SBAS Australian-NZ Test Bed: Exploring New Services

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BIOGRAPHIES

Hugo Sobreira holds a M.Sc. in Computer Engineering from Technological Institute of Aeronautics (ITA), Brazil. He started working at Septentrio in 2008 in the development of DO-229 compliant receivers and since then was involved in SBAS related projects such as the development of the next generation ground monitoring stations for the EGNOS V3 system (RIMS). He is currently working on the implementation of Dual Frequency Multi-Constellation SBAS for Septentrio GNSS receivers.

Bruno Bougard received his M.Sc. in electrical engineering from the University of Mons, Belgium in 2000 and his PhD from the Catholic University of Leuven, Belgium in 2006. He used to be a staff researcher in the wireless system group of IMEC, Belgium before joining Septentrio in 2008, and is now responsible for the development of new OEM and scientific products. Since 2014, Bruno is Septentrio R&D Director, in charge of research, development, and engineering operations.

Julián Barrios holds a M.Sc. degree in Physics from the University of Valladolid. Since 2007, he has worked at GMV in the Advanced System division within the GNSS Business Unit. Along these years he has acquired an extensive experience into SBAS system through his participation in SBAS demonstrations and experiments. His activities are mainly focused on the architecture of processing chains as well as SBAS algorithms enhancement. He is currently leading ***magicSBAS*** product and is the project manager of the GMV activities contributing to the Australian and New Zealand's SBAS test-bed.

David Calle holds a MSc. in Computer Engineering from the University of Salamanca. He joined GMV in 2008 and he has been working in the GNSS business unit involved in the design and development of GNSS algorithms, applications and systems. He is currently Head of GNSS Advance Services Section coordinating the activities related to the Galileo Commercial Service, Open Service Authentication and High Accuracy provision services.

ABSTRACT

The GNSS panorama has drastically changed during the last years, with multiple constellations providing PNT services as well as an increasing number of augmentation systems, either already or under development providing SBAS and PPP corrections in different regions around the world. In this context, the SBAS systems are being redesigned to support Dual Frequency and Multiple Constellations (DFMC) augmentation to the GNSS systems.

Within the scope of evolving GNSS services, the Australian and New Zealand SBAS test-bed is broadcasting SBAS and PPP corrections over the Asia-Pacific and Australasia areas since September 2017. The early availability of the DFMC SBAS, together with the availability of GEO based PPP corrections, enables the industry to experiment with their solutions, suggest improvements and propose new positioning techniques and applications. It also helps manufacturers to prepare their products for these new services.

In this paper, we will analyze the positioning performance obtained with the use of the signals broadcasted by the Australia and New Zealand's SBAS test-bed (with legacy DO-229, DFMC and PPP corrections) using Septentrio commercial receivers. First, the Septentrio products supporting SBAS L1 have been augmented with the SBAS L5 DFMC functionality. Secondly, through the cooperation of GMV, the PPP information broadcast through the Australian and NZ test-bed has been used to compute a post-processed PPP solution with the receiver data.

The obtained results shall illustrate both the level of performance achieved through the Australian-NZ SBAS-PPP test-bed, and exemplify the maturity of the new services as well as of our rover-side implementation.

1 INTRODUCTION

Satellite Based Augmentation Systems have been used to provide improved navigation services to civil aviation for many years. With more than 20 years of operation, WAAS has become one of the backbone systems of the civil aviation infrastructure in the US. Followed by the Japanese MSAS and the European EGNOS, they were the first systems to implement public differential and integrity services defined by the DO-229 standards. In these years there was practically no overlap between the areas served by such systems.

The availability of four core GNSS constellation with GLONASS, Galileo or BeiDou is driving the evolution of the single-constellation single-frequency SBAS L1 standard in to the future SBAS L5 Dual-Frequency Multi-Constellation. The new standard will be capable of providing SBAS augmentation for 90 SVs belonging to different constellations and is designed to enable more robust navigation services. The SBAS L1 service will coexist as a legacy service with the new SBAS L5 DFMC signals. Adding up to the complexity of the SBAS system, the GNSS technologies include multiple alternative solutions for augmenting the GNSS constellation. Technologies such as RT-PPP are capable of providing high-precision services.

This is the context in which the Australian and New Zealand test-bed is deployed. In order to evaluate the feasibility and convenience of the future development of a SBAS system in Australia and New Zealand, test-bed operations started in September 2017, with signals being broadcasted until at least January 2019. Amongst various prototype DFMCs, The Australia-NZ SBAS test-bed is probably the most advanced.

Two different SBAS signals are used: first, the legacy SBAS L1 signal which meets the RTCA/DO-229 standard and is open to current mass-market receivers implementing SBAS positioning mode. Secondly, an SBAS L5 DFMC prototype signal aligned with WG62 GAL GPS SBAS MOPS (March 2017) [5], a draft standard that defines future dual-frequency multi-constellation services. While the SBAS L1 service transmits range, orbit, clock and ionospheric delay corrections, applicable to the service area covering the complete Australian and New Zealand territories, the SBAS L5 DFMC provides GPS and Galileo dual-frequency augmentation that can be used anywhere across the whole footprint of the GEO Inmarsat 4F1 satellite located at longitude of 143.4 degrees East.

In addition to the SBAS information, both the L1 and L5 signals include precise orbit and clock information in proprietary format, enabling Precise Point Positioning (PPP) services to authorized receivers. The SBAS L1 signal provides corrections for GPS PPP users whereas SBAS L5 signal broadcasts PPP corrections for GPS and Galileo PPP users.

The early availability of DFMC SBAS and PPP in the Australia-NZ test-bed enables the industry to prototype and test future GNSS-based positional techniques and solutions. The potential of the SBAS+PPP combined technologies goes beyond the use cases currently drafted by the civil aviation community and could benefit many other sectors. The open availability of the SBAS L5 signal allows manufacturers to develop and test such future GNSS services.

In this paper, we will analyze the positional performance of the services provided by the Australia-NZ SBAS test-bed (legacy DO229, DFMC and PPP) using commercial receivers from the Septentrio product line.

2 RECEIVER IMPLEMENTATION AND SETUP

Two Septentrio receivers were used to experiment with two SBAS signals provided by the Australian-New Zealand test-bed, namely the PolaRx5 (located in Canberra) connected to a Trimble choke ring TRM59800 antenna and the AsteRx-U (located in Kanagawa) connected to a Septentrio PolaNt choke ring B3/E6 antenna. Both receivers have more than 400 hardware channels for simultaneous tracking and can therefore monitor all GPS, Galileo, GLONASS, BeiDou, QZSS, IRNSS and SBAS satellites in view. Signals from the L1, L2, L5 and L6 bands from these constellations were recorded for post-processing together with the corresponding raw navigation data for a period of 30 days (August 23rd to September 21st of 2018) in Australia and during five days in Japan (August 30st till September 3rd).

The positioning engine of Septentrio's receivers allows full configurability both in real time and in post processing: a selection of multi or mono constellation (GPS and/or Galileo), single or dual frequency operation (with selection of desired frequency pairs) and selection of SBAS stream (SBAS L5 or SBAS L1). This can be seen in Figure 1, where the SBAS L1 stream is indicated as 'DO229' and the SBAS L5 stream is indicated as 'DFMC'. For this experimentation campaign, the receiver in Canberra was configured in the multi-constellation, dual-frequency mode using the SBAS L5 data stream (PRN 122). The receiver installed in Kanagawa was configured in single-constellation, single-frequency mode using the SBAS L1 data from the local SBAS provider (MSAS PRN 137).

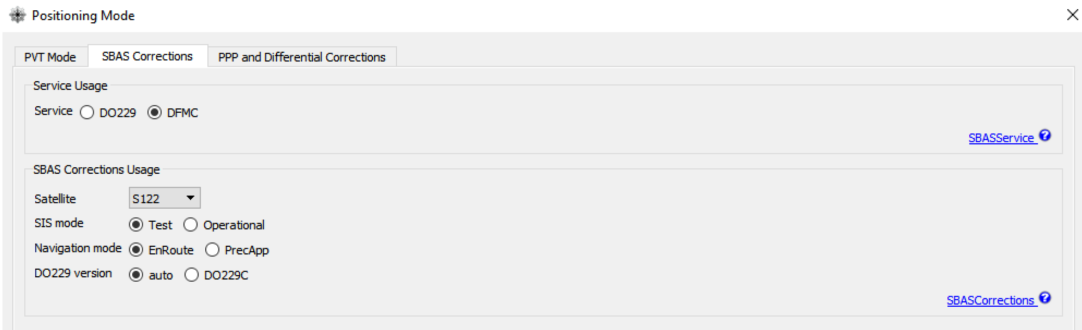

Figure 1 – Receiver configuration window showing the selection of the SBAS stream used in Canberra

Figure 2 shows a snapshot of a position fix in Canberra with typical positioning accuracies when using the DFMC corrections. It is also possible to observe from the graphical user interface that 17 satellites are used in the SBAS augmented solution: 11 GPS and 6 Galileo. The 'LC' info indicates that satellite clock and orbit corrections are applied to the satellites in use. The SBAS tab is displayed to show the number of SBAS signals tracked; MSAS satellites (PRN 129 and 137) transmitting only on L1, SDCM PRN 140 transmitting on L1, GAGAN PRN 128 transmitting on both L1 and L5 and finally the Australian-NZ test-bed PRN 122 transmitting both L1 and L5 signals. It is worth noting that, with the increasing number of correction providers and services (DO229, DFMC, PPP), automatic selection of a signal that offers the best service in terms of accuracy or integrity remains a challenge. Nevertheless, the availability of multiple correction streams allows receiver manufacturers to experiment with different strategies for an optimal searching, which is a topic for future work.

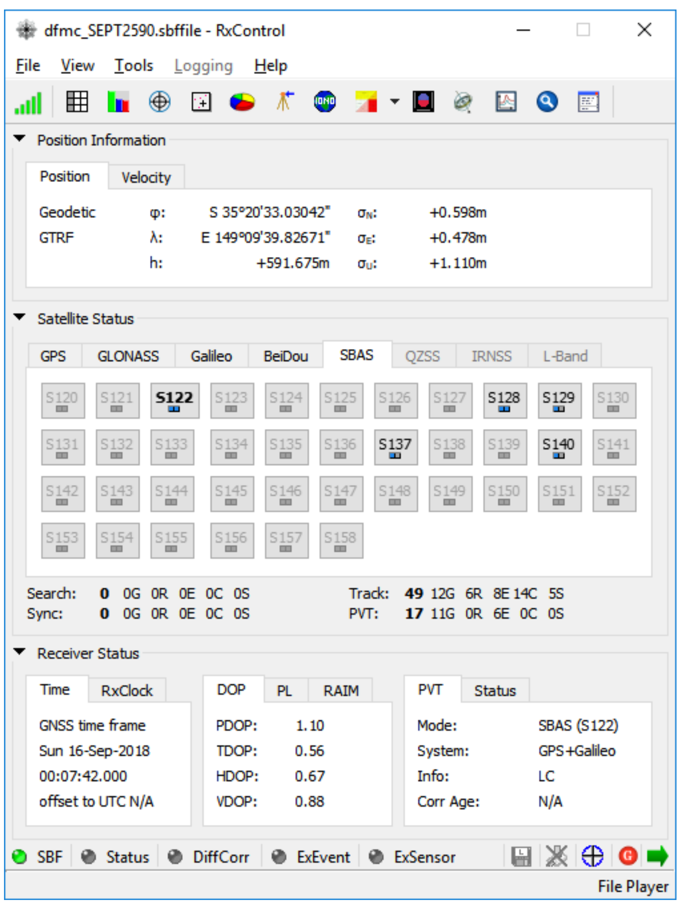

Figure 2 – Snapshot of a position fix with receiver in Canberra

The DFMC implementation complies with the specification defined in WG62 GAL GPS SBAS MOPS v0.6.1 draft [1], thus only Galileo and GPS satellites for which corrections and integrity data are available were used in the SBAS positional solution. Galileo satellites whose signal status are in test mode (vehicle ID’s E14 and E18) but still provide usable clock and ephemeris data were also used for positioning when the necessary SBAS corrections were broadcasted.

For the SBAS L1 augmented mode, both receivers have to option of configuring a carrier phase-based, single-frequency smoothing filter for each signal with individually specified time constants, as it can be seen in **Figure 3**. No smoothing was applied to the measurements at the time of recording. Additionally, a proprietary multipath mitigation technique (APME+, A-Posteriori Multipath Estimator) is applied to improve measurement quality by removing short-multipath without introducing biases. The APME correction can either be disabled on the receiver or removed in post-processing.

In the SBAS L5 augmented mode the ionosphere-free code range measurements are smoothed by carrier phase measurements with a filter that uses a fixed time constant of 100 seconds. The implementation selected by Septentrio uses the time-variant version of the weighting factor α as described in RTCA/DO-253 [2] since it converges faster to a steady state solution. The filter implementation is defined as:

$$P_{proj} = P_{n-1} + \frac{\lambda_i(\varphi_{Li,n} - \varphi_{Li,n-1}) - \gamma(\varphi_{Lj,n} - \varphi_{Lj,n-1})}{1-\gamma}$$

$$P_n = \alpha\left(\frac{\rho_{Li,n} - \gamma\rho_{Lj,n}}{1-\gamma}\right) + (1-\alpha)P_{proj}$$

Where P_n is the ionosphere-free dual-frequency carrier-smoothed pseudorange of the n-eth epoch, P_{proj} is the projected ionosphere-free dual-frequency pseudorange, $\rho_{Li,n}$ is the raw pseudorange for frequency L_i at the n-eth epoch, $\varphi_{Li,n}$ is the accumulated carrier phase measurement in cycles for frequency L_i at the n-eth epoch, γ is frequency ratio, equal to $(154/115)^2$ for Galileo measurements (the E1 to E5a) or $(154/120)^2$ for GPS measurements (L1 to L2). In the first 100 seconds since filter initialization, α is equal to the sample interval divided by the time since filter initialization; after 100 seconds α is equal to the sample interval divided by 100 seconds.

Newer versions of the DFMC MOPS suggest an increase in the 100 seconds time constant since the code-carrier divergence effect is not a concern for the smoothed ionosphere-free code range measurements. Future software versions are planned to provide configurability of the time constant for the ionosphere-free smoothing filter, similarly to what is available for single-frequency operation.

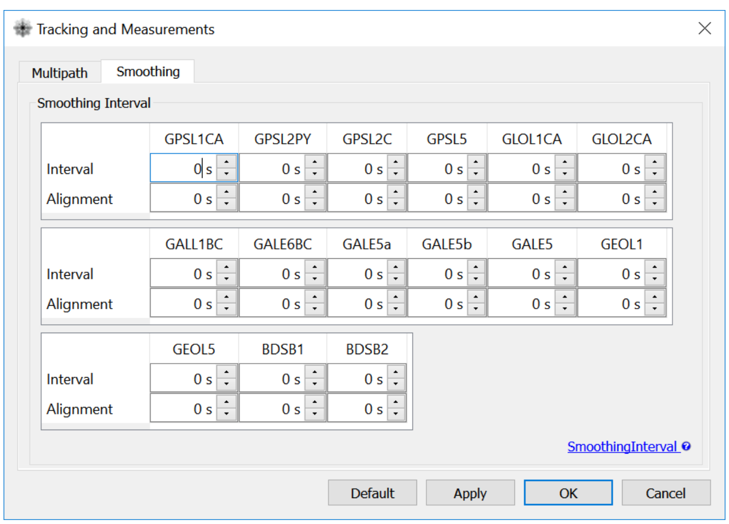

Figure 3 – The configuration window of the single frequency smoothing filter

The PPP solution presented in this paper is obtained with the GMV MagicPPP software module that can process RINEX data collected by Septentrio receivers. The integration of the PPP positioning engine on handheld receivers is under development by GMV [3], and the integration of the PPP module into Septentrio receivers can be demonstrated in the future.

3 AUSTRALIA AND NEW ZEALAND SBAS TESTBED SERVICES

3.1 Description

Early 2017, the Australian and New Zealand governments announced the initiation of the 2nd Generation SBAS Test-bed including the demonstration of applications in transport and other industry sectors. GMV in conjunction with Lockheed Martin Space Systems Company and Inmarsat launched a two-year collaborative project with Geoscience Australia (GA), the Cooperative Research Centre for Spatial Information (CRCSI) (now known as FrontierSI) and Land Information New Zealand (LINZ) for the deployment of a satellite positioning augmentation Test-bed system. The results of the planned demonstrations will provide substantial proof of how this technology can benefit safety, productivity, efficiency and innovation in Australian and New Zealand industrial and research sectors.

The Test-bed enables the evaluation of a wide range of GNSS augmentation technologies including integrity and high-precision techniques. The proposed technological solution combines the SBAS service with PPP technology. This unique combination of capabilities allows the service to meet the demands of civil aviation and other user communities while using common infrastructure. The Test-bed continuously broadcasts four services.

- **SBAS L1 Legacy service since May 2017:** SBAS L1 legacy service is broadcast using PRN 122 in accordance with RTCA/DO229E [4] (as EGNOS, WAAS, GAGAN and MSAS). The service is configured for test purposes only (don't use for safety applications) and therefore includes the broadcast of MT 0 message every 6 seconds. The SBAS L1 message broadcasts both corrections and integrity information for GPS satellite ephemeris and regional ionosphere corrections. The Test-bed service region is defined to cover the Australia and New Zealand territories as depicted in Figure 4. This service is accessible to all receivers available in the market with an SBAS-enabled mode of operation.

- **SBAS L5 DFMC service since Oct 2017:** The Australian SBAS DFMC L5 service is implemented in accordance with WG62 GAL GPS SBAS MOPS v0.3.8_10 draft [5], which was the latest draft version available at the beginning of the Test-bed broadcast. The Test-bed signal contains corrections and DFREI bounds applicable to GPS L1/L2 + GAL E1/E5a ionosphere-free combinations. The service coverage area corresponds to the footprint of the PRN 122 GEO as shown in Figure 4.

- **RT-PPP through SBAS L1 and SBAS L5 since Oct 2017:** The Australian and New Zealand Test-bed solution uses the spare bits present in the SBAS message to provide additional information with a higher resolution. This is compatible with the SBAS service, as the SBAS receivers complying with the standard are instructed to ignore the unused message bits. However, PPP-enabled receivers can use this information to access the high accuracy data. The PPP corrections transmitted within the SBAS L1 provides corrections for GPS L1/L2 frequencies while the PPP corrections transmitted through the SBAS L5 signal provide corrections for GPS L1/L2 + GAL E1/E5a frequencies. Both services are available in the entire GEO footprint.

The SBAS L1 service can be used by many receivers in the market which have an SBAS-enabled mode of operation thanks to the consolidated use of the SBAS L1 services in North America through WAAS and in Europe through EGNOS. On top of that, the early availability of the Australia and New Zealand SBAS signal has helped receiver manufacturers to develop and validate positional solutions that combine both SBAS L1 and L5 services.

The implementation of a DFMC SBAS capable receiver at Septentrio is part of a broader program to provide the Galileo Test User Receiver (TUR) to the European Space Agency. This is the equipment used to the satellite signals on the ground during validation phase and is meant to support every positioning mode where Galileo satellites are used. The availability of live SBAS L5 signals in Australia was crucial to successfully complete the development of the current version of the DFMC functionality. Software updates are planned to follow up on the evolution of the DFMC SBAS MOPS.

While the receiver software supports another version of the DFMC SBAS L5 standard [1], there are no compatibility issues since only few discrepancies between the data interfaces of the two versions exist; these are mainly related to the ranging function of the SBAS satellites and rearrangement of Week Number Roll Over (WNRO) field to message type 47. As the Australian-NZ test-bed doesn't support any of these functionalities, processing of the corresponding message types was not implemented. Furthermore, the processing of the DFREI table for message type 37 was adapted to account for the differences in the signal interface control document.

Figure 4 – SBAS L1 (left) and SBAS L5 (right) coverage areas

4 SBAS EXPERIMENTATION CAMPAIGN RESULTS (CANBERRA)

4.1 Method of Analysis

One PolaRx5 receiver has been deployed at Geoscience Australia facilities in Canberra and connected to a GPS + Galileo L1, L2 and L5 antenna under open-sky environment conditions as shown in Figure 5 . The receiver has been with the SBAS L5 DFMC solution (in addition to the traditional SBAS L1 Legacy solution) and with the capability to record the receiver information allowing the post-processing of the data. The receiver and post-processing software are generated with the same source code compiled to run in a different platform (either in the receiver processor or a in personal computer).

Figure 5 – Location of GPS+GAL Antenna and receiver at Geoscience Australia, Canberra.

The daily performance obtained at the testing location are analyzed under three different modes:

- GPS solution with SBAS L1 legacy mode DO-229E [4] ;
- GPS solution with SBAS L5 DFMC mode SBAS DFMC WG62 draft [5].
- GPS+GAL solution with SBAS L5 DFMC SBAS DFMC WG62 draft [5].

A few elements of the implemented algorithms must be considered. The implementation of the SBAS solution is intended to be as close as possible to the SBAS aeronautical solution. In this respect the SBAS L1 implementation is compliant with DO-229 [4] and SBAS L5 DFMC implementation is aligned DFMC WG62 draft [5] with an addition of a few more modifications driven by the design of the Australian and New Zealand SBAS test-bed:

- Australia and New Zealand Test-bed signals are not certified for Safety of Life use. Consistently with the ICD they include the MT_0 message within the SBAS message sequence. SBAS L1 signal is configured to broadcast MT_0 instead of MT_2, so the use of the MT_0 message is not degrading the channel bandwidth.

    - Ionosphere-free code range combination augmented by the Australian and New Zealand test-bed corresponds to GPS L1CA/L2P pair of signals instead of the GPS L1/L5 as indicated by the standard. This is a design choice taken at the start of the test-bed operation. Because the GPS L5 enabled constellation is not yet fully deployed it was decided to use the GPS L1/L2 full constellation in order to assure a consistent satellite visibility during the experimentation. In this connection it is noted that GPS L1/L2 ionosphere-free combination has slightly weaker noise characteristics than GPS L1/L5.

- The SBAS L5 correction broadcast by the test-bed assumes that the user is not compensating for the GPS group delay bias broadcast (T_{GD}) when applying satellite clock corrections. This is required by the DFMC SBAS MOPS.

- The receiver implementation is performing a time-variant 100-second phase smoothing on code range measurement. However, it must be remarked that because dual-frequency smoothing is free of ionospheric divergence, the future SBAS DFMC standard will benefit from a longer smoothing window that would allow to reduce the final noise of GPS and Galileo observations.

- The SBAS L5 data stream is systematically providing corrections for 31 GPS satellites and 20 Galileo satellites, including all the Galileo satellites broadcasting ephemerides (even if declared in testing mode or not yet operational). Since the beginning of the Australia and New Zealand test-bed operation more than 8 Galileo SV have been commissioned into service or declared operational. By the summer of 2018 the number of Galileo satellites available in the Australia-Pacific area is high enough to consistently take part of the user solution and improve its performance. This is one of the key topics to be analyzed in in this paper.

4.2 Canberra Accuracy Performance

The following figures shows the key statistics of the various SBAS-aided solutions obtained with the receiver at Canberra during more than 30 days in August and September 2018, with data sampled at 1Hz. The different SBAS solutions are compared with a calibrated reference position obtained through PPP processing. The following figures shows the daily horizontal and vertical (absolute) error percentile 95.

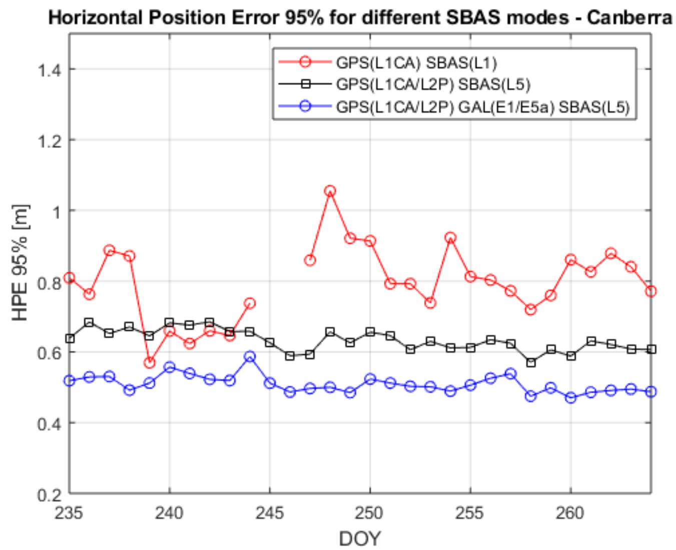

Figure 6 – Horizontal errors (in terms of P95 performance) at Canberra receiver

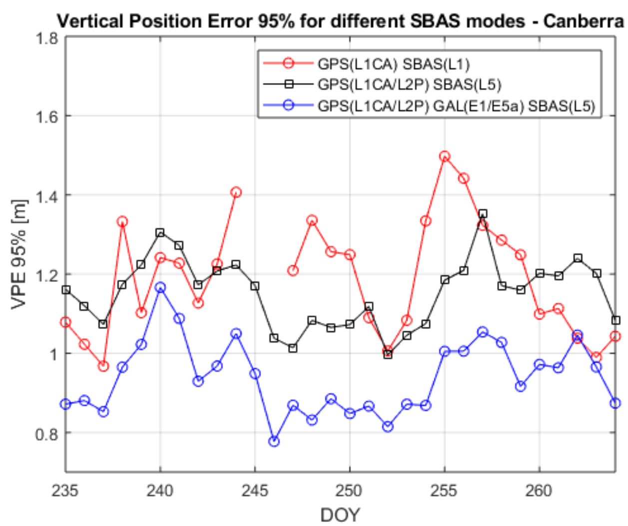

Figure 7 –Vertical Error (in terms of P95 performance) at Canberra receiver

Horizontal results show a very stable behavior of the SBAS L5 DFMC-aided solution compared to a higher noise of the SBAS L1 legacy solution. This can be explained by lower sensitivity of the L5 to ionospheric delays compared to the L1 service. The results show how the performance is improved in the expected order of solutions with the GPS+GAL DFMC solution being the best. The level of performance achieved is better than 0.6 cm in horizontal positioning.

In comparison it is observed that the vertical accuracy of GPS SBAS L1 and GPS SBAS L5 solutions are similar. This is not a totally unexpected result. The ionosphere-free combination presents a higher noise than the L1CA single-frequency measurements. This is a consequence of the combination of the noises from the two observables used. The SBAS L1- only would be better or worse than or the SBAS L5-only solution, depending upon the residual error left from the SBAS L1 ionospheric correction being greater or lower than the contribution of the additional noise from the ionosphere-free combination used with SBAS L5 corrections.

Finally, the results show how the availability of the Galileo satellites helps to improve the robustness of the positioning solution in the vertical direction making the GPS+GAL SBAS DFMC L5 solution champion in all the days analyzed. The average P95 vertical accuracy amounts to approximately 1 meter.

Note that the data gaps in SBAS L1 solutions for Day of Year 245 (2018/09/02) and 246 (2018/09/03) are due to a hardware incident at test-bed processing chain. During this period, the test-bed was broadcasting and SBAS L1 sequence with no satellites monitored.

4.3 Canberra Service Availability

The following figure shows the obtained P99 performance for the Vertical Protection Level for the Canberra receiver. The results show how in all cases the service level is compatible with LPV-200 performances with a VAL of 35 meters. The GPS+GAL solution is also within the 10-15 meters thus enabling the CAT-I service. It is expected that CAT-I auto-land service with a VAL of 10 meters could be reached with the complete deployment of the Galileo constellation.

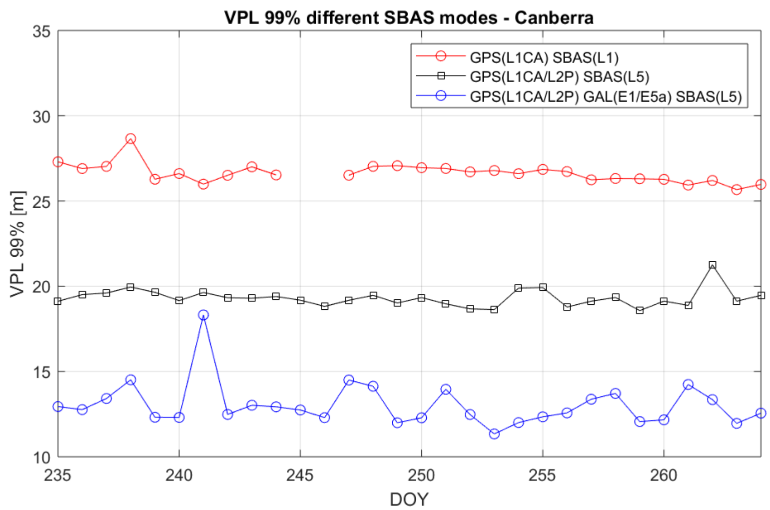

Figure 8 – P99 performance of Vertical Protection Level at Canberra.

5 SBAS EXPERIMENTATION CAMPAING RESULTS (KANAGAWA)

5.1 Method of Analysis

As part of Septentrio's benchmark and testing activities, an a AsteRx-U receiver was placed for a few days in Kanagawa, near Tokyo, Japan. Although the duration of the data acquisition campaign was shorter than with the Canberra receiver, the value of this experimentation is that it allowed to test the Australia - New Zealand test-bed in a location far from the main service area, but still within the broadcasting GEO footprint. It also allows to test the rover-side implementation with an alternative SBAS signal, in this case the one corresponding to the MSAS SBAS L1 operational service (PRN 137). It must be noted that Australia and New Zealand Test-bed SBAS L1 service is not available outside Australia due to the limitations of the regional coverage of the ionospheric corrections.

The following figure shows the location of the Kanagawa antenna site. The AsteRx-U receiver is thus placed in an urban environment with a relatively benign nearly open sky conditions.

Figure 9 – Location of GPS+GAL Antenna and receiver at Kanagawa (Tokyo)

5.2 Kanagawa Accuracy Performance

The following figures show the key statistics of the different SBAS-aided solutions for the Kanagawa receiver during the four day long experimentation campaign in August and September 2018. The data was sampled at 1Hz. The different SBAS solutions obtained are compared with a calibrated reference position obtained through PPP processing. The following figures present the daily horizontal and vertical (absolute) error according to the percentile 95.

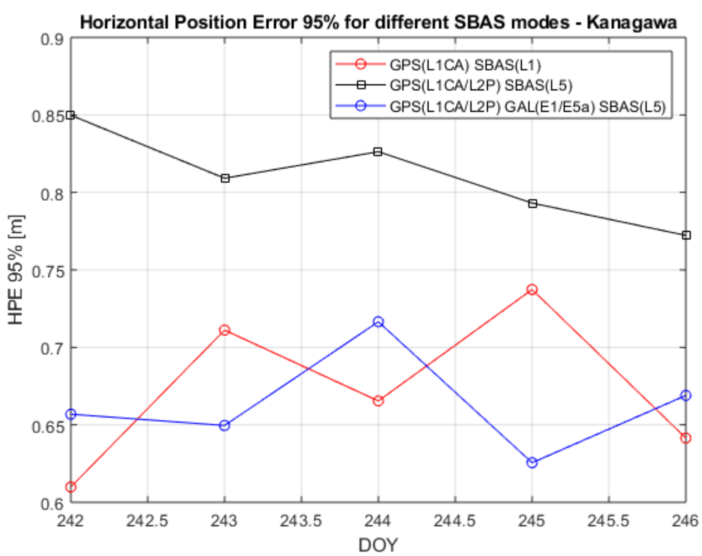

Figure 10 – Horizontal error P95 performances for the receiver in Kanagawa

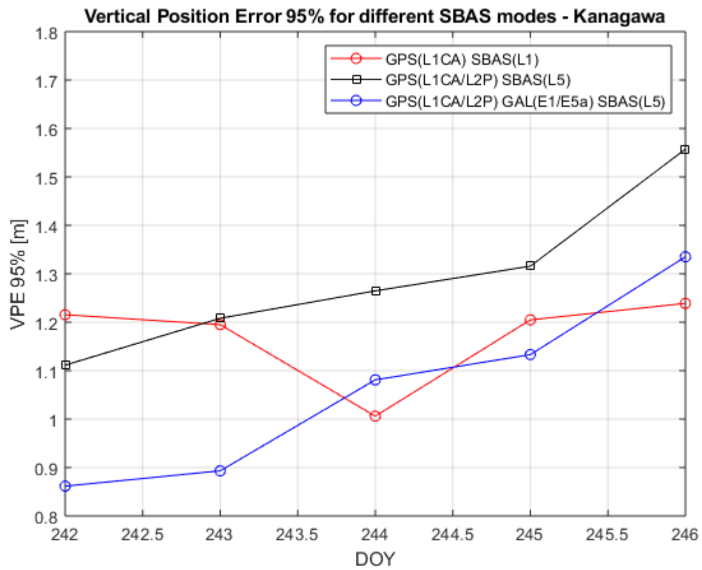

Figure 11 – Vertical error P95 performances for the receiver in Kanagawa

Although the comparison below is made between the results obtained from two receivers with different hardware and located in very different environments, also covering different time intervals and processing different service providers (as is the case of SBAS L1), it is still an interesting exercise to observe the obtained performance. The following tables compare the ranges obtained in these two experiments:

Table 1 – Range of P95 in Horizontal and Vertical Errors (m)

	Canberra (~30 days)		Kanagawa (~4 days)	
Mode	Horizontal	Vertical	Horizontal	Vertical
SBAS L1 HPE	**0.60 –1.10 m**	**1.00– 1.50 m**	**0.60 –0.75 m**	**1.00 – 1.20m**
GPS SBAS L5	**0.60 –0.70 m**	**1.00 – 1.40 m**	**0.75 –0.85 m**	**1.10 – 1.60 m**
GPS GAL SBAS L5	**0.50 –0.60 m**	**0.80 – 1.20 m**	**0.63 –0.72 m**	**0.85 – 1.35 m**

The first conclusion is that the 95-percentile for the different solutions are of the same order of magnitude. For both locations the GPS+GAL SBAS L5 solutions was systematically better than the GPS SBAS L5 solution, which is expected in view of the added robustness and geometry improvement when using Galileo and GPS measurements combined.

Also, for these two receivers, the accuracy of the SBAS L1 solution is comparable the one obtained by the DFMC solution. This effect illustrates the balance between the ionosphere-free combination observation higher noise and the residual ionosphere error remaining after applying the SBAS L1 corrections. This balance has two key elements: first, the actual noise observed in each one of the frequencies, depending on the antenna and the environment set-up. Secondly, the actual location of the receiver with regards to the service area of the SBAS L1, is expected to exhibit better performance because it is closer to the central part of this service area.

Another relevant conclusion is that, in the short interval analyzed, the accuracy performances provided by the MSAS service in Japan and the Australian-New Zealand test-bed in Australia are comparable, and that the Australia and New Zealand test-bed is demonstrating uniform accuracy performance across the entire Inmarsat 4F1 footprint.

5.3 Kanagawa Service Availability

The following figure shows the obtained P99 performance obtained for the Vertical Protection Level for the receiver in Kanagawa. In the same way as the receiver in Canberra, the service enabled by the Australian and New Zealand test-bed is consistent with LPV-200 performance requirements and the VPL obtained with GPS and Galileo is close to meet the CAT-I performance requirements (it is expected that CAT-I requirements are fully met feasible with full deployment of the Galileo constellation). Noted that no integrity events were flagged for neither MSAS nor Australian and New Zealand test-bed during the entire testing campaign.

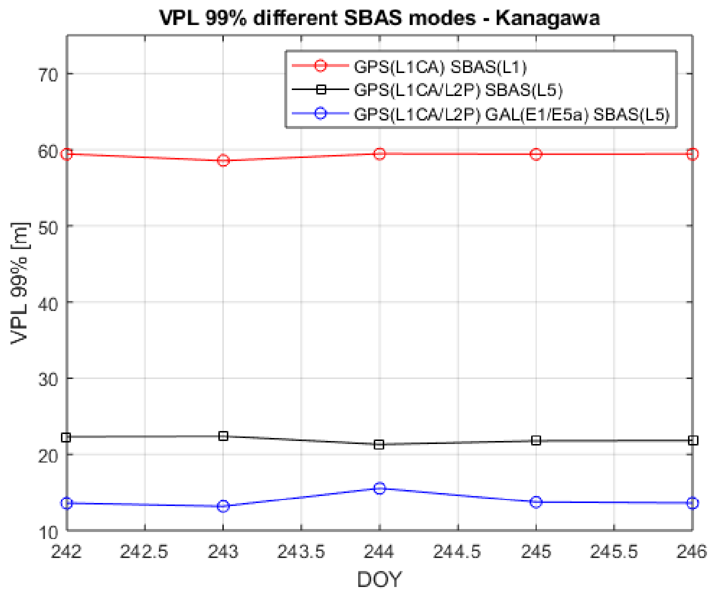

Figure 12 –P99 Vertical Protection Level Performance at Kanagawa.

6 PPP EXPERIMENTATION CAMPAIGN RESULTS

6.1 Method of Analysis

The observation collected by the Septentrio receiver located at Geoscience facilities in Canberra has been also used to conduct at test on the PPP performances of the test-bed. In this experimentation GMV's PPP module has been configured to process the following inputs:

- Septentrio receiver code and carrier phase measurements and navigation recorded by Septentrio receiver.
- RTCM corrections recorded at Test-bed infrastructure.
- GPS Satellite ephemeris and clock corrections as decoded from SBAS L1 messages broadcast by Inmarsat 4F1.
- GPS+GAL Satellite ephemeris and clock correction as decoded from SBAS L5 message broadcast by Inmarsat 4F1.

The RTCM corrections recorded at the test-bed infrastructure corresponds to the original orbit and clock estimated by the ODTS service within the Australia and New Zealand test-bed processing center prior to its codification into SBAS L1 and SBAS L5 message format. Because of the lower bandwidth available at the GEO SBAS signals, the encoding of the information into the SBAS messages reduces the resolution of the correction and increases its latency.

The processing results for the North, East and Up errors of the real-time PPP solution are obtained covering the time interval of 6 days from the 26/08/2018 until the 31/08/2018 for three use-cases:

- RTCM solution used as reference case.
- SBAS L1 PPP solution obtained with the use of the GPS information included in the SBAS L1 stream.
- SBAS L5 PPP solution obtained with the use of the GPS+GAL information included in the SBAS L5 stream.

The RT-PPP module produces a user position which is compared with a calibrated reference antenna phase center location obtained through magicgnss.com service [6], corresponding to the first use-case. This reference position is computed with a post-processing PPP algorithm configured to use IGS reference orbits. This way no correlation or systematic common error is expected to be found with the Test-bed RT-PPP solution given that a different algorithm and different corrections are used.

6.2 RT-PPP results

The following figures show the variability of the North, East and Up errors during the 6-day test campaign for the three processing modes (RTCM, SBAS L1 and SBAS L5)

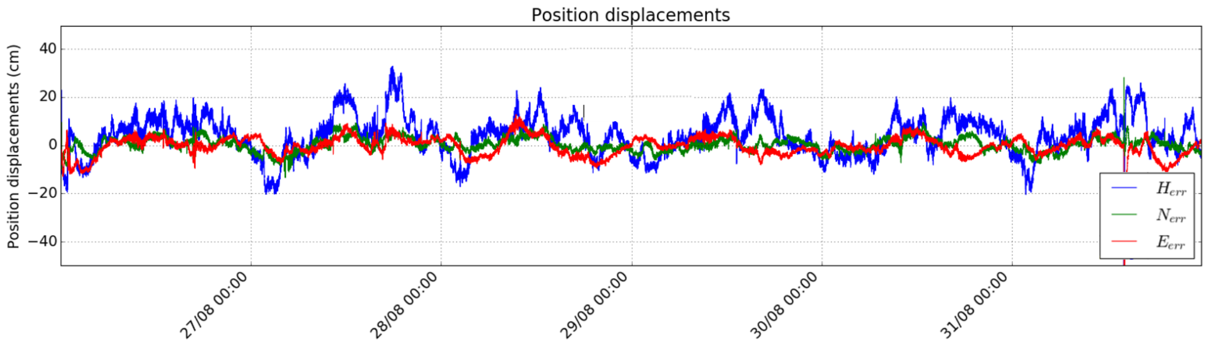

Figure 13 – PPP Position with Testbed GPS+GAL RTCM corrections

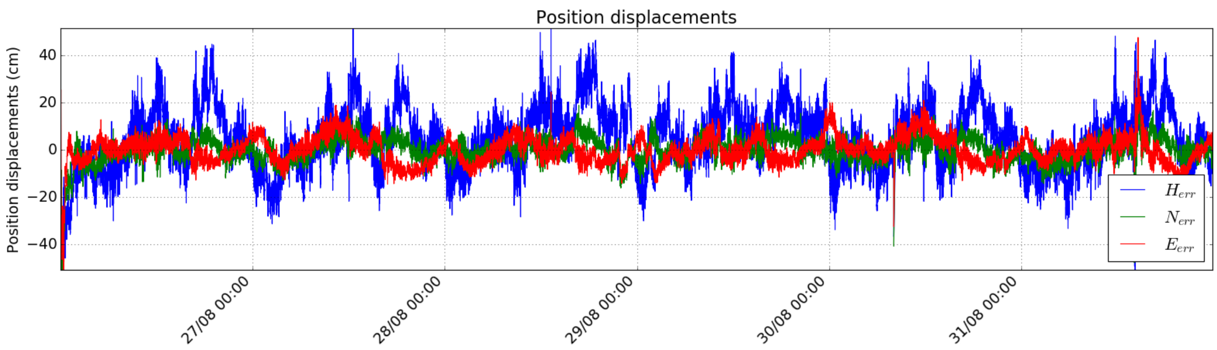

Figure 14 – PPP Position with Testbed GPS SBAS L1 corrections

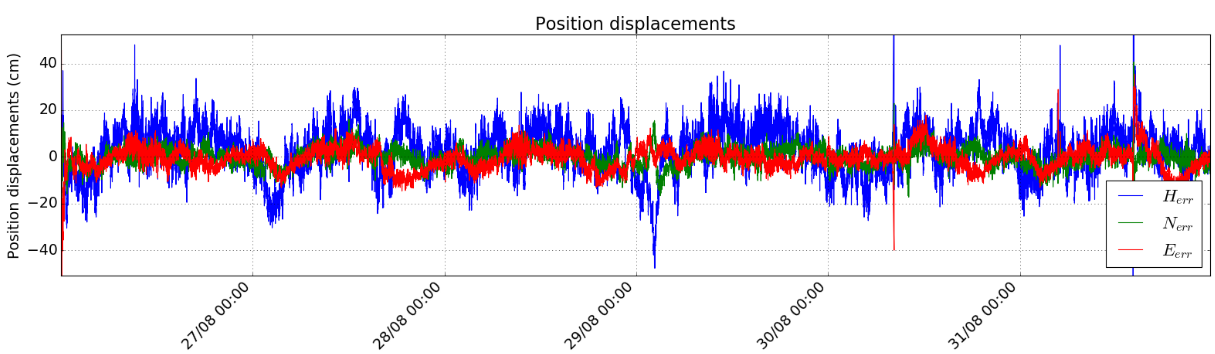

Figure 15 – PPP Position with Testbed GPS+GAL SBAS L5 corrections

When the solutions are compared one by one it is observed how well the SBAS positioning reproduces the RTCM solution but with a somewhat higher solution variability. This is more clearly observed when checking the overall accuracy statistics. The following table clarifies the RMS accumulated during the 6 days of experimentation:

Table 2 – PPP RMS with Septentrio receiver and GMV's PPP module

	RTCM GPS+GAL	SBAS L1 GPS	SBAS L1 GPS+GAL
RMS North (cm)	**2.96**	**4.64**	**3.79**
RMS East (cm)	**4.55**	**5.48**	**4.75**
RMS Up (cm)	**9.21**	**13.61**	**10.72**

The SBAS solutions are degraded from 2 to 4 cm, which with a greater relative degradation of the SBAS L1 solution than that of the SBAS L5. This is mainly due to the difference in the correction resolution but above all due to the availability of the additional Galileo satellites in the SBAS L5 augmentation streams.

The main conclusion is that the PPP integration within the SBAS signal is capable to support a high-accuracy service with performances around 5 cm RMS in horizontal and 10 cm RMS in vertical, coupled with just a minor degradation with regards to the original precise orbit and clock information integrated into the SBAS messages.

7 CONCLUSIONS

Our main conclusion is that the early availability of the Australian and New Zealand test-bed has allowed the early experimentation with SBAS L5 DFMC signals by receiver manufacturers. In particular, this helped Septentrio to develop a family of receivers already integrating the SBAS L5 DFMC solution and aligned with the latest version of the standard.

When checking the performances achieved with the Septentrio receivers it was found that both accuracy parameters and protection levels are consistent with the values expected for the corresponding services. It is observed that the SBAS DFMC supports accuracies in the order of 1 m P95 in the vertical direction and 0.6 m in the horizontal plane. The protection levels obtained are fully consistent with the specifications of an LPV-200 service (and they are indicative that a CAT-I service will be possible with future completion of full GPS+GAL constellations).

Finally, during this experiment we tested the integration of the Septentrio receivers with the GPS's PPP module enabled by the test-bed RTCM correction stream as well as by the PPP information inserted into the SBAS messages. The results confirm that nominal PPP performances is reached when working with the RTCM stream and a very little degradation is found when using the GEO channel. An accuracy of the level of 5 cm horizontal RMS is obtained for both SBAS L1 and SBAS L5 solutions.

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DISCLAIMER

The views and opinions expressed in this article are those of the authors and do not necessarily reflect the position of any institution of Australia or New Zealand.

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