PRECISE POINT POSITIONING WITH GALILEO OBSERVABLES

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ABSTRACT

In order to assess potential improvements in positioning performance associated with the use of Galileo observables, the University of New Brunswick's GNSS Analysis and Positioning Software (GAPS) has been modified to utilize the Galileo Open Service (OS) carrier-phase and pseudorange observables. In this paper, results of GPS-only, Galileo-only, and GPS + Galileo combined static processing are presented, including the use of the Galileo E1/E5a, E1/E5b, and E1/E5 linear combinations. A comparison of solutions obtained using each of the five currently-available Galileo orbit and clock product providers are discussed as is the estimation of Galileo-GPS inter-system biases and other atmospheric parameters. Additionally, a comparison of kinematic mode positioning solutions using both GPS-only and GPS + Galileo observables is presented.

1. INTRODUCTION

Following the successful orbit injection of the two most recently-launched Galileo full-operational-capability (FOC) satellites, the European Space Agency has moved one step closer to reaching FOC for its Galileo program. With 9 operational satellites (10 including one satellite transmitting only the E1 signal) now broadcasting the Galileo Open Service (OS) signals and the anticipated launch of several more satellites over the next year, positioning, navigation, and timing users can begin to exploit the potential benefits of the Galileo GNSS. Improvements in performance such as increased accuracy in positional estimation and increased availability and reliability of kinematic solutions should become evident following the inclusion of Galileo observables into a precise point positioning (PPP) processing scheme, particularly in situations where signal loss is likely to occur due to limitations in the number of observable satellites.

Using an offline version of the University of New Brunswick's GNSS Analysis and Positioning Software (GAPS) that has been modified to include the Galileo OS carrier-phase and pseudorange observables, preliminary performance of the inclusion of Galileo can now be assessed in both static and kinematic positioning modes. This modified version of GAPS makes use of precise Galileo orbit and clock products contributed to the International GNSS Service (IGS) Multi-GNSS Experiment (MGEX) campaign [1] by various agencies, including Centre National d'Etudes Spatiales (CNES) [2], Technische Universität München (TUM) [3], Wuhan University (WUM) [4], the German Research Centre for Geosciences (GFZ) [5], and the Center for Orbit Determination in Europe (CODE) [6]. Use of the precise orbit and clock products also allows for the mitigation of detrimental inter-system biases (ISB), including the use of the Galileo Terrestrial Reference Frame as the reference datum for broadcast Galileo satellite positions and Galileo System Time as their reference time. To account for further system differences, residual ISBs including associated Galileo hardware delays are estimated as a combined parameter within GAPS' sequential least-squares filter and subsequently used to model observables during processing.

Currently, Galileo users are limited to observability of 7 total satellites broadcasting dual-frequency observables (PRNs 11, 12, 14, 18, 19, 22, and 26). Following the recent launch of two more satellites (PRNs 24 and 30), dual-frequency users will soon have access to a total of 9 satellites. Despite this increasing number, typical periods of simultaneous observability with a minimum of 4 satellites remain limited to approximately 3 to 4 hours in length, greatly limiting the achievable accuracy and availability of Galileo-only positioning estimates. Other than the inherent estimation degradation caused by poor satellite availability and geometry, use of the yet experimental IGS MGEX orbit and clock products further contributes to the current accuracy limitations of Galileo positional estimates.

2. PROCESSING STRATEGY

In order to assess the performance impact of Galileo observable inclusion into a PPP processing scheme, positioning solutions were obtained using the modified version of GAPS and subsequently analysed for discrepancies from the IGS weekly combined solutions for a set of four globally-distributed IGS MGEX reference stations (Fig.1). This data set included stations BRUX (Belgium), CHPG (Brazil), HARB (South Africa), and UNB3 (Canada). With the exception of station BRUX (utilizing a Septentrio PolaRx4 receiver), all other stations used Trimble NetR9 receivers. For stations BRUX, CHPG, and UNB3, 24-hour RINEX 3.02 observation files were obtained for days-of-year

(DOYs) 110, 130, 160, and 190. Due to differing availability of 4 simultaneously-observable Galileo satellites at station HARB, observation files for DOYs 116, 136, 166, and 189 were selected. Each of these station/DOY combinations provided approximately 3 to 4 hours of GPS and Galileo simultaneous observability of four satellites per constellation with four satellites being the minimum number of satellites required in order to establish a GPS-only or Galileo-only positional solution in PPP.

Figure 1: IGS MGEX stations used in static mode processing comparisons

Observables used in all GPS processing included the legacy L1/L2 carrier-phase and pseudorange iono-free linear combinations. For the majority of the static mode processing, the standard Galileo E1/E5a carrier-phase and pseudorange iono-free linear combinations were used. For the comparison of positional solutions obtained using alternative Galileo observables, the E1/E5b and E1/E5 linear combinations were additionally utilized. Alternatively, as the Javad Triumph LS receiver used in the kinematic testing provided only one of the three possible E5 observables, kinematic mode processing utilized the Galileo E1/E5b linear combination. All GPS and Galileo observables received equal weights during static and kinematic mode processing.

While the static mode processing elevation angle cut-off was set to 5° for all static solutions, a 10° threshold was applied for the kinematic mode testing in order to avoid excessive multipath errors. In order to mitigate the effects of neutral atmosphere delay (NAD), the UNB3m NAD prediction model was used. Using the Vienna mapping functions, residual NAD was additionally estimated as a least-squares parameter to model the observables. Tropospheric gradients were not estimated or applied during any of the static or kinematic processing. Additionally, first-order ionospheric delay was mitigated through use of the iono-free linear combination of observables. Standard IGS ANTEX antenna calibrations were used for the application of antenna-specific satellite and receiver phase centre offsets, including preliminary values for the Galileo in-orbit validation (IOV) and FOC satellites.

For all static mode GPS processing, IGS combined analysis centre (AC) final orbit and clock products were applied with orbit determinations at a 15-minute sampling interval and 5-minute interval, respectively. For the kinematic mode GPS processing, IGS combined AC rapid orbits and clocks were used as the latency of final products prohibited use of the more common IGS final products. For the majority of the static mode and kinematic mode Galileo processing, the IGS individual AC MGEX CODE final orbit and clock products were applied with orbit determinations at a 15-minute sampling interval and clocks at a 5-minute interval. Additional IGS individual AC MGEX orbit and clock products were applied for Galileo processing during the alternative Galileo product comparison (Tab. 1).

Table 1: IGS MGEX product details

Provider	Orbits	Orbit Interval	Clocks	Clock Interval
CODE	.sp3	15-minute	.clk	5-minute
TUM	.sp3	5-minute	.sp3	5-minute
CNES	.sp3	15-minute	.clk	30-second
GFZ	.sp3	5-minute	.clk	30-second
WUH	.sp3	15-minute	.clk	5-minute

3. SOLUTION ANALYSIS

To determine the varying performance impacts of the use of Galileo observables in PPP processing, several different testing scenarios were utilized. These included tests of static mode processing comparisons using GPS-only, Galileo-only, and GPS + Galileo observables, static mode Galileo-only processing using each of the five currently-available IGS MGEX product providers, static mode Galileo-only processing using each of the E1/E5a, E1/E5b, and E1/E5 linear combinations, and kinematic mode processing comparisons of GPS-only and GPS + Galileo observables.

3.1. GPS-only, Galileo-only, and GPS + Galileo Positioning Comparisons

A critical test of initial Galileo positioning performance was to benchmark GPS-only, Galileo-only, and GPS + Galileo processing solutions against those of the IGS weekly combined solutions for the selected stations. For each scenario, four satellites of each constellation were utilized. In this way, a four-satellite GPS-only solution could be compared to a four-satellite Galileo-only solution as the playing field had been effectively “levelled”. Selection of the four GPS satellites used in the GPS-only and GPS + Galileo processing were based on the comparison of obtainable dilution of precision (DOP) values. The combination of four GPS satellites that produced DOP values as close as possible to those of the 4 Galileo satellites were used for each station/DOY combination. Fig. 2 and 3 show both GPS-only and Galileo-only PDOP and HDOP values for station UNB3 on DOY 130. Fig. 4 shows the subsequently improved DOP values obtained when both GPS and Galileo observables were utilized. Subsequent GPS + Galileo solutions were additionally analysed in order to assess if the GPS-only solutions were perhaps enhanced by the inclusion of Galileo observables.

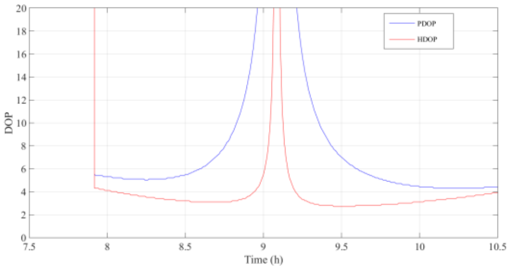

Figure 2: Station UNB3 DOY 130 GPS-only DOP

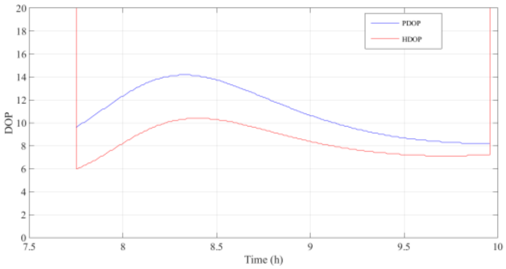

Figure 3: Station UNB3 DOY 130 Galileo-only DOP

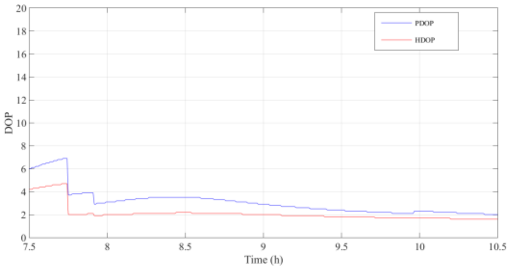

Figure 4: Station UNB3 DOY 130 GPS + Galileo DOP

Processing solutions for each station's three different processing types (GPS-only, Galileo-only, and GPS + Galileo) show estimated discrepancies in northing, easting, and height from those of the respective IGS weekly combined solutions as well as each solution's mean 3D RMS offset from the IGS solutions (Fig. 5-8). Note that station HARB's DOY 189 Galileo-only solution contains relatively large discrepancies, most likely due to the CODE AC's inclusion of Galileo PRN 18. For subsequent Galileo-only processing, smaller discrepancies have been observed when using other available products such as those of WUH and GFZ, which had alternatively removed PRN 18 from their solutions, presumably due to issues with this satellite's performance.

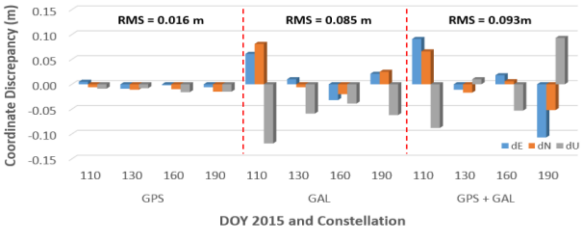

Figure 5: Station BRUX coordinate discrepancy from IGS weekly combined solutions

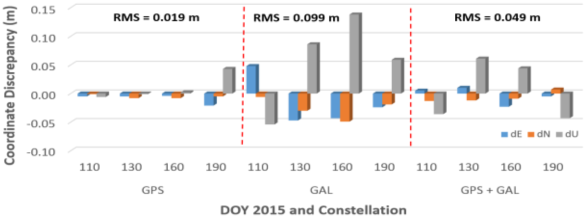

Figure 6: Station CHPG coordinate discrepancy from IGS weekly combined solutions

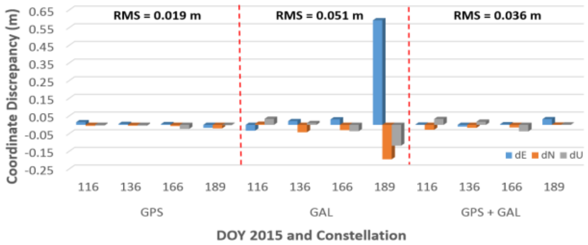

Figure 7: Station HARB coordinate discrepancy from IGS weekly combined solutions

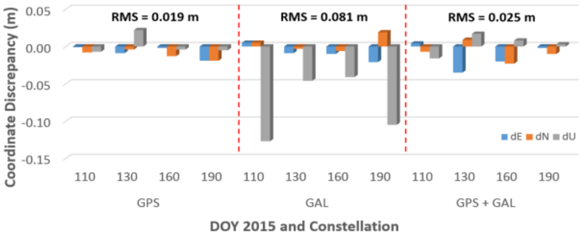

Figure 8: Station UNB3 coordinate discrepancy from IGS weekly combined solutions

Tab. 2 and 3 summarize mean 3D RMS coordinate discrepancies for each separate station and all stations combined, respectively. While GPS-only 3D RMS values fall to within 2 cm, on average, of the IGS weekly combined solutions, Galileo-only solutions remain within approximately 8 cm, on average, of these solutions and GPS + Galileo solutions within approximately 5.5 cm, on average. For each of the three solution types, the observed degradation in coordinate proximity to IGS solutions can be mainly attributed to limitations in satellite geometry as well as to the use of the IGS MGEX orbit and clock products as these separate AC products are un-combined and still considered to be experimental.

Table 2: Mean 3D RMS discrepancies for each site from IGS weekly combined solutions using CODE products

System	BRUX	CHPG	HARB	UNB3
GPS-only	0.016 m	0.019 m	0.019 m	0.019 m
Galileo-only	0.085 m	0.099 m	0.051 m*	0.081 m
GPS + Galileo	0.093 m	0.049 m	0.036 m	0.025 m

* Excluding solution for DOY 189 as an outlier

Table 3: Mean 3D RMS discrepancies for all sites from IGS weekly combined solutions using CODE products

GPS-only	Galileo-only	GPS + Galileo
0.018 m	0.081 m	0.053 m

3.2. Alternative Observable Analysis

Aside from the standard Galileo E1/E5a linear combination, other possibilities, including use of the E1/E5b and E1/E5 linear combinations, provide for alternative options that may offer users other potential benefits. For example, the Galileo E5 frequency utilizes the AltBOC code modulation technique – a technique that is thought to help mitigate the effects of multipath error. In order to assess the performance aspects of these alternative Galileo observables, processing solutions for each of the four stations and DOY combinations were obtained (Fig. 9-12). As CODE orbit and clock products were once more used for processing, a relatively large discrepancy can be seen for station HARB on DOY 189. Again, this is thought to be due to the inclusion of Galileo PRN 18 in these particular products.

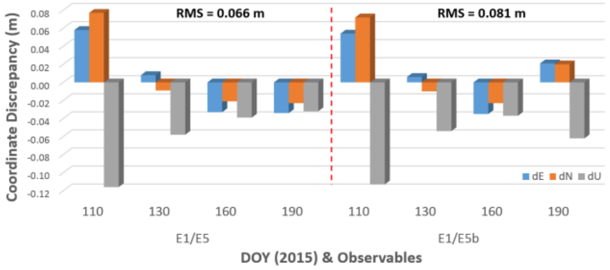

Figure 9: Station BRUX coordinate discrepancy from IGS weekly combined solutions

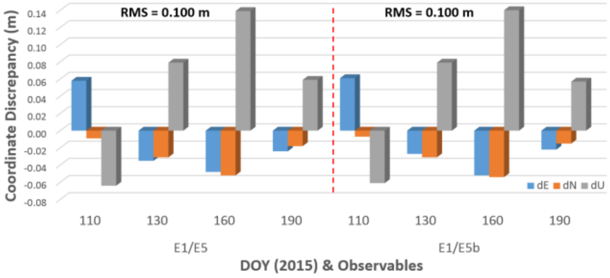

Figure 10: Station CHPG coordinate discrepancy from IGS weekly combined solutions

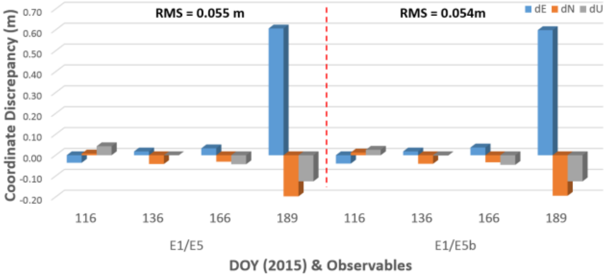

Figure 11: Station HARB coordinate discrepancy from IGS weekly combined solutions

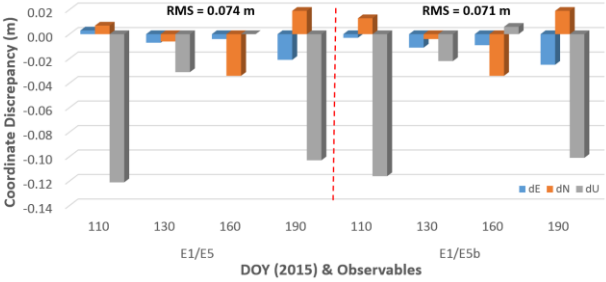

Figure 12: Station UNB3 coordinate discrepancy from IGS weekly combined solutions

Tab. 4 and 5 summarize the mean 3D RMS coordinate discrepancies for each separate station and all stations combined, respectively. While the mean 3D RMS results for both alternative linear combinations at station CHPG show a relatively large discrepancy of 10 cm from the IGS weekly combined solutions, a smaller discrepancy of approximately 5.5 cm can be seen at station HARB. On average, the solutions obtained using each linear combination remain within 5 mm of each other overall, although an improvement in mean 3D RMS can be seen through use of the E1/E5 combination for station BRUX. This improvement can perhaps be attributed to the AltBOC modulation technique utilized on the E5 code observable as well as this station's utilization of a Septentrio receiver. Although further investigation is needed to validate this hypothesis, the AltBOC modulation of E5 observables may have helped to mitigate multipath errors experienced when using the E1/E5a or E1/E5b linear combinations.

Table 4: Mean Galileo 3D RMS discrepancies for each site from IGS weekly combined solutions

Observables	BRUX	CHPG	HARB	UNB3
E1/E5	0.066 m	0.100 m	0.055 m	0.074 m
E1/E5b	0.081 m	0.100 m	0.054 m	0.071 m

Table 5: Mean Galileo 3D RMS discrepancies for all sites from IGS weekly combined solutions

E1/E5	E1/E5b
0.075 m	0.078 m

3.3. Galileo Product Analysis

As the IGS MGEX products provided for the Galileo GNSS are yet held as experimental products, preliminary analysis of their quality was essential in order to determine the overall quality of each product in terms of achievable accuracies of positional solutions as well as which product is currently best-suited for consistent use in Galileo processing. In this determination, several factors needed to be considered, including achievable positional accuracy, consistency of solution accuracy, latency of availability, and overall product availability.

Fig. 13-16 show the estimated coordinate discrepancies at each station/DOY combination from those of the IGS weekly combined solutions as well as the mean 3D RMS offsets for each of the five currently available IGS MGEX product providers. Note that solutions for DOY 189 and 190 have not been included for solutions where GFZ and WUH products were used as these products omitted Galileo PRN 18, subsequently providing only a 3-satellite solution. Also note that the large coordinate discrepancies for DOY 189 at station HARB can again be observed when CODE, TUM, and CNES products were utilized.

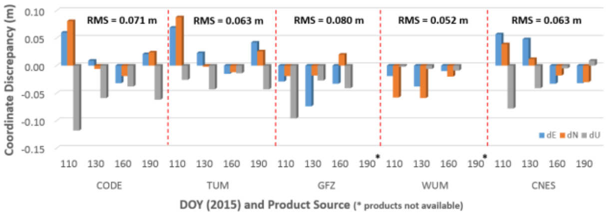

Figure 13: Station BRUX coordinate discrepancies from IGS weekly combined solutions

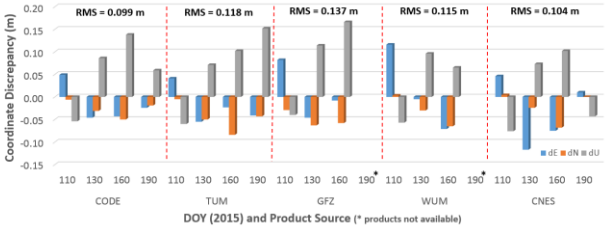

Figure 14: Station CHPG coordinate discrepancies from IGS weekly combined solutions

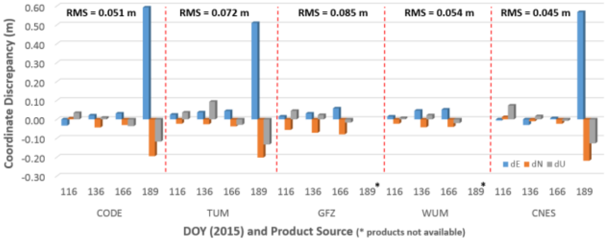

Figure 15: Station HARB coordinate discrepancies from IGS weekly combined solutions

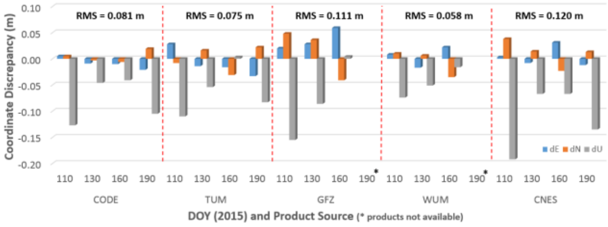

Figure 16: Station UNB3 coordinate discrepancies from IGS weekly combined solutions

Tab. 6 and 7 summarize the estimated mean 3D RMS coordinate discrepancies from those of the IGS weekly combined solutions. With the exception of station CHPG, mean 3D RMS values are generally within 10 cm, on average, of the IGS solutions with station HARB producing the smallest average discrepancy (6 cm) of the four stations. Also, mean 3D RMS discrepancies obtained for each station for all four days using each of the five product providers were within 1.3 cm of each other, demonstrating relative agreement in product determinations from each provider.

Table 6: Mean Galileo 3D RMS discrepancies for each site from IGS weekly combined solutions

Provider	BRUX	CHPG	HARB	UNB3
CODE	0.071 m	0.099 m	0.051 m	0.081 m
TUM	0.063 m	0.118 m	0.072 m	0.075 m
GFZ	0.080 m	0.137 m	0.085 m	0.111 m
WUM	0.052 m	0.115 m	0.054 m	0.058 m
CNES	0.063 m	0.104 m	0.045 m	0.120 m

As seen in Tab. 7, the product provider with the smallest average 3D RMS discrepancies for all stations for each of the four days were the Wuhan University products with a mean 3D RMS offset of 6.9 cm from those of the IGS weekly combined solutions. While the data set used to determine this offset is limited to just for stations for three to four days, the Wuhan product clearly outperforms the other providers in terms of average proximity to the benchmark positions.

Table 7: Mean Galileo 3D RMS discrepancies for all sites from IGS weekly combined solutions

CODE	TUM	GFZ	WUM	CNES
0.112 m	0.083 m	0.097 m	0.069 m	0.114 m

It is also important to note that the product latency of each IGS MGEX provider is approximately 14-18 days, on average, as are the IGS final products. While certain issues in product availability remain (i.e. lack of consistency in making products available to IGS MGEX), most contributors make their products available on a consistent basis commensurate with their product latency.

3.4. Inter-System Biases

Another critical step in the implementation of combined GPS + Galileo processing is the introduction of an inter-system bias parameter. As GPS and Galileo each use their own unique time systems (GPS time vs. Galileo system time), these time systems must be precisely aligned in order to correctly combine observables in processing. While the IGS MGEX clock products are currently provided in reference to GPS time for Galileo observables, residual time system differences and associated hardware delays remain that need to be accounted for in order to achieve the highest level of positional accuracy available. In the GAPS Galileo implementation, an ISB parameter has been added to the existing sequential least-squares filter in order to effectively absorb this residual time system error as well as differences in hardware delays experienced with Galileo observables versus those of GPS. As can be seen in Fig. 17-20, ISB estimates for each of the processed station/DOY combinations remain fairly consistent throughout the processing period aside from initial convergence periods. Note that the estimated ISB values for station BRUX (Fig. 17) differ in dispersion from those of the other station's estimates. This is most likely do to the differing utilization of the Septentrio PolaRx4 receiver versus the Trimble NetR9.

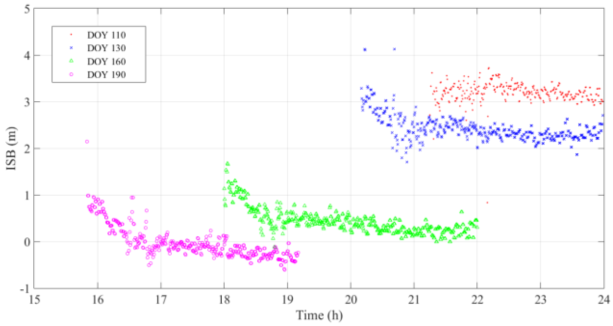

Figure 17: Station BRUX ISB estimates using CODE orbit and clock products

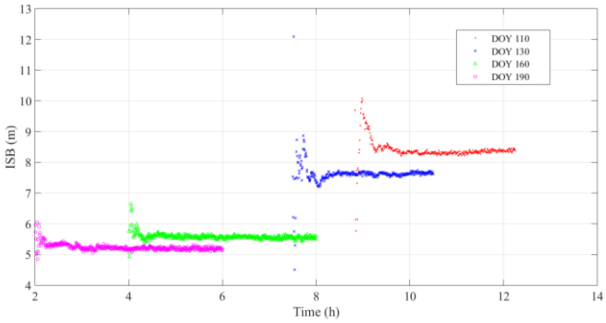

Figure 18: Station CHPG ISB estimates using CODE orbit and clock products

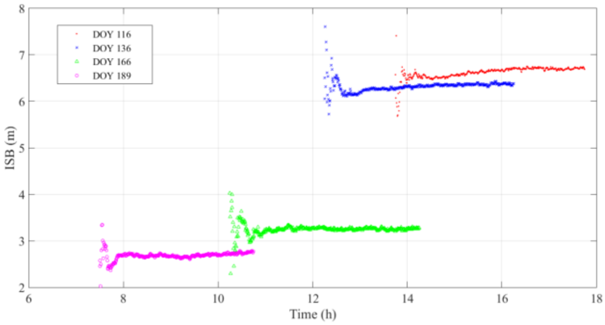

Figure 19: Station HARB ISB estimates using CODE orbit and clock products

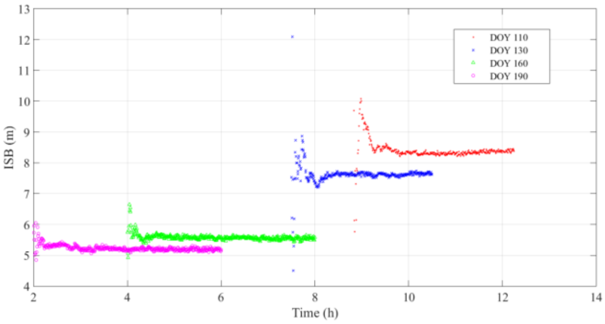

Figure 20: Station UNB3 ISB estimates using CODE orbit and clock products

3.5. GPS + Galileo Atmospheric Parameters

Aside from offering positional solutions, GAPS also provides users with estimates of important atmospheric parameters including NAD and vertical ionospheric delay. As the addition of further satellite observables theoretically serve to strengthen the accuracy of these atmospheric parameter estimates, the inclusion of Galileo observables should help to improve the quality of GAPS' NAD and ionospheric delay estimates. Unfortunately, due to initial convergence periods, limited availability of the number and time of observability of the current Galileo satellites, and the preliminary quality of IGS MGEX products, the NAD and ionospheric delay estimates obtained when using Galileo observables actually provide a degradation in the overall accuracy of these estimates. While the aforementioned limitations currently hinder improvement of atmospheric parameter estimation in GAPS PPP, the implementation of additional Galileo satellites as they become available and subsequent improvement of IGS MGEX orbit and clock products should enhance the achievable accuracies.

3.6. GPS-only vs. GPS + Galileo Kinematic Solutions

Another area in which inclusion of Galileo observables into a PPP processing scheme may contribute to performance gains is that of kinematic mode positioning, particularly in areas where lock to satellites from other constellations is likely to be lost due to obstructions such as trees and buildings or extreme multipath conditions. In this instance, supplementing a kinematic solution with available Galileo observables should serve to improve satellite availability and geometry as well as potentially mitigate signal loss and multipath error through the inclusion of modernized observables. In order to validate any such performance improvements, a kinematic data collection survey was performed using a Javad Triumph LS GNSS receiver and a Septentrio GNSS antenna affixed to the roof of a vehicle as it navigated through the greater-Fredericton, New Brunswick, Canada, area. Observations were collected at a 1-Hz rate.

The collected data were subsequently processed using the modified version of GAPS with both GPS-only and GPS + Galileo observables. As seen in Fig. 21-24, inclusion of Galileo observables along with those of GPS significantly improved the availability of a positional solution, particularly in locations where lock to some of the GPS satellite signals was lost. With the inclusion of Galileo observables, a total of 2,655 solution epochs were obtained versus a total of 2,540 solution epochs with GPS-only observables, demonstrating an increased availability of 115 solution epochs. Areas of increased solution availability are shown highlighted in red in Fig. 22 and 24.

Aside from an increase in availability, a general increase in estimated pseudorange residual performance was also observed. Following the inclusion of Galileo observables, the pseudorange residual mean decreased from -46 cm (GPS-only) to -14 cm (GPS + Galileo). Also, the pseudorange residual RMS decreased from 2.270 m (GPS-only) to 2.225 m (GPS + Galileo). No significant change was noted in the estimated carrier-phase residuals.

Figure 21: GPS-only kinematic solution

Figure 22: GPS + Galileo kinematic solution

Figure 23: GPS-only kinematic solution

Figure 24: GPS + Galileo kinematic solution

4. CONCLUSIONS

Following the inclusion of Galileo observables into an offline version of UNB's GAPS software suite, static and kinematic mode processing solutions have provided insight into the currently achievable positioning accuracies. Though simultaneous observability of four Galileo satellites is limited to between three and four hours at the current time, Galileo-only positional solutions have been found to be within approximately 8 cm, on average, of the IGS weekly combined solutions and GPS + Galileo solutions to within approximately 5 cm, on average. While these solutions show greater error than those obtained when using GPS-only, they still serve to validate the preliminary interoperability and interchangability of Galileo observables. The Galileo-only solutions, in particular, further validate early Galileo performance by demonstrating sub-decimetre-level static mode positioning accuracies.

Another aspect of GAPS Galileo-only processing is the validation of the quality of the orbit and clock products of the five current IGS MGEX product providers. While each of the separate AC products fall short of the accuracies obtainable through use of the IGS combined AC final products, use of these MGEX products still provide for positional estimates of within 10 cm, on average, of the IGS weekly combined solutions. Analysis of estimated mean 3D RMS offsets from the IGS solutions also demonstrate the current superiority of the Wuhan University product, which provided a mean 3D RMS coordinate discrepancy of 6.9 cm for all station and DOY combinations.

Galileo observable inclusion into GAPS also provided insight into additional parameter estimation, including the ISB, NAD, and ionospheric delay parameters. It has been found that, while neglecting initial convergence times, ISB estimates appear to show consistent temporal resolution. NAD and ionospheric delay parameters, on the other hand, vary considerably from estimates achieved through use of GPS alone. Due to this variation, the use of Galileo-only observables for atmospheric parameter estimation is currently limited. Although not in the scope of this work, Galileo observable inclusion along with all available GPS observables should serve to improve atmospheric parameter estimation.

As has been previously demonstrated [7], the inclusion of Galileo observables in GPS + Galileo kinematic mode processing has been shown to improve position solution availability and reliability, particularly in areas where signal loss is likely to occur. Following inclusion of Galileo observables, the GAPS kinematic mode positioning solution provided an increase of 115 solution epochs from the GPS-only solution. Such increased solution availability demonstrates the value of including Galileo observables with those of other constellations in situations where loss of lock to satellites will occur.

5. FUTURE WORK

As the deployment of the Galileo constellation remains a work in progress, future work will mainly involve the integration of new Galileo satellites as they become available. Use of additional satellites will serve to continually improve the simultaneous observation period as well as the achievable satellite geometry, solution redundancy, and availability of positional solutions. Further study is also necessary for the analysis of improvements to kinematic positioning with the inclusion of increasing numbers of Galileo satellites. Increased availability and reliability of kinematic positioning solutions is expected as is a general decrease in positional solution convergence time. Also, the potential impact of the use of alternative Galileo observables, such as Galileo E5 with its AltBOC modulation technique, is worthy of additional research in terms of increased multipath mitigation potential.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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