SBAS POSITIONING FOR TRACKING WORKERS IN THE RAILWAY INDUSTRY

P7008

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		Signoff	Date
Prepared by	Sebastian Young Engineer, Buildvation		07/09/2020
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FrontierSI reviewer	Eldar Rubinov SBAS Technical Manager	Eldar Rubinov	09/09/2020

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Executive Summary

FrontierSI approached Aurizon and Buildvation in late 2019 to work together on a project to develop a railway safety device using the ANZ Satellite Based Augmentation System (SBAS) trial service in order to evaluate the possible benefits of fully functional SBAS in Australia.

This document contains all the testing and review of results relating to the accuracy of the SBAS modules for the use case of safety tracking railway workers working on rail lines. There are three (3) companies involved; Aurizon, Australia's largest freight rail operator; Buildvation, specialising in the development of technology to improve industrial safety and efficiency; and FrontierSI, a leading cooperative research centre for spatial information for Australia and New Zealand.

Buildvation were charged with developing the hardware required for this project, integrating two different SBAS compatible GPS modules (u-blox M8N and SkyTraQ V838) with a Bluetooth capable microcontroller, as required by Aurizon specifications.

The railway safety device is used to locate the worker on a particular track during railway maintenance. This scenario involves an Aurizon employee placing the device on or next to the railway track that requires maintenance, and the positioning data from the device is streamed via Bluetooth to an Aurizon work laptop/tablet, which processes the data and transfers over a cellular data link to the central Aurizon Track Access System (TAS). TAS puts a coded block on the track that requires maintenance in the operational system used to coordinate train traffic, preventing trains from using the selected track, but still allowing trains to use nearby tracks. The device must output data accurate enough to differentiate the worker's position between two railway tracks, which at their closest can be 3-4m apart.

Buildvation and Aurizon worked together to run tests for the two trial SBAS devices, targeting the accuracy of the GPS modules. Lab testing and field testing allowed a wide range of specific and operational requirements to be evaluated.

The results from the M8N proved to be more reliable than the V838. The M8N provided consistently good performance, with errors ranging from 1-3m, and it would not output a location if the module was not able to get a sufficient GPS lock. The SkyTraQ performed well in ideal conditions, typically ranging from 1-4m, but interference would cause larger errors, and sometimes there were unexplainable spikes in error. The V838 performed worse in the electrical interference test compared to the M8N. In the partial sky testing, the V838 reported locations that were up to 8.5m inaccurate, compared to the M8N that did not output any locations.

After the field test results were reviewed, FrontierSI commissioned Buildvation to run further tests on a more accurate and more expensive GPS module, the ZED-F9P from u-blox. A recent firmware update May 2020 enabled SBAS corrections on this module, but this was after field testing had concluded for the original modules. These subsequent tests revealed that the ZED-F9P was more accurate than the other two modules tested and looks to be a preferred solution for industrial situations but at a higher price point than the original modules.

Commonly Used Terms

TERM	DESCRIPTION
GPS	Global Positioning System, a satellite-based communication system that allows a position on the globe to be determined.
GNSS	Global Navigation Satellite System, refers to a constellation of satellites providing signals from orbit that transmit positioning data that is used to determine locations.
EPG	External Precise GPS, the device developed by Buildvation
RTK	Real-time Kinematic, a technique to apply corrections to a GPS signal for improved accuracy.
u-blox Module	An all-in-one microcontroller board that is GPS enabled, from the company u-blox. This term refers to the u-blox M8N Mikroe Click board inside the EPG.
SkyTraQ Module	An all-in-one microcontroller board that is GPS enabled, from the company SkyTraQ. This term refers to the SkyTraQ Venus 838 evaluation board inside the EPG.
SBAS	Satellite Based Augmentation System, a method of receiving position corrections via satellite.
Microcontroller	A microprocessor with peripherals that enable more functionality. The ESP32 microprocessor from Espressif was used for this project.
UAT	User Acceptance Test, a form of testing to ensure the product is acceptable for use by targeted user.
TAS	Track Access System, Aurizon software used to retrieve railway information.
DOP	Dilution of Precision, refers to how the arrangement of the GPS satellites affect the possible accuracy of the result. **HDOP** is horizontal dilution of precision and takes into account only the horizontal distances between the satellites. **PDOP** is position dilution of precision and takes into account vertical and horizontal displacement.

1. Introduction

1.1. SBAS Overview

SBAS is a positioning augmentation service based on satellite broadcast. The infrastructure for this process includes a network of satellite monitoring and reference stations, a data processing facility, an uplink station, a geostationary satellite, and the client GPS module (see **Error! Reference source not found.**). The reference stations transmit raw data to the central processing facility, which then sends the processed correction data to SBAS satellites, which broadcast to the client GPS module. The client GPS module is now being corrected, resulting in higher position accuracy.

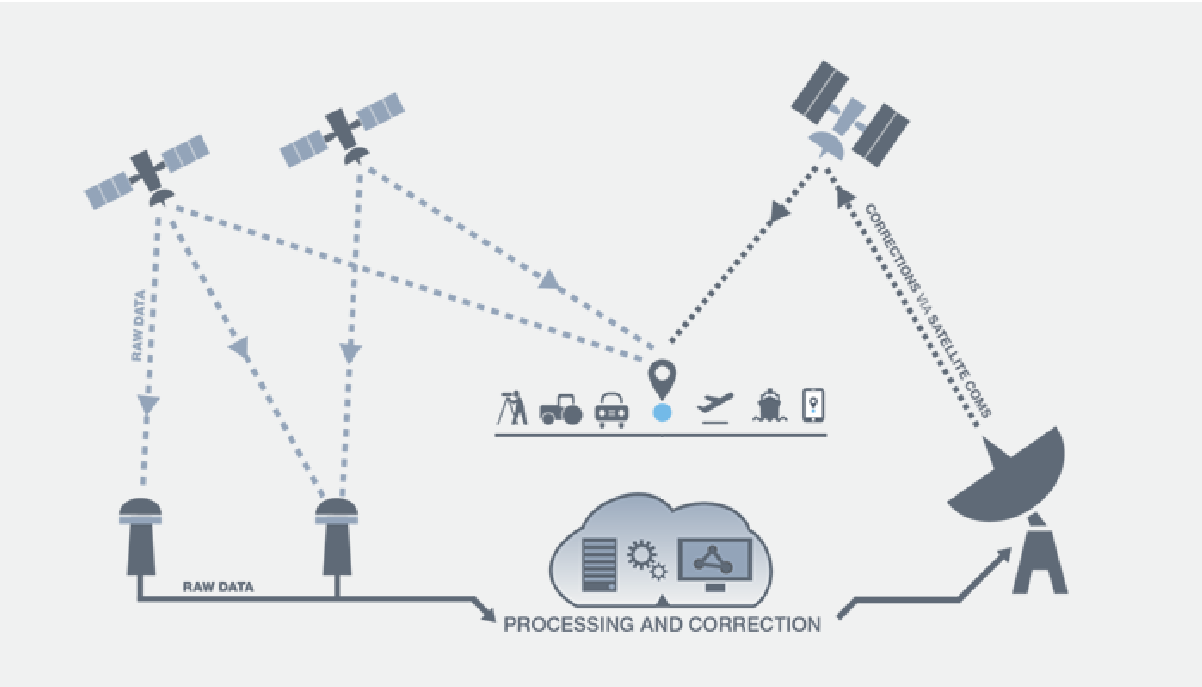


Figure 1: SBAS Service Diagram (source: Geoscience Australia).

See Appendix A for an overview of the SBAS configuration for the Aurizon trial.

1.2. Aurizon SBAS Trial

Aurizon is continuously looking for ways to improve railway safety. One such way is to disable access to a track if the track requires maintenance. Currently, the process requires an Aurizon employee to visually identify the desired track on a map in the Track Access System (TAS) application. The Aurizon employee can then use the TAS Client on a laptop to electronically request and obtain a Coded Block from the Network Controller, to prevent train access to the desired track. Determination and confirmation of the worksite location is possible by using the current GPS position and geographical maps that show the position of nearby signalling equipment.

Aurizon wants a more accurate, more reliable, and faster way to complete this process as the current process is manual requiring several checks and takes time. Basic GPS technology provides accuracy of around 2-3 metres, which is not accurate enough to distinguish nearby tracks under poor conditions. SBAS is able to provide corrections to GPS modules, theoretically increasing accuracy to less than 1 metre which is suitable for use by Aurizon for this use case.

The solution is to develop a device that can accurately determine which track is to be disabled, utilising the higher accuracy provided by SBAS. The proposed solution incorporates a GPS module configured for SBAS corrections and a Bluetooth serial connection to communicate from the GPS device to the TAS software, allowing the Aurizon employee to more accurately determine which track to disable. In this document, the SBAS device developed by Buildvation is termed EPG (External Precise GPS).

At the same time, Aurizon are also exploring the use of a Real-Time Kinematic (RTK) based solution using internet streamed corrections from terrestrial base stations for this safety use case. These two technologies are being tested as they are suited for different use cases and environments. The RTK solution requires an internet connection and is therefore not guaranteed to provide national coverage of all rail lines, where SBAS requires only satellite reception.

1.3. Project Deliverables

The following are formal deliverables for the project:

- 2 x SBAS modules (1 x u-blox, 1 x SkyTraQ) developed according to SYS.WAYSIDE.TAS.SR.SR013 – Requirements Specification TAS Precision GPS.
- Documentation of the modifications made to standard units & source code
- System Design documentation and acceptance testing documentation
- Additional tests for the new u-blox F9P high precision module as the firmware for SBAS support became available at the end of this engagement.
- Final report for Aurizon and FrontierSI.

1.4. Project Timeline

ACTIVITY	RESPONSIBLE	DATE COMPLETED
TAS Software changes to interface with SBAS GNSS data stream	Aurizon	14/02/20
Hardware Specification	Buildvation	14/02/20
Proof of Concept Hardware	Buildvation	14/02/20
Proof of Concept Integration Test	Buildvation / Aurizon	14/02/20
Trial Pass 1 (initial prototype)	Aurizon	27/02/20
SkyTraQ and u-blox prototype	Buildvation	06/04/20

Test Plan	Buildvation / Aurizon	High level plan developed and released to Aurizon 07/02/20
Interface Discussion with Aurizon	Aurizon / Buildvation	10/02/20
Initial Field Test Plan	Buildvation	25/03/20
Final build and packaging	Buildvation	06/04/20
System tests	Buildvation	06/04/20
Test Plan Initialisation (including logistics). Copies supplied to Aurizon and FrontierSI for comment	Aurizon / Buildvation	16/04/20
User Acceptance Test (UAT) #1	Aurizon / Buildvation	22/04/20
UAT #2	Aurizon / Buildvation	05/05/20
SkyTraQ Accuracy Discussion	Aurizon / Buildvation / FrontierSI	08/05/20
SkyTraQ Accuracy Investigation	Buildvation / FrontierSI	15/05/20
UAT #3	Aurizon / Buildvation	21/05/20
Field Test	Aurizon	03/06/20 – 04/06/20
Field Test Report	Aurizon	21/06/20
Final Report Draft	Buildvation / FrontierSI	30/06/20
ZED-F9P Tests	Buildvation	25/06/20
Final Report	Buildvation / FrontierSI	15/07/20

2. Equipment

The various tests were carried out using equipment such as GPS modules, GPS antennas and other device hardware.

2.1. GPS Modules and Hardware

The GPS modules were chosen for their relatively low cost (<$100), and adequate manufacturer-specified performance for the use case. These GPS modules were the SkyTraQ V838 evaluation board, and the u-blox M8N Mikroe Click GNSS board. An additional high-precision GPS board was also trialled later in the process, the C099-F9P Development Board, which is around $300.

Figure 2: SkyTraQ V838 (left), u-blox M8N (Mikroe Click GNSS 5)(centre), and u-blox C099-F9P (right).

The antenna used for all of the testing was the u-blox ANN-MB active antenna, with a ground plane.

Figure 3: u-blox ANN-MB Antenna

The microcontroller used for both modules was the ESP32 Wrover, featuring built in support for Bluetooth. Buildvation developed firmware for the microcontroller to interface and process the data between the GPS and the TAS software. The device was fitted with a 2.4GHz Bluetooth antenna via a PCB RF connector that was used to transmit the data to the TAS laptop. Buildvation designed a custom PCB to provide power and interconnect the modules, and the PCB also provided the physical mounting for the modules in the box.

Figure 4: ESP32 WROVER (left), 2.4GHz Wireless Antenna (right)

Buildvation developed two custom Bluetooth GPS EPG prototypes for use in the project. This device contained a battery, a power button, status LEDs, an ESP32 WROVER module, a 2.4GHz wireless antenna, one of the aforementioned GPS modules, and an active GNSS antenna.

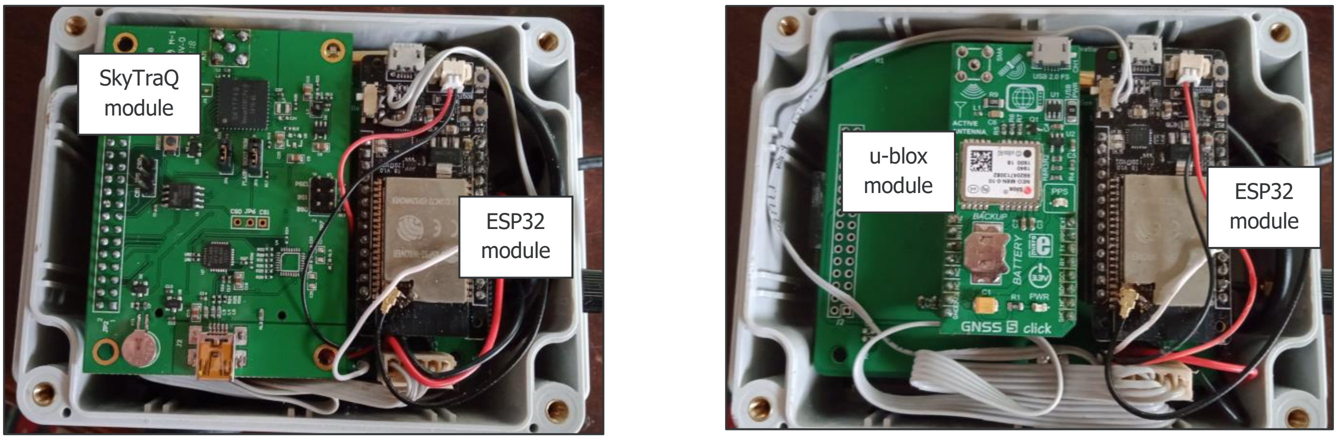


Figure 5: SkyTraQ EPG (left), u-blox EPG (right)

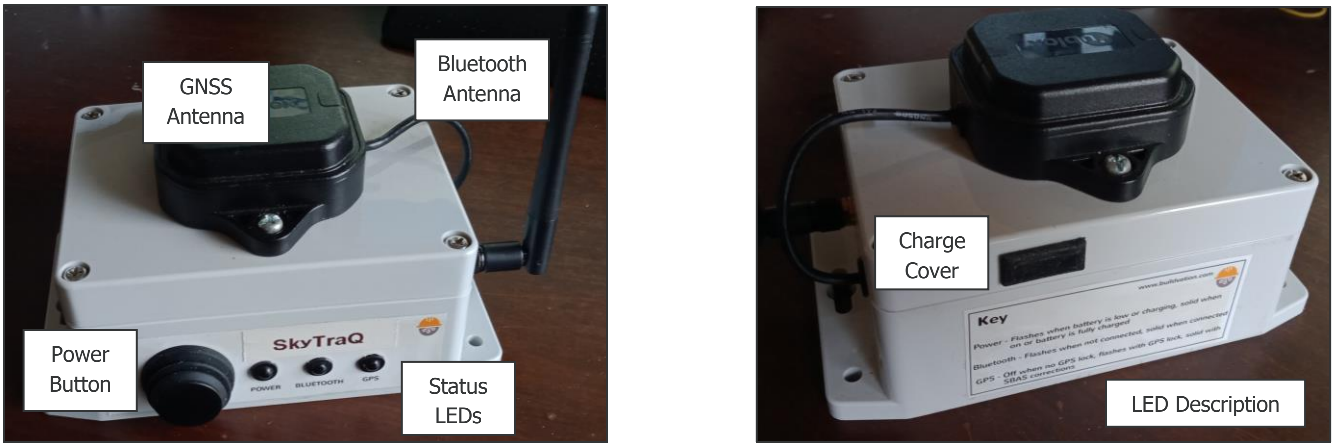


Figure 6: Front of EPG (left), Back of EPG (right)

3. Project Aims and Objectives

A number of separate tests were carried out to trial various aspects of the performance of both GPS modules. The tests were designed to determine if the GPS modules were appropriate for use in the Aurizon use case, and to acquire information to report on the performance of SBAS itself. This section describes the various tests that were carried out and the hypotheses behind each test

3.1. Cold Start Accuracy of u-blox M8N and SkyTraQ V838 from Unit Tests

Cold start tests were carried out to examine the performance of the GPS modules in the use case Aurizon had specified; placing the GPS modules on a track, turning them on and expecting to achieve an adequate positioning result. The UATs emulated this by testing the GPS modules only from cold starts.

See Appendices 'G' and 'H' for more information.

Hypothesis: SBAS enabled GPS modules should report locations within 1m of error after cold start, to ensure suitability for use in the scenario of railway safety.

3.2. SBAS Lock Time of u-blox M8N and SkyTraQ V838 from Field Tests

The SBAS lock time was a requirement by Aurizon, as the GPS module needs to output the position information in a reasonable amount of time for use in rail safety. The requirement is quantified as less than 5 minutes from a cold start.

See Appendix 'D' for more information.

Hypothesis: A large SBAS lock time indicates that the device does not have adequate satellite reception of the SBAS GEO satellite, and should therefore have reduced position accuracy in line with standalone GNSS.

3.3. Cold Start Accuracy of u-blox M8N and SkyTraQ V838 from Field Tests

It had to be ensured that the GPS position the modules report are accurate to within the required specifications. The reported GPS position needed to be within 1m error with a safety margin of 1-2m in order to be reliable and usable to determine which railway track the device was placed on.

See appendix 'E' for more information.

Hypothesis: The SBAS enabled GPS modules will output a position within 1m error when using SBAS corrections, so that the TAS application can display the correct track the device has been placed on.

3.4. Interference Testing with u-blox M8N and SkyTraQ V838 from Field Tests

GPS interference is an important factor to test when reliability is key. It had to be ensured that the types of interference in the railway environment would not have an impact on the performance of the GPS modules.

See appendix ‘E’ for more information.

Hypothesis: The types of interference common in the railway environment should not have a significant impact on the performance of the GPS modules.

3.5. Partial Sky Testing with u-blox M8N and SkyTraQ V838 from Field Tests

Partial sky is another important factor to test when reliability is key. There are sections of the railway environment where there is poor sky view. The performance of SBAS enabled GPS modules had to be tested in these locations of poor sky view to determine whether SBAS improves the accuracy of the GPS modules to a point where the position data is usable.

See appendix ‘E’ for more information.

Hypothesis: Partial sky view will have a significant impact on the performance of the GPS modules, due to poor satellite reception.

3.6. Effectiveness of Averaging Field Tests

Initial testing showed that the position output on the u-blox M8N seemed to drift around the true position, meaning that if an average was calculated on the position output, then position accuracy would improve. This was implemented as a 30 second (30s) average window to smooth the output on the u-blox module. It should be noted that the average was calculated on the EPG and output in real time at the same time as the raw data, the average was not post-processed. This was not important for the SkyTraQ V838 as the output did not drift around a certain point, the output was more constantly pulled in a single direction, the average would not improve the results. As such, the effect of the average on this module was not included.

See appendix ‘E’ for more information.

Hypothesis: A 30s average should increase the accuracy of the position output, due to reducing the deviation of the position output for outlying values.

3.7. Cold Start Accuracy Testing of ZED-F9P

FrontierSI extended the project to commission Buildvation to run further tests on a more accurate GPS module, the ZED-F9P from u-blox. This is a professional-grade high-precision module, and a recent firmware update (1.13) allows SBAS corrections. We aimed to test the accuracy of the high precision module, as well as the effectiveness of lifting the antenna off the ground to reduce multipath interference. It should be noted that and M8N module costs $15.05 USD per module in bulk, and an F9P module costs $167.77 USD per module in bulk.

See appendix ‘C’ for more information.

Hypothesis: A higher quality (more expensive) GPS board will produce more accurate position output, and elevating the antenna off the ground will result in a more accurate position output and faster lock time.

3.8. HDOP and PDOP Tests of SkyTraQ V838

HDOP stands for Horizontal Dilution of Precision, and PDOP stands for Position Dilution of Precision. These indicators report on the spread of the currently used satellites by the GPS module, and represent a view of expected accuracy. On GPS modules, a mask of these values is configurable, meaning that the GPS modules won't output data unless they meet the HDOP or PDOP thresholds. By configuring the HDOP and PDOP thresholds the GPS module can be tuned for accuracy versus ability to lock and lock speed. These tests were run after the SkyTraQ V838 initially showed an accuracy deficit compared to the u-blox module, and as such were only done with the SkyTraQ module.

See Appendix 'B' for more information.

Hypothesis: Adjusting the DOP mask will provide increased GPS accuracy, due to the GPS not obtaining lock until there is adequate satellite coverage.

4. Testing Locations

Testing was taken at a number of locations in Brisbane and Rockhampton. The locations were chosen for their availability, and their variable degrees of sky view, and interference conditions. The field tests took place near Rockhampton, and the UATs took place in Brisbane.

4.1. Field Test Locations

The field test locations were chosen for their close proximity between sites, and their wide range of testing environments.

Figure 7: field test locations (Rangal left, Dingo centre, Tunnel right)

During the field tests, the precise locations where each test was performed was recorded – as shown in the table below. Photos showing where the devices were placed during each test were also taken to identify the location.

Test Site	Location Description
Rangal	On the up road on the approach side of RL27 signal on top of the outer rail and in line with the last sleeper before the insulated joint.
Dingo	On the down road on the approach side of DO16 signal on top of the outer rail and in line with the toe of switch for the ER2 release.
Tunnel	On the down road on the approach side of TL14 signal on top of the outer rail and just before the signal gantry.

To ensure our tests were as realistic as possible, we needed tests where the device was placed on track (as per the use case) rather than on top of a signal post, points machine, survey control point, etc. This made determining the exact location of each test more difficult. While the Aurizon GIS data does include track centrelines, it doesn't record the exact location of every sleeper. However, Aurizon have access to have high-resolution aerial photography of the entire rail network. These photos have been overlaid on Aurizon WebMap – an application (similar to Queensland Globe) which lets you zoom in close enough to see individual sleepers. Like Queensland Globe, you can also click on a location to get the coordinates for that location. These photos of the rail network were taken in 2019 and are assumed to accurately reflect the physical infrastructure currently installed onsite.

On return to Brisbane after the field data was captured, the Aurizon WebMap was used to determine the coordinates for each test location. Some inaccuracy (probably in the order of 20-30 cm) was likely introduced by this method, but the purpose of the field tests (for Aurizon's use-case) was to prove whether the devices can reliably determine which track is in use with sub-metre accuracy.

4.1.1. Dingo Tests

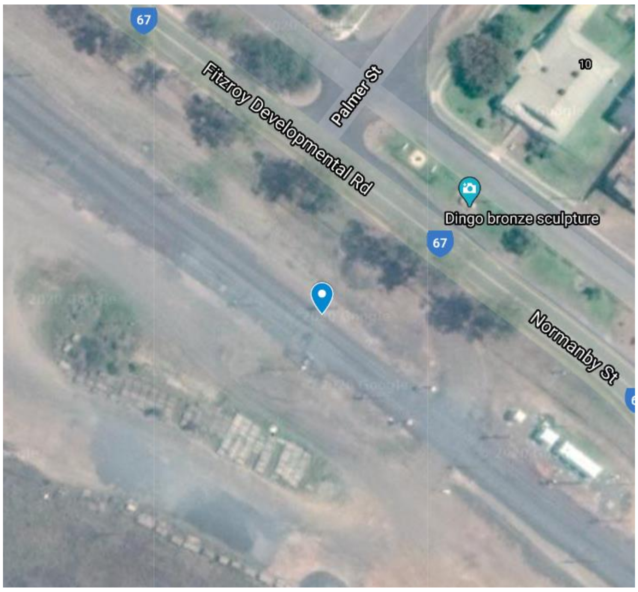


Figure 8: Dingo Test Location

The location Dingo was chosen as a baseline to test all of the other test locations against. This location featured good sky view and no interference, offering optimal conditions for the GPS modules to achieve their best possible positioning results.

4.1.2. Rangal Tests

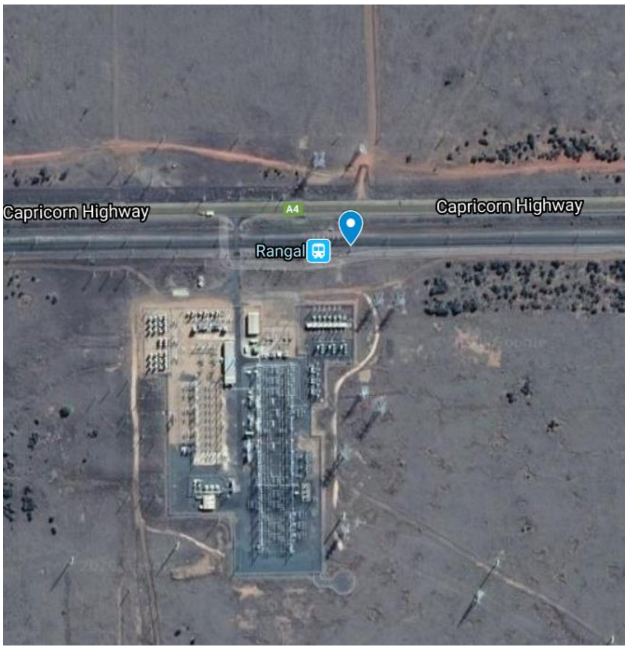


Figure 9: Rangal Test Location

The location Rangal was chosen to test the impact of interference on the output accuracy of the EPGs. This location featured an electrical feeder station with many overhead power lines, which offered a level of electrical interference. Other than the power lines, this location has a good sky view, meaning only electrical interference was tested.

4.1.3. Tunnel

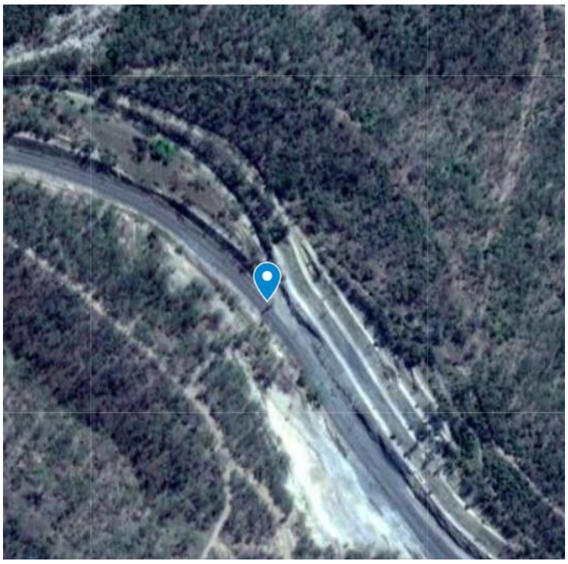


Figure 10: Tunnel Test Location

The location tunnel was chosen to test the impact of partial sky view on the output accuracy of the EPGs. This location featured large rock walls sidelining the track on both sides, creating an environment with reduced satellite reception, and increased signal reflections. This is a near worst-case scenario for GPS systems, as the technology is limited by the available satellite reception.

4.2. User Acceptance Tests

All UATs took place at this location, using a permanent survey control point found using the Queensland Globe website. This Survey Control Point is SCP #154234, and is a Derived Fixed by Survey no height control point. It was last checked by Queensland Globe on 28/07/2017 and was transformed to GDA 2020 on 18/01/2020. This site was chosen for UATs as it is an accurate and convenient location available for testing.

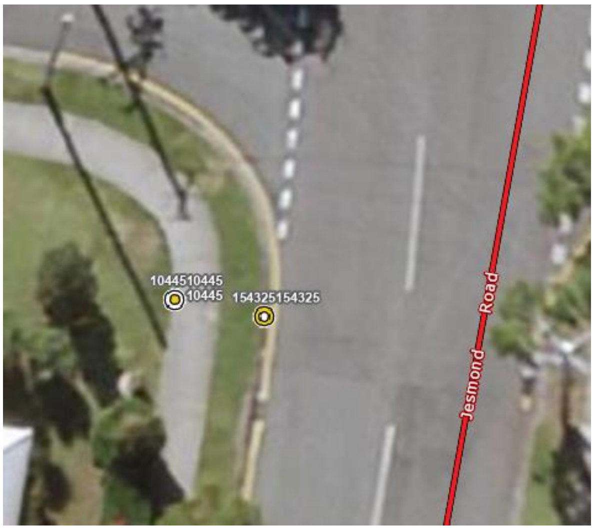


Figure 11: Map Location of UAT Testing (left), Satellite view of UAT Testing (right)

5. Testing Methodology

This section describes the methodology of the various tests in detail, including the equipment used and the testing steps.

5.1. Cold Start Accuracy Tests from UATs

Two tests were conducted at the same location, with an open sky view for the best possible results. The tests were aimed at investigating the performance of the GPS modules in an ideal scenario, but still with the use case in mind. Both tests follow the same testing routine. This location is at a minor road in suburban western Brisbane.

Prior to testing, a survey control point was found on the Queensland Globe website. This served as the true point to test the position output by the GPS modules.

Figure 12: Survey Control Point 154325

Equipment:

- EPG with u-blox M8N GPS module
- EPG with SkyTraQ V838 GPS module
- Laptop with TAS software

Locations:

- Survey Point 154325 at the intersection of Jesmond and Cubberla Streets, Fig Tree Pocket, QLD 4069.

The testing setup involved placing the EPG on top of the survey control point, turning it on, and connecting it to a laptop via Bluetooth in order to receive output position data. The GPS modules were allowed to achieve SBAS lock (the lock time was recorded), and then after 30 seconds the position was recorded. The EPG was then turned completely off (a cold-start) before the next session. This was repeated 5-6 times for each GPS module, per UAT. The position error was then calculated by comparison to the survey control point's published coordinates, and the difference was recorded.

5.2. SBAS Lock Time Field Tests

The lock time test was used as a baseline to determine the expected operational time it would take until the device is able to function as expected. The Lock Time test was completed in parallel with all other field tests.

Equipment:

- EPG with u-blox M8N GPS module
- EPG with SkyTraQ V838 GPS module
- Laptop with TAS software

Locations:

- Dingo
- Rangal
- Tunnel

The testing setup involved placing the EPG on an identified position on a track that was chosen in the TAS client software. The EPG was powered on and connected to the Aurizon laptop running the TAS client software, and at this point the start time was recorded. When the GPS module achieved SBAS lock, the time of lock was recorded, and then using the start time and time of lock, the lock time was calculated.

5.3. Cold Start Accuracy of u-blox M8N and SkyTraQ V838 from Field Tests

The Cold Start Accuracy test was completed in parallel with all other field tests. This was the main focus of the field tests, as the accuracy output by the GPS modules would determine whether they were fit for purpose or not.

Equipment:

- EPG with u-blox M8N GPS module
- EPG with SkyTraQ V838 GPS module
- Laptop with TAS software

Locations:

- Dingo
- Rangal
- Tunnel

The testing setup involved placing the EPG on top of a visually identifiable position on a track that was chosen in the TAS client software. This visually identifiable position was recorded as the reference point. The EPG was switched on, waiting for the GPS to achieve SBAS lock. When the GPS module achieved SBAS lock, the user waited another 30 seconds and then recorded the position output by the EPG. The error between the output position and the true position was then calculated.

5.4. Interference Field Tests

This test took place at a track with a form of electrical interference; a feeder substation at Rangal. This location has many overhead electrical cables that could provide interference in the GPS modules.

Figure 13: Rangal Feeder Substation next to Railway

Equipment:

- EPG with u-blox M8N GPS module
- EPG with SkyTraQ V838 GPS module
- Laptop with TAS software

Locations:

- Rangal

This test involved placing the EPG onto a position that was visually identified and chosen in the TAS client software. This reference point was recorded as the true position. The EPG was turned on and the operator waited for the module to achieve SBAS lock. When the GPS module achieved SBAS lock, an extra 30 seconds was allowed to pass and then the position output by the EPG was recorded. The error between the output position and the true position was then calculated.

5.5. Partial Sky View Field Tests

This test took place at a track with very poor sky view. This provides a challenge for GPS systems, as satellite reception is poor, and as such the output GPS positioning is negatively affected.

Figure 14: Tunnel Railway Location

Equipment:

- EPG with u-blox M8N GPS module
- EPG with SkyTraQ V838 GPS module
- Laptop with TAS software

Locations:

- Tunnel

To setup this test, a reference position was chosen and recorded in the TAS client software, and the EPG was placed at this position. The EPG was then turned on and waited upon until it achieved SBAS lock. When the GPS module achieved SBAS lock, the operator waited 30 seconds and then recorded the position output by the EPG. The error between the output position and the reference position was then calculated.

5.6. Effectiveness of Averaging Field Tests

Tests at various railway locations were carried out to get a wide range of data for this test. The 30 second average window that was implemented had to be tested to determine whether it provided any improvements to the accuracy. This test was completed in parallel with all other field tests. It should be noted that the average was calculated on the EPG and output in real time along with the raw data, the average was not post-processed.

Equipment:

- EPG with u-blox M8N GPS module
- EPG with SkyTraQ V838 GPS module
- Laptop with TAS software

Locations:

- Dingo
- Rangal
- Tunnel

To test the effectiveness of averaging, it was setup like the cold start accuracy tests. A reference point was found and recorded using the TAS client software. The EPG was turned on and allowed to achieve SBAS lock. The user waited another 30 seconds and then recorded the average position output by the EPG. The error between the average output position and the true position was then calculated.

5.7. Cold Start Accuracy Testing of ZED-F9P

This test was completed at the same location as the previous UATs, as there was no opportunity to perform field tests around Rockhampton, with open sky view for the best possible results. The test was aimed at investigating and compare the performance of the more expensive high-precision GPS module in an ideal scenario.

Prior to testing, a survey control point was located to allow testing against the positions output by the GPS modules. This survey control point is the same used in the UATs, found on the Queensland Globe website.

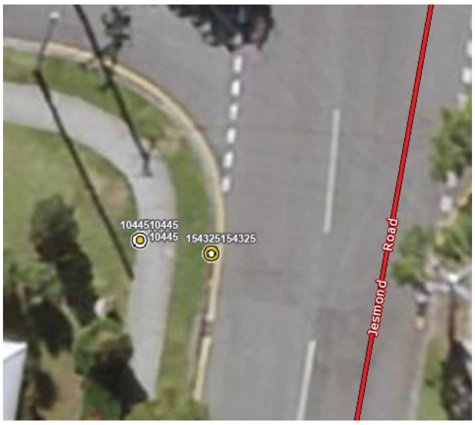


Figure 15: Survey Control Point 154325

Equipment:

- U-blox C099-F9P ZED-F9P development board and ANN-MB antenna
- Laptop with u-blox software

Locations:

- Corner of Jesmond road and Cubberla Street, Fig Tree Pocket QLD 4069

The testing setup involved placing the GPS antenna on top of the survey control point that would serve as the reference point. The C099-F9P was turned on and connected to a laptop via USB cable in order to receive the output positions. The GPS module was allowed to achieve SBAS lock, the lock time was recorded, and then after 30 seconds the position was recorded. This was repeated 6 times. The antenna was then elevated by 1.5m using a stand, and the testing process was repeated. After testing, the error between the reference point and the output positions were calculated.

5.8. HDOP and PDOP Tests

This test was completed in a place with open sky view, ideal conditions for the GPS module. The testing aimed to test various values of the HDOP and PDOP mask to increase the accuracy of the position output. Only the SkyTraQ module was used in this test as previous tests had shown sub-optimal performance, achieving errors of up to 9m. This was deemed unacceptable, and these tests were completed in an attempt to manage these errors.

Prior to testing, a visually identifiable landmark was found using Queensland Globe, and the coordinates of the landmark were recorded.

Equipment:

- SkyTraQ V838 Evaluation Board and ANN-MB antenna
- Laptop with GNSS viewer software

Locations:

- Corner of Jesmond road and Cubberla Street, Fig Tree Pocket QLD 4069

The testing setup involved configuring the H-DOP or P-DOP mask, then placing the GPS antenna on top of the landmark which would serve as the reference point, turning on the SkyTraQ V838 Evaluation Board, and connecting it to a laptop via USB cable in order to receive the output positions. The GPS module was allowed to achieve SBAS lock, and then after 30 seconds the position was recorded. This was repeated 4 times for each different mask. Five different mask settings were used; no mask, H-

DOP=1.5, P-DOP=1.5, H-DOP=1.0, H-DOP=1.2. After the tests were completed, the error between the reference point and the position output was calculated for each configuration.

6. Challenges Experienced

The following challenges were experienced during the project:

- Buildvation experienced precision problems where the GPS location would wander well outside expected variances when running system tests with the initial SkyTraQ evaluation board, requiring a replacement SkyTraQ board as the initial board was possibly damaged due to the integration work required to set it up. Testing proved that this new board was more accurate than the first one, however the results were still less than desirable, in some instances getting up to 7m of error at first fix immediately after cold-start. It should be noted that in every instance, the output would slowly drift back towards the true value. This then led to the HDOP and PDOP tuning in an attempt to make the SkyTraQ module more accurate under these conditions.

- Buildvation needed to prove that placing the GPS modules inside the housing of the EPG did not detract from the accuracy of the GPS modules. This had to be done, as it is known that placing unshielded electronics in close proximity of an antenna can cause interference and reduce accuracy and we wanted to ensure the enclosure was not impacting results. For the SkyTraQ board, the antenna connector orientation also had to be modified, so the housing testing ensured that this also did not detract from the accuracy of the GPS modules.

- The COVID pandemic caused significant delays to the project, especially as field testing had to be delayed then completed with less personnel. This meant that Buildvation staff were not allowed to attend field testing, so the field testing results were completed by Aurizon staff and passed onto Buildvation to process results. To compensate, Buildvation and Aurizon performed additional system testing in suburban Brisbane to compare with the railway field test results.

- There was an issue with the Bluetooth software library for the chosen microcontroller, it caused a clash of interrupts with the software serial library due the particular way the data transfer was setup. This was rectified by switching to a hardware serial instead of a software serial. This simply meant that the serial communications were handled by the ESP32 firmware instead of a software implementation of serial communications. A few sections of the program had to be changed, as the hardware serial does not allow the baud rate to be changed multiple times. This meant that both modules had to be set to 9600, as the u-blox module did not remember configurations between restarts, and the default was 9600. Originally we were configuring it on startup to use a higher baud rate, but because we were not able to change the baud rate on the ESP32 after startup, there was no way to use the now higher baud rate. Delays were caused while the code was rebuilt and retested.

7. Results

Results of all the various testing completed during the project are presented in this section. In all cases, the measurements taken from the GPS modules are compared to a static reference point, and the resulting error was computed. The results have been quantified in terms of a few different parameters: minimum error, maximum error, mean error, and standard deviation. These results allow a very good encapsulation of the performance of the GPS modules. These are combined with visual depictions of deviation, with the centre of the graph being the true reference point.

7.1. Cold Start Accuracy Tests from UATs

Results of all of the UATs are described in this section. From the results it can be seen that the GPS modules do not stay below the initial 1m error requirement on cold-start. This was updated to 2m as a more realistic target, which was still within the operational parameters of the use case for Aurizon.

The following tables show the average error, minimum error, maximum error, and standard deviation acquired over all the tests for that UAT. UAT#1 is not included, as Bluetooth issues resulted in the GPS accuracy not being tested.

GPS MODULE	MEAN ERROR (M)	MIN ERROR (M)	MAX ERROR (M)	ST DEV(M)	# OF EPOCHS
SkyTraQ	4.54	1.90	9.50	2.96	5
u-blox	1.50	1.20	1.70	0.20	5

Table 1: UAT#2

GPS MODULE	MEAN ERROR (M)	MIN ERROR (M)	MAX ERROR (M)	ST DEV (M)	# OF EPOCHS
SkyTraQ	3.46	1.00	5.30	1.35	5
u-blox	2.59	1.89	3.12	0.50	5

Table 2: UAT#3

From this data it is seen that u-blox is more accurate than SkyTraQ, always scoring a better average, standard deviation, and minimum error after cold-starts. The large maximum error seen on the SkyTraQ board was unacceptable for the user requirements, so an investigation into this problem was scheduled. For UAT#3, the SkyTraQ module was replaced with a new board, which improved the performance, and subsequently the UAT#2 SkyTraQ results can be disregarded due to hardware fault. Both modules do not satisfy the initial requirement of sub 1m accuracy, and this requirement was then updated to sub 2m. It was also observed that the accuracy improved once the device was powered on for more than a couple of minutes.

From these tests, the modules seem unfit for the purpose of railway safety in terms of the initial sub 1m accuracy requirement, but the u-blox module seems more fit than the SkyTraQ module.

It is seen that the standard deviation is much higher for the SkyTraQ module than the u-blox module, indicating that the u-blox module is also much more precise than the SkyTraQ module.

7.2. SBAS Lock Time Field Tests

The results of the SBAS lock times are collated in this section.

The following tables show the average SBAS lock times from field testing, where a very distinct separation appeared between the two modules.

LOCATION	MEAN SBAS LOCK TIME	NOTES
Rangal	91s	Electrical Interference
Dingo	225s	The large lock time was found to be a low battery issue.
Dingo (re-test)	122s	None.
Tunnel	Failed to achieve SBAS Lock at this location.	None.

Table 3: u-blox results

LOCATION	MEAN SBAS LOCK TIME	NOTES
Rangal	11s	None.
Dingo	9s	None.
Tunnel	6s	Had very large accuracy error.

Table 4: SkyTraQ results

On the u-blox module, the tests in Rangal showed an expected lock time between 60 and 120 seconds, and the subsequent large lock times at Dingo were a sign that the module was not performing correctly. The failure to achieve an SBAS lock at Tunnel showed that the module did not have adequate satellite reception, which was expected due to the limited sky view. At Rangal, the lock time was shorter, and the position accuracy was slightly better than at Dingo, so it can be said that as lock time decreases, the satellite reception is better, and should have better position accuracy.

It is seen that the SkyTraQ module achieves the SBAS Lock in very little time compared to the u-blox module. However as seen in following tests, even though the lock time was fast, the lock time was not directly related to the accuracy of the output. It is possible that the SkyTraQ module displays when it has a connection to the SBAS satellite rather than when the output position includes the SBAS corrections, which seems to be how the u-blox module operates.

The u-blox module will take longer to achieve a lock if sky view is undesirable, but the SkyTraQ module does not seem to follow any pattern, and the SBAS lock on the SkyTraQ module is not an indication of an accurate position output. It also shows the different approach the vendors take to the algorithms for computing SBAS lock. The exact internal implementation of the SBAS corrections differs between these receiver modules and was not explored as part of this research.

7.3. Cold Start Accuracy Field Tests

These are the results from the accuracy tests completed during the field testing. This test showed that the modules have somewhat similar performance.

The following table includes accuracy parameters such as average error, standard deviation, minimum error, maximum error, and the number of epochs.

LOCATION	DEVICE	MEAN ERROR (M)	ST DEV (M)	MIN ERROR (M)	MAX ERROR (M)	NOTES	# OF EPOCHS
Dingo	u-blox	1.49	0.49	1.34	1.64	No Interference.	2
Dingo	SkyTraQ	1.23	0.39	0.69	1.61	No Interference.	4

Table 5: Cold Start Accuracy Field Test Results

At the Dingo track location, the SkyTraQ module performed better than the u-blox module. It is seen to get a better average error, standard deviation, minimum error and maximum error. Both modules scored lower than 2m for all of the tests, meaning both modules are fit for purpose.

7.4. Interference Testing from Field Tests

These are the results from the interference tests completed during the field testing which was located next to an electrical sub-station with an array of high voltage lines, in addition to the usual high voltage overhead lines for the trains. This test showed that the u-blox module seems to be a little more resilient to electrical interference than the SkyTraQ module, but that is likely due to the SkyTraQ module being an evaluation kit and not a production PCB / layout, while the u-blox module we used was a commercially sold module with metal housing (from Mikroelectronica).

The following table shows the data from the open sky testing at Dingo, and the electrical interference testing at Rangal, allowing a comparison of the interference results at Rangal with the baseline results at Dingo.

LOCATION	DEVICE	MEAN ERROR (M)	ST DEV (M)	MIN ERROR (M)	MAX ERROR (M)	# OF EPOCHS	NOTES
Dingo	u-blox	1.49	0.49	1.34	1.64	2	No Interference.
Dingo	SkyTraQ	1.23	0.39	0.69	1.61	4	No Interference.
Rangal	u-blox	1.41	0.51	1.04	2.08	6	Electrical Interference.
Rangal	SkyTraQ	1.79	0.97	0.58	2.75	6	Electrical Interference.

Table 6: Interference Testing Field Test Results

Looking at the u-blox module, we see that the average is slightly better with electrical interference, with 8cm better accuracy. The minimum also improves under electrical interference, however the maximum is shown to get slightly worse under electrical interference. For the u-blox module, electrical interference did not seem to have much of an impact.

Comparing the SkyTraQ module, we see that the average gets significantly worse with electrical interference, by 56cm. The minimum does not change much, but under electrical interference it is seen that the maximum increases by 114cm. For the SkyTraQ module, electrical interference does seem to have an impact.

This test was taken under a different sky view compared to the Dingo testing. This means these results could have been explained by the physical obstructions and multi-pathing caused by the structures, not just the interference. However, it can be stated that the electrical interference could be a factor in the decreased accuracy, but it is also possible that it was due to different environmental conditions.

The types of interference common in the railway environment do not affect the u-blox module, but do seem to have a small impact on the SkyTraQ module (which could be optimised with a better PCB layout for the development board we used).

7.5. Partial Sky Testing Field Tests

The following is the results from the partial sky testing completed during the field tests. This test proved that GPS technology is still unable to overcome poor satellite reception.

The following table shows the data from the open sky testing at Dingo, and the partial sky testing at Tunnel, allowing a comparison of the baseline results at Dingo with the partial sky results at Tunnel.

LOCATION	DEVICE	MEAN ERROR (M)	ST DEV (M)	MIN ERROR (M)	MAX ERROR (M)	# OF EPOCHS	NOTES

Dingo	u-blox	1.49	0.49	1.34	1.64	2	Clear Sky View.
Dingo	SkyTraQ	1.23	0.39	0.69	1.61	4	Clear Sky View.
Tunnel	u-blox	-	-	-	-	-	Very Poor Sky View.
Tunnel	SkyTraQ	4.84	3.52	1.46	8.58	4	Very poor sky view.

Table 7: Partial Sky Field Test Results

Both the u-blox and SkyTraQ modules performed significantly worse at this site, due to the significant reduction in sky visibility affecting the GPS performance.

The u-blox module was unable to get a lock, and the SkyTraQ module was on average 3.61m less accurate. The standard deviation also showed a large variance in the results. This test shows that partial sky view is still a problem for GPS technology.

Partial sky significantly affects the performance of both GPS modules, this is a restriction of the satellite technology, and will be worse in locations where the SBAS satellite is not visible. Therefore, the GPS modules are not fit for use in places where satellite reception, in particular for the satellite hosting the SBAS signal, is an issue.

7.6. Effectiveness of Averaging Field Tests

The following contains the results from the average testing completed during the field tests, and shows that the implemented average does not increase the position accuracy. This testing was only conducted using the u-blox M8N. This was because the behaviour of the output on this module seemed to wander around a certain point. Averaging the results should therefore pull the output closer to this certain point. This was not important for the SkyTraQ V838 as the output did not drift around a certain point, the output was more constantly pulled in a single direction, the average would not improve the results. As such, the effect of the average on this module was not included.

It should be noted that the average was calculated on the EPG and output at the same time as the raw data, the average was not post-processed.

The figures below show the deviation of the raw data, and the deviation of the averaged data. The table shows summarised data for both the raw data and the averaged data.

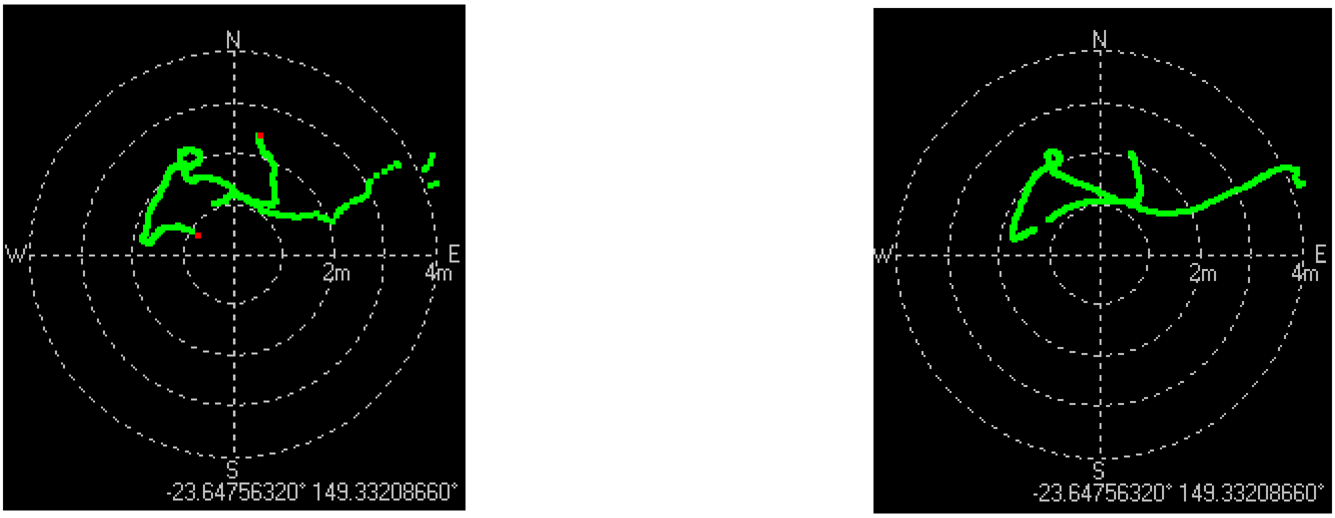


Figure 16: Raw Dingo Deviation (left), Average Dingo Deviation (right)

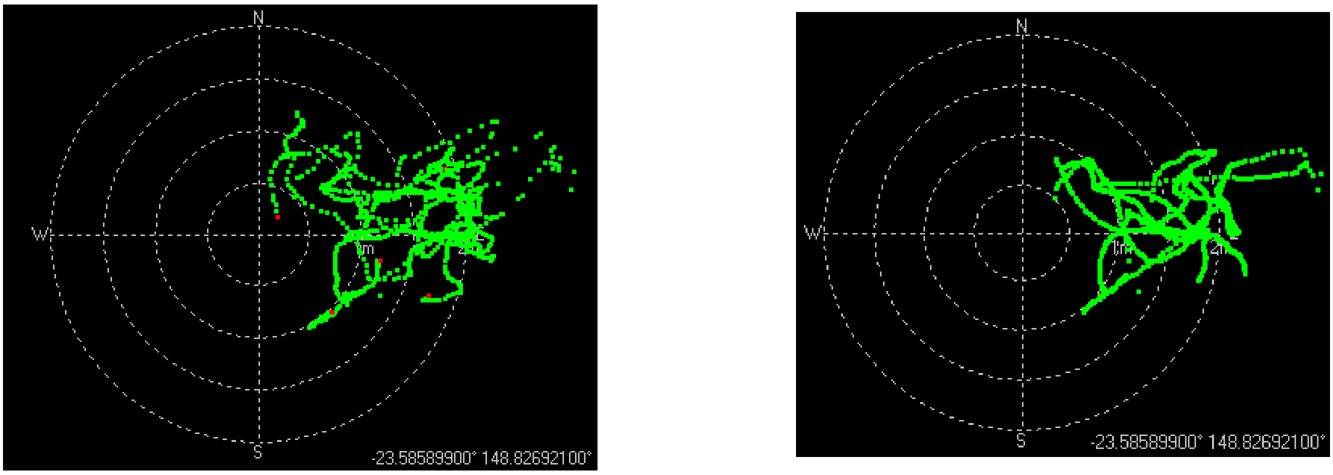


Figure 17: Raw Rangal Deviation (left), Average Rangal Deviation (right)

LOCATION	MEAN ERROR (M)	STANDARD DEVIATION (M)	MEAN ERROR FOR 30S AVERAGE (M)	MEAN STANDARD DEVIATION FOR 30S AVERAGE (M)	# OF EPOCHS
Dingo	1.49	0.49	1.49	0.42	2
Rangal	1.41	0.51	1.50	0.54	4

Table 8: Effectiveness of Averaging Field Test Results

At Dingo, the tests did not seem to benefit from the average. Due to the behaviour of the output not hovering around the true point, the average was not able to create a tighter deviation around the true point.

At Rangal, the above is repeated. The output seems to hover somewhere about 1.5m to the East, resulting in a tighter deviation around this point, but not pulling it closer to the true point, resulting in a slightly larger error.

A 30s average does not improve position output, and if the position output does not centre around the true point, a tighter deviation causes the position output to pull away from the true point.

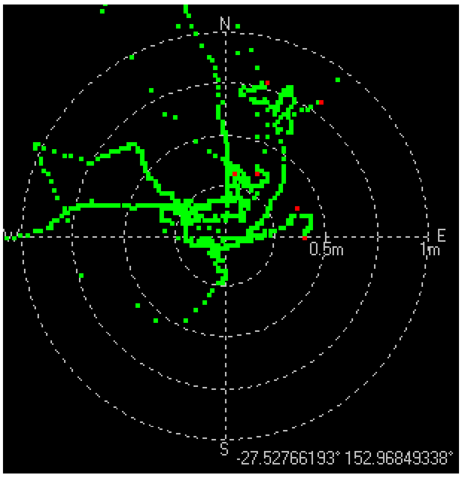
7.7. Cold Start Accuracy Testing of ZED-F9P

This results of the ZED-F9P testing are detailed below. These tests show that the higher accuracy GPS module results in a much better accuracy, and that elevating the antenna off the ground did not improve the accuracy.

The table below shows the summary data, including the lock time, average error, standard deviation, minimum error, maximum error, and number of epochs. The figures show the visual deviation of the position output.

MEAN LOCK TIME (M:SS)	MEAN POSITION ERROR (M)	ST DEV (M)	MIN ERROR (M)	MAX ERROR (M)	# OF EPOCHS	NOTES
2:43	0.422	0.24	0.03	0.72	6	On Ground
2:49	0.425	0.28	0.07	0.9	6	On Stand

Table 9: Cold Start Accuracy Testing of ZED-F9P Results



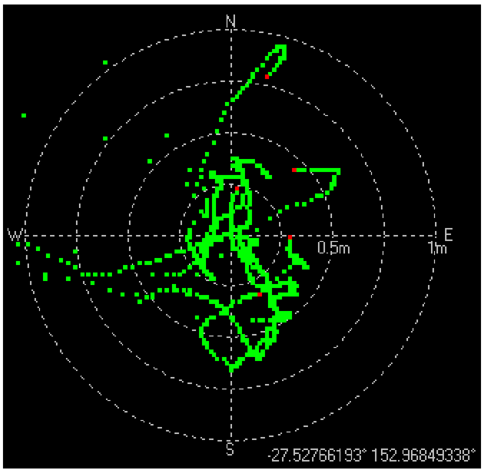


Figure 18: On Ground (left), On Stand (right)

The average position error is shown to be 0.43m, which is almost 3 times less than the average position error for the u-blox M8N module tested in UAT2. The standard deviation is very small, meaning it has improved precision over the M8N. This module also satisfies the initial requirement of less than 1m position error, in all fields including maximum error. The graphs do show some positions outside the 1m radius, but these points are reported during start up, i.e. before the SBAS lock. While the module reports SBAS lock, the error was inside 1m 100% of the time. During the project, the accuracy requirement was changed from 1m to 2m, which indicates that this may be a soft requirement. Nevertheless, this exceptional accuracy may cause a switch to this module, as railway safety requires this level of accuracy.

The antenna was elevated 1m off the ground, reducing reflection interference. This change did not seem to cause much improvement in the data, it increased the lock time, average position error, minimum error and maximum error. However, the graph shows that the deviations are more centred around the true point, so it can be said qualitatively that position output is more accurate when the antenna is placed on a stand.

The u-blox ZED-F9P module delivers a very accurate position output, 100% within 1m after SBAS lock and close to the theoretical performance expected of a SBAS solution. This module is more accurate than the u-blox M8N module. Elevating the antenna off the ground did not seem to make a significant improvement in position output.

7.8. HDOP and PDOP Tests of SkyTraQ V838

The following details the results from the HDOP and PDOP tests using the SkyTraQ V838 GPS module. By gradually modifying the DOP mask the average error was able to be improved.

This is because the GPS module won't output positions until these thresholds are met. This does cause a trade-off, as there will be a longer lock time due to the rejection of the early positions, until the thresholds are met.

The table below shows the average error, minimum error, maximum error, number of epochs, and standard deviation for 5 different DOP mask configurations.

TEST	MEAN ERROR (M)	MINIMUM ERROR (M)	MAXIMUM ERROR (M)	# OF EPOCHS	ST DEV (M)
No Mask	2.68	1.00	5.40	4	1.99
HDOP = 1.5	2.78	0.80	4.20	4	1.44
PDOP = 1.5	2.50	2.50	2.50	1	N/A
HDOP = 1.0	-	-	-	0	N/A
HDOP = 1.2	2.03	0.60	7.60	11	1.94

Table 10: HDOP and PDOP Test Results

A HDOP of 1.2 resulted in the highest accuracy, but is still seen to have relatively large jumps in the accuracy from cold starts. As seen above, it does jump to 7.6m, indicating it may not be reliably accurate enough for the purposes of railway safety. This is also indicated in the standard deviation, that while is slightly smaller than the basic configuration, is still larger than the HDOP 1.5 test.

Adjusting the DOP mask improved the accuracy of the average output, but was still seen to contain large unexplainable deviations, indicating it may not be accurate enough in the scenario of railway safety.

8. Conclusion

A series of testing procedures have been completed to determine if the SBAS enabled GPS modules are fit for purpose in the scenario of track safety provided by Aurizon.

Some challenges had to be overcome over the course of the project; a faulty SkyTraQ GPS module was replaced with a new SkyTraQ GPS module, an issue with the Bluetooth library was rectified, and the possibility of housing interference was tested to prove that there was no interference, and there were many logistics problems and delays caused by the impact of the COVID-19 pandemic.

A number of tests of the cold start performance indicate that the u-blox M8N module and the u-blox ZED-F9P module are fit for the purpose that Aurizon specified, and the SkyTraQ V838 module is not fit for purpose, at least in the form tested (Evaluation Kit).

From the UAT cold start testing, it was seen that the SkyTraQ module would consistently get position errors well above 2m, up to 5m, where the u-blox module would get between 1.5m and 2.5m. The u-blox module was also more precise, scoring a standard deviation of 0.5m, where SkyTraQ had a standard deviation of 1.35m. The cold start testing from the open sky field test results showed that the SkyTraQ module actually performed slightly better than the u-blox module, getting an average error of 1.23m with a standard deviation of 0.39, compared to the u-blox module getting an average error of 1.49m with a standard deviation of 0.49.

The cold start testing from the interference test may not have been conducted in a way to properly isolate the effects of the electrical interference impact on the GPS modules. As such the following conclusions need to be read with the possibility that while electrical interference may have been the main contributing factor, there may have been other sources of interference not accounted for.

The cold start testing from the interference field test show that the SkyTraQ module may be susceptible to electrical interference, where the u-blox module may not be. The SkyTraQ module had a 30cm increase in average error and increased the standard deviation to 0.97. Comparatively, the u-blox module averaged slightly better under electrical interference, decreasing average error by 8cm.

The partial sky testing showed the biggest weakness of the SkyTraQ module. Under poor sky conditions, the module was able to achieve SBAS lock, and reported an SBAS fix. However, after cold-starts it reported a very large average error of 4.84m, with a maximum error at 8.58m, which is completely unacceptable when reliability of results is required. The u-blox module simply did not output any results, due to the inability to receive good satellite visibility. This makes the u-blox module better for this use case, as it is less likely to output wildly inaccurate results.

It was also proven that a 30 second average on the position output did not help to increase accuracy, in many cases it decreased accuracy. This is because by averaging the position output, it creates a tighter deviation, but if the position output mean-centre is not centred on the true point, it pulls the position output away from the true point. Additionally, adjusting the DOP masks did see some improvement in accuracy in the SkyTraQ GPS module, however it did not fix the seemingly random spikes in error.

The u-blox ZED-F9P GPS module is a more expensive but more accurate GPS module, and showed exceptional results in testing. All of the testing points were inside 1m, with the average error hovering around 0.4m.

The SkyTraQ V838 GPS module cannot be recommended for the use case, due to larger position error, as well as seemingly random and unreliable position locks. The u-blox M8N GPS module is recommended for the use case, as it fulfils the criteria that Aurizon specified, is more accurate than the SkyTraQ GPS module, and the position locks are more reliable. If Aurizon wants a more accurate (but more expensive) solution to ensure the highest reliability in results, the ZED-F9P GPS module is recommended.

Appendix A Aurizon SBAS Solution

The SBAS solution was integrated with TAS C# client on a laptop over a Bluetooth connection setup as a virtual serial port with data structured using the NMEA GNSS protocol (to be determined), which was sent to the control centre via the communication link on the laptop. The SBAS unit is standalone, with a rechargeable battery with a life of a minimum 14 hours and small enough to be placed in the middle of the rail tracks.

Buildvation developed 2 custom SBAS units to suit Aurizon's operating conditions, each using one of the leading semi-professional SBAS modules (U-Blox, Skytraq) for the purposes of performance comparison, trial and testing. Buildvation worked with Aurizon for acceptance testing including interpretation of the test results (eg. measuring accuracy errors) and produced a report as an outcome of the testing / trial which was shared with GeoScience Australia as collateral for the national SBAS initiative.

The SBAS device, aka External Precise GPS (EPG) was designed so that it can be safely operated in Australian outback conditions to suit high temperatures, dust, shock/vibration as well as moisture (IP65 rating).

The TAS tablet has Bluetooth to receive data from the EPG and a 4Gx modem that can be used to transmit location data from the GPS unit (with other identification data). The TAS application then handles sending this GPS data back to central control.

The distance between the EPG and the TAS laptop is restricted by Bluetooth range considerations, however the EPG was designed so that the range fit within the Aurizon operational constraints.

A setup process is required to initially configure the EPG and to pair it with Bluetooth on the TAS laptop. The data required by the TAS application is then sent to it over Bluetooth.

The responsibility for communication between the TAS laptop and the network operations centre is handled by the TAS system and out of scope for the Buildvation SBAS solution.

Part of the initial project planning was to determine the protocol and method for integrating the SBAS GNSS data stream with the TAS application over a Bluetooth link, where Buildvation configured the EPG to send the appropriate information that is compatible with the Tas application.

Appendix B HDOP and PDOP Tests

All coordinates were based against these coordinates :

-27.524900, 152.969970

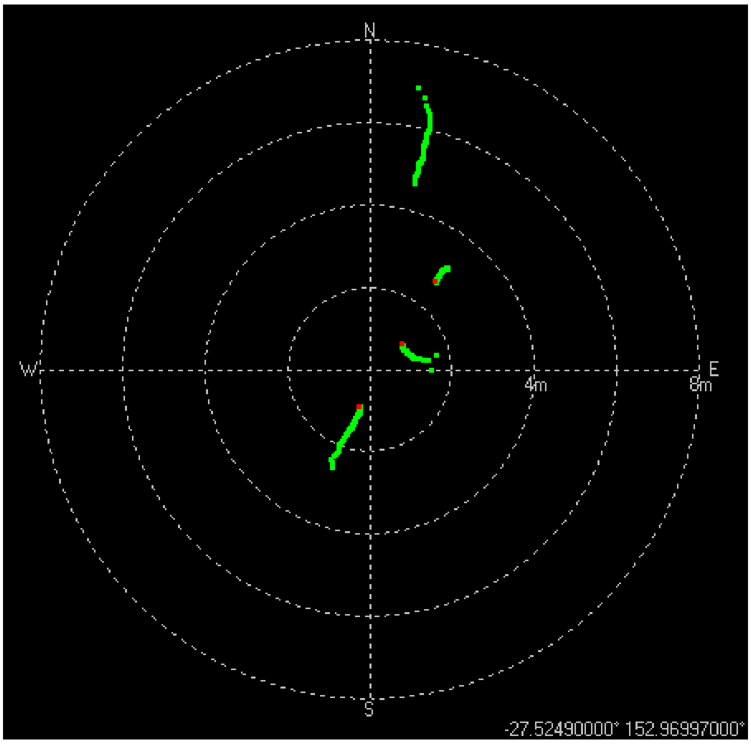
These coordinates were found on QLD Globe, on top of a visually identifiable landmark. The antenna was placed on top of this landmark.

Procedure:

1. The board is to be powered off for at least 30 seconds.
2. The board is powered, starting a timer to time how long the board takes to acquire SBAS lock.
3. Latitude and Longitude readings are taken 10 seconds after DGPS lock is acquired.

Base Configuration Test

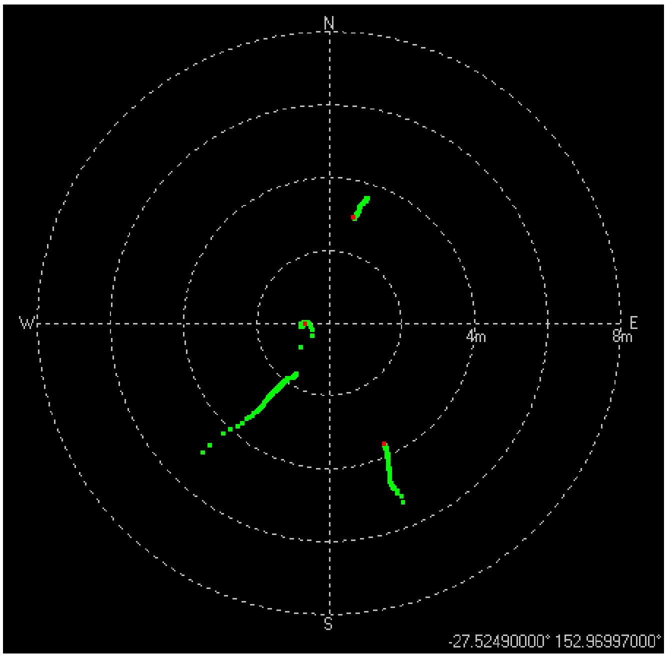
Lat/lon	Displacement	Notes
-27.52487917, 152.96998717	2.9m	DGPS within 10 seconds of startup
-27.52491233, 152.96996550	1.4m	DGPS within 20 seconds of startup
-27.52489500, 152.969977833	1m	DGPS within 20 seconds of startup
-27.52485283, 152.96998300	5.4m	DGPS within 40 seconds of startup



HDOP 1.5 Test

Upon getting a couple incorrect displacements, the **HDOP** was configured to be 1.5

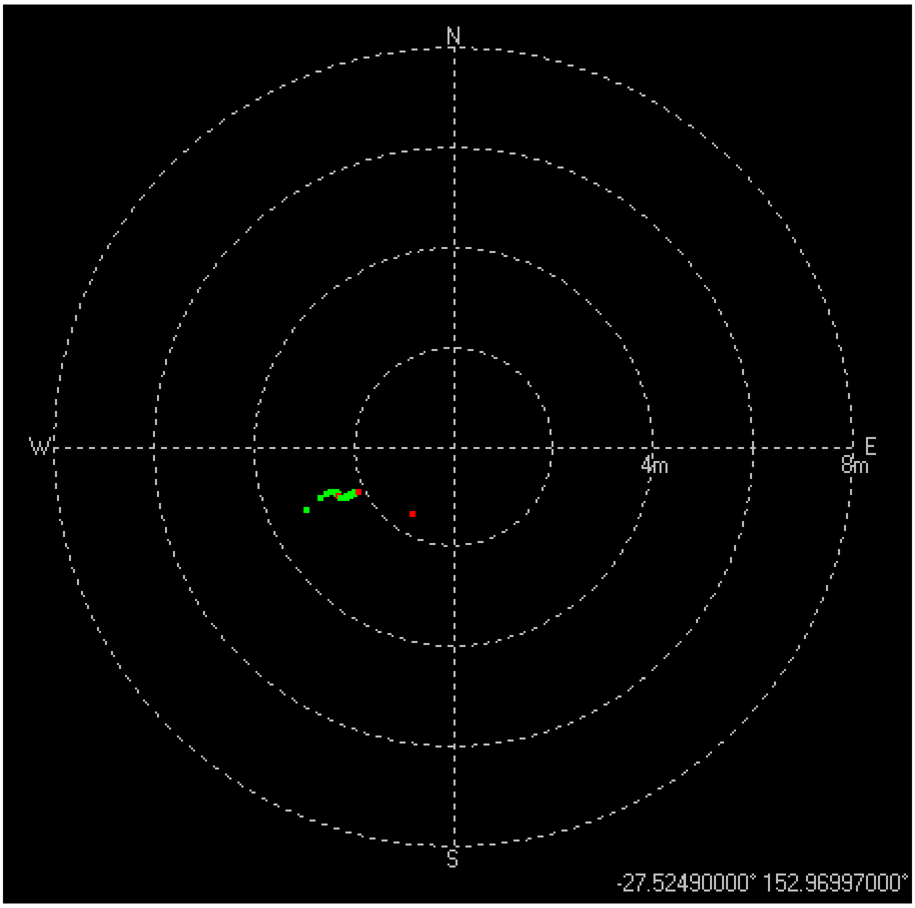
Lat/lon	Displacement	Notes
-27.52487133, 152.96997833	3.3m	DGPS within 30 seconds of startup
-27.52493467, 152.96998650	4.2m	DGPS within 25 seconds of startup
-27.52490083, 152.96996183	0.8m	DGPS within 40 seconds of startup
-27.52491767, 152.96995350	2.6m	DGPS within 25 seconds of startup



PDOP 1.5 Test

Upon still getting mostly incorrect displacements, the **PDOP** was configured to be 1.5

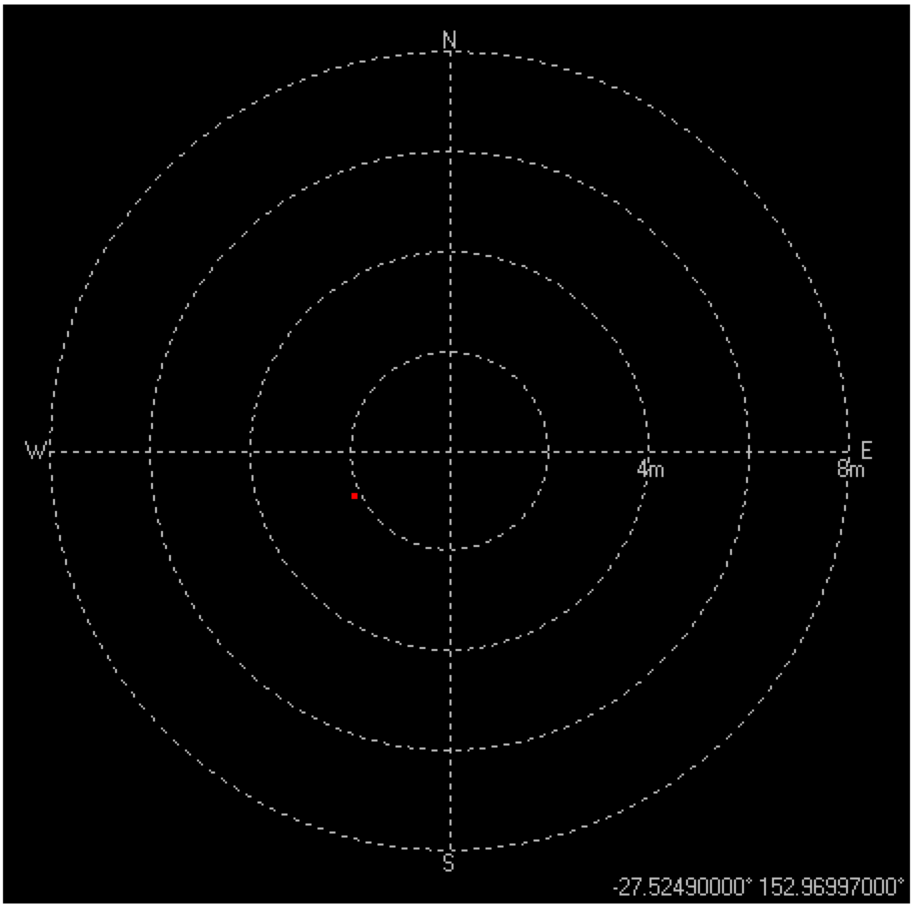
Lat/lon	Displacement	Notes
-	-	Did not achieve any fix in 5 minutes
-27.524890917, 152.96994717	2.5m	3min 30sec It did seem to switch between fixed and not fixed as the PDOP went over and under 1.5
-	-	Did not achieve any fix in 5 minutes
-	-	Did not achieve any fix in 5 minutes



HDOP 1.0 Test

Given that the 1.5 **PDOP** seemed to be too hard to reach, the **HDOP** will be tested again but set to 1.0

Lat/lon	Displacement	Notes
-	-	No fix in 5 mins
-	-	No fix in 5 mins
-	-	No fix in 5 mins
-	-	No fix in 5 mins

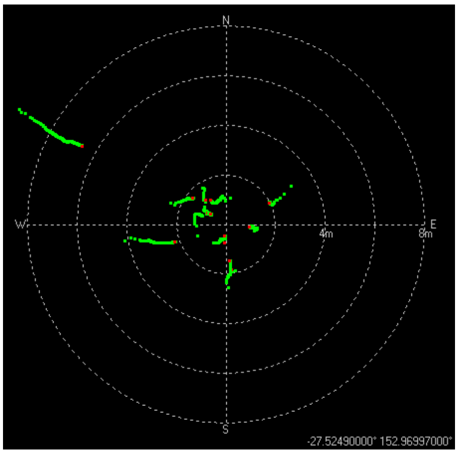


HDOP 1.2 Test

Given that the 1.0 **HDOP** seemed to be too hard to reach, the **HDOP** will be tested again but set to 1.2

Lat/lon	Displacement	Notes
-27.52489483, 152.96996167	1m	DGPS within 25 seconds of startup
-27.52489050, 152.96996050	1.4m	DGPS within 25 seconds of startup
-27.52489083, 152.96996683	1.1m	DGPS within 20 seconds of startup
-27.52489033, 152.96995367	1.9m	DGPS within 15 seconds of startup
-27.52490067, 152.96998067	1.1m	DGPS within 55 seconds of startup
-27.52491350, 152.96997183	1.5m	DGPS within 45 seconds of startup
-27.52489167, 152.96998800	2m	DGPS within 20 seconds of startup
-27.52486850, 152.96990217	7.6m	DGPS within 40 seconds of startup Seen on the deviation chart, this measurement seems to wander

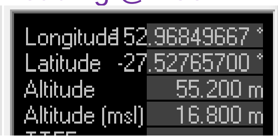
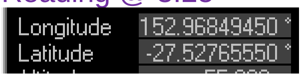
		quicker than others towards the "correct" value
-27.52490667, 152.96994267	2.8m	DGPS within 25 seconds of startup
-27.52490500, 152.96996950	0.6m	DGPS within 40 seconds of startup
-27.52489600, 152.96995717	1.3m	DGPS within 30 seconds of startup

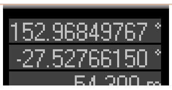


Results:

Test	**Average Error (m)**	**Minimum Error (m)**	**Maximum Error (m)**	**Standard Deviation (m)**
Basic Configuration	2.675	1	5.4	1.99
HDOP = 1.5	2.725	0.8	4.2	1.44
PDOP = 1.5	2.5	2.5	2.5	N/A
HDOP = 1.0	-	-	-	N/A
HDOP = 1.2	2.03	0.6	7.6	1.94

Appendix C ZED-F9P Testing

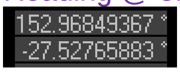
Test	F9P
Testing Accuracy	Min/Max/Mean error on ground: **0.03m/0.72m/0.422m** Min/Max/Mean lock time on ground: **2:23/2:59/2:43** Min/Max/Mean error on stand: **0.07m/0.9m/0.425m** Min/Max/Mean lock time on stand: **1:32/3:15/2:49** **Tests from survey control point at -27.527661933, 152.968493382**
Position reported should be accurate to within 1m when no interference is present	<u>Test 1</u> Dgnss @ 2:23 Reading @2:53:  -27.52765700 152.96849667 **0.64m** <u>Test 2</u> Dgnss @ 2:55 Reading @ 3:25  -27.52765550 152.96849450 **0.72m** <u>Test 3</u> Dgnss @ 2:33 Reading @ 2:53  -27.52765917 152.96849533 **0.36m** <u>Test 4</u> Dgnss @ 2:58 Reading @ 3:28



-27.52766150
152.96849767
0.43m

Test 5:
Dgnss @ 2:59
Reading @ 3:29


-27.52766200
152.96849367
0.03m

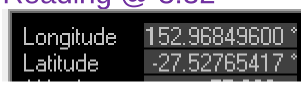
Test 6:
Dgnss @ 2:34
Reading @ 3:04


-27.52765883
152.96849367
0.35m

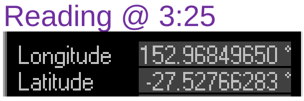
On the stand

Test 1:
Dgnss @ 1:32
Reading @ 2:02


-27.52765900
152.96849783
0.55m

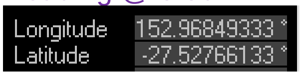
Test 2:
Dgnss @ 3:02
Reading @ 3:32


-27.52765417
152.96849600
0.9m

Test 3:
Dgnss @ 2:55
Reading @ 3:25


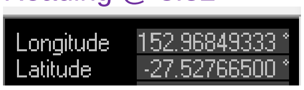
-27.52766283
152.96849650
0.32m

Test 4:
Dgnss: @ 3:00
Reading @ 3:30



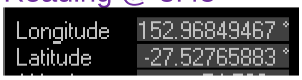
-27.52766133
152.96849333
0.07m

Test 5:
Dgnss @ 3:12
Reading @ 3:32



-27.52766500
152.96849333
0.34m

Test 6:
Dgnss @ 3:15
Reading @ 3:45



-27.52765883
152.96849467
0.37m

Results

Mean Lock Time (m:ss)	Mean Position Error (m)	Standard Deviation (m)	Min Error	Max Error	Notes
2:43	0.422	0.24	0.03	0.72	On Ground
2:49	0.425	0.28	0.07	0.9	On Stand

Appendix D SBAS Lock Time Field Test

u-blox:

Location	Test	Time taken to obtain SBAS lock	Notes	Tester	Date
Rangal	Indication of Accuracy	Test 1: 50s Test 2: 53s Test 3: 113s Test 4: 116s Test 5: 117s Test 6: 96s	On track on the approach side of RL27 signal (refer "Indication of Accuracy" tests below).	Maurice	03/06/2020
Dingo	Indication of Accuracy	Test 1: 410s (low battery) Test 2: 94s (low battery) Test 3: 172s (low battery) Test 4: 113s (high battery) Test 5: 130s (high battery)	On track on the approach side of DO16 signal (refer "Indication of Accuracy" tests below).	Maurice	04/06/2020

SkyTraQ:

Location	Test	Time taken to obtain SBAS lock	Notes	Tester	Date
Rangal	Indication of Accuracy	Test 1: 21s Test 2: 6s Test 3: 31s Test 4: 1s Test 5: 0s Test 6: 6s	On track on the approach side of RL27 signal (refer "Indication of Accuracy" tests below).	Maurice	03/06/2020

Dingo	Indication of Accuracy	Test 1: 1s Test 2: 6s Test 3: 22s Test 4: 5s	On track on the approach side of DO16 signal (refer "Indication of Accuracy" tests below).	Maurice	04/06/2020
Tunnel	Indication of Accuracy	Test 1: 1s Test 2: 14s Test 3: 1s Test 4: 6s	On track on the approach side of TL14 signal (refer "Indication of Accuracy" tests below).	Maurice	04/06/2020

Appendix E Indication of Accuracy Field Test Results

u-blox:

Location	Reference	True Error (From reference using PUBX-00)	True Error (From reference using Buildvation average)	Device Indicated Error (PUBX-00)	Differential Age (PUBX-00)	Horizontal Dilution of Precision (PUBX-00)	Number of Tracked Satellites (PUBX-00)	Raw	Notes	Tester	Date/Time
Rangal Location Description: We placed the EPGs on the up road on the approach side of RL27 signal on top of the outer rail and in line with the last sleeper before the insulated joint. Location Coordinates: -23.585899, 148.826921											
On Track at Rangal	Aurizon WebMap	2.05m	2.20m	0.63m	Unknown	0.52	19	-23.58590050, 148.82694100 (PUBX-00) -23.58590100, 148.82694250 (Buildvation Average)	Device fully charged. Good sky view. Electrical interference nearby	Maurice	03/06/2020 10:20:25

Location	Reference	True Error (From reference using PUBX-00)	True Error (From reference using Buildvation average)	Device Indicated Error (PUBX-00)	Differential Age (PUBX-00)	Horizontal Dilution of Precision (PUBX-00)	Number of Tracked Satellites (PUBX-00)	Raw	Notes	Tester	Date/Time
On Track at Rangal	Aurizon WebMap	2.08m	2.04m	0.65m	Unknown	0.50	20	-23.58589683, 148.82694133 (PUBX-00) -23.58589633, 148.82694083 (Buildvation Average)	Device fully charged. Good sky view. Electrical interference nearby	Maurice	03/06/2020 10:24:26

Location	Reference	True Error (From reference using PUBX-00)	True Error (From reference using Buildvation average)	Device Indicated Error (PUBX-00)	Differential Age (PUBX-00)	Horizontal Dilution of Precision (PUBX-00)	Number of Tracked Satellites (PUBX-00)	Raw	Notes	Tester	Date/Time
On Track at Rangal	Aurizon WebMap	1.08m	0.88m	0.65m	Unknown	0.48	21	-23.58590500, 148.82692933 (PUBX-00) -23.58590250, 148.82692867 (Buildvation Average)	Device fully charged. Good sky view. Electrical interference nearby	Maurice	03/06/2020 10:29:29

Location	Reference	True Error (From reference using PUBX-00)	True Error (From reference using Buildvation average)	Device Indicated Error (PUBX-00)	Differential Age (PUBX-00)	Horizontal Dilution of Precision (PUBX-00)	Number of Tracked Satellites (PUBX-00)	Raw	Notes	Tester	Date/Time
On Track at Rangal	Aurizon WebMap	1.10m	1.58m	0.65m	Unknown	0.51	20	-23.58589933, 148.82693183 (PUBX-00) -23.58589700, 148.82693633 (Buildvation Average)	Device fully charged. Good sky view. Electrical interference nearby	Maurice	03/06/2020 10:34:17

Location	Reference	True Error (From reference using PUBX-00)	True Error (From reference using Buildvation average)	Device Indicated Error (PUBX-00)	Differential Age (PUBX-00)	Horizontal Dilution of Precision (PUBX-00)	Number of Tracked Satellites (PUBX-00)	Raw	Notes	Tester	Date/Time
On Track at Rangal	Aurizon WebMap	1.11m	1.20m	0.45m	Unknown	0.50	20	-23.58589567, 148.82693133 (PUBX-00) -23.58589617, 148.82693233 (Buildvation Average)	Device fully charged. Good sky view. Electrical interference nearby	Maurice	03/06/2020 10:39:10

Location	Reference	True Error (From reference using PUBX-00)	True Error (From reference using Buildvation average)	Device Indicated Error (PUBX-00)	Differential Age (PUBX-00)	Horizontal Dilution of Precision (PUBX-00)	Number of Tracked Satellites (PUBX-00)	Raw	Notes	Tester	Date/Time
On Track at Rangal (after moving device away)	Aurizon WebMap	1.04m	1.07m	0.57m	Unknown	0.50	20	-23.58590533, 148.82692850 (PUBX-00) -23.58590417, 148.82692983 (Buildvation Average)	Device fully charged. Good sky view. Electrical interference nearby.	Maurice	03/06/2020 10:45:47

<u>Dingo</u>

Location Description: We placed the EPGs on the down road on the approach side of DO16 signal on the outer rail opposite the toe of switch for ER2 release.

Location Coordinates: -23.6475632, 149.3320866

Location	Reference	True Error (From reference using PUBX-00)	True Error (From reference using Buildvation average)	Device Indicated Error (PUBX-00)	Differential Age (PUBX-00)	Horizontal Dilution of Precision (PUBX-00)	Number of Tracked Satellites (PUBX-00)	Raw	Notes	Tester	Date/Time
On Track at Dingo	Aurizon WebMap	3.20m	3.34m	0.65m	Unknown	0.53	19	-23.64753550, 149.33207800 (PUBX-00) -23.64753517, 149.33207483 (Buildvation Average)	Battery may have been low. Good sky view.	Maurice	04/06/2020 11:13:19

Location	Reference	True Error (From reference using PUBX-00)	True Error (From reference using Buildvation average)	Device Indicated Error (PUBX-00)	Differential Age (PUBX-00)	Horizontal Dilution of Precision (PUBX-00)	Number of Tracked Satellites (PUBX-00)	Raw	Notes	Tester	Date/Time
On Track at Dingo	Aurizon WebMap	1.93m	1.87m	0.63m	Unknown	0.54	19	-23.64754700, 149.33207967 (PUBX-00) -23.64754700, 149.33208183 (Buildvation Average)	Battery may have been low. Good sky view.	Maurice	04/06/2020 11:17:05

Location	Reference	True Error (From reference using PUBX-00)	True Error (From reference using Buildvation average)	Device Indicated Error (PUBX-00)	Differential Age (PUBX-00)	Horizontal Dilution of Precision (PUBX-00)	Number of Tracked Satellites (PUBX-00)	Raw	Notes	Tester	Date/Time
On Track at Dingo	Aurizon WebMap	2.54m	2.29m	0.63m	Unknown	0.52	20	-23.64754217, 149.33207683 (PUBX-00) -23.64754367, 149.33207933 (Buildvation Average)	Battery may have been low. Good sky view.	Maurice	04/06/2020 11:22:07

Location	Reference	True Error (From reference using PUBX-00)	True Error (From reference using Buildvation average)	Device Indicated Error (PUBX-00)	Differential Age (PUBX-00)	Horizontal Dilution of Precision (PUBX-00)	Number of Tracked Satellites (PUBX-00)	Raw	Notes	Tester	Date/Time
On Track at Dingo (after battery recharged and tested elsewhere first)	Aurizon WebMap	1.34m	1.19m	0.56m	Unknown	0.57	17	-23.64755367, 149.33209467 (PUBX-00) -23.64755350, 149.33209150 (Buildvation Average)	Device fully charged. Good sky view.	Maurice	04/06/2020 12:04:40

Location	Reference	True Error (From reference using PUBX-00)	True Error (From reference using Buildvation average)	Device Indicated Error (PUBX-00)	Differential Age (PUBX-00)	Horizontal Dilution of Precision (PUBX-00)	Number of Tracked Satellites (PUBX-00)	Raw	Notes	Tester	Date/Time
On Track at Dingo	Aurizon WebMap	1.64m	1.78m	0.66m	Unknown	0.55	18	-23.64756000, 149.33207083 (PUBX-00) -23.64755983, 149.33206950 (Buildvation Average)	Device fully charged. Good sky view.	Maurice	04/06/2020 12:10:00

<table>
<tr><th>Location</th><th>Reference</th><th>True Error (From reference using PUBX-00)</th><th>True Error (From reference using Buildvation average)</th><th>Device Indicated Error (PUBX-00)</th><th>Differential Age (PUBX-00)</th><th>Horizontal Dilution of Precision (PUBX-00)</th><th>Number of Tracked Satellites (PUBX-00)</th><th>Raw</th><th>Notes</th><th>Tester</th><th>Date/Time</th></tr>
<tr><td colspan="12"><u>Tunnel</u>
Location Description: We placed the EPGs on the down road on the approach side of TL14 signal on the outer rail just before the signal gantry.
Location Coordinates: -23.699042, 149.920873

Restarted the u-blox device several times – couldn’t even get Standard GPS at this location.
Battery was fully charged at time of testing.
Suspect u-blox chipset is conservative and only reports positions when a good lock is achieved.</td></tr>
</table>

SkyTraQ:

Location	Reference	True Error (From reference)	True Error (From reference using Buildvation average)	Differential Age (GGA)	Horizontal Dilution of Precision (GGA)	Number of Tracked Satellites (GGA)	Raw	Notes	Tester	Date
Rangal Location Description: We placed the EPGs on the up road on the approach side of RL27 signal on top of the outer rail and in line with the last sleeper before the insulated joint. Location Coordinates: -23.585899, 148.826921										
On Track at Rangal	Aurizon WebMap	2.75m	2.79m	Unknown	0.9	12	-23.58590300, 148.82694767 (GGA) -23.58590300, 148.82694800 (Buildvation Average)	Good sky view. Electrical interference nearby	Maurice	03/06/2020 10:54:55
On Track at Rangal	Aurizon WebMap	0.58m	0.57m	Unknown	0.8	12	-23.58590400, 148.82692267 (GGA) -23.58590400, 148.82692250 (Buildvation Average)	Good sky view. Electrical interference nearby	Maurice	03/06/2020 11:01:04

Location	Reference	True Error (From reference)	True Error (From reference using Buildvation average)	Differential Age (GGA)	Horizontal Dilution of Precision (GGA)	Number of Tracked Satellites (GGA)	Raw	Notes	Tester	Date
On Track at Rangal	Aurizon WebMap	2.28m	2.31m	Unknown	0.8	12	-23.58590350, 148.82694283 (GGA) -23.58590350, 148.82694317 (Buildvation Average)	Good sky view. Electrical interference nearby	Maurice	03/06/2020 11:05:20
On Track at Rangal	Aurizon WebMap	0.66m	0.68m	Unknown	0.9	12	-23.58589883, 148.82691450 (GGA) -23.58589917, 148.82691433 (Buildvation Average)	Good sky view. Electrical interference nearby	Maurice	03/06/2020 11:10:24

Location	Reference	True Error (From reference)	True Error (From reference using Buildvation average)	Differential Age (GGA)	Horizontal Dilution of Precision (GGA)	Number of Tracked Satellites (GGA)	Raw	Notes	Tester	Date
On Track at Rangal	Aurizon WebMap	1.80m	1.83m	Unknown	0.8	12	-23.58588867, 148.82690733 (GGA) -23.58588850, 148.82690717 (Buildvation Average)	Good sky view. Electrical interference nearby	Maurice	03/06/2020 11:15:27
On Track at Rangal (after moving device away)	Aurizon WebMap	2.67m	2.71m	Unknown	0.8	12	-23.58587867, 148.82690700 (GGA) -23.58587850, 148.82690667 (Buildvation Average)	Good sky view. Electrical interference nearby	Maurice	03/06/2020 11:23:10
Dingo Location Description: We placed the EPGs on the down road on the approach side of DO16 signal on the outer rail opposite the toe of switch for ER2 release. Location Coordinates: -23.6475632, 149.3320866										

Location	Reference	True Error (From reference)	True Error (From reference using Buildvation average)	Differential Age (GGA)	Horizontal Dilution of Precision (GGA)	Number of Tracked Satellites (GGA)	Raw	Notes	Tester	Date
On Track at Dingo	Aurizon WebMap	0.69m	0.70m	Unknown	0.9	11	-23.64756167, 149.33209317 (GGA) -23.64756167, 149.33209333 (Buildvation Average)	Good sky view.	Maurice	04/06/2020 11:44:38
On Track at Dingo	Aurizon WebMap	1.61m	1.65m	Unknown	0.9	11	-23.64756633, 149.33207117 (GGA) -23.64756650, 149.33207083 (Buildvation Average)	Good sky view.	Maurice	04/06/2020 11:49:58

Location	Reference	True Error (From reference)	True Error (From reference using Buildvation average)	Differential Age (GGA)	Horizontal Dilution of Precision (GGA)	Number of Tracked Satellites (GGA)	Raw	Notes	Tester	Date
On Track at Dingo	Aurizon WebMap	1.28m	1.29m	Unknown	0.8	12	-23.64755617, 149.33207667 (GGA) -23.64755617, 149.33207650 (Buildvation Average)	Good sky view.	Maurice	04/06/2020 11:55:02
On Track at Dingo	Aurizon WebMap	1.34m	1.35m	Unknown	0.8	12	-23.64755150, 149.33208350 (GGA) -23.64755133, 149.33208367 (Buildvation Average)	Good sky view.	Maurice	04/06/2020 11:59:40

Tunnel

Location Description: We placed the EPGs on the down road on the approach side of TL14 signal on the outer rail just before the signal gantry.

Location Coordinates: -23.699042, 149.920873

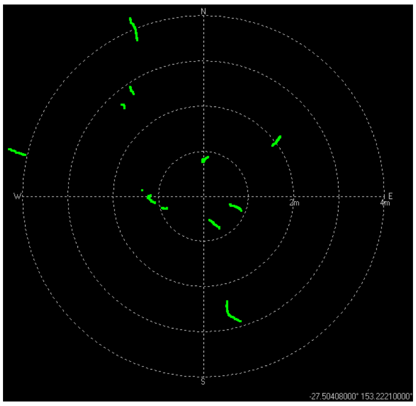
Location	Reference	True Error (From reference)	True Error (From reference using Buildvation average)	Differential Age (GGA)	Horizontal Dilution of Precision (GGA)	Number of Tracked Satellites (GGA)	Raw	Notes	Tester	Date
On Track at Tunnel	Aurizon WebMap	2.23m	2.20m	Unknown	0.9	9	-23.69902467, 149.92088400 (GGA) -23.69902483, 149.92088383 (Buildvation Average)	Sky view obstructed by cutting	Maurice	04/06/2020 15:55:52
On Track at Tunnel	Aurizon WebMap	8.58m	8.68m	Unknown	0.8	10	-23.69903533, 149.92095700 (GGA) -23.69903567, 149.92095800 (Buildvation Average)	Sky view obstructed by cutting	Maurice	04/06/2020 16:02:58

Location	Reference	True Error (From reference)	True Error (From reference using Buildvation average)	Differential Age (GGA)	Horizontal Dilution of Precision (GGA)	Number of Tracked Satellites (GGA)	Raw	Notes	Tester	Date
On Track at Tunnel (after moving device away)	Aurizon WebMap	7.10m	7.15m	Unknown	0.8	10	-23.69898150, 149.92085067 (GGA) -23.69898117, 149.92085017 (Buildvation Average)	Sky view obstructed by cutting	Maurice	04/06/2020 16:11:55
On Track at Tunnel	Aurizon WebMap	1.46m	1.48m	Unknown	0.8	10	-23.69903267, 149.92086283 (GGA) -23.69903250, 149.92086283 (Buildvation Average)	Sky view obstructed by cutting	Maurice	04/06/2020 16:16:48

Appendix F Modified Antenna Connector

Modified Antenna Connector. The purpose of this test was to evaluate if the modification of the SkyTraQ antenna necessary to fit the board into the EPG box, was impacting results.

Latitude / Longitude	Displacement
-27.50408100, 153.22208833	1.2m
-27.50407300, 153.22210000	0.8m
-27.50406933, 153.22211617	2m
-27.50410250, 153.22210533	2.6m
-27.50408200, 153.22210700	0.7m
-27.50408250, 153.22209100	0.9m
-27.50404683, 153.22208467	4m
-27.50407167, 153.22206000	4.1m
-27.50405950, 153.22208417	2.8m
-27.50406233, 153.22208217	2.7m
-27.50408467, 153.22210133	0.5m



Results:

Test	Average Error (m)	Minimum Error (m)	Maximum Error (m)	Standard Deviation (m)
Modified Antenna Connector	2.03	0.5	4.1	1.31
HDOP = 1.2 (unmodified board)	2.03	0.6	7.6	1.94

Appendix G UAT#2

Survey Control Point #154325 (GDA94 Position): -27.527661933, 152.968493382

Test	Skytraq Results	U-Blox Results	Inits	Date
Testing Accuracy	Best reading was within 1.9m. Worst reading was within 9.5m.	Most readings are within 1.6m	MEW	05/05/20
Lock time from cold start should be less than 2 minutes	(#1) 40s + 30s for BV AVG (#2) 40s + 30s for BV AVG (#3) 40s + 30s for BV AVG (#4) 38s + 30s for BV AVG (#5) 38s + 30s for BV AVG	(#1) 1m12s + 30s for BV AVG (#2) 2m50s + 30s for BV AVG but accuracy improved well before SBAS LED was lit. (#3) 2m05s + 30s for BV AVG. (#4) 2m10s + 30s for BV AVG (#5) 3m25s + 30s for BV AVG	MEW	05/05/20
Lock time after changing locations should be less than 2 minutes	30s + 30s for BV AVG	2m20s + 30s for BV AVG	MEW	05/05/20
Position reported should be accurate to within 1m when no interference is present	(#1) -27.52762750, 152.96852183 (4.8m) (#2) -27.52767783, 152.96849783 (1.9m) (#3) -27.52774383, 152.96852067 (9.5m) (#4) -27.52768333, 152.96851550 (3.2m) (#5) -27.52763767, 152.96851350 (3.3m)	(#1) -27.52765417, 152.96850717 (~1.6m) (#2) -27.52765400, 152.96850533 (~1.4m) (#3) -27.52765600, 152.96850867 (1.7m) (#4) -27.52766233, 152.96850567 (1.2m) (#5) -27.52766267, 152.96850983 (1.6m)	MEW	05/05/20

Appendix H UAT#3

Survey Control Point #154325 (GDA94 Position): -27.527661933, 152.968493382

Survey Control Point #154325 (GDA2020 Position): -27.527649373, 152.968499415

Test	Skytraq Results	U-Blox Results	Inits	Date
Testing Accuracy	Best reading was within 1.00m of GDA94 position (and 1.36m of GDA2020 position). Worst reading was within 5.30m of GDA94 position (and 3.84m of GDA2020 position). Some of these tests were rushed (SCP #154325's location is popular for Sunday walks). More time doesn't necessarily improve the accuracy of the Skytraq unit (although it does have a very fast startup).	Best reading was within 1.89m of GDA94 position (and 0.99m of GDA2020 position). Worst reading was within 3.12m of GDA94 position (and 2.73m of GDA2020 position). Some of these tests were rushed (SCP #154325's location is popular for Sunday walks). More time does lead to better accuracy on the Ublox unit.	MEW	24/05/20
Lock time from cold start should be less than 2 minutes	(#1) 49s + 30s for BV AVG (#2) 12s + 30s for BV AVG (#3) 27s + 30s for BV AVG (#4) 26s + 30s for BV AVG (#5) 14s + 30s for BV AVG Lock time is under 2 mins in all cases.	(#1) 57s + 30s for BV AVG (#2) 29s + 30s for BV AVG (#3) 49s + 30s for BV AVG (#4) 38s + 30s for BV AVG (#5) 83s + 30s for BV AVG Lock time is under 2 mins in all cases. In all cases, waiting longer than 2 mins	MEW	24/05/20

		led to more accurate positions.		
Lock time after changing locations should be less than 2 minutes	27s + 30s for BV AVG	34s +30s for BV AVG	MEW	24/05/20
Position reported should be accurate to within 1m when no interference is present	Test #1 Unit started @ 15:42:44 D3 Nav Status @ 15:43:33 Reading taken @ 15:46:03 -27.52763883, 152.96850633 (**2.87m** from GDA94 position) (**1.36m** from GDA2020 position). Test #2 Unit started @ 15:47:14 D3 Nav Status @ 15:47:26 Reading taken @ 15:48:34 -27.52762900, 152.96847450 (**4.11m** from GDA94 position). (**3.34m** from GDA2020 position) Test #3 Unit stated @ 15:49:50 D3 Nav Status @ 15:50:17 Reading taken @ 15:59:45 -27.52762467, 152.96849183 (**4.15m** from GDA94 position) (**2.85m** from GDA2020 position). Test #4	Test #1: Unit started @ 14:55:56 D3 Nav Status @ 14:56:53 Reading taken @ 14:57:43 27.52765667, 152.96851900 (Note: Waited around 1 minute after achieving D3 before taking reading. Didn't wait for hAcc field to drop below 0.8 unlike in subsequent tests). (**2.59m** from GDA94 position). (**2.09m** from GDA2020 position). Test #2 Unit started @ 14:59:43 D3 Nav Status @ 15:00:12 Reading taken @ 15:01:49 -27.52765917, 152.96852483 (Note: Waited around 90 seconds after achieving D3 before taking reading. Didn't wait for hAcc field to drop below 0.8 unlike in subsequent tests). (**3.12m** from GDA94 position) (**2.73m** from GDA94 position. Test #3	MEW	24/05/20

	Unit started @ 16:00:54 D3 Nav Status @ 16:01:20 Reading taken @ 16:02:43 -27.52767083, 152.96849217 (**1.00m** from GDA94 position). (**2.49m** from GDA2020 position). Test #5 Unit started @ 16:08:50 D3 Nav Status @ 16:09:04 Reading taken @ 16:10:40 -27.52763433, 152.96849283 (**3.07m** from GDA94 position). (**1.79m** from GDA2020 position).	Unit started @ 15:04:26 D3 Nav Status @ 15:05:15 Reading Taken @ 15:08:03 -27.52765217, 152.96852283 (Note: Waited longer since accuracy seemed to be improving with time). (**3.10m** from GDA94 position) (**2.33m** from GDA2020 position). Test #4 Unit started @ 15:09:40 D3 Nav Status @ 15:10:18 Reading Taken @ 15:12:15 -27.52765233, 152.96852183 (Waited until PUBX indicated hacc < 0.8m). (**3.00m** from GDA94 position). (**2.23m** from GDA2020 position) Test #5 Unit started @ 15:13:54 D3 Nav Status @ 15:15:21 Reading Taken @ 15:16:31 -27.52765467, 152.96851367 (Also waited longer) (**2.16m** from GDA94 position). (**1.52m** from GDA2020 position)		

Position reported should be accurate to within 1m when interference is present (test by placing a mobile phone next to the device and calling it).	N/A for UAT	N/A for UAT	MEW	24/05/20
When position accuracy is reduced due to partial sky conditions, device gives some indication of inaccuracy (e.g. horizontal accuracy estimate, navigation status, HDOP, low number of satellites, etc).	N/A for UAT	N/A for UAT	MEW	24/05/20
5 readings (all from a cold start) should all be within 1m of the true location	All are within 4.15m of the GDA94 position. All are within 3.34m of the GDA2020 position.	All are within 3.12m of the GDA94 position. All are within 2.73m of the GDA2020 position.	MEW	24/05/20
Move device to another location, startup, shutdown and move it back. The next reading should also be within 1m of the true location.	<u>Test #6</u> <u>Unit started @ 15:49:50</u> <u>D3 Nav Status @ 15:50:17</u> <u>Reading taken @ 15:56:33</u> (Between #2 and #3 was a good time to do this test): -27.52763517, 152.96847017 (**3.75m** from GDA94 position) (**3.29m** from GDA2020 position). <u>Test #7</u> <u>Unit started @ 16:12:11</u> <u>D3 Nav Status @ 16:12:27</u> <u>Reading taken @ 16:13:48</u>	<u>Test #6</u> <u>Unit started @ 15:28:08</u> <u>D3 Nav Status @ 15:28:42</u> <u>Reading taken @ 15:30:57</u> -27.52765467, 152.96851067 (**1.89m** from GDA94 position) (**1.26m** from GDA2020 position) <u>Test #7</u> <u>Unit started @ 15:38:28</u> <u>D3 Nav Status @ 15:38:49</u> <u>Reading taken @ 15:41:04</u> One last test with unit raised off ground: -27.52764667, 152.96850900	MEW	24/05/20

	One last test with unit raised off ground: -27.52762350, 152.96852517 (**5.30m** from GDA94 position). (**3.84m** from GDA2020 position).	(**2.29m** from GDA94 position). (**0.99m** from GDA2020 position).		
Place device at fixed reference point out in the sun. Leave for one hour. Record coords. Device location shouldn't drift by more than 1m.	N/A for UAT	N/A for UAT	MEW	24/05/20