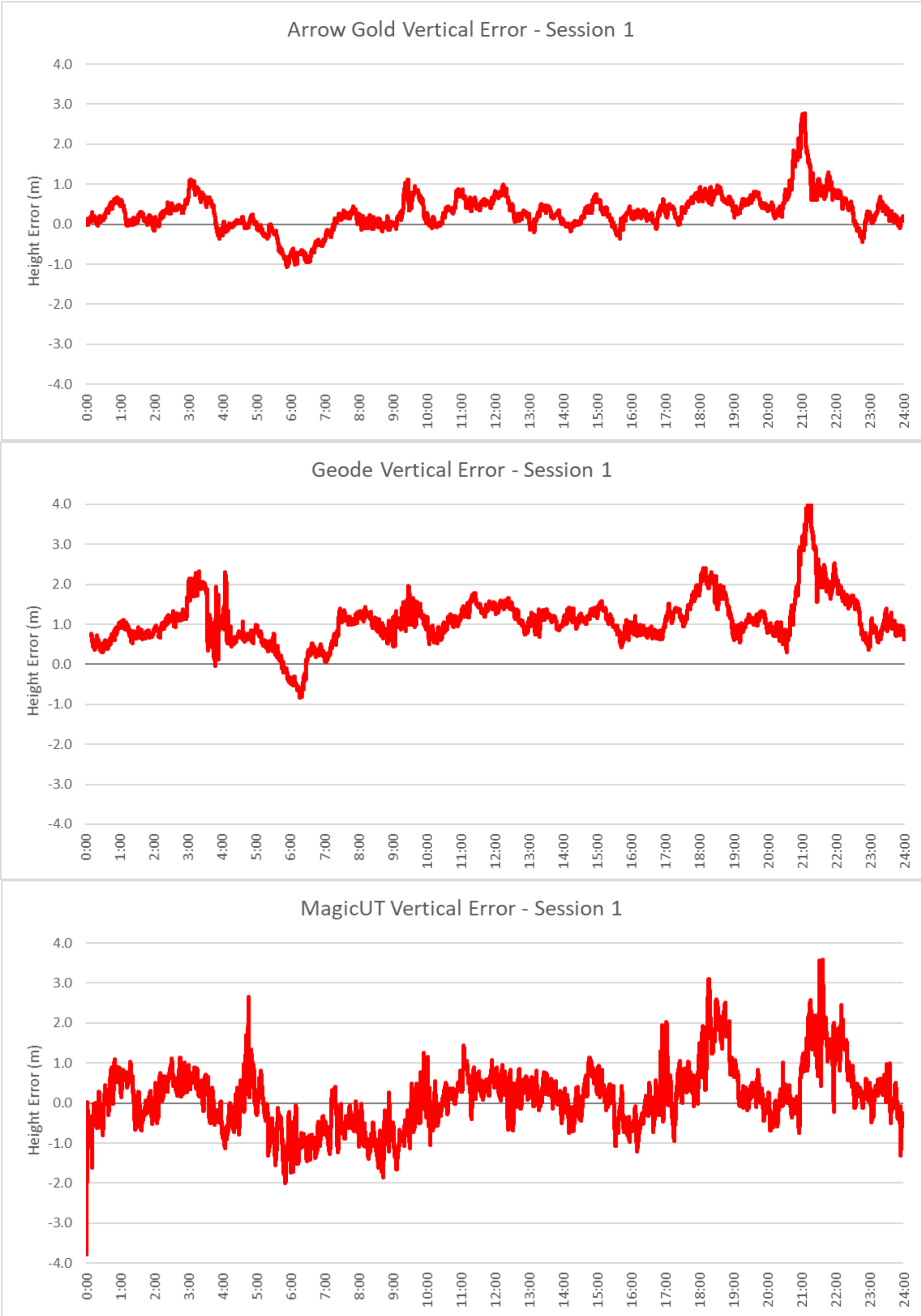

Figure 26. Mid-range test 1 vertical plots for Arrow Gold, Geode and magicUT receivers.

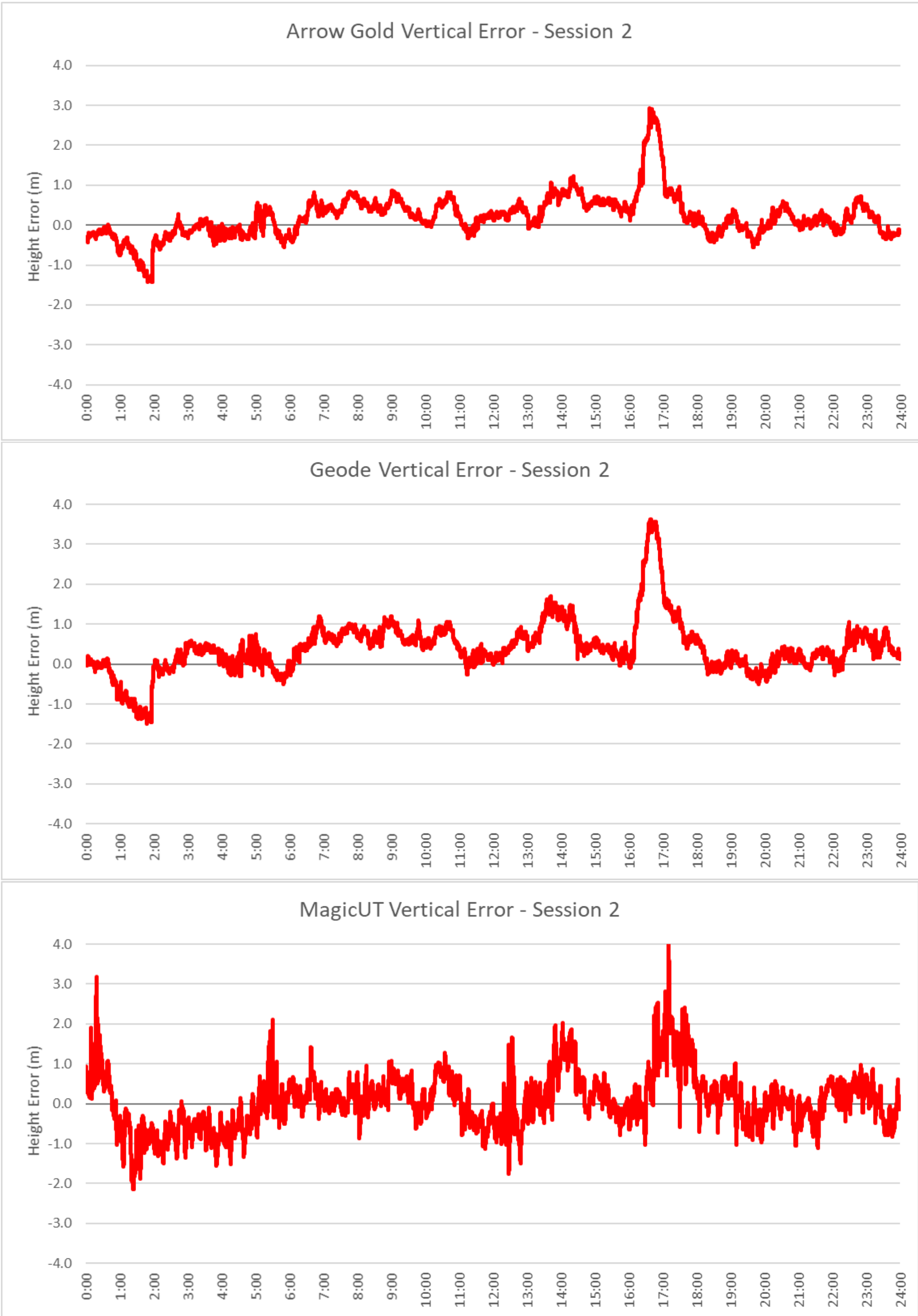

Figure 27. Mid-range test 2 vertical plots for Arrow Gold, Geode and magicUT receivers.

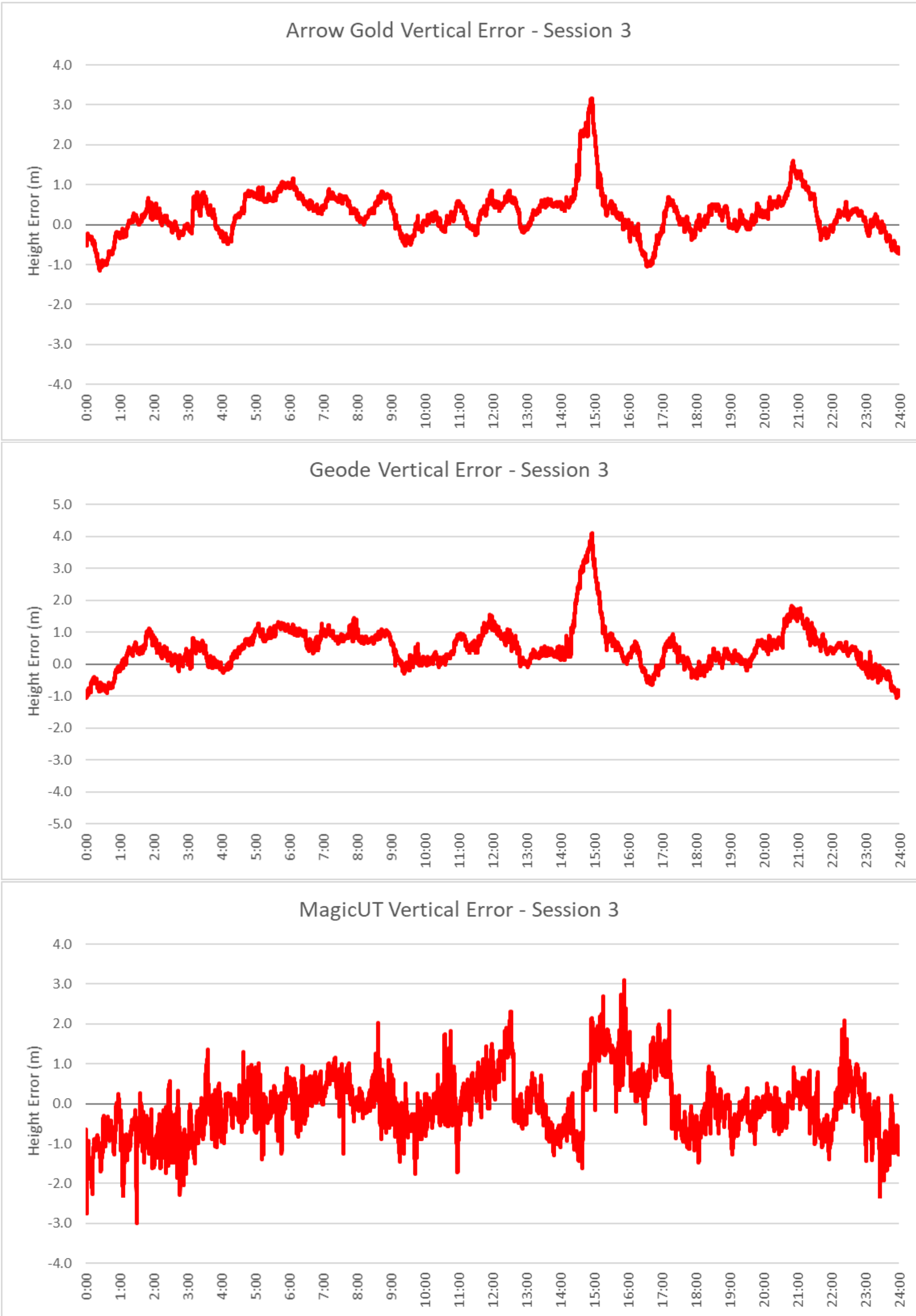

Figure 28. Mid-range test 3 vertical plots for Arrow Gold, Geode and magicUT receivers.

In the vertical domain the results were more spread than in the horizontal. Arrow Gold provided the best performance with an RMS of 0.46m, followed by the Geode with 0.60m and magicUT with 0.69m. magicUT data proved visibly noisier compared to both Geode and Arrow Gold. Similarly to the horizontal, Arrow Gold and the Geode have shown very similar characteristics, having spikes at the same time in the time series.

5.1.2 Static antenna testing with SBAS L1 results

The impact of the antenna on GNSS positioning quality was tested using one consumer-grade and one professional receiver. Septentrio AsteRx-U and U-blox M8N receivers were connected to a number of different antennas from patch to geodetic quality via a splitter. Two 4-hour datasets were recorded for each antenna, the first with both receivers configured to receive SBAS L1 corrections, and the second with both receivers in standalone mode. Table 5 to Table 8 show the results of both receivers in horizontal and vertical modes.

Table 5. Septentrio Horizontal Results.

Antenna Setup	Septentrio – SBAS L1			Septentrio – Standalone		
	Mean (m)	St Dev (m)	RMS (m)	Mean (m)	St Dev (m)	RMS (m)
Topcon G3-A1	0.22	0.27	0.35	0.34	0.50	0.60
Tallysman TW7972 with GP	0.37	0.33	0.50	0.58	0.52	0.78
Tallysman TW7972	0.86	0.39	0.95	0.57	0.88	1.05
Patch with GP	0.37	0.45	0.58	1.16	0.32	0.97
Patch	0.99	0.47	1.09	2.47	0.58	2.53

Table 6. U-blox Horizontal Results.

Antenna Setup	U-blox – SBAS L1			U-blox – Standalone		
	Mean (m)	St Dev (m)	RMS (m)	Mean (m)	St Dev (m)	RMS (m)
Topcon G3-A1	0.21	0.72	0.75	0.90	1.43	1.69
Tallysman TW7972 with GP	0.11	0.99	1.00	0.92	1.15	1.47
Tallysman TW7972	0.79	0.84	1.15	0.66	0.85	1.07
Patch with GP	0.25	1.42	1.44	1.60	1.29	1.39
Patch	0.47	1.24	1.33	1.53	1.53	2.16

Table 7. Septentrio Vertical Results.

Antenna Setup	Septentrio – SBAS L1			Septentrio – Standalone		
	Mean (m)	St Dev (m)	RMS (m)	Mean (m)	St Dev (m)	RMS (m)
Topcon G3-A1	0.48	0.27	0.53	-0.25	0.99	1.02
Tallysman TW7972 with GP	0.99	0.26	1.02	0.35	0.35	0.49
Tallysman TW7972	0.21	0.75	0.77	-0.91	1.20	1.51
Patch with GP	1.53	0.43	1.59	-0.19	0.37	0.41
Patch	0.81	0.87	1.18	-1.11	0.49	1.22

Table 8. U-blox Vertical Results.

Antenna Setup	U-blox – SBAS L1			U-blox – Standalone		
	Mean (m)	St Dev (m)	RMS (m)	Mean (m)	St Dev (m)	RMS (m)
Topcon G3-A1	0.45	1.18	1.26	-0.11	2.11	2.12
Tallysman TW7972 with GP	1.89	1.67	2.52	-2.25	1.57	2.74
Tallysman TW7972	0.97	1.53	1.81	-2.37	1.23	2.67
Patch with GP	1.90	1.70	2.55	-1.68	2.04	2.64
Patch	1.96	2.48	3.16	-0.88	2.96	3.09

Figures Figure 29 to Figure 33 show the horizontal results for all antennas with SBAS L1 and standalone modes.

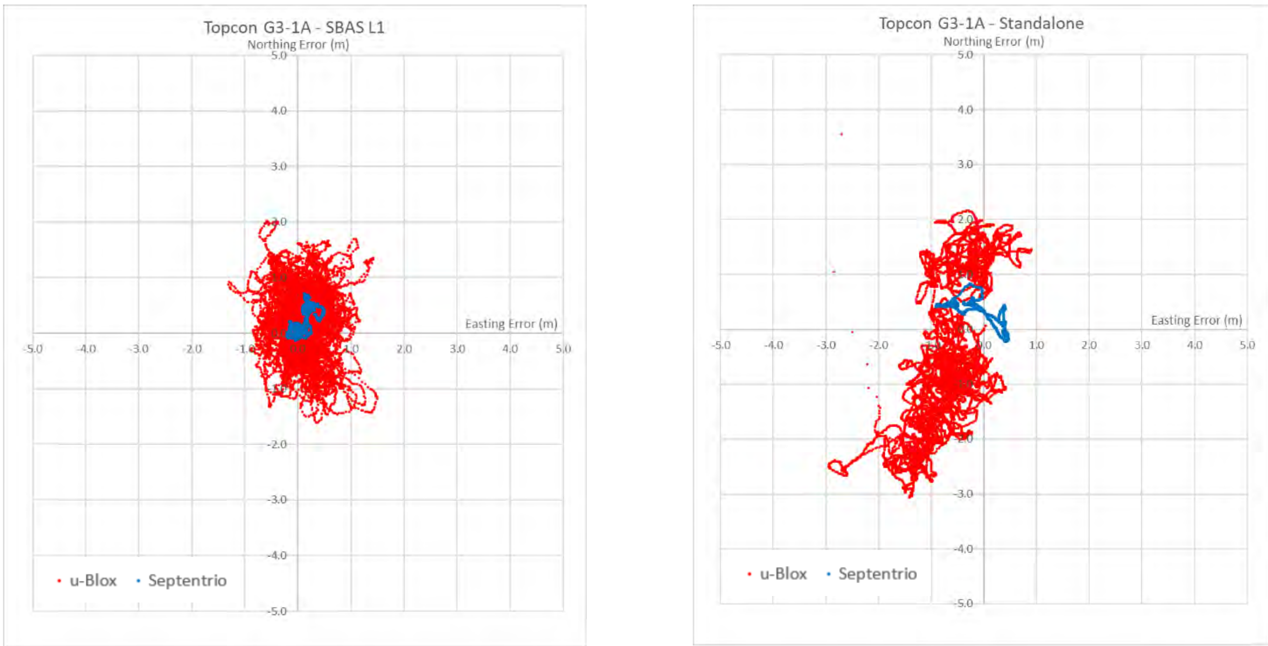

Figure 29. Horizontal plots for Topcon G3-1A antenna.

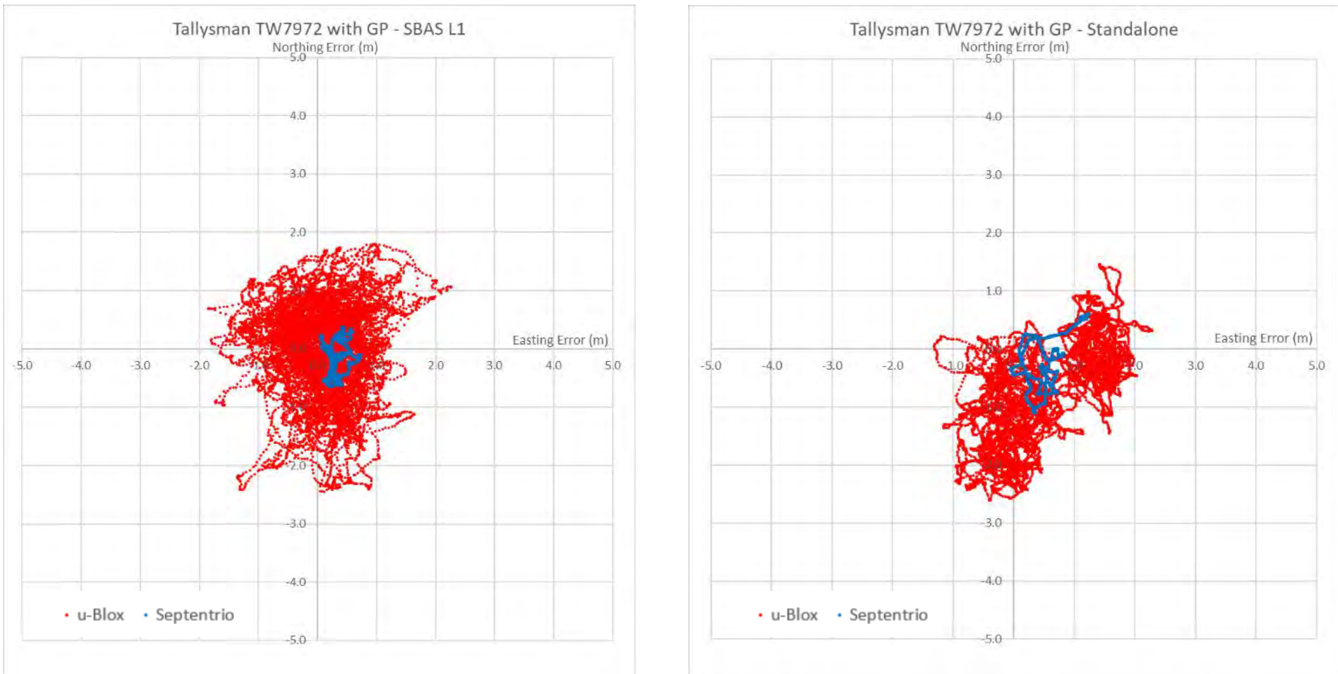

Figure 30. Horizontal plots for Tallysman TW7972 antenna with ground plane.

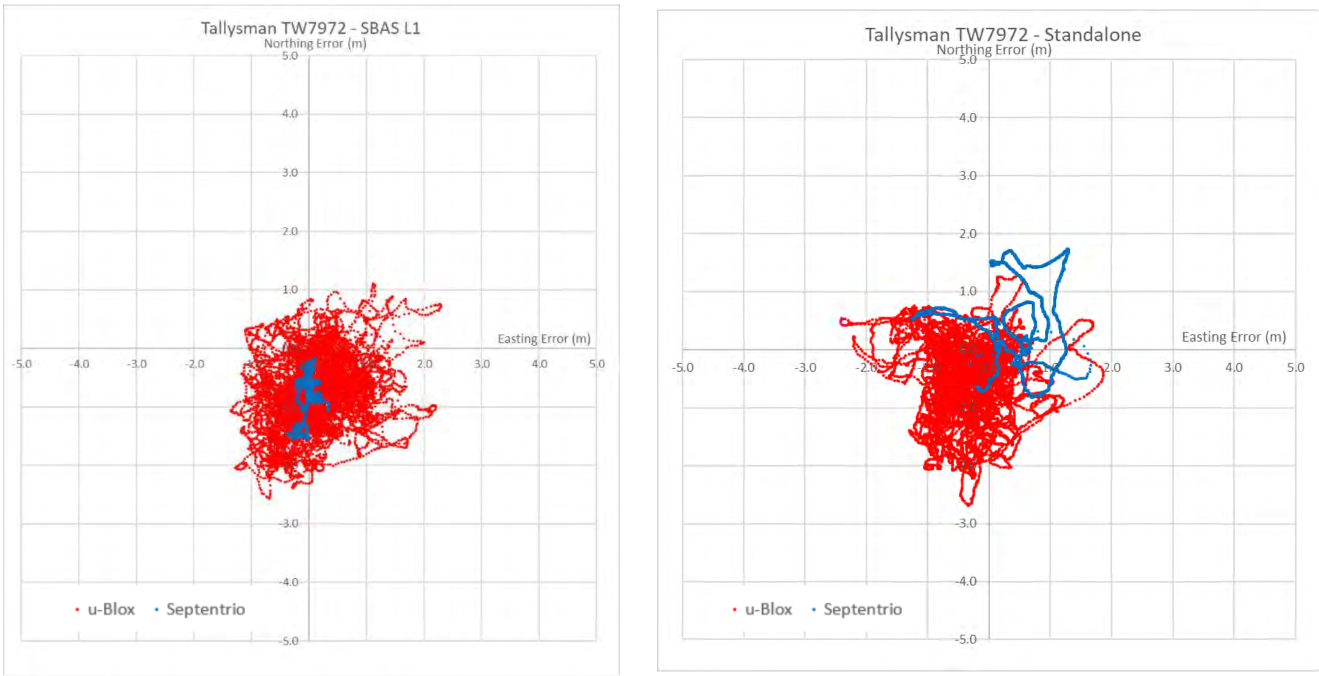

Figure 31. Horizontal plots for Tallysman TW7972 antenna without ground plane.

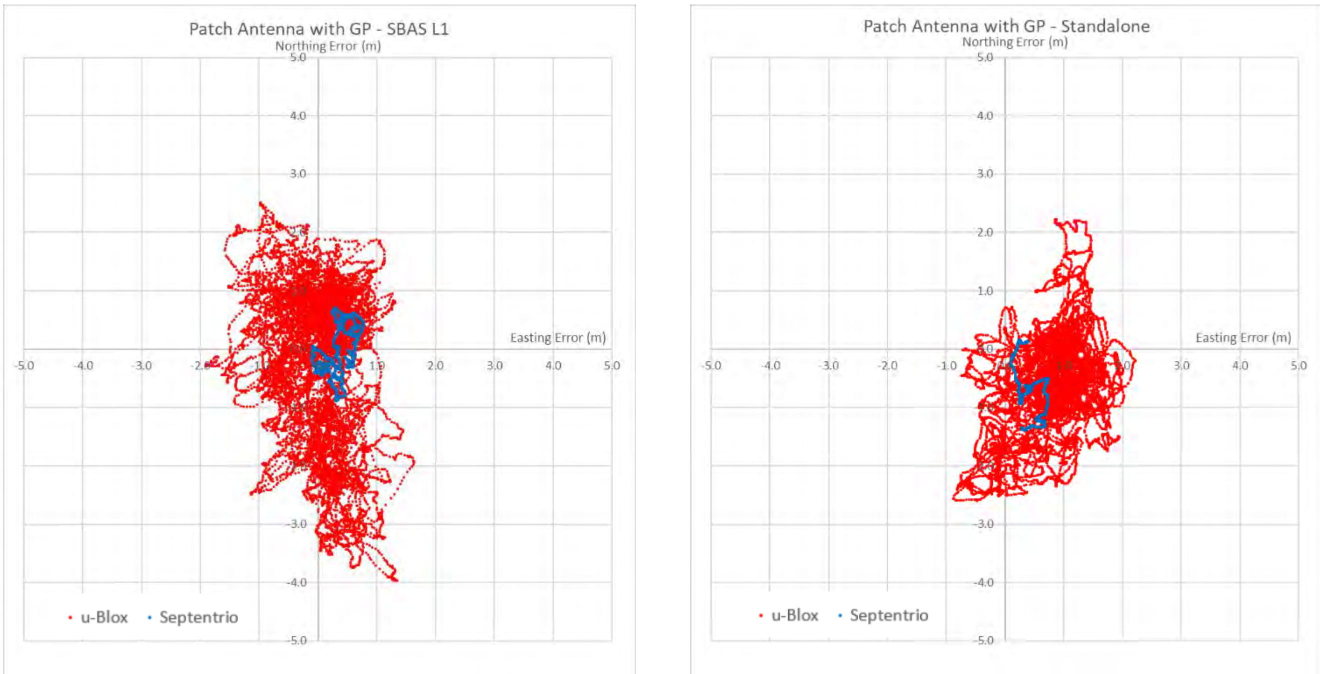

Figure 32. Horizontal plots for Tallysman patch antenna with ground plane.

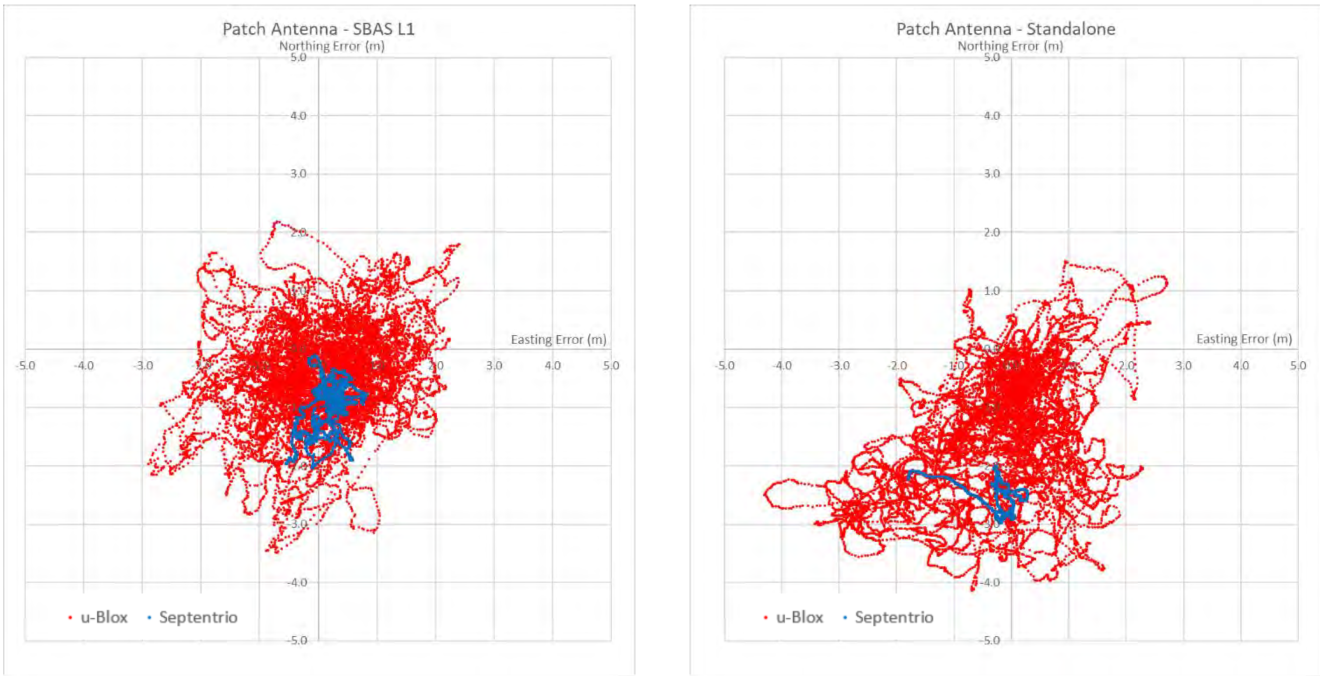

Figure 33. Horizontal plots for patch antenna without ground plane.

The analysis of the results shows that the quality of positioning performance increases gradually as the quality of antenna increases. With the Septentrio receiver the RMS of the horizontal solution with SBAS L1 went from 0.35m with the geodetic antenna to 1.09m with a patch antenna. Respective results for U-blox receiver were 0.75m to 1.33m. Another interesting finding is that with the Septentrio receiver, the impact of introducing the ground plane to the Tallysman and patch antenna improved the results by a factor of two, whereas on the U-blox receiver the effect was minimal.

From the Tallysman antenna experiment there was a bias evident in the Northing component, potentially caused by the satellite geometry, which impacted the horizontal mean for both Septentrio and U-blox coordinates. The SBAS L1 performance was generally twice as good as the standalone performance with the same antenna for both Septentrio and U-blox receivers.

Figure 34 to Figure 38 show corresponding vertical results for the antenna testing.

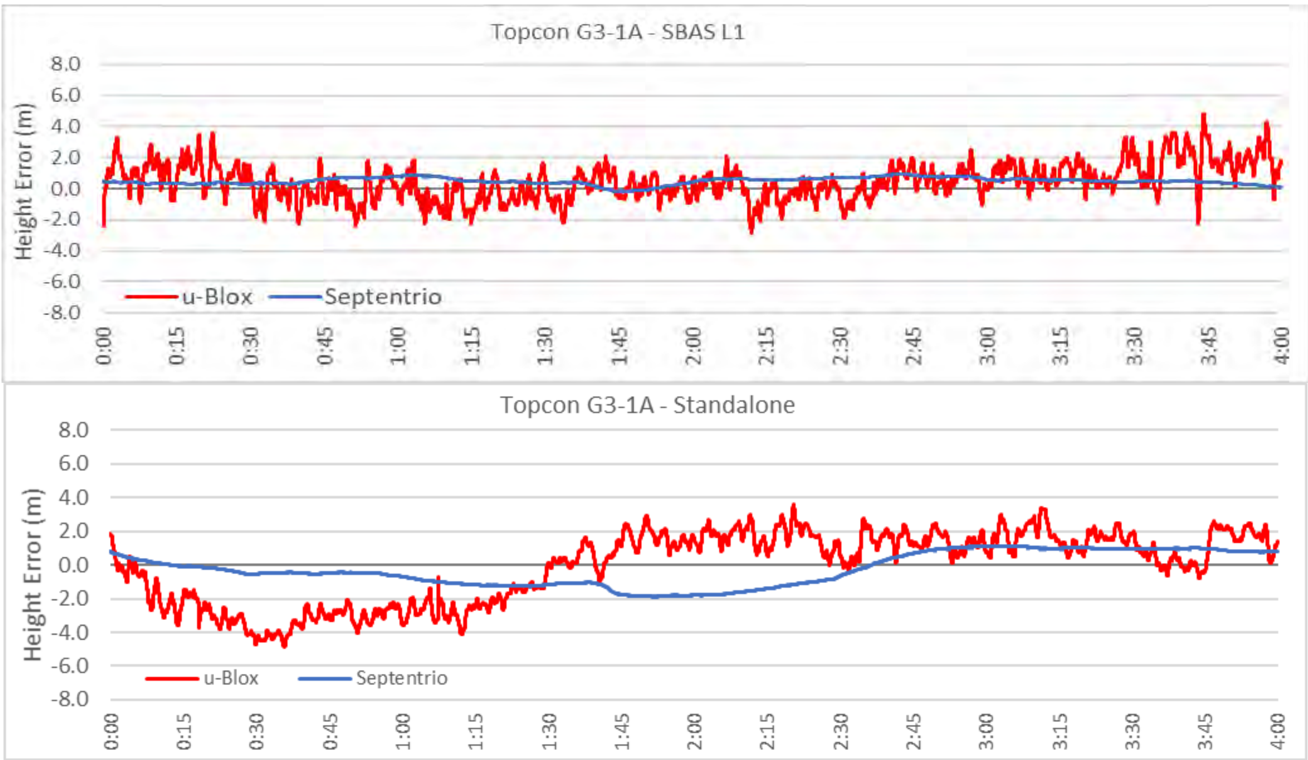

Figure 34. Vertical plots for Topcon G3-1A antenna.

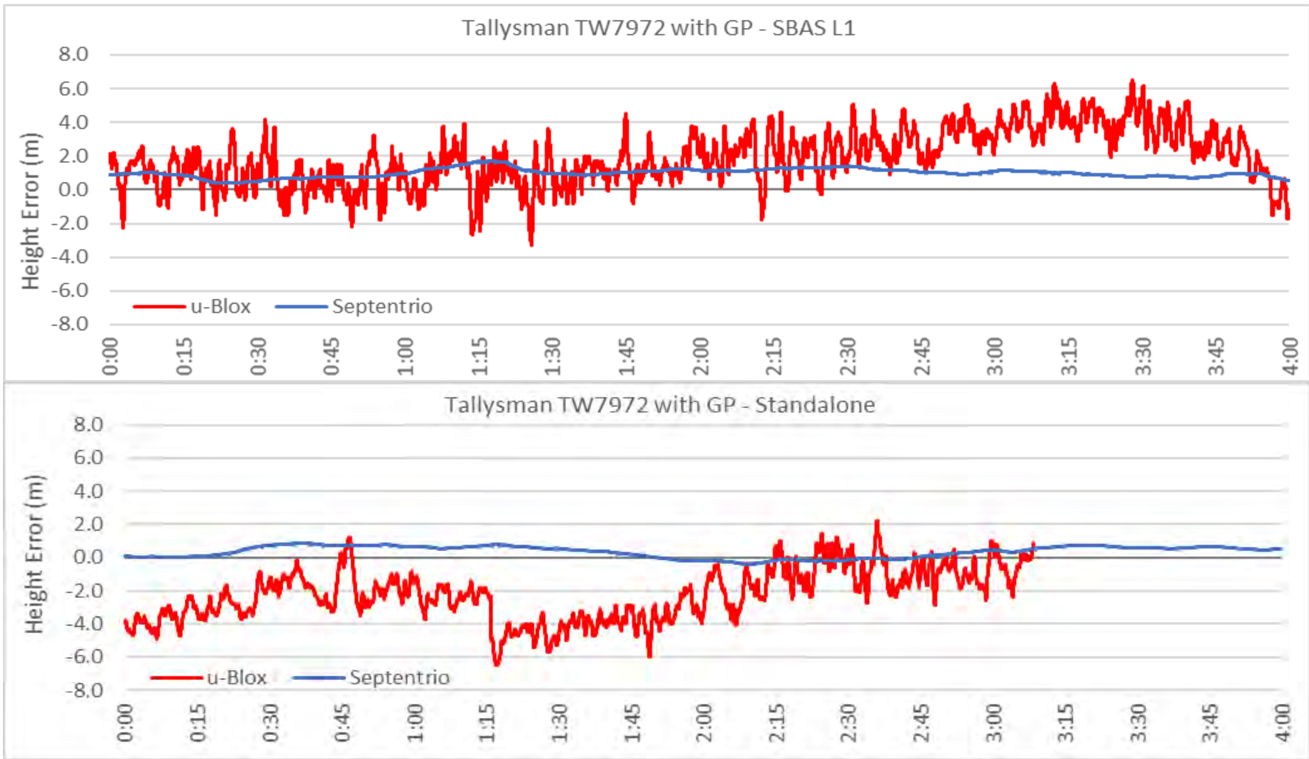

Figure 35. Vertical plots for Tallysman TW7972 with ground plane antenna.

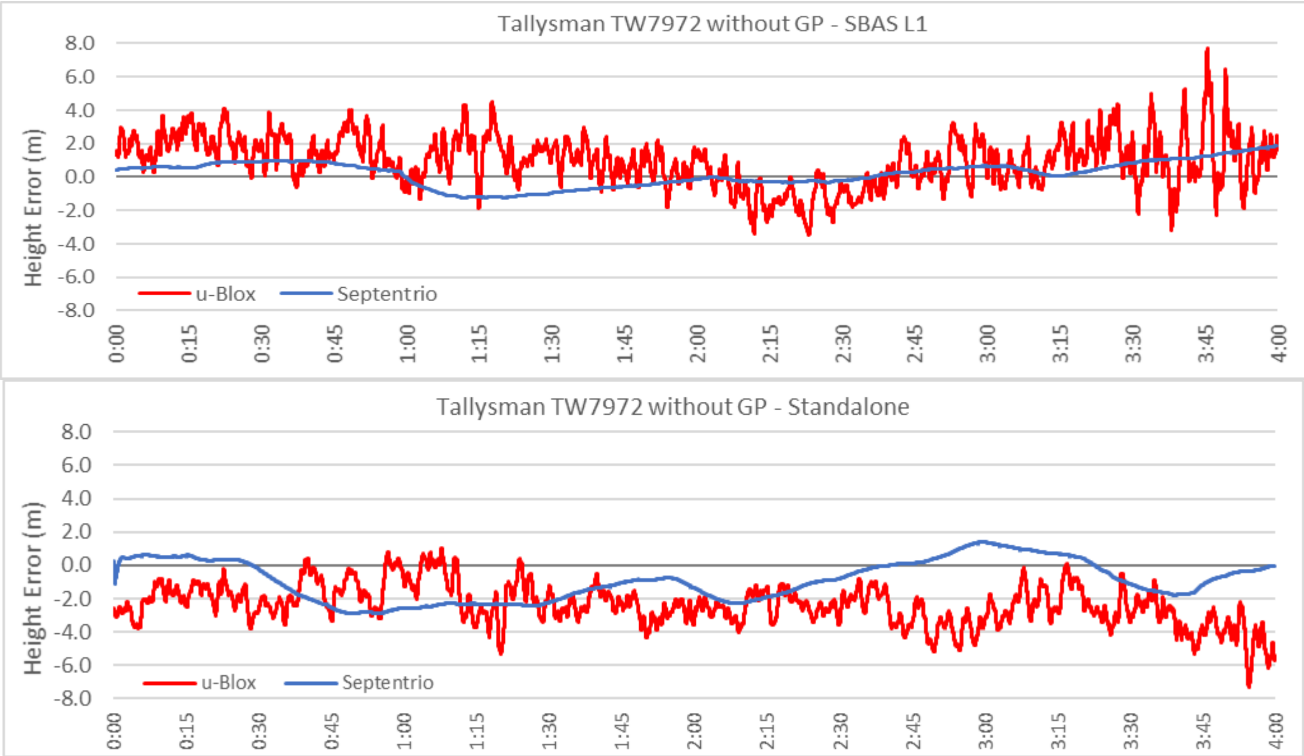

Figure 36. Vertical plots for Tallysman TW7972 without ground plane antenna.

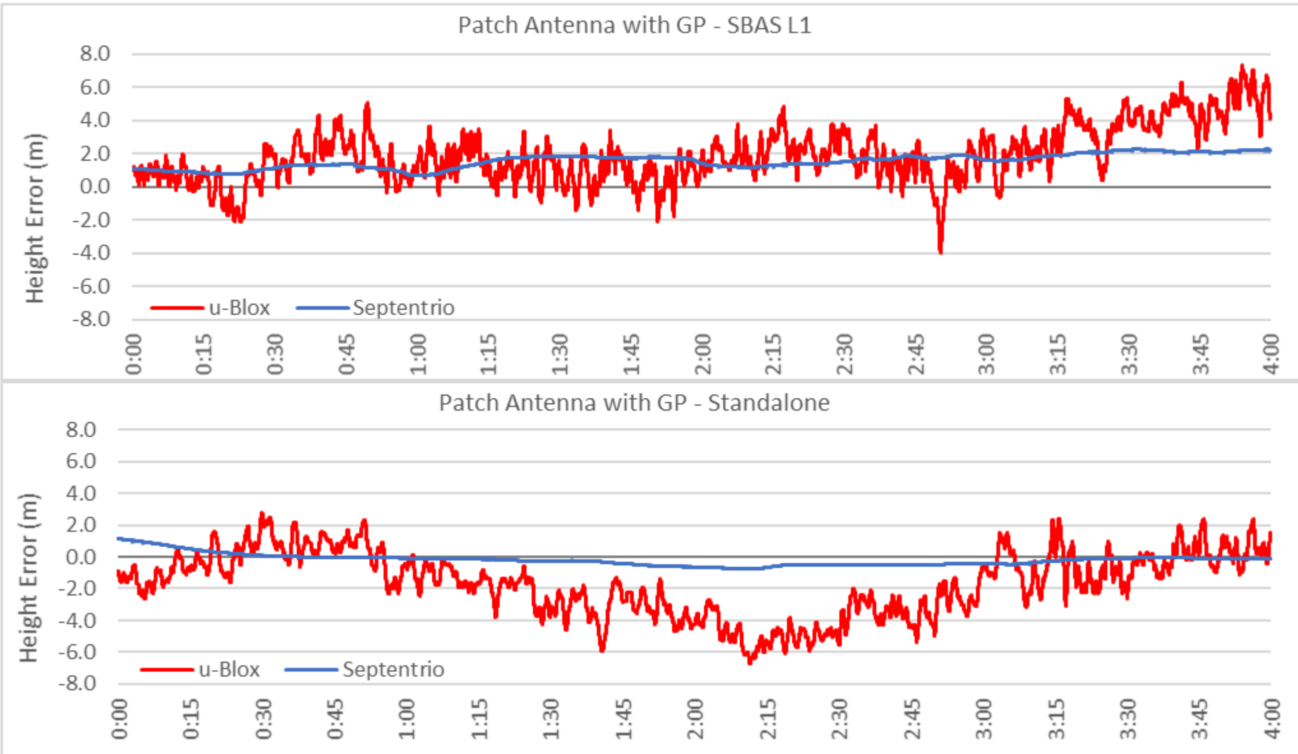

Figure 37. Vertical plots for patch antenna with ground plane.

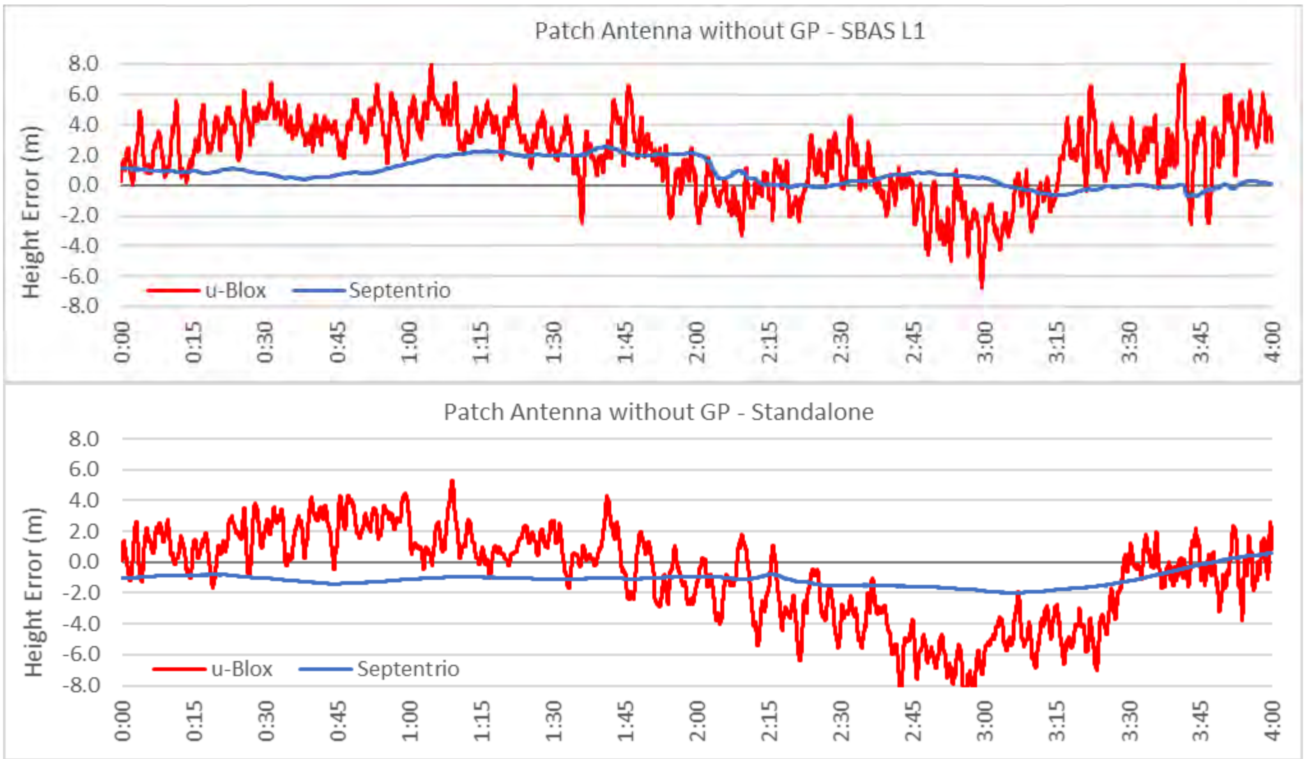

Figure 38. Vertical plots for patch antenna without ground plane.

With the vertical results, more variation was observed between the various antenna models. In general the geodetic antenna provided the best results as expected, with the results decreasing as the antenna grade decreased. Septentrio observed RMS values of 0.5-1.5m with both SBAS L1 and standalone, interestingly, in some cases better standalone values were observed compared to SBAS L1 values. With U-blox, the values varied between 1.2m to 3.1m for SBAS L1, and between 2.1m to 3.1m for standalone.

5.1.3 Static SBAS L1 vs DFMC test results

Table 9 and Figure 39 show the results of SBAS L1 and DFMC testing. Two magicUT receivers were connected to the same antenna via a splitter (each configured to the respective SBAS service) and logged data for 24 hours. The resulting coordinates were compared to the ground truth and the differences quantified.

Table 9. Mid-range receiver static results.

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

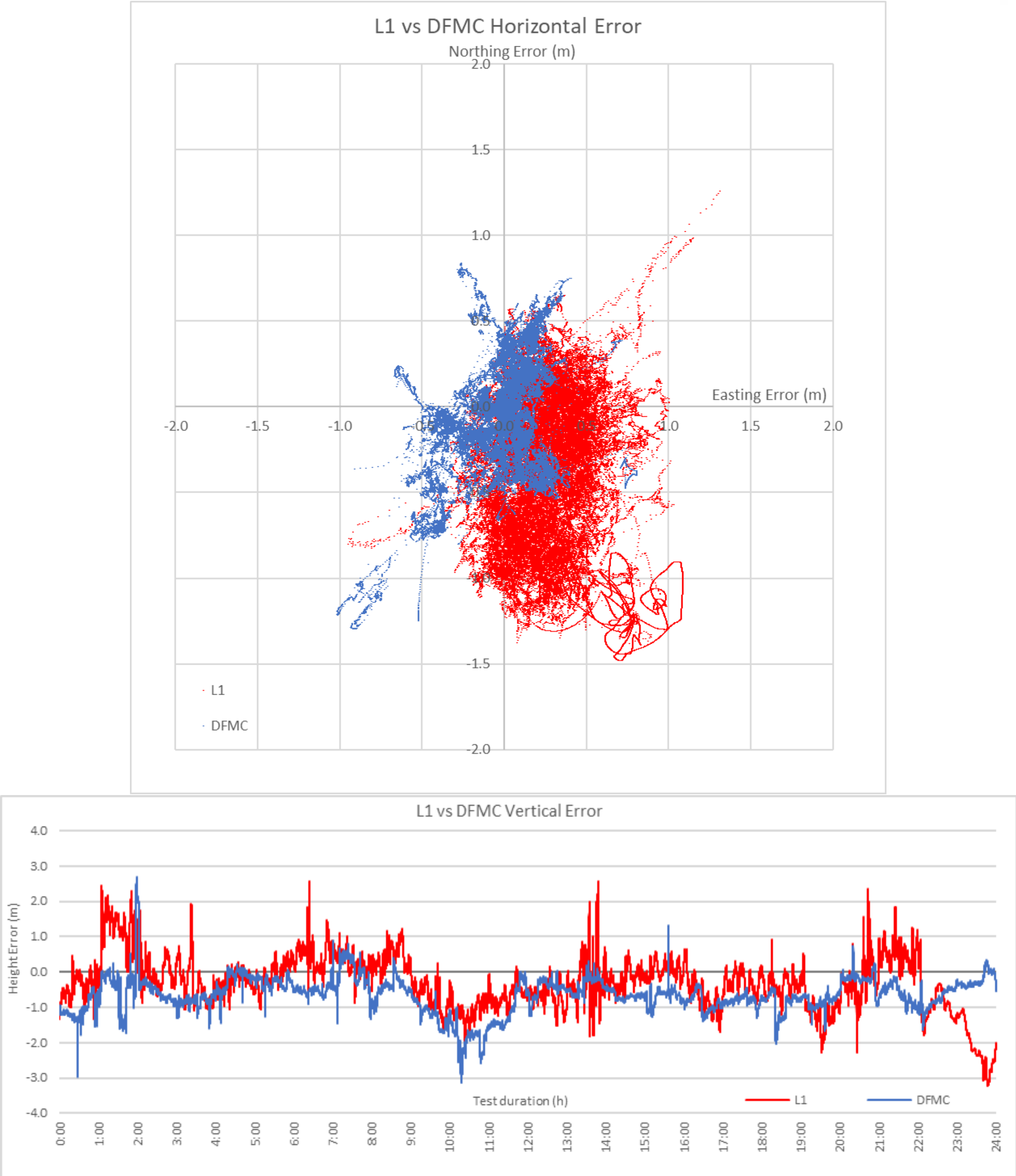

Figure 39. SBAS L1 vs DFMC Plots for horizontal and vertical positioning.

From Table 9 and Figure 39 it can be seen that DFMC has provided much tighter solution horizontally with the RMS of 0.38m compared to 0.70m from SBAS L1 service. Vertically both services provided RMS of 0.83m, however DFMC solution was less noisy.

5.1.4 Static PPP test 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. Convergence time was measured to provide an indication of how long it would take to achieve the indicative performance. Table 10 shows the statistics for PPP testing, and Figure 40 and Figure 41 show the plots of horizontal and vertical positioning. The horizontal position graph shows the positions after convergence.

Table 10. PPP testing results.

PPP Service	Horizontal Difference (m)			Height 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 10 it follows that all three solutions have provided very similar results at ~4cm horizontal and 7-8cm vertical RMS figures. The biggest difference was in convergence time, where RTCM method was a clear winner with 29 minutes compared to the 72 and 83 minutes achieved by GEO and SISNeT. This was the expected result, as RTCM provides a more complete set of correction messages compared to the other two methods.

Figure 40 to Figure 42 show that horizontally the RTCM solution was less noisy compared to both GEO and SISNeT solutions, which was also expected result.

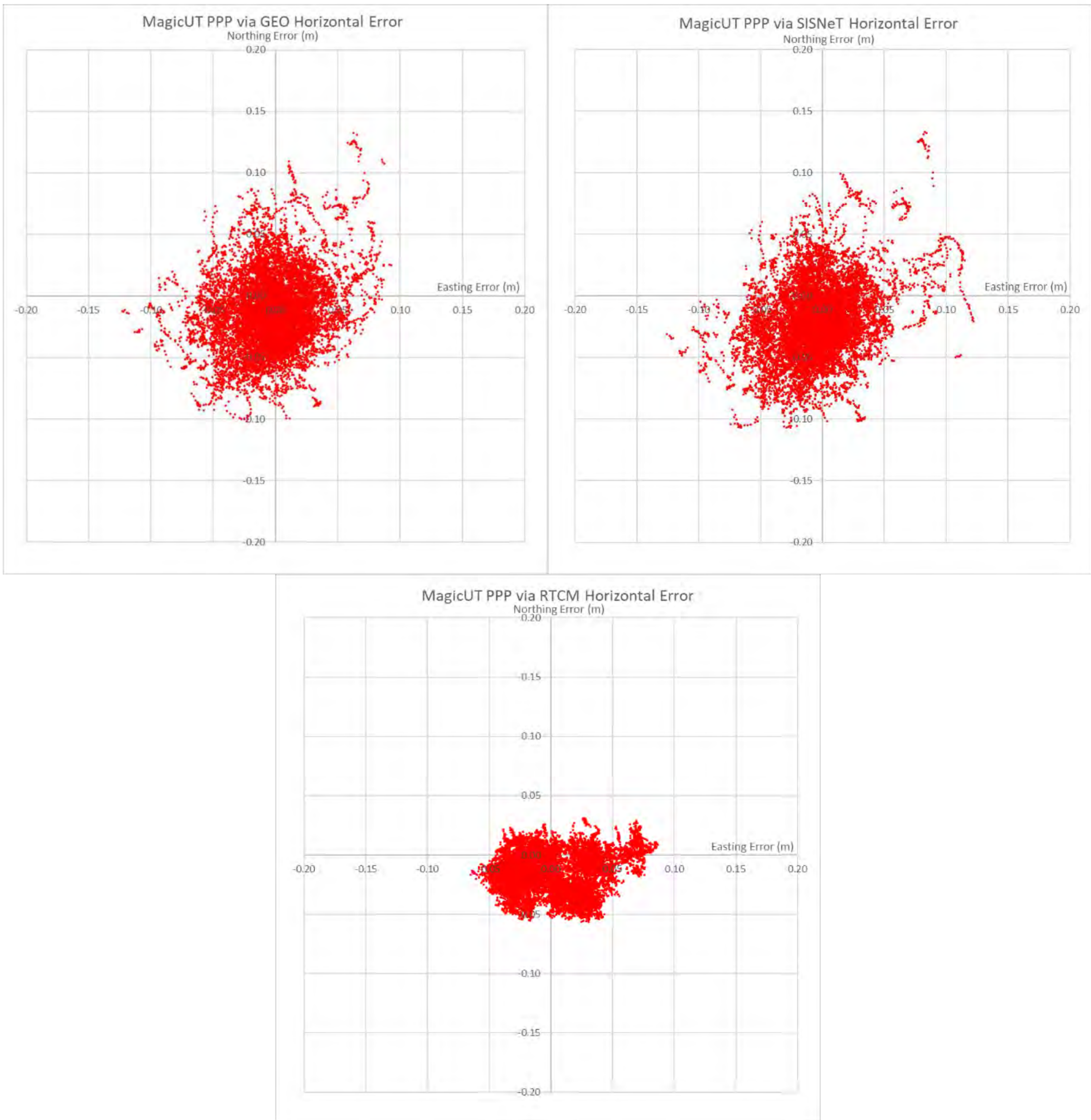

Figure 40. PPP horizontal results for GEO, SISNeT and RTCM.

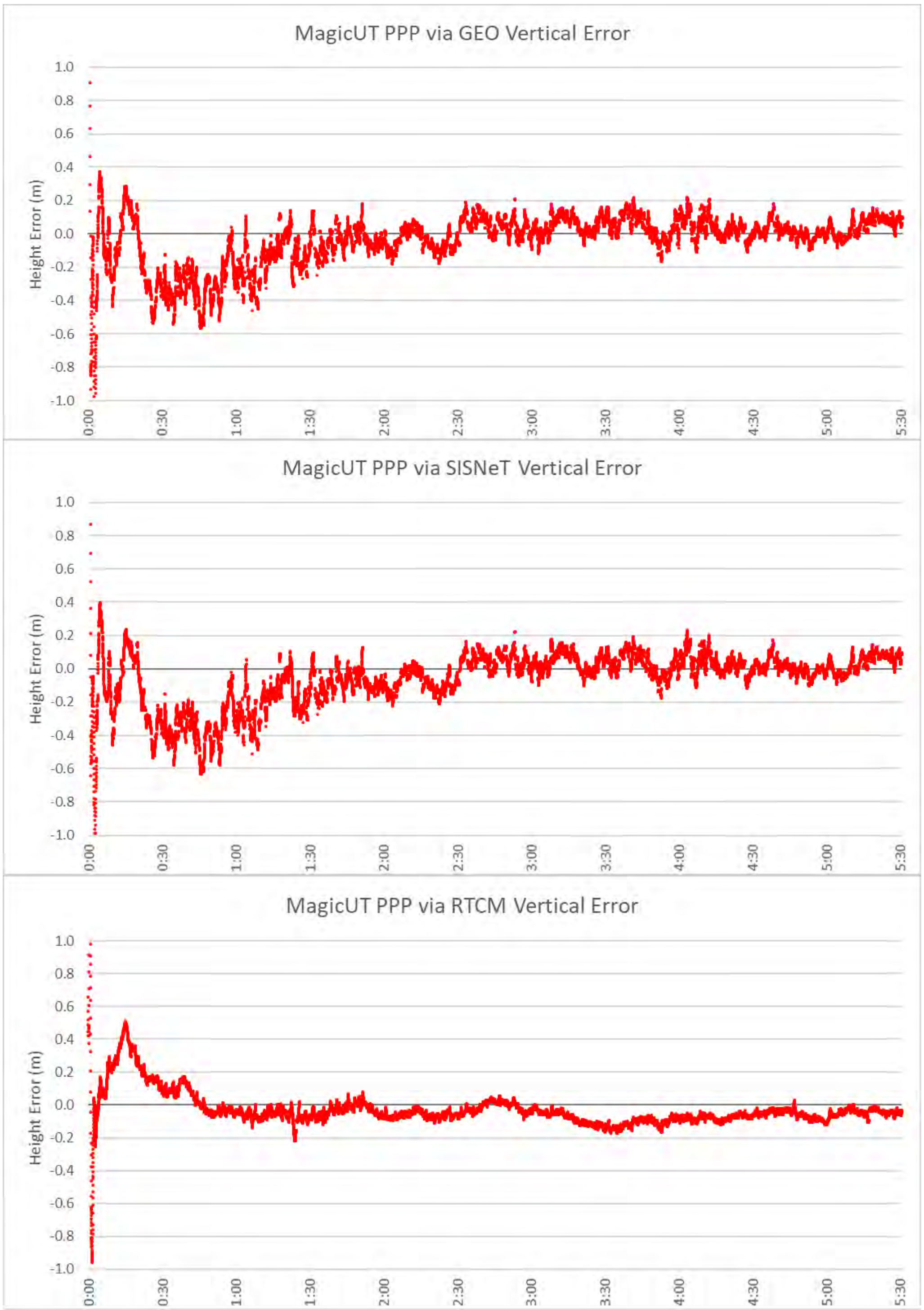

Figure 41. PPP vertical Results for GEO, SiSNeT, RTCM.

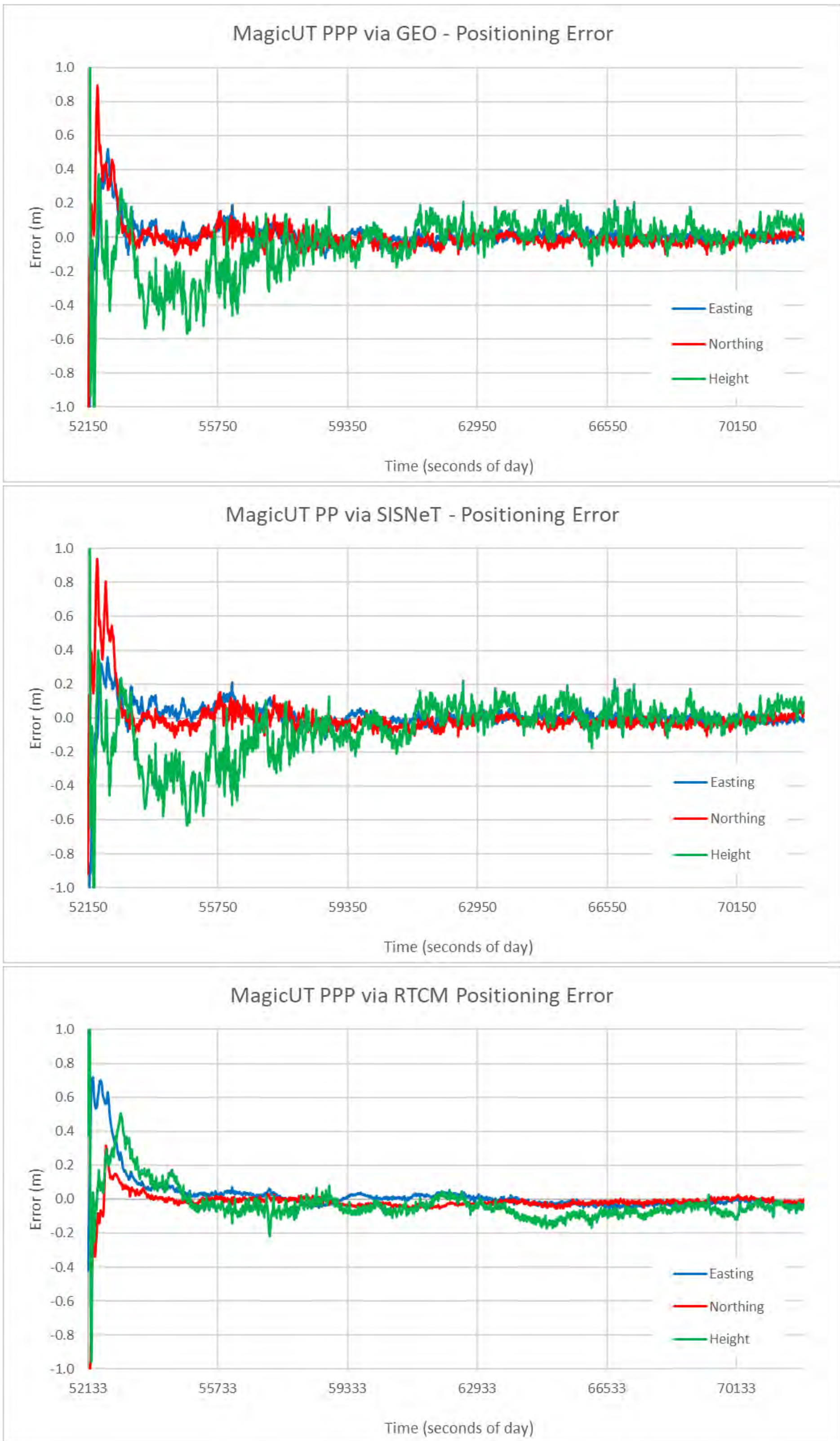

Figure 42. PPP positioning error for GEO, SiSNeT, RTCM.

5.2 Kinematic testing results

The results for all the kinematic tests are presented in this section.

5.2.1 Kinematic results of mid-range receivers with SBAS L1

The accuracy and availability of the kinematic testing campaign for Arrow Gold, Geode and magicUT receivers are presented in Table 11 and Table 12. The results of the ComNav receiver are left out as the receiver did not function properly in SBAS L1 mode. Kinematic availability was calculated for each road environment shown in Figure 12, i.e. urban canyon, inner suburbs, vegetated suburbs, open freeway and outer suburbs.

Table 11. SBAS L1 kinematic accuracy results.

Receiver	Drive	Horizontal Difference (m)			Height Difference (m)		
		Mean	St Dev	RMS	Mean	St Dev	RMS
Arrow Gold	1	0.20	0.29	0.53	1.52	0.60	1.64
	2	0.38	0.37	0.72	1.31	0.65	1.46
	3	0.30	0.14	0.43	0.98	0.70	1.20
Arrow Gold	Average	0.29	0.27	0.56	1.27	0.65	1.43
Geode	1	0.10	0.16	0.32	0.33	0.41	0.53
	2	0.25	0.20	0.44	1.10	0.54	1.23
	3	0.07	0.13	0.30	0.57	0.38	0.69
Geode	Average	0.14	0.16	0.35	0.67	0.44	0.82
magicUT	1	0.21	0.42	0.73	0.74	1.10	1.34
	2	0.19	0.43	0.78	0.71	1.30	1.48
	3	0.28	0.34	0.67	0.71	0.76	1.04
magicUT	Average	0.23	0.40	0.73	0.72	1.05	1.29

Table 12. SBAS L1 kinematic availability results.

Receiver	Drive	Urban Canyon (%)	Inner Suburbs (%)	Vegetated Suburbs (%)	Open Freeway (%)	Outer Suburbs (%)
Arrow Gold	1	68.4	100	100	98.5	100
	2	87.8	100	100	98.7	100
	3	53.4	100	100	98.4	100
Arrow Gold	Average	69.9	100	100	98.5	100
Geode	1	55.1	100	100	98.3	100
	2	65.9	100	100	98.3	100
	3	28.8	100	100	98.4	100
Geode	Average	49.9	100	100	98.3	100
magicUT	1	3.3	91.8	70.3	96.9	100
	2	8.3	100	73.8	100	100
	3	10.5	88.5	63.9	99.8	100
magicUT	Average	7.4	93.4	69.3	98.9	100

From Table 12 it follows that Geode and Arrow Gold receivers achieved 98-100% availability in each of the test environments shown in Table 12, with the exception of the urban canyon, where the average availability dropped to 50% and 70% respectively. The magicUT achieved over 90% availability in inner suburbs, open freeway and outer suburbs, but in the vegetated suburbs the availability dropped to 69%. In the urban canyon, the magicUT struggled to acquire position achieving only 7% availability.

Figure 43 to Figure 45 show the horizontal positioning errors for the mid-range receivers with the SBAS L1 service for the three drives.

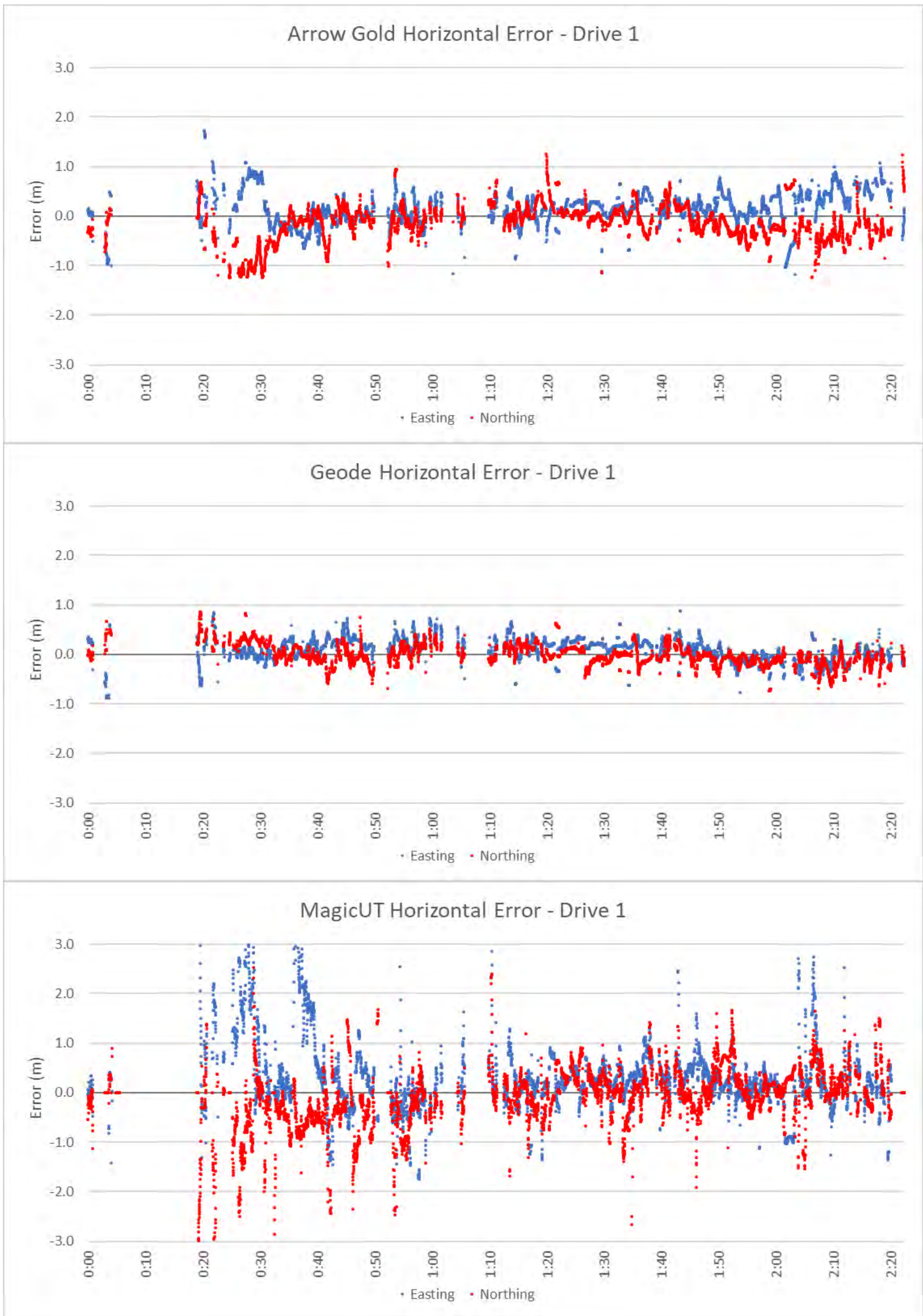

Figure 43. Kinematic horizontal results for mid-range receivers – Drive 1.

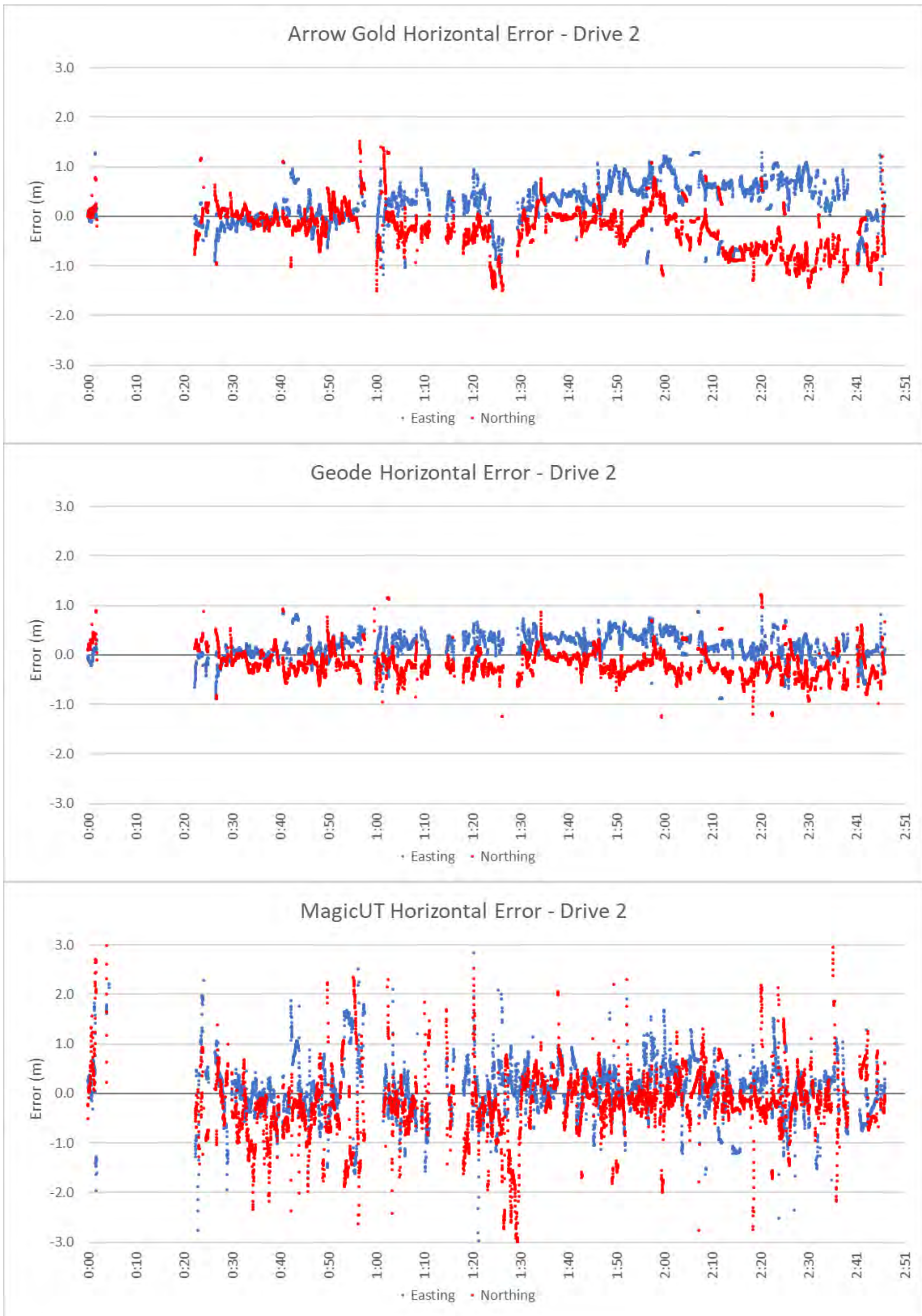

Figure 44. Kinematic horizontal results for mid-range receivers – Drive 2.

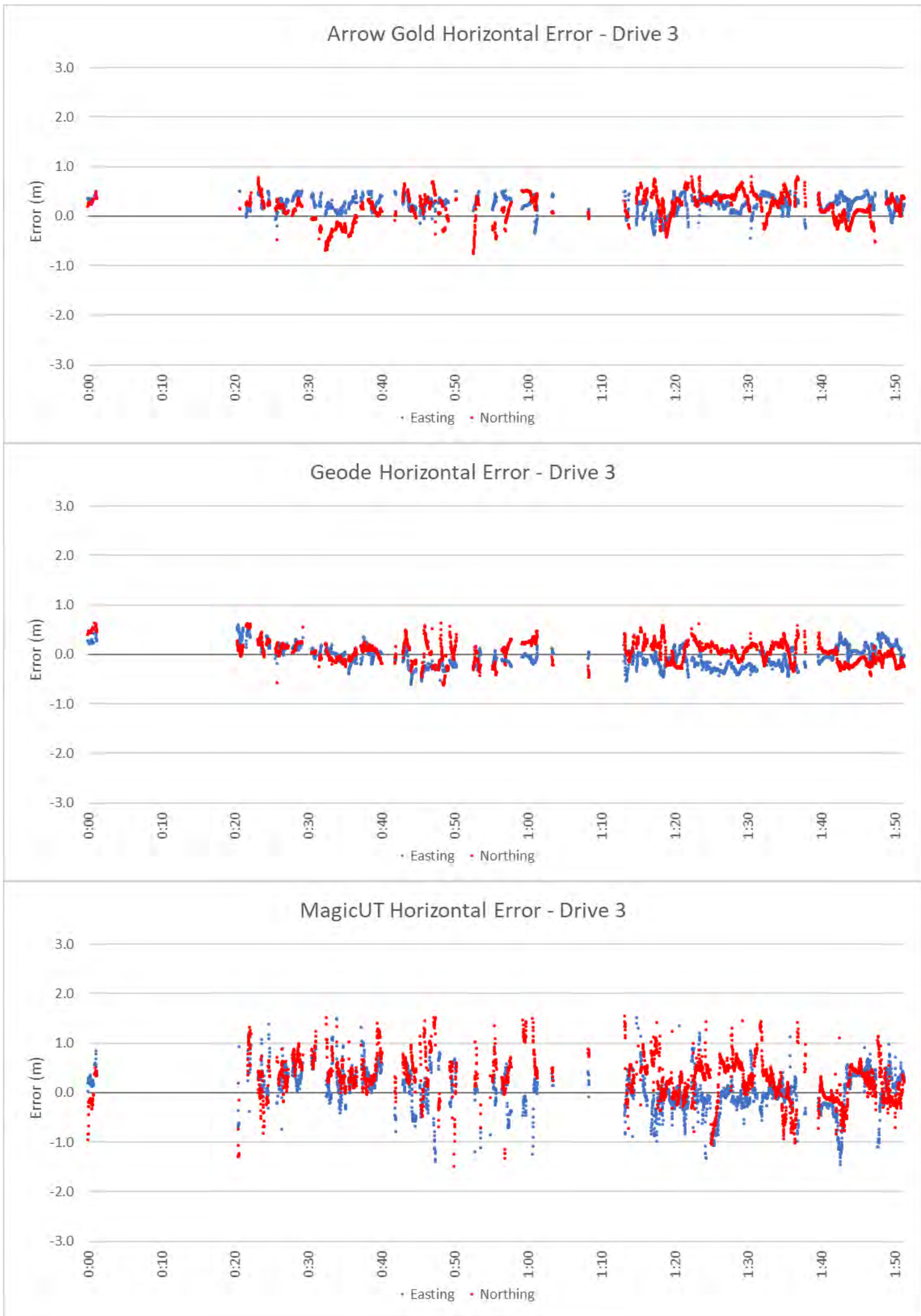

Figure 45. Kinematic horizontal results for mid-range receivers – Drive 3.

It is worth noting that availability figures were computed by defining a region for each observation environment (see Figure 12) and computing how many valid epochs of data were observed as the car was driven through that particular environment. Any position that was recorded outside of the road was considered an outlier and removed from computation. On the other hand the horizontal positioning performance was carried out by computing a reference trajectory (by post-processing the kinematic data from a nearby CORS) and comparing the observed SBAS data to the trajectory. In cases where the trajectory could not be computed, the analysis could not be carried out. A good example of that is the first 20 minutes of the drive (following convergence) as the car was in the urban canyon environment and the reference trajectory could not be computed, but that does not necessarily mean that the position was not available. As such, the graphs in Figure 43 to Figure 45 do not correlate to the availability statistics in Table 12.

From Table 11 and Figure 43 to Figure 45 it can be seen that the Geode receiver provided the best results with a horizontal RMS of 0.35m, followed by Arrow Gold with 0.56m and magicUT with 0.73m. magicUT has proved to be much noisier compared to the other two solutions, but an important finding was that all three receivers have managed to maintain sub-metre horizontal positioning, which opens the door to many applications where lane-level accuracy is required, such as road pricing. Figure 46 to Figure 48 show the corresponding vertical results for the three receivers.

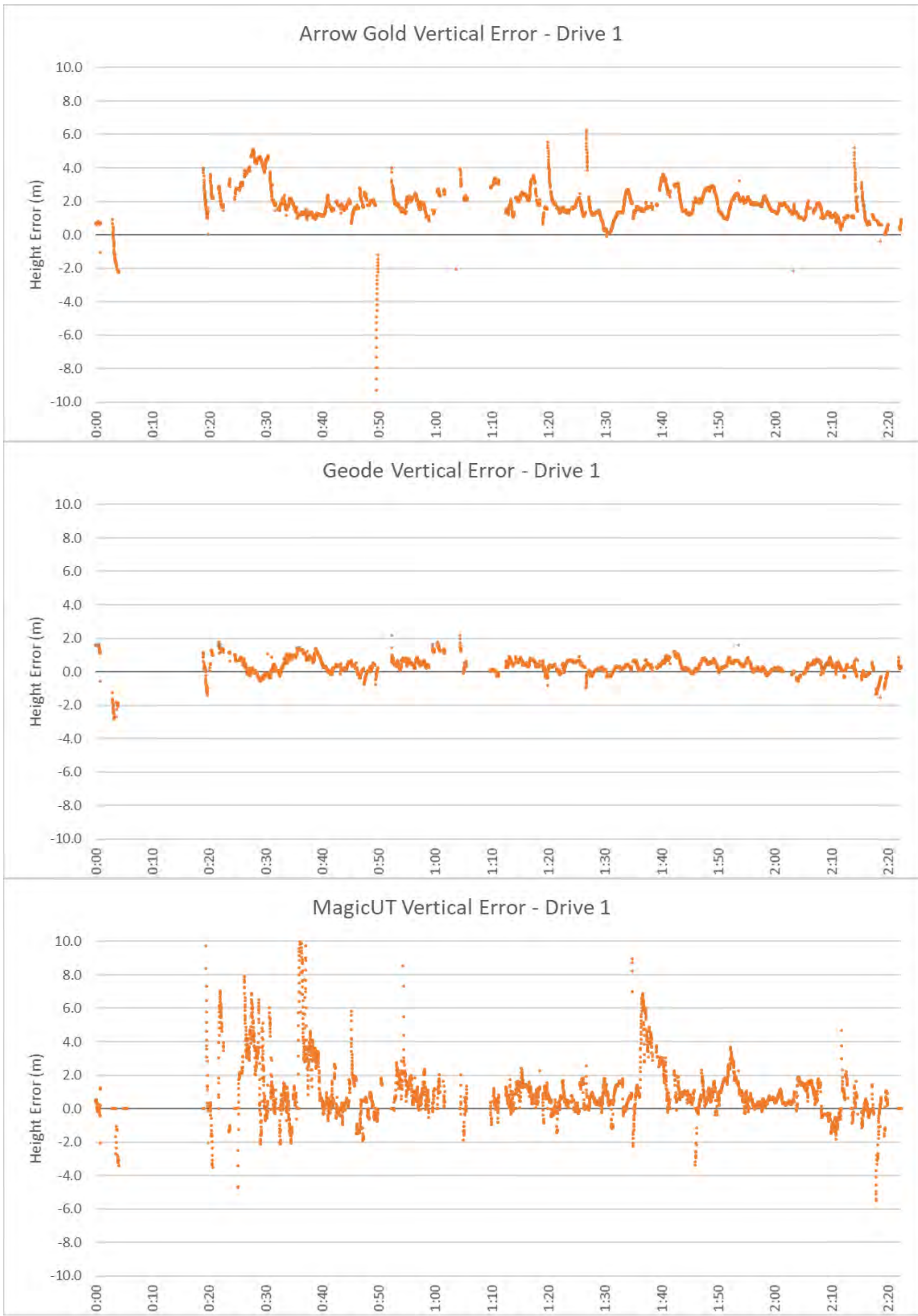

Figure 46. Kinematic vertical results for mid-range receivers – Drive 1.

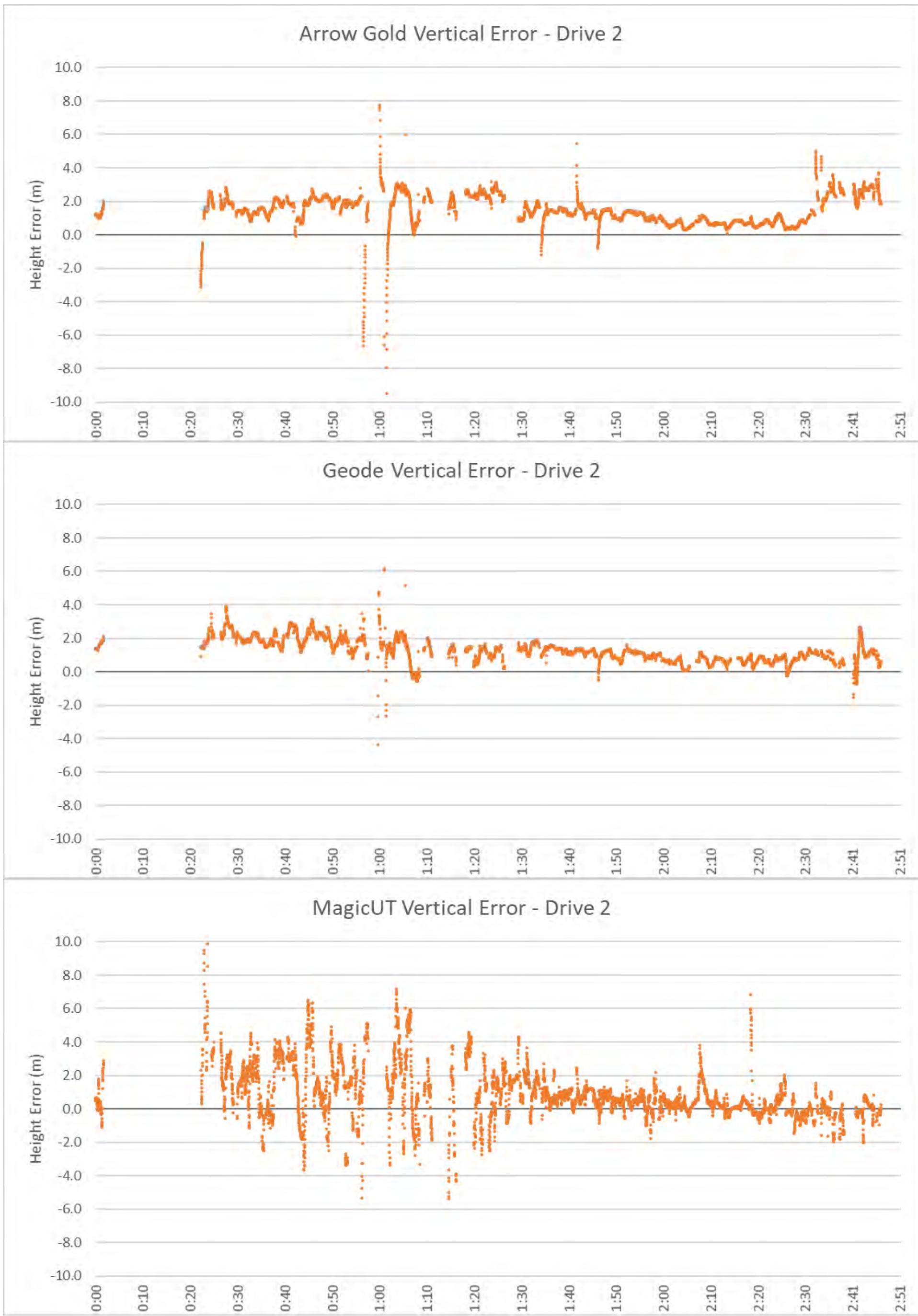

Figure 47. Kinematic vertical results for mid-range receivers – Drive 2.

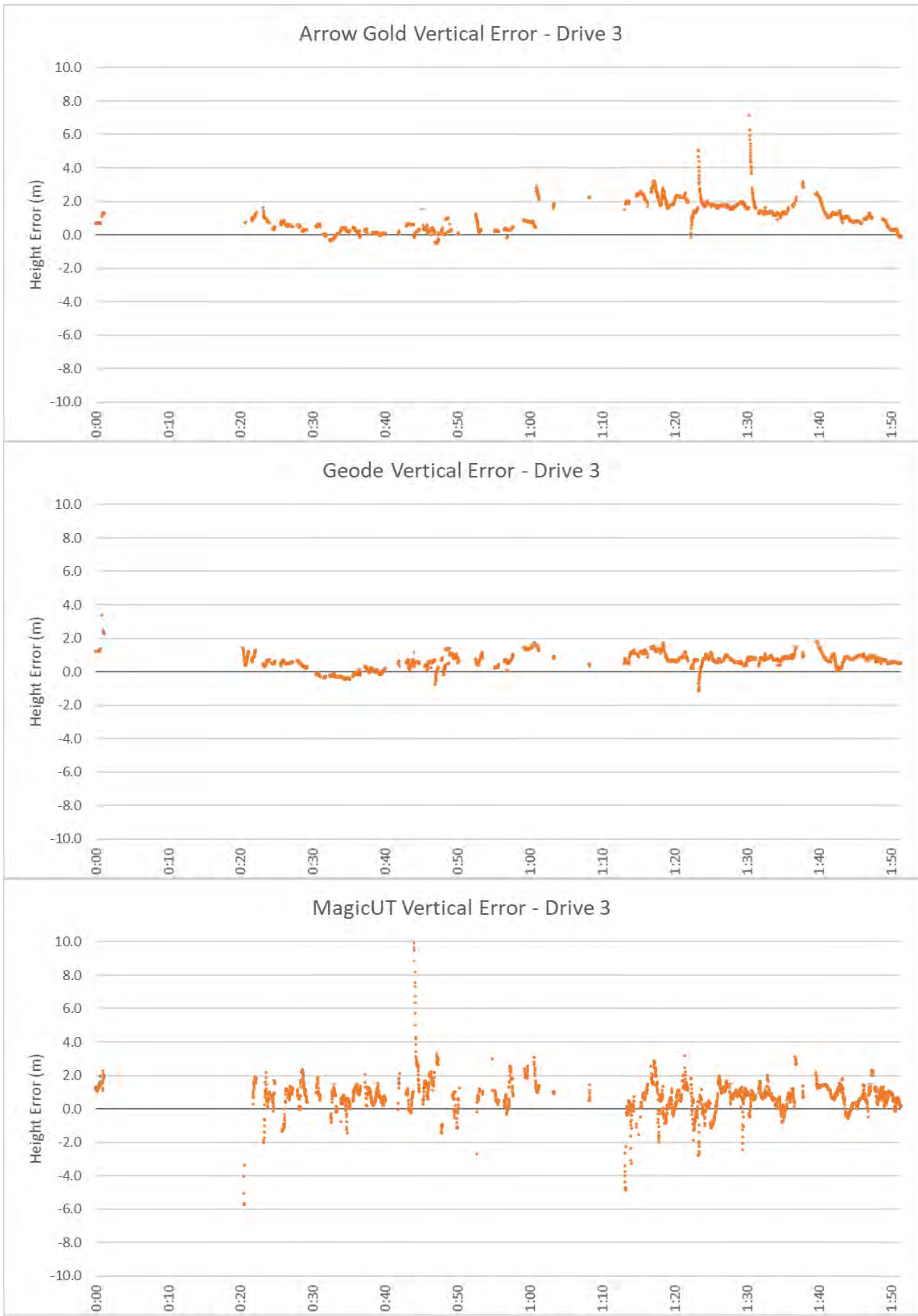

Figure 48. Kinematic vertical results for mid-range receivers – Drive 3.

The Geode receiver again achieved the best performance with a vertical RMS of 0.82m. The Arrow Gold and magicUT receivers reported 1.43m and 1.29m vertical RMS respectively. This is a reasonable result in a challenging environment, although generally the vertical accuracy is not as critical for transport applications. Horizontal accuracy is of interest in most cases for automated driving and intelligent transport support; though the vertical component is potentially necessary to aid in distinguishing between overpassing roadways and tunnels. These obstructed environments are already challenging for GNSS positioning, suggesting integration with Inertial Measurement Unit (IMU) to support high-accuracy tracking regardless of sky visibility.

5.2.2 Kinematic results for DFMC

The accuracy and availability of the kinematic testing campaign using DFMC service is presented in Table 13 Table 14. Three receivers were used in the test – magicUT with DFMC via GEO, magicUT with DFMC via SISNeT and Septentrio with DFMC via GEO. Kinematic availability was calculated for each road environment shown in Figure 12 as per the explanation in section 5.2.1.

Table 13. DFMC kinematic accuracy results.

Receiver	Drive	Horizontal Difference (m)			Height Difference (m)		
		Mean	St Dev	RMS	Mean	St Dev	RMS
magicUT DFMC via GEO	1	0.31	0.62	1.12	-0.11	1.91	1.92
	2	0.12	0.66	1.31	0.02	2.84	2.84
	3	0.09	0.77	1.25	0.04	2.05	2.05
magicUT DFMC via GEO	Average	0.17	0.68	1.23	-0.02	2.27	2.27
magicUT DFMC via SISNeT	1	0.30	0.87	1.50	-0.21	2.78	2.79
	2	0.32	0.63	1.21	0.51	3.16	3.2
	3	0.29	0.76	1.28	0.26	2.65	2.66
magicUT DFMC via SISNeT	Average	0.30	0.75	1.33	0.19	2.86	2.88
Septentrio DFMC via GEO	1	0.03	0.37	0.42	-0.83	1.34	1.57
	2	0.34	0.46	0.84	0.18	1.77	1.78
	3	0.17	0.56	0.89	-0.26	1.36	1.39
Septentrio DFMC via GEO	Average	0.18	0.46	0.72	-0.30	1.49	1.58

Table 14. DFMC kinematic availability results by area.

Receiver	Drive	Urban Canyon (%)	Inner Suburbs (%)	Vegetated Suburbs (%)	Open Freeway (%)	Outer Suburbs (%)
magicUT DFMC via GEO	1	6.0	94.6	56.9	98.5	100.0
	2	2.6	94.6	78.6	94.1	100.0
	3	0.9	95.0	59.3	96.8	100.0
magicUT DFMC via GEO	Average	3.2	94.7	64.9	96.5	100.0
magicUT DFMC via SISNeT	1	13.0	89.2	45.7	97.9	100.0
	2	13.6	100.0	81.3	97.8	100.0
	3	0.0	94.4	56.1	96.4	100.0
magicUT DFMC via SISNeT	Average	8.9	94.5	61.0	97.4	100.0
Septentrio DFMC via GEO	1	0.1	81.3	87.0	90.8	100.0
	2	0.0	78.5	85.8	81.3	98.1
	3	5.4	87.5	86.0	95.6	100.0
Septentrio DFMC via GEO	Average	1.8	82.4	86.3	89.2	99.4

From Table 14 it can be seen that the availability statistics are worse than those for SBAS L1. This is especially evident in the vegetated suburbs and urban canyon environment. This could be due to the fact that DFMC is still a very new technology, for which performance is expected to improve over time as the algorithms are developed further and bugs in the systems are eliminated. It can also be seen that the DFMC performance of the magicUT via GEO and SISNeT were very similar, whereas the DFMC on a Septentrio receiver improved upon the accuracy provided by both magicUT solutions. Figure 49 to Figure 51 show the horizontal performance of the three DFMC receivers.

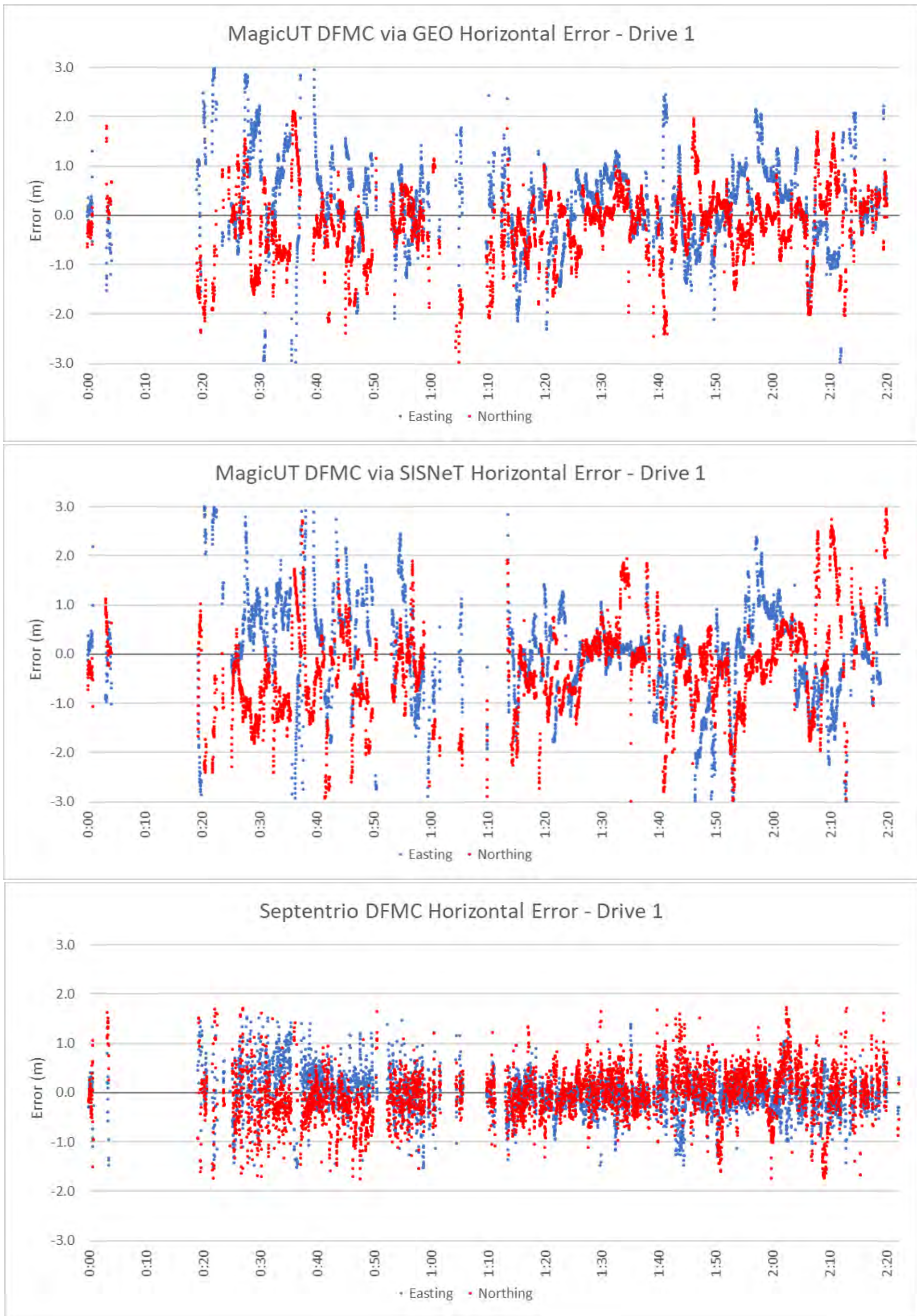

Figure 49. Kinematic horizontal DFMC results – Drive 1.

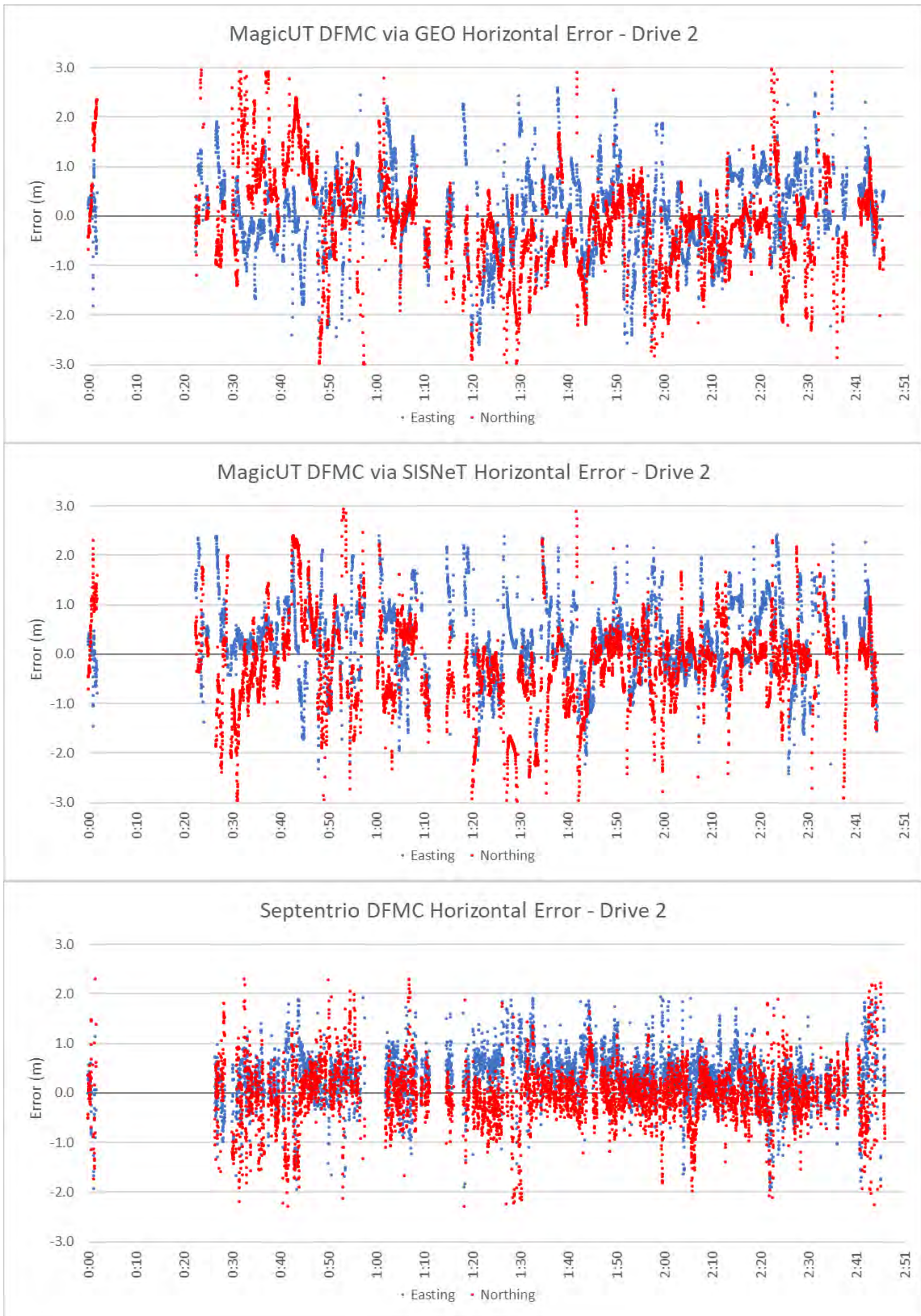

Figure 50. Kinematic horizontal DFMC results – Drive 2.

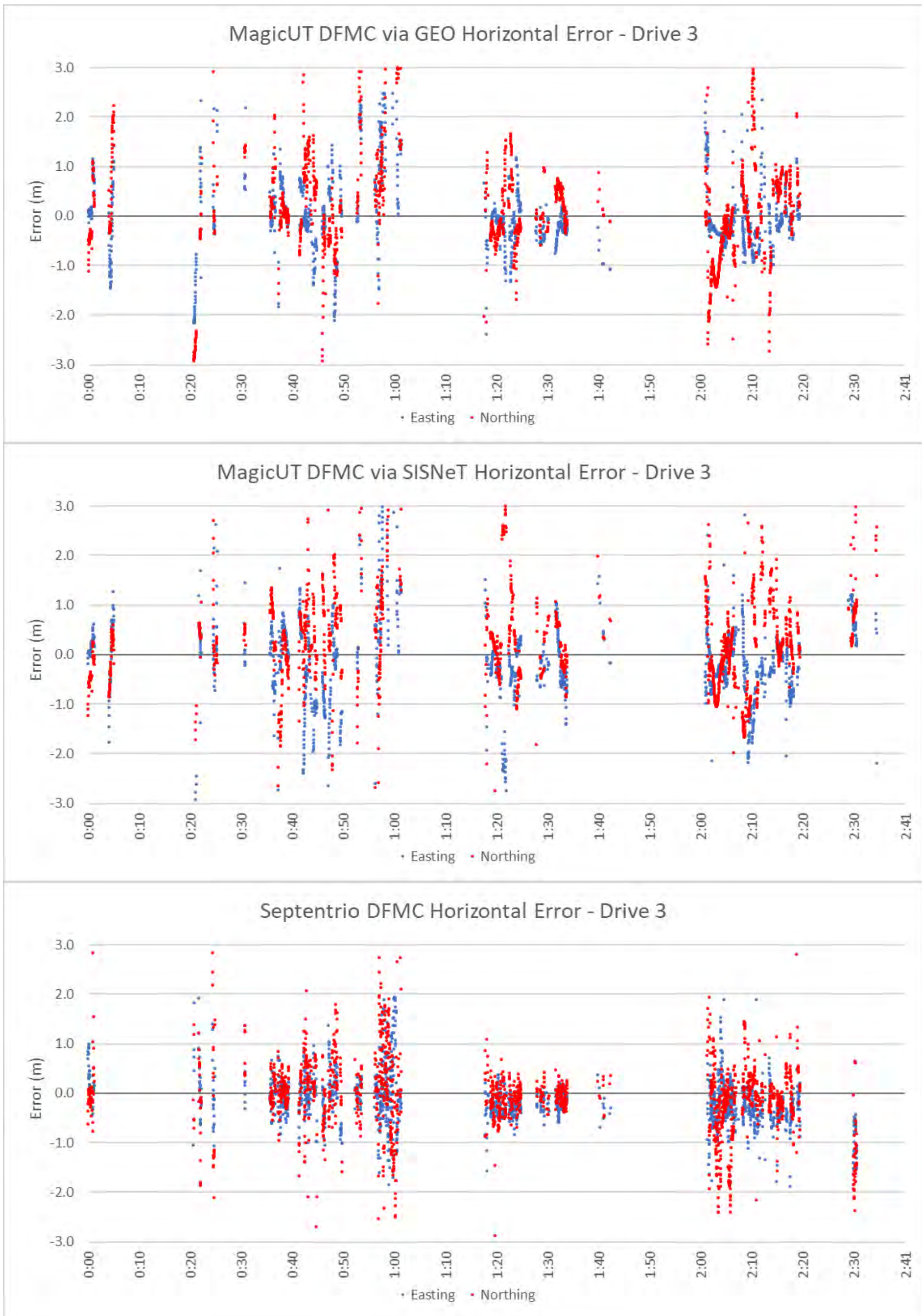

Figure 51. Kinematic horizontal DFMC results – Drive 3.

From the figures above, it can be seen that the DFMC on a Septentrio receiver has provided superior performance with an RMS of 0.72m, compared to the solutions from the magicUT, which appeared quite noisy and had an RMS of 1.2-1.3m. It can also be seen that during the third drive a limited number of epochs were able to be post-processed compared to the previous two drives. The reason for this result remains unknown. Figure 52 to Figure 54 show the corresponding vertical results.

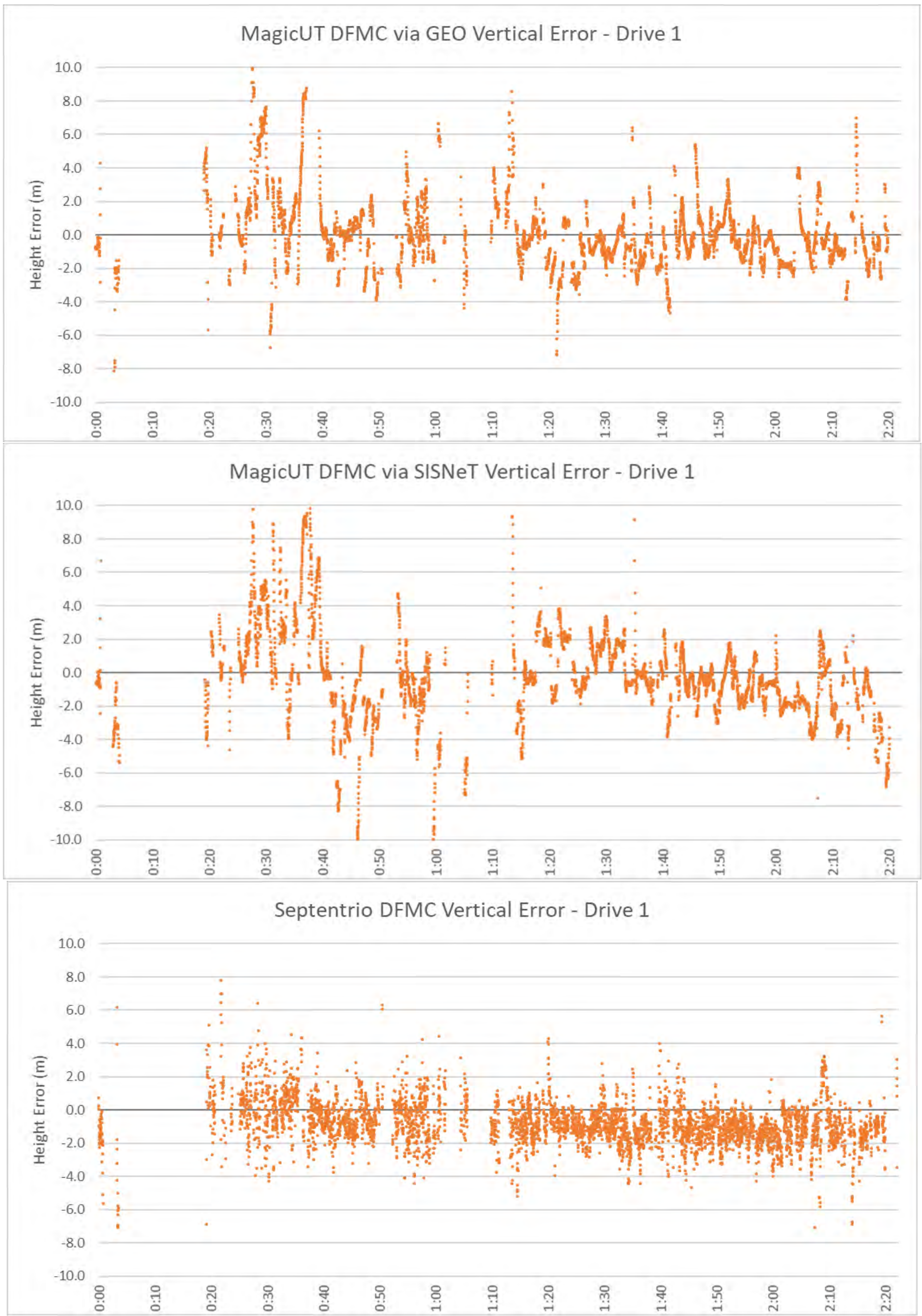

Figure 52. Kinematic vertical DFMC results – Drive 1.

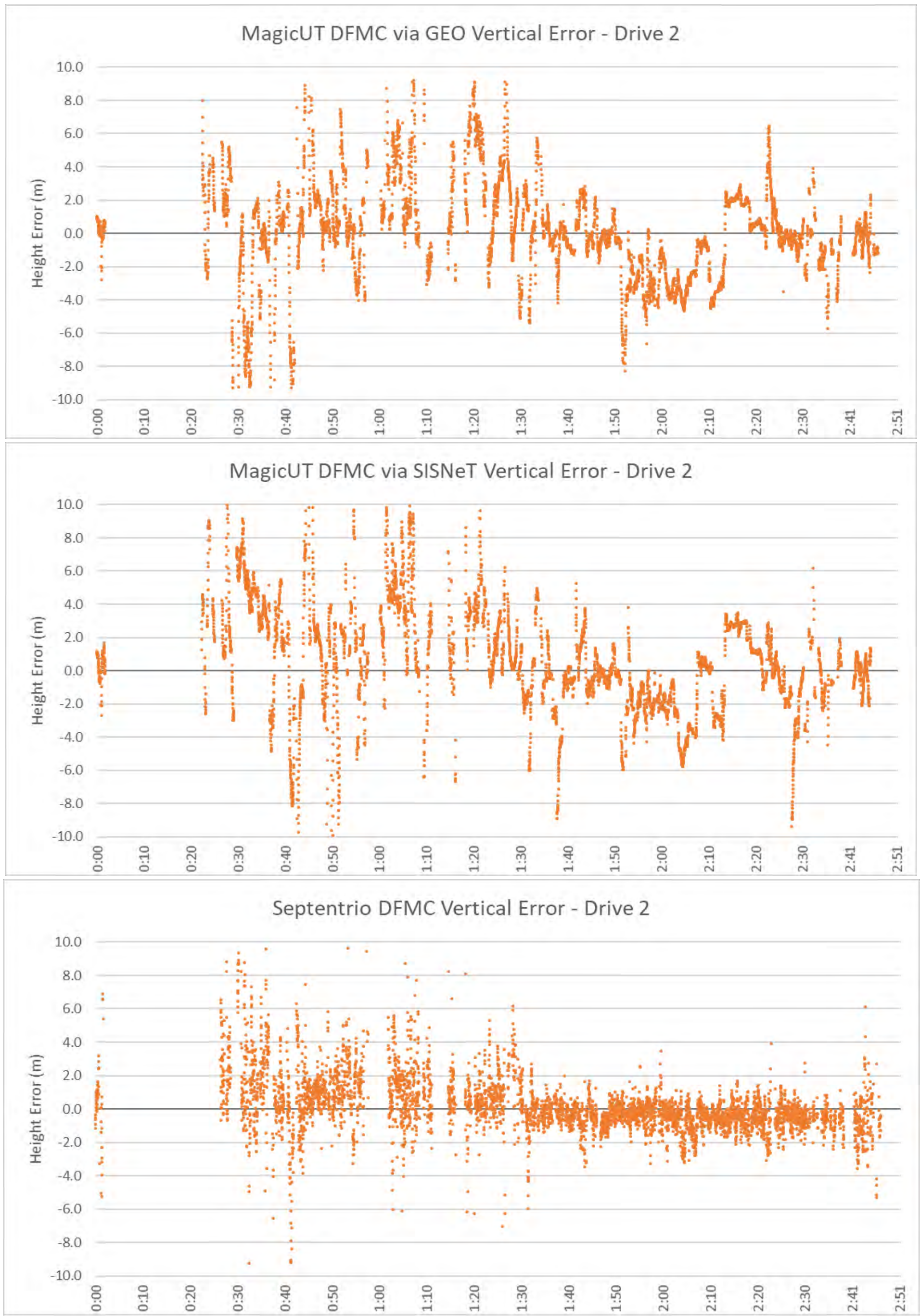

Figure 53. Kinematic vertical DFMC results – Drive 2.

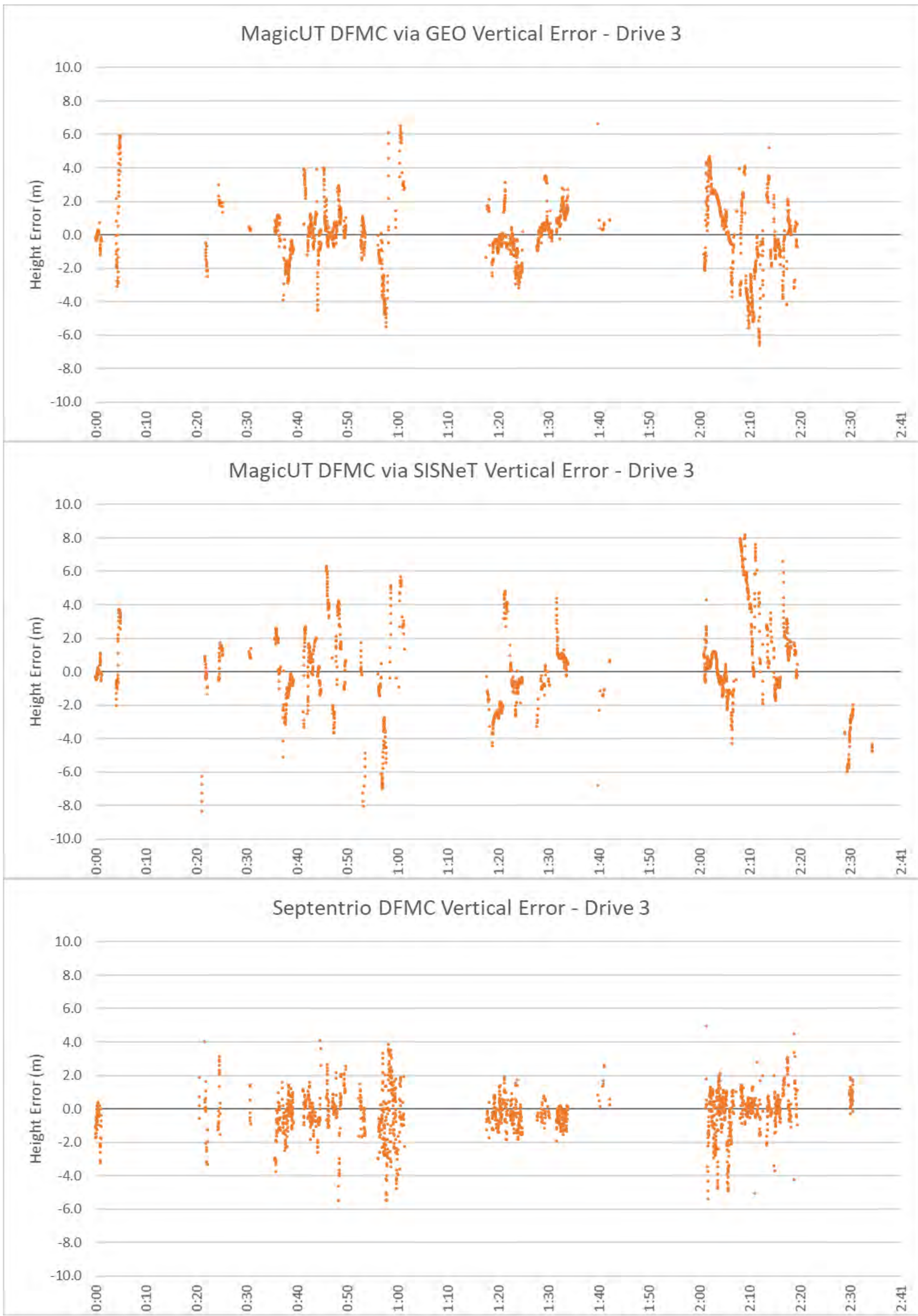

Figure 54. Kinematic vertical DFMC results – Drive 3.

Similar behaviour is observed in the vertical results with Septentrio DFMC solution providing the best performance.

5.2.3 Kinematic results for PPP

A single magicUT receiver was used in the PPP mode during the three kinematic tests. The results of the PPP positioning are shown in this section. Kinematic availability was calculated for each road environment shown in Figure 12, i.e. urban canyon, inner suburbs, vegetated suburbs, open freeway and outer suburbs.

Table 15. PPP kinematic positioning error results.

Receiver	Drive	Horizontal Difference (m)			Height Difference (m)		
		Mean	St Dev	RMS	Mean	St Dev	RMS
magicUT PPP via GEO	1	0.25	0.19	0.45	-0.3	0.83	0.88
	2	0.50	0.21	0.67	-0.45	1.16	1.25
	3	0.33	0.41	0.73	-0.5	0.73	0.89
magicUT PPP via GEO	Average	0.36	0.27	0.62	-0.42	0.91	1.01

Table 16. PPP kinematic availability results by area.

Receiver	Drive	Urban Canyon (%)	Inner Suburbs (%)	Vegetated Suburbs (%)	Open Freeway (%)	Outer Suburbs (%)
magicUT PPP via GEO	1	13.2	98.0	58.1	94.3	99.5
	2	19.5	98.6	78.0	94.8	97.3
	3	1.05	97.8	58.5	93.2	99.83
magicUT PPP via GEO	Average	11.3	98.1	64.9	94.1	98.9

From Table 15 and Table 16, it can be seen that the horizontal RMS was 0.62m, which is in the same range as SBAS L1 and DFMC solutions. Whilst in static mode PPP can provide sub-decimetre level accuracy, however driving through obstructed or partially obstructed environments is more challenging, as the solution is forced to repeatedly re-converge, and hence the accuracy drops to the level of the SBAS solution. The availability figures were also found to be similar to the SBAS solutions on the magicUT receivers. These results indicate that PPP may not provide a substantial improvement over SBAS L1 or DFMC for automotive applications under challenging GNSS environments.

Figure 55 and Figure 56 display the horizontal and vertical results for the PPP respectively.

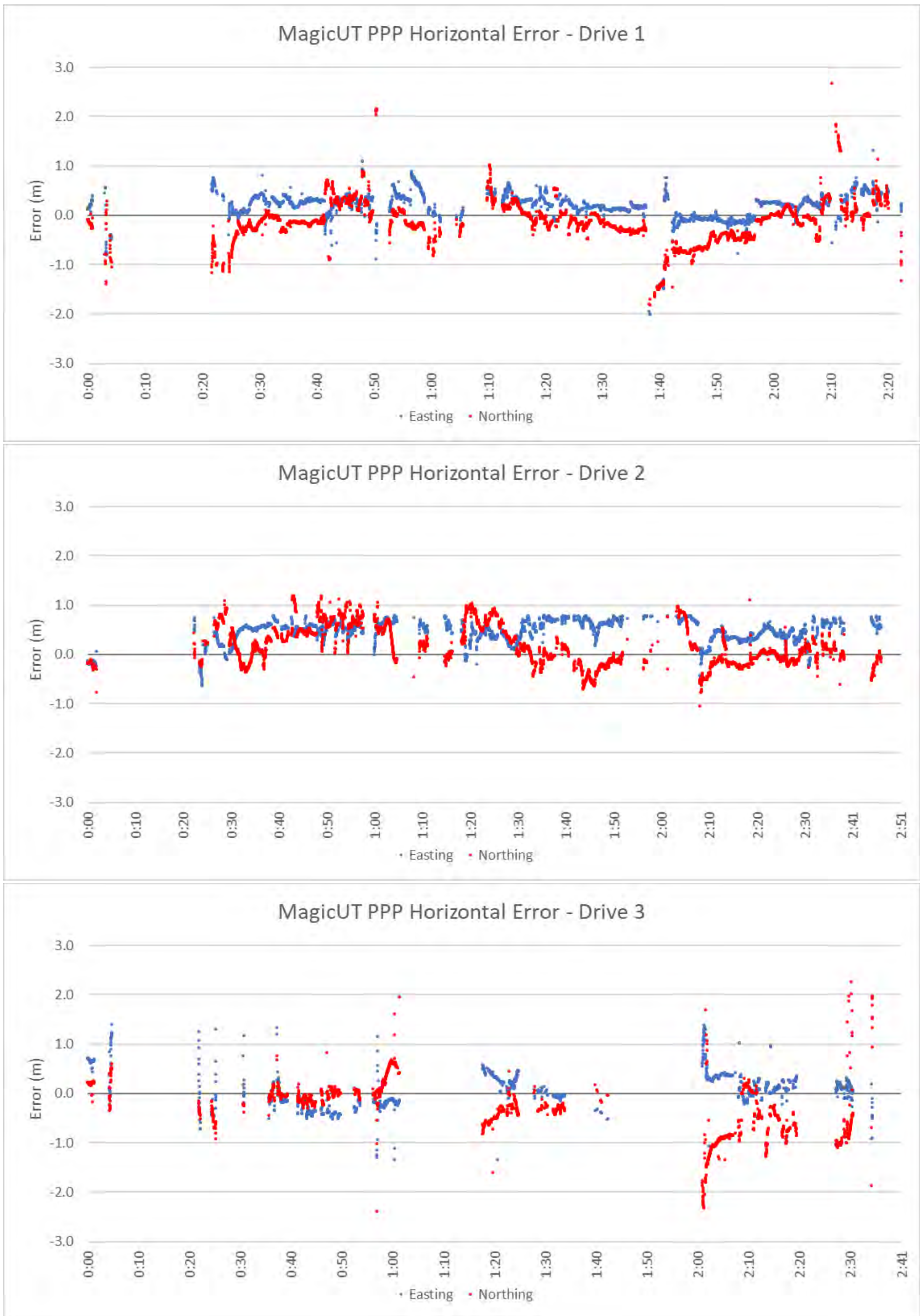

Figure 55. Kinematic horizontal PPP results – Drives 1, 2 and 3.

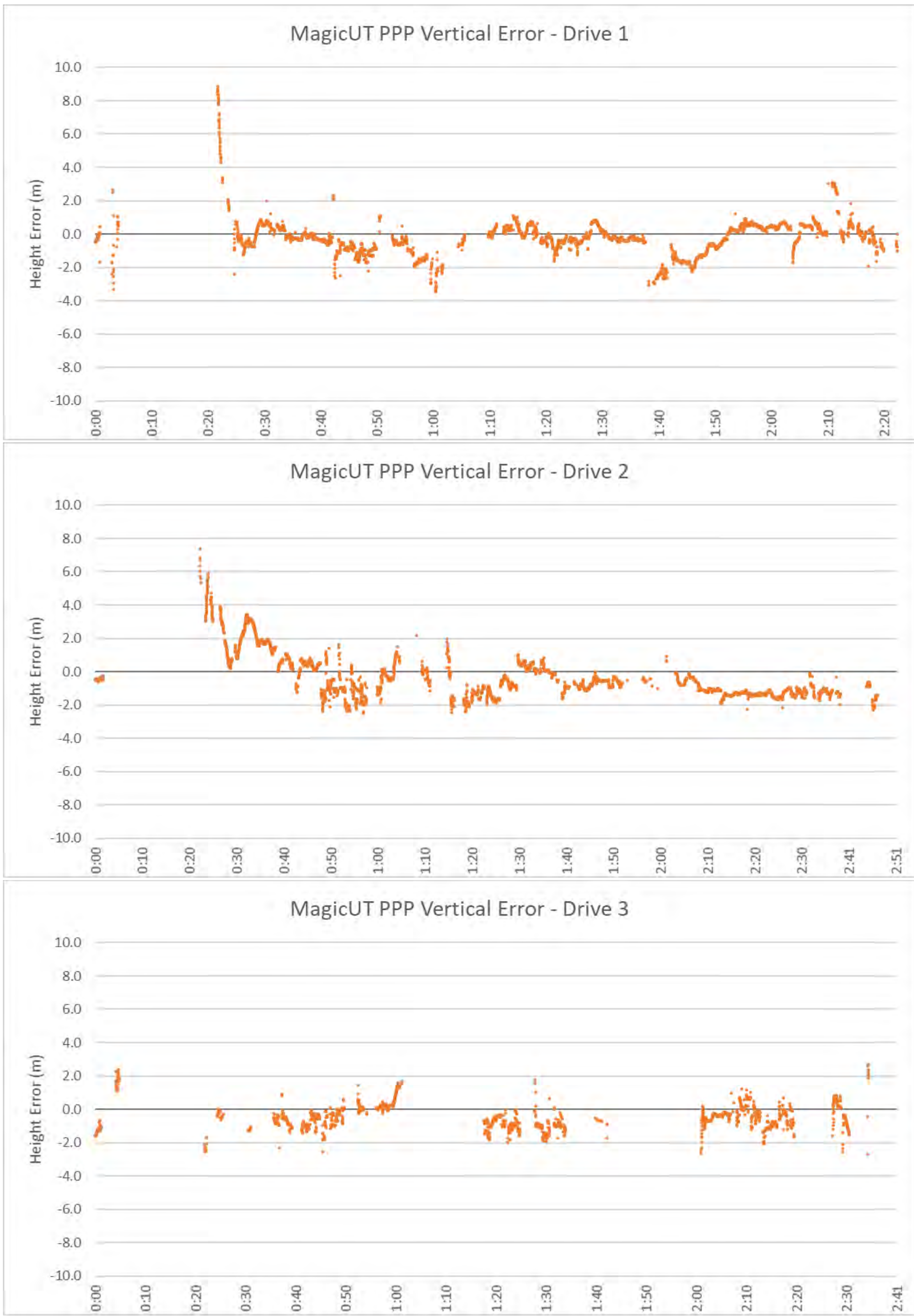

Figure 56. Kinematic vertical PPP results – Drives 1, 2 and 3.

5.3 Forestry testing results

The results from the forestry testing are presented in this section. The data analysis required transforming the POI horizontal coordinates from ITRF2014 to GDA94, then converting the coordinates from geographic to Map Grid of Australia (MGA). Subsequently, the horizontal difference in metres between the observed POI coordinates and the truth was calculated. Since each POI represents the first epoch over a control point, the results emulate those from a kinematic scenario, i.e. a forester walking through the environment without stopping. The mean and standard deviation of the horizontal differences are calculated and quantify each receiver's horizontal accuracy and precision respectively. It should be noted that any POI further than 5m from its ground truth was deemed an outlier and removed from the analysis. For the magicUT L1 results 13 of 60 coordinates were outliers, for the magicUT PPP results 25 of 60 coordinates were outliers, and for the Geode L1 no coordinates were outliers.

Table 17 to Table 19 and Figure 57 to Figure 59 show the accuracy and precision statistics for each of the tested scenarios and Table 20 shows the availability results for all three scenarios.

Table 17. Forestry test 1 results – Thinned pine.

Point	magicUT L1		magicUT PPP		Geode L1	
	Mean (m)	Std Dev (m)	Mean (m)	Std Dev (m)	Mean (m)	Std Dev (m)
1	1.76	1.27	0.55	1.06	0.39	0.48
2	0.77	2.16	0.57	1.56	0.35	0.94
3	1.91	1.20	0.80	2.71	0.29	0.87
4	1.48	1.92	1.38	1.91	0.23	0.70
5	2.66	2.27	0.70	0.88	0.18	1.60

Table 18. Forestry test 2 results– Unthinned pine.

Point	magicUT L1		magicUT PPP		Geode L1	
	Mean (m)	Std Dev (m)	Mean (m)	Std Dev (m)	Mean (m)	Std Dev (m)
1	1.56	2.19	0.59	2.53	1.00	1.59
2	0.72	3.33	1.45	1.88	0.65	1.77
3	1.44	1.93	2.22	4.01	0.45	1.31
4	1.69	1.45	1.93	2.97	1.03	1.15
5	2.42	1.78	3.22	3.06	0.27	0.95

Table 19. Forestry test 3 results – Native forest.

Point	Geode L1	
	Mean (m)	Std Dev (m)
1	0.44	1.06
2	0.56	1.16
3	0.85	0.93
4	1.23	0.69
5	1.13	1.02

Table 20. Forestry testing availability Statistics.

Test	Receiver	SBAS Availability
Thinned Pine	magicUT L1	88.5%
	magicUT PPP	81.9%
	Geode L1	100.0%
Unthinned Pine	magicUT L1	77.5%
	magicUT PPP	60.2%
	Geode L1	100.0%
Native Forest	Geode L1	100.0%

Results from the testing indicate that dense forests present a difficult environment for all services tested, generally with the results lying in the 1-2m range. The Geode with SBAS L1 has provided better performance than either of the magicUT receivers and in some cases, was able to achieve sub-metre positioning.

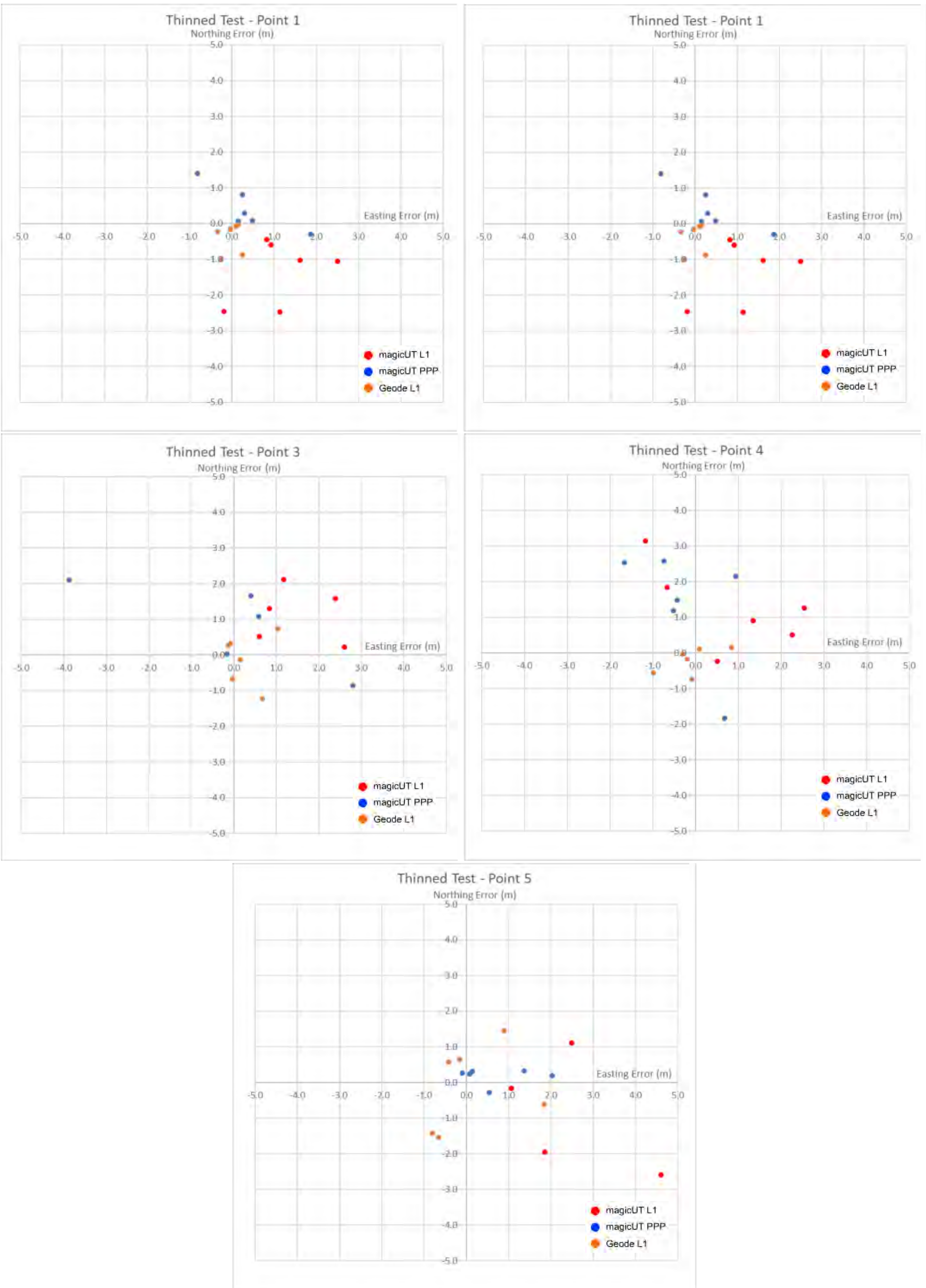

Figure 57. Forestry testing results, thinned pine environment.

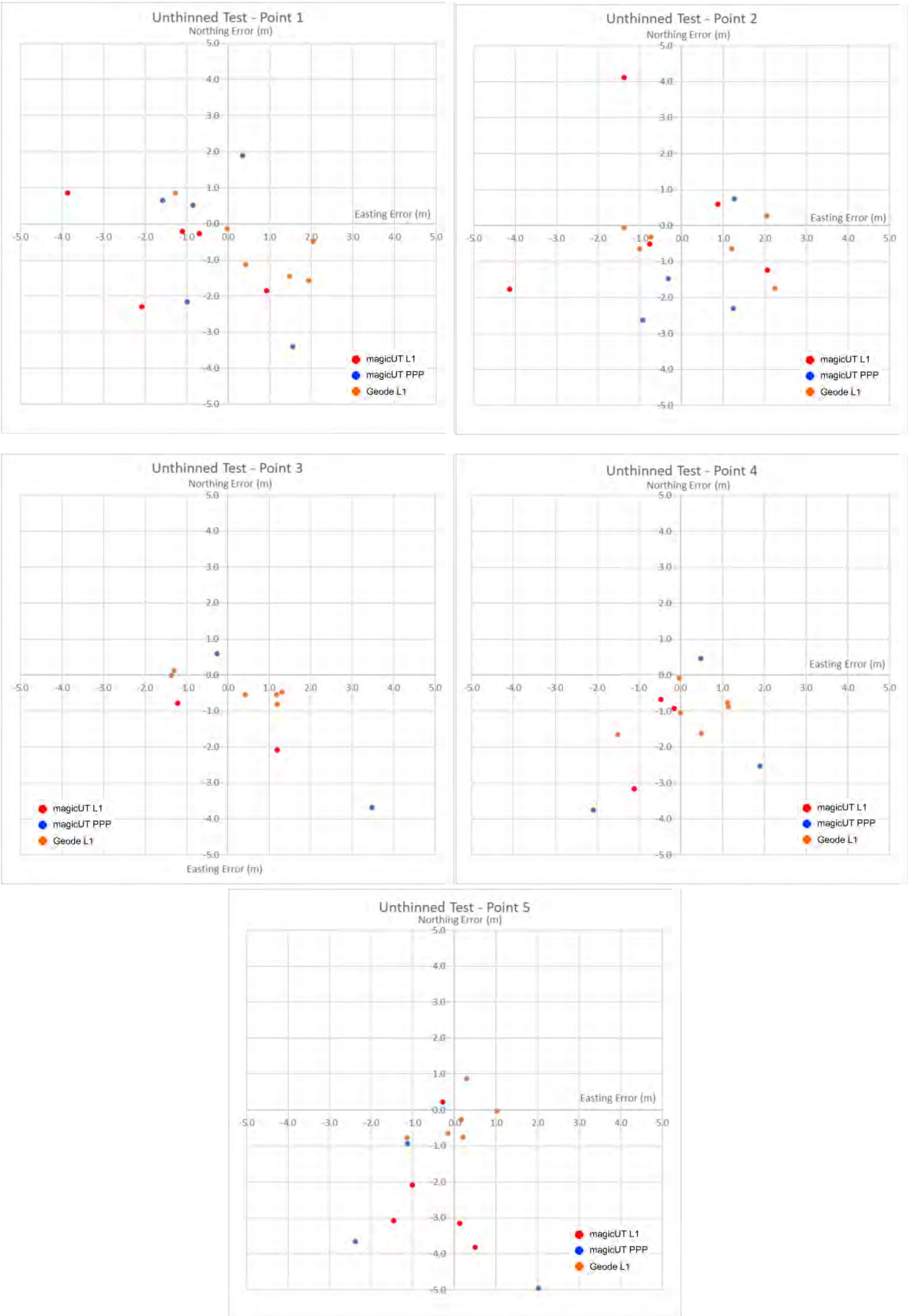

Figure 58. Forestry testing results, unthinned pine environment.

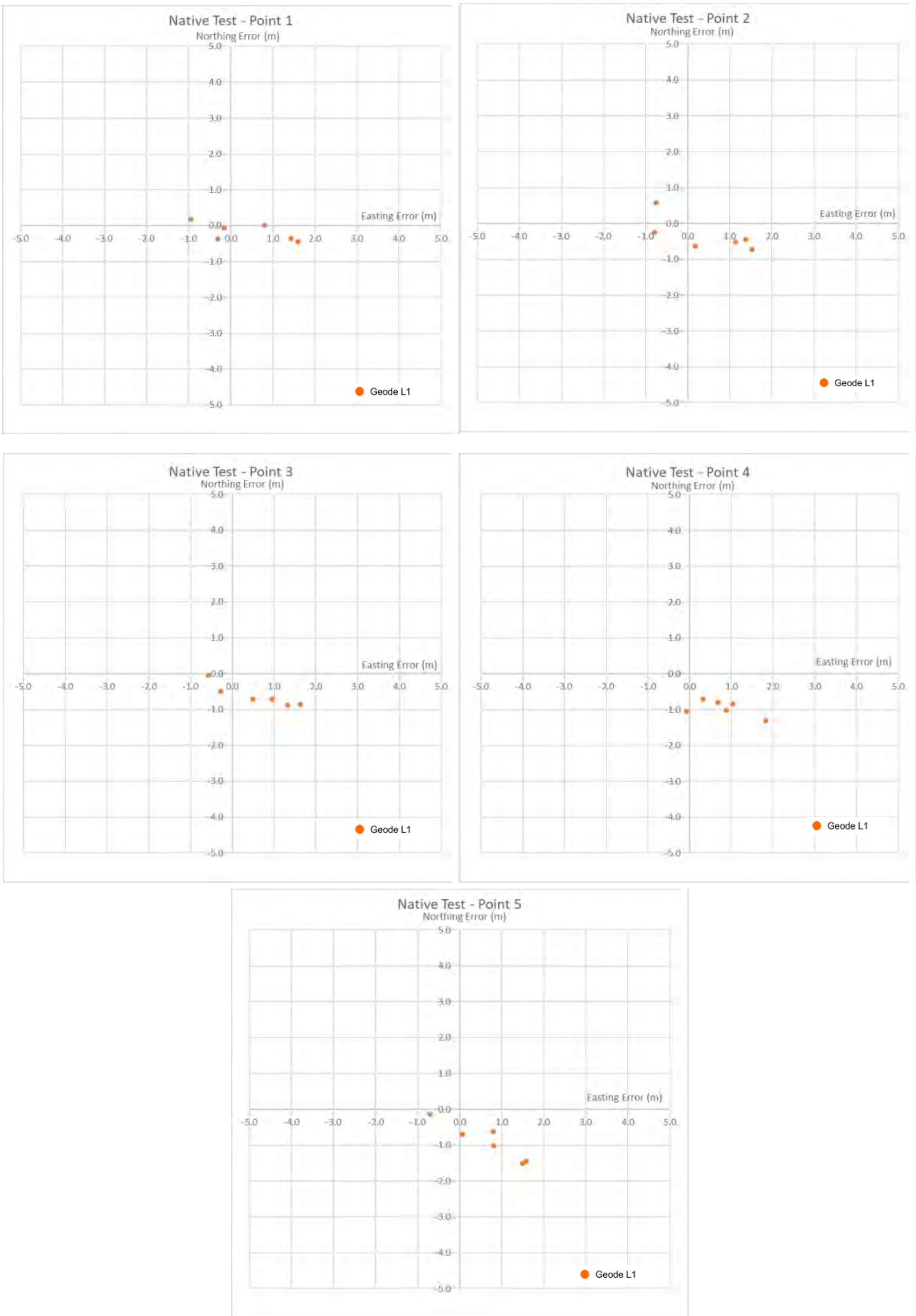

Figure 59. Forestry testing results, native forest environment.

6 Discussion

This section discusses the results achieved in each of the testing campaigns.

6.1 Static Analysis

Out of the consumer-grade receivers tested, the best horizontal and vertical accuracy and precision were achieved by the SkyTraq receiver, which improved upon the standard deviation of the other receivers by 1m on average in the horizontal component, and by 1.1m in the vertical. The Antenova, Quectel and SkyTraq receivers were still subject to the navigational speed threshold despite disabling the setting, which meant that these receivers recorded the same position for approximately 30-60 seconds before updating. Moreover, the Antenova and Quectel receivers recorded NMEA coordinates to only four decimal places, which affected their precision results and caused their scatter plot results to be in a regular grid pattern.

For the mid-range receiver static tests, the Geode and Arrow Gold provided very similar results in both horizontal and vertical positioning. The magicUT had the lowest mean, but the standard deviations were 0.1-0.2m higher than the other receivers. The Geode and Arrow Gold have returned very similar figures for both accuracy and precision in the horizontal domain, though the Arrow Gold achieved smaller horizontal and vertical RMS.

The results of the static SBAS L1 vs DFMC test suggests that the magicUT positioning with DFMC provided considerably more accurate and precise horizontal results than SBAS L1. The two receivers performed similarly in terms of the vertical component, with the SBAS L1 slightly outperforming the DFMC receiver. Furthermore, the SBAS L1 receiver was more reliable during testing, as the DFMC receiver lost SBAS fix multiple times during the final 24-hours, whilst the SBAS L1 receiver maintained fix for the entire duration of testing. The performance of DFMC is expected to continue to improve over time as the surrounding technologies mature.

The results of the PPP test provided similar results for each PPP data transfer format. PPP via RTCM had the most precise horizontal and vertical results, confirmed through the reduced spread observed in Figure 40, Figure 41, and Figure 42. PPP via RTCM produced a tighter clustering of positions around the ground truth and also fewer coordinate outliers, while the scatter plots for the magicUT PPP via GEO and magicUT PPP via SISNeT were very similar. The PPP via GEO and PPP via SISNeT results were comparable in terms of horizontal precision, while the GEO solution performed marginally better in vertical precision. PPP via RTCM took the shortest time to converge, taking less than half that required for PPP via GEO and PPP via SISNeT. Overall, these results indicate that the RTCM format is the most efficient PPP data transfer format of those tested, providing more precise coordinate solutions and a significantly shorter convergence time. However, for regions without reliable mobile network coverage, PPP via GEO will be able to provide significant improvements over standalone GNSS.

Antenna testing showed that the receivers performed as expected in the horizontal domain. The Septentrio and U-blox receivers both achieved the most precise results with the high-quality geodetic antenna. It is evident that there is a trend of degrading positional quality with lower quality antennas for the horizontal results, whereby the geodetic grade Topcon antenna often performed the best, followed by the compact Tallysman and patch antennas. The vertical results showed similar behaviour, though with a greater degree of inconsistency. Often better horizontal results were recorded for antennas with a ground plane, which is expected due to the reduction of multipath error, however in some cases the ground plane did not improve vertical positioning quality significantly. Overall, the horizontal positioning results were significantly better with SBAS compared to standalone. This improvement was of a larger magnitude for the u-Blox receiver.

6.2 Kinematic Analysis

During the SBAS L1 kinematic tests the most accurate and precise horizontal results were from the Geode receiver. The Arrow Gold and magicUT performed similarly, all providing a sub-metre horizontal accuracy and precision. The Arrow Gold and the Geode receivers showed nearly 100% availability in all environments apart from the urban canyon, where the availability figures dropped to 70% and 50% respectively. The magicUT has showed reduced availability compared to the other receivers.

For the DFMC kinematic tests the best results were recorded using the Septentrio DFMC via GEO, slightly out-performing the magicUT in terms of both horizontal and vertical precision. The magicUT PPP outperformed the DFMC receivers as expected. The magicUT receivers suffered from a large number of loss of SBAS fix notifications, reflective of fragmentation of the satellite availability in harsher GNSS conditions.

Kinematic positioning in a moving vehicle presents the most difficult environment for any satellite-based positioning due to the fast-changing nature of the environment and many obstructions. However, both SBAS and PPP positioning have shown promising results at sub-metre level with good availability. The degraded performance under challenging observation environments suggests that GNSS by itself will not be enough to position vehicles within their lane safely and securely at all times, especially in built-up areas. The next area of research in this field would be to integrate an Inertial Measurement Unit (IMU) to help with positioning in environments where GNSS is lost, such as tunnels, parking garages, or urban canyons.

6.3 Forestry Analysis

Dense forest canopy also presents a difficult observing environment for many GNSS applications. Limitations in achievable accuracy mean that foresters cannot do many tasks efficiently and introduce potential for errors. The forestry testing carried out also produced some promising results in this area.

The most accurate and precise results under forestry conditions were achieved using the Geode Multi-GNSS; which recorded a sub-metre accuracy at 11 of 15 forest check-points. The Geode performed best in the thinned forest and worst in the more heavily obstructed native forest, as expected. The Geode was also the most reliable of the receivers as it did not record any outliers, maintained an SBAS correction fix for the entire duration of all tests, and tracked the greatest number of satellites during all tests compared to the other receivers. The magicUT PPP results provided moderate accuracy results, recording five of 10 forest points with a sub-metre accuracy. The magicUT PPP performed better in the thinned forest compared to the unthinned forest, as expected. The magicUT PPP suffered significantly from loss of SBAS fix particularly during the unthinned test and it also tracked the lowest number of satellites compared to the other solutions tested. The magicUT SBAS L1 performed most poorly out of the tested solutions, recording only two of 10 forest points with sub-metre accuracy. The receiver performed similarly in unthinned and thinned forest. The SBAS L1 receiver also suffered from loss of SBAS fix, observed in the field with several loss of SBAS fix notifications occurring at the receiver during all tests.

7 Conclusion

A series of testing campaigns including static, kinematic and forestry were carried out by FrontierSI using a variety of receivers from consumer-grade to professional, aimed at testing SBAS L1, DFMC and PPP signals as part of the two year Australia and New Zealand SBAS Test-bed.

A series of static tests has been conducted from March 2018 to January 2019 to quantify the static positioning performance of a range of consumer, mid-range and professional-grade GNSS receivers and antennas. From the results in Table 3 and Figure 17 to Figure 19 it can be concluded that SkyTraq has provided the best performance with SBAS L1 positioning with an average RMS of 0.80m, but it failed to provide an independent coordinate output on an second-by-second basis. U-blox was the only device that able to provide an independent output, but the spread of the results was larger with an average RMS of 1.12m. The Arrow Gold receiver provided the best accuracy and precision of the mid-range receivers tested; achieving a horizontal RMS of 0.44m and a vertical RMS of 0.49m. The SBAS L1 vs DFMC tests determined that the DFMC receiver outperformed the L1 receiver in the horizontal domain and showed a slight improvement in the vertical domain. From the PPP tests it was determined that there are slight differences between the accuracy of the three PPP formats, with PPP via RTCM providing the most precise results and the fastest convergence time. The antenna tests found that the horizontal positioning quality of the antennas was significantly improved with SBAS L1 compared to standalone for each receiver, with similar improvement in the vertical domain, though with increased inconsistency in the results. It was also shown that the quality of antenna also plays a significant role in the resulting positioning performance.

The forestry testing was conducted in December 2018 at Neerim Plantation, Victoria, in order to assess receiver performance under various plantation and native forest conditions. The Geode with its internal antenna offered the highest accuracy results with sub-metre horizontal accuracies for the majority of the forest points. It was also the most reliable receiver, as it did not lose SBAS fix throughout testing in any of the test environments. These results suggest that the Geode using SBAS L1 positioning is capable of providing a sub-metre horizontal accuracy in harsh GNSS conditions, thereby presenting high potential for improving the forestry industry’s operational efficiency and safety.

Two kinematic tests were undertaken in January 2019 to quantify and compare the kinematic positioning performance of various SBAS signals and GNSS receivers. From the SBAS L1 tests it was found that the most accurate and precise horizontal and vertical results were from the Geode receiver, with the Arrow Gold performing to a similar standard. The Geode and Arrow Gold receivers also performed the best in terms of availability, recording good results even in very poor GNSS conditions. The DFMC and PPP tests determined that the most accurate horizontal and vertical results were recorded by the magicUT PPP via GEO, followed closely by the Septentrio DFMC. The availability analysis found variations in receiver performance across the range of test environments, with the best result by a slight margin achieved by the magicUT PPP via GEO, followed by the magicUT DFMC via SISNeT.

The FrontierSI testing campaign has determined that the SBAS signals provide clear benefits over standalone GNSS in terms of accuracy, precision, and availability. These benefits vary significantly depending on the equipment (Receiver and Antenna), and the environment in which they are operated. Each of SBAS signals analysed in the Test-bed have shown promise for widespread use across industry. Future improvements to the technology will likely accelerate this uptake, and deliver improved positioning, navigation, and timing for users throughout Australia and New Zealand in the coming years.

8 References

Digikey (2019). *Antenova M20050-EVB*. [image] Original available at: https://media.digikey.com/photos/Antenova%20Photos/M20050-EVB-1.jpg [Accessed 23 Jan. 2019].

Digikey (2019). *Tallysman TW7972*. [image] Available at: https://media.digikey.com/Photos/Tallysman%20Wireless/MFG_TW2x00.jpg [Accessed 23 Jan. 2019].

Quectel (2019). *L76 Series EVB Kit*. [image] Available at: https://www.quectel.com/UploadImage/Product/20170413103422158.png [Accessed 23 Jan. 2019].

RF-Design (2019).EVK-M8: *u-Blox M8 GNSS Evaluation Kit*. [image] Available at: https://rf-design.co.za/wp-content/uploads/2016/03/EVK-M8.jpg [Accessed 23 Jan. 2019].

Juniper Systems (2019). *Geode Real-Time Sub-Metre GPS Receiver*. [image] Available at: http://www.junipersys.com/design/new_junipersys/images/2018/geode/geode.png [Accessed 23 Jan. 2019].

MGISS (2019). *Arrow Gold*. [image] Available at: https://mgiss.co.uk/wp-content/uploads/2018/04/arrow-gold-front-HD.jpg [Accessed 23 Jan. 2019].

ComNav Technology (2019). *G100 GNSS Receiver*. [image] Available at: http://www.comnavtech.com/UploadFile/201821224033688.jpg [Accessed 23 Jan. 2019].

TOPCON (2019). *G3-A1 Antenna*. [image] Available at: http://www.topconcare.com/files/cache/20074ea5001140281c68a9b60e095f3c_f14307.jpg [Accessed 23 Jan. 2019].

Septentrio (2018). *AsteRx-U*. [image] Available at: https://www.septentrio.com/sites/default/files/products/product/image_asterx-u_left_orientation_website.png [Accessed 23 Jan. 2019].

Google. (2019). *Melbourne Eastern Suburbs, VIC*. Terrain basemap, Available at: https://www.google.com/maps [Accessed 29 January 2019]

Google. (2019). *Collins Street, Melbourne, VIC*. Street View imagery, Available at: https://www.google.com/maps [Accessed 7 February 2019]

Google. (2019). *Bridge Road, Richmond, VIC*. Street View imagery Available at: https://www.google.com/maps [Accessed 7 February 2019]

Google. (2019). *Heads Road, Donvale, VIC*. Street View imagery, Available at: https://www.google.com/maps [Accessed 7 February 2019]

Google. (2019). *Eastlink, Ringwood, VIC*. Street View imagery, Available at: https://www.google.com/maps [Accessed 7 February 2019]

Google. (2019). *Princes Highway, Oakleigh, VIC*. Street View imagery, Available at: https://www.google.com/maps [Accessed 7 February 2019]