Assessing GPS + Galileo Precise Point Positioning Capability for Integrated Water Vapor Estimation

Marco Mendonça, Ryan M. White, Marcelo C. Santos, and Richard B. Langley

Abstract

Although conventionally used for positioning, navigation, and timing, GNSS observations constitute a useful tool for atmospheric remote sensing. By quantifying and analyzing the influence of the atmosphere on the propagating electromagnetic signals, we can infer a significant amount of information for further understanding Earth's atmosphere as well as its relationship with satellite positioning activities. For some industrial sectors that require high accuracy and reliability, such as oil exploration, dredging, and aviation, the understanding of how GNSS satellite signals propagate across the atmosphere is crucial information. Among several improvements related to GNSS, the increasing number of in-orbit Galileo satellites opens a new window of opportunities for atmospheric research. Users can achieve improved satellite geometry and take advantage of Galileo signal characteristics, such as improved signal strength. In this study, the usage of Galileo signals for neutral atmospheric delay (NAD) estimation is assessed along with its integration with signals from the already established GPS constellation. Using the University of New Brunswick's GNSS Analysis and Positioning Software (GAPS) precise point positioning suite, the NAD values are estimated and integrated with in situ measurements of pressure, temperature, and humidity, allowing us to estimate the integrated water vapor (IWV) of the atmosphere above a GNSS station. As a reference for the estimation assessment, existing IWV values from radiosondes are used. Preliminary results show that the Galileo + GPS NAD estimations are close to those of GPS at the 2-centimeter level. The recently-released multi-GNSS processing online version of GAPS is now able to provide users with a useful tool for atmospheric research.

Keywords

Atmospheric studies • Galileo • GAPS • Geodesy • IWV • Multi-GNSS • NAD

1 Introduction

The integration of different satellite constellations for any given positioning-oriented purpose is a challenge (Montenbruck et al. 2014; Dow et al. 2009). When using two or more systems with different reference frames for both position and time, a series of biases and statistical models should be considered in order to achieve a satisfactory synergy. In this study, the integration between the Global Positioning System (GPS) and Galileo is assessed in the scope of the neutral atmospheric delay estimation by the calculation of integrated water vapor (IWV).

In an attempt to validate the IWV estimated via the integration of the aforementioned systems and the Vienna Mapping Function 1 (VMF1) gridded product, this study uses radiosonde data provided by the Department of Atmospheric

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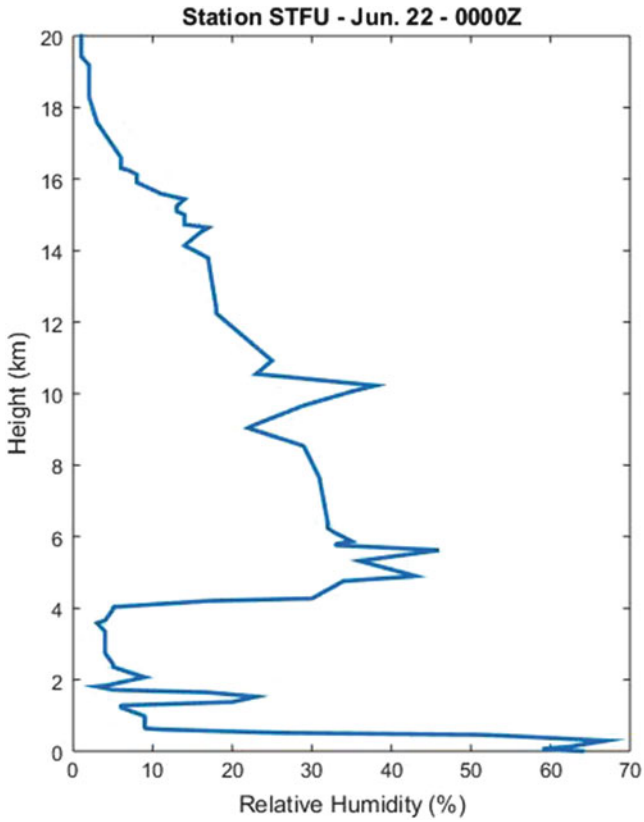

Fig. 1 Example of radiosonde relative humidity profiling

Sciences of the University of Wyoming[1] (UWYO) and compares these values with the same parameters estimated using the precise point positioning (PPP) technique utilized by the GNSS Analysis and Positioning Software (GAPS). An example of a relative humidity vertical profile as calculated using a radiosonde and provided by UWYO is presented in Fig. 1.

When considering the expected biases and errors encountered during the integration of different constellation observables, it is possible to see that the integration will not only provide a direct benefit to the solution in terms of accuracy of the IWV estimation, but will also increase the robustness and availability of the solution, since more satellites can be observed and subsequently integrated into the mathematical model.

Several studies have been conducted considering the impact of new GNSS satellites in atmospheric remote sensing activities. Li et al. (2015a, b) studied the impact of the Beidou constellation in IWV estimation, concluding that this constellation is ready for being integrated into tropospheric parameters estimation, as well high-precision GNSS activities. Rohm et al. (2014) showed that, although PPP is inferior in accuracy to double-differencing positioning, it still provides a high consistency solution, agreeing to radiosonde references up to the centimeter level. Li et al. (2015a) studied the integration of different GNSS constellations, arriving to the conclusion that even for real time applications, the integration of different systems is achievable and beneficial for GNSS and meteorology applications.

Considering the aforementioned, this study aims to analyze the integration between GPS and Galileo on a PPP solution regarding the IWV estimation product. This paper is organized in order to present the dataset used and processing parameters, followed by the IWV estimation technique, data analysis, conclusions, and future work.

2 Data

For use in this investigation, 4 days of four globally-distributed International GNSS Service (IGS) Multi-GNSS Experiment (MGEX) tracking stations were selected at locations within 10 km of radiosondes launched daily at 0000Z and 1200Z. Their approximate locations are shown in Fig. 2.

These selected stations provide receivers with Galileo tracking capability as well as radiosonde data availability for the time interval of each station's 24-hour GNSS observation period. While dual-frequency observables are available from the 11 current Galileo satellites, observation periods are rather inconsistent due to their limited number. Additionally, simultaneous observability of a minimum of four Galileo satellites is currently limited to 4 h (at best) with, in most situations, relatively poor satellite geometric distribution. These conditions hinder any accurate estimation of IWV using Galileo-only processing at this time. For the processing of GPS observables, standard IGS final clock (5-minute) and orbit products have been utilized. For Galileo observable processing, clock (5-minute) and orbit products from the Center for Orbit Determination in Europe (CODE) made available through the IGS MGEX campaign have been utilized (Montenbruck et al. 2014). While observables were logged at a 30-second sampling interval at each of the selected stations, processing was performed at a 5-minute interval as to avoid interpolation of satellite clock corrections, including the subsequent estimation of IWV. All of the aforementioned products are available from the IGS FTP servers with a latency of approximately 2 weeks (Dow et al. 2009).

In order to appropriately combine observables from different constellations, additional system-dependent corrections must be applied. These corrections include estimated inter-system biases (ISBs), differential code biases (DCBs), and

[1]http://weather.uwyo.edu/wyoming/.

Fig. 2 Location of the selected GNSS stations and radiosonde launching sites

antenna phase-centre offsets. In GAPS modified algorithm, ISBs are estimated in order to account for the varying antenna differential delays experienced when tracking multi-constellation observables. A random-walk with a process noise of 0.10 m/$\sqrt{\text{h}}$ is subsequently applied in order to properly constrain ISB parameters. As the IGS MGEX orbit and clock products reflect the use of the E1/E5a iono-free linear combinations also used in GAPS, no DCB corrections to Galileo observables are currently required. Differing antenna phase-centre offsets, on the other hand, must be considered when combining multi-constellation observables. While standard IGS ANTEX phase-centre offsets (PCOs) and variations (PCVs) are used for GPS observables, GAPS applies generic Galileo IOV and FOC satellite PCO corrections as recommended by the IGS MGEX campaign (http://mgex.igs.org/IGS_MGEX_Status_GAL.html). At this time, no corrections for PCVs are considered as no data is yet available.

The residual wet component (as well as a trace of the dry component) of the neutral atmospheric delay (D_{ZW}) is estimated within GAPS sequential least-squares filter and constrained with a random-walk process noise of 5 mm/$\sqrt{\text{hr}}$. VMF1 (ECMWF) was utilized as the a priori NAD prediction model and reduced to a vertical delay through use of the Vienna mapping functions. Observables used in processing include the iono-free linear combination of the GPS legacy L1/L2 and Galileo Open Service E1/E5a signals. A 10° elevation angle cutoff threshold was applied as was a GDOP cutoff threshold of 20 to avoid outliers caused by poor geometry. Additionally, both Earth body tides and ocean tidal loading corrections were applied to modeled parameters during processing. The station coordinates were left unconstrained at the beginning of the processing and then propagated between days.

3 IWV Estimation

In order to assess the impact of using Galileo observables in a PPP solution, the chosen dataset was processed with GAPS using GPS-only and GPS + Galileo strategies. Estimates resulting from GPS-only and GPS + Galileo processing are subsequently analyzed and compared to each other to see if the multi-GNSS solution is able to provide satisfactory results in terms of inferring total NAD. As a second step, the wet component of the delay (D_{ZW}), along with troposphere mean temperature (T_m) from VMF1 model, water vapor specific constant (R_w), and atmospheric refractivity constants (k_2',k_3) are used to estimate IWV (Sapucci et al. 2005):

$$\text{IWV} = D_{ZW} \frac{10^6}{R_w \left[k_2' + \frac{k_3}{T_m}\right]}, \tag{1}$$

where the constants k_2' and k_3 are, respectively, 22.1 ± 2.2 (in Kelvin per hectopascal (K/hPa)) and $3.739 \pm 0.012 \times 10^5$ (K^2/hPa) (Davis et al. 1985).

Once IWV is determined, a comparison is performed against in situ radiosonde precipitable water sounding. The difference is then summarized and analyzed to assess the interoperability between GPS and Galileo for such an application as well as to determine the appropriateness of the least-squares algorithm used in GAPS to estimate the wet delay.

4 Data Analysis

Even though the Galileo constellation is still in its infancy, integration of Galileo observables with those of GPS is currently achievable and shows satisfactory results in

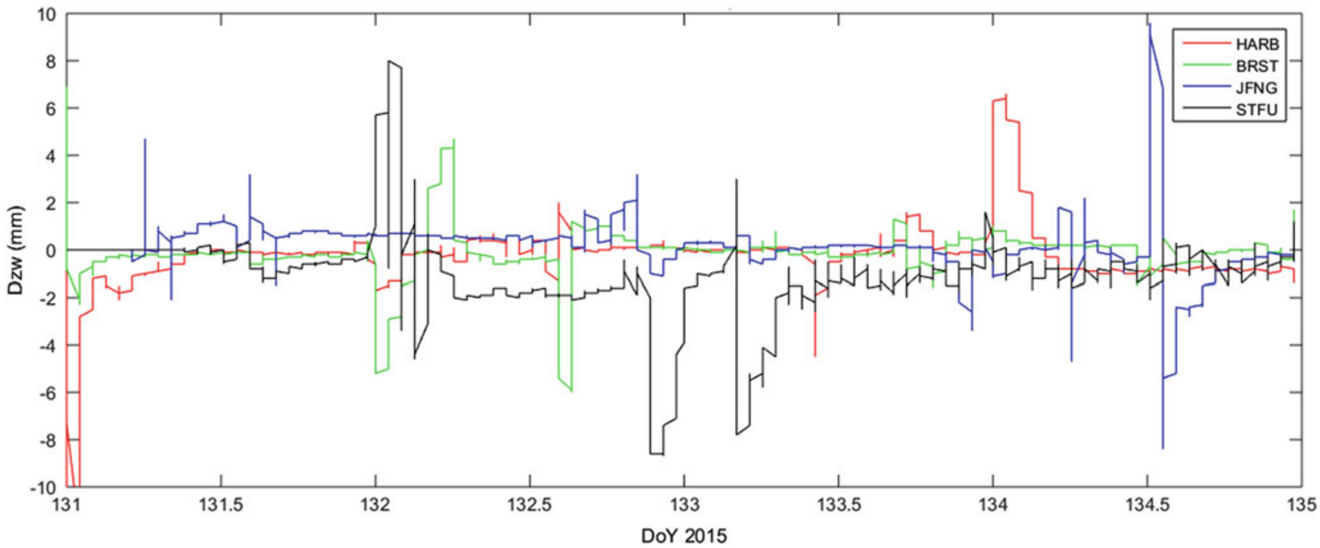

Fig. 3 Time series of the difference between GPS-only and GPS + Galileo D_{ZW} estimates between DOY 131 and 135, 2015

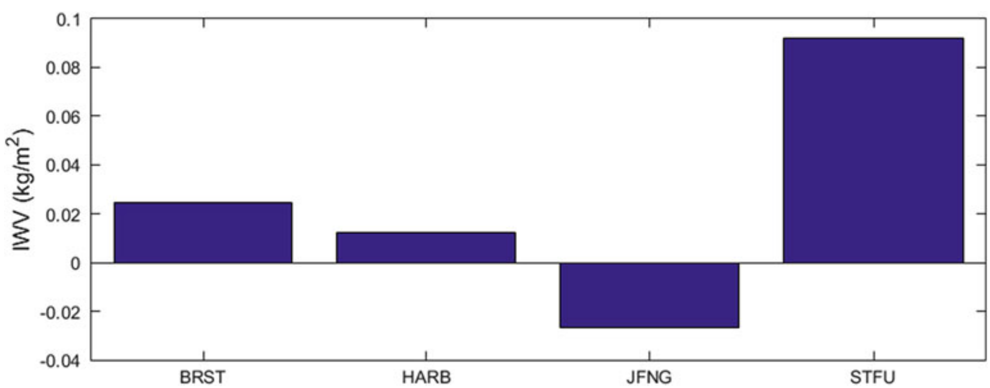

Fig. 4 Discrepancy between GPS-only minus GPS + Galileo IWV

terms of position and atmospheric parameter estimation. By analyzing the differences between GPS-only and GPS + Galileo D_{ZW} estimates, it can be seen that the differences between each are, on average, within 1 mm of the estimated D_{ZW} (station STFU) with a minimum difference of 0.08 mm (station JFNG). This represents approximately 0.16 and 0.013 kg/m^2 of precipitable water in the atmosphere, respectively. A maximum difference of about 1 cm occurred at station JFNG at 1200Z on day-of-year (DOY) 134, representing a discrepancy in the precipitable water estimate of approximately 1.7 kg/m^2. Figure 3 summarizes the analysis of the entire dataset. With the exception of station STFU, all the GPS minus GPS + Galileo solutions are below the millimeter level on average and 1.5 mm of standard deviation. For STFU, the average is 2.2 mm and a standard deviation of 2.8 mm.

Although occasional outliers exist, the average difference remains within the expected noise of Galileo observable integration when considering the sporadic availability of Galileo satellites and the use of experimental Galileo orbit and clock products. To investigate if these outliers are due to the integration algorithm or, perhaps, with the tropospheric delay estimation, radiosonde sounding data are used as a benchmarking tool for further comparison of estimated precipitable water. Figure 4 shows the discrepancy between GPS-only minus GPS + Galileo IWV. Figure 5 shows error bars for each station related to the difference between the GPS + Galileo PPP-based estimation of IWV and the radiosonde-measured IWV.

It is possible to see that the error in both estimates are close in terms of bias and dispersion from the radiosonde estimates (Fig. 5). This, again, indicates a success in terms of the system integration being that GPS + Galileo estimations are, on average, closer to the radiosonde IWV measurements than GPS-only solutions, but points towards a necessary investigation of the D_{ZW} estimation algorithm for both methods.

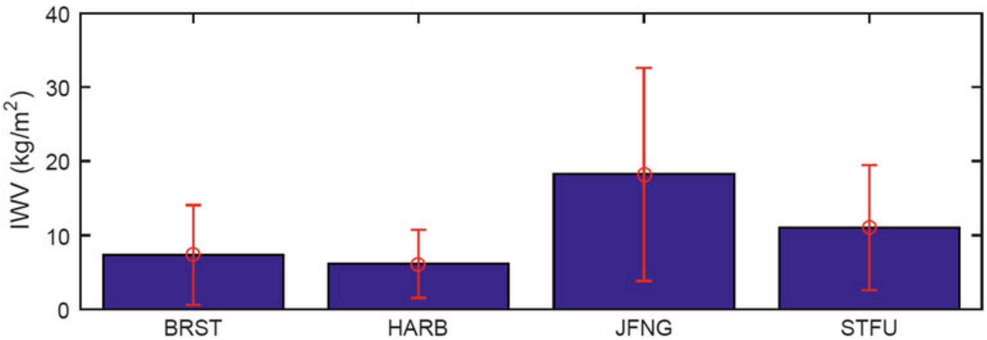

Fig. 5 Error bars for each station related to the difference between the PPP-based estimation of IWV and the radiosonde-measured IWV

It is important to stress that the immaturity of the Galileo products combined with challenges in finding a reasonable geometry contribute to occasional spikes in the solution. In spite of the fact that their source is hard to track without proper geometry and orbit repeatability, from the analyzed dataset it is possible to conclude that they are occasional and not a recurrent problem in the integration.

5 Conclusions

Results show that the Galileo + GPS IWV estimates are close to those of GPS-only at a level of 0.13 kg/m^2 of precipitable water. This demonstrates that both systems can be successfully used together to improve data quality, specifically in challenging environments where satellite geometry can be an issue. Although the selected datasets were obtained from sites with unobstructed surroundings to eliminate other possible error sources, it is safe to say that users can, by now, begin to take advantage of the Galileo GNSS, particularly in the case of estimation of atmospheric parameters. For atmospheric research, Galileo-only processing is still not currently feasible as the constellation as-is provides very large DOP values due to the limited number of observable satellites as well as the limited availability of a minimum of four simultaneously-observable satellites. However, with the anticipated launch of several more full-operational-capability satellites in the coming year, Galileo will soon become a useful tool for atmospheric parameter estimation and IWV determination.

Another point to be emphasized is that GAPS is able to integrate both constellations, estimate the wet component of the troposphere delay and calculate the IWV parameter. This implementation is a novelty among the free online PPP software suites currently available to the research community.

6 Future Work

As previously mentioned, the Galileo constellation remains at an early stage in its development. Following successful completion of the Galileo In-Orbit-Validation (IOV) campaign and the salvage mission to restore the two Galileo satellites affected by the orbit injection anomaly of 2014, the constellation is rapidly progressing towards Full-Operation-Capability. As more and more satellites are added to the constellation, satellite availability and geometry will improve significantly, thus enhancing the performance of GPS + Galileo and Galileo-only atmospheric parameter estimation through use of the PPP estimation technique. Additional improvements to the IGS MGEX Galileo orbit and clock product line are sure to follow, further enhancing the accuracy potential of atmospheric parameters like IWV. Future research will investigate this potential enhancement in accuracy by including each new Galileo satellite as they become available as well as utilizing new and improved Galileo products as they are introduced.

Further work will also need to be done in order to optimize the GAPS NAD estimation algorithm in order to account for biases seen between its integrated IWV estimates and those of the radiosonde data. Alternative estimation routines will be investigated as will use of various NAD prediction models and mapping functions.

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